Geohydrology and Simulated Effects of Large Ground-Water Withdrawals on the Mississippi River Alluvial Aquifer in Northwestern Mississippi

United States Geological Survey Water-Supply Paper 2292

Prepared in cooperation with the Mississippi Department of Natural Resources, Bureau of Land and Water Resources

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Geohydrology and Simulated Effects of Large Ground-Water Withdrawals on the Mississippi River Alluvial Aquifer in Northwestern Mississippi

By D.M. SUMNER and B.E. WASSON

Prepared in cooperation with the
Mississippi Department of Natural Resources,
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U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2292

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE : 1990

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

Library of Congress Cataloging in Publication Data

Sumner, D.M.
Geohydrology and simulated effects of large ground-water withdrawals on the Mississippi River alluvial aquifer in northwestern Mississippi.

(Water-supply paper ; 2292)
Bibliography: p.
Supt. of Docs. no.: I 19.13:2292
1. Water, Underground—Mississippi—Data processing. 2. Water, Underground—Mississippi—Mathemathical models. 3. Aquifers—Mississippi—Data processing. 4. Aquifers—Mississippi—Mathematical models. 5. Water-supply—Mississippi—Data processing. 6. Water-supply—Mississippi—Mathematical models. 7. Water withdrawals—Mississippi—Data processing. I. Wasson, B.E. (Billie E.), 1925- . II. Title. III. Series: Geological Survey water-supply paper ; 2292.
GB1025.M7S86 1990 553.7'9'097624 85-600332

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Factors for Converting U.S. Customary Units to International System (SI) Units

The following factors may be used to convert inch-pound units published herein to the International System of Units (SI):

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.004	square kilometer (km^2)
	Volume	
cubic foot	0.02832	cubic meter
acre foot	1233	cubic meter
	Flow	
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Gradient	
foot per mile (ft/mi)	18.9	centimeter per kilometer (cm/km)
	0.189	meter per kilometer (m/km)
	Hydraulic conductivity	
foot per day (ft/d) or cubic foot per square foot per day [$(ft^3/ft^2)/d$]	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d) or cubic foot per day per foot [$(ft^3/d)/ft$]	0.0920	meter squared per day (m^2/d)
	Riverbed conductance	
foot squared per day (ft^2/d) or cubic foot per day per foot [$(ft^3/d)/ft$]	0.0929	meter squared per day (m^2/d)
	Leakance	
per day (d^{-1}) or cubic foot per day per square foot per foot [$(ft^3/d)/ft^2]/ft$	1	per day (d^{-1})

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.

Geohydrology and Simulated Effects of Large Ground-Water Withdrawals on the Mississippi River Alluvial Aquifer in Northwestern Mississippi

By D.M. Sumner *and* B.E. Wasson

Abstract

The 7,000-square-mile Mississippi River alluvial plain in northwestern Mississippi, locally known as the "Delta," is underlain by a prolific aquifer that yielded about 1,100 million gallons per day of water to irrigation wells in 1983. About 20 feet of clay underlying the Delta land surface commonly is underlain by about 80 to 180 feet of sand and gravel that forms the Mississippi River alluvial aquifer. This study of the alluvial aquifer was prompted by recent declines of water levels. The study was designed to better define the hydrology of the aquifer and to quantify availability of water from the aquifer.

The Mississippi River is in good hydraulic connection with the alluvial aquifer. Generally, smaller streams are less likely to recharge the aquifer than larger streams. Direct vertical recharge to the alluvial aquifer from the 52 inches per year of precipitation is small, especially in the central part of the Delta.

A two-dimensional finite-difference computer model of the alluvial aquifer was constructed, calibrated, and verified using water levels observed for five dates from April 1981 to September 1983. The values of some of the calibration-derived parameters are hydraulic conductivity, 400 feet per day; specific yield, 0.30; and infiltration of precipitation to the aquifer, 0.5 inch per year.

The model showed that the aquifer had a net loss in storage of about 360 million gallons per day from April 1981 to April 1983. During this period, pumpage was about 1,100 million gallons per day (1,270,000 acre-feet per year), and the net inflows from the sources of recharge were as follows, in million gallons per day: Mississippi River, 390; recharge along the east edge of the Delta, 170; streams within the Delta, 57; areal recharge from infiltration, 180; and oxbow lakes, 24.

The effects of several levels of pumpage by wells—0, 670, 1,100, 1,900, and 4,000 million gallons per day—were projected 20 years into the future. In 2003, the 1,100-million-gallon-per-day pumping rate, about average for the early 1980's, would take 46 percent of the water withdrawn from aquifer storage, water levels would be lowered more than 20 feet in a large area in the central part of the Delta, and ground-water levels would continue to decline in future years.

INTRODUCTION

The Mississippi River alluvial aquifer underlies the Mississippi River alluvial plain, which is part of several States adjoining the lower part of the Mississippi River. The part of the Mississippi River alluvial plain in northwestern Mississippi is known locally as the "Delta." The Delta slopes about 0.5 foot per mile (ft/mi) from about 220 feet (ft) above sea level at the upper end near Memphis, Tenn., to about 80 ft near Vicksburg, Miss., a distance of 200 miles (mi). The Delta has an area of about 7,000 square miles (mi^2). The Mississippi River forms the western edge of the Delta, or study area (figs. 1, 14). An escarpment, the Bluff Hills, which are about 100 to 200 ft higher than the alluvial plain, forms the eastern edge of the Delta. The Yazoo-Tallahatchie-Coldwater River system drains the eastern edge of the plain and collects water from many streams that enter the plain from the hills to the east (fig. 14).

Precipitation in the Delta averages about 52 inches per year (in/yr). The approximate seasonal distribution of precipitation, in inches, is as follows: winter, 17; spring, 15; summer, 11; and fall, 9. Average annual temperature ranges from 62°F near Memphis to 66°F near Vicksburg. The normal frost-free growing season extends from early April to early November.

Most of the water pumped in the Delta is used for irrigation and comes from the Mississippi River alluvial aquifer. In recent years, catfish farming has become a major user of ground water, second only to irrigation. Increasing use of water from the alluvium and decreasing water levels in the early 1980's prompted this study. Use of water from the alluvial aquifer increased from about 200 million gallons per day (Mgal/d) in the early 1970's to about 1,100 Mgal/d in the early 1980's.

Before 1800, the Delta was covered with hardwood forest. By 1930, about one-half of the Delta had been

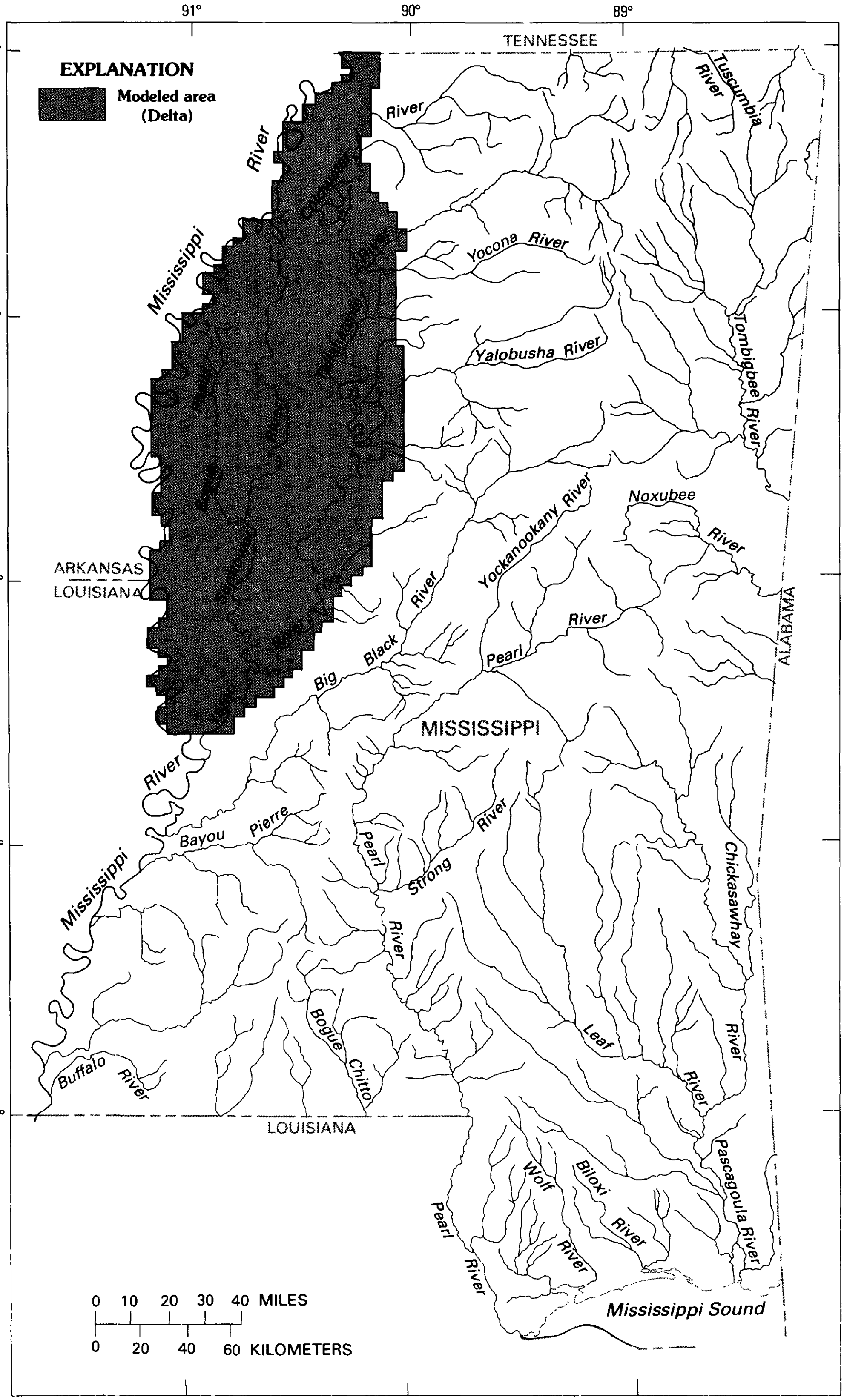

Figure 1. Location of the study area (Delta) in northwestern Mississippi.

cleared and was in row crops—primarily cotton. In 1983, only small areas of the hardwood forest remained, except for the Delta National Forest in Sharkey and Issaquena Counties and the floodway area between the levees of the Mississippi River.

The purpose of this study was to better understand and define the hydrology of the Mississippi River alluvial aquifer in northwestern Mississippi and to quantify the effects of future withdrawals of water for irrigation, catfish farming, and other uses.This report describes the geohydrology of the Mississippi River alluvial aquifer as determined by field investigations and digital modeling of the aquifer. The report was prepared by the U.S. Geological Survey in cooperation with the Mississippi Department of Natural Resources, Bureau of Land and Water Resources. The Mississippi Research and Development Center also provided financial support. Water use in the Delta was studied in cooperation with the U.S. Soil Conservation Service. The authors wish to acknowledge several people within the U.S. Geological Survey who made significant contributions to the study and report. R. E. Taylor did most of the computer-related work and aided greatly in development of the digital model. J. S. Weiss served as a technical advisor to the project personnel. Principal technical reviewers of the report were M. J. Mallory, D. J. Ackerman, John Vecchioli, and D. G. Jordan, all of whom made constructive suggestions that greatly enhanced the final result.

Potentiometric surface maps were constructed for the Mississippi River alluvial aquifer in the Delta for each April and September from September 1980 to September 1983. These potentiometric surface map reports also presented preliminary interpretations of the aquifer hydrology. Work was started in 1982 on the conceptual and digital models of the alluvial aquifer.

CONCEPTUAL MODEL OF GEOHYDROLOGY OF THE MISSISSIPPI RIVER ALLUVIAL AQUIFER

Geohydrology of Units Underlying the Alluvial Aquifer

In northwestern Mississippi, the Mississippi River alluvium was deposited upon an unconformable Eocene surface. The principal units underlying the Mississippi River alluvial aquifer, from northeast to southwest and from oldest to youngest, are as follows: Zilpha Clay, Sparta Sand, Cook Mountain Formation, Cockfield Formation, and Jackson Group. The relations of these geologic units to each other and to the overlying Mississippi River alluvial aquifer are shown on a map (fig. 2), which illustrates outcrops and subcrops of the geologic units in the study area, and three geologic sections (fig. 3). The geologic units generally dip 15 to 40 ft/mi to the west toward the axis of the Mississippi River embayment trough, which approximately parallels the Mississippi River. Table 1 summarizes the geohydrology of the

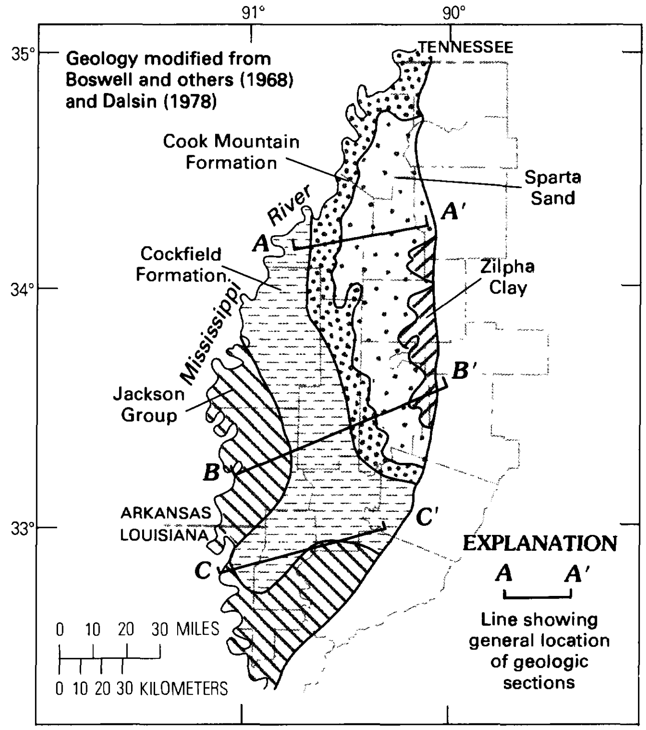

Figure 2. Geologic units subjacent to the Mississippi River alluvium and general location of geologic sections.

principal geologic units underlying the Mississippi River alluvial aquifer.

Mississippi River Alluvial Aquifer

Geology

The Mississippi River alluvium, which is of Quaternary age, was deposited by the Mississippi River and its tributaries. The alluvium was deposited on an erosional surface having a system of north-south valleys (Fisk, 1944). The coarsest sediments (gravel and coarse sand) generally occur at or near the base of the alluvium and tend to be thicker where the alluvium is thickest. The alluvium grades upward from gravel and coarse sand to medium or fine sand to clay. The upper part of the alluvium generally consists of clay of variable thickness but averages about 20 ft of clay; clay thickness can be as much as 70 ft in some of the abandoned stream channels. Average thickness of the alluvium is about 140 ft but ranges from about 80 to about 240 ft. The coarse lower sediments, sands and gravels that comprise the alluvial aquifer, tend to be thickest in the center of the alluvial plain and thinner towards the periphery of the Delta (fig. 4). The alluvium thins to a feather edge along the eastern side of the Delta.

Aquifer Boundaries

The alluvial aquifer in northwest Mississippi is a relatively distinct hydrologic unit as described in the previous section. Along the eastern edge of the Delta abutting the

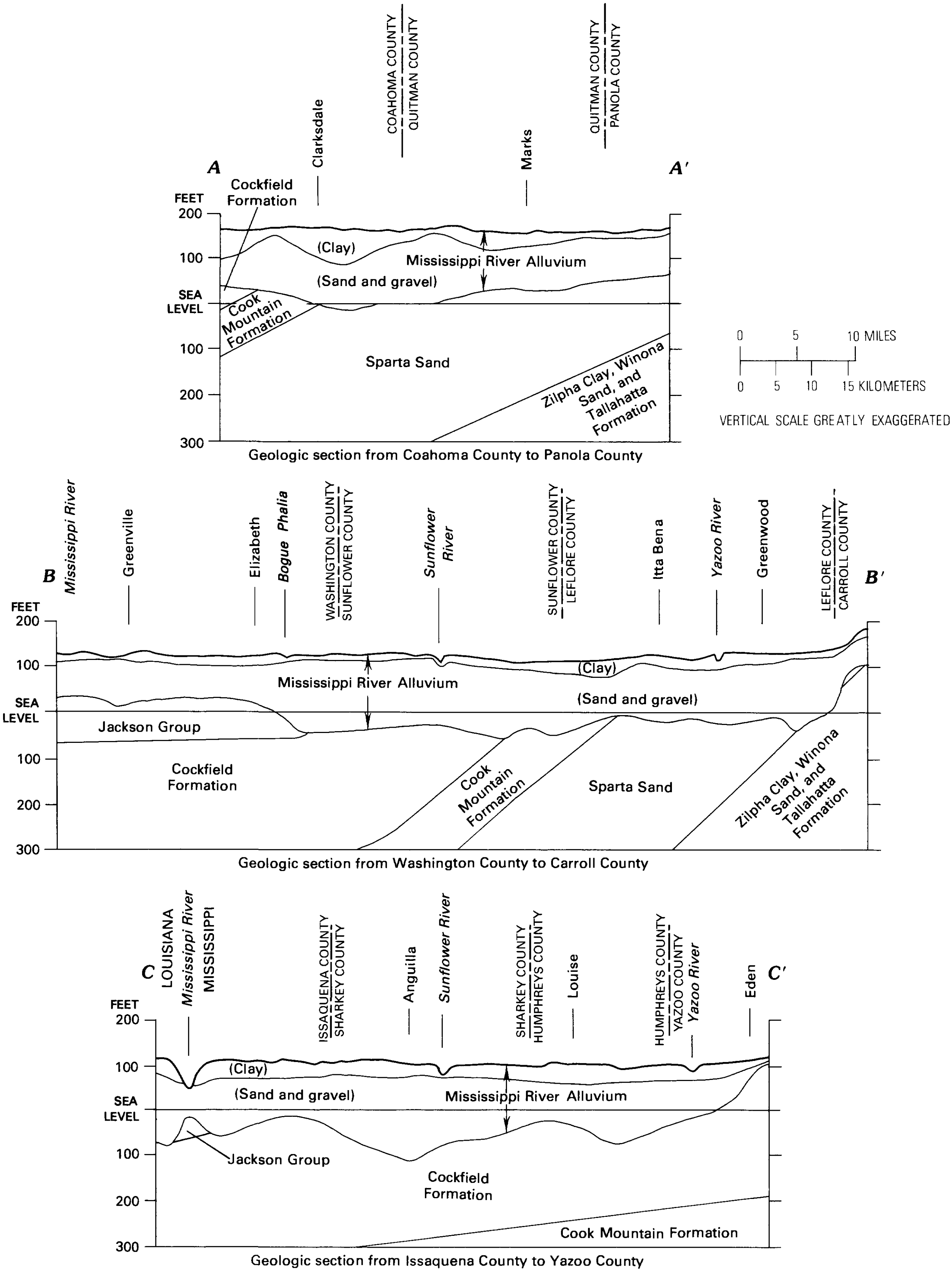

Figure 3. Geologic sections east-west across the Delta.

Table 1. Geohydrology of the principal geologic units underlying the Mississippi River alluvial aquifer

Geologic unit	Maximum thickness (feet)	Lithology	Water-bearing characteristics
Yazoo Clay of the Jackson Group	100	Clay	Not an aquifer.
Cockfield Formation	500	Sand and clay	Sand beds form the Cockfield aquifer (Spiers, 1977). Potentiometric surface is about the same as that in alluvial aquifer.
Cook Mountain Formation	170	Clay and sandy clay	Not an aquifer.
Sparta Sand	700	Sand and clay	Sand beds form the Sparta aquifer system (Newcome, 1976). Potentiometric surface is about the same as that in the alluvial aquifer.
Zilpha Clay	150	Clay; becomes sandy northward.	Not an aquifer.

Bluff Hills, the surficial, sandy, permeable alluvial fans allow water from the streams crossing the fans and precipitation falling on the fans to infiltrate the alluvial aquifer. Also, along most of the eastern edge of the Delta, the Cockfield or Sparta aquifers underlie the alluvial aquifer and have sufficient head to cause water to flow into it.

The Mississippi River, deeply incised in the coarser part of the alluvium and in complete hydologic connection with the alluvial aquifer, forms the western boundary of the aquifer. The aquifer is recharged and drained by the Mississippi River on a seasonal basis, but the net effect is one of recharge to the aquifer. On the northern and southern ends of the Delta, the alluvial plain narrows to a few miles in width. The Yazoo River, although not as deeply incised as the Mississippi River, forms nearly as effective a hydraulic barrier on the southern end. Because the Mississippi River and Bluff Hills are within a few miles of each other along the northern boundary of the study area, the resulting narrow width of the alluvium in this area results in an effective isolation of the bulk of the alluvium in Mississippi from the alluvium north of the area.

Aquifer Confinement

The alluvial aquifer varies between confined and unconfined conditions with space and time. The area of the aquifer near the Mississippi River changes between the two regimes with variations in river stages. In the center of the Delta, the aquifer generally is unconfined, largely due to the relatively deep ground-water levels that have resulted from the withdrawals. In the eastern part of the Delta (with the exception of a band immediately adjacent to the Bluff Hills where the clay confining cap is absent), the aquifer usually is confined due to several recharge mechanisms that serve to maintain shallow water levels.

Surface-Subsurface Hydrologic Relations

With several notable exceptions, surface and ground water in the Delta are insulated fairly well from one another due to the relatively impermeable clay cap over the alluvial aquifer. The exceptions include the Mississippi, Yazoo, and Tallahatchie Rivers, and, to a lesser extent, the Coldwater and Sunflower Rivers and the Bogue Phalia. These streams have penetrated, completely or partially, the clay cap; therefore, the streams are in varying degrees of hydraulic contact with the aquifer. The amount of ground-water–surface-water interflow along a river stretch varies areally (degree of stream-aquifer connection varies with areal variation in clay thickness) and temporally (large seasonal fluctuations in stream stages change magnitude and direction of interflow).

Water-Level Fluctuations, Potentiometric Surface, and Direction of Flow

In the central part of the Delta, the water level in the alluvial aquifer generally is from 30 to 50 ft below land surface, whereas, in other areas, the water levels usually are less than 25 ft below land surface. Since 1980, some short-term hydrographs show rates of water-level decline of about 2 ft/yr in the central part of the Delta. Several long-term observation well hydrographs show the effect of nearby fluctuating stream stages but exhibit no long-term changes.

Potentiometric surface maps of all or parts of the alluvial aquifer are available for the years 1955, 1965, 1976, and 1980 (Harvey, 1956; Boswell and others, 1968; Dalsin, 1978; and Wasson, 1980b). Subsequently, potentiometric surface maps were made each April and September from 1981 to 1983 (Darden, 1981, 1982a, b, 1983; Sumner, 1984a, b). Ground-water level measurements were made in late April, shortly before the rice irrigation season, and in late September, after the end of the irrigation season. These maps show that regional aquifer flow is composed of two components—a north-to-south axial flow and a periphery-to-interior transaxial flow, the former due to the topographic highs in the north and the latter due to the influence of the predominantly peripheral aquifer recharge (fig. 5).

Along the major streams having good hydraulic connection with the aquifer, the direction of ground-water flow is

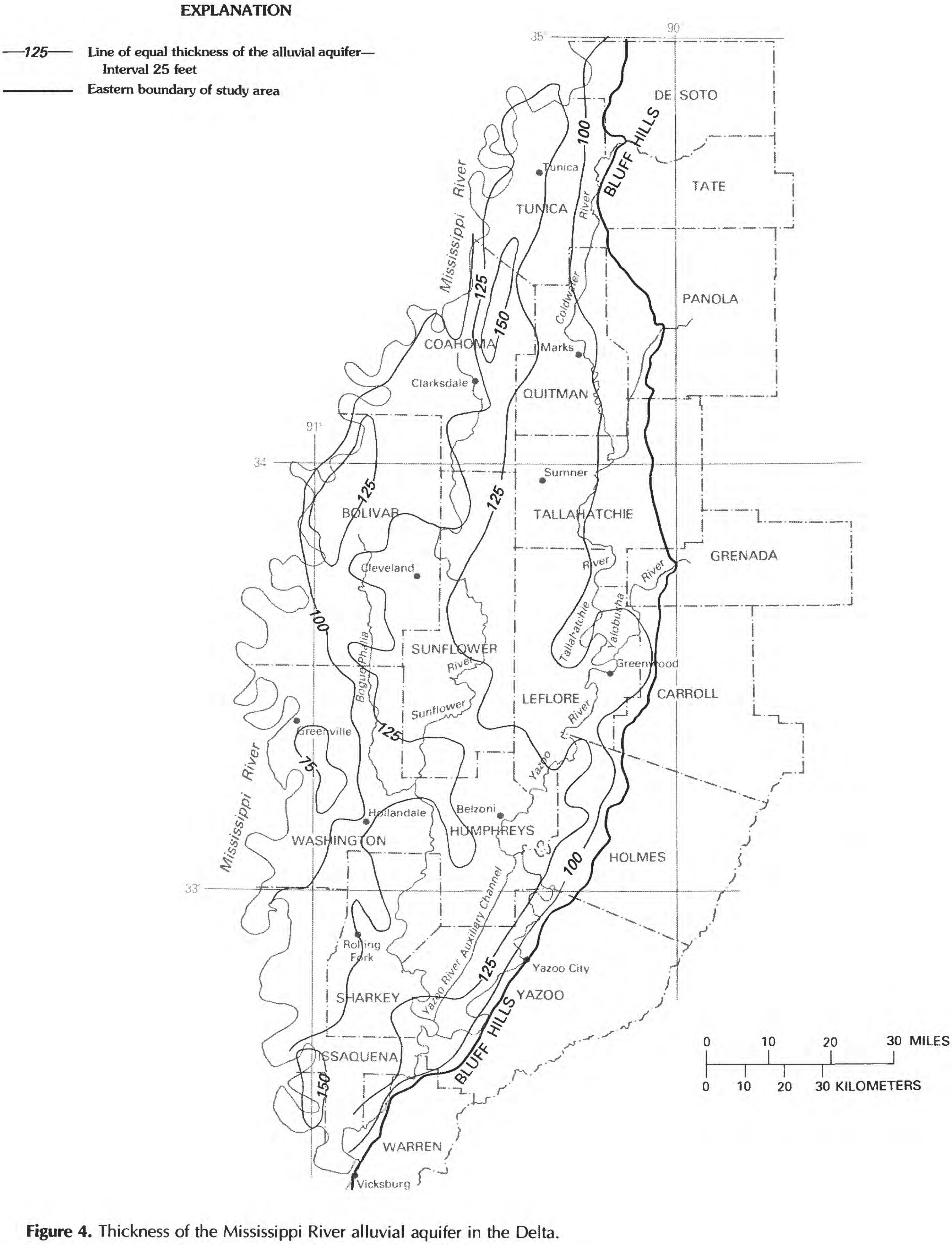

Figure 4. Thickness of the Mississippi River alluvial aquifer in the Delta.

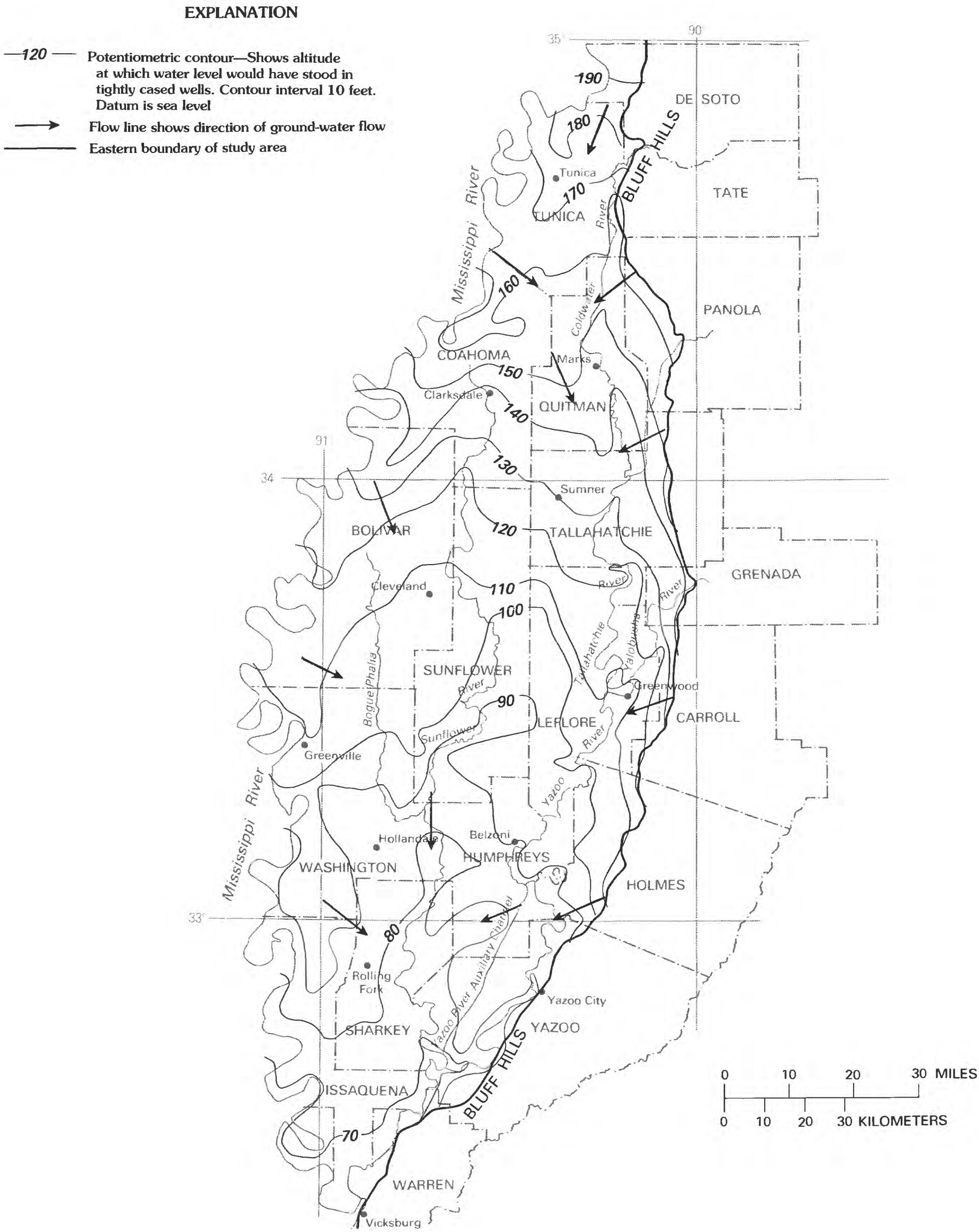

Figure 5. Potentiometric surface of the alluvial aquifer in the Delta for April 1981.

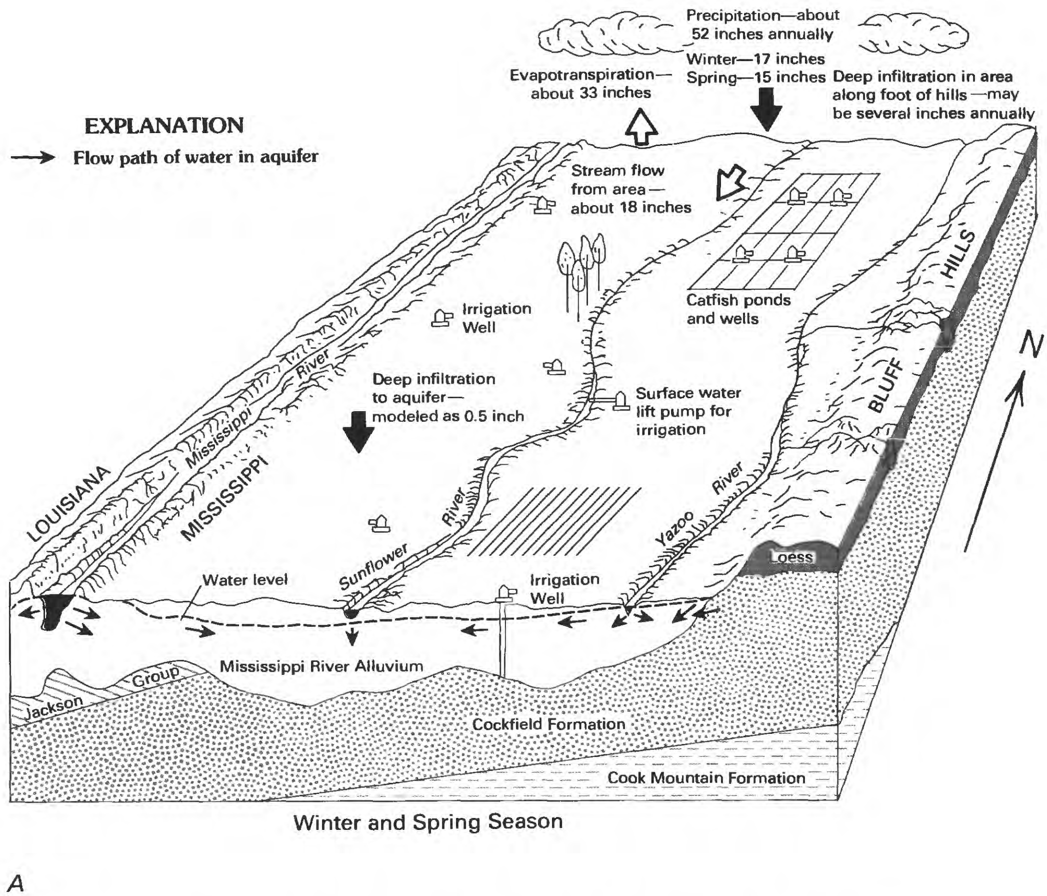

Figure 6. Relations among geologic, hydrologic, and climatic processes in the Delta.

away from the streams during high stream stages in winter and spring (fig. 6). Flow in the aquifer is toward these streams during low stream stages in the summer and fall. The Mississippi River is the stream having the most pronounced seasonal effects on the potentiometric surface and on water-level profiles (figs. 7, 8). The Yazoo and Tallahatchie Rivers have less effect on the aquifer than the Mississippi River, and smaller streams have even less effect. Large fluctuations in the stage of the Sunflower River, Coldwater River, and Bogue Phalia, in comparison to water-level changes in the alluvial aquifer, indicate that the hydraulic connection between them and the aquifer is poorer than that of the other major streams.

The Sunflower River and that part of the Yazoo River below the mouth of the Sunflower historically have acted as long-term drains from the alluvial aquifer in the central part of the Delta. Average stages in the Sunflower River are about 20 ft lower than those in the Mississippi River to the west and in the Yazoo River to the east. This difference in head has influenced the configuration of the potentiometric surface in the alluvial aquifer. Historically, the potentiometric surface of the aquifer has sloped toward the Sunflower River from the north, west, and east (fig. 5) even though hydraulic connection is poor. Pumpage for irrigation and catfish ponds since 1980 has caused a general decline of 1 to 2 ft/yr in the potentiometric surface in the central part of the Delta. As a result, in some reaches of the Sunflower River, the potentiometric surface has declined slightly below the level of the lower stages in the river, and the river may now recharge the aquifer in these areas all year as indicated in the profiles in figure 8.

Water also enters the alluvial aquifer areally as direct infiltration of precipitation. However, as determined by simulation studies, this infiltration is only a small fraction of the total precipitation.

Aquifer Characteristics

Transmissivity, hydraulic conductivity, specific yield, and storage coefficient are aquifer characteristics that indicate the capacity of an aquifer to transmit and store water. Transmissivity is a measure of the ability of an aquifer to transmit water through a unit width of the aquifer in response to a hydraulic gradient. Hydraulic conductivity (transmissivity divided by saturated aquifer thickness) is a measure of the ability of the aquifer to transmit water though a unit area of the aquifer. The storage coefficient is the volume of water that an aquifer releases from or takes into

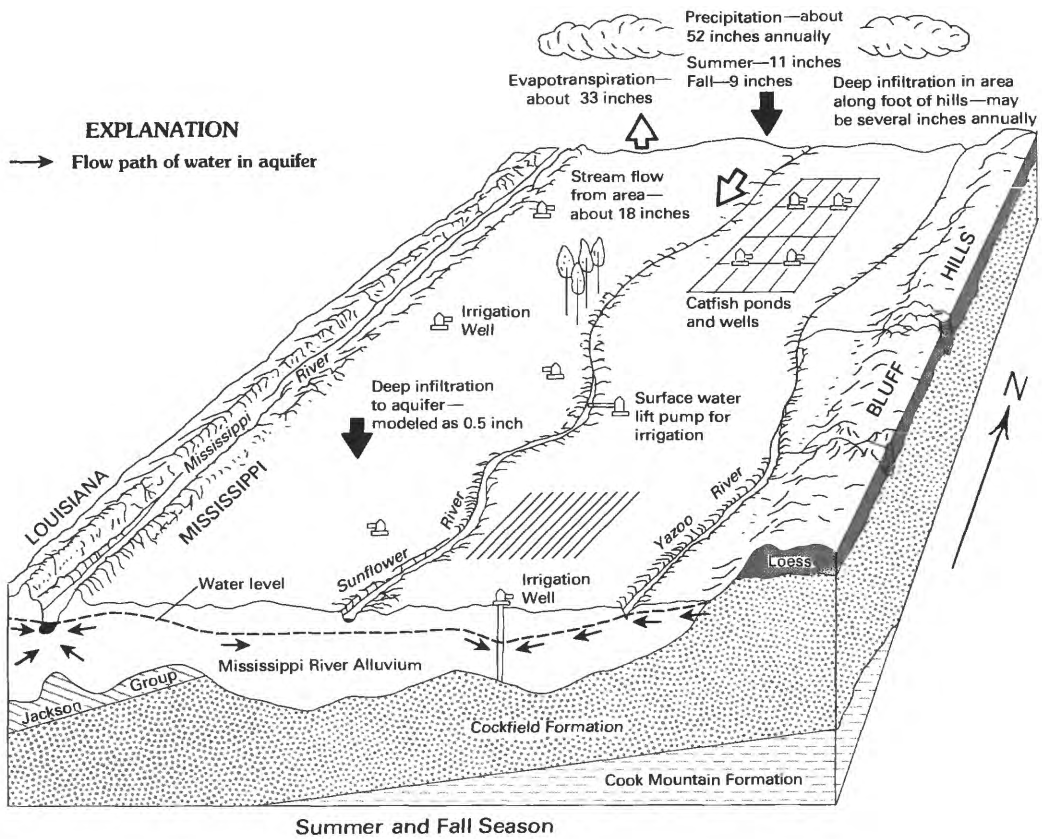

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Figure 6. Continued.

storage per unit surface area of the aquifer per unit change in hydraulic head. Storage coefficients for confining aquifers range from about 0.005 to 0.00005. The specific yield of the aquifer is the volume of water that a unit volume of aquifer material will yield by gravity drainage.

Aquifer tests of the Mississippi River alluvial aquifer at four sites (Newcome, 1971) have maximum, average, and minimum transmissivity values of 51,000, 35,000, and 21,000 cubic feet per day per foot [feet squared per day (ft^2/d)], respectively. The same tests have maximum, average, and minimum hydraulic conductivity values of 400, 320, and 230 cubic feet per square foot per day [foot per day (ft/d)], respectively. The areal distribution of transmissivity (fig. 9) generally follows that of aquifer thickness (fig. 4)—a trend of progressively higher values toward the center of the alluvial plain.

The coefficient of storage for the aquifer tests ranged from 0.0003 to 0.016, reflecting confined and unconfined conditions. The coefficients of storage were determined from tests that were run from 13 hours to 6 days—durations too short to reflect complete pore-space dewatering. A long-term aquifer test probably would yield a storage coefficient approaching the specific yield of the aquifer. The specific yield of the alluvial aquifer has not been measured in the Delta, but, west of the Mississippi River in Arkansas, the specific yield of the Mississippi River alluvial aquifer is reported to range from 0.27 to 0.38 based on laboratory measurements of repacked samples (Johnson and others, 1966).

Pumpage From Aquifer

Irrigation, principally for rice, is the largest use of water from the Mississippi River alluvial aquifer. Another large use of water from the alluvial aquifer is to fill, maintain the water level, and aerate the water in catfish ponds. The use of water for irrigating other crops, principally soybeans and cotton, was estimated to be 10 percent of the volume used for rice in 1982. The city of Vicksburg and three thermoelectric power generation plants at Clarksdale, Greenwood, and Yazoo City each use about 10 Mgal/d of water from the alluvial aquifer.

Before 1948, less than 5,000 acres of rice were planted annually in the Delta, but, by 1954, acreage had increased to 79,000 acres. From 1955 to 1973, rice acreage in the Delta was nearly constant at about 55,000 acres. Since 1973, rice acreage has fluctuated widely—as much as 340,000 acres in 1981 and as little as 155,000 acres in 1983 (fig. 10).

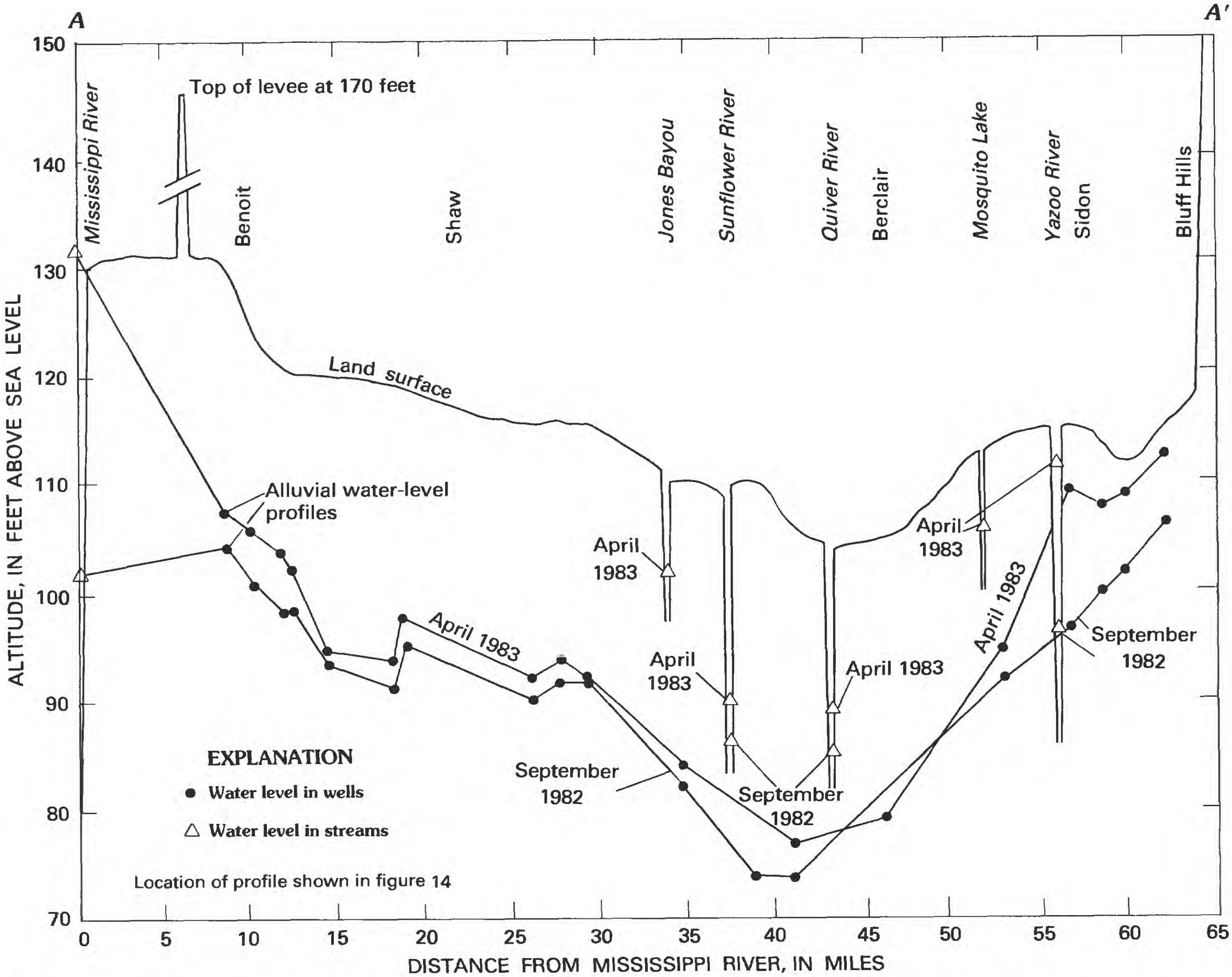


Figure 7. Water-level profile (*A–A'*) across the Delta from Benoit in Bolivar County to Sidon in Leflore County.

Catfish-pond acreage increased in the Delta from about 18,000 acres in 1977 to about 61,000 acres in 1983 (fig. 10). Estimated application rates for rice and catfish in the 1980's are tabulated as follows:

Rice irrigation (feet per year)		Catfish ponds (feet per year)	
1981	3.3	1981	5.1
1982	4.2	1982	7.3
1983	3.6	1983	6.0

Halberg (1977) reported application rates on rice in two areas of the Mississippi River alluvial aquifer in Arkansas to be 2.6 and 3.2 ft/yr. He also reported an application rate of 8 ft/yr for catfish ponds.

Agricultural and aquacultural water use in the Delta increased from about 200 Mgal/d in 1970 to almost 1,400 Mgal/d in 1982 (fig. 11). From 1981 to 1982, rice acreage decreased from 340,000 to 240,000 acres, and catfish acreage increased from 44,000 to 60,000 acres. Water use per acre for both purposes was higher in 1982 than in 1981, resulting in an increase in total use of about 10 percent in 1982. Agricultural and aquacultural pumpage is concentrated in the central part of the Delta (fig. 12).

Water Quality

Water from the alluvial aquifer in the Delta commonly is a hard, calcium-bicarbonate type containing from 100 to 700 milligrams per liter (mg/L) of dissolved solids. The water usually contains appreciable amounts of manganese and iron, which make it less attractive to many users or potential users; however, the quality of water in the alluvium is generally well suited for irrigation. Chemical analyses of the water are presented by Harvey (1956), Boswell and others (1968), and Dalsin (1978).

The distribution of dissolved solids in water in the Delta's alluvial aquifer is related to lithology, hydraulics, and history of the aquifer. A dissolved-solids distribution map (fig. 13) shows that, near the Mississippi River in the northern part of the Delta, the dissolved-solids concentration generally ranges from 300 to 400 mg/L. In the southern part of the Delta, the dissolved solids generally range from 400 to 500 mg/L, except in an area in Washington and Sharkey Counties where they are higher due to recharge to the alluvium from an underlying aquifer. The map also shows a strip along the eastern edge of the Delta that has less than 200 mg/L of dissolved solids.

The quality of water available to recharge the alluvial aquifer varies with space and time. Dissolved-solids concentrations in the Mississippi River commonly ranged from 170 to 270 mg/L between 1973 and 1981. Water in streams along the eastern edge of the Delta commonly contains between 25 and 125 mg/L of dissolved solids. Precipitation in the Delta usually contains less than 10 mg/L of dissolved solids. However, as the water percolates to and through the aquifer, the dissolved-solids concentration increases, depending on the soil and rock through which it moves. Water in aquifers immediately underlying the alluvial aquifer commonly has a lower dissolved-solids concentration than that in the alluvial aquifer, except in a part of Washington and Sharkey Counties where the Cockfield aquifer may contain water with more than 1,000 mg/L of dissolved solids. The levees along the Mississippi River now prevent annual flooding of the Delta by water from the river and may contribute to a long-term change in water quality in the alluvial aquifer.

COMPUTER MODEL CONSTRUCTION AND CALIBRATION

A finite-difference digital model (McDonald and Harbaugh, 1984) was selected to simulate ground-water flow in the alluvial aquifer in the Delta. The steps in the evolution and application of the model are outlined as follows:

1. Development of conceptual model of aquifer system (discussed in previous part of report).

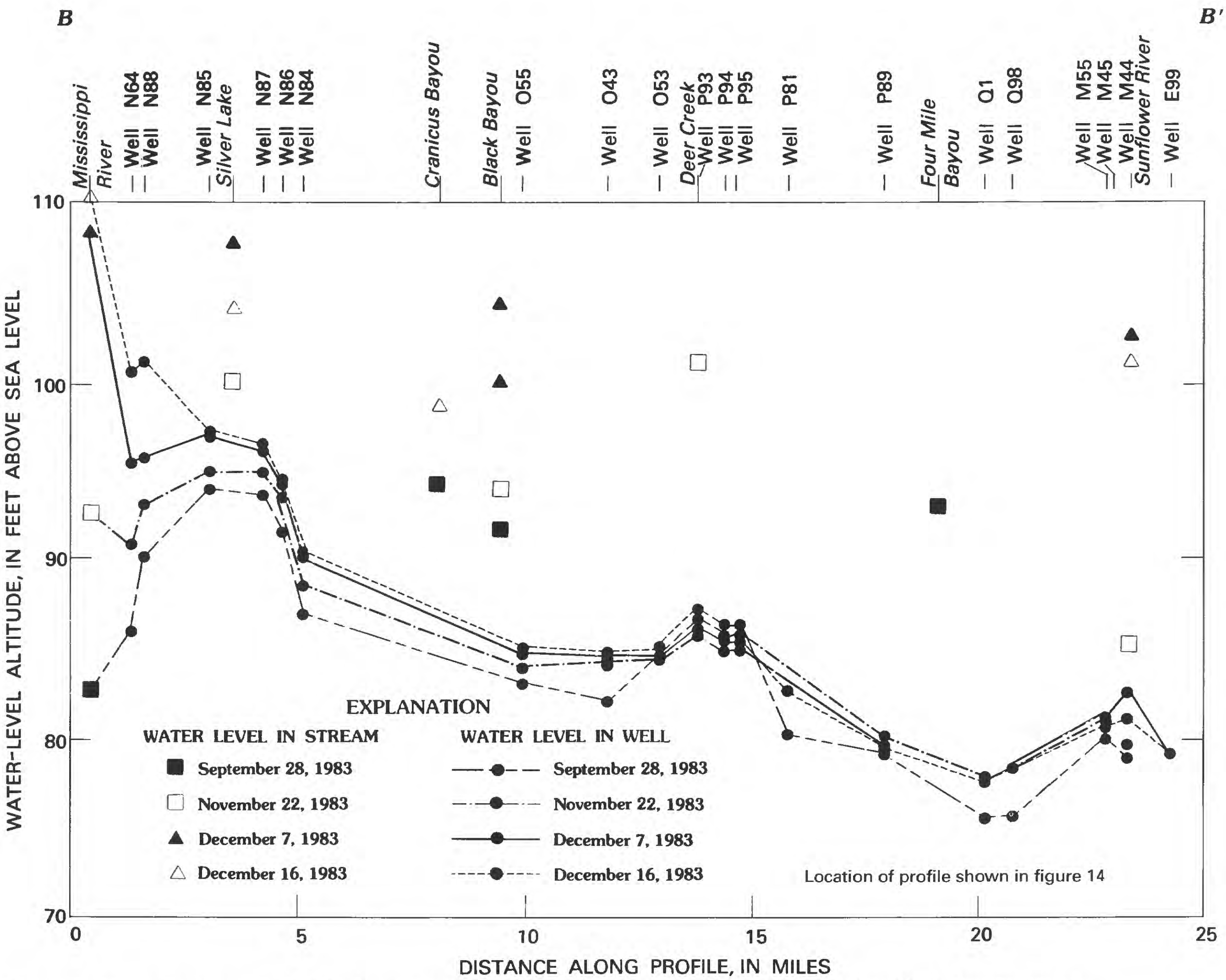


Figure 8. Water-level profile (B-B') along State Highway 12 through Hollandale showing the effect of water-level change in the Mississippi River on the water level in the alluvial aquifer.

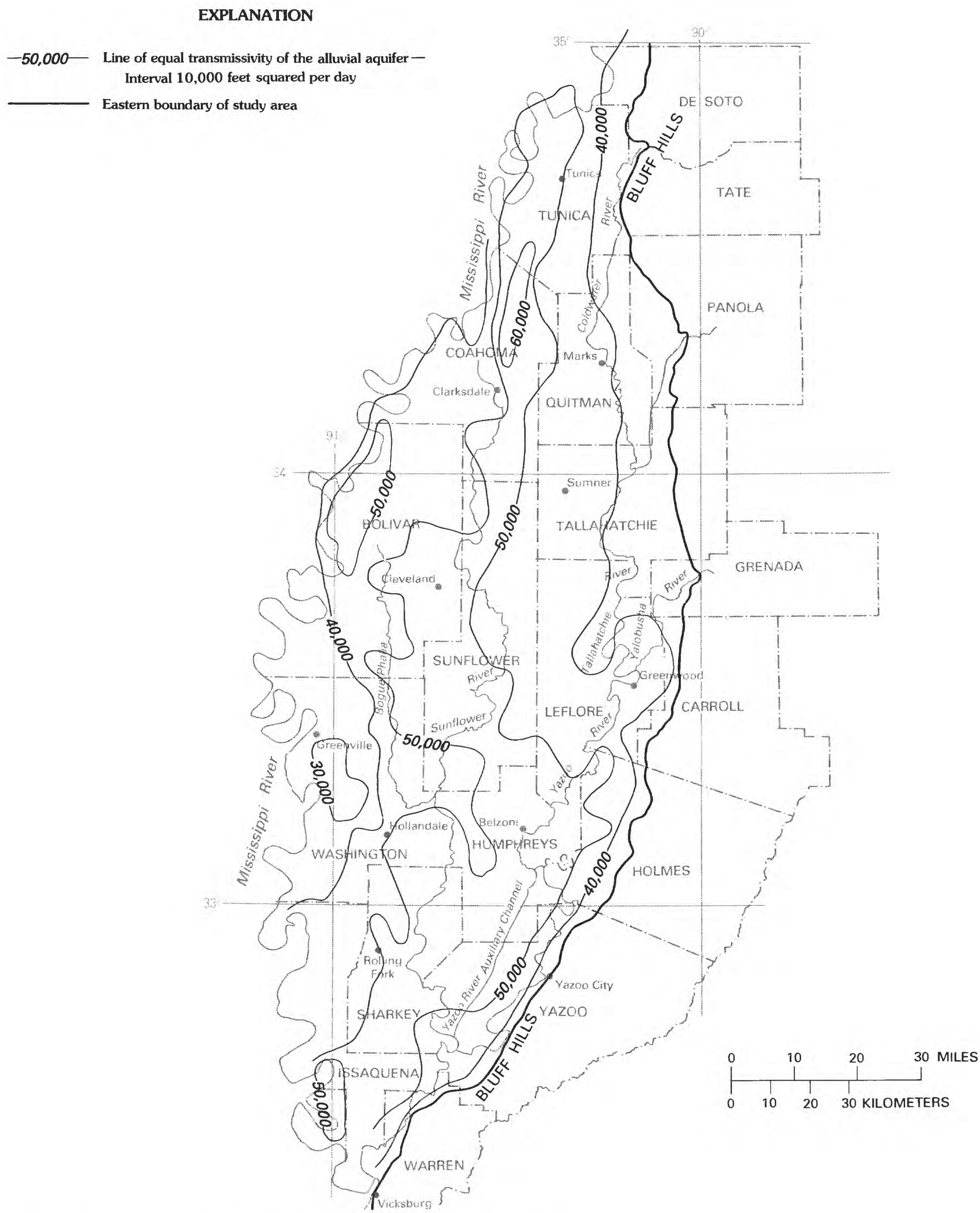


Figure 9. Transmissivity of the Mississippi River alluvial aquifer in the Delta.

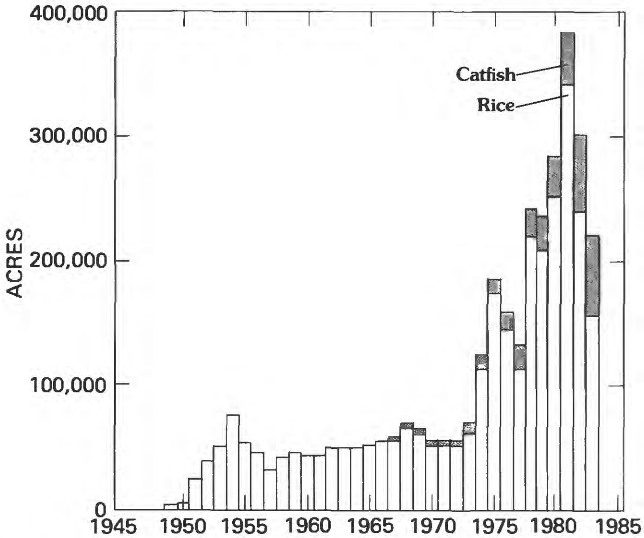


Figure 10. Rice and catfish-pond acreage in the Delta, 1949–83.

2. Finite-difference discretization of conceptual model of aquifer system.
3. Calibration of digital model.
4. Sensitivity analysis.
5. Model verification.
6. Application of model for predictive purposes.

Model Construction

Finite-difference models require input and produce output in spatial and temporal discretized form. Thus, an initial step in the transition from the conceptual model to the finite-difference model involves determining the form of spatial discretization; that is, a grid system. Figure 14 illustrates the grid system used in this study. Nodes (points of spatial resolution) are squares having sides of 4 kilometers (2.5 mi). The grid is composed of 1,846 nodes in an array of 71 rows by 26 columns. Only those nodes within the alluvial aquifer of northwestern Mississippi (1,211 nodes) were used within the model.

Ground-water flow is described by a second-order partial-differential equation that requires specification of either head or flux along the aquifer boundaries. The boundaries of the alluvial aquifer are quite distinct. The Mississippi River is in nearly complete hydraulic connection with the aquifer, producing an aquifer head along the western boundary of the aquifer that is virtually equal to the river stage and is specified as such in the aquifer model. The location of the eastern boundary was chosen to coincide with the western edge of the Bluff Hills. In this area, the hydrologic environment is rather complex. The absence of the clay confining cap allows for much greater rainfall recharge than elsewhere, allows for recharge from a multitude of streams, and makes evapotranspiration an important factor in the hydrologic budget. Also, leakage from the underlying Tertiary aquifers is important near the Bluff Hills. To the west of the Bluff Hills, water levels in aquifers of Tertiary age have declined to near those in the alluvium, and interaquifer leakage is not important to the water budget. Rather than attempt to simulate this complex system, aquifer heads along the Bluff Hills were specified in the flow model based upon observed head values. A linear change in head between observations was assumed.

Similarly, the relatively short north and south boundaries of the aquifer were simulated by specified head boundaries. All specified head boundaries were simulated by means of head-dependent flux nodes in which the hydraulic conductance was set sufficiently high (10^9 ft^2/d) such that a negligible difference existed between the specified head (Mississippi River stages along the western boundary and observed heads along the other boundaries) and the aquifer head along these boundaries.

In modeling the alluvial aquifer, the assumption was made that the deposits consist of two distinct layers—a lower, highly permeable aquifer consisting of gravel and sand and an overlying, nearly impermeable confining layer of clay. The altitude of the aquifer base was discretized from contour maps of the top of the Tertiary age rocks (Smith, 1979). Assuming that the surficial clay layer is 20 ft thick, the elevation of the discretized aquifer top was generated from the discretized land surface elevation described by 5-ft-interval topographic maps. A provision is made in the McDonald-Harbaugh model (McDonald and Harbaugh, 1984) for conversion from water-table to confined conditions, or vice versa, based on the relation of the potentiometric head to the base of the confining layer. Under water-table conditions, the model recomputes transmissivity values as changes occur in saturated aquifer thickness.

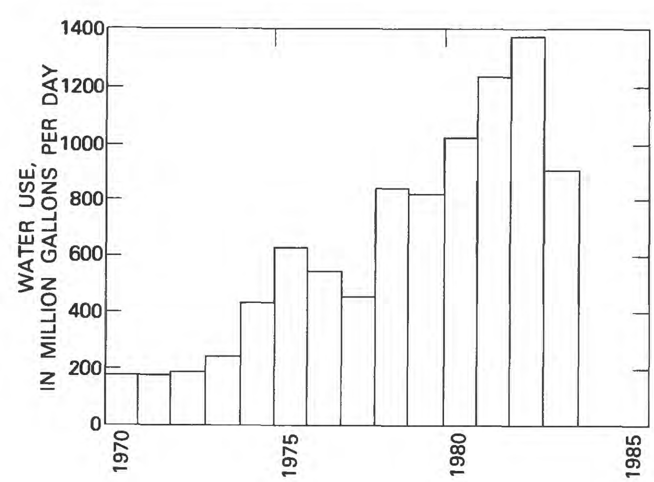


Figure 11. Agricultural and aquacultural water use in the Delta, 1970–83.

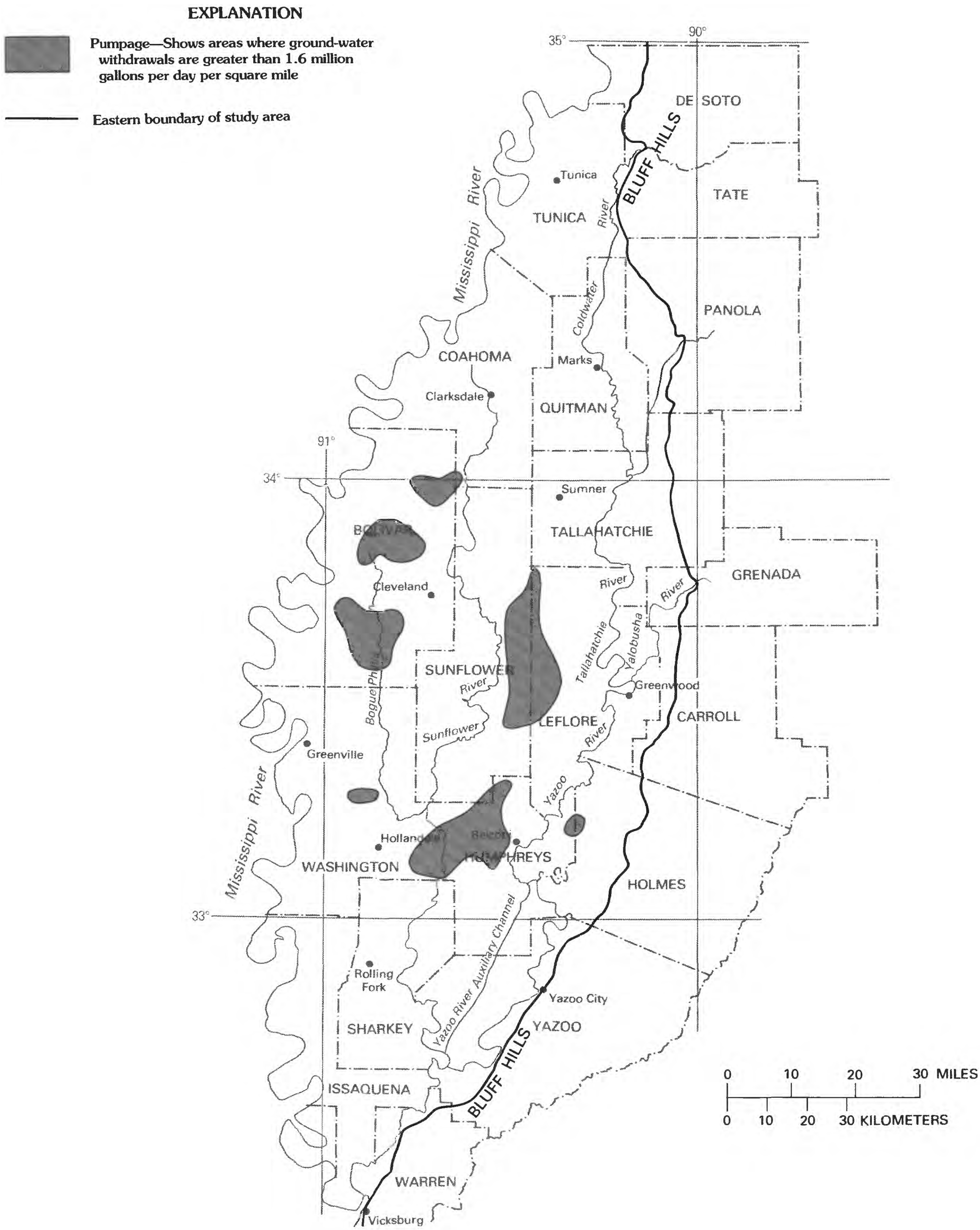


Figure 12. Areas of concentrated ground-water withdrawals for agriculture and aquaculture in the Delta during summer 1982.

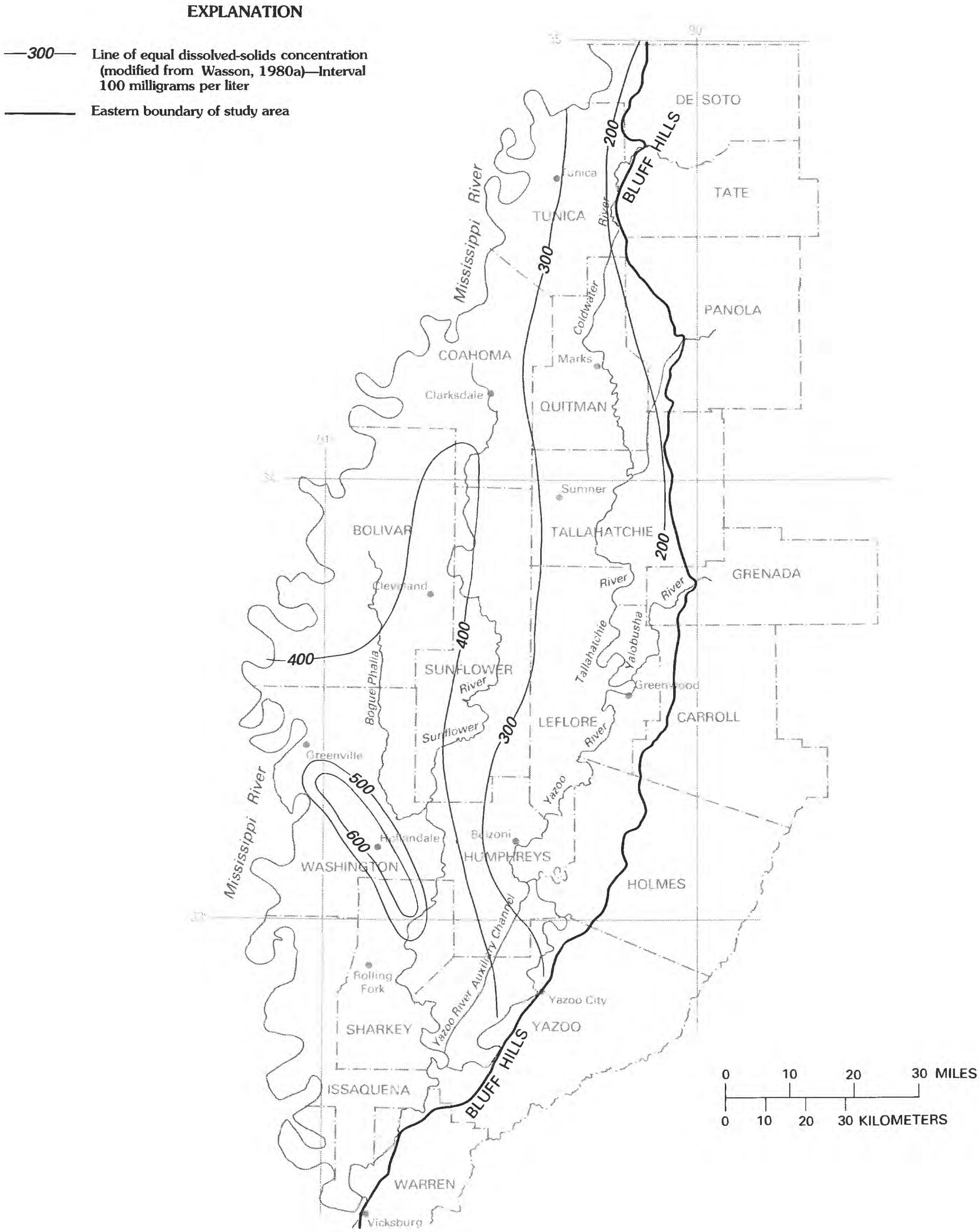


Figure 13. Dissolved-solids concentration of water in the alluvial aquifer in the Delta.

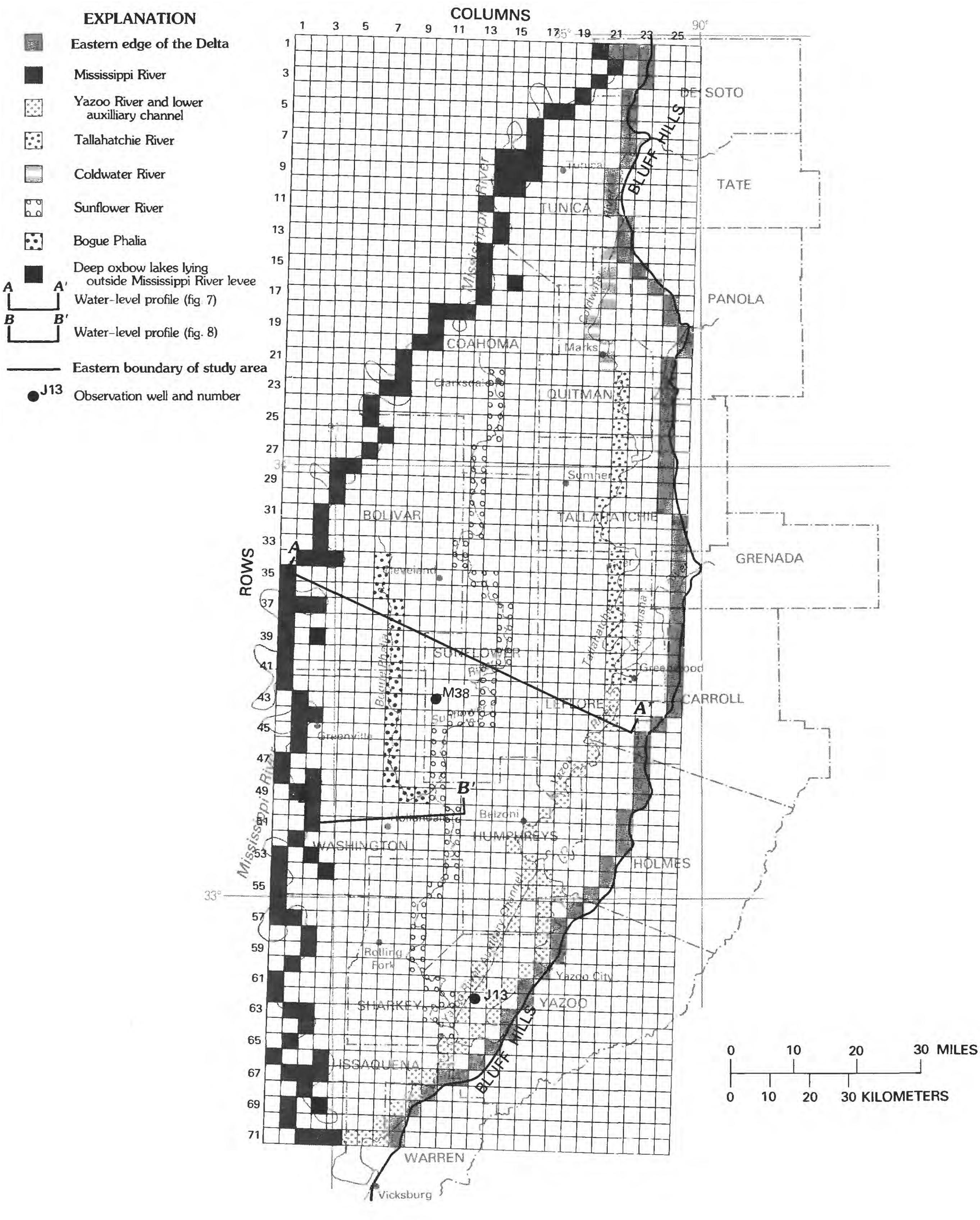


Figure 14. Culture of the Delta and overlay of digital model grid.

Model Calibration

The aquifer responds to stress (pumpage, river leakage, rainfall recharge, and so forth) to produce a response in the form of a particular distribution of head and discharge values; therefore, if the aquifer system can be defined, then the aquifer response to any stress can be determined. Some of the parameters that define the aquifer system, as well as some of the aquifer stresses, are unknown or poorly known. The aquifer model was used to determine these unknowns by means of model calibration.

Model calibration can be accomplished with either steady-state or transient simulations. In steady-state calibration, observed heads at equilibrium (usually predevelopment) conditions are used as the known aquifer response. Steady-state calibration of the alluvial model was not considered acceptable for the following reasons:

1. Even in predevelopment time, water levels in many parts of the aquifer were highly seasonal, never approaching equilibrium conditions.
2. The seasonal average predevelopment potentiometric surface was not determinable within sufficient accuracy because of the large temporal head variations relative to the spatial head variations upon which steady-state calibration is based; that is, model noise due to measurement error would overshadow model parameter sensitivity.
3. In those areas where equilibrium conditions might have been approximated, neither the head distribution, nor aquifer discharges are known to sufficient accuracy for model calibration.

Calibration of the alluvial aquifer model was based on transient simulations. Transient simulations more realistically model the nonequilibrium conditions now occurring in the alluvial aquifer and allow for simulation of flow conditions on a date for which the potentiometric surface is well defined. The simulation period chosen for calibration was April 1981 to April 1983. This time period was selected because of the availability of water-use and potentiometric surface data. The basis for model calibration was four potentiometric maps for September 1981, April 1982, September 1982, and April 1983 (figs. 15–18). Initial model heads were provided by an April 1981 potentiometric surface map (fig. 5).

As with space, time was broken into discrete steps. The time-step length chosen for use in model calibration was 30.4 days. A simulation made with 10 times this temporal resolution produced a negligible difference in model-generated heads; therefore, a time step of 30.4 days is sufficient to avoid significant temporal truncation error. The length of each stress period (time periods during which aquifer stresses are simulated as constant) was set equal to the time-step length. Thus, pumpage, rainfall recharge, and river stages were updated every 30.4 days of the calibration simulation period.

Aquifer Stresses

Pumpage

Agricultural and aquacultural pumpage is the dominant stress on the alluvial aquifer; therefore, a major effort was expended to determine the distribution and magnitude of this pumpage. Rice and catfish farming account for most of the alluvial ground-water withdrawals. The spatial pumpage distribution was determined through the use of Agricultural Stabilization and Conservation Service photographs made of the study area in summer 1982. Acreage of rice (fig. 19) and catfish (fig. 20) were recorded for each model node. The two resulting acreage arrays provided the base for generation of pumpage arrays (fig. 21). In accordance with farming practices of the area, pumpage for rice was concentrated uniformly within the May to August growing season of each simulated year. Three-fourths of the catfish pumpage was placed within this same period, and the remaining one-fourth was spread evenly from September through the following April. Total rice acreage within the alluvial plain of northwestern Mississippi was 340,000 acres in 1981, 240,000 acres in 1982, and 155,000 acres in 1983.

To account for ground-water withdrawals for row crop irrigation (cotton, soybeans, and corn), rice acreage values were increased by 5 percent in 1981, 10 percent in 1982, and 15 percent in 1983, to produce effective rice acreage values of 360,000 250,000 and 180,000 acres in 1981, 1982, and 1983, respectively. This scheme was used because row crop irrigation generally is found in areas of rice cultivation due to the availability of wells in these areas. The percentage increase in actual rice acreage is related to observations of the degree of row crop irrigation during 1981, 1982, and 1983. The 1983 effective rice acreage array was generated by multiplying all 1982 rice acreage array values by the ratio of 1983 to 1982 total effective rice acreage. The 1981 effective rice acreage array was generated in a similar manner. This method is justified by the fact that the regional rice acreage distribution changes little from year to year. A factor of 0.82 then was applied to the rice acreage arrays to eliminate approximately 18 percent of rice acreage that was irrigated from surface-water sources.

Total catfish acreage in the alluvial plain was 44,000, 60,000, and 61,000 acres for 1981, 1982, and 1983, respectively. Thus, in a manner similar to that discussed above for rice, factors of 44/60, 60/60, and 61/60 were applied to the 1982 catfish acreage array to generate arrays for all 3 years. Ground water is the sole source of water used by catfish farmers in the alluvial plain.

Irrigation application rates for rice averaged 3.3, 4.2, and 3.6 ft/yr for 1981, 1982, and 1983, respectively, whereas application rates for catfish averaged 5.1, 7.3, and 6.0 ft/yr for 1981, 1982, and 1983, respectively. The changing application rates are related to changing meteorologic conditions. Each application rate was applied to the corresponding acreage file to create a water-volume-withdrawal array.

EXPLANATION

—140— Observed water-level contour—Shows altitude at which water level would stand in tightly cased wells. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

– –140– – Simulated water-level contour—Shows altitude at which water level would stand in tightly cased wells. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

——— Eastern boundary of study area

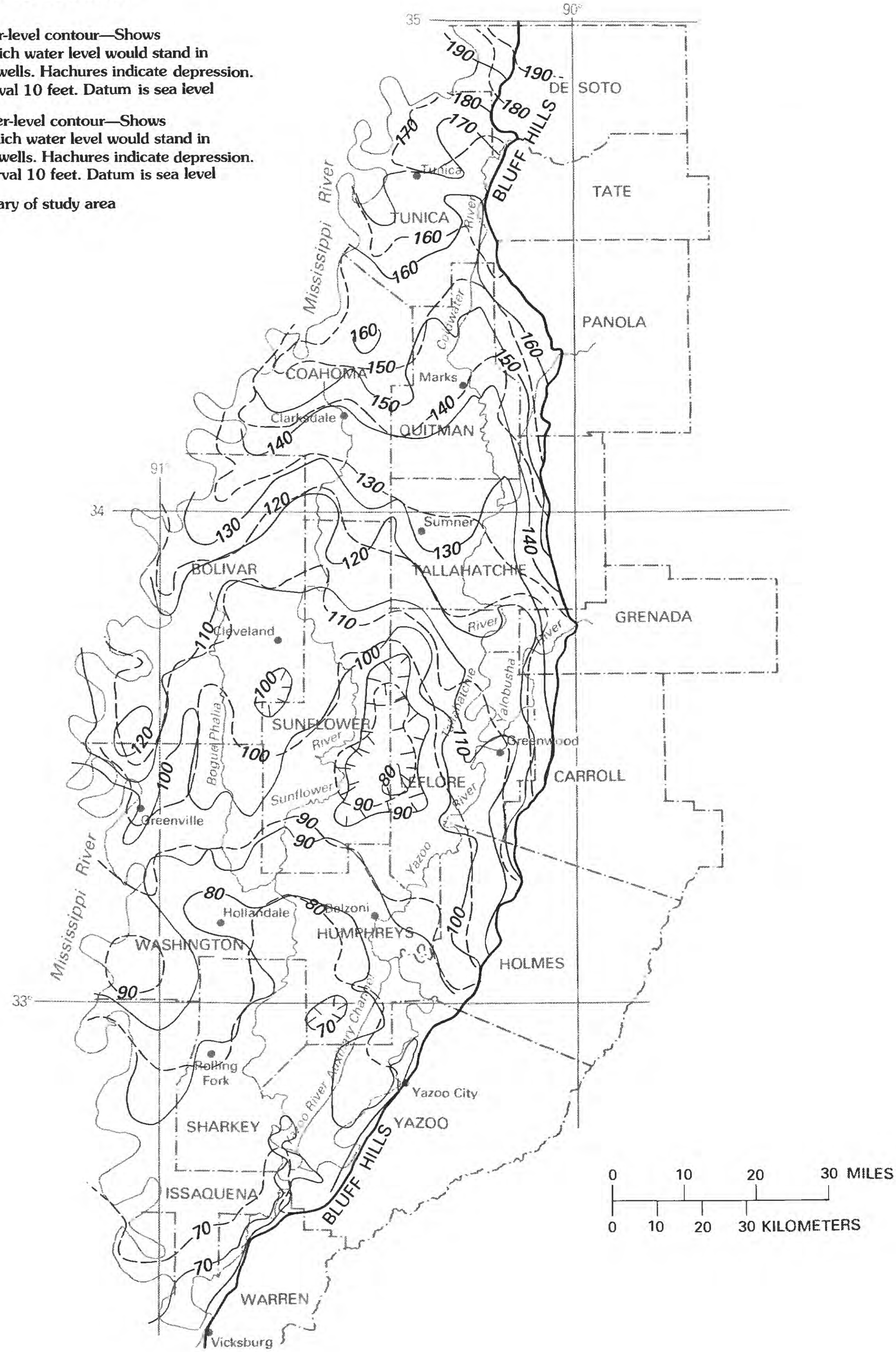


Figure 15. Observed and model-generated potentiometric surfaces of the alluvial aquifer in the Delta for September 1981.

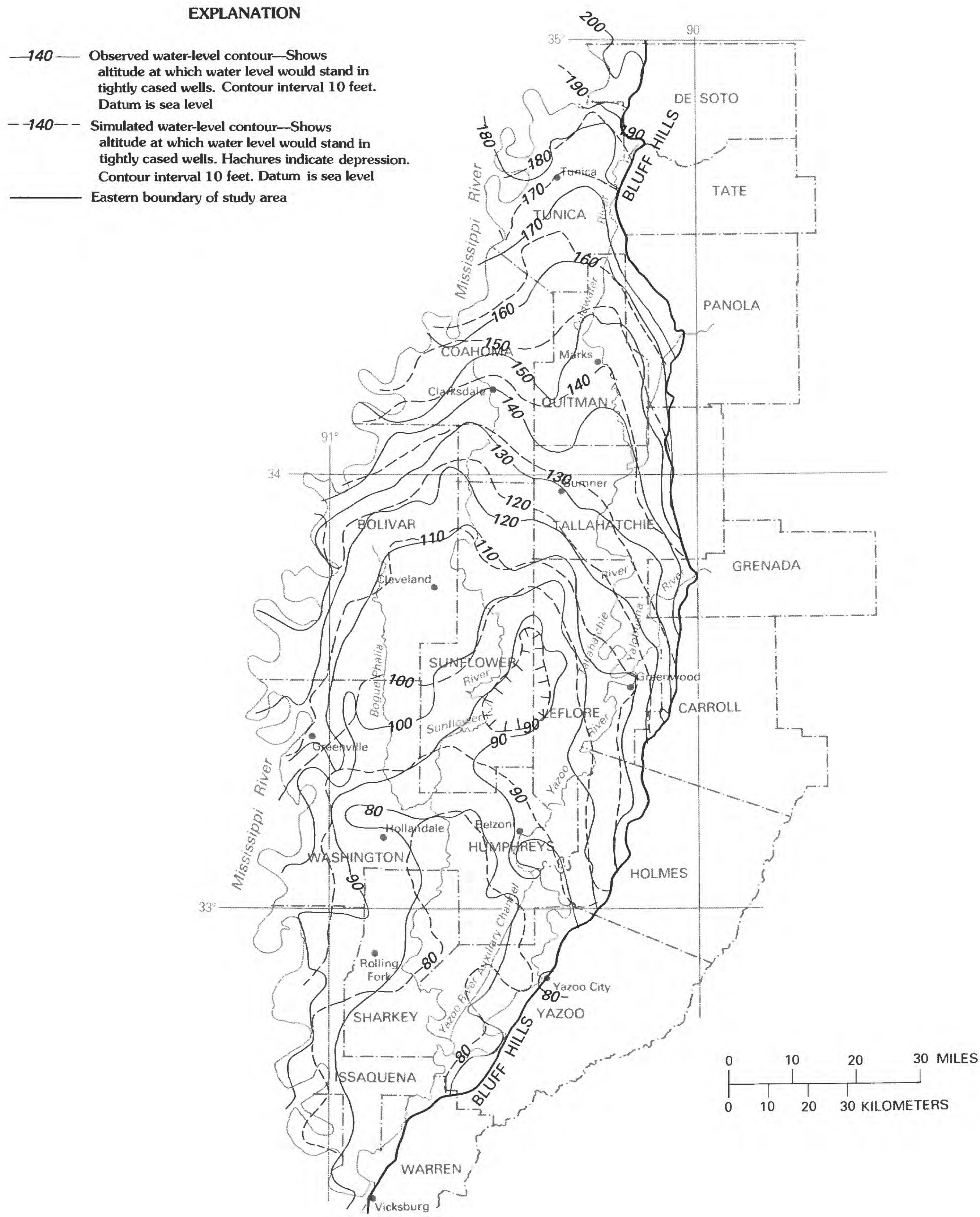


Figure 16. Observed and model-generated potentiometric surfaces of the alluvial aquifer in the Delta for April 1982.

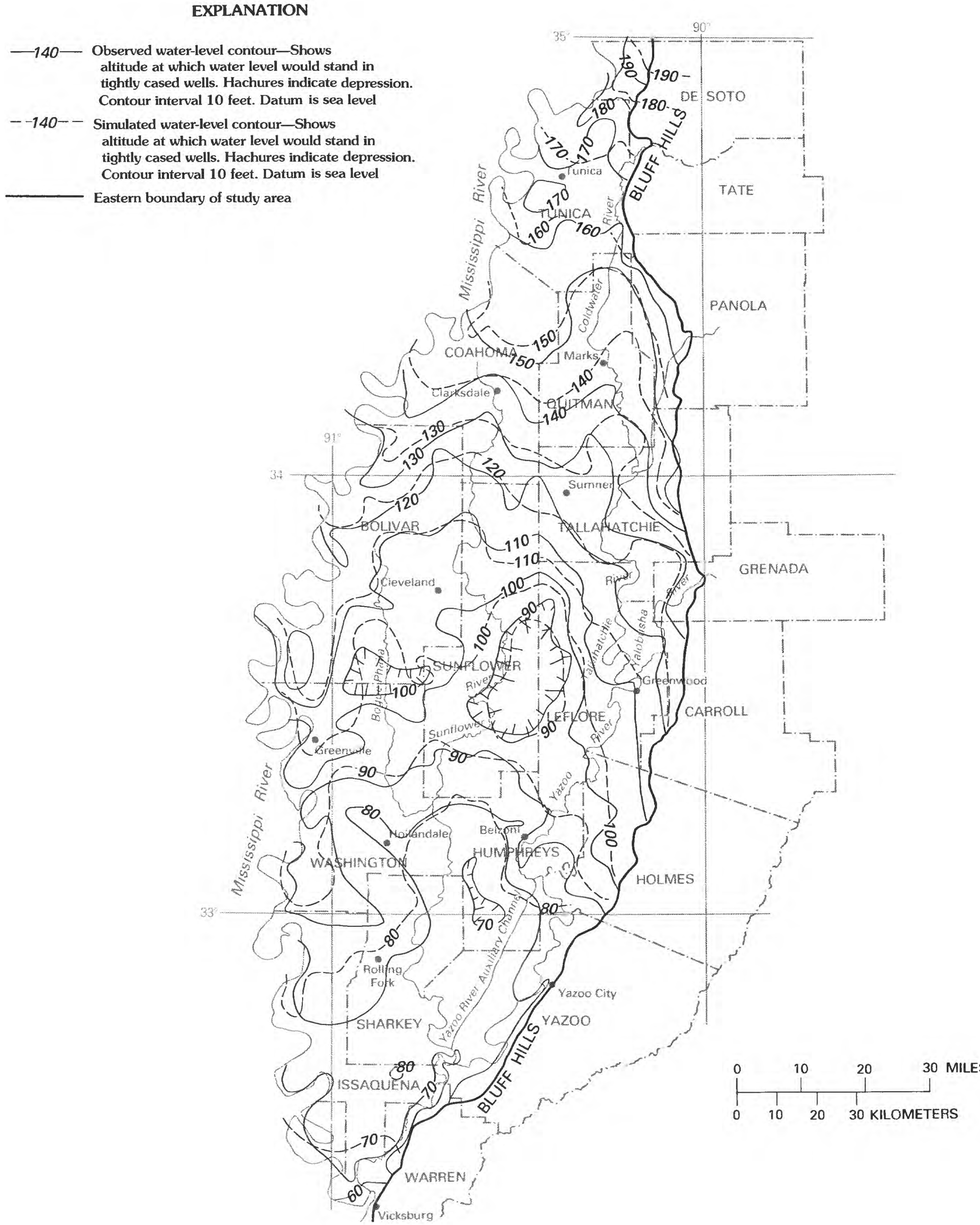


Figure 17. Observed and model-generated potentiometric surfaces of the alluvial aquifer in the Delta for September 1982.

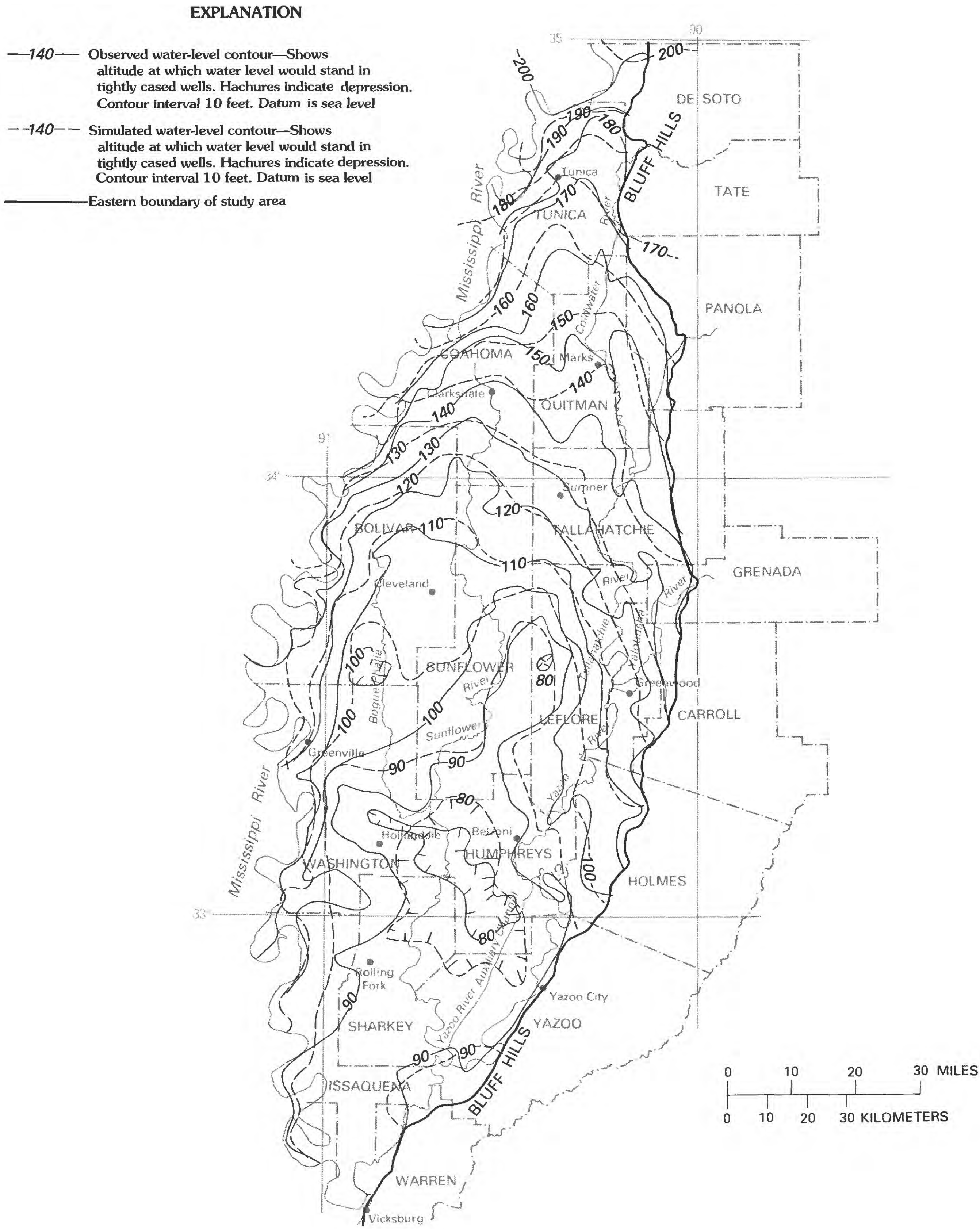


Figure 18. Observed and model-generated potentiometric surfaces of the alluvial aquifer in the Delta for April 1983.

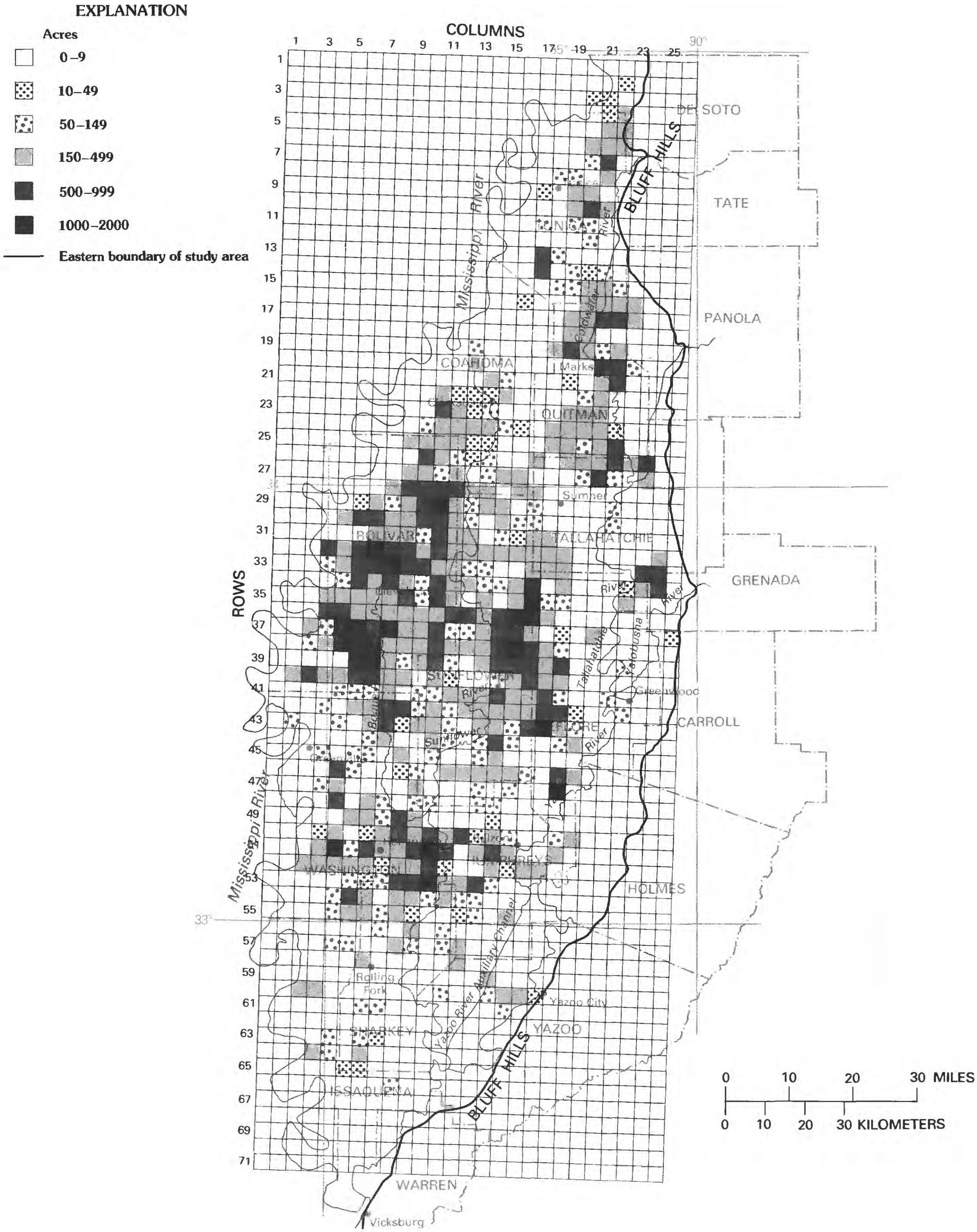


Figure 19. Rice acreage in the Delta in 1982 by digital model grid.

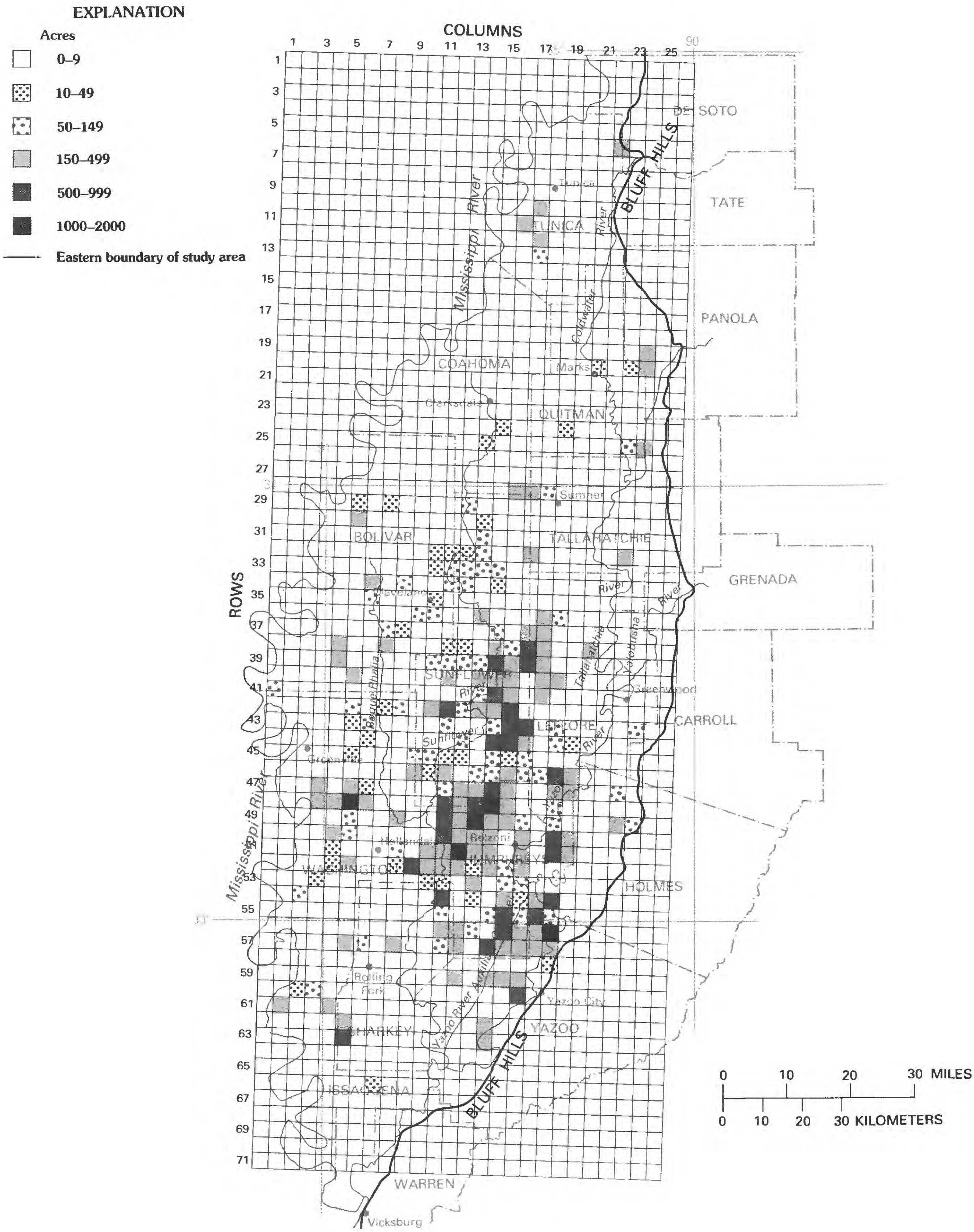


Figure 20. Catfish-pond acreage in the Delta in 1982 by digital model grid.

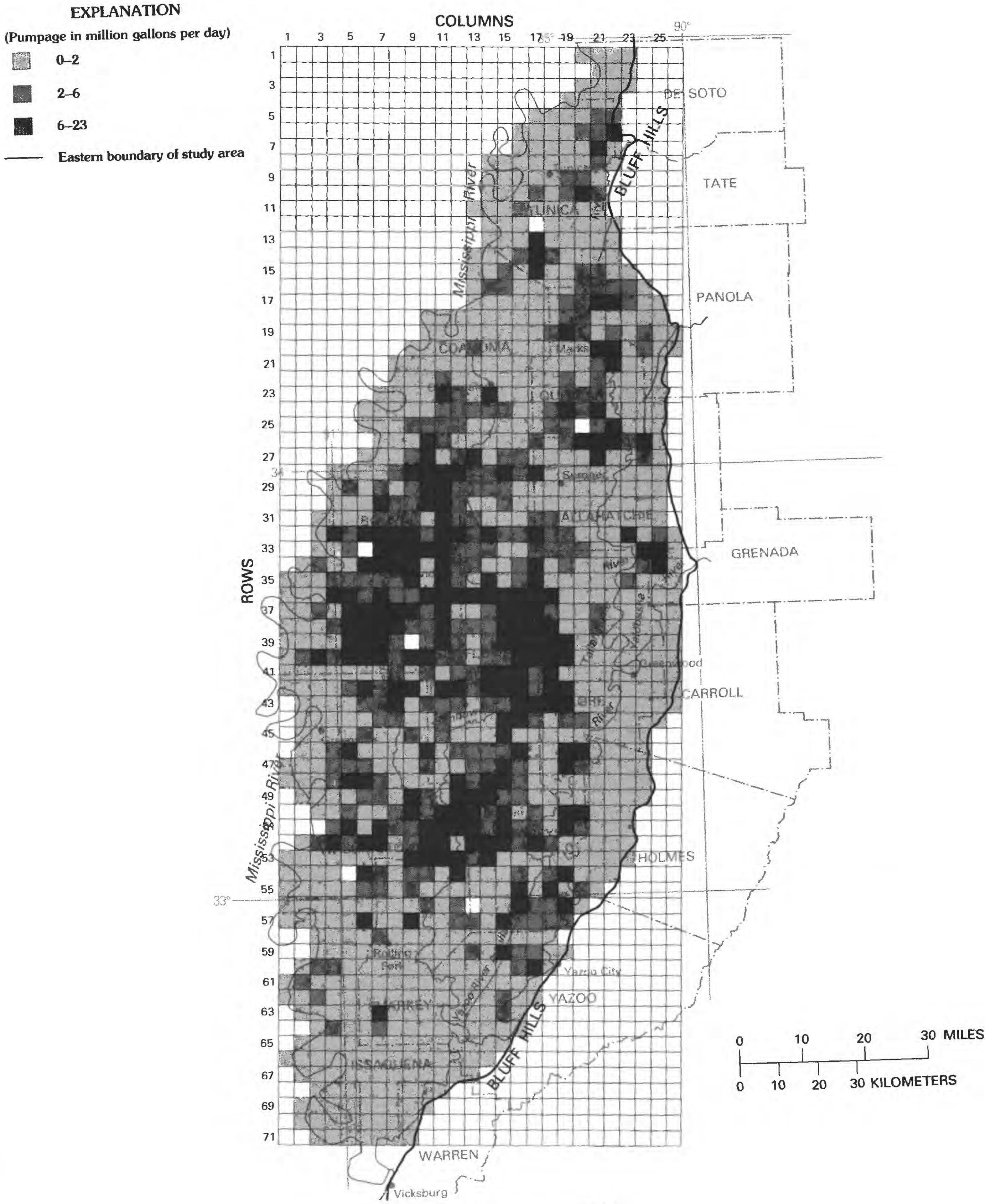


Figure 21. Rate of pumpage in the Delta by model grid during summer 1982.

which was distributed temporally as previously discussed. Rice and catfish pumpage arrays then were merged to create a master pumpage array, which was updated every stress period.

Stream Leakage

The effects of several streams (Mississippi, Yazoo, Tallahatchie, Coldwater, and Sunflower Rivers; the Yazoo Navigation Canal; and the Bogue Phalia) and oxbow lakes (Lake Washington, Eagle Lake, Lake Bolivar, and Moon Lake) were simulated in the alluvial aquifer model. Observed differences in surface- and ground-water heads indicate an imperfect connection between the two flow regimes due to flow-retarding riverbeds that partially separate rivers from the aquifer. The finite-difference model used in this study makes a provision for this situation in the form of "river nodes," which allow for ground-water–surface-water interchange, the extent of which is governed by "riverbed conductance," which is a function of riverbed geometry and riverbed hydraulic characteristics and is defined as

$$K'A/b,$$

where

K' = hydraulic conductivity of riverbed,
A = plan area of river within node, and
b = thickness of riverbed.

The product of riverbed conductance and the head differential across the riverbed equals the flow through the riverbed. In the alluvial aquifer model, the following assumptions were made concerning the riverbed conductances of the various streams in contact with the aquifer:

1. Hydraulic conductivity of the riverbed is constant along the river reaches shown in figure 14.
2. A 1:2:3 relationship was assumed for the riverbed conductances of the upper, middle, and lower reaches, respectively, of the Yazoo-Tallahatchie-Coldwater River system. This relation is based upon a continual increase in river width and depth from upstream to downstream. The riverbed conductance of the Yazoo Navigation Canal was assumed to be equal to that of the lower reach of the Yazoo-Tallahatchie-Coldwater River system.
3. A 3:10 relation was assumed for the riverbed conductances of the Bogue Phalia and Sunflower River, respectively.
4. The Mississippi River riverbed conductance and the "lakebed" conductance of several oxbow lakes were assumed to be very high (10^9 ft^2/d) to reflect the negligible difference in river-lake and aquifer head.

Rainfall Recharge

Rainfall on the alluvial plain of northwestern Mississippi averages 52 in/yr. Only a small amount of this precipitation enters the alluvial aquifer because of the relatively impermeable surficial clay. Most of the rainfall goes into surface runoff and evapotranspiration. Unlike pumpage, for which magnitude and distribution are known approximately during the calibration period, rainfall recharge was an unknown factor to be determined through model calibration. In the calibration period simulations, rainfall recharge was assumed to be areally uniform and to be concentrated uniformly within the heavy rainfall months of December through April.

Underlying Aquifers

The effects on the alluvial aquifer of the underlying Tertiary aquifers were assumed to be negligible for the following reasons:

- The Zilpha Clay, Yazoo Clay, and Cook Mountain Formation are effective barriers to interflow in areas other than the Sparta and Cockfield subcrop areas (fig. 2). In the subcrop areas, the differences between alluvial and Tertiary aquifer predevelopment heads probably were less than 10 ft. With distance from the subcrop areas of the Tertiary aquifers, the head differences generally increased and were greater than 50 ft in places in and near the Delta.
- The transmissivity values of the Tertiary aquifers are almost an order of magnitude less than those found in the alluvial aquifer.
- In 1980, head difference (generally less than 10 ft) between the alluvial and the shallow Tertiary aquifers in the subcrop areas was not significant. Thus, interaquifer flow is currently negligible.
- Continued heavy irrigation pumpage could significantly lower water levels in the alluvial aquifer and indirectly in the Tertiary aquifers; however, the alluvial aquifer is becoming largely unconfined, whereas the Tertiary aquifers are confined. The volume of water released from the confined Tertiary aquifers will be insignificant compared with release from storage by dewatering pore space within the alluvial aquifer.
- To further investigate the possible influence of the subcropping confined aquifers on the alluvial aquifer, a generalized three-dimensional model was constructed, which included the underlying Sparta and Cockfield aquifers and the Jackson and Cook Mountain confining layers. The alluvial aquifer was represented more precisely than the other geologic units. Model simulations indicated that the effect of these subcropping aquifers on the alluvial aquifer was negligible. The effect of the alluvial aquifer on the underlying aquifers, however, is quite significant. Because this study is of the alluvial aquifer, the underlying aquifers were ignored in later simulations.

Evapotranspiration

The rate of ground-water loss to evapotranspiration is a function of the depth to saturation within the water-bearing strata. As the level of saturation becomes lower, fewer plants are able to access the water, and losses decrease. The effects of evapotranspiration were neglected in modeling flow in the alluvial aquifer for the following reasons:

1. Water levels in the alluvial aquifer are below the depth of plant root penetration over most of the alluvial plain.
2. In those areas of the alluvial aquifer where the potentiometric surface is above the depth of plant root penetration, the water itself usually is confined near the bottom of the clay cap, well below the root zone, because the clay greatly inhibits vertical water movement.

Calibration Strategy and Results

The unknowns in the alluvial aquifer system to be determined by means of model calibration included hydraulic conductivity, specific yield, storage coefficient, riverbed conductances (Yazoo-Tallahatchie-Coldwater, Sunflower, and Bogue Phalia), and rate of areal recharge. Calibration was facilitated by identifying areas of the aquifer in which water levels are predominantly sensitive to only a few of the several unknowns. These areas are delineated in figure 22. For the short calibration period being used, the three areas can be considered virtually isolated one from another. Thus, the original calibration problem can be reduced to a number of smaller problems, which have fewer unknowns and, thus, are easier to calibrate than the original problem.

Area I includes the area adjacent to the Yazoo-Tallahatchie-Coldwater River system and the Bluff Hills. The dominant unknown aquifer parameters in this area are assumed to be as follows:

Hydraulic conductivity.—Transport of ground water is important due to the steep hydraulic gradients.

Storage coefficient.—The aquifer is confined predominantly except for a narrow strip along the Bluff Hills.

Yazoo-Tallahatchie-Coldwater riverbed conductance.—The presence of these streams has a significant influence on water levels due to partial or complete stream penetration of the clay cap. The Yazoo Navigation Canal is part of the lower reach of the river in the model.

Areal recharge.—Water levels are particularly sensitive to recharge due to the confined nature of the aquifer.

Area II includes the central part of the alluvial plain. Here, it is assumed that the dominant unknown aquifer parameters are as follows:

Specific yield.—The aquifer is unconfined predominantly.

Sunflower River and Bogue Phalia riverbed conductances.—These streams have a moderate effect upon water levels.

Areal recharge.—Water levels are only moderately sensitive to recharge due to the unconfined nature of the aquifer.

Hydraulic conductivity is only of minor importance due to the low hydraulic gradients.

Area III includes that part of the aquifer adjacent to the Mississippi River. Here, the dominant unknown aquifer parameters are assumed to be as follows:

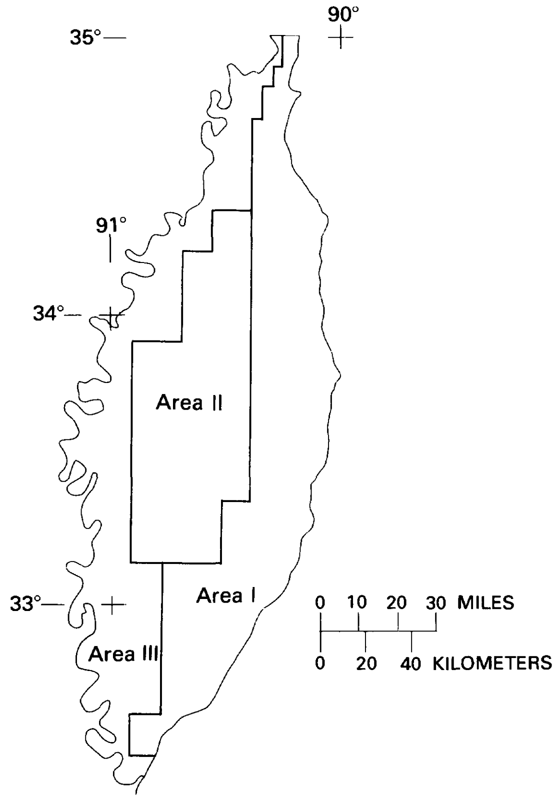


Figure 22. Delineation of three aquifer areas in the Delta as used for model calibration.

Hydraulic conductivity.—Transport of water is important due to the high hydraulic gradients.

Specific yield and storage coefficient.—The aquifer has confined and unconfined zones.

Areal recharge.—Water levels are moderately sensitive to recharge.

The general calibration chronology proceeded as follows: Preliminary to the more systematic calibration to follow, about 10 simulations were made to arrive at approximations for all model parameters. Further model calibration was accomplished through multidimensional arrays of simulations; that is, each unknown aquifer parameter was allowed to take on discrete values within a reasonable range, and an array of simulation involving the resulting possible parameter combinations then was constructed. The best approximation to the unknown aquifer parameter then was taken to be that parameter combination which produced the best correlation between observed and computed heads. Additional arrays then were constructed to provide greater calibration resolution.

The first calibration array was used to determine approximations for those aquifer parameters dominant in Area I—areal recharge, storage coefficient, hydraulic conductivity, and Yazoo-Tallahatchie-Coldwater riverbed conductances. The values for other aquifer parameters remained constant within this array and were estimated based upon the preliminary model runs and field measurements.

The sum of the squares of the deviations of observed heads from calculated heads for the four calibration dates was computed for the three areas and for the aquifer as a whole. The results (table 2) indicate that head deviations were minimized in Area I and the aquifer as a whole with a hydraulic conductivity of 600 ft/d; riverbed conductances of 10,000, 20,000, and 30,000 ft^2/d for the upper, middle, and lower reaches, respectively, of the Yazoo-Tallahatchie-Coldwater River system; and no areal recharge. Without areal recharge, the model is fairly insensitive to changes in storage coefficient. Thus, selection of a value for storage coefficient at this stage of calibration was arbitrary.

The second calibration array was used to determine approximations for those aquifer parameters dominant in Area II—specific yield, Sunflower and Bogue Phalia riverbed conductances, and areal recharge. The values for hydraulic conductivity and Yazoo-Tallahatchie-Coldwater riverbed conductances determined from the previous array of model runs were assumed to be known parameters for this stage of calibration. A value of 0.0001 was assumed for storage coefficient.

Because of the extremely poor fit obtained with high areal recharge rates in the previous calibration array, recharge was varied between 0 and 1 in/yr in this stage of calibration. The results (table 3) indicated that specific yield values of 0.30 and 0.35 produce almost equally good fits and that produced with the value of 0.25 is relatively poor, particularly in Area III. The value of 0.30 is closer to the generally accepted values for specific yield and was chosen over the value of 0.35 for this reason.

An areal recharge rate of 1 in/yr produced a poor head match in Areas I and III, whereas Area II showed a slightly better match with this value. Simulations made using an areal recharge value of 0.5 in/yr produced optimal head matches for the aquifer as a whole and was chosen over other values of area recharge for that reason.

The model is relatively insensitive to changes in the riverbed conductance values for the Sunflower River and Bogue Phalia. Because of field observations which indicate that the aquifer is less sensitive to changes in the stage of these streams than to stage changes in the Yazoo River, conductance values lower than that determined for the Yazoo River were assumed (conductance values of 10,000 and 3,000 ft^2/d for the Sunflower River and Bogue Phalia, respectively).

A third calibration array (table 4) was constructed to arrive at new estimates for those unknown parameters dominant in Area I (with the exception of areal recharge for which the value of 0.5 in/yr was assumed based upon the second array of model runs). Of those values tested, riverbed conductance values of 30,000, 20,000, and 10,000 ft^2/d for the lower, middle, and upper reaches, respectively, of the Yazoo-Tallahatchie-Coldwater River system, were found to produce the optimal head match in Area I and the aquifer as a whole.

In Areas I and II, the head match is relatively poor for values of hydraulic conductivity less than 400 ft/d and is relatively insensitive to changes in this parameter greater than 400 ft/d. Because a value of 400 ft/d is more in keeping with the generally accepted value of hydraulic conductivity in the alluvial aquifer, it was chosen over higher values that produced similar head fits. Area III indicates an apparent need for a higher value of hydraulic conductivity primarily due to a poor head match along the Mississippi River in April 1983. The authors believe that this situation is due to conceptual error in some of the simplifying assumptions used in model construction. Due to sandy areas near the river, direct vertical recharge from precipitation may be greater in some areas adjacent to the Mississippi River than is included in the model.

Another likely error in the conceptual model is the assumption of a distinct upper confining layer of 20-ft thickness. Because the aquifer in the area near the Mississippi River alternately is recharged and then is drained by the river, which changes the aquifer from the unconfined to the confined regime and back, and because of the drastically different aquifer responses under the two regimes, correct placement of the clay confining layer is essential. Because of the complex nature of alluvial geology, precise placement of this confining layer is virtually impossible. Also, distinctiveness of the clay-aquifer interface in this continuously stratified formation is questionable. Thus, it is possible that the transition from unconfined to confined conditions is not abrupt, but rather that a transition period exists, during which time pore-space saturation-desaturation and elastic deformation play an important role in changes in aquifer storage. These effects would be most important during periods of intense aquifer stress (April 1983, near the Mississippi River, for example). The long-term error in head prediction in the area of primary interest, the central drawdown region, caused by not including the above-mentioned model embellishments, is probably negligible because of the short-term nature of the extreme events that make the conceptual errors most evident and the remoteness of the central drawdown region from the rapidly stressed area. A slightly better overall head match was obtained with a storage coefficient of 0.0001 than with the other values tested in those simulations with the preferred values of hydraulic conductivity and riverbed conductance.

A summary of calibration-derived values for alluvial aquifer parameters and a comparison of these values with previous estimates follow:

Hydraulic conductivity.—The value of 400 ft/d determined by means of model calibration is reasonably close to the value of 320 ft/d based upon four aquifer tests (Newcome, 1971).

Specific yield.—The value of 0.30, which was determined by means of model calibration, is the same value used in

Table 2. First calibration array showing the sum of the squares of the differences between observed and computed head values for various values of the model parameters dominant in Area I (Areas I, II, and III, fig. 22)

[*S*, storage coefficient; *K*, hydraulic conductivity of alluvial aquifer (feet per day); *R*, areal recharge (inches per year); *K'*, Yazoo riverbed conductance (feet per day); and C, riverbed conductance = 10,000, 20,000, and 30,000 ft/d for upper, middle, and lower reaches, respectively, of the Yazoo-Tallahatchie-Coldwater River system]

S	*K*	*R*	*K'*	Sum of squares of head residuals			
				Total	Area I	Area II	Area III
0.0001	200	0	0.1C	118,095	48,324	13,684	56,087
			C	107,743	38,836	13,684	55,223
			10 C	109,238	41,389	13,668	54,181
		2	.1C	706,371	334,741	23,868	347,762
			C	595,034	251,003	23,173	320,858
			10 C	530,714	210,062	22,843	297,809
	400	0	.1C	89,997	31,982	12,970	45,045
			C	84,662	27,309	12,968	44,385
			10 C	92,287	35,629	12,952	43,706
		2	.1C	364,272	209,270	14,622	140,380
			C	305,364	162,276	14,208	128,880
			10 C	249,549	118,592	13,510	117,447
	600	0	.1C	77,700	26,377	13,037	38,286
			C	74,512	23,609	13,037	37,866
			10 C	83,494	33,107	13,046	37,341
		2	.1C	291,472	174,868	14,676	101,928
			C	246,836	138,696	14,021	94,119
			10 C	189,260	95,028	13,049	81,183
0.001	200	0	.1C	118,558	48,440	13,675	56,443
			C	108,399	39,130	13,675	55,594
		2	10 C	109,190	40,953	13,661	54,576
			.1C	425,695	212,984	20,239	192,472
			C	382,687	178,605	19,860	184,222
			10 C	357,199	162,822	19,741	174,636
		4	.1C	5,442,521	3,264,100	514,321	1,664,100
			C	3,807,368	1,881,040	394,708	1,531,620
			10 C	2,664,815	986,593	280,212	1,398,010
	400	0	.1C	90,549	32,100	12,955	45,494
			C	84,935	27,201	12,953	44,781
			10 C	91,705	34,713	12,932	44,060
		2	.1C	270,367	155,301	13,859	101,207

a model of the alluvium across the Mississippi River in Arkansas (Broom and Lyford, 1981) and falls within the range of laboratory measurements of specific yield mentioned earlier.

Storage coefficient.—The relatively high value of 0.001, which was determined by means of model calibration, is reasonable in light of the fact that shallow unconsolidated aquifers are often more compressible than more consolidated, deeper aquifers. Any uncertainty in this parameter is relatively unimportant, particularly in the central drawdown region, because of the lack of model sensitivity to the storage coefficient.

Areal recharge.—The value of 0.5 in/yr, which was determined by means of model calibration, is reasonably close to the value of 0.36 in/yr reported for some areas of the alluvial aquifer in Arkansas (Broom and Lyford, 1981).

Riverbed conductance.—No previous estimates for this parameter have been made on any stream within the study area. The calibration-derived values are as follows:

	Riverbed conductance (feet squared per day)	Riverbed leakance (per day)
Mississippi River includes oxbow lakes[1] --------	1,000,000,000	
Yazoo-Tallahatchie-Coldwater River system:		
Upper Reach ----------	10,000	0.008
Middle Reach ---------	20,000	.008
Lower Reach ----------	30,000	.008
Sunflower River ---------	10,000	.004
Bogue Phalia ------------	3,000	.002

[1]Conductance value assumed to be very high to give near perfect hydraulic connection between river and alluvial aquifer.

NOTE: Riverbed conductance is a function of the grid system chosen. Thus, the above-mentioned values for riverbed conductance should be linked with the grid system used in this study. To make these values transferable to other grid systems, riverbed leakance values were calculated for each river reach based upon average values for the plan area of the river within a node.

Table 2. First calibration array showing the sum of the squares of the differences between observed and computed head values for various values of the model parameters dominant in Area I (Areas I, II, and III, fig. 22)—Continued

S	*K*	*R*	*K'*	Sum of squares of head residuals			
				Total	Area I	Area II	Area III
			C	241,127	131,561	13,665	95,901
			10 C	208,858	106,936	13,272	88,650
		4	.1C	2,608,111	1,657,090	251,860	699,161
			C	1,892,962	1,066,270	191,538	635,154
			10 C	1,132,717	481,431	107,578	543,708
	600	0	.1C	78,248	26,318	13,020	38,910
			C	74,947	23,451	13,021	38,475
			10 C	83,115	32,293	13,028	37,794
		2	.1C	229,132	137,593	13,851	77,688
			C	202,117	115,101	13,493	73,523
			10 C	165,954	87,100	12,924	65,930
		4	.1C	1,579,583	1,019,570	154,880	405,133
			C	1,145,725	717,081	120,933	307,711
			10 C	700,741	327,571	63,812	309,358
0.005	200	0	.1C	119,871	48,910	13,585	57,376
			C	110,369	40,190	13,583	55,596
			10 C	108,625	39,432	13,574	55,619
		2	.1C	138,727	72,655	15,346	50,726
			C	139,202	73,020	15,301	50,881
			10 C	152,025	85,922	15,267	50,836
		4	.1C	1,088,033	643,199	92,972	351,862
			C	946,596	516,846	87,742	342,008
			10 C	795,060	385,181	80,514	329,365
	400	0	.1C	92,271	32,682	12,876	46,713
			C	86,292	27,309	12,872	46,111
			10 C	89,792	31,721	12,854	45,217
		2	.1C	123,006	67,351	12,726	42,929
			C	122,721	67,628	12,710	42,383
			10 C	129,695	75,525	12,682	41,488
		4	.1C	774,396	494,954	61,912	217,530
			C	665,360	400,330	56,087	208,943
			10 C	496,884	258,016	45,050	193,818
	600	0	.1C	79,589	26,190	12,941	40,458
			C	76,168	23,074	12,943	40,151
			10 C	82,194	29,734	12,944	39,516
		2	.1C	122,397	70,164	12,681	39,552
			C	118,432	66,863	12,644	38,925
			10 C	118,029	67,733	12,609	37,687
		4	.1C	618,874	404,121	51,879	162,874
			C	536,218	333,766	46,411	156,041
			10 C	380,867	205,557	34,219	141,091

Figures 15–18 show observed potentiometric maps and potentiometric surface maps generated by the calibrated model. Comparison of these observed and model-generated water-level maps shows that the alluvial aquifer model has simulated successfully ground-water levels within reasonable accuracy for the four periods of significant aquifer stress. More than 95 percent of the model-generated head values for the calibrated dates (with the exception of April 1983) were within 8 ft of the observed head values, as shown by figure 23, which presents the distribution of error in histogram form. Only 87 percent of the model-generated head values for April 1983 were within 8 ft of the observed head values, due to the head mismatch near the Mississippi River discussed above.

Figures 24 and 25 show computed and observed hydrographs for wells M38, Sunflower County, and J13, Yazoo County, respectively. Well M38 is about 2 mi north of Holly Ridge, Miss., and well J13 is about 0.5 mi southeast of the intersection of the Yazoo Navigation Canal and Lake George, within 3 mi of both the Yazoo and Sunflower Rivers (fig. 14). Well M38 is within the central drawdown region of the alluvial aquifer where long-term declines in water levels have been observed. Although observed water levels in well M38 fluctuate more than simulated water

Table 3. Second calibration array showing the sum of the squares of the differences between observed and computed head values for various values of the model parameters dominant in Area II (Areas I, II, and III shown on fig. 22)

[*SY*, specific yield; *R*, areal recharge (inches per year); *K'*, Sunflower riverbed conductance (feet per day); and C, riverbed conductance = 10,000 ft/d for Sunflower River and 3,000 ft/d for Bogue Phalia]

SY	*R*	*K'*	Sum of squares of head residuals: Total	Area I	Area II	Area III
0.25	0	.1C	78,357	24,532	14,253	39,572
		C	77,928	24,335	14,121	39,472
		10 C	75,838	23,384	13,599	38,855
	.5	.1C	77,214	28,058	13,437	35,719
		C	77,004	27,977	13,322	35,705
		10 C	75,997	27,491	12,953	35,553
	1	.1C	99,622	44,673	12,746	42,203
		C	98,137	43,897	12,649	41,591
		10 C	93,775	41,739	12,409	39,627
0.30	0	.1C	75,759	24,126	13,315	38,318
		C	75,113	23,715	13,234	38,164
		10 C	73,534	22,786	13,021	37,727
	.5	.1C	74,908	27,607	12,826	34,475
		C	74,753	27,530	12,759	34,464
		10 C	73,986	26,984	12,631	34,371
	1	.1C	94,105	42,567	12,406	39,132
		C	93,062	42,026	12,352	38,684
		10 C	90,159	40,563	12,320	37,276
0.35	0	.1C	75,477	24,186	13,090	38,201
		C	74,509	23,608	13,036	37,865
		10 C	72,517	22,466	12,973	37,078
	.5	.1C	73,965	27,503	12,764	33,698
		C	73,953	27,449	12,727	33,777
		10 C	73,388	26,914	12,724	33,750
	1	.1C	91,899	41,836	12,499	37,564
		C	91,068	41,380	12,468	37,220
		10 C	88,514	40,000	12,547	35,967

levels, the long-term decline in water levels of about 1 ft/yr is reproduced by the model. Water levels in J13 are dominated by the influence of the Yazoo Navigation Canal. Although simulated water levels are usually lower than observed water levels, the general trend of the observed hydrograph is reasonably well reproduced.

Figures 26–31 illustrate the flow terms involved in the calibrated model for the 24-month simulation period. The following conclusions can be drawn from these data:

- Both aquifer stresses and responses are highly seasonal.
- The model showed that the aquifer had a net loss in storage of about 400,000 acre-feet per year (acre-ft/yr) (360 Mgal/d) from April 1981 to April 1983. During this period, pumpage was about 1,270,000 acre-ft/yr (1,100 Mgal/d), and the net inflows from the sources of recharge were

	Acre-feet per year	Million gallons per day
Mississippi River	440,000	390
Areal recharge	200,000	180
Recharge area along east edge of the Delta	190,000	170
Yazoo-Tallahatchie-Coldwater River System	51,000	45
Oxbow lakes	27,000	24
Sunflower River	12,000	11
Bogue Phalia	1,100	1

- Almost 0.35×10^{11} cubic feet (ft^3) or 0.8 million acre-feet, was removed from aquifer storage during the 24-month simulation period (fig. 31).
- The great majority of flow from the Mississippi River to the alluvial aquifer occurs during the first rise of a series of river rises (fig. 27). This phenomenon is due to the greatly reduced hydraulic gradients near the river after the first rise.

Sensitivity Analysis

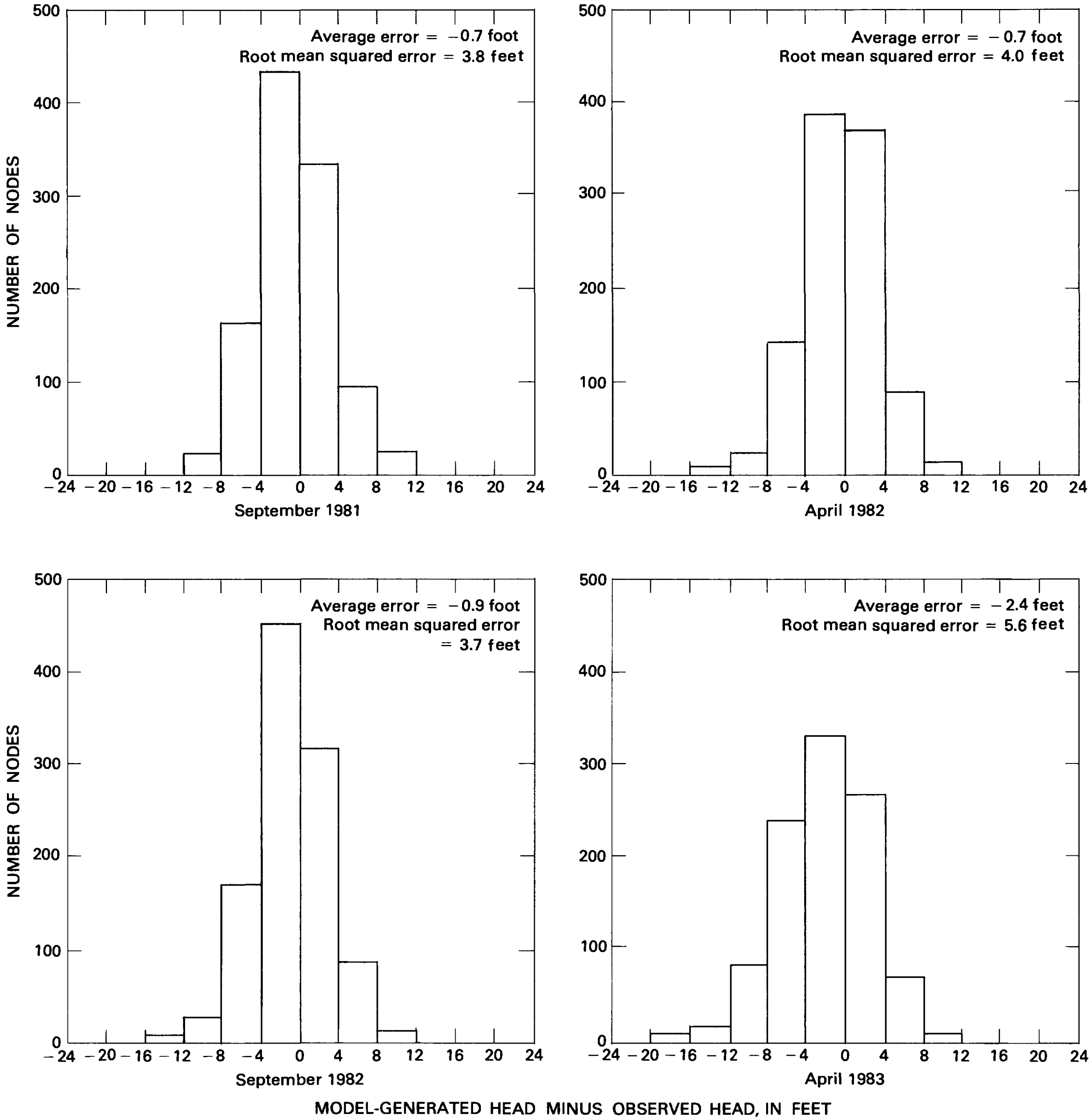
As a means of evaluating the sensitivity of the model to changes in the values for specific yield, hydraulic conductivity, areal recharge, riverbed conductances, and storage coefficient, a number of simulations were made, the results of which are presented in figure 32. The following conclusions can be drawn from an examination of these graphs.

Table 4. Third calibration array showing the sum of the squares of the differences between observed and computed head values for various values of the model parameters dominant in Area I (Areas I, II, and III shown on fig. 22)

[*S*, storage coefficient; *K'*, Yazoo-Tallahatchie-Coldwater riverbed conductance (feet per day); *K*, hydraulic conductivity (feet per day); and C, riverbed conductance = 10,000, 20,000, and 30,000 ft/d for upper, middle, and lower reaches, respectively, of the Yazoo-Tallahatchie Coldwater River system]

S	*K'*	*K*	Sum of squares of head residuals			
			Total	Area I	Area II	Area III
0.001	0.1C	200	98,336	37,618	13,592	47,126
		300	85,516	30,926	12,954	41,636
		400	78,199	27,518	12,700	37,981
		500	74,507	26,979	12,640	34,888
		600	73,149	26,821	12,752	33,576
	C	200	94,791	34,410	13,591	46,790
		300	83,782	29,658	12,954	41,170
		400	77,266	26,748	12,702	37,816
		500	73,880	26,434	12,640	34,806
		600	72,354	26,089	12,751	33,514
	10 C	200	97,663	37,748	13,586	46,329
		300	87,196	33,584	12,952	40,660
		400	81,729	31,322	12,714	37,693
		500	77,678	30,299	12,645	34,734
		600	75,867	29,608	12,765	33,494
0.0005	.1C	200	97,998	37,567	13,599	46,832
		300	85,450	31,272	12,972	41,206
		400	78,550	27,947	12,715	37,888
		500	75,107	27,553	12,658	34,896
		600	74,304	27,524	12,755	34,025
	C	200	94,713	34,596	13,598	46,519
		300	83,983	30,241	12,970	40,772
		400	77,772	27,336	12,716	37,720
		500	74,596	27,122	12,660	34,814
		600	73,520	26,824	12,753	33,943
	10 C	200	98,020	38,374	13,597	46,049
		300	87,850	34,523	12,965	40,362
		400	82,453	32,125	12,724	37,604
		500	78,548	31,125	12,661	34,762
		600	76,964	30,308	12,774	33,882
0.0001	.1C	200	97,700	37,546	13,602	46,252
		300	85,601	31,758	12,979	40,874
		400	79,055	28,430	12,723	37,902
		500	76,058	28,163	12,665	35,230
		600	75,555	28,224	12,761	34,570
	C	200	94,651	34,791	13,601	46,259
		300	84,410	30,943	12,979	40,488
		400	78,333	27,903	12,724	37,706
		500	75,612	27,792	12,662	35,158
		600	74,750	27,528	12,759	34,463
	10 C	200	98,214	38,858	13,598	45,758
		300	88,639	35,421	12,973	40,245
		400	83,123	32,840	12,731	37,552
		500	79,700	31,929	12,667	35,104
		600	78,103	30,952	12,786	34,365

- The model is relatively insensitive to changes in hydraulic conductivity and specific yield for values higher than 400 ft/d and 0.30, respectively, for these parameters.
- Within Areas I and III, the model is quite sensitive to areal recharge rate. Because of this sensitivity, future field work in the area would be applied most profitably to the further definition of magnitude and distribution of areal recharge.
- Within Area I, the model is rather sensitive to changes in Yazoo-Tallahatchie-Coldwater riverbed conductances.



$$\text{Average error} = \sum_{i=1}^{N} \frac{(h_{cal_1} - h_{obs_1})}{N}$$

$$\text{Root mean squared error} = \sqrt{\frac{\sum_{i=1}^{N} (h_{cal_1} - h_{obs_1})^2}{N}}$$

where h_{cal} = Model-generated head
h_{obs} = Observed head
N = Number of nodes used in error computations (nonspecified nodes)

Figure 23. Distribution of head error for the September 1981 through April 1983 calibration simulations.

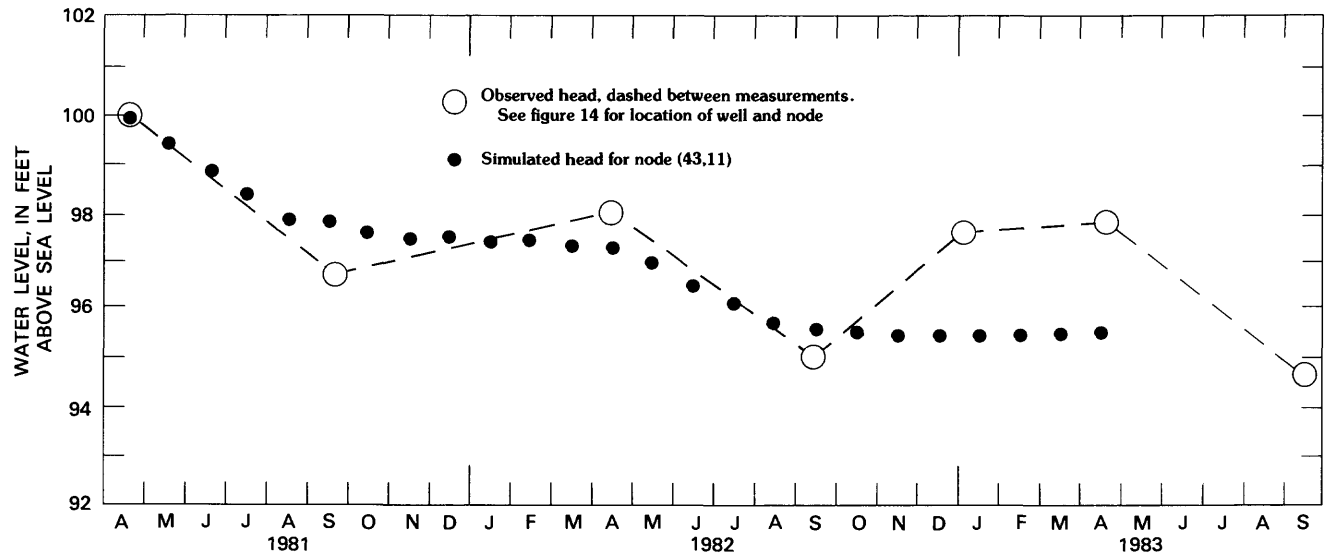


Figure 24. Observed and model-generated hydrographs for well M38, Sunflower County.

- The model is rather insensitive to changes in the Sunflower-Bogue Phalia riverbed conductances.
- The model is only slightly sensitive to changes in storage coefficient.

Model Verification

Model verification was accomplished by simulating the aquifer response from April 1983 to September 1983, a rather short verification period but one in which the aquifer experienced a significant stress as agricultural pumpage began and the rivers fell from their higher-than-normal spring stages. As the error histogram indicates, the model simulated the aquifer reasonably well during this period. About 96 percent of the nodes had computed head values within 8 ft of observed heads (fig. 33). Figure 34 illustrates observed and computed water levels.

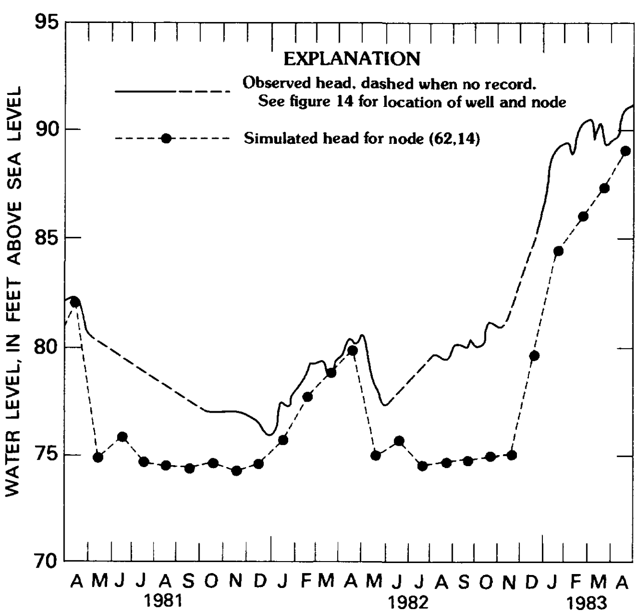


Figure 25. Observed and model-generated hydrographs for well J13, Yazoo County.

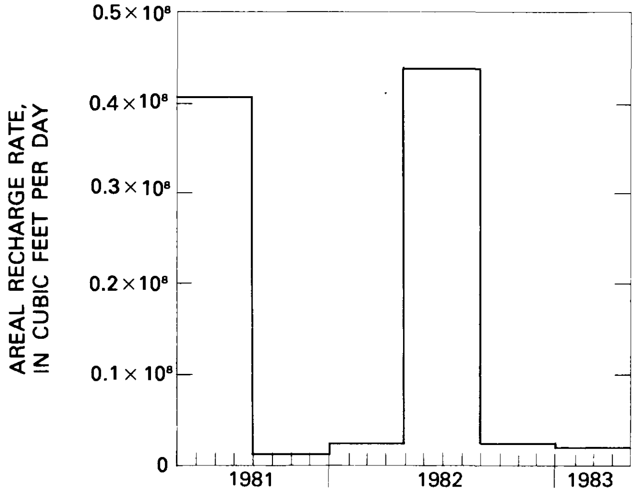
EFFECTS OF SIMULATED GROUND-WATER WITHDRAWALS

The calibrated and verified model of the alluvial aquifer, as described in the two previous sections is used herewith to estimate aquifer responses in the future. The following pumping stresses were simulated for the 20-year period beginning September 1983:

- Simulation 170—No pumpage.
- Simulation 171—Pumpage of 670 Mgal/d, minimum average pumpage during the next 20 years as estimated by Delta Council (oral commun., 1983).
- Simulation 173—Pumpage of 1,100 Mgal/d; 1983 pumpage as estimated by Delta Council.
- Simulation 172—Pumpage of 1,900 Mgal/d; maximum average pumpage as estimated by Delta Council.
- Simulation 174—Pumpage of 4,000 Mgal/d; highest predicted demand.

The five scenarios of pumpage input to the 20-year projection model cover a wide range of possibilities. The Delta Council's estimated pumpage for 1983 of 1,100 Mgal/d (table 5) is about equal to the average pumpage since 1978 (fig. 11). The 4,000-Mgal/d scenario was used to approximately double the next lower pumping rate and to have a closer match with other higher predictions of maximum agricultural water demand. The 4,000 Mgal/d was distributed evenly among the 1,211 active nodes of the model (3.3 Mgal/d per 6.3-mi^2 node).

For model simulations 171 to 173, the pumpage for rice and catfish ponds was distributed to model nodes in the



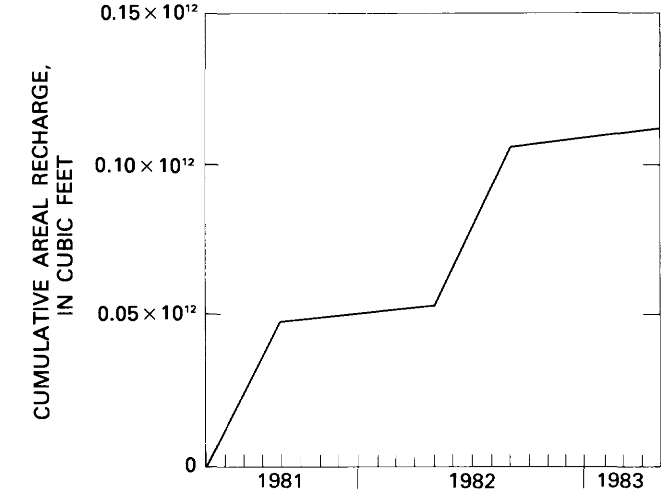


Figure 26. Recharge and cumulative pumpage within the calibrated model for the April 1981 to April 1983 simulation.

proportions as mapped for 1982 (figs. 19, 20). Pumpage for soybeans and cotton was distributed uniformly among the active nodes of the model. The pumpage projection scenarios are assumed to be supplied from the alluvial aquifer and not from surface sources. In recent years, streams and lakes have supplied about 15 percent of the irrigation water if water for catfish ponds is excluded and about 10 percent if catfish pumpage is included. Pumpage at three powerplants was assigned as appropriate. Another change from the basic calibration model was the use of long-term average head values for boundary nodes, rather than updated monthly values. The time-step length was changed from monthly for the calibration simulations to 2 years for the predictive simulations (170–174).

Results of the predictive model (simulations 170–174) are presented in table 6 and in figures 35 to 50. Water budgets (table 6) for the ending stress period for each of the simulations show various shifts in flow as pumpage is increased or as pumpage is redistributed.

A schematic diagram illustrating the flow budget for the 1,900-Mgal/d pumping rate is shown in figure 35. The predictive simulations have constant-stress stream stages and pumping rates. With increasing pumpage rates from wells (table 6), increases occur in withdrawals of water from aquifer storage, percentage of pumpage derived from storage, eastern recharge area to aquifer flow, and stream to aquifer leakage. At 670 Mgal/d, the percentage of pumpage coming from storage is 32 percent; at 1,100 Mgal/d, 46 percent; and at 1,900 Mgal/d, 56 percent. However, for 4,000-Mgal/d pumpage, the percentage of water from storage is only 52 percent because pumpage for this scenario is distributed uniformly.

A series of five maps (figs. 36–40) shows the simulated potentiometric surface for 2003 for the different pumping scenarios. With each increase in pumpage, the simulated potentiometric surface maps show a lower water surface and enlargement of the depressed potentiometric surface in the central part of the Delta compared to the September 1983 potentiometric surface map. Pumpage more than doubles between the 1,900- and 4,000-Mgal/d pumpage scenarios, but, because areal distribution is different, the maximum drawdowns or minimum heads are about the same for the two simulations. However, the 4,000 Mgal/d causes a much larger area of water-level depression in the aquifer.

Another series of maps (figs. 41–45) shows the drawdown or recovery that occurs during the 20-year projections. The no-pumpage simulation shows a maximum of about 30 ft of recovery (fig. 41) from 1983 water levels. With increasing pumping rates, the magnitude and extent of drawdown increase (figs. 42–45).

A third series of maps (figs. 46–50) shows the remaining saturated thickness of the alluvial aquifer after 20 years of continuous pumpage at specified rates. As water levels decline and the saturated thickness of the aquifer becomes less, it will become more difficult to obtain large yields from wells. At present, large-capacity irrigation wells in the Delta are constructed with 20 to 60 ft of screen and have 20 to 50 ft of drawdown space above the screens. As saturated thickness diminishes, the average yields of wells will be smaller, and water-supply problems are likely to occur.

Areal variation in saturated aquifer thickness in 2003 for five pumping rates are shown in figures 46 through 50. Figure 46 shows that, if no pumpage occurs during the 20-year period, most of the Delta would have more than 100 ft of saturated aquifer and that some large areas of the Delta would have more than 150 ft of saturated aquifer. The saturated aquifer thickness map (fig. 47) resulting from the 670-Mgal/d pumping rate simulation shows several small areas in the Delta where no more than 75 ft of the alluvial aquifer is saturated. The largest area having less than 75 ft of saturated aquifer is in the part of Washington County where the total thickness of the alluvial aquifer tends to be less than in most of the Delta. The 1,100-Mgal/d simulation (fig. 48) shows that several large areas will have less than 75 ft of saturated aquifer and some small areas will have less than 50 ft of saturated aquifer. The 1,900-Mgal/d simulation (fig. 49) shows that a large part of the central Delta would have less than 75 ft of saturated aquifer and two small areas in Bolivar and Sunflower Counties would have less than 25 ft. The 4,000-Mgal/d pumpage scenario (fig. 50) is more than twice the 1,900-Mgal/d scenario, but, because of the uniform distribution of pumpage in the former, the total area having less than 25 ft of saturated aquifer is about the same for both simulations. However, the area that will have less than 75 ft of saturated aquifer will be much greater for the higher pumping rate (fig. 50) than for the lower rate (fig. 49).

CONCLUSIONS AND SUMMARY

The 7,000-mi^2 Mississippi River alluvial plain in northwestern Mississippi, locally known as the Delta, is underlain by a prolific aquifer that yielded about 1,100 Mgal/d of water to irrigation wells in 1983. About 20 ft of clay underlying the Delta land surface commonly is underlain by about 80 to 180 ft of sand and gravel that forms the Mississippi River alluvial aquifer. This study of the alluvial aquifer was prompted by recent declines of water levels in the alluvial aquifer. The study was designed to better define the hydrology of the aquifer and to quantify availability of water from the aquifer.

New hydrologic data collected during this investigation have resulted in a better understanding of the geohydrology of the Delta. Water-level profiles developed during the study proved that the Mississippi River is in good hydraulic connection with the Mississippi River alluvial aquifer. These profiles generally show that the smaller and less deeply incised the stream, the less likely it is to recharge the aquifer. Water-level profiles, potentiometric surface maps, and well hydrographs generally show that direct vertical recharge to the alluvial aquifer from the 52 in/yr of precipitation is small, especially in the central part of the Delta.

The aquifer is underlain by subcrops of older, less permeable aquifers (Sparta and Cockfield aquifers) and by three belts of relatively impermeable clay beds. A multilayer model that includes the Sparta and Cockfield aquifers indicates that the deeper aquifers have little effect on the hydrology of the Mississippi River alluvium.

A two-dimensional, finite-difference computer model of the alluvial aquifer was constructed. The model was calibrated and verified based on water levels observed for five dates from April 1981 to September 1983. A satisfactory correlation between model-generated heads and observed heads was achieved.

The values of the calibration-derived parameters are as follows:

Hydraulic conductivity.—400 ft/d, assumed uniform throughout the aquifer.
Specific yield.—0.30, assumed uniform throughout the aquifer.
Storage coefficient.—0.001, assumed uniform throughout the aquifer.
Areal recharge.—0.5 in/yr, assumed uniform throughout the area of aquifer.
Riverbed leakance.—
Yazoo-Tallahatchie-Coldwater River system—0.008 per day (d^{-1}).
Sunflower River—0.004 d^{-1}.
Bogue Phalia—0.002 d^{-1}.

The model showed that the aquifer had a net loss in storage of about 400,000 acre-ft/yr (360 Mgal/d) from April 1981 to April 1983. During this period, pumpage was about 1,270,000 acre-ft/yr (1,100 Mgal/d), and the net inflows from the sources of recharge were

	Acre-feet per year	Million gallons per day
Mississippi River	440,000	390
Areal recharge	200,000	180
Recharge area along eastern edge of the Delta	190,000	170
Yazoo-Tallahatchie-Coldwater River system	51,000	45
Oxbow lakes	27,000	24
Sunflower River	12,000	11
Bogue Phalia	1,100	1

The simulated effects of rates of pumpage by wells—0, 670, 1,100, 1,900, and 4,000 Mgal/d—were projected 20 years into the future. The pumping rate of 1,100 Mgal/d is about average for the early 1980's. For this pumping rate, 46 percent of the water pumped would be coming from storage at the end of 20 years, and declining ground-water levels would continue. Increasing the pumping rate to 1,900 Mgal/d for the same 20-year period increases the percentage of water coming from storage to 56 percent (table 6). Simulated water levels for a pumping rate of 1,100 Mgal/d for the year 2003 show water levels to be more than 40 ft lower than those of 1983 in part of Humphreys County and more than 20 ft lower in a large area in the central part of the Delta (fig. 43). It is not possible to simulate steady-state water levels for the aquifer for a 1,100-Mgal/d pumping rate because parts of the aquifer become unsaturated at some time exceeding 20 years but before equilibrium of flow in the aquifer is reached.

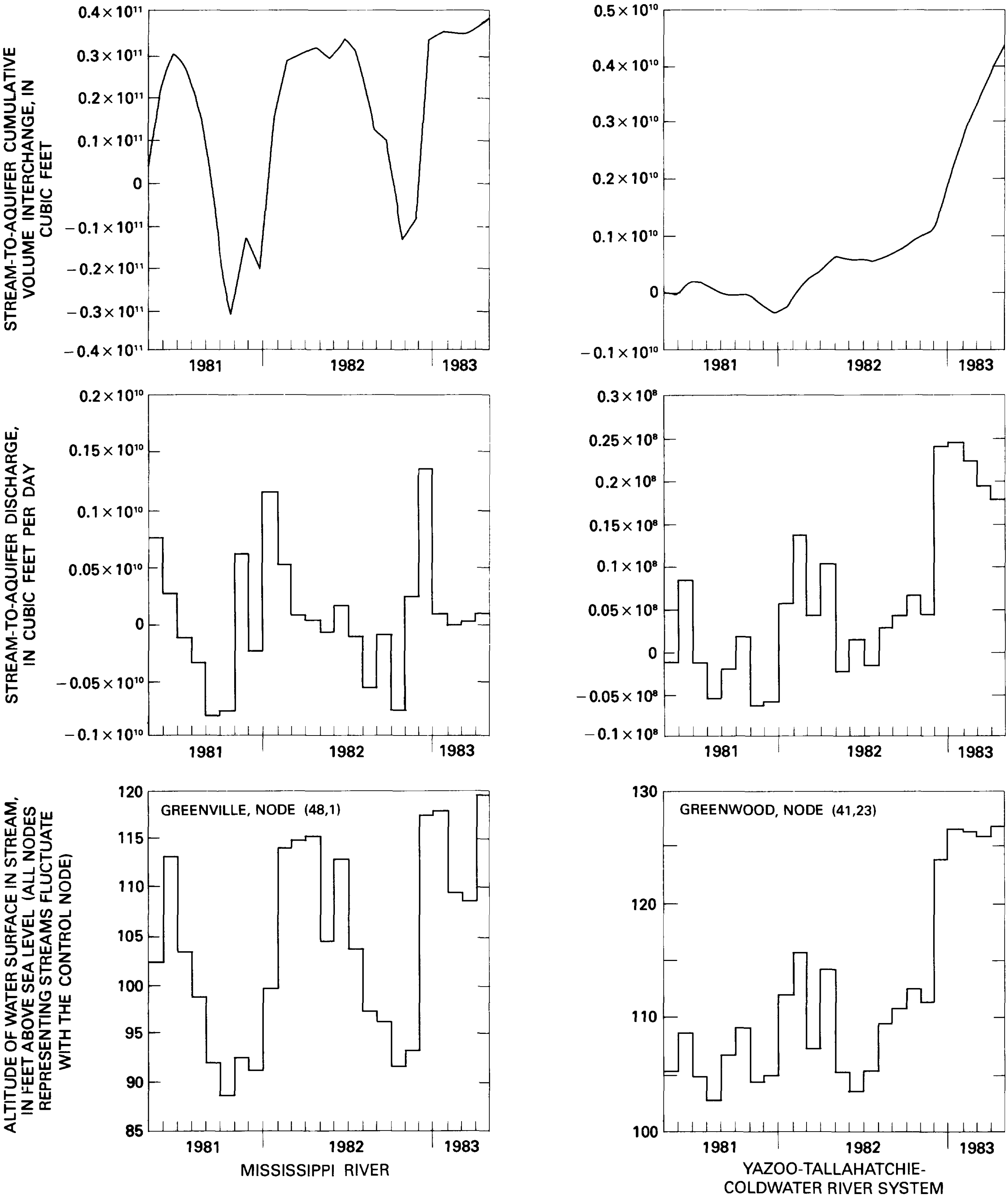


Figure 27. Relations of streams to the alluvial aquifer within the calibrated model for the April 1981 to April 1983 simulation.

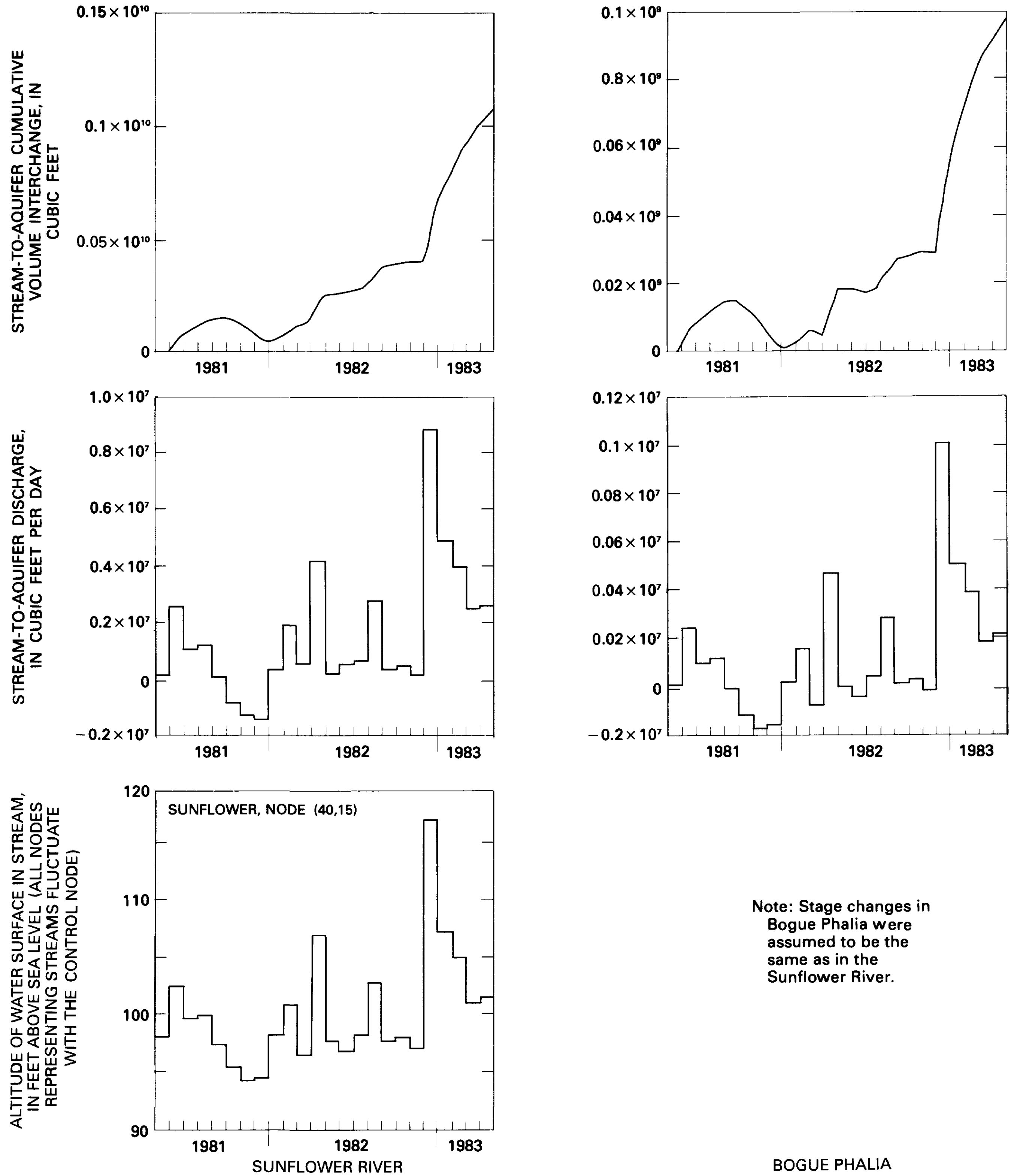


Figure 27. Continued.

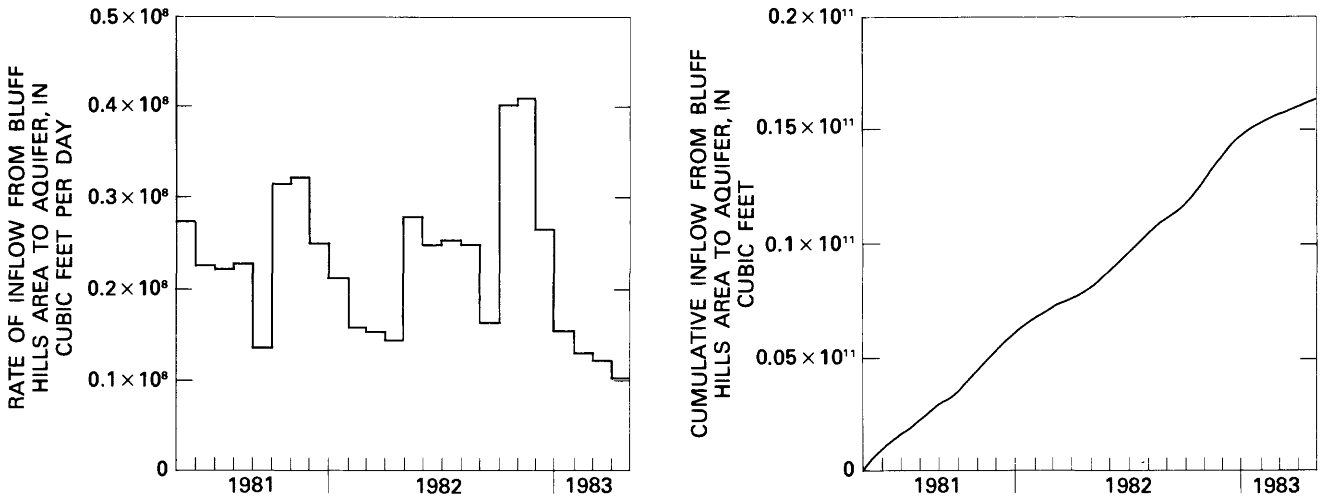


Figure 28. Relations of recharge area along the eastern edge of the Delta to the alluvial aquifer within the calibrated model for the April 1981 to April 1983 simulation.

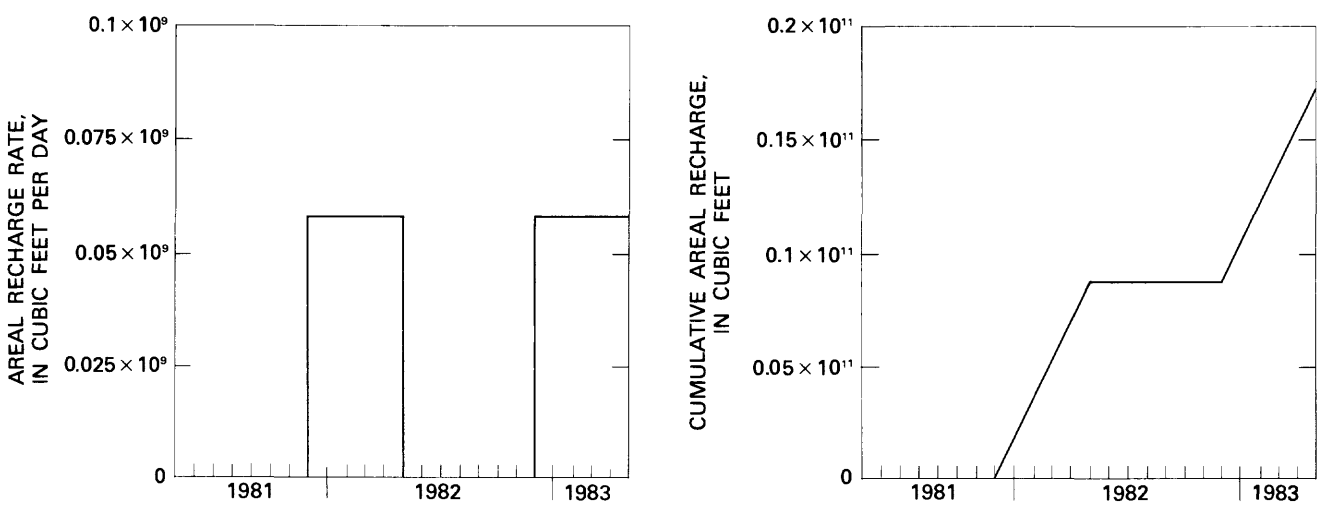


Figure 29. Areal recharge rate and cumulative volume interchange within the calibrated model for the April 1981 to April 1983 simulation.

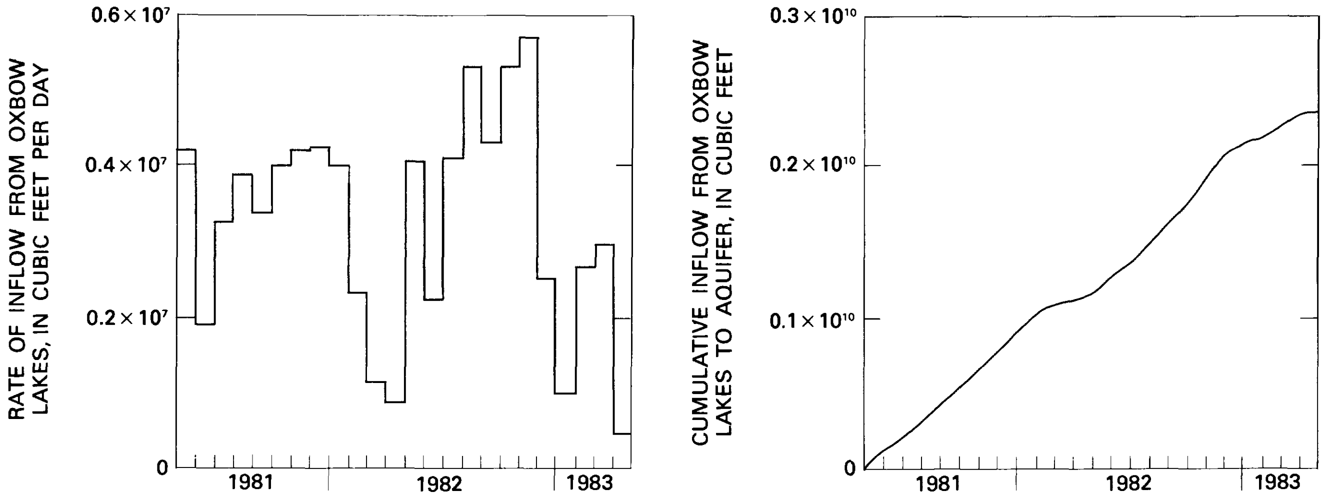


Figure 30. Relation of oxbow lakes to alluvial aquifer within the calibrated model for the April 1981 to April 1983 simulation.

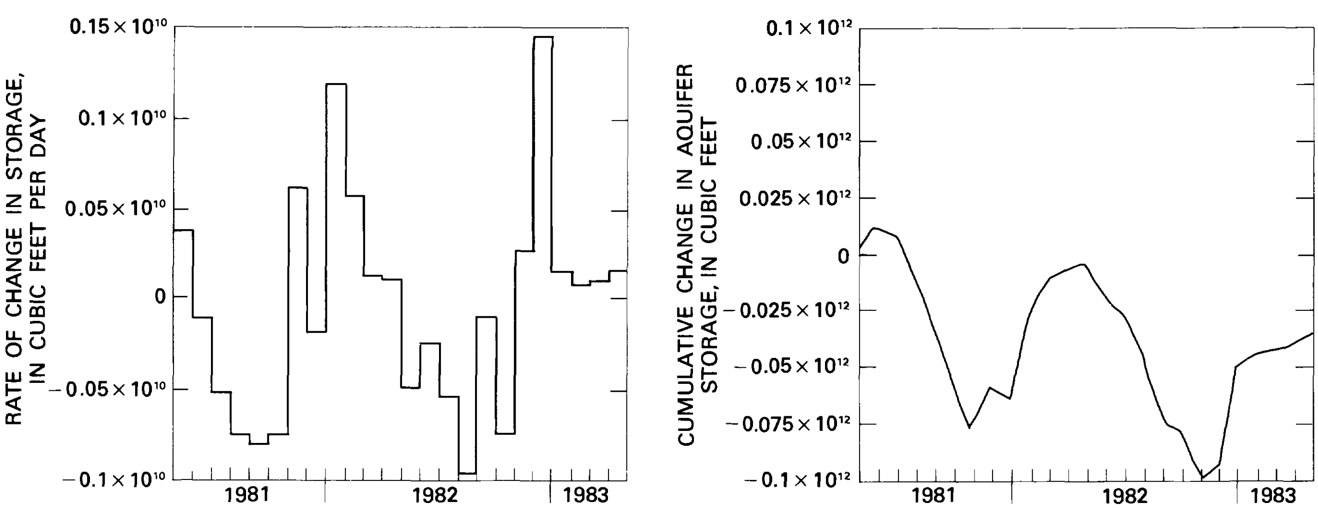


Figure 31. Rate and cumulative volume intercharge of water added to aquifer storage within the calibrated model for the April 1981 to April 1983 simulation.

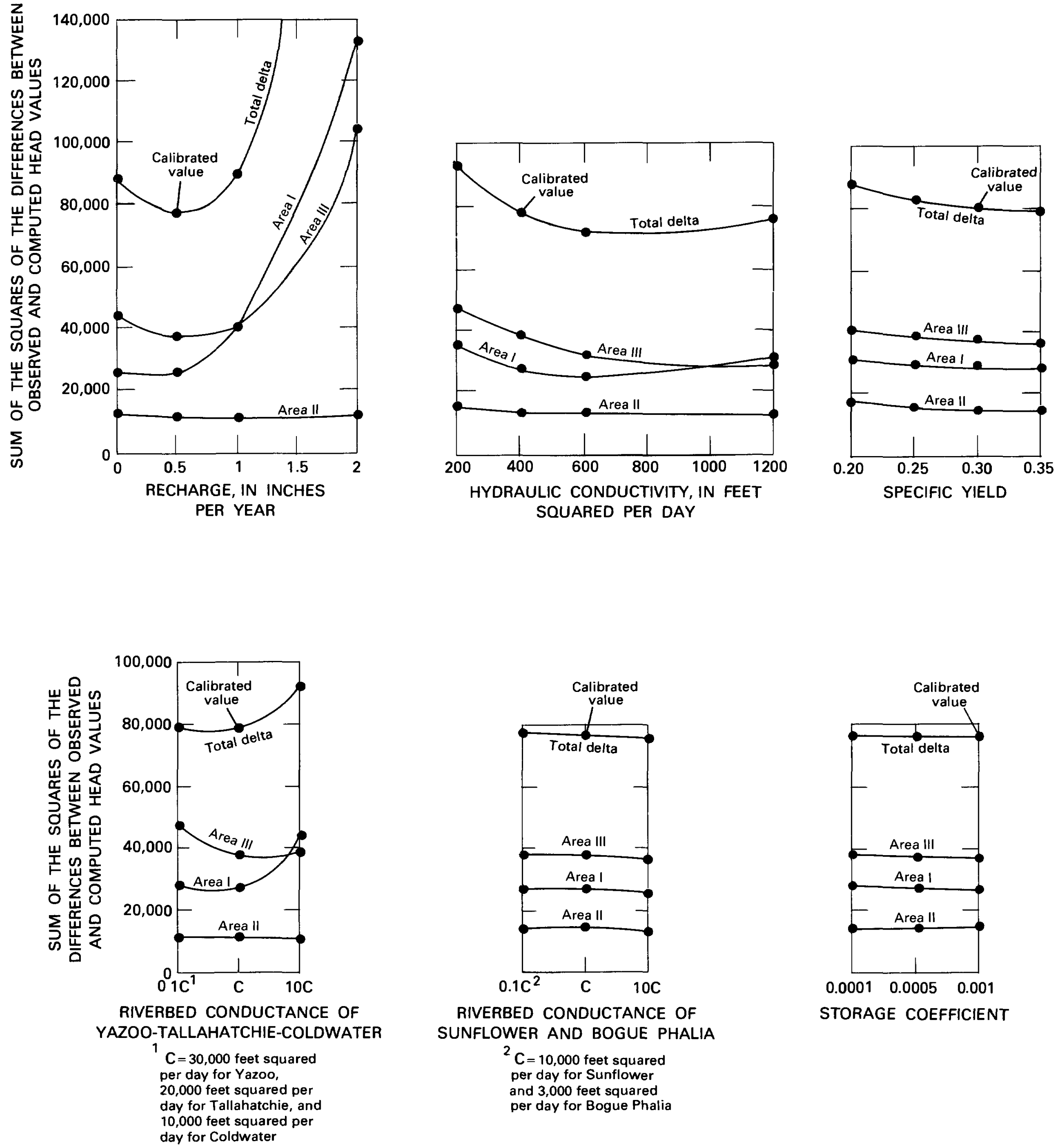


Figure 32. Sensitivity of calibrated 24-month model to variations in various input parameters.

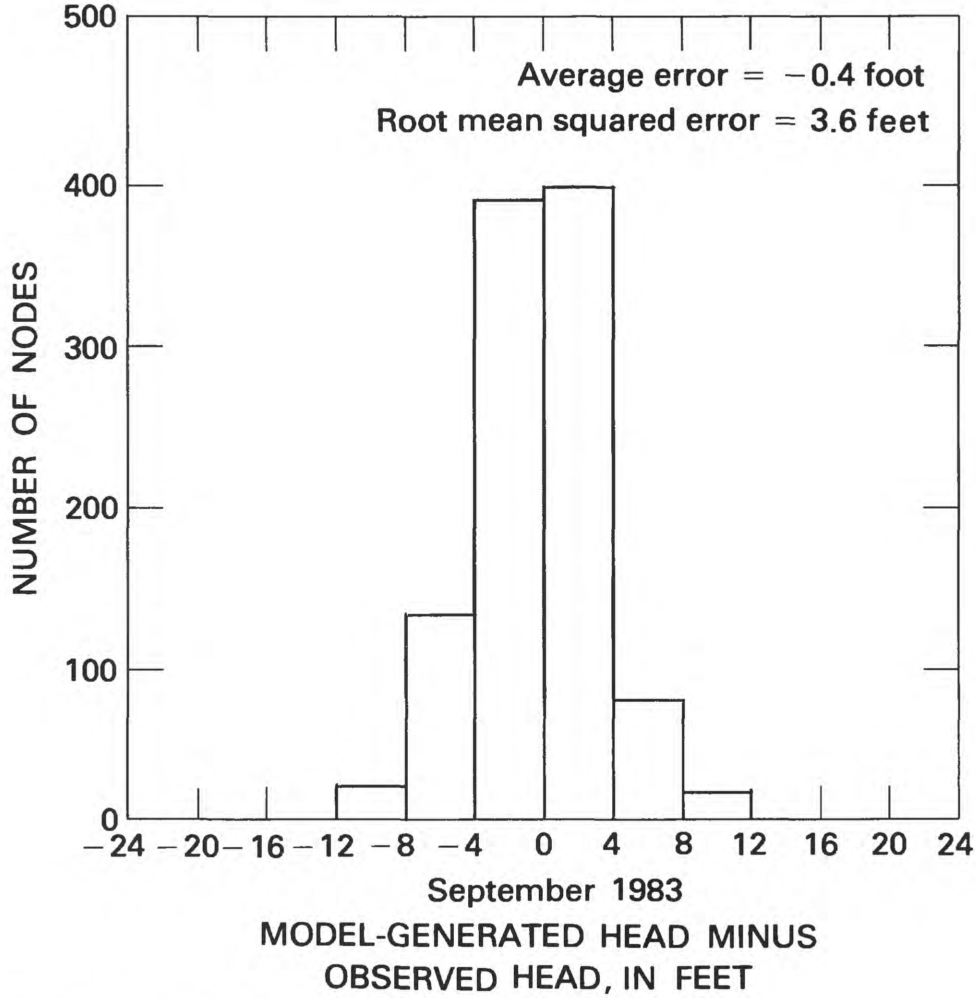


Figure 33. Distribution of head error for April to September 1983 simulation.

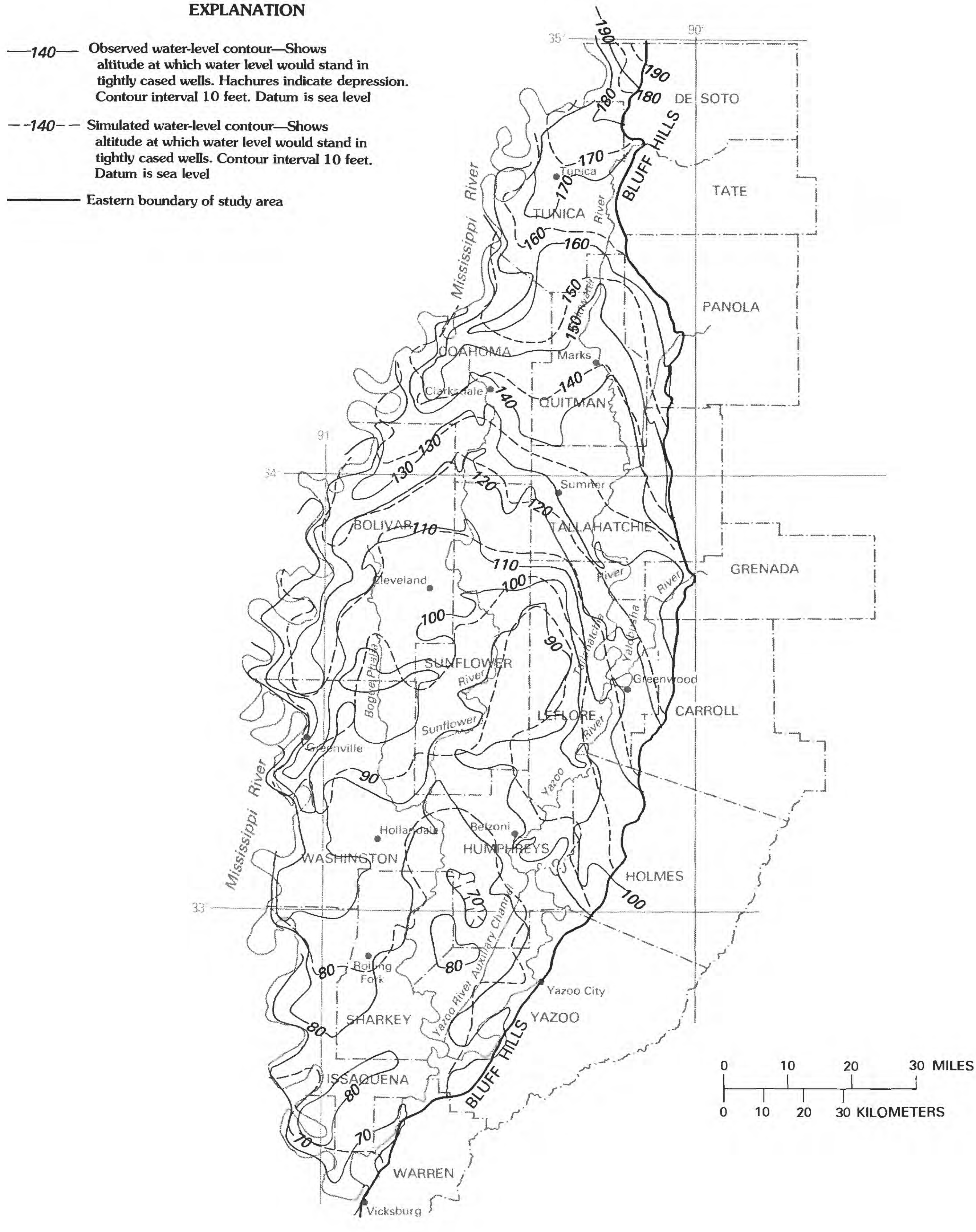


Figure 34. Observed and model-generated water levels of the alluvial aquifer in the Delta for September 1983.

Table 5. Delta Council estimates of minimum, 1983, and maximum agricultural pumpage used to simulate aquifer conditions during the next 20 years
[Staff and several members participated in making estimates, December 2, 1983]

Crop	Acres		Feet of water applied		Acre-feet
Minimum Acreage Projection					
Cotton	150,000	×	$0.5 \times {}^{1}2/5$	=	30,000
Soybeans	300,000	×	$0.5 \times {}^{2}4/5$	=	120,000
Rice	100,000	×	3	=	300,000
Catfish	60,000	×	5	=	300,000
Total					750,000 = 670 Mgal/d
1983 Acreage Estimate					
Cotton	150,000	×	0.5	=	75,000
Soybeans	300,000	×	0.5	=	150,000
Rice	155,000	×	4	=	620,000
Catfish	60,000	×	7	=	420,000
Total					1,265,000 = 1,100 Mgal/d
Maximum Acreage Projection					
Cotton	450,000	×	$0.5 \times {}^{2}2/5$	=	90,000
Soybeans	900,000	×	$0.5 \times {}^{3}4/5$	=	360,000
Rice	400,000	×	3	=	1,200,000
Catfish	100,000	×	5	=	500,000
Total					2,150,000 = 1,900 Mgal/d

[1]Expect to irrigate cotton 2 out of 5 years.
[2]Expect to irrigate soybeans 4 out of 5 years.

Table 6. Water budget for entire model at end of each 20-year simulation
[Flow rates in million gallons per day]

Simulation number	170	171	173	172	174
Approximate pumpage, in million gallons per day	0	670	1,100	1,900	4,000
Flow to aquifer from:					
Storage	0	229	539	1,079	2,106
Wells	0	0	0	0	0
Recharge	178	178	178	178	178
River leakage	26	220	317	455	1,208
Specified head	44	124	171	248	533
Total in	248	751	1,205	1,960	4,025
Flow from aquifer to :					
Storage	70	0	0	0	0
Wells	0	705	1,166	1,929	4,013
Recharge	0	0	0	0	0
River leakage	134	33	26	19	0
Specified head	29	1	1	0	0
Total out	234	739	1,193	1,948	4,013
Percent discrepancy of in-out calculations	6.04	1.58	1.00	0.60	0.30
Percentage of water pumped that comes from storage		32	46	56	52

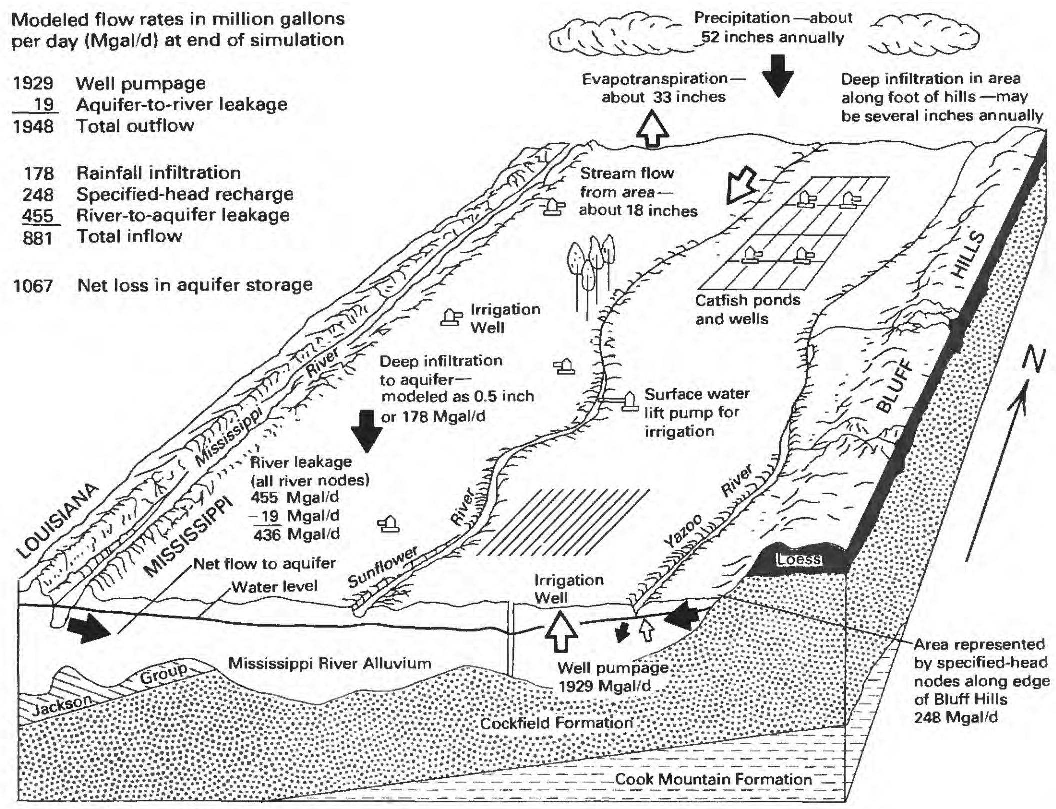


Figure 35. Simulated flow diagram for the alluvial aquifer for a 1,900-million-gallon-per-day pumping rate for 2003.

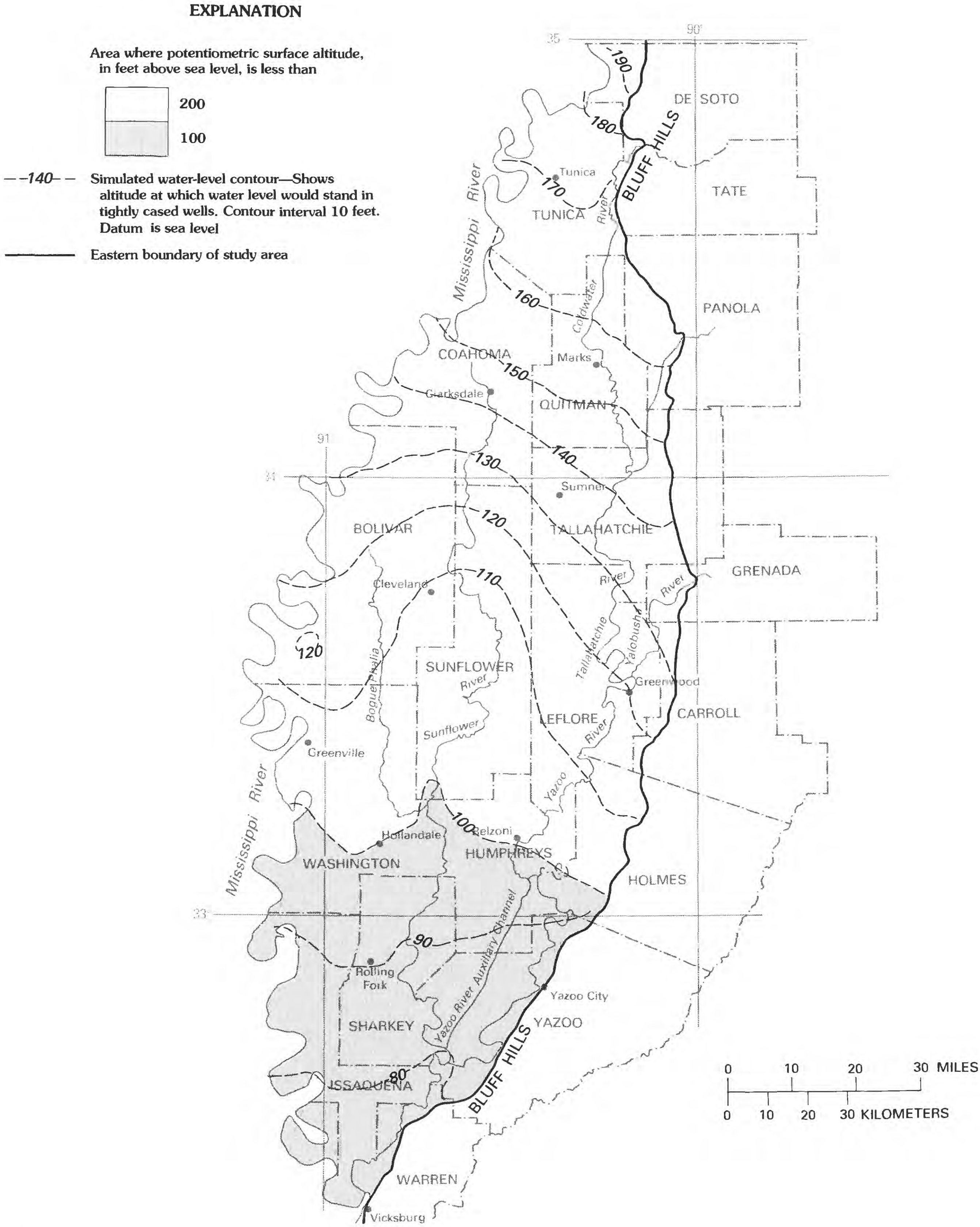


Figure 36. Simulated potentiometric surface of the alluvial aquifer in the Delta for 2003 assuming no pumpage.

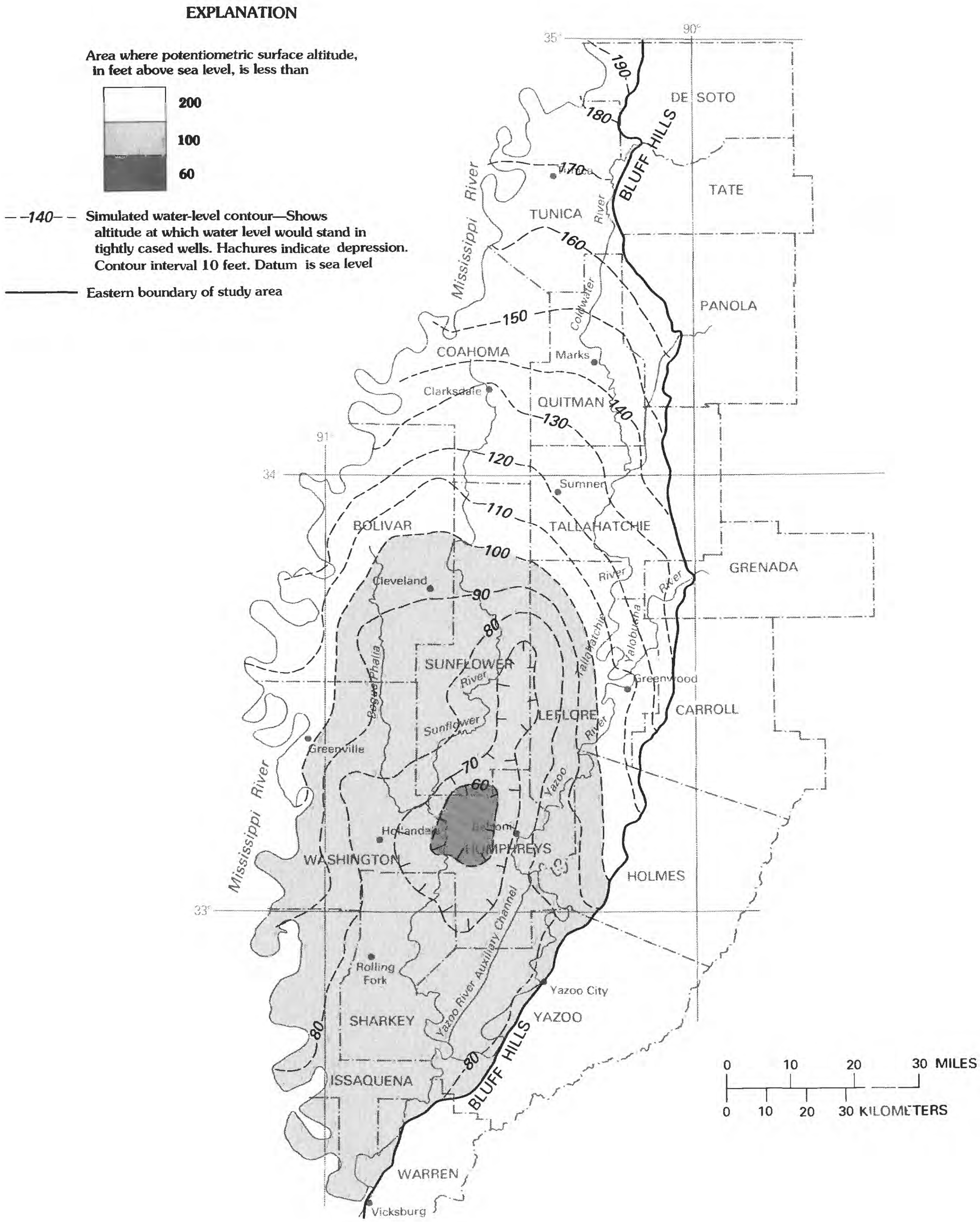


Figure 37. Simulated potentiometric surface of the alluvial aquifer in the Delta for 2003 assuming pumpage is 670 million gallons per day.

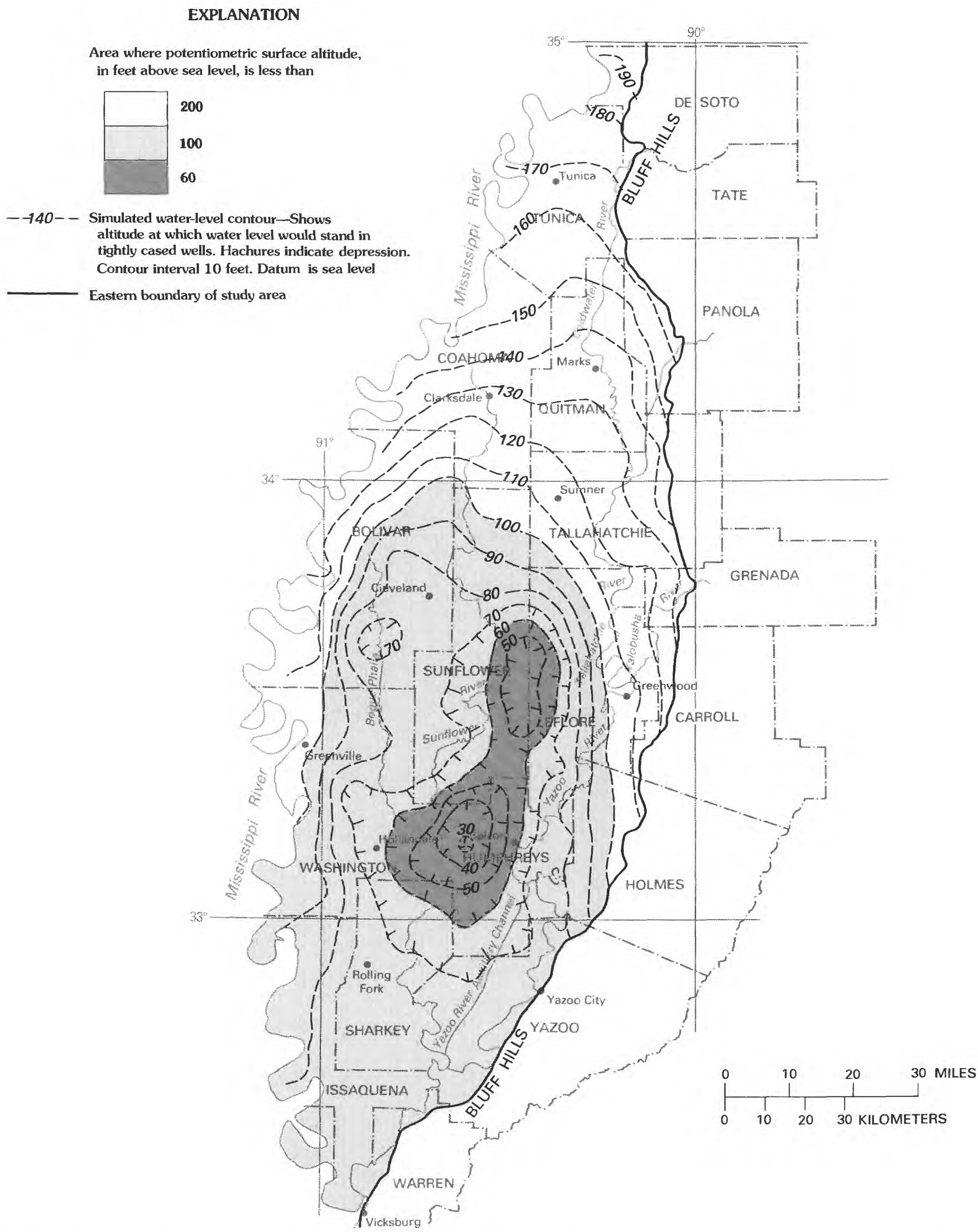


Figure 38. Simulated potentiometric surface of the alluvial aquifer in the Delta for 2003 assuming pumpage is 1,100 million gallons per day.

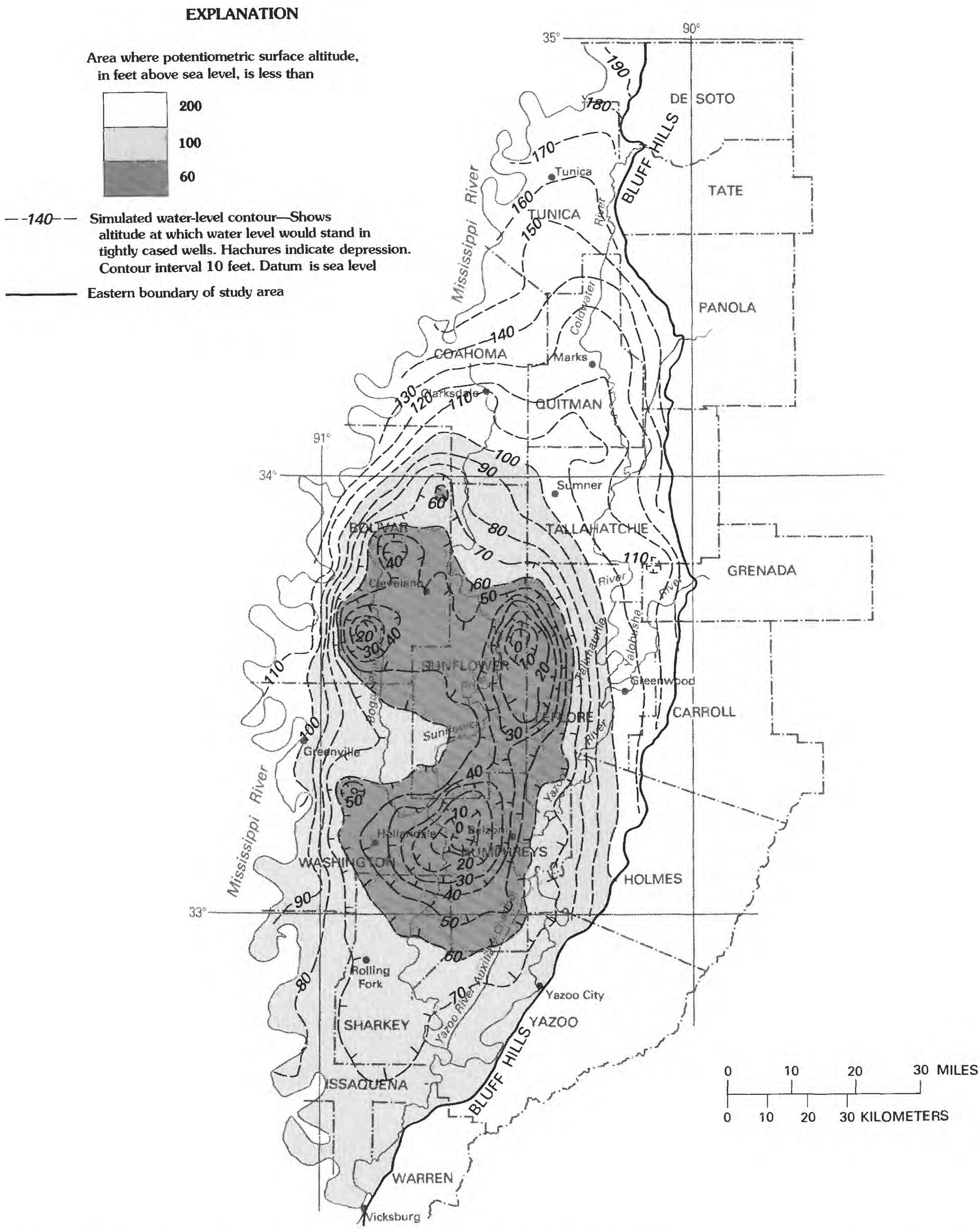


Figure 39. Simulated potentiometric surface of the alluvial aquifer in the Delta for 2003 assuming pumpage is 1,900 million gallons per day.

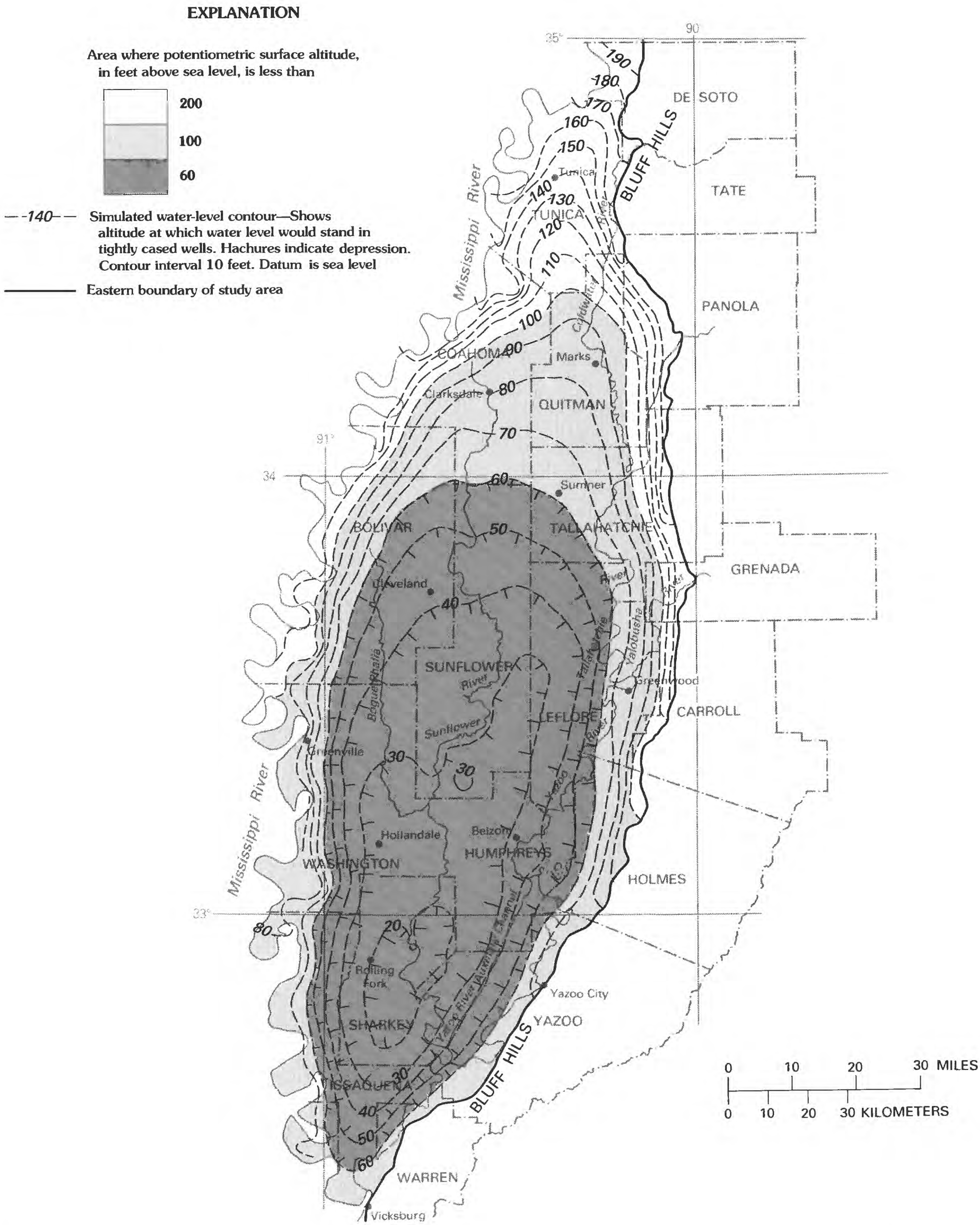


Figure 40. Simulated potentiometric surface of the alluvial aquifer in the Delta for 2003 assuming pumpage is 4,000 million gallons per day and is distributed uniformly.

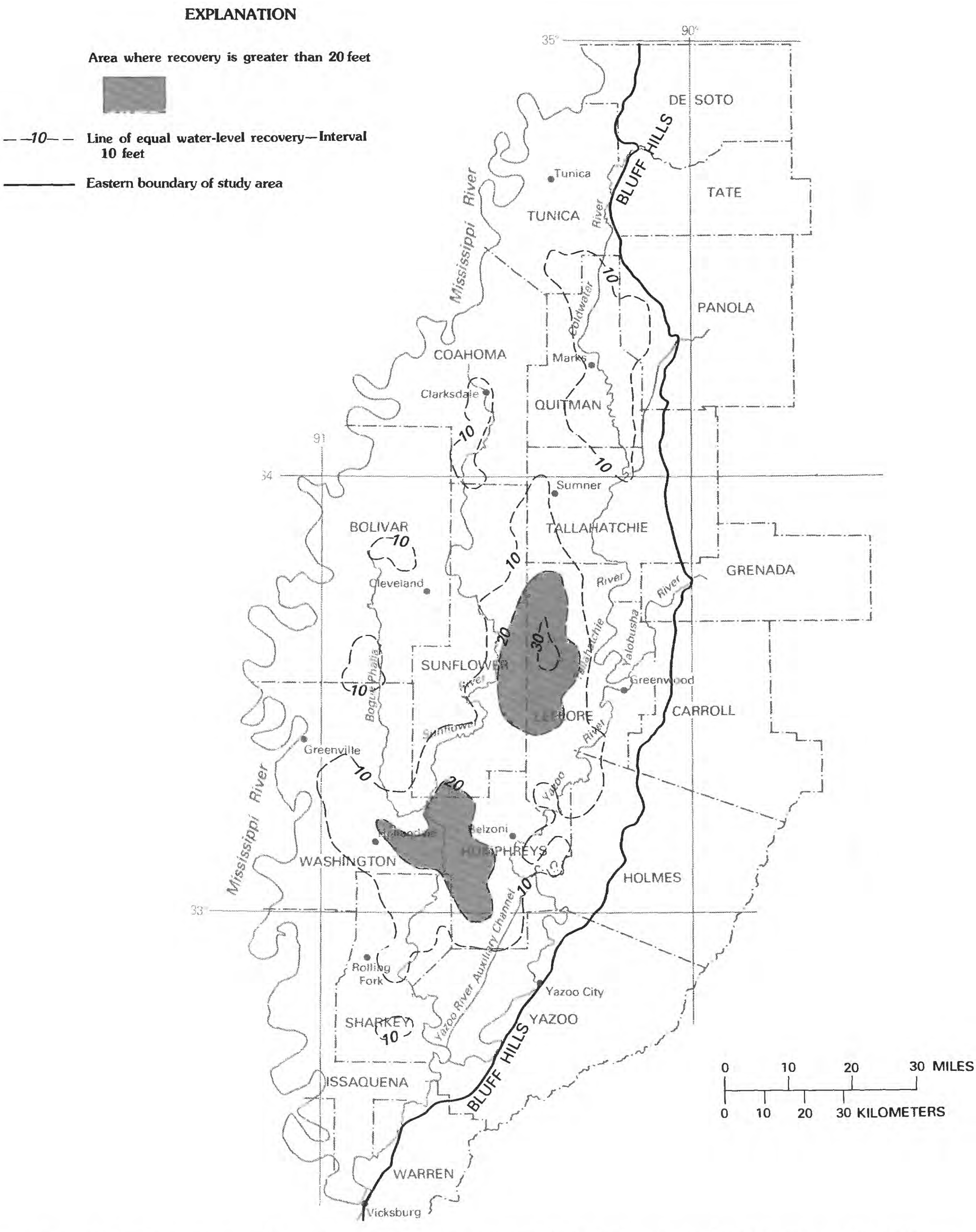


Figure 41. Simulated recovery of water levels in the alluvial aquifer in the Delta from September 1983 to September 2003 assuming no pumpage.

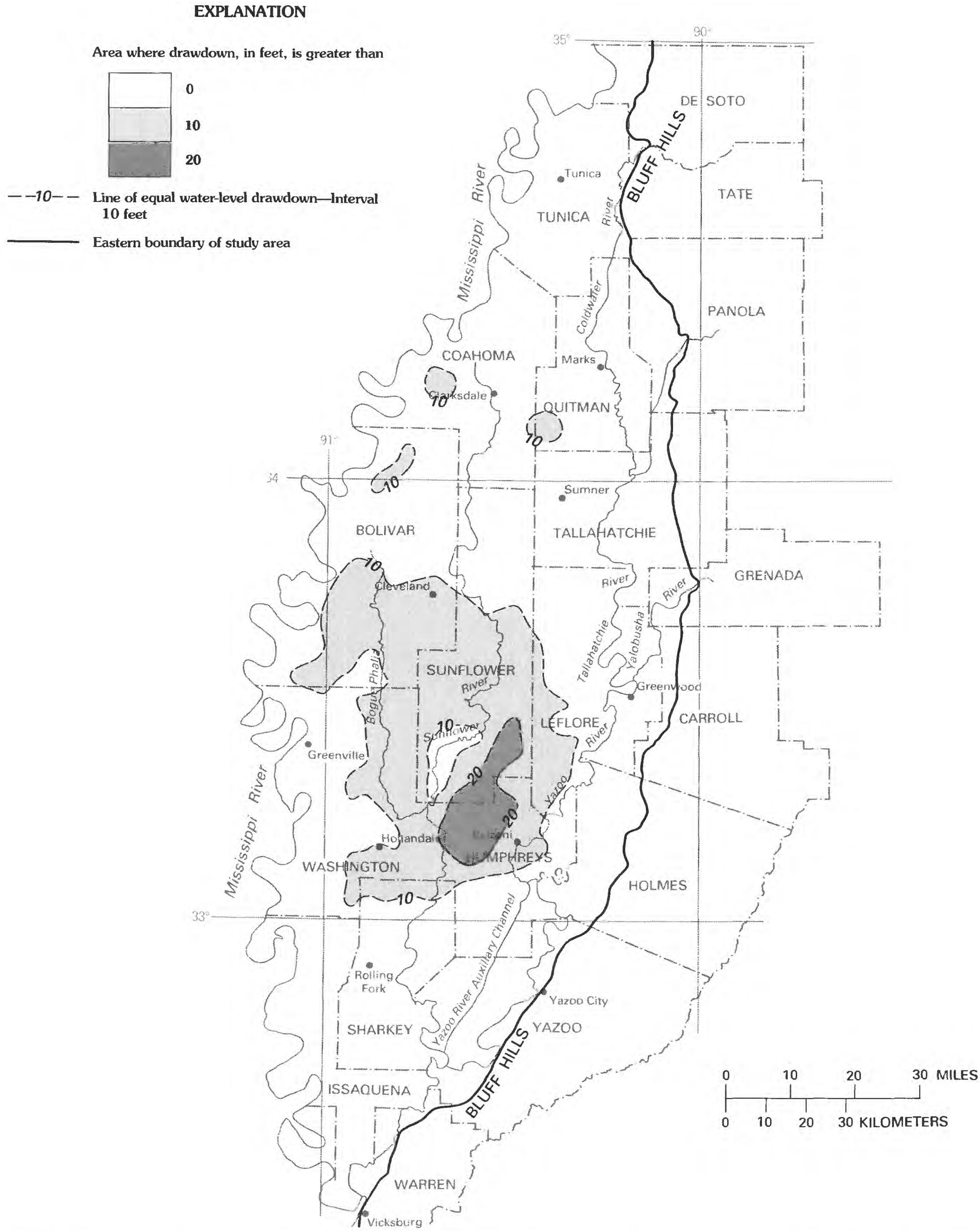


Figure 42. Simulated drawdown of water levels in the alluvial aquifer in the Delta from September 1983 to September 2003 assuming pumpage is 670 million gallons per day.

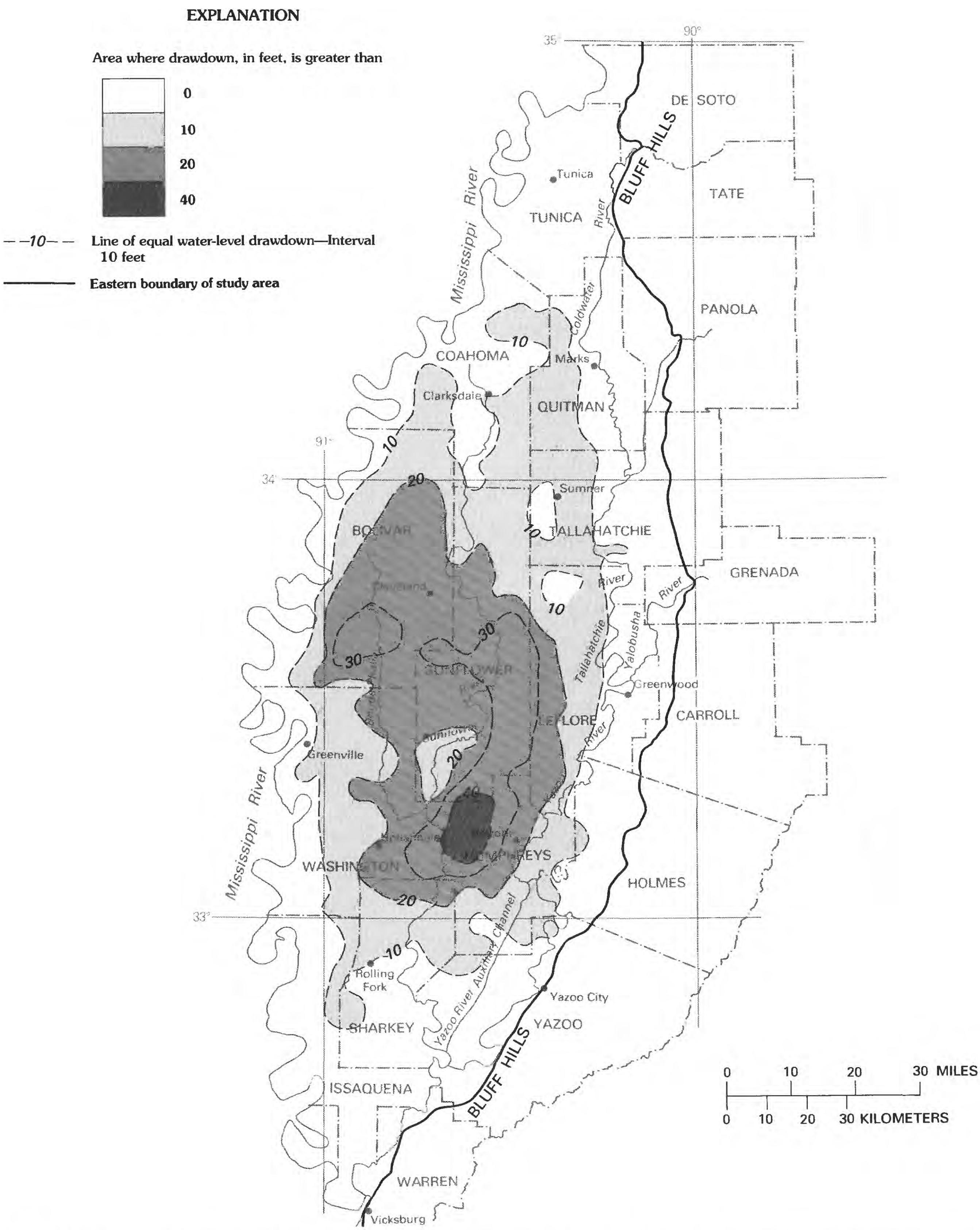


Figure 43. Simulated drawdown of water levels in the alluvial aquifer in the Delta from September 1983 to September 2003 assuming pumpage is 1,100 million gallons per day.

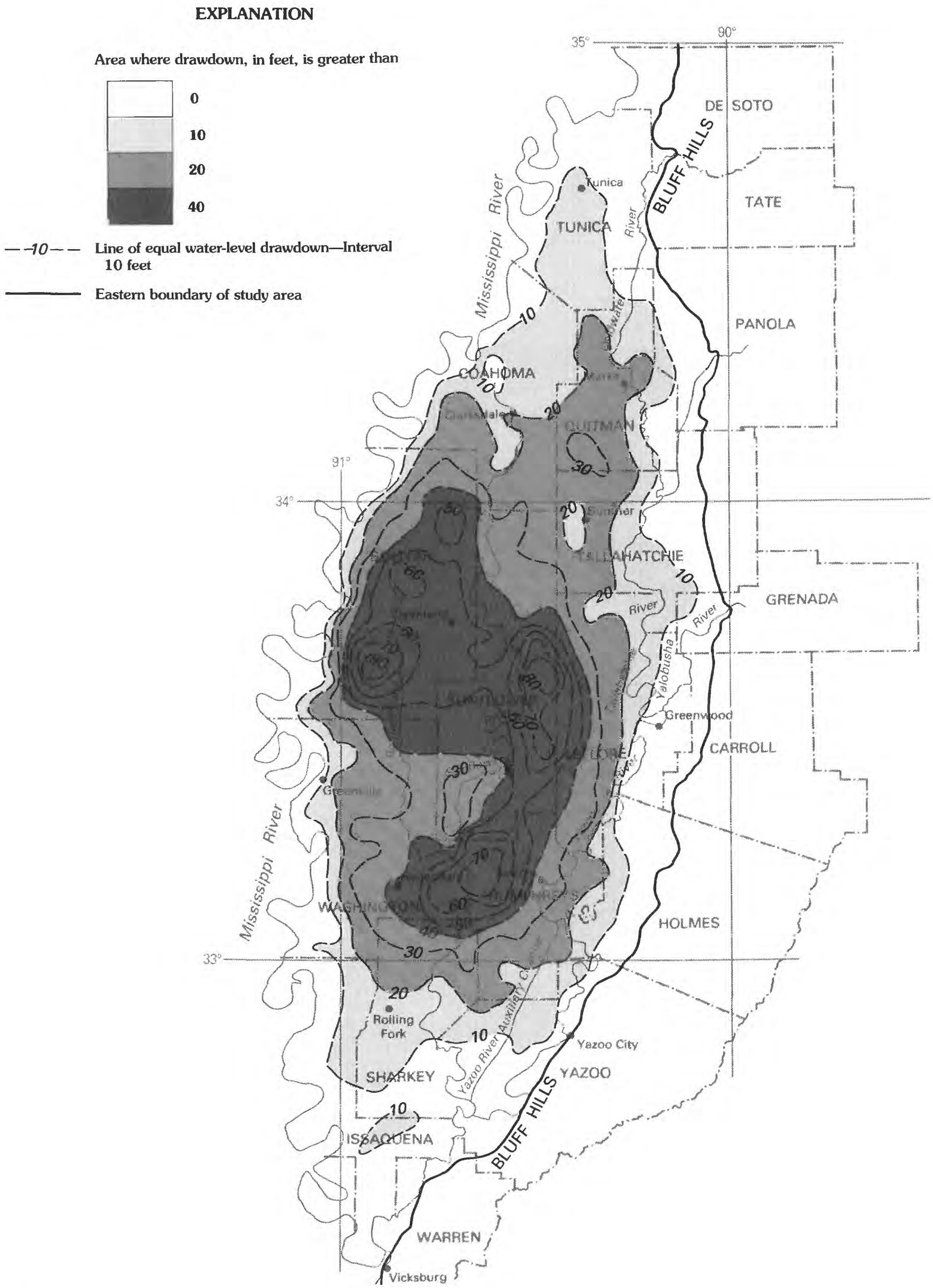


Figure 44. Simulated drawdown of water levels in the alluvial aquifer in the Delta from September 1983 to September 2003 assuming pumpage is 1,900 million gallons per day.

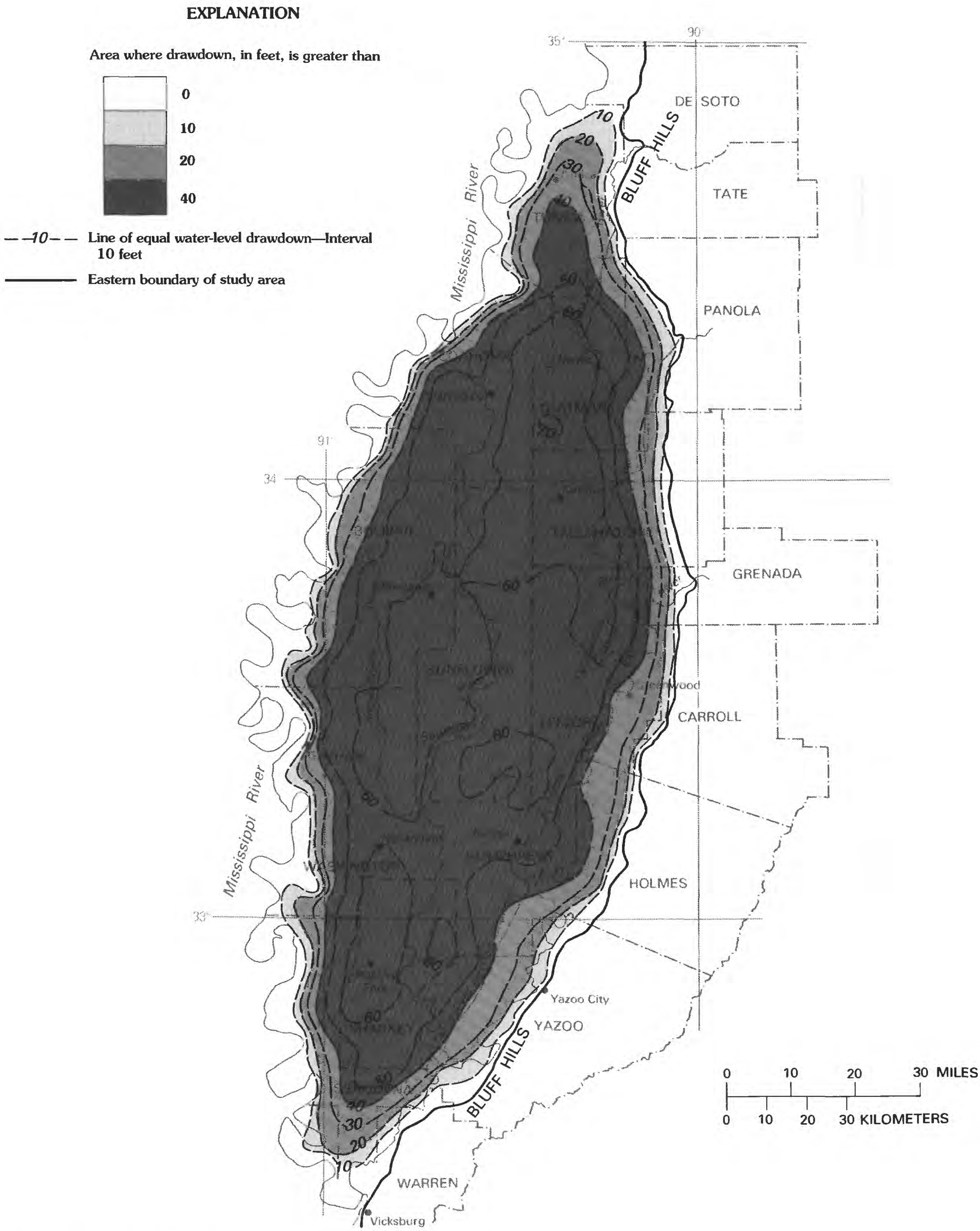


Figure 45. Simulated drawdown of water levels in the alluvial aquifer in the Delta from September 1983 to September 2003 assuming pumpage is 4,000 million gallons per day and is distributed uniformly.

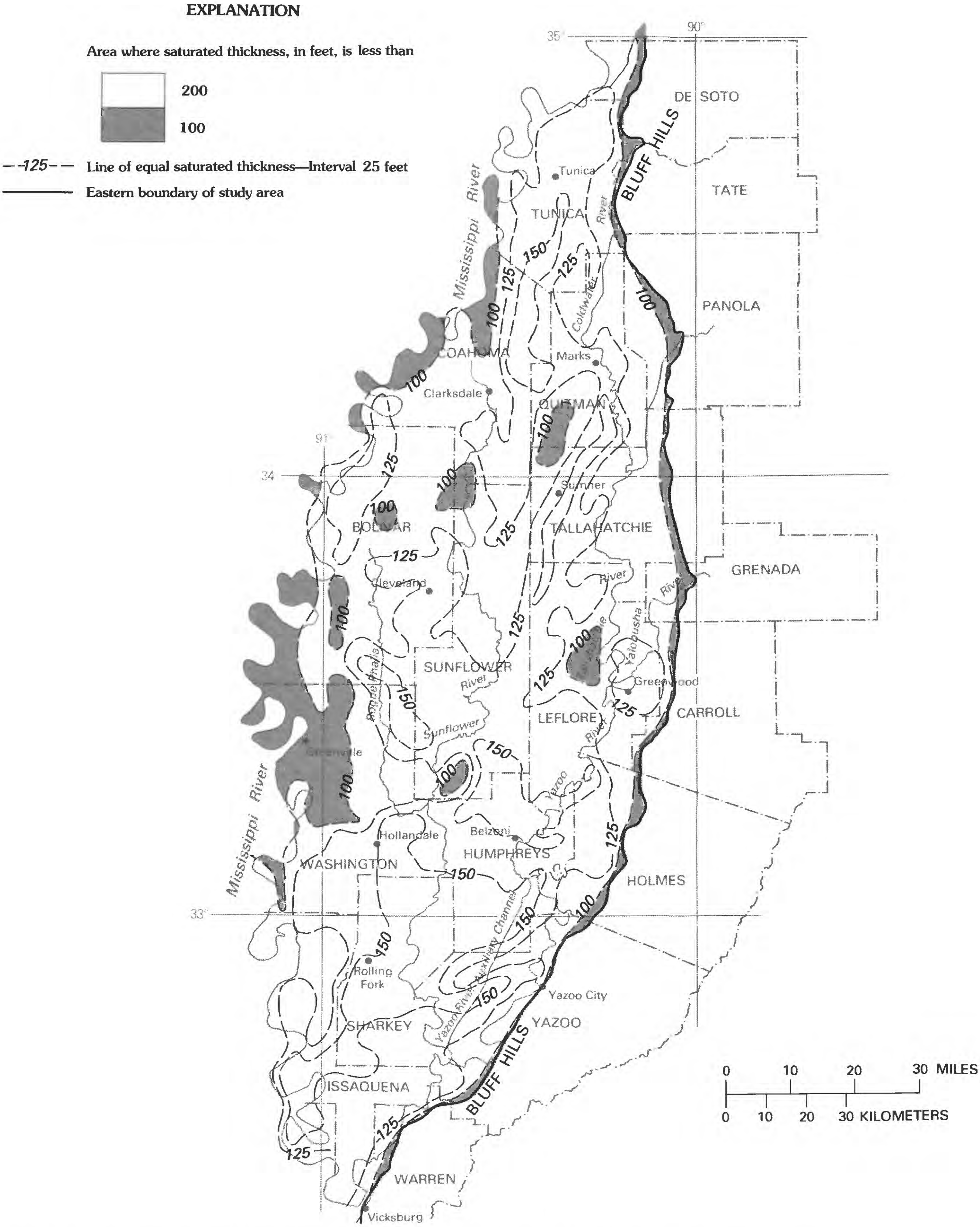


Figure 46. Simulated saturated thickness of the alluvial aquifer in the Delta for 2003 assuming no pumpage.

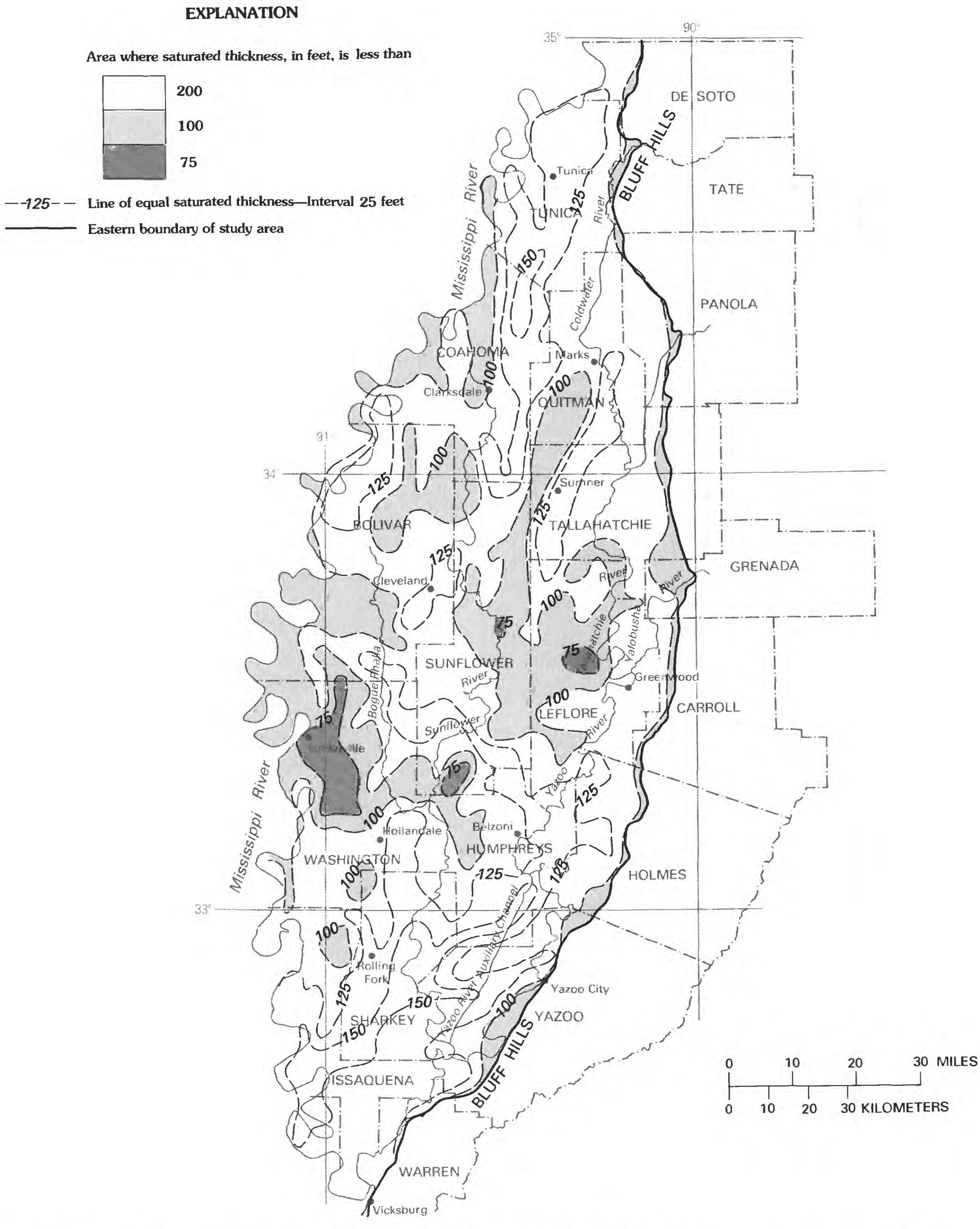


Figure 47. Simulated saturated thickness of the alluvial aquifer in the Delta for 2003 assuming pumpage is 670 million gallons per day.

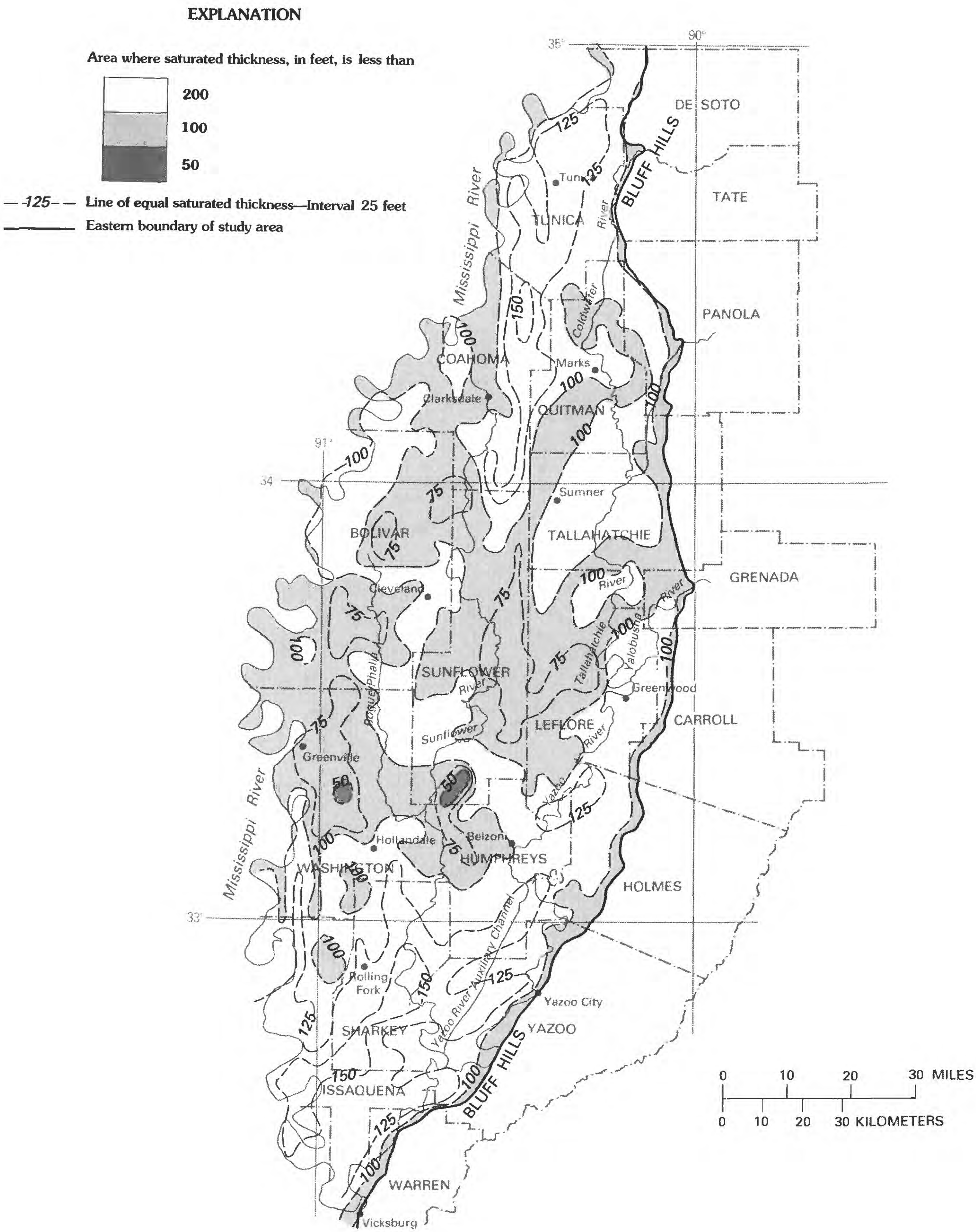


Figure 48. Simulated saturated thickness of the alluvial aquifer in the Delta for 2003 assuming pumpage is 1,100 million gallons per day.

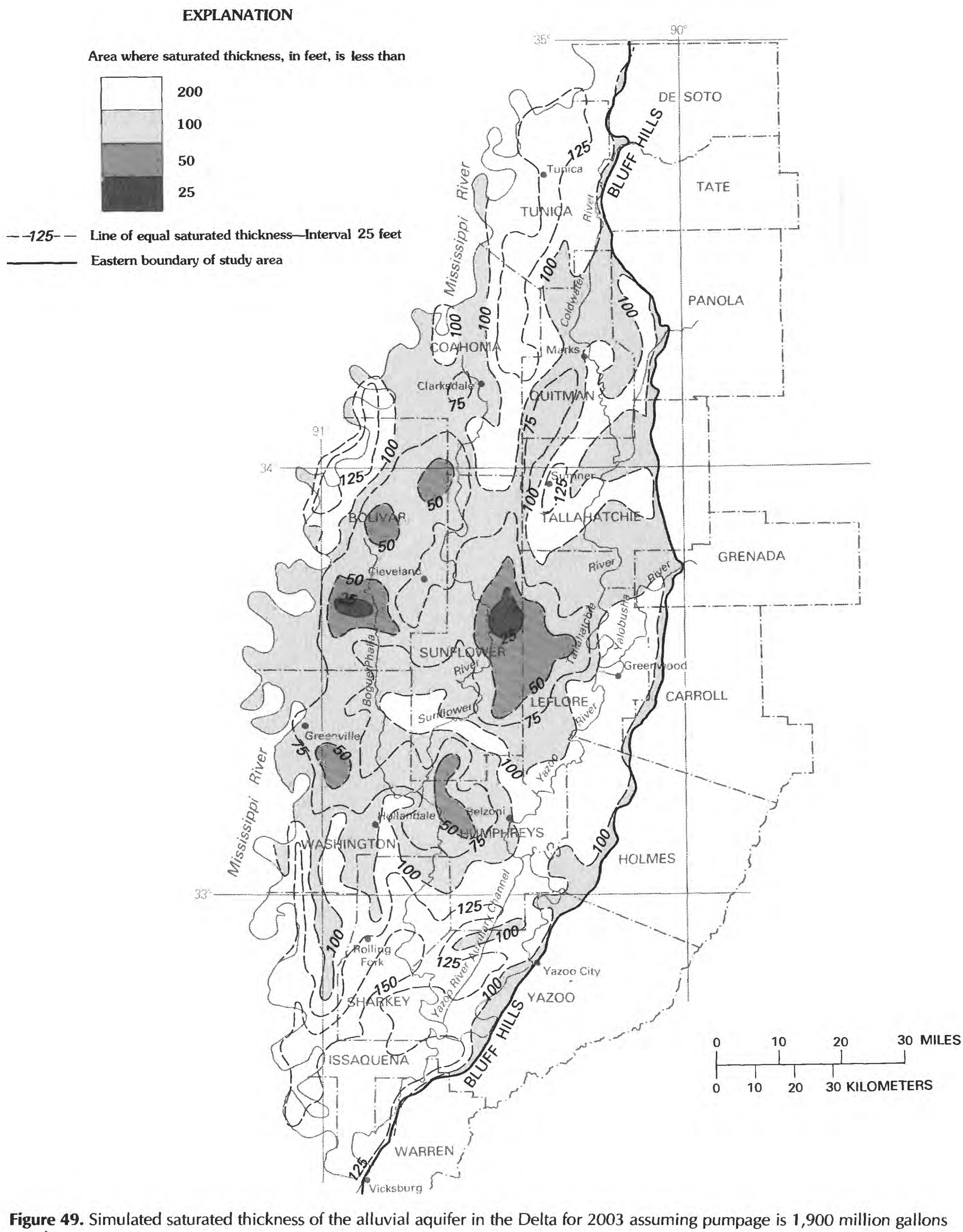


Figure 49. Simulated saturated thickness of the alluvial aquifer in the Delta for 2003 assuming pumpage is 1,900 million gallons per day.

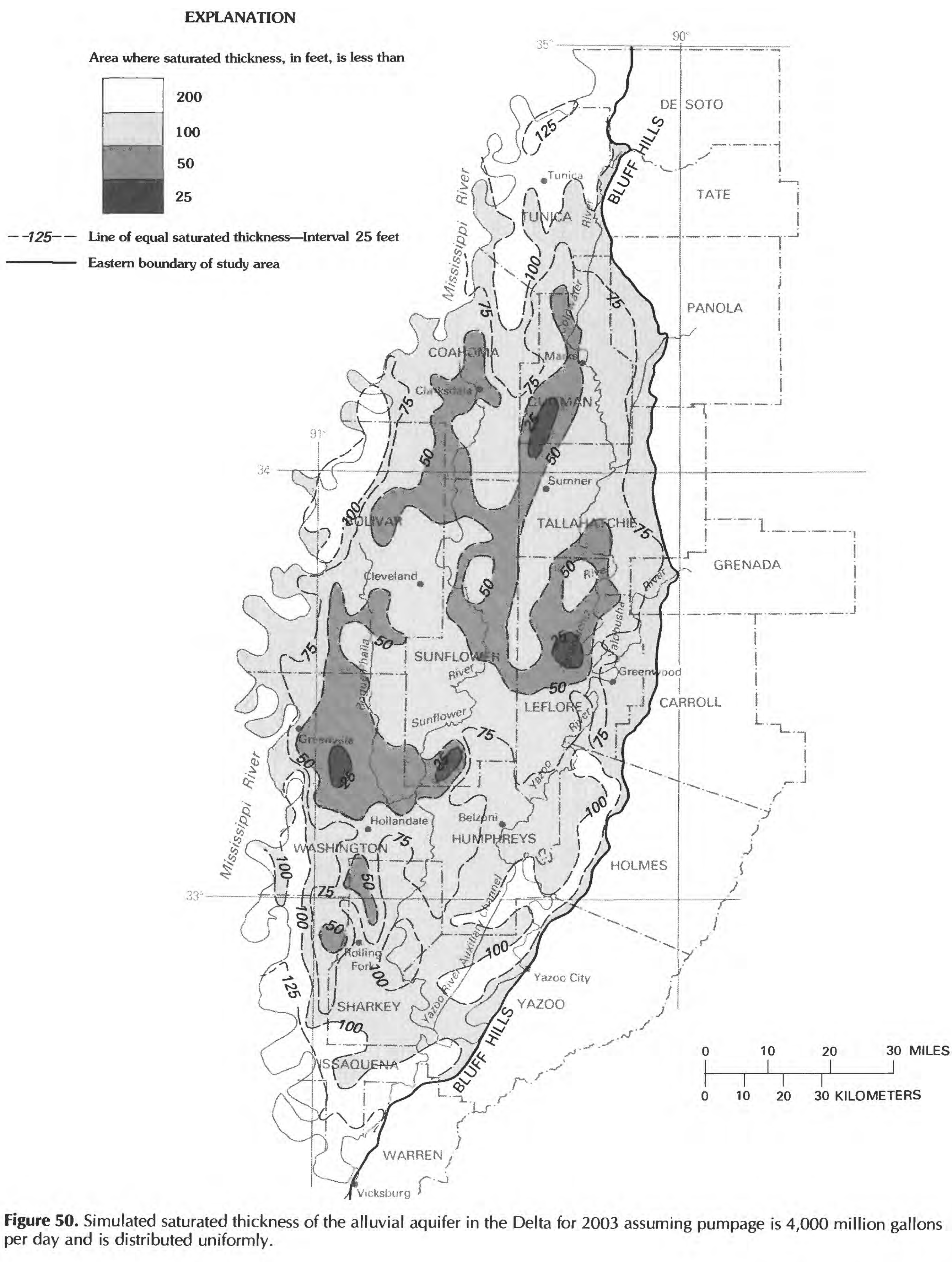


Figure 50. Simulated saturated thickness of the alluvial aquifer in the Delta for 2003 assuming pumpage is 4,000 million gallons per day and is distributed uniformly.

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