DEFINITION OF THE GEOHYDROLOGIC FRAMEWORK AND PRELIMINARY SIMULATION OF GROUND-WATER FLOW IN THE MISSISSIPPI EMBAYMENT AQUIFER SYSTEM, GULF COASTAL PLAIN, UNITED STATES

By J. Kerry Arthur and R.E. Taylor

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 86-4364

Jackson, Mississippi
1990

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

ILLUSTRATIONS--Continued

ILLUSTRATIONS--Continued

TABLES

CONVERSION TABLE

For those readers interested in metric units, the factors for converting inch-pound unit to the International System (SI) of Units are given below:

Multiply inch-pound units	By	To obtain SI units
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi2)	2.590	square kilometer (km2)
inch per year (in/yr)	2.54	centimeters per year (cm/yr)
cubic foot per day (ft3/d)	0.0283	cubic meter per day (m3/d)
feet per mile (ft/mi)	0.1894	meters per kilometer (m/km)
feet per day (ft/d)	0.3048	meters per day (m/d)

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ABSTRACT

The Mississippi embayment aquifer system study is a subproject of the U.S. Geological Survey's Gulf Coast Regional Aquifer-System Analysis project. Within the Mississippi embayment aquifer system, five major aquifers and two confining units in the Wilcox and Claiborne Groups in the Tertiary System were identified in the 160,000-square-mile subproject area. The major aquifers and confining units identified are: (1) upper Claiborne aquifer, (2) middle Claiborne confining unit, (3) middle Claiborne aquifer, (4) lower Claiborne confining unit, (5) lower Claiborne-upper Wilcox aquifer, (6) middle Wilcox aquifer and, (7) lower Wilcox aquifer. The digital ground-water flow model developed to represent the aquifer system has five layers representing the five major aquifers.

In 1980, pumpage from the aquifers within the system ranged from 67 million cubic feet per day (501 million gallons per day) in the middle Claiborne aquifer to 3 million cubic feet per day (22 million gallons per day) in the middle Wilcox aquifer. Mean horizontal hydraulic conductivity values from aquifer tests range from 11 feet per day in the lower Claiborne-upper Wilcox aquifer in Louisiana to 172 feet per day in the middle Claiborne aquifer in Arkansas. Vertical hydraulic conductivity values used in the model for confining units range from $1x10^{-3}$ to $1x10^{-5}$ feet per day.

Steady-state predevelopment model simulation results indicate that flow from the subcropping Mississippi embayment aquifer system to the overlying Mississippi River Valley alluvial aquifer ranges from less than 1/10 million cubic feet per day (¾ million gallons per day) in the lower Wilcox aquifer to 25 million cubic feet per day (187 million gallons per day) in the upper Claiborne aquifer. Under stressed conditions (1980 pumping rates) flow to the alluvial aquifer is significantly reduced and the net flow is reversed in several of the aquifers. Flow rates range from 2¾ million cubic feet per day (21 million gallons per day) from the alluvial aquifer into the middle Claiborne aquifer to 10 million cubic feet per day (75 million gallons per day) from the upper Claiborne aquifer into the alluvial aquifer. Model results indicate that ¼ million cubic feet per day (1¾ million gallons per day) of water moved upward from the Mississippi embayment aquifer system into the Coastal lowlands aquifer system under predevelopment conditions. With 1980 pumping rates applied to the Mississippi embayment aquifer system, the net flow is reversed and about ⅓ million cubic feet per day (2½ million gallons per day) moves into the Mississippi embayment aquifer system from the Coastal lowlands aquifer system.

INTRODUCTION

The Gulf Coast Regional Aquifer-System Analysis (GCRASA) project is part of the Survey's regional aquifer-system analysis program (fig. 1). The program, which began in 1979, will describe the aquifers in the Nation that are regional in extent and are major sources of freshwater for municipal, industrial, and agricultural use. The GCRASA is a study of the Upper Cretaceous and younger aquifers that underlie about 230,000 mi^2 (square miles) in all or parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and Texas (fig. 2). The objectives of the GCRASA project are to define the geohydrologic framework in which the regional aquifers exist, to describe the chemical and physical characteristics of the ground water, and to analyze the flow patterns within the regional ground-water system. The three regional aquifer systems defined in the GCRASA project are the Mississippi embayment, the Texas Coastal uplands, and the Coastal lowlands (Grubb, 1984). Each of the regional aquifer systems will be studied in more detail by several subregional projects under the larger GCRASA project. This report presents the preliminary results of the subregional project study involving several of the major aquifers in the Mississippi embayment aquifer system.

Purpose and Scope

The purpose of this report is to describe the geohydrologic framework of the Mississippi embayment aquifer system and to give a preliminary description of the ground-water flow system. The study includes all of the aquifers in the Mississippi embayment aquifer system as defined by Grubb (1984, table 1, p. 11) except the Mississippi River Valley alluvial aquifer of Holocene and Pleistocene age and the Ripley Formation in sediments of late Cretaceous age, which are studied in other GCRASA subregional projects.

Description of Area

The study area for this report includes about 160,000 mi^2 in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri and Tennessee (fig. 3). The area roughly bisected by the Mississippi River, extends from about the confluence of the Mississippi and Ohio Rivers to the Gulf of Mexico, and from about the Texas-Louisiana line to the Mobile River in western Alabama.

Topography

The area lies mainly in the Gulf Coastal Plain. A large part (about 35 percent) of the area is in the Mississippi River alluvial plain, a flat to slightly undulating surface with about a ½ ft/mi (foot per mile) Gulfward slope. The remainder of the area is in the Gulf Coastal Plain uplands and is characterized by a gently rolling terrain. A major interruption in the alluvial plain is Crowleys Ridge, a narrow segmented ridge about 200 miles long in northeastern Arkansas and southern Missouri (fig. 4). The ridge, which is as much as 250 feet higher than the alluvial plain, is an erosional remnant of the Gulf Coastal Plain uplands. Upland areas on the eastern side of the study area are significantly higher in altitude than those on the western side.

Climate

The climate of the study area is basically humid subtropical in the southern part of the area to temperate in the northern part. Normal annual temperature ranges from 60 to 70 °F. Precipitation throughout the area generally is abundant and well distributed areally. Average annual precipitation ranges from about 48 inches in the northern part of the area to 68 inches in the southeastern part (fig. 5). Most of the precipitation occurs in the winter and spring throughout the entire study area.

Drainage

Drainage from roughly one-third of the study area flows into the Mississippi River from its major tributary streams. Major tributary streams to the Mississippi River are the St. Francis River in Arkansas and Missouri, the White and Arkansas Rivers in Arkansas, and the Yazoo and Big Black Rivers in Mississippi. Other major streams in the area that are not tributaries to the Mississippi River are the Ouachita-Black River in Arkansas and Louisiana, the Atchafalaya and Calcasieu Rivers in Louisiana, and the Pearl and Pascagoula Rivers in Mississippi (fig. 6). The remainder of the area is drained by streams in southern Louisiana and southern Mississippi that flow directly into the Gulf of Mexico. Average annual runoff in the area ranges from about 12 inches in southern Arkansas to about 32 inches in southeastern Mississippi (fig. 7).

GEOHYDROLOGIC FRAMEWORK

Defining the geohydrologic framework is one of the objectives of the GCRASA study on a regional scale and subsequently of the subregional projects on a more detailed scale. The following overview describes the general setting of the geohydrologic environment in the Mississippi embayment aquifer system.

General Geology

The Mississippi embayment area has experienced a gentle downwarping accompanied by cyclic invasion and regression of the sea for the last 225 million years. Sediment deposition and subsequent subsidence resulted in the formation of the Mississippi embayment syncline, a structural trough now filled with sedimentary deposits (fig. 3). During the Tertiary Period, each marine transgression stopped successively farther to the south. The outcrops of the older units, the Wilcox and Claiborne Groups of Paleocene and Eocene age, roughly parallel the edge of the Mississippi embayment (fig. 4). Outcrop areas of these units on the eastern edge of the embayment have significantly higher land altitudes and water-table altitudes than the corresponding outcrop areas on the western side (fig. 8). Miocene and younger units roughly parallel the present Gulf of Mexico coastline. In the northern part of the area, beds generally dip toward the axis of the embayment, which generally coincides with the present Mississippi River. In the central part of the area the dip of the beds changes gradually as a result of regional structure and in southern Mississippi and Louisiana the dip is toward the axis of the Gulf Coast geosyncline (fig. 3). Structural features such as the Desha basin, Jackson dome, Monroe uplift, and the Sabine uplift affect the thickness and dip of the beds. Generally the beds thicken downdip.

Mississippi embayment deposits are composed predominately of unconsolidated to slightly consolidated beds of sand and clay with some interbedded gravel, silt, lignite, chalk, and limestone. The Midway Group, a thick sequence of marine clays of Paleocene age, is the basal confining unit for the Mississippi embayment aquifer system. Where present, the Jackson and Vicksburg Groups of Eocene and Oligocene age, respectively, which include thick marine clays, overlie the Mississippi embayment aquifer system. These confining groups virtually isolate hydraulically the aquifers of this study by restricting the movement of water to and from the underlying and overlying geologic units. Relation of previously mapped regional aquifers and confining units in the Mississippi embayment aquifer system has been reported by Grubb (1984, p.11).

Major Water-bearing Units

The Mississippi embayment aquifer system in the study area comprises five major aquifers of Paleocene and Eocene age. Within the system, two confining units separate the upper three aquifers, while the lower two aquifers are separated by discontinuous clay beds in the Wilcox Group. Because equivalent aquifers have different names in adjacent states, names have been designated that represent equivalent aquifers in the study area (table 1). These names do not always reflect one stratigraphic unit but in some instances represent parts of adjacent units. All aquifers in this report will be referred to by their GCRASA name.

Figure 9 is a generalized geohydrologic section from west to east across the embayment just south of a line from Monroe, Louisiana, to Jackson, Mississippi, and shows the relation between the regional geology and hydrology of the aquifer system. In the study area, movement of water is from the outcrop areas on the western and eastern flanks of the embayment downdip into the aquifers (fig. 9). As water moves downdip, flow is upward through overlying units to the regional discharge area, which is mainly the Mississippi River Valley alluvial aquifer. The balance of the upward component of flow is shifted westward of the axis of the embayment because of the higher outcrop altitudes on the east flank of the embayment.

Although large drawdowns occurred in the middle Claiborne aquifer in several urban areas in Arkansas, Louisiana, and Tennessee, most of the other aquifers in the study area have not been stressed sufficiently to cause large areas of severe water-level declines.

Upper Claiborne Aquifer

The upper Claiborne aquifer, which includes sand beds in the Cockfield Formation and all sand beds in the Cook Mountain Formation in direct contact with the Cockfield sand beds, crops out on both the east and west sides of the Mississippi embayment. It underlies the loess hills in west Tennessee and the Mississippi River alluvium in the central part of the study area. The upper Claiborne aquifer is the major subcropping unit in the study area, occurring beneath 43 percent of the surface area of the alluvial plain. The aquifer has an average subsurface thickness of about 250 feet and is composed of fine to medium quartz sand and carbonaceous clay. In the area where it contains freshwater, total sand-bed thickness ranges from less than 100 feet in the north to more than 300 feet in the Vicksburg, Mississippi area (fig. 10).

In 1980 about 7½ million ft^3/d (56 Mgal/d) of water was pumped from the upper Claiborne aquifer. Pumpage tabulated in 25 square-mile blocks by State is shown in figure 11. An individual per capita consumption rate for each State was used to compute uniform pumpage for each block on the basis of average consumption rates for that State. This value was added to point pumpage rates to obtain a total pumpage rate for each block. The largest pumpage centers are in Greenville and Jackson, Miss. Figure 12 shows the potentiometric surface for the upper Claiborne aquifer based on water-level measurements made in 1980.

Middle Claiborne Aquifer

The middle Claiborne aquifer, composed mostly of the Sparta Sand in Louisiana and most of Arkansas and Mississippi plus the upper quarter of the Memphis Sand in east-central Arkansas, northwestern Mississippi, and Tennessee, crops out on both sides of the embayment and underlies the entire central part of the study area. The aquifer subcrops under about 15 percent of the Mississippi River alluvium and underlies the loess hills in northwestern Mississippi. The aquifer includes sand beds in the Cook Mountain Formation where they are in direct contact with the sand beds in the Sparta. Similarly, in areas where the Cook Mountain is composed of clay and the immediately underlying part of the Sparta is clay, the top of the aquifer is at the top of the uppermost sand bed in the Sparta. The base of the middle Claiborne aquifer is the top of the underlying Zilpha Clay or Cane River Formation where the top of that formation is clay. Where the basal Sparta is clay overlying clay in the Zilpha or Cane River, the base of the aquifer is at the top of that clay. Where the basal Sparta is sandy and the upper part of the underlying geologic unit is also sandy, the base of the aquifer is at the top of the first clay in the underlying unit.

In extreme northwest Mississippi and east-central Arkansas just south of the Memphis, Tenn., area, the clay section comprising the lower Claiborne confining unit changes to a sand facies. Figure 32 shows a geohydrologic section that illustrates this facies change. In this area, the middle Claiborne aquifer includes about one-fourth of the sand beds from the bottom of the middle Claiborne confining unit to the top of the middle Wilcox aquifer. The remaining three-fourths of the sand section is included in the lower Claiborne-upper Wilcox aquifer and directly underlies the middle Claiborne aquifer. Thus, the middle Claiborne aquifer includes part of the section that to the south had been represented by the lower Claiborne confining unit. Total sand-bed thickness ranges from less than 100 to more than 600 feet in the subsurface (fig. 13). The middle Claiborne aquifer is composed of irregular beds of fluviatile sand, clay, shale, and lignite.

In 1980, 67 million ft^3/d (501 Mgal/d) of water was pumped from the middle Claiborne aquifer. About 26 million ft^3/d (194 Mgal/d) of the total was pumped in the Memphis, Tenn., area (fig. 14). Other large pumping centers are in El Dorado, Magnolia, and the Pine Bluff-Stuttgart area, Ark., Monroe, Jonesboro, Ruston, and Bastrop, La., and Jackson and Yazoo City, Miss. Figure 15 illustrates the potentiometric surface representing water-level measurements made in 1980.

Lower Claiborne-Upper Wilcox Aquifer

The lower Claiborne-upper Wilcox aquifer includes all sand beds below the clay beds of the lower Claiborne confining unit down to and including the sand beds of the upper Wilcox aquifer. In Mississippi, this includes the sand beds of the Winona Sand and Tallahatta Formation and Meridian Sand member of the Tallahatta Formation and sand beds of the Wilcox Group, in Louisiana the Carrizo Sand and upper sand beds of the Wilcox Group, and in southern Arkansas the Carrizo Sand. The aquifer is continuous throughout the study area, and in the northern part of the embayment in northwest Mississippi and east-central Arkansas where the lower Claiborne confining unit becomes sandy, it includes the lower three-fourths of the sand beds between the middle Claiborne confining unit and the middle Wilcox aquifer. Total sand-bed thickness ranges from less than 100 to more than 500 feet (fig. 16). The aquifer, made up of irregular hydraulically connected sand beds in different geologic units, can vary widely in thickness and lithology.

In 1980, 15 million ft^3/d (112 Mgal/d) of water was pumped from the lower Claiborne-upper Wilcox aquifer in the study area. The main pumping center is in the Greenwood-Indianola, Miss., area (fig. 17). The potentiometric surface based on water-level measurements made in 1980 is shown in figure 18.

Middle Wilcox Aquifer

The middle Wilcox aquifer is the least significant aquifer in the Mississippi embayment aquifer system. It is composed of all the sand beds in the Wilcox Group between the lower Claiborne-upper Wilcox aquifer and the lower Wilcox aquifer. Sand beds are irregular and discontinuous with interbedded layers of clay, silt, and lignite, and therefore, the aquifer is not widely used. Total sand-bed thickness ranges from less than 100 feet in northern and southern extremities of study area to more than 1,800 feet in central Louisana (fig. 19). About 3 million ft^3/d (22 Mgal/d) of water was pumped from the middle Wilcox aquifer in 1980. There is no major pumping from this aquifer, but the primary users are in northwestern Louisiana and north-central Mississippi (fig. 20). The potentiometric surface for the middle Wilcox aquifer in 1980 is shown in figure 21.

Lower Wilcox Aquifer

The lower Wilcox aquifer is an extensively developed source of freshwater in Mississippi, Arkansas, and in Tennessee where it includes the Fort Pillow Sand. It is not a significant source of freshwater in Louisiana. The lower Wilcox aquifer, in the basal part of the Wilcox Group, is exposed at the surface in a narrow belt in Kentucky, northern Mississippi, and Tennessee, and subcrops beneath the Mississippi River alluvium in Arkansas and Missouri. The lower Wilcox aquifer is predominantly sand but has some interbedded layers of clay, silt, and lignite. Total sand-bed thickness ranges from less than 100 feet in the periphery of the study area to more than 600 feet in south-central Mississippi (fig. 22).

In 1980 about 9½ million ft^3/d (71 Mgal/d) of water was pumped from the lower Wilcox aquifer in the study area. Significant pumping centers are in the Memphis area in Tennessee (which gets less than 10 percent of its ground-water supply from the lower Wilcox), the Osceola-Blytheville area in Arkansas, and the Batesville, Louisville, Philadelphia, and Meridian areas in Mississippi. Areal distribution of pumpage for the study area is shown in figure 23. A potentiometric map based on water-level measurements made in 1980 is shown in figure 24.

Major Confining Units

Four major confining units influence the geohydrology of the Mississippi embayment aquifer system. Two of these confining units are within the aquifer system, and one unit overlies and one underlies the system.

The Vicksburg-Jackson confining unit separates the upper Claiborne aquifer from the younger Oligocene and Miocene aquifers. Total thickness of the Vicksburg-Jackson confining unit ranges from less than 100 feet to more than 3,000 feet at places in south-central Louisiana (fig. 25). The Yazoo Clay of the Jackson Group in Louisiana and Mississippi, the principal regional confining unit, consists of calcareous, fossiliferous dark-gray to blue clay. The Vicksburg-Jackson confining unit crops out in Arkansas, Louisiana, Mississippi, and subcrops about 23 percent of the Mississippi River alluvium.

The middle Claiborne confining unit consists of clay beds in the Cook Mountain Formation and clay beds in the Cockfield Formation and Sparta Sand that are continuous with the Cook Mountain. The confining unit separates the upper Claiborne aquifer from the middle Claiborne aquifer. The middle Claiborne confining unit crops out in Arkansas, Louisiana, and Mississippi and in places underlies the Mississippi River alluvium. Total thickness of the middle Claiborne confining unit ranges from less than 100 feet to more than 500 feet in south-central Louisiana (fig. 26). The unit consists of clay, sandy marl, and limestone; however, the upper section is mostly carbonaceous clay or shale.

The lower Claiborne confining unit consists of the Cane River Formation in south-central Arkansas and Louisiana and the Zilpha Clay in Mississippi. It includes any clay beds in the base of the Sparta Sand that are continuous with the clay beds of the Zilpha Clay or Cane River Formation. The unit is equivalent to the the upper part of lower Claiborne-upper Wilcox aquifer in Tennessee, Missouri, and northeast Arkansas where the lower Claiborne confining unit changes to a sand facies. The lower Claiborne confining unit separates the middle Claiborne aquifer from the lower Claiborne-upper Wilcox aquifer. The unit ranges in thickness from less than 100 to more than 700 feet in south-central Louisiana and consists of marine clay, marl, and thin beds of fine sand (fig. 27).

The Midway confining unit is made up of clay beds in the Midway Group. It crops out in Arkansas, Illinois, Kentucky, northern Louisiana, Mississippi, Missouri, and Tennessee. The confining unit, composed of marine clay and shale, ranges in thickness from less than 100 to more than 2,000 feet in east south-central Louisiana (fig. 28). It averages about 500 feet thick over the majority of the study area. It serves as a regional flow boundary separating the five major aquifers of the Mississippi embayment aquifer system from the underlying Upper Cretaceous aquifers.

MODEL DEVELOPMENT

Data Assimilation

To define the geohydologic framework of the Mississippi embayment aquifer system, data from many sources and information from earlier reports were assembled to help determine a regionally consistent interpretation of the system. Geophysical well logs, mostly from the petroleum industry, were selected for locations throughout the study area (fig. 29). One geophysical well log was selected for approximately every 320 mi^2. Logs were analyzed to determine depths and thickness of aquifers and confining units. Downdip limits of freshwater were determined from dissolved-solids concentration data or were calculated using data from geophysical well logs. Sand beds in the Wilcox and Claiborne Groups were grouped into aquifer layers and given GCRASA designation names (table 1). These data from the geophysical well logs were used as a major source of information for defining the geohydrologic framework of the study area and to develop geohydrologic sections (figs. 30-32). Aquifer tests from each State in the study area were selected, evaluated, and entered into the GCRASA data base by aquifer layer. These tests were used to determine the range of hydraulic conductivity values for each major aquifer unit (table 2). Water-use information for 1980 was tabulated for each layer in the study area (figs. 11, 14, 17, 20, and 23).

Model Description

Regional-flow patterns in the study area were analyzed using a multi-layer, numerical model that simulated steady-state, confined-flow conditions. The model adapted to the Mississippi embayment aquifer system was the Survey's modular three-dimensional, finite-difference, ground-water flow model (McDonald and Harbaugh, 1984).

The model uses a finite-difference method to numerically solve partial differential equations that represent ground-water flow in response to stresses and boundary conditions. Resultant heads generated from the solving routine are compared to measured water levels. The simulation with the minimum head error best represents the system within the constraints of representative hydraulic parameters.

The model has 5 layers, each subdivided into a uniform grid of 100 rows and 88 columns (fig. 33). Each cell is 5 miles on a side or 25 mi^2. Row numeration is from northeast to southwest with the origin in southern Illinois. The model is compatible with the other Gulf Coast RASA subproject models and with the larger scale regional model.

The model simulates in descending order, (1) upper Claiborne aquifer, (2) middle Claiborne aquifer, (3) lower Claiborne-upper Wilcox aquifer, (4) middle Wilcox aquifer, and (5) lower Wilcox aquifer. Each model layer is separated from the layer beneath it by a vertical resistence to flow term. Only the influence of the resisting units (in descending order, the middle Claiborne confining unit, lower Claiborne confining unit, clay beds in the upper part of the Wilcox Group, and clay beds in the lower part of the Wilcox Group) on the vertical flow of water between adjacent aquifers, and not the head distribution within the resisting units, is simulated. Hydraulic connection between aquifers is represented by vertical conductance (vertical conductance equals vertical hydraulic conductivity of confining unit multiplied by the cell area divided by thickness of the confining unit) between each pair of aquifer layers. Confining-unit thickness is defined as the sum of the clay-bed thickness in the confining unit plus one-half the sum of the clay-bed thickness in the two aquifers that the confining unit separates. A vertical conductance is computed between all vertically adjacent nodes. Hydraulic gradient within confining units is assumed to be linear.

In the Memphis, Tenn., area the silts and clays of the lower Claiborne confining unit undergo a facies change and become a sand unit. In this area the absence of the lower Claiborne confining unit causes the middle Claiborne aquifer and the lower Claiborne-upper Wilcox aquifer to be continuous (fig. 32). The condition is simulated in the model by using a large vertical conductance value between model layers 2 and 3, effectively coalescing the middle Claiborne and lower Claiborne-upper Wilcox aquifers. This condition was created as the result of no clay in the lower Claiborne confining unit and a very small amount of clay in the adjacent aquifers. This permits the simulation to represent the two layers as virtually one aquifer (Memphis Sand).

Much of the study area (about 35 percent) underlies the Mississippi River alluvial plain (fig. 4). Parts of several of the Mississippi embayment system aquifers subcrop under the alluvium (figs. 31 and 32). The Mississippi River Valley alluvial aquifer is a major water-bearing aquifer and is in hydraulic contact with the underlying subcropping units. This condition results in the probability of significant interactive flow between the alluvial aquifer and the underlying aquifers. The Survey's ground-water flow model river package module simulates this condition as a head-dependent flux component. Riverbed conductances represent the degree of hydraulic connection between the alluvial aquifer and the subcropping aquifer. Riverbed conductance is computed by using total clay-bed thickness of the confining unit where it subcrops and one-half of the clay-bed thickness in the aquifers where they subcrop. Water levels in the alluvium simulate river stages. Interactive flow between the alluvium and the subcropping layer is determined by the riverbed conductance and the head difference between the alluvial aquifer and the subcropping aquifer.

Recharge-discharge in outcrop areas is also simulated by the river package. Water-table altitudes in outcrop areas represent river stages. Recharge-discharge is controlled by the degree of vertical conductance and the difference in heads between the water table and aquifer.

In the central and southern part of the study area, the Mississippi embayment aquifer system underlies the Vicksburg-Jackson confining unit and the Coastal lowlands aquifer system of Miocene age. The Vicksburg-Jackson confining unit retards the flow between the Mississippi embayment aquifer system and the Coastal lowlands aquifer system. The model simulates the interaction with head-dependent flux components using the water-level differences between the Coastal lowlands system and the upper Claiborne aquifer to determine the magnitude and direction of the flow.

Boundary Conditions

The extent of the boundaries of the modeled area is established by the geologic configuration of the study area and by the flow and the quality of the water in the aquifer system. A typical model section from west to east is shown in figure 34. The lower boundary of the model is a no-flow boundary that represents the thick clay beds of the Midway Group, a regional confining unit that separates the five major aquifers of the Mississippi embayment aquifer system from the Upper Cretaceous aquifers. An assumption incorporated into this model is that there is no flow interaction between the Mississippi embayment aquifer system and the Upper Cretaceous aquifers. This assumption will be evaluated by another flow-model simulation subproject study made under the GCRASA project. The no-flow boundary at the edge of each aquifer layer represents either an area where the aquifer does not exist (landward of outcrop area) or an area where the flow of water into and out of the model area is assumed to be negligible. At the western edge of the study area near the Louisiana-Texas border the Sabine uplift creates a natural constriction to horizontal flow in the Mississippi embayment aquifer system. In this uplift area only the middle Wilcox and lower Wilcox aquifers are present. Some shallow horizontal flow does occur, but it is assumed insignificant, and this area is considered a no-flow boundary. The magnitude of the flow that does occur will be investigated by the regional modeling effort. At the eastern edge of the study area in Alabama the combined geohydrologic effects of the Mobile Bay-Mobile River, the Mobile grabben, and a facies change preclude any significant horizontal flow in that direction. The extent of the aquifers defined the northern and southern boundaries.

The upper boundary of the model is simulated by head-dependent flux components that act as a source-sink layer providing flow into and out of the system. Small total clay-bed thickness in aquifer outcrop areas provides good hydraulic connection between aquifers and the surface environment. This condition is represented in the model by high conductance values between the outcropping layers and the source-sink layer. This representation essentially provides for a near-constant-head simulation in the aquifer outcrop areas and makes water-table elevations the driving head for each layer. Subcrop areas were treated in a similar manner. Generally the contact zone between the base of the alluvium and the subcropping aquifer is less permeable than the aquifer. One half the clay-bed thickness in the aquifer layer is used with its assigned conductivity to determine resistence to interactive flow. Water levels in the alluvium simulate driving heads, and the direction of the interactive flow is determined by the magnitude of the head differences between the alluvium and the underlying aquifers.

The downdip boundary of each layer is a no-flow boundary. This was established either at the extent of the aquifer or where dissolved-solids concentrations in the water exceed 10,000 mg/L (milligrams per liter). At the 10,000 mg/L dissolved-solids interface no flow is assumed into or out of the model area. This assumption may not be entirely valid but is reasonable because pumpage in each layer is significantly updip from the freshwater-saltwater interface. Even if there is a slight flow at these extreme downdip locations, the amount is probably too small to affect water levels in the areas of maximum aquifer usage. This assumption will be investigated in the regional study that incorporates a variable density flow model. Figures 35-39 show the extent of each model layer and areas of outcrop and subcrop.

Hydraulic Properties

Hydraulic properties (horizontal and vertical hydraulic conductivity values) were estimated by using selected aquifer tests (table 2) and data from published reports (Heath, 1983). Mean values of horizontal conductivity from the aquifer tests ranged from 11 ft/d in the lower Claiborne-upper Wilcox aquifer in Louisiana to 172 ft/d in the middle Claiborne aquifer in Arkansas (table 2).

Transmissivity values for each cell were computed by multiplying the layer sand thickness by the horizontal hydraulic conductivity. Layer sand thicknesses were summed for each cell in each layer (figs. 10, 13, 16, 19, and 22). The sand thicknesses were determined from the geophysical well logs shown on figure 29. Data were initially tabulated by State, and thus the preliminary simulations used a constant hydraulic conductivity value for each State for an individual layer.

Vertical hydraulic conductivity values for the confining units range from 10^{-3} to 10^{-5} ft/d. The large value (10^{-3} ft/d) is used where no uniform, pure clay exists, but rather a silty-clay sequence. Smaller values (10^{-4} to 10^{-5} ft/d) are used for the tight marine clays of the Vicksburg-Jackson, lower Claiborne, and Wilcox confining units. Vertical conductance values were computed between cells in adjacent layers by dividing the product of vertical hydraulic conductivity and cell area by the sum of the clay-bed thickness between cells. Clay-bed thickness was determined by using information obtained from the geophysical well logs (figs. 25-28).

In the central part of the study area where the Vicksburg-Jackson confining unit overlies the upper Claiborne aquifer, a vertical hydraulic conductivity value of 10^{-5} ft/d is used to represent the predominant confining unit, the Yazoo Clay and equivalent in the Jackson Group. The very thick uniform nature of the unit probably allows little flow between the Miocene and Pliocene deposits and the Mississippi embayment aquifer system.

Because this model is a steady-state simulation, the effects of storage in the aquifer are not considered; hence, the storage coefficient is not required for the simulation.

PRELIMINARY PREDEVELOPMENT GROUND-WATER FLOW SYSTEM

A model was constructed to represent the steady-state flow system of the Mississippi embayment aquifers prior to development. Hydraulic parameters were varied within the constraints of values determined from aquifer tests, information from published reports, and geophysical well logs.

Only a limited degree of calibration could be achieved owing to the scarcity of predevelopment water-level information. However, the simulations allowed a preliminary evaluation of regional flow patterns prior to development and determination of potential aquifer recharge and discharge areas (figs. 40 and 41). Analysis of recharge-discharge patterns indicates that areas of recirculation or interactive flow exist where flow enters and leaves the system within a relatively short distance. This interactive flow is caused by an undulating water table that reflects land-surface relief.

Upper Claiborne Aquifer

The predevelopment potentiometric map of the upper Claiborne aquifer representing model-generated heads is shown in figure 42. In the outcrop areas in central Mississippi, western Tennessee, north-central Louisiana, and south-central Arkansas the head gradients are steep and non-uniform. This phenomenon reflects water-table conditions generated by the undulating land surface. In central Mississippi and eastern Arkansas the downdip gradient flattens and becomes more uniform (about 1½ ft/mi). Flow is generally toward the axis of the embayment from both the east and the west outcrop areas. Much of the upper Claiborne aquifer subcrops under the Mississippi River alluvium, and water is exchanged between the alluvium and the upper Claiborne aquifer. A flow of 25 million ft^3/d (187 Mgal/d) moves into the alluvium from the upper Claiborne aquifer under predevelopment steady-state conditions (fig. 43). Figure 43 will not show a complete balance for any aquifer owing to rounding error in model output.

Most of the upward movement of water from the upper Claiborne aquifer to the alluvium is in northeastern Louisiana. In southern Mississippi and Louisiana, the Vicksburg-Jackson confining unit overlies the upper Claiborne aquifer. The thick sequence of marine clays of this confining unit restricts flow between the upper Claiborne aquifer and the Coastal lowlands aquifer system. Massive clays overlying the upper Claiborne aquifer restrict the flow upward to the Coastal lowlands aquifer system to about ¼ million ft^3/d (1 ¾ Mgal/d) under predevelopment steady-state conditions (fig. 43).

Middle Claiborne Aquifer

The predevelopment potentiometric map of the middle Claiborne aquifer representing model-generated heads is shown in figure 44. Flow from the outcrop areas is generally toward the axis of the embayment with the gradient being greatest in Mississippi (about 2 ft/mi). As the flow moves downdip, it also moves vertically up into the upper Claiborne aquifer, with northeastern Louisiana and southwestern Tennessee being the areas of greatest upward movement (fig. 45). In these areas, more than ½ in/yr moves up to the upper Claiborne aquifer through the middle Claiborne confining unit. The middle Claiborne aquifer also subcrops under the Mississippi River alluvium in parts of Arkansas, Mississippi, and Missouri. About 6 ¼ million ft^3/d (47 Mgal/d) moves upward from the middle Claiborne aquifer into the Mississippi River alluvium in the subcrop areas (fig. 43).

Lower Claiborne-Upper Wilcox Aquifer

The predevelopment potentiometric map of the lower Claiborne-upper Wilcox aquifer representing model-generated heads is shown in figure 46. Heads in the outcrop areas, especially in Mississippi and Tennessee, are erratic due to the land-surface relief. Flow from the outcrop areas is generally toward the axis of the embayment. The gradient downdip of the outcrop area is uniform (about 1 ft/mi). The flow also moves upward through the lower Claiborne confining unit into the middle Claiborne aquifer (fig. 47). Flow upward is less than 0.1 in/yr in most of the area, except in the upper end of the embayment beginning in north Mississippi, where the lower Claiborne confining unit becomes sandy providing good vertical hydraulic connection between the middle Claiborne aquifer and the lower Claiborne-upper Wilcox aquifer. In this area the indicated vertical flow is merely vertical movement within the Memphis Sand. The lower Claiborne-upper Wilcox aquifer subcrops under the Mississippi River alluvium in parts of Arkansas, Louisiana, and Missouri. About 8¼ million ft^3/d (62 Mgal/d) moves into the alluvium from the aquifer in the subcrop areas (fig. 43).

Middle Wilcox Aquifer

The predevelopment potentiometric map of the middle Wilcox aquifer representing model-generated heads is shown in figure 48. Flow from the outcrop areas in Mississippi and Tennessee generally is to the west-southwest toward the discharge area in northwest Louisiana. Head gradients are uniform downdip from the outcrop area (about ½ to 1 ft/mi). Flow out of the aquifer is upward through the interbedded clays in the Wilcox Group to the lower Claiborne-upper Wilcox aquifer (fig. 49). Flow upward is less than 0.1 in/yr in most of the area. Significant flow out of the aquifer occurs in the outcrop area in northwest Louisiana in the Red River area. The middle Wilcox aquifer also loses about ¼ million ft^3/d (1¾ Mgal/d) of flow to the alluvium in Arkansas and Louisiana where it is a subcropping unit (fig. 43).

Lower Wilcox Aquifer

The predevelopment potentiometric map of the lower Wilcox aquifer representing model-generated heads is shown in figure 50. In Mississippi and Tennessee, flow downdip from the outcrop area is westward at a uniform gradient of about 1 to 1½ ft/mi. Vertical flow upward through the interbedded clays in the Wilcox Group into the middle Wilcox aquifer is less than 0.1 in/yr in most of the area (fig. 51). Flow to the alluvium in the subcrop areas in Arkansas and Missouri is less than 1/10 million ft^3/d (¾ Mgal/d) (fig. 43). Thick clay beds of the Midway Group underlie the lower Wilcox aquifer and are simulated in the model as a no-flow boundary, which does not allow interchange of flow between the lower Wilcox aquifer and the Upper Cretaceous aquifers.

PRELIMINARY 1980 GROUND-WATER FLOW SYSTEM

A steady-state model simulation using 1980 pumpage data was made using the hydraulic values and geohydrologic framework determined from aquifer-test information, published reports, and geophysical well logs. The assumption that water levels produced by the 1980 pumpage are at steady-state is not entirely accurate, but the rate of decline of water levels in the five major aquifers did decrease significantly during the period 1975-80. Hydrographs of wells in areas of heaviest pumpage are shown on figure 52. Four wells in the middle Claiborne aquifer (Sparta Sand) are in the heavily pumped areas of El Dorado (Union County) and Pine Bluff, Ark. (Jefferson County), Monroe, La., (Ouachita Parish) and Jackson, Miss. (Hinds County). One well in the middle Claiborne aquifer (Memphis Sand) is at Memphis, Tenn. (Shelby County). Two wells in the upper Claiborne aquifer (Cockfield Formation) and the lower Claiborne-upper Wilcox aquifer (Meridian-upper Wilcox aquifer) are in Bolivar and Humphreys Counties, Miss., respectively. Hydrographs in these areas indicate that the assumption of steady-state water levels in 1980 will not introduce large error in comparing simulated to observed water levels. The comparison will not be an ideal calibration check, but it will reveal areas which may need additional model modification to provide a better conceptional representation. As the project effort continues and the understanding of the flow system improves, additional refinements will be made in the model.

Simulating 1980 pumping conditions induces additional recharge to the aquifer system and decreases the natural discharge from the aquifer system. Regions of recharge and discharge in outcrop and subcrop areas of the five aquifers determined by the preliminary model under

1980 pumpage conditions are shown in figures 53 and 54.

An important characteristic of a ground-water flow model is its sensitivity to various hydraulic parameters. Analysis of sensitivity, as used to describe a model characteristic, is a determination of the degree of head error over a range of values for a particular parameter while holding all other parameters constant. Because head or potentiometric surface is the easiest parameter to determine, and thus, the most accurately known value, it is used to test effects of varying an input parameter over a range of values. If the head error (difference between model-generated head and measured head) varies greatly over a narrow range of input values for a particular parameter, then the model is said to be highly sensitive to that parameter. Essentially, it gives a confidence limit on which lesser known input values can be in error and still not drastically affect model results.

The preliminary nature of the project status and modeling effort offered the opportunity for only a cursory sensitivity analysis. Initial model results indicate that vertical hydraulic conductivity is one of the more sensitive parameters in the model. The reason for the model's greater sensitivity to this parameter may be the shape of the Mississippi embayment with its five-layer aquifer stacking and a natural upward flow component of discharge. The inverted U-shaped study area with its continuous aquifer outcrop on both the east and the west flanks of the embayment, encourages regional flow toward the embayment axis with a natural upward flow component to the system's discharge areas (fig. 9).

A vertical hydraulic conductivity value of 0.1 ft/day in aquifer outcrop areas was used in head-dependent flux computations to simulate recharge to the system. The relatively large vertical conductivity value virtually simulated constant heads in the aquifer outcrop areas. To test model sensitivity to this parameter, vertical conductivity input values were varied from 10^{-1} to 10^{-5} ft/day in the outcrop cells of every aquifer for 1980 conditions. A root-mean-square error relation for each aquifer layer was developed (fig. 55). Results indicate that a vertical conductivity value of 10^{-4} ft/day would result in an overall better simulation while the other hydraulic parameters remain constant. The smaller vertical conductivity value would increase the resistance to aquifer recharge in the outcrop areas.

Pumpage was varied over a range of values to ascertain model sensitivity to this parameter. Pumpage for 1980 for individual aquifers should be reliable, but varying tabulation methods and per capita usage rates incorporated by the individual states could introduce error. To test model sensitivity to pumpage, total 1980 pumpage was varied ±60 percent of the reported value. Root-mean-square head error was computed for each aquifer layer for the various pumpage rates (fig. 56). The analysis indicates that 1980 pumpage rates can be in error about ±15 percent and not introduce major additional error in the model-generated head values. Thus, it was concluded that the 1980 pumpage values are within this range.

As the modeling effort continues, additional sensitivity analyses will be made to include more parameters and individual aquifer layers.

Upper Claiborne Aquifer

The 1980 potentiometric map of the upper Claiborne aquifer representing model generated heads is shown in figure 57. The distribution of the total 1980 pumpage (7½ million ft^3/d) (56 Mgal/d) is shown in figure 11. The potentiometric map representing the 1980 measured water levels is shown in figure 12. Only about one-half of the area simulated as the upper Claiborne aquifer in the model has 1980 potentiometric information available. In the two major pumping areas, Greenville and Jackson, Miss., the model simulates the 1980 water levels very reasonably. The area in northeastern Louisiana, where the upper Claiborne aquifer subcrops under the alluvium, also represents a good simulation. Figure 58 illustrates differences between the water levels generated by the model and the measured 1980 water levels. In the

Greenville area the model produces a head slightly lower than measured. In the Jackson area the heads generated by the model are higher than the measured heads.

Pumpage from the aquifer causes water levels to decline from the model-generated predevelopment altitudes (fig. 59). In the Greenville area the drawdown averaged about 80 feet, and in the Jackson area about 60 feet. Most of the area had a drawdown of 20 feet or less. Pumpage from the aquifer induces more recharge in outcrop areas and allows less discharge in subcrop areas. Pumpage from the aquifer results in less flow to the alluvium from the upper Claiborne aquifer [10 million ft^3/d (75 Mgal/d) with pumpage, compared to 25 million ft^3/d (187 Mgal/d) without pumpage] (fig. 43). Vertical movement of flow between the upper Claiborne and middle Claiborne aquifers through the middle Claiborne confining unit is shown in figure 60. As much as 0.2 in/yr is moving downward into the middle Claiborne aquifer in a small area in north-central Louisiana. In the Memphis area, in southwest Tennessee, up to 4.0 in/yr is moving downward through the middle Claiborne confining unit to the middle Claiborne aquifer. This reversal in flow direction from upward in predevelopment to downward is caused by the large withdrawal from the middle Claiborne aquifer in the Memphis area. Movement of water through the Vicksburg-Jackson confining unit from the Coastal lowlands aquifer system under 1980 conditions is about 1/3 million ft^3/d (2½ Mgal/d). Under predevelopment conditions about ¼ million ft^3/d (1¾ Mgal/d) moved upward from the upper Claiborne aquifer into the Coastal lowlands aquifer system (fig. 43).

Middle Claiborne Aquifer

The 1980 potentiometric map of the middle Claiborne aquifer representing the model-generated heads is shown in figure 61. The distribution of the total 1980 pumpage in the middle Claiborne aquifer [67 million ft^3/d (501 Mgal/d)] is shown in figure 14. The potentiometric map representing the 1980 measured water levels is shown in figure 15. There are five major areas of drawdown indicated, the Pine Bluff and El Dorado, Ark. areas, the Monroe, La., the Memphis, Tenn., and the Jackson, Miss., areas. The Memphis area has the largest pumpage with about 26 million ft^3/d (194 Mgal/d). The simulated heads in the Memphis, Tenn., area appear to be representative. The heads at the pumping centers (fig. 14) in Arkansas are too high in the El Dorado area and too low in the Pine Bluff area (fig. 61). The most probable explanation for the higher simulated 1980 water levels in the El Dorado area as compared with the measured 1980 water levels, is the methodology used in reporting the measured 1980 heads in the middle Claiborne aquifer. In the El Dorado area, the middle Claiborne aquifer consists of two major sand beds hydraulically separated by 50 to 150 feet of silt and clay. Most of the pumpage in the area is from the deeper sand bed, and the measured heads represent water levels from only this zone. In the model simulation the two sand beds are combined to simulate one unit and heads generated using the 1980 pumpage represent the potentiometric surface from the combined thickness of both sand beds. Another possible but less probable reason for the lack of drawdown in the El Dorado area is that the pumping center is relatively close to the aquifer outcrop and too much flow is allowed to enter the system. The reverse may be true in the Pine Bluff area. Additional modification to the model will be made to investigate these possibilities. Figure 62 illustrates differences between the water level generated by the model and the measured 1980 water levels.

Simulated drawdowns are greater in the middle Claiborne aquifer than in any of the other aquifers in the Mississippi embayment aquifer system (fig. 63). In the Memphis, Tenn., area the maximum simulated drawdown from simulated predevelopment conditions is more than 100 feet. The greatest drawdown is about 280 feet in the Pine Bluff area. In the Jackson, Miss., area the drawdown is about 80 feet. Other significant drawdown areas are El Dorado, Ark., and Monroe, La., where water levels in the cones of depression are greater than 100 feet below predevelopment heads.

Pumpage from the middle Claiborne aquifer causes the net flow in subcrop areas of the middle Claiborne aquifer to be from the alluvium rather than into the alluvium under predevelopment conditions. The flow from the alluvium is 2¾ million ft^3/d (21 Mgal/d) (fig. 43). Vertical movement of water to the middle Claiborne aquifer through the lower Claiborne confining unit from the lower Claiborne-upper Wilcox aquifer is less than 0.1 in/yr in all areas except in the upper part of the embayment, mainly in the Memphis area (fig. 64). In the Memphis area the lower Claiborne confining unit changes to a sand facies, causing the middle Claiborne aquifer and the lower Claiborne-upper Wilcox aquifer to have little vertical resistance to flow between them. Vertical movement of water between the two layers in this area is caused by heavy pumpage in the Memphis area.

Heavy pumpage in the Memphis area also causes an increase in aquifer recharge in outcrop areas adjacent to the pumping center (figs. 41 and 54). Model simulation results show that about 35 percent of the pumpage in the Memphis area comes from downward induced leakage from the upper Claiborne aquifer in the immediate area of heavy pumpage. The remainder of the flow comes from leakage from adjacent aquifers outside the Memphis area and from the middle Claiborne aquifer outcrop recharge areas.

Lower Claiborne-Upper Wilcox Aquifer

The 1980 potentiometric map of the lower Claiborne-upper Wilcox aquifer representing model-generated heads is shown in figure 65. The distribution of the total 1980 pumpage in the lower Claiborne-upper Wilcox aquifer [15 million ft^3/d (112 Mgal/d)] is shown in figure 17. The main pumping center in the study area is in the Greenwood-Indianola, Miss., area. The potentiometric map representing 1980 measured water levels is shown in figure 18. Only about 50 percent of the area modeled has measured water-level information for 1980. Figure 66 illustrates the difference between model-generated heads and measured 1980 heads. In the main pumping center in Mississippi, 1980 simulated heads are 25 to 50 feet too high. At the pumping center in the middle of the Greenwood-Indianola area, Miss. (fig. 17), the model-simulated drawdown from simulated predevelopment conditions is about 80 feet (fig. 67). The large drawdown in the lower Claiborne aquifer in the Memphis. Tenn., area is the same as the drawdown in the middle Claiborne aquifer because these two aquifers (Memphis Sand) are continuous in the area.

In Arkansas and Missouri where the lower Claiborne-upper Wilcox aquifer subcrops under the alluvium, the alluvium receives more flow under predevelopment pumpage conditions than during 1980 pumpage conditions [8¼ million ft^3/d (62 Mgal/d) compared to about 5½ million ft^3/d (41 Mgal/d)] (fig. 43).

Vertical flow between the lower Claiborne-upper Wilcox and the middle Wilcox aquifers is shown in figure 68. Upward movement of flow over a majority of the areal extent of the aquifer is less than 0.1 in/yr.

Middle Wilcox Aquifer

The 1980 potentiometric map of the middle Wilcox aquifer representing model-generated heads is shown in figure 69. The distribution of the total 1980 pumpage in the project area for the middle Wilcox aquifer [3 million ft^3/d (22 Mgal/d)] is shown in figure 20. The main pumping centers in the modeled area are in south-central Arkansas, northwest Louisiana, and north-central Mississippi. Water levels representing 1980 conditions are available only in northwestern Louisiana and in Mississippi (fig. 21). The middle Wilcox aquifer is the least used aquifer in the Mississippi embayment aquifer system.

In areas where 1980 water-level information is available, the model-generated heads compare favorably with the measured heads (fig. 70). Pumpage from the three principal usage areas results in model-generated drawdowns of about 40 feet from simulated predevelopment conditions (fig. 71). The drawdown in the Middle Wilcox in the Memphis, Tenn., area, where locally it is not considered an aquifer, is caused by the large pumpage from the Memphis Sand, which induces upward flow from the middle Wilcox. About 0.1 in/yr moves upward in the Memphis area. Less than 0.1 in/yr flow moves upward into the middle Wilcox aquifer through the interbedded clay layers in the Wilcox Group from the lower Wilcox aquifer in most of the area of aquifer extent (fig. 72). In the upper part of the embayment, starting in northern Mississippi, the typical trend is a downward movement of flow. This is caused by the heavy pumpage from the lower Wilcox aquifer in this area. In most of the area, the downward flow is less than 0.1 in/yr.

The middle Wilcox aquifer subcrops under the alluvium in Arkansas and Missouri. Less than 1/10 million ft^3/d (¾ Mgal/d) of flow moves downward from the alluvium to the middle Wilcox aquifer under 1980 pumpage conditions. Under predevelopment conditions the aquifer lost about ¼ million ft^3/d (1¾ Mgal/d) to the alluvium (fig. 43).

Lower Wilcox Aquifer

The 1980 potentiometric map of the lower Wilcox aquifer representing model-generated heads is shown in figure 73. The distribution of the total 1980 pumpage in the study area for the lower Wilcox aquifer [9½ million ft^3/d (71 Mgal/d)] is shown in figure 23. Most of the pumpage in the lower Wilcox aquifer is in a 50-mile-wide band in and adjacent to its outcrop area extending from Meridian, Miss., to the east-central part of the State through the Memphis, Tenn., area, into northeast Arkansas. The potentiometric map representing 1980 water-level measurements covers virtually the same area (fig. 24). Figure 74 shows the difference between the model-generated heads and the measured 1980 heads in the area of data availability.

Model-simulated drawdown from predevelopment conditions using 1980 stresses is 40 feet or less in most of the aquifer extent, except in an oval-shaped area, centered near Memphis, Tenn. (fig. 75). This area, which extends north-south along the Mississippi River, has a drawdown of up to 100 feet. The drawdown is caused by the withdrawals in the west Tennessee and east Arkansas areas.

Thick clay beds of the Midway Group underlie the lower Wilcox aquifer. The model simulates the Midway Group as a no-flow boundary, which allows no vertical flow into or out of the lower Wilcox aquifer through the Midway Group. Flow does occur through the interbedded clays between the lower Wilcox and middle Wilcox aquifers (fig. 72).

The lower Wilcox aquifer subcrops under the alluvium in Arkansas and Missouri. Model-simulation results indicate that the lower Wilcox aquifer receives less than 1/10 million ft^3/d (¾ Mgal/d) water from the alluvium under 1980 conditions (fig. 43). Under predevelopment conditions the net flow was reversed and the alluvium received less than 1/10 million ft^3/d (¾ Mgal/d) from the aquifer. The reversal of vertical flow is the result of a lower head in the lower Wilcox aquifer caused by 1980 induced stresses.

SUMMARY

The Mississippi embayment aquifer system consists of five major aquifers of Paleocene and Eocene age. The system was simulated by using the U.S. Geological Survey's modular three-dimensional, finite-difference ground-water flow model. The model has five active layers representing the following aquifers in descending order: (1) upper Claiborne, (2) middle Claiborne, (3) lower Claiborne-upper Wilcox, (4) middle Wilcox, and (5) lower Wilcox.

The extent of the boundaries of the modeled area is determined by the geohydrologic configuration of the study area and by the flow and chemical characteristics of the waters in the aquifer system. In general, the bottom, and eastern and western sides of the model are no-flow boundaries, whereas the top of the model is a head-dependent boundary whose flux components regulate flow into and out of the system. The updip limit of the aquifer defined the northern boundary, while the southern boundary is defined by the extent of the aquifer and by the occurrence of water with dissolved-solids concentrations greater than 10,000 mg/L.

Mean horizontal hydraulic conductivity values from aquifer tests ranged from 11 ft/d in the lower Claiborne-upper Wilcox aquifer in Louisiana to 172 ft/d in the middle Claiborne aquifer in Arkansas. Vertical hydraulic conductivity values for the confining units ranged from 1×10^{-3} to 1×10^{-5} ft/d.

Under steady-state predevelopment conditions, model-simulated flow from the aquifers in the Mississippi embayment aquifer system to the Mississippi River Valley alluvial aquifer range from less than 1/10 million ft^3/d (¾ Mgal/d) in the lower Wilcox aquifer to 25 million ft^3/d (187 Mgal/d) in the upper Claiborne aquifer. Under stressed conditions that use 1980 pumpage rates, total flow to the alluvial aquifer from the Mississippi embayment aquifer system is significantly reduced and the flow is reversed in several of the aquifers. Values range from 2¾ million ft^3/d (21 Mgal/d) flow from the alluvial aquifer into the middle Claiborne aquifer to 10 million ft^3/d (75 Mgal/d) flow from the upper Claiborne aquifer into the alluvial aquifer. The 1980 pumpage rates used in the model simulation varied from 3 million ft^3/d (22 Mgal/d) in the middle Wilcox aquifer to 67 million ft^3/d (501 Mgal/d) in the middle Claiborne aquifer. In the Memphis, Tenn., area, 26 million ft^3/d (194 Mgal/d) was pumped from the middle Claiborne aquifer, of which 35 percent comes from downward leakage from the upper Claiborne aquifer in the vicinity of heavy pumpage.

Model simulations indicate that predevelopment-head gradients downdip of the outcrop areas range from ½ to 2 ft/mi. The slope is generally toward the axis of the Mississippi embayment.

The steady-state predevelopment model indicates that about ¼ million ft^3/d (1¾ Mgal/d) of water moves upward from the upper Claiborne aquifer through the Vicksburg-Jackson confining unit into the Coastal lowlands aquifer system. Under 1980 pumping conditions the net flow is reversed and about ⅓ million ft^3/d (2½ Mgal/d) moves into the upper Claiborne aquifer from the Coastal lowlands aquifer system.

Model simulations indicate that flow in the Mississippi embayment aquifer system moves downdip from the outcrop area and upward through the confining units as it traverses toward the Mississippi embayment axis. Regions of recirculation exist in the outcrop areas where flow enters the system and is discharged within a short distance. This interactive flow is caused by the undulating water table that reflects land-surface relief. In the majority of the area, the movement of flow through the confining unit between adjacent aquifers is less than 0.1 in/yr. One exception is in the heavily pumped Memphis, Tenn., area where up to 4.0 in/yr moves downward from the upper Claiborne aquifer through the middle Claiborne confining unit into the middle Claiborne aquifer.

Water-level measurements made in 1980 indicate that the middle Claiborne aquifer in the Mississippi embayment aquifer system is the most heavily stressed. The other aquifers have significant drawdown only in specific areas of heavy pumpage.

Model simulations that use 1980 pumpage rates indicate several areas with significant drawdown from simulated predevelopment conditions in the middle Claiborne aquifer. In the Memphis area a drawdown of more than 100 feet is produced in the middle Claiborne aquifer. Large drawdowns (as much as 280 ft) are indicated in the Pine Bluff, Ark., area in the middle Claiborne aquifer. In the Greenville, Miss. area, water levels in the upper Claiborne aquifer are drawn down as much as 80 feet. In the Memphis, Tenn. area, water levels in the lower Wilcox aquifer are drawn down as much as 100 feet.

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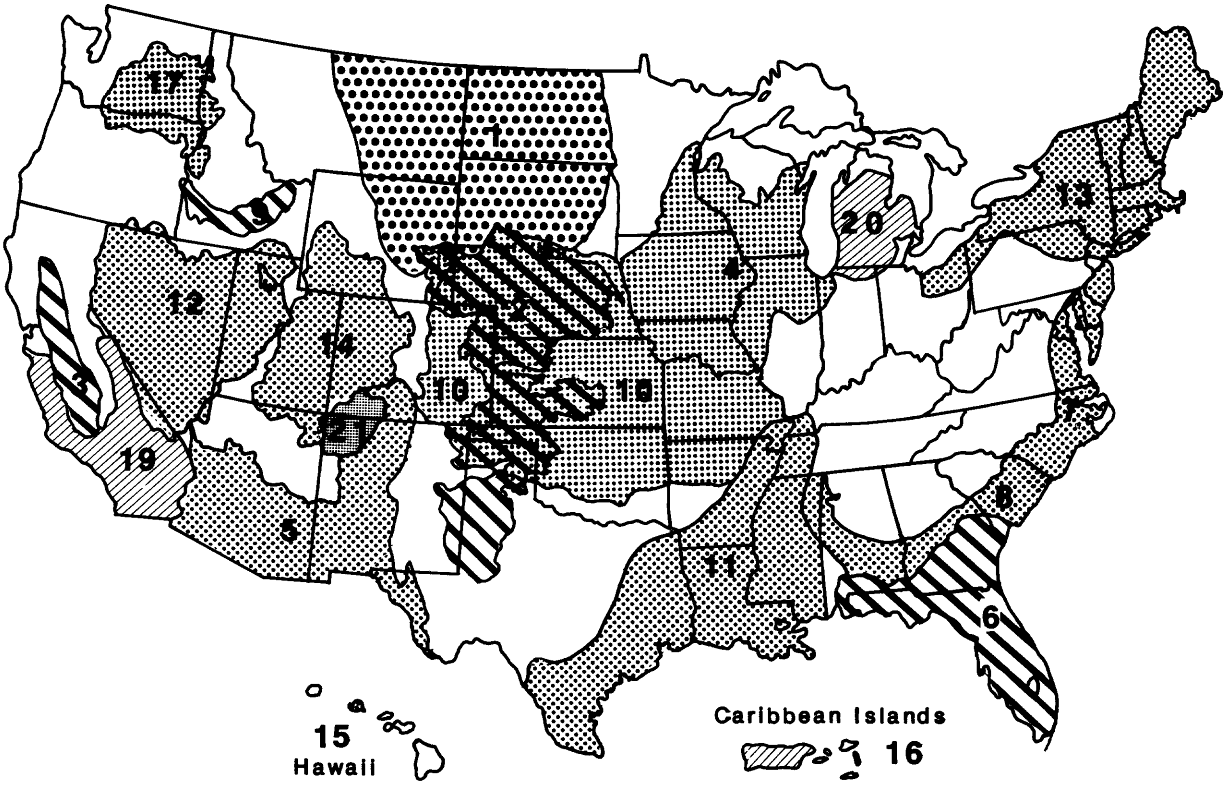

EXPLANATION

STATUS OF THE REGIONAL AQUIFER-SYSTEMS ANALYSIS PROGRAM in 1984
(Actual or planned duration shown by span of years)

STUDIES COMPLETED

PHASE I STUDIES COMPLETED
PHASE II STUDIES UNDERWAY, FY 1984

STUDIES UNDERWAY, FY 1984

STUDIES INITIATED, FY 1984

STUDIES PLANNED, FY 1985

1. Northern Great Plains; FY 1978-82
2. High Plains; FY 1978-82; Phase II study
3. Central Valley, California; FY 1978-82; Phase II study
4. Northern Midwest; FY 1979-84
5. Southwest alluvial basins; FY1979-84
6. Floridan aquifer; FY 1979-82; Phase II study
7. Northern Atlantic Coastal Plain; FY 1980-85
8. Southeastern Coastal Plain; FY 1980-86
9. Snake River Plain; FY 1980-84; Phase II study
10. Central Midwest; FY 1981-86
11. Gulf Coastal Plain; FY 1981-88
12. Great Basin; FY 1981-85
13. Northeast glacial valleys; FY 1982-86
14. Upper Colorado River Basin; FY 1982-86
15. Oahu Island, Hawaii; FY 1982-86
16. Caribbean Islands; FY 1984-87
17. Columbia Plateau; FY 1983-86
19. Southern California alluvial basins; FY 1984-87
20. Michigan Basin; FY 1984-87
21. San Juan Basin; to be initiated in FY 1985

Figure 1.--Geographic distribution of the Regional Aquifer System Analysis program.

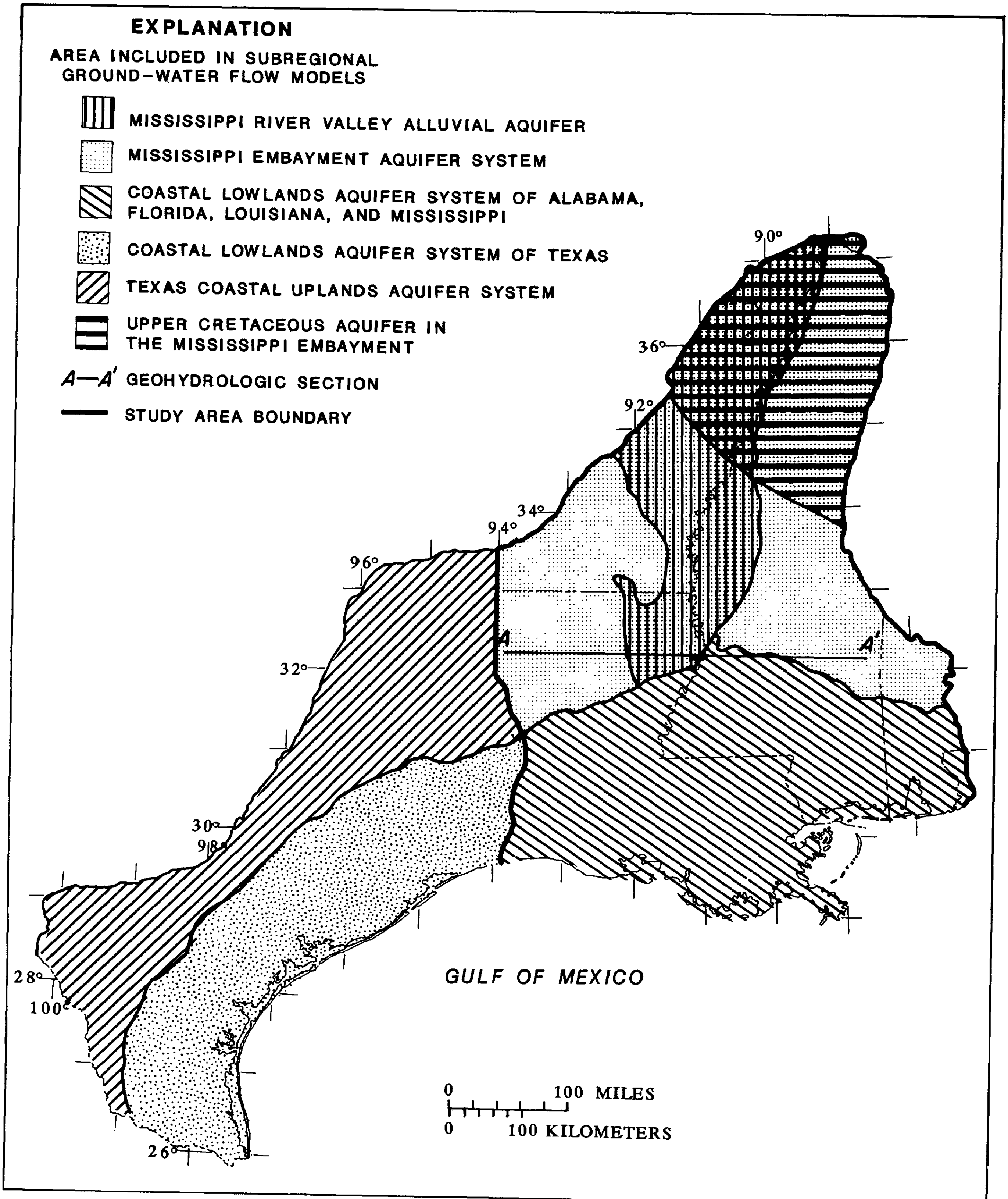

Figure 2.--Location of aquifer systems and study areas in the Gulf Coast RASA project area.

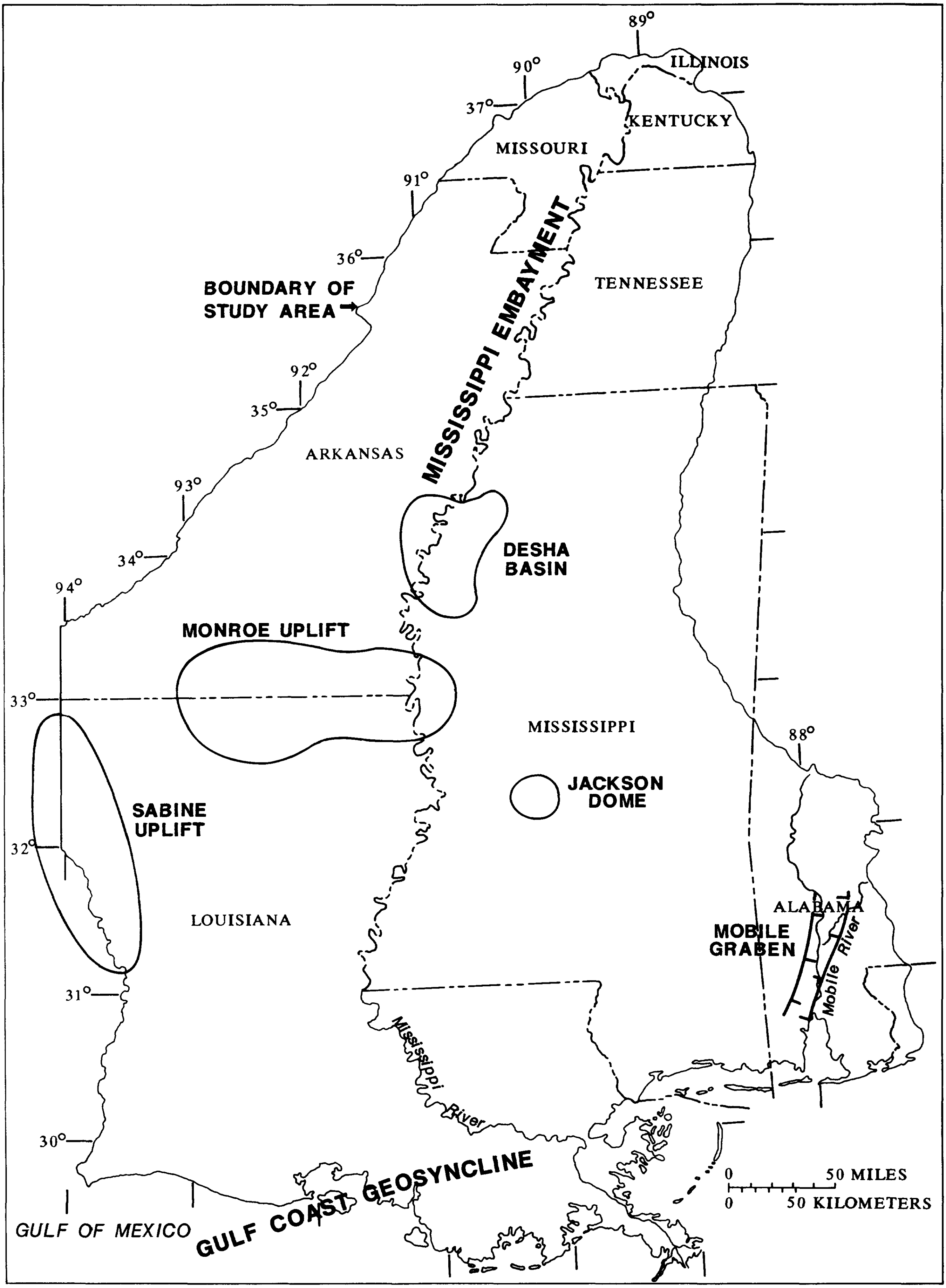

Figure 3.--Mississippi embayment aquifer system and major structural features in the Gulf Coast RASA project area.

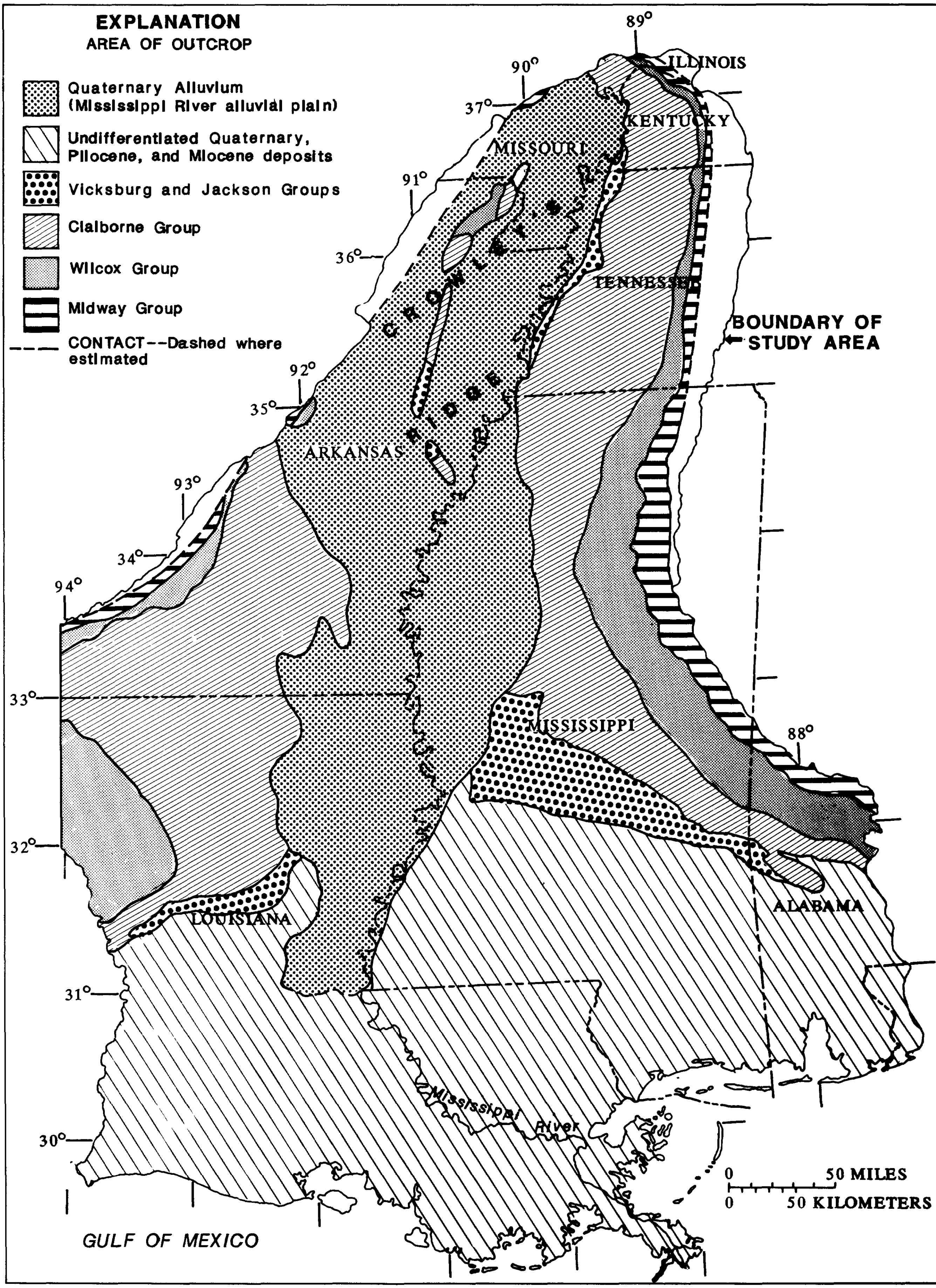

Figure 4.--Generalized geology of study area.

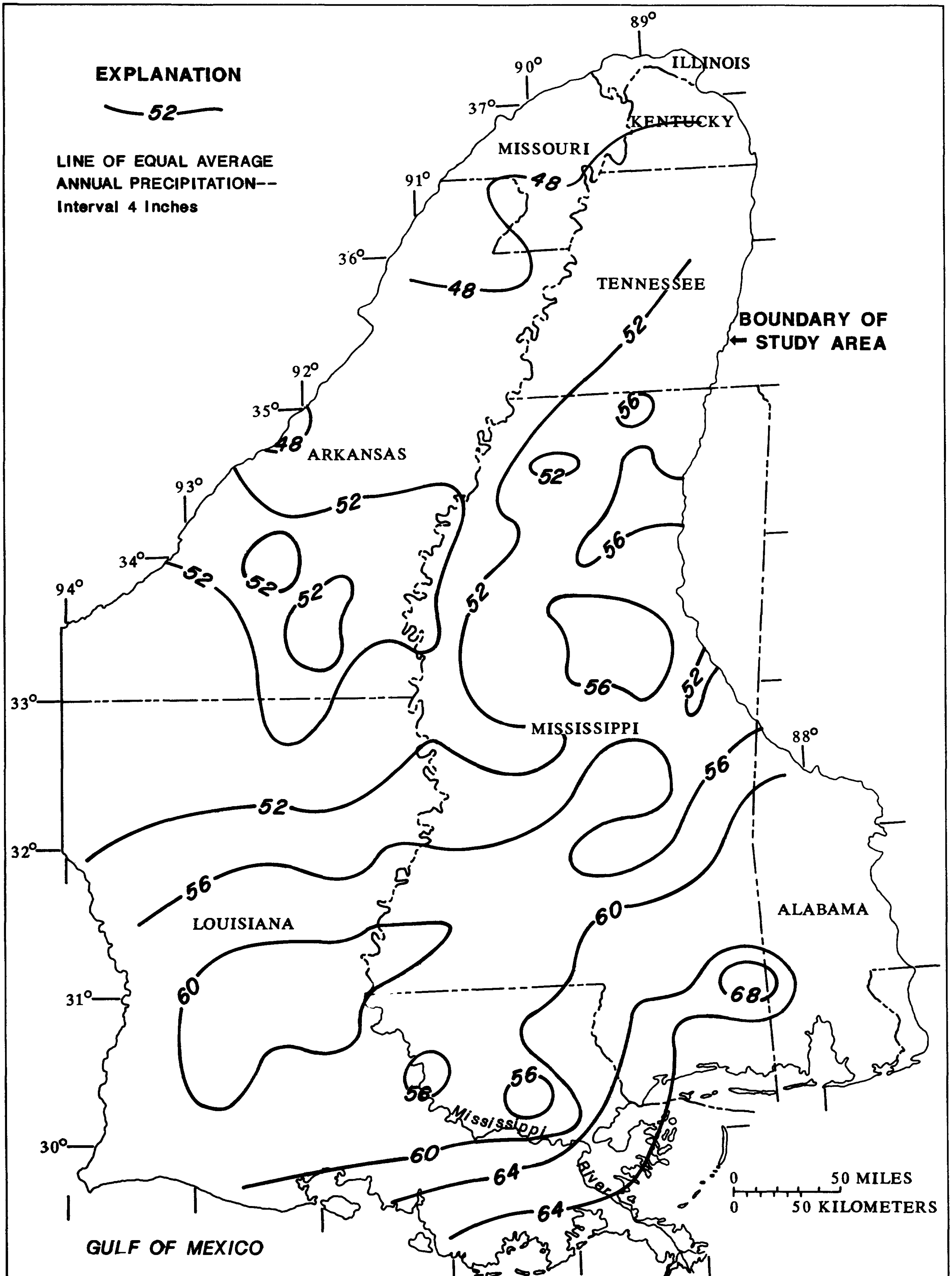

Figure 5.--Average annual precipitation.

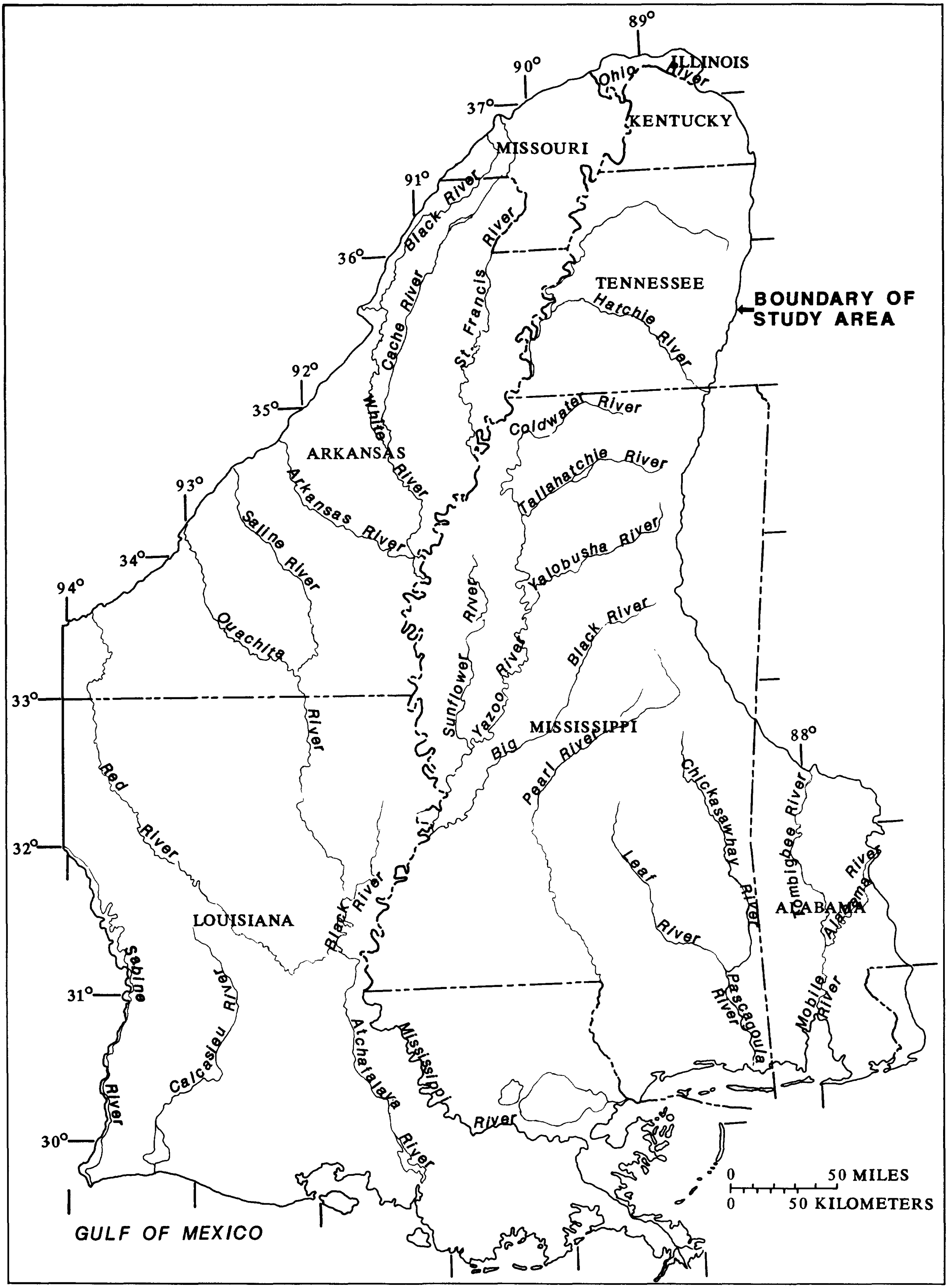

Figure 6.--Major drainage in study area.

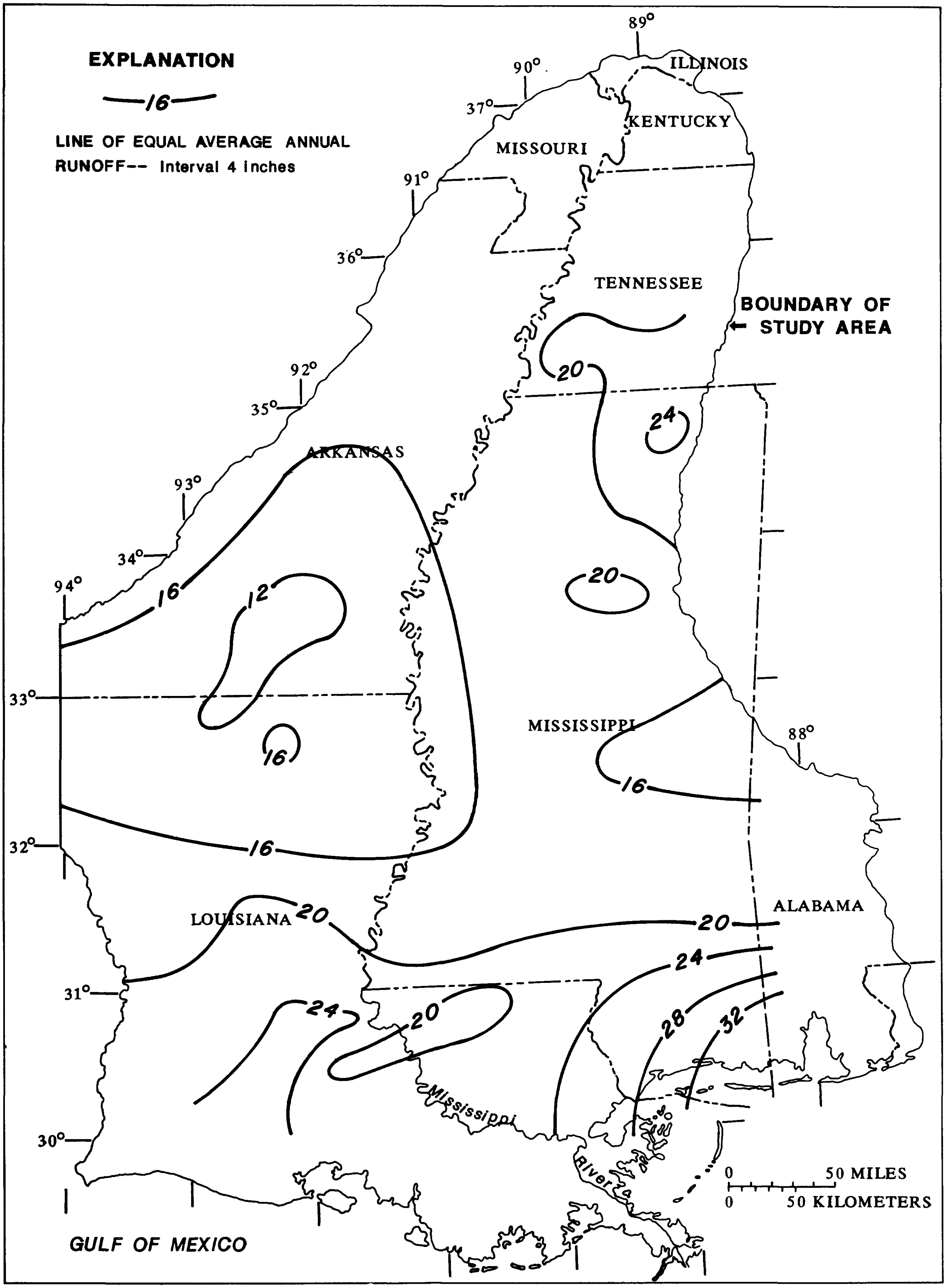

Figure 7.--Average annual runoff.

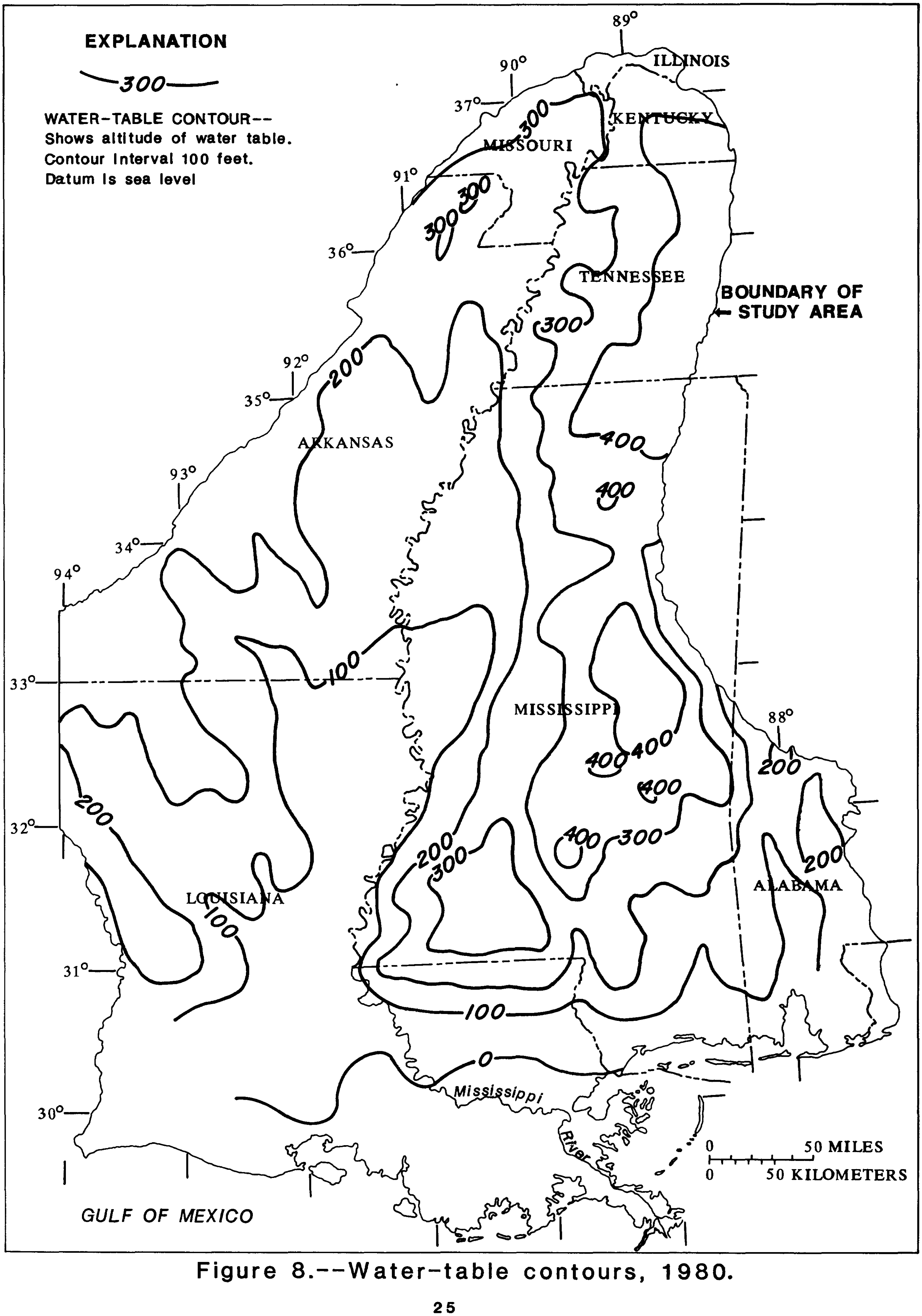

Figure 8.--Water-table contours, 1980.

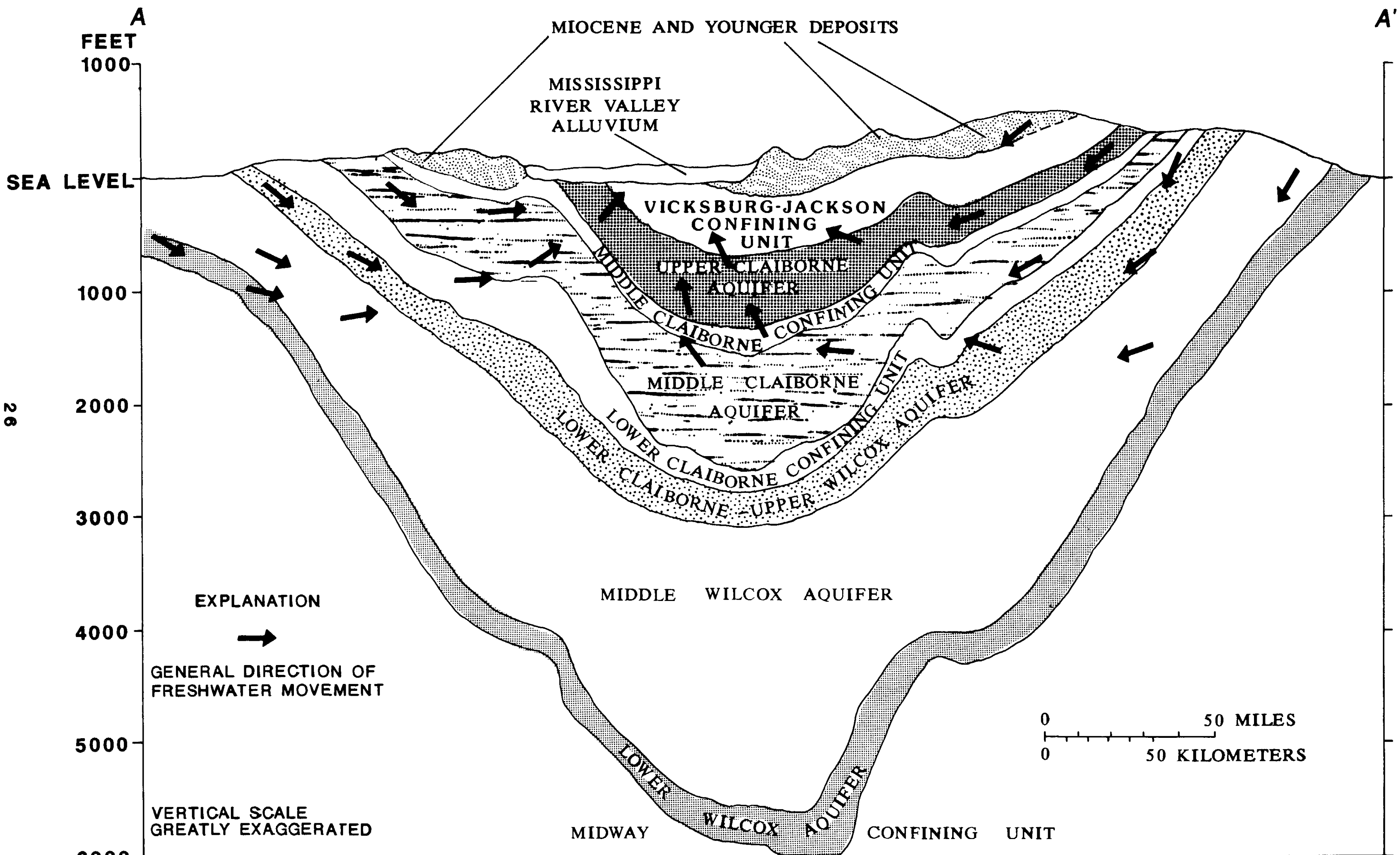

Figure 9.--Generalized geohydrologic section and flow pattern.

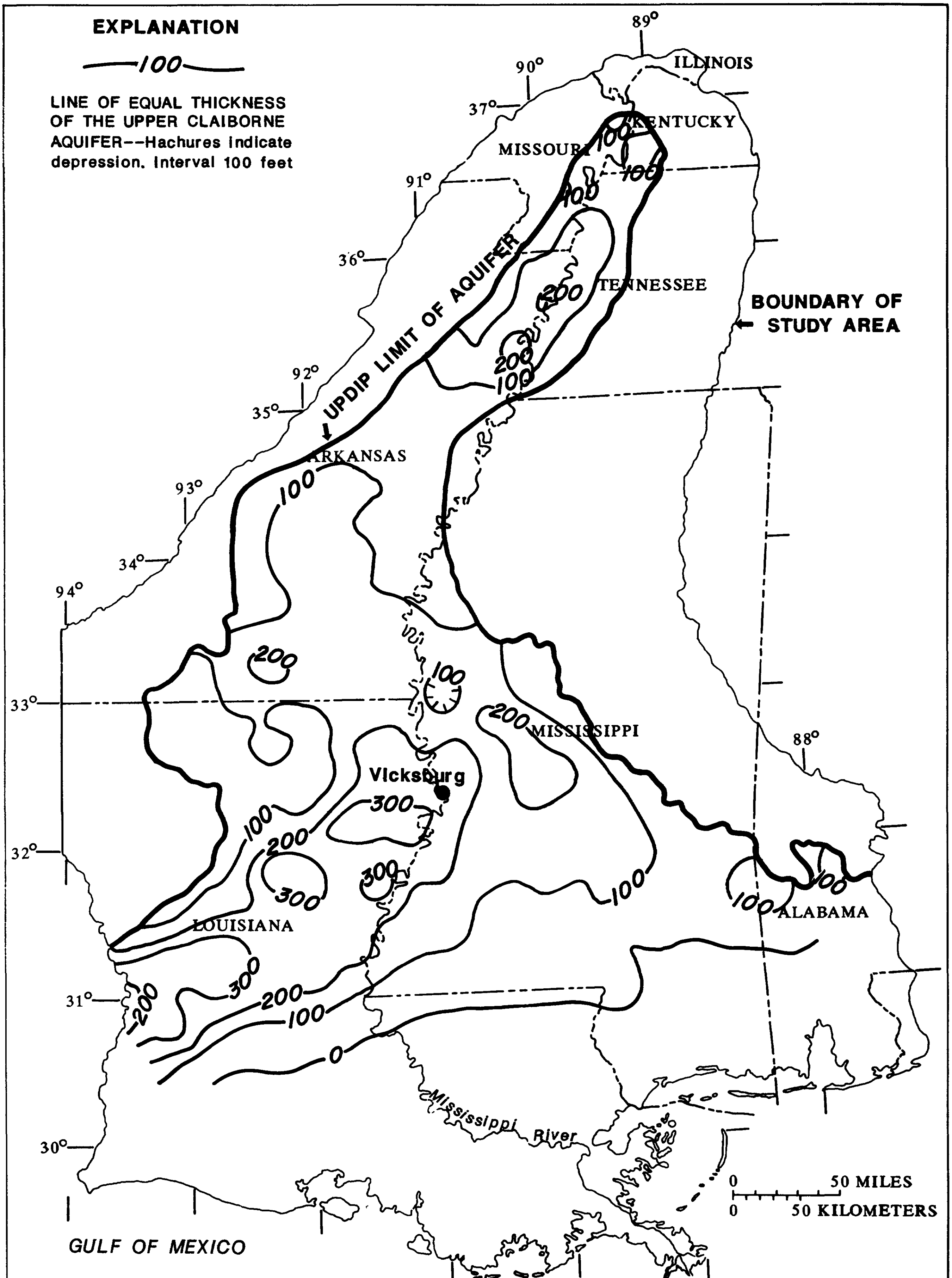

Figure 10.--Total sand bed thickness of upper Claiborne aquifer.

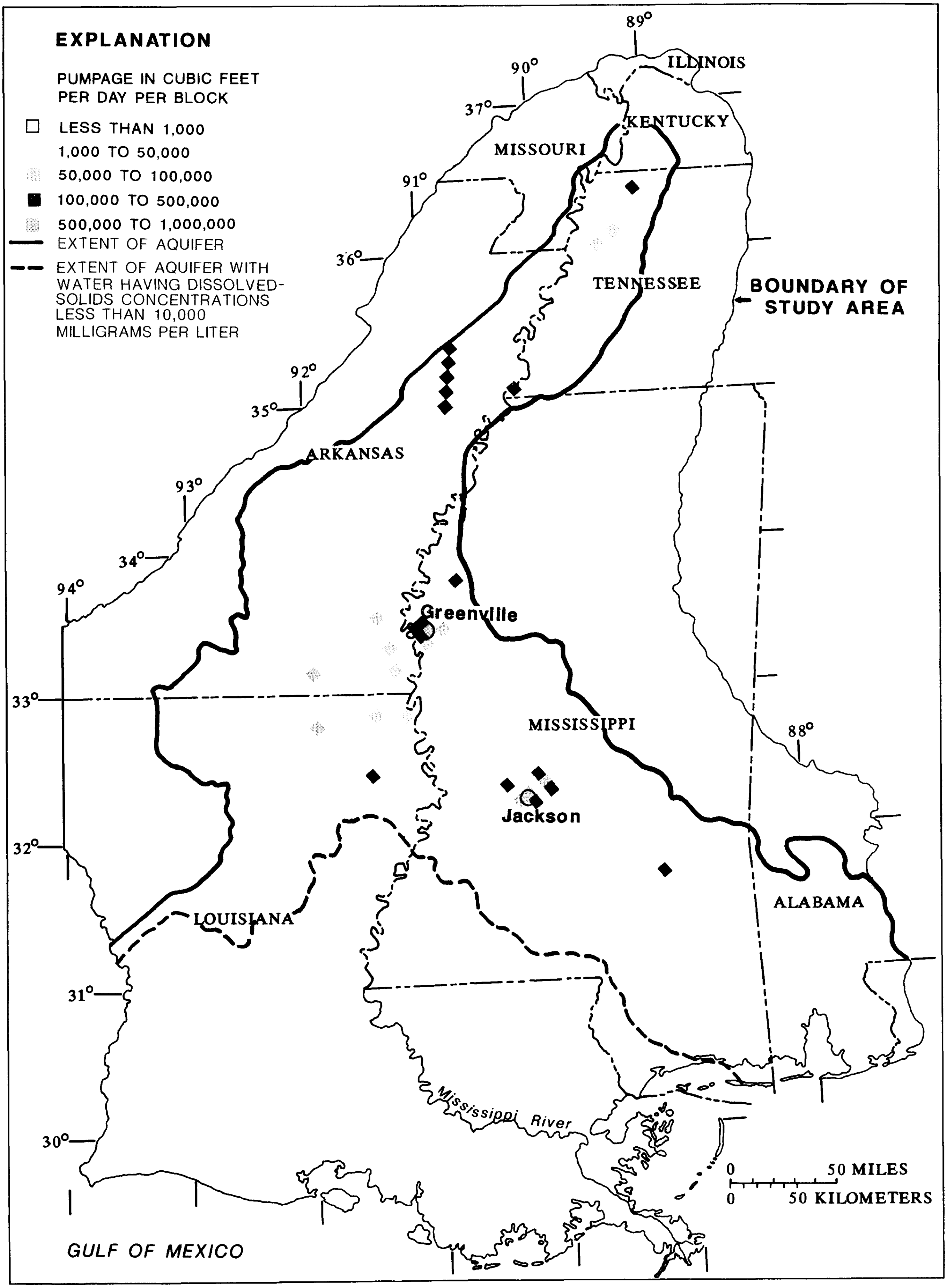

Figure 11.--1980 pumpage from upper Claiborne aquifer in each 25-square-mile block

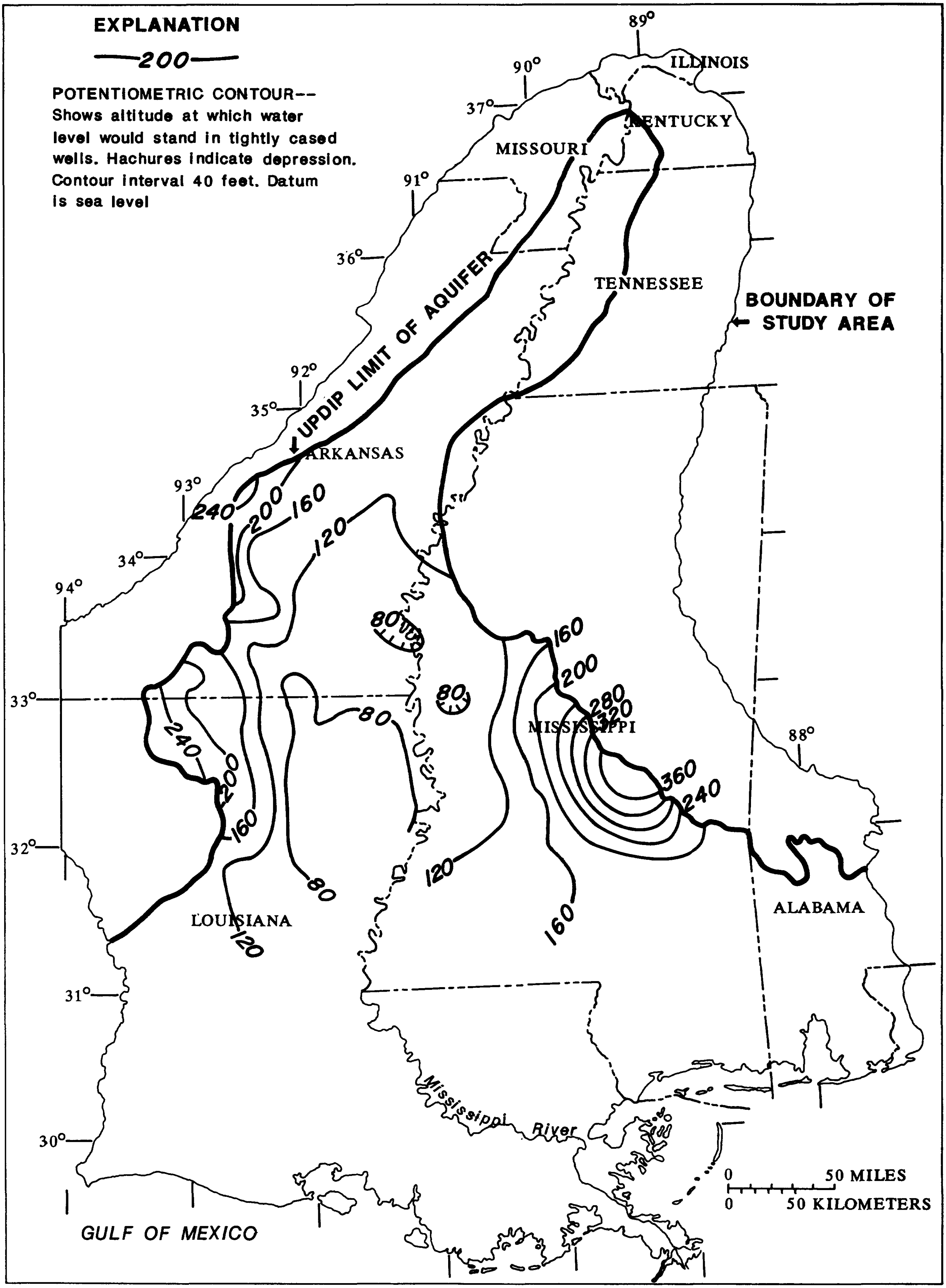

Figure 12.--Potentiometric surface of upper Claiborne aquifer, 1980.

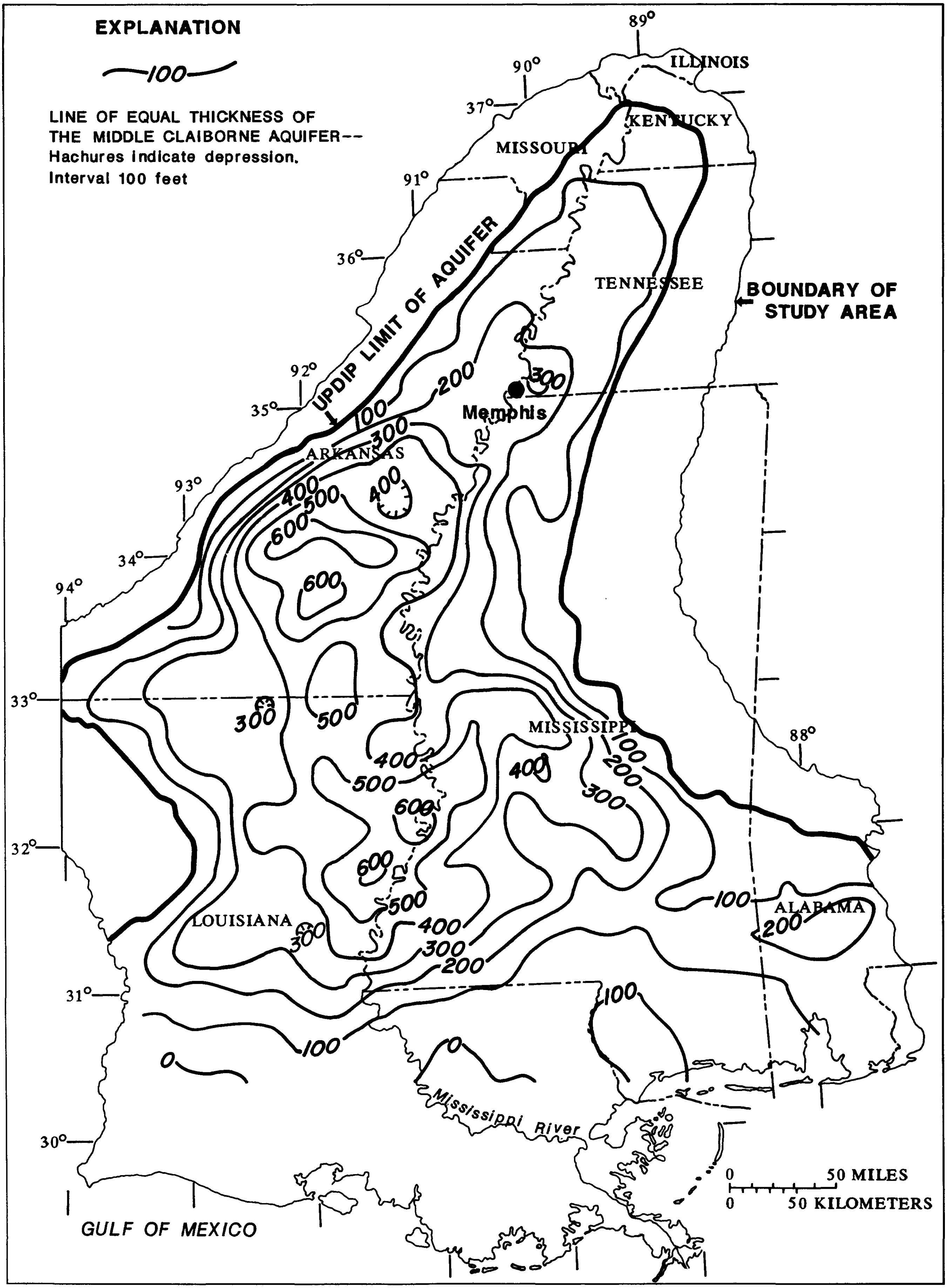

Figure 13.--Total sand bed thickness of middle Claiborne aquifer.

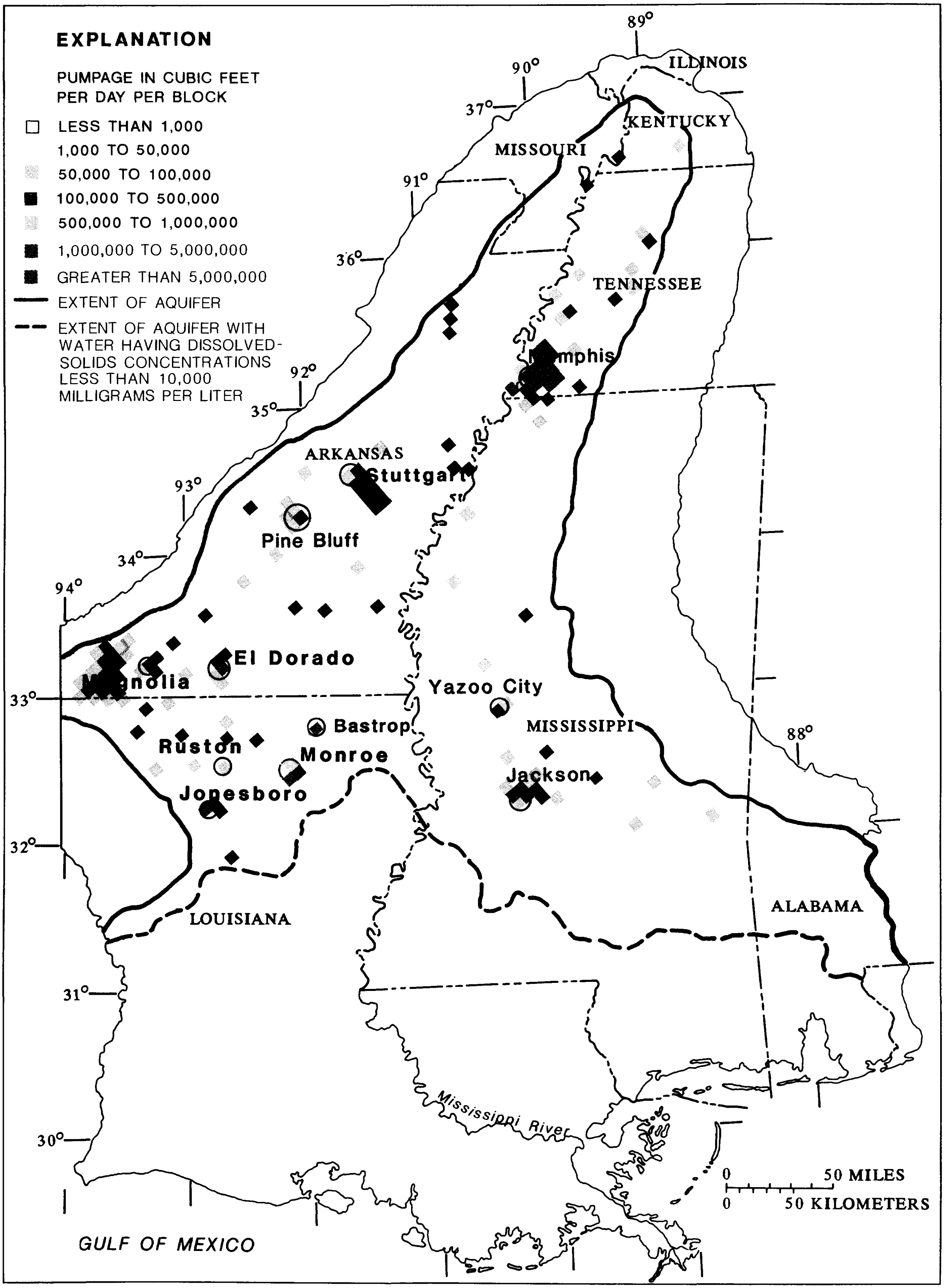

Figure 14.--1980 pumpage from middle Claiborne aquifer in each 25-square-mile block.

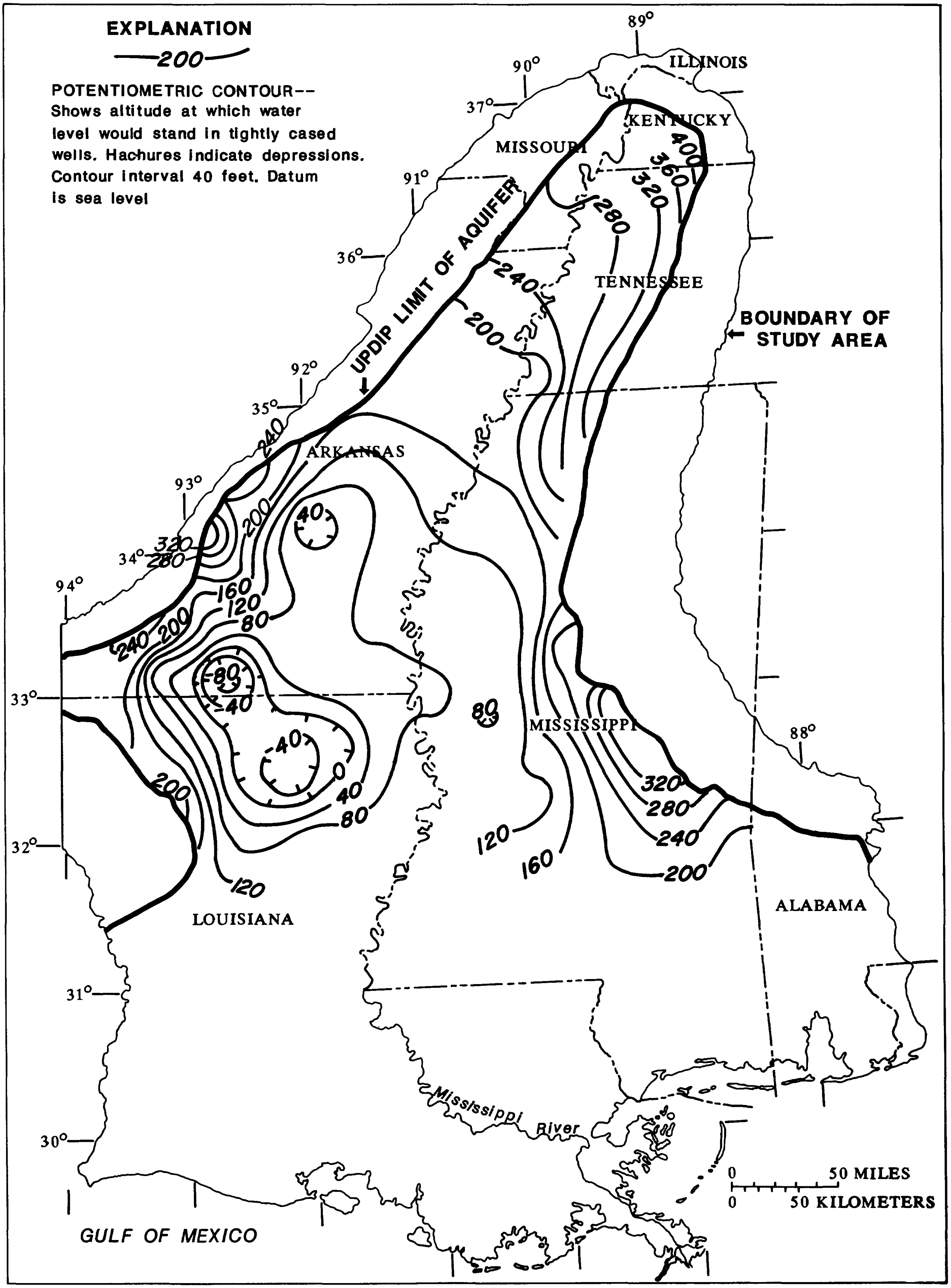

Figure 15.--Potentiometric surface of middle Claiborne aquifer, 1980.

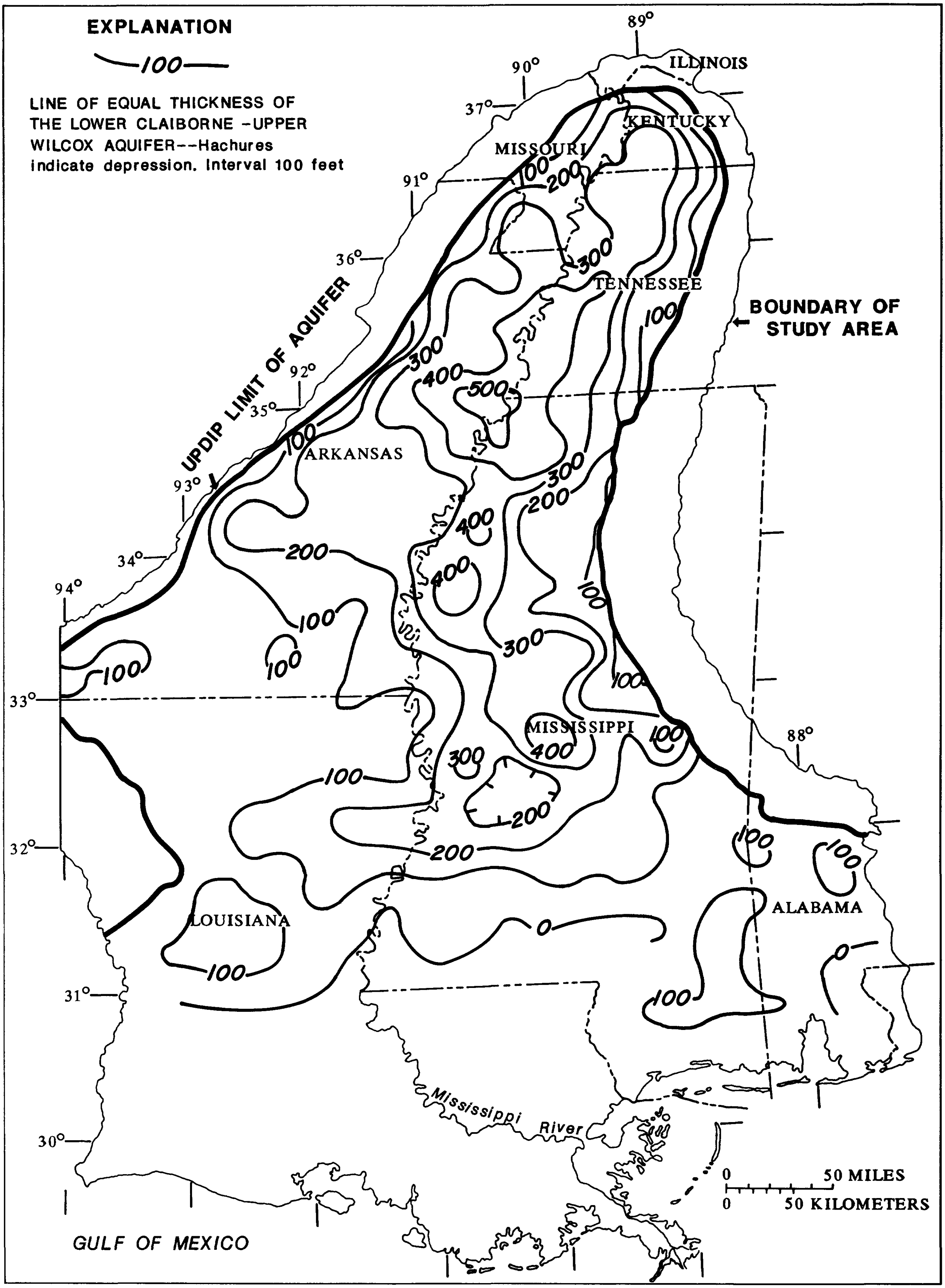

Figure 16.--Total sand bed thickness of lower Claiborne-upper Wilcox aquifer.

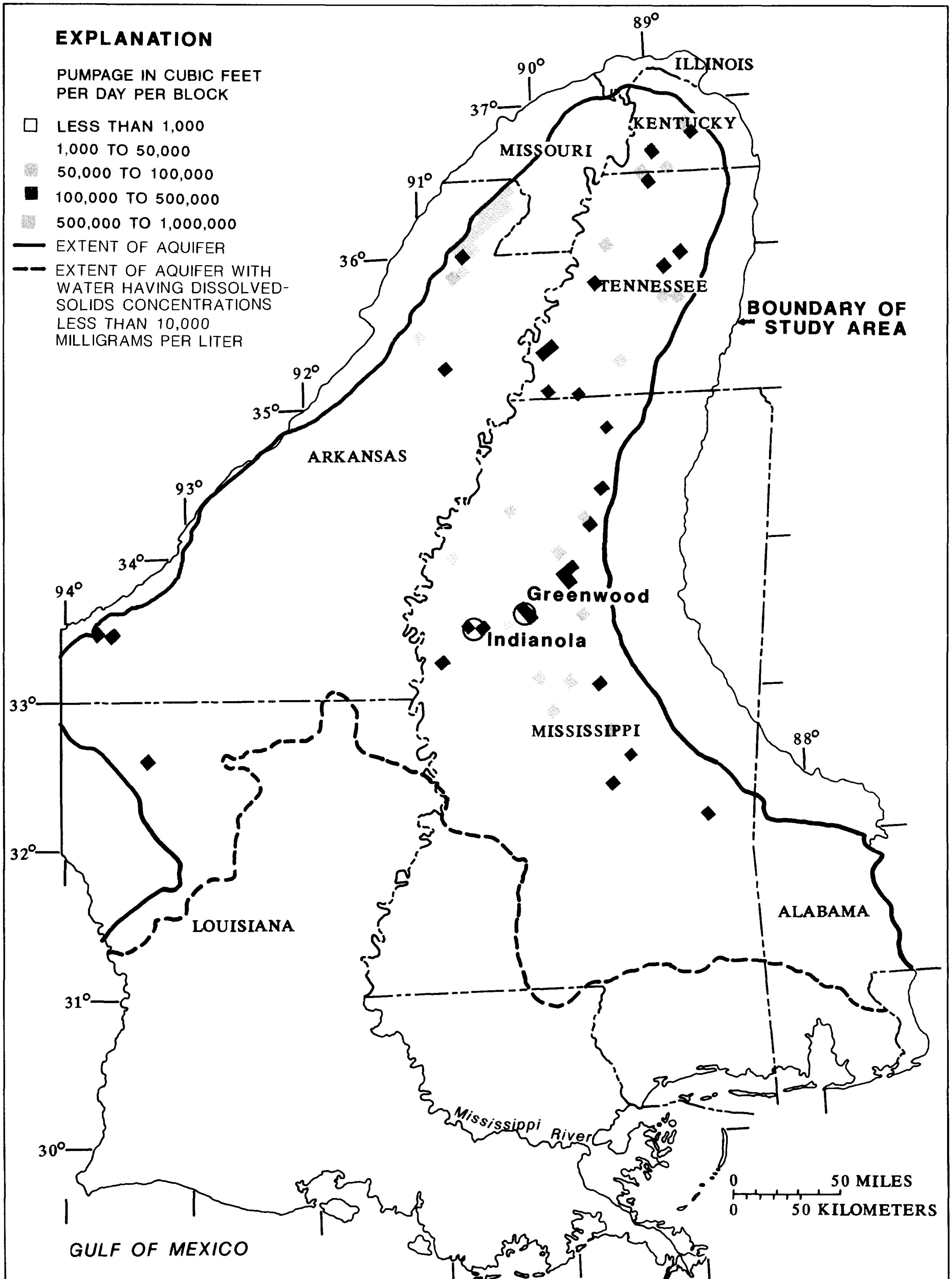

Figure 17.--1980 pumpage from lower Claiborne-upper Wilcox aquifer in each 25-square-mile block

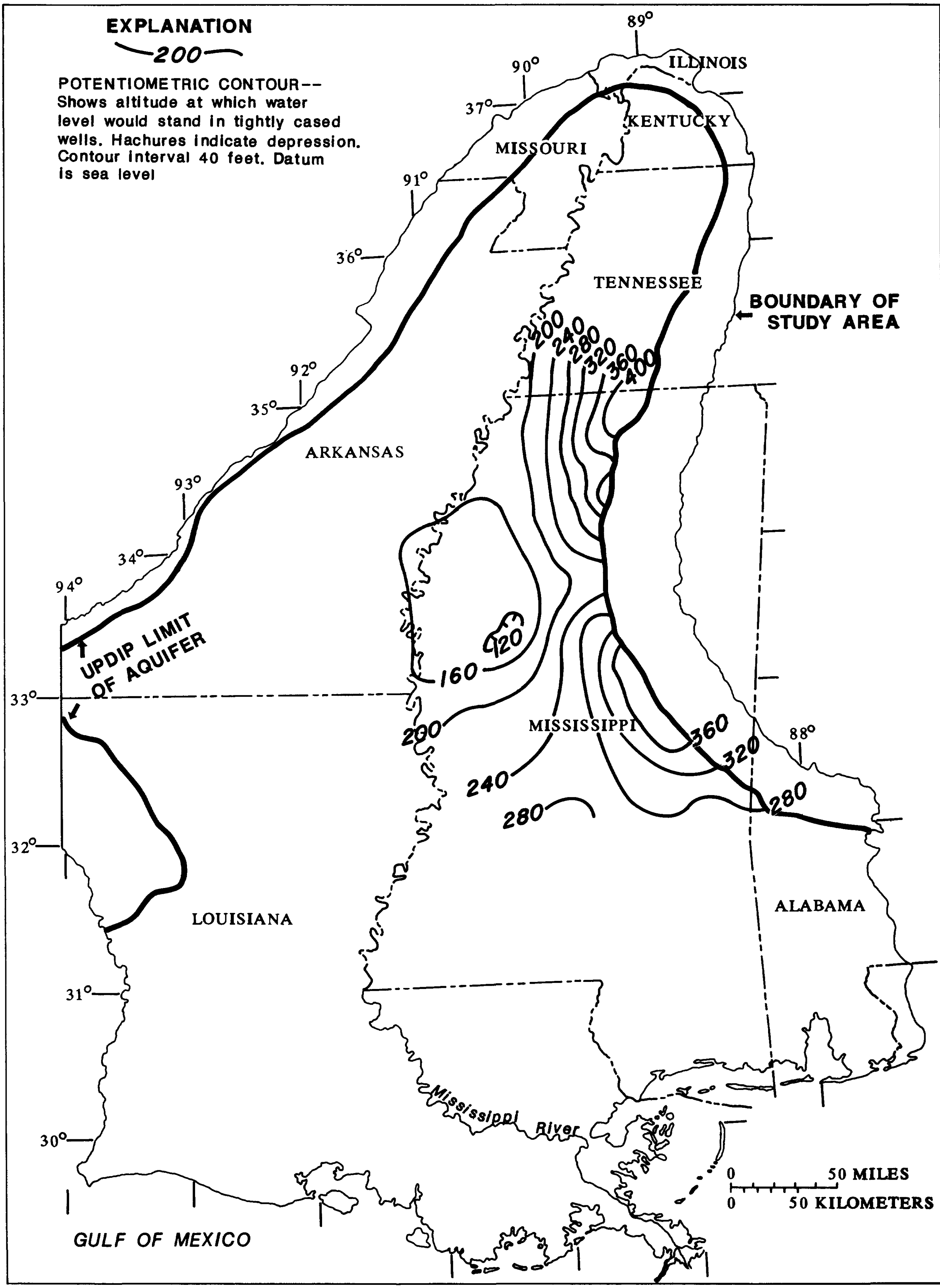

Figure 18.--Potentiometric surface of lower Claiborne-upper Wilcox aquifer, 1980.

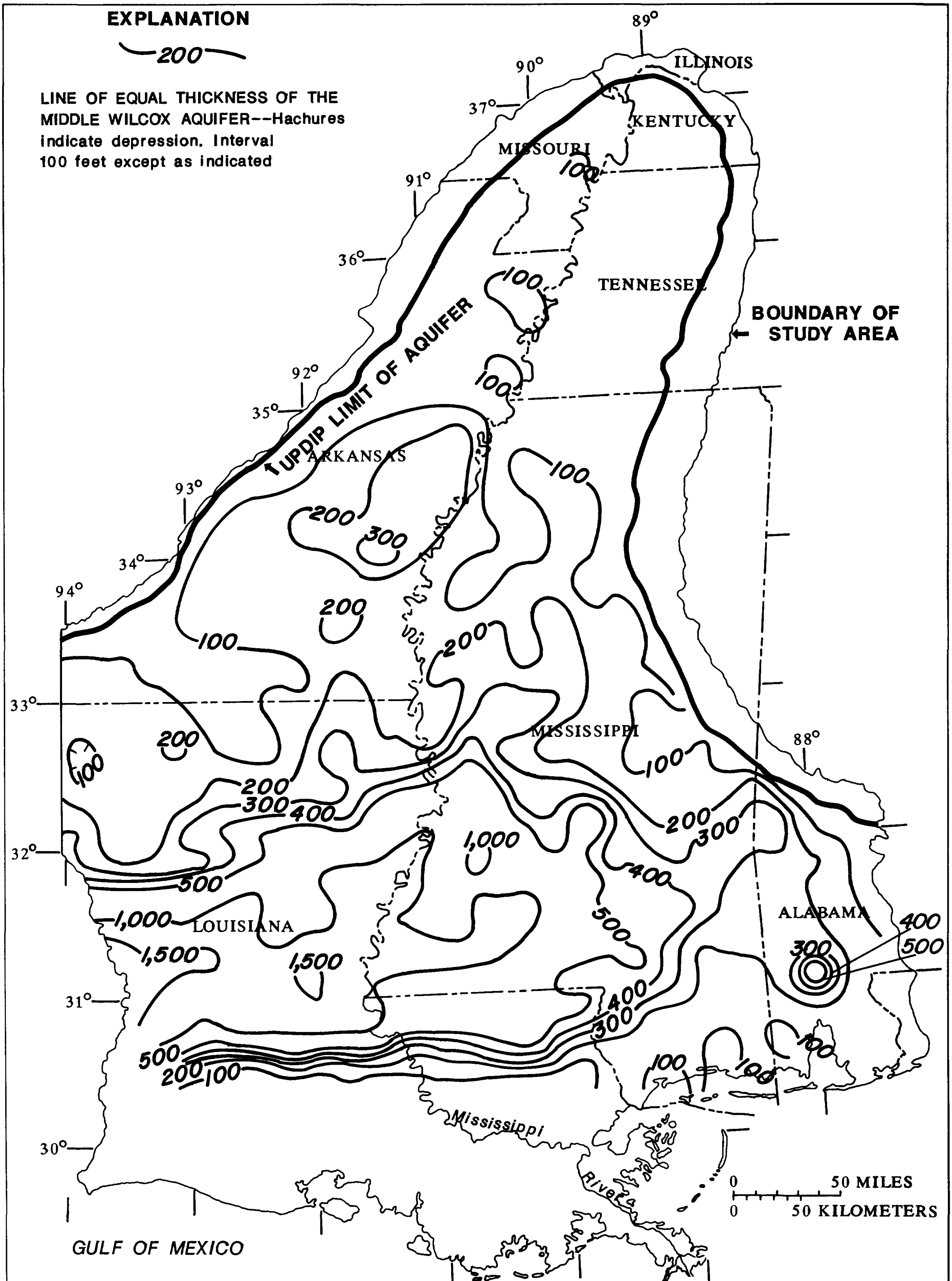

Figure 19.--Total sand bed thickness of middle Wilcox aquifer Wilcox aquifer, 1980.

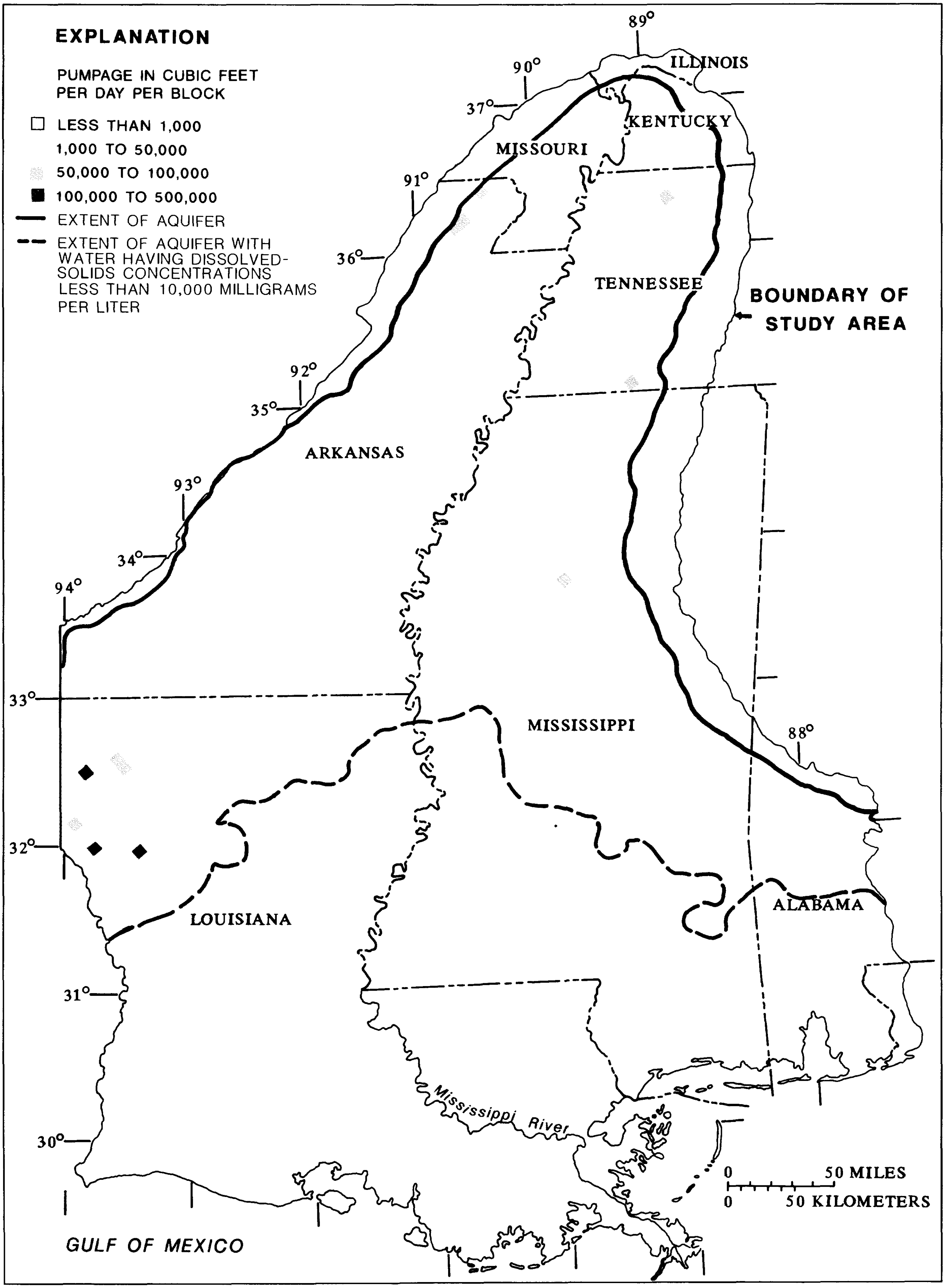

Figure 20.--1980 pumpage from middle Wilcox aquifer in each 25-square-mile block

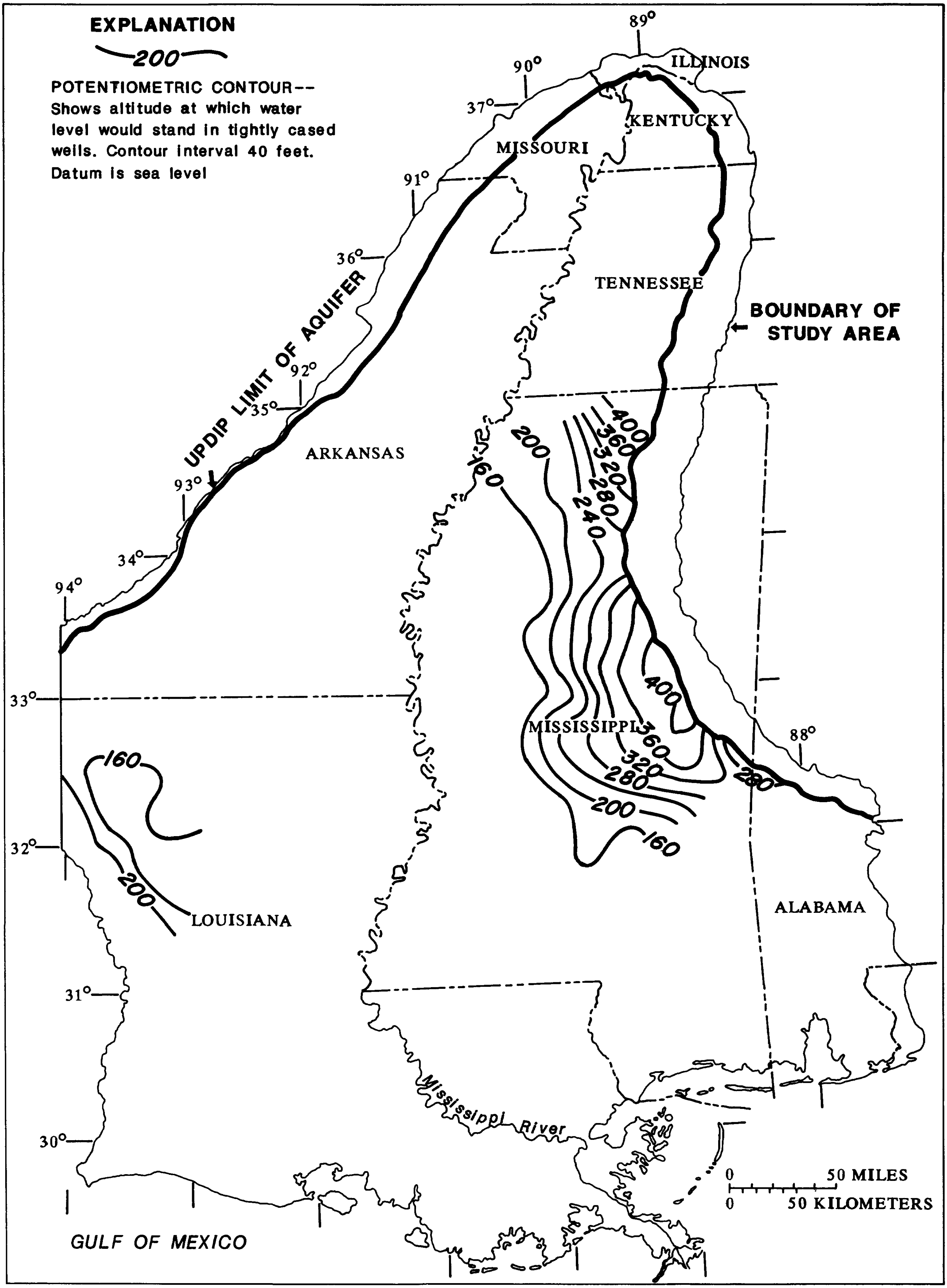

Figure 21.--Potentiometric surface of middle Wilcox aquifer, 1980.

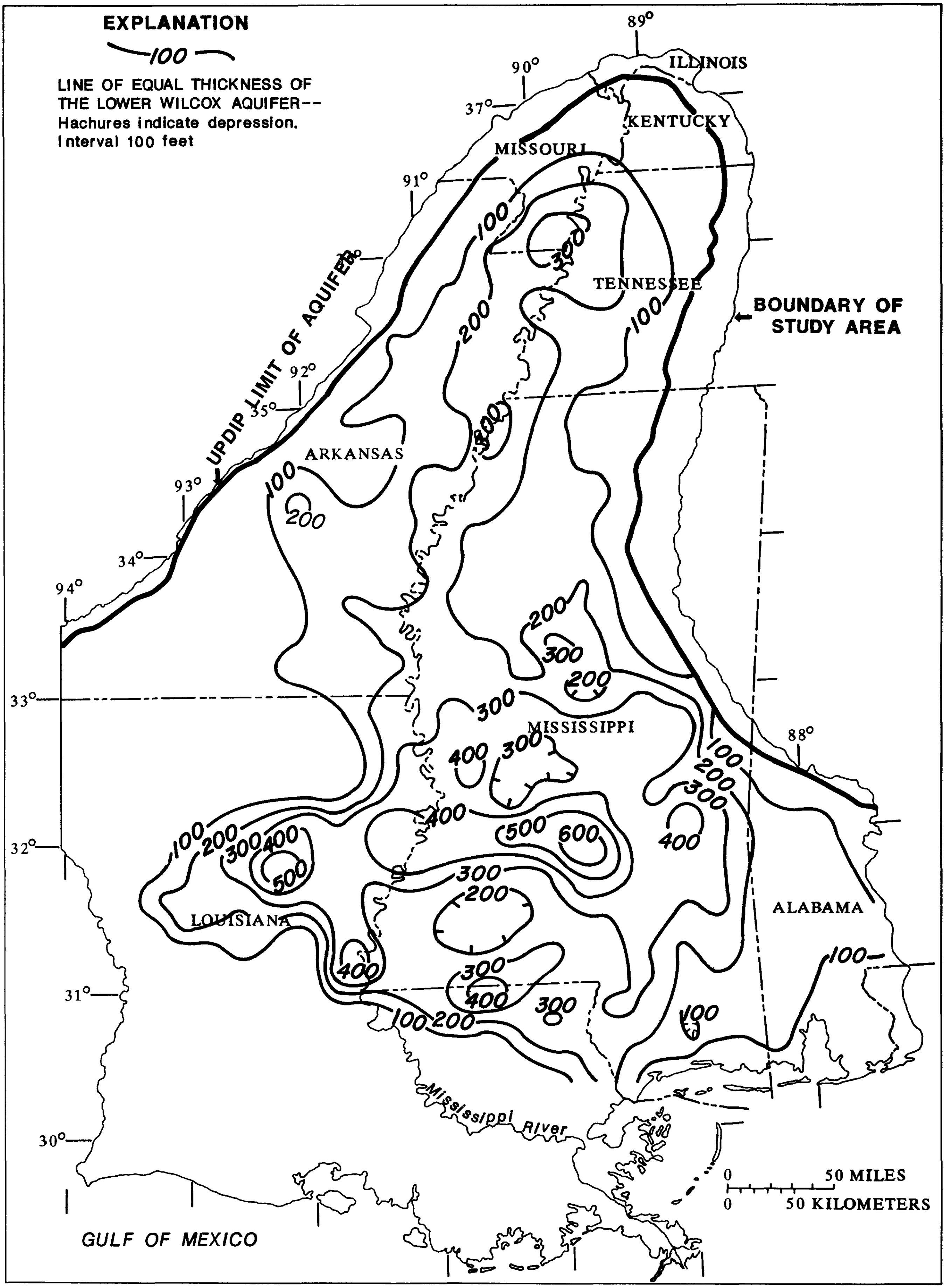

Figure 22.--Total sand bed thickness of lower Wilcox aquifer.

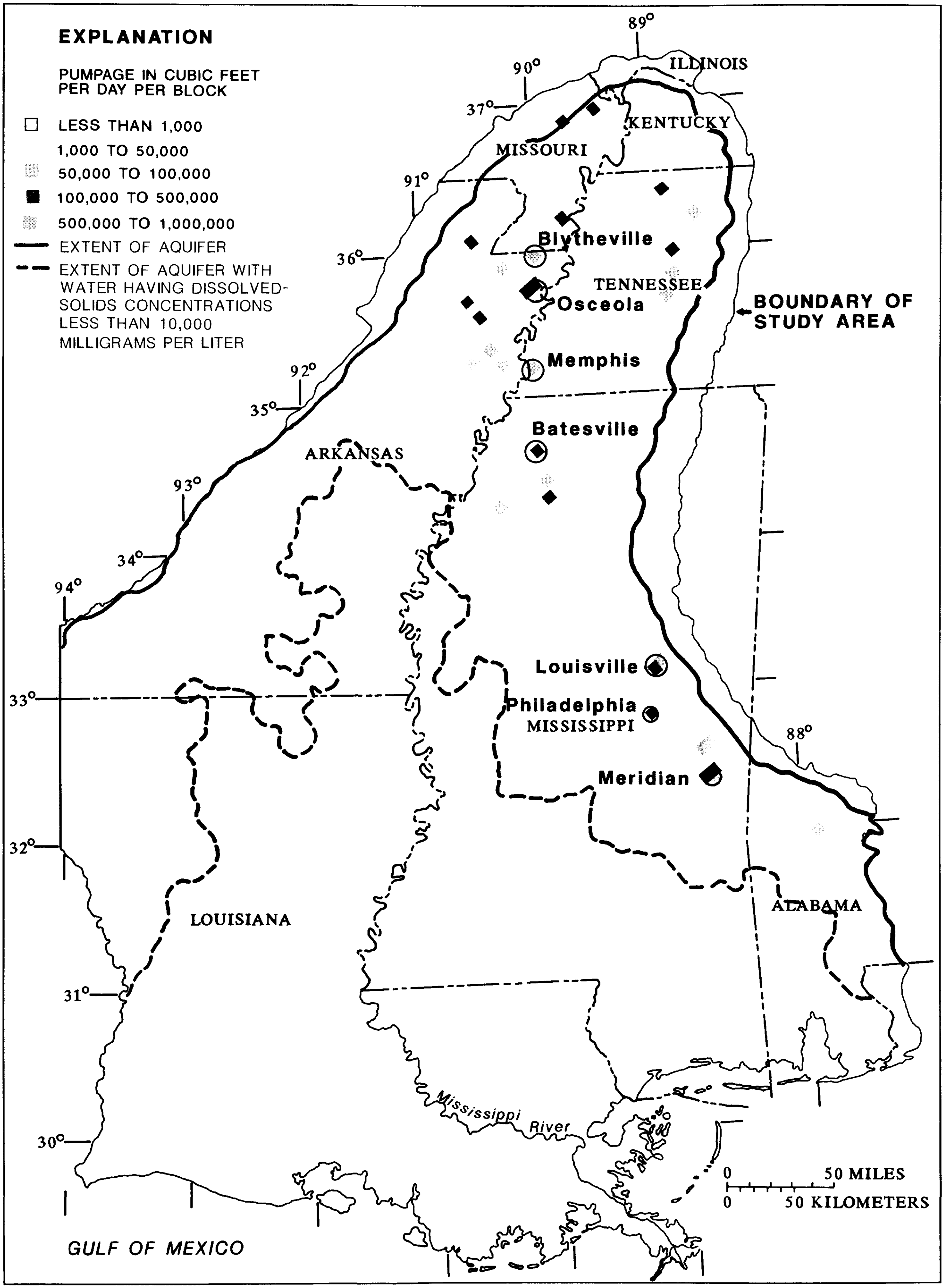

Figure 23.--1980 pumpage from lower Wilcox aquifer in each 25-square-mile block

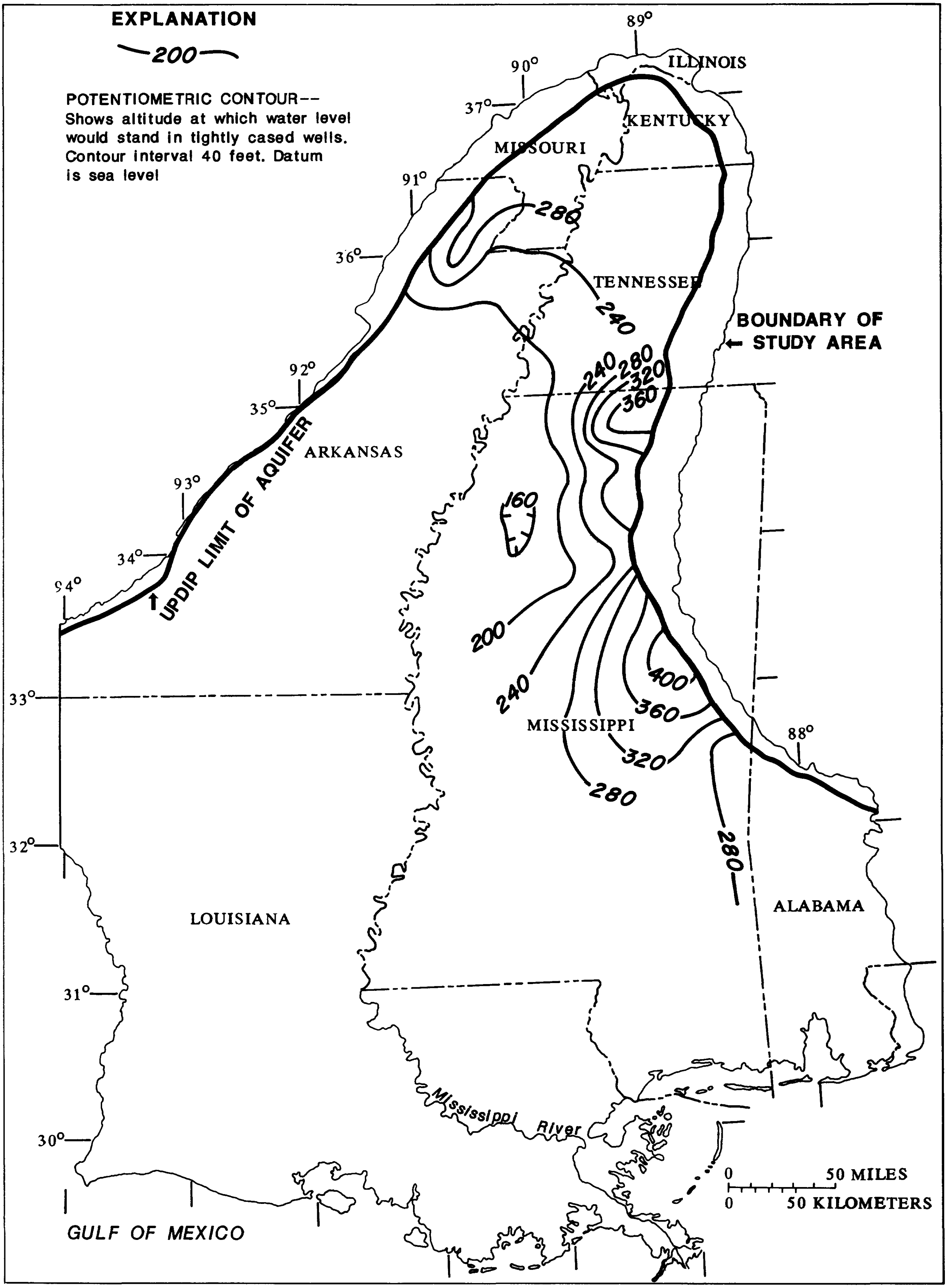

Figure 24.--Potentiometric surface of lower Wilcox aquifer, 1980.

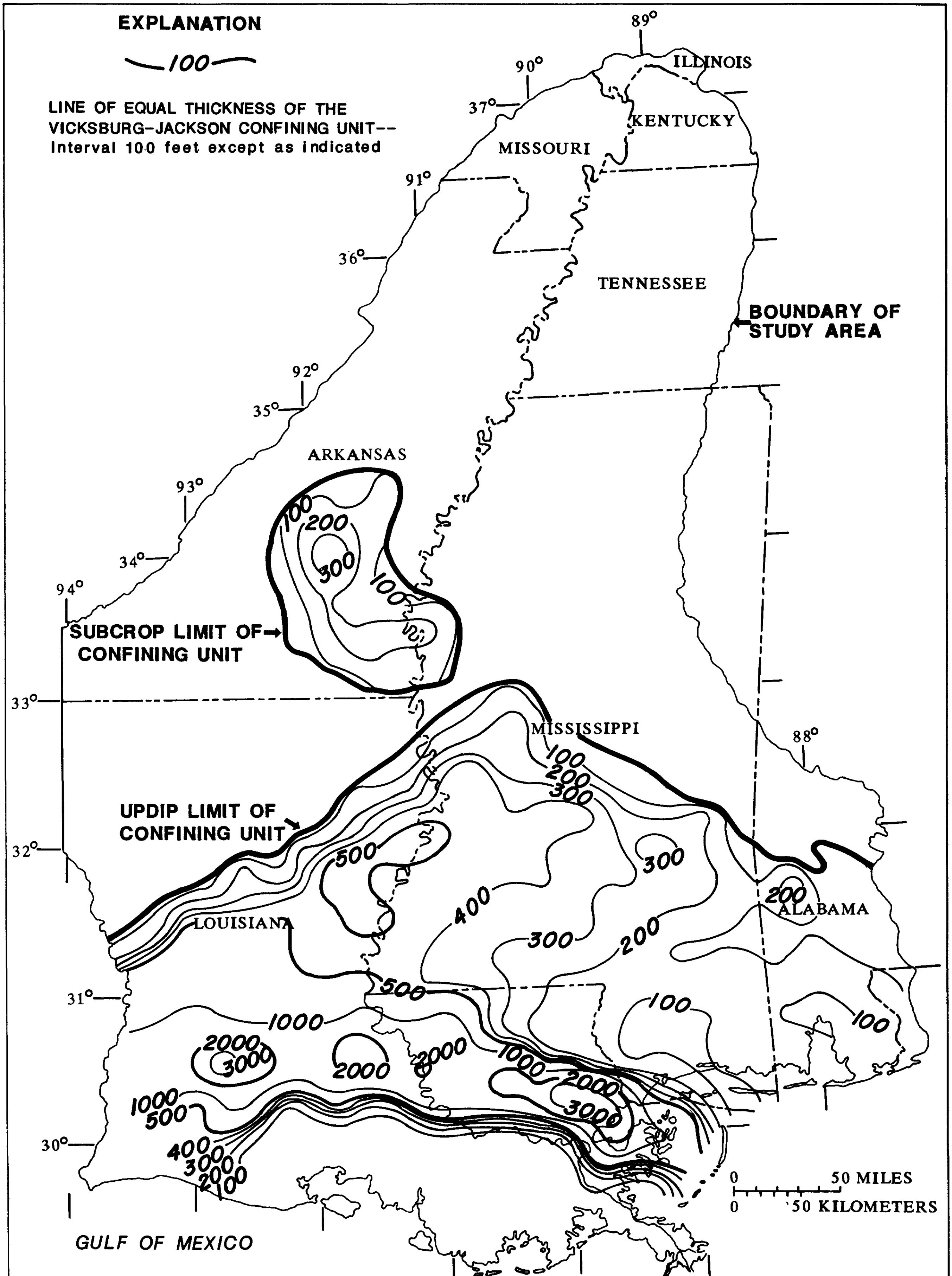

Figure 25.--Total clay thickness of Vicksburg-Jackson confining unit.

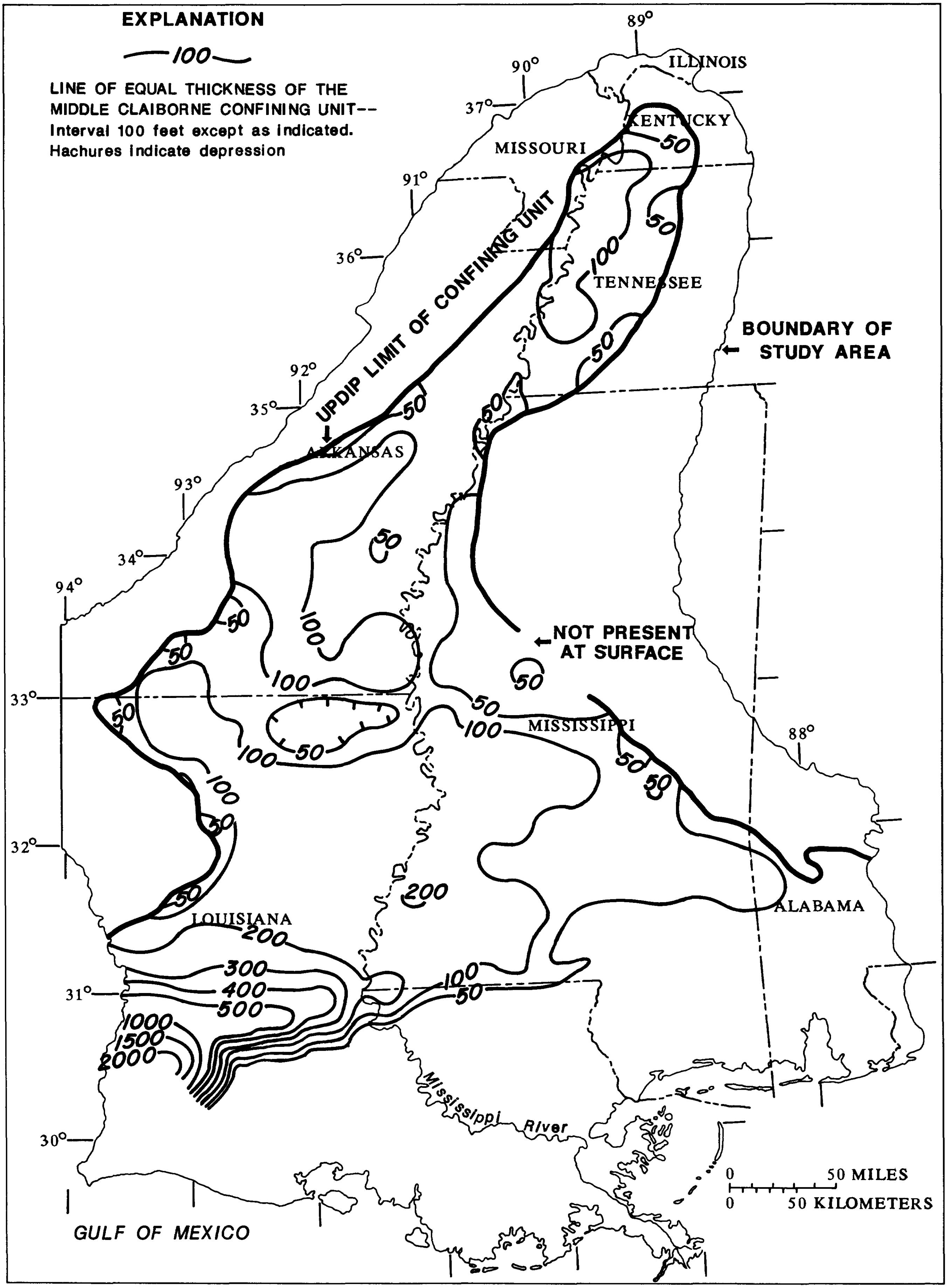

Figure 26.--Total clay thickness of middle Claiborne confining unit.

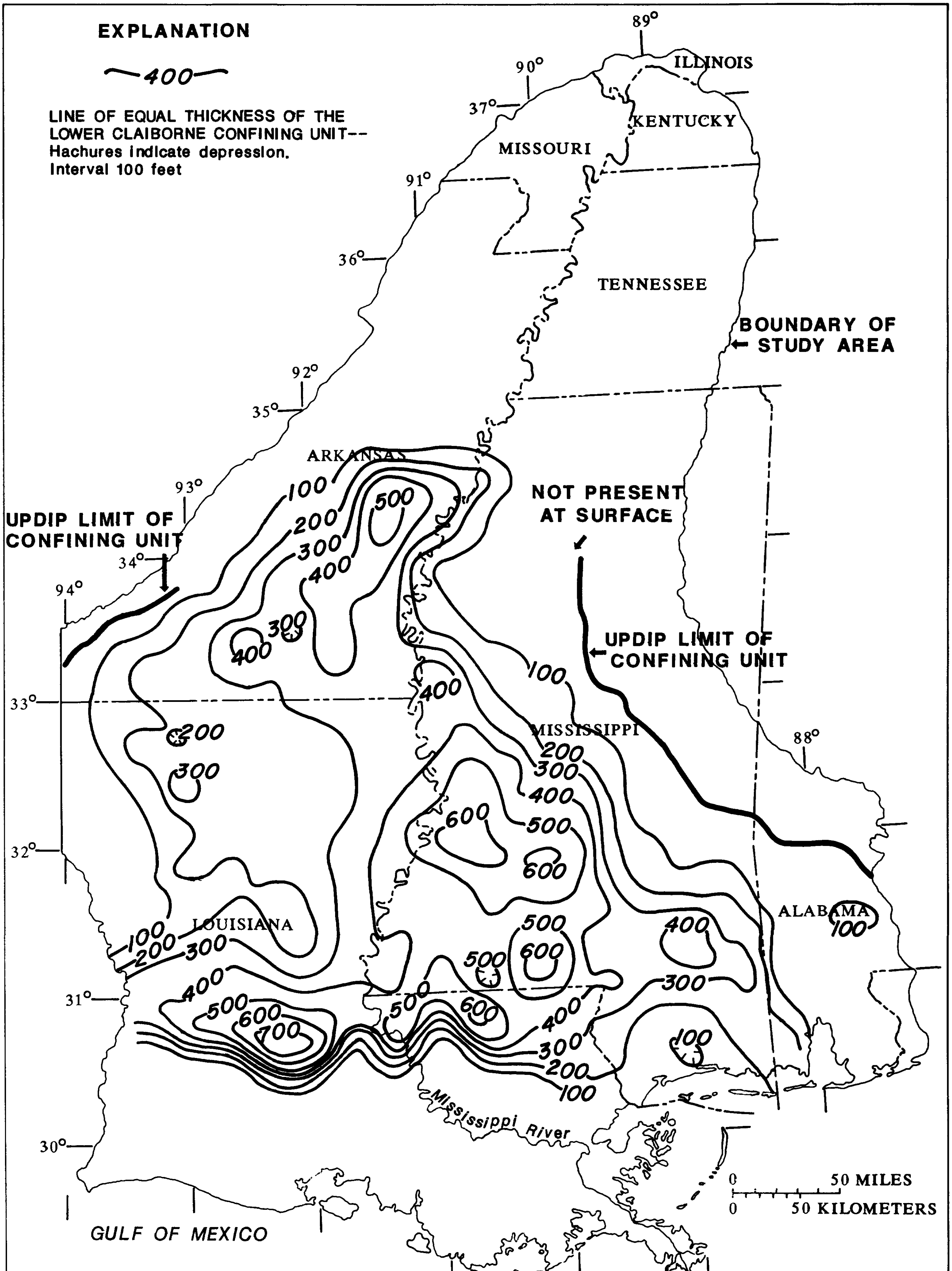

Figure 27.--Total clay thickness of lower Claiborne confining unit.

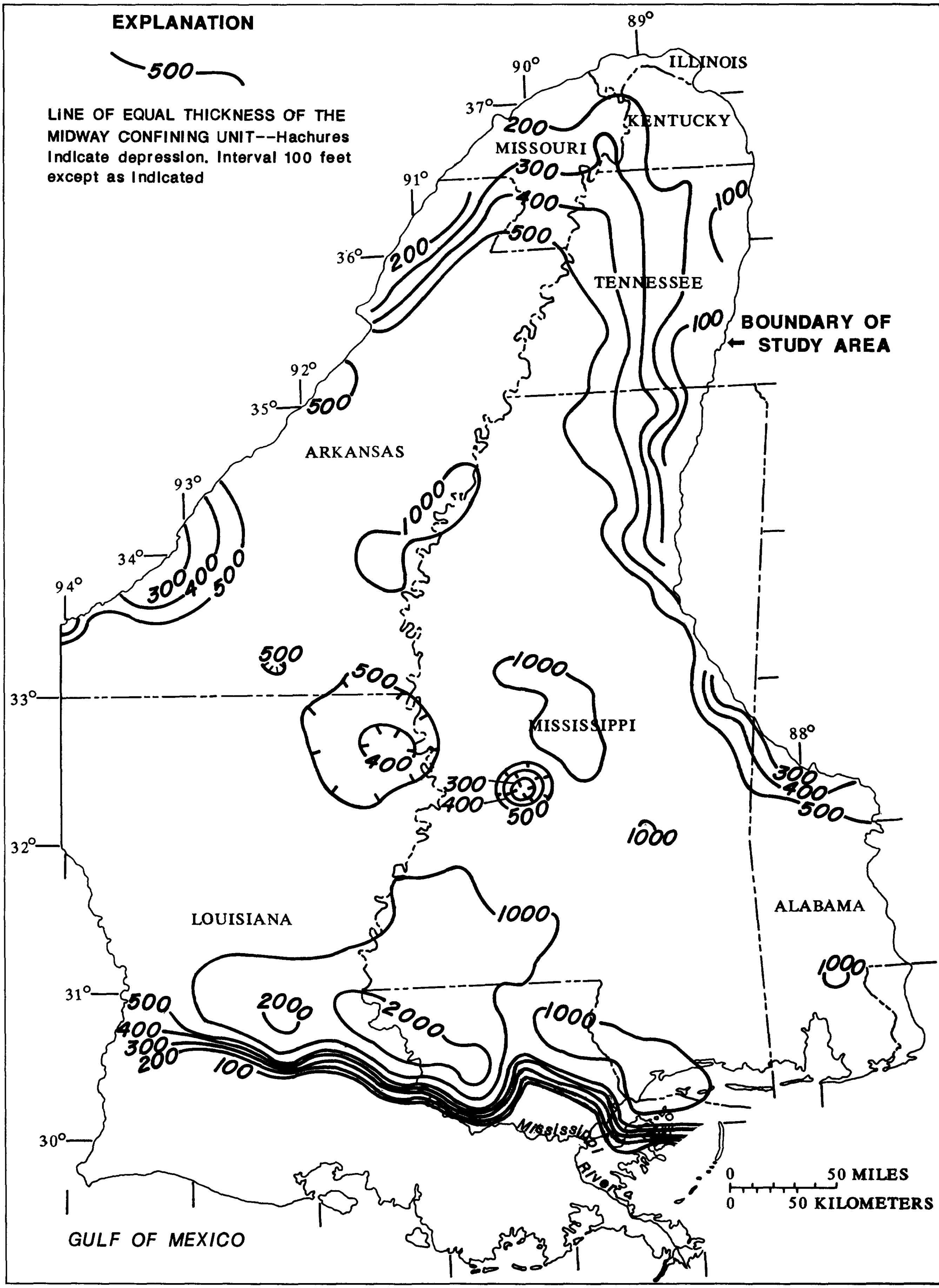

Figure 28.--Total clay thickness of Midway confining unit.

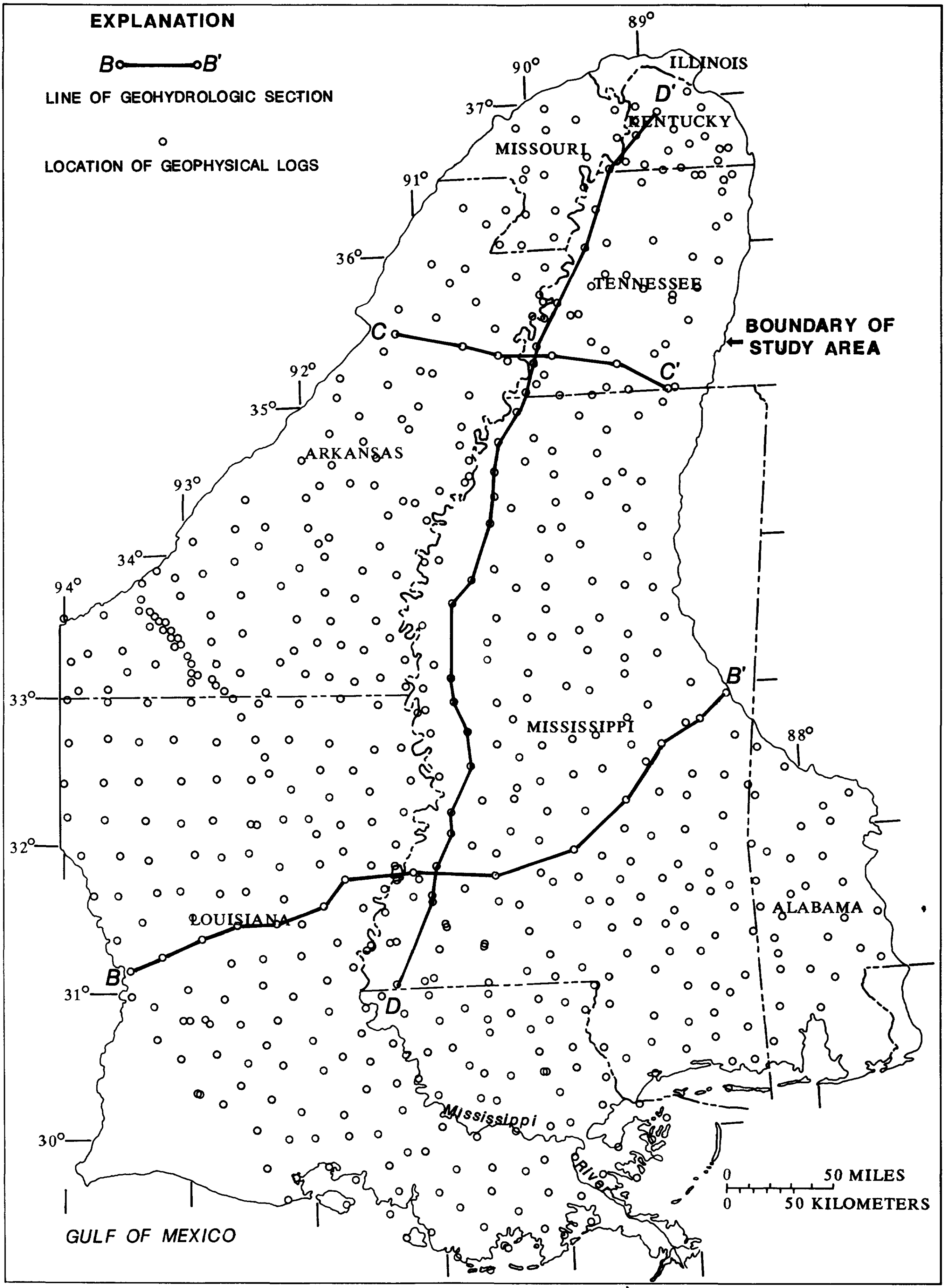

Figure 29.--Location of geophysical logs and geohydrologic sections.

 page 49 follows

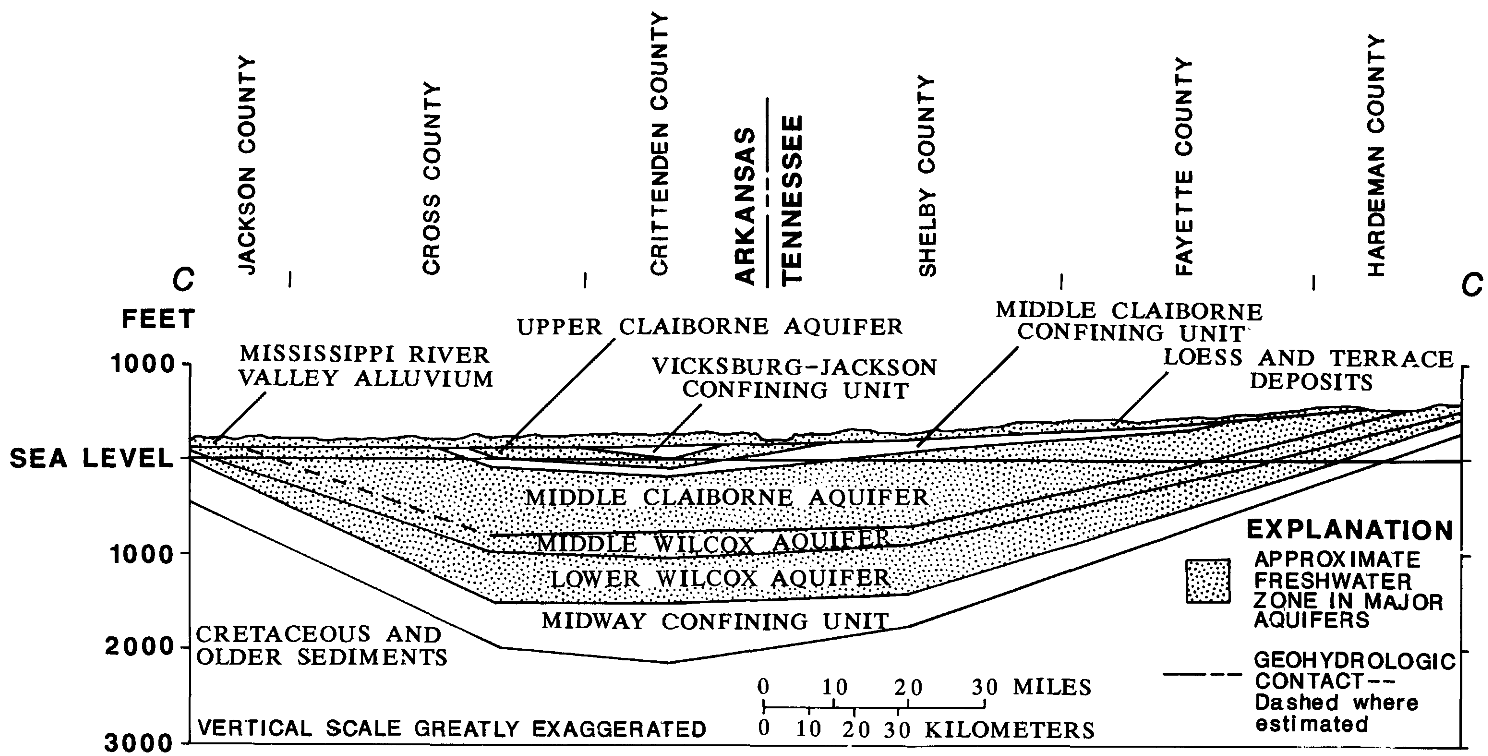

Figure 31.--Geohydrologic section from east Arkansas to west Tennessee.

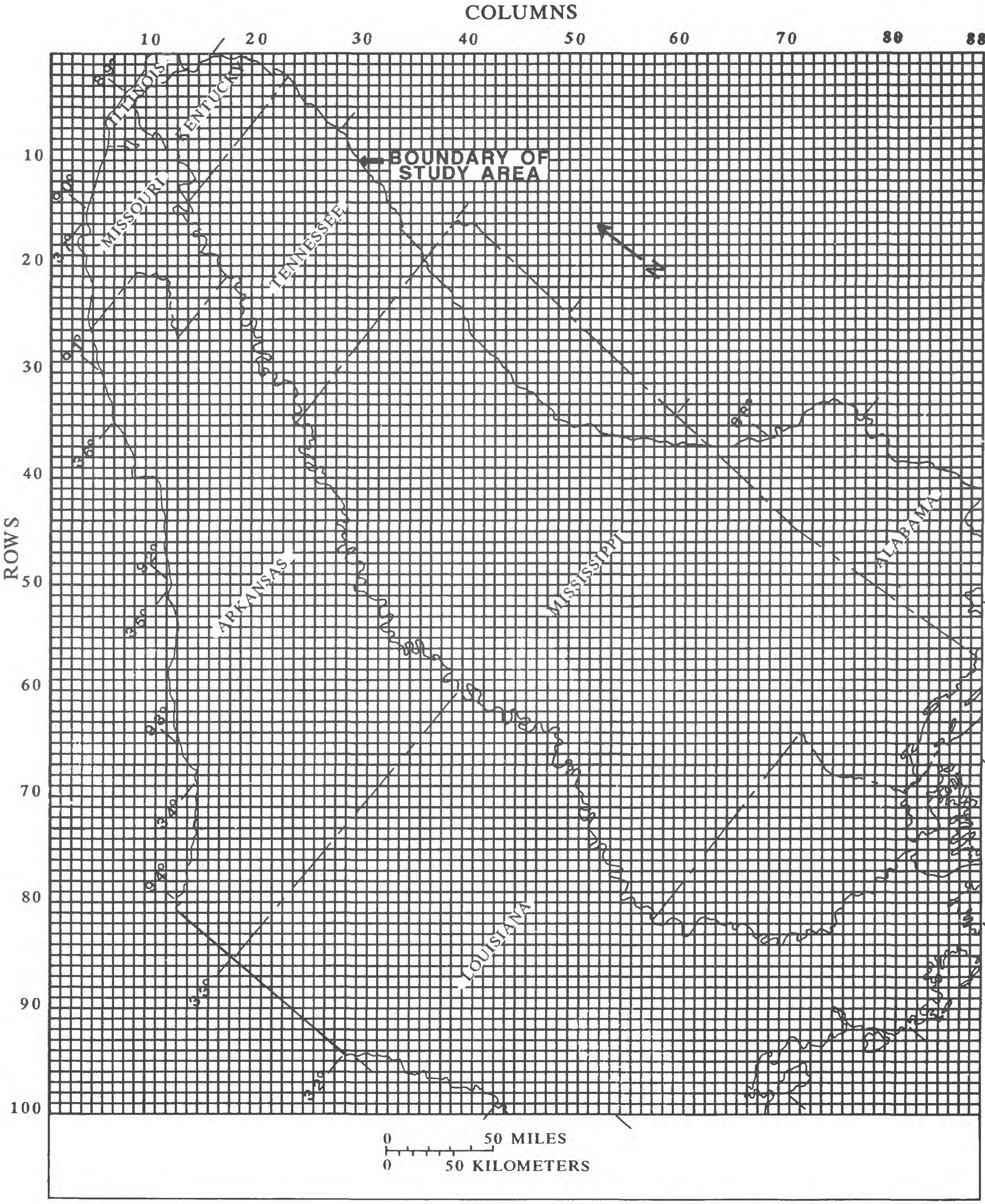

Figure 33.--Map showing model grid orientation in study area, 100 rows by 88 columns.

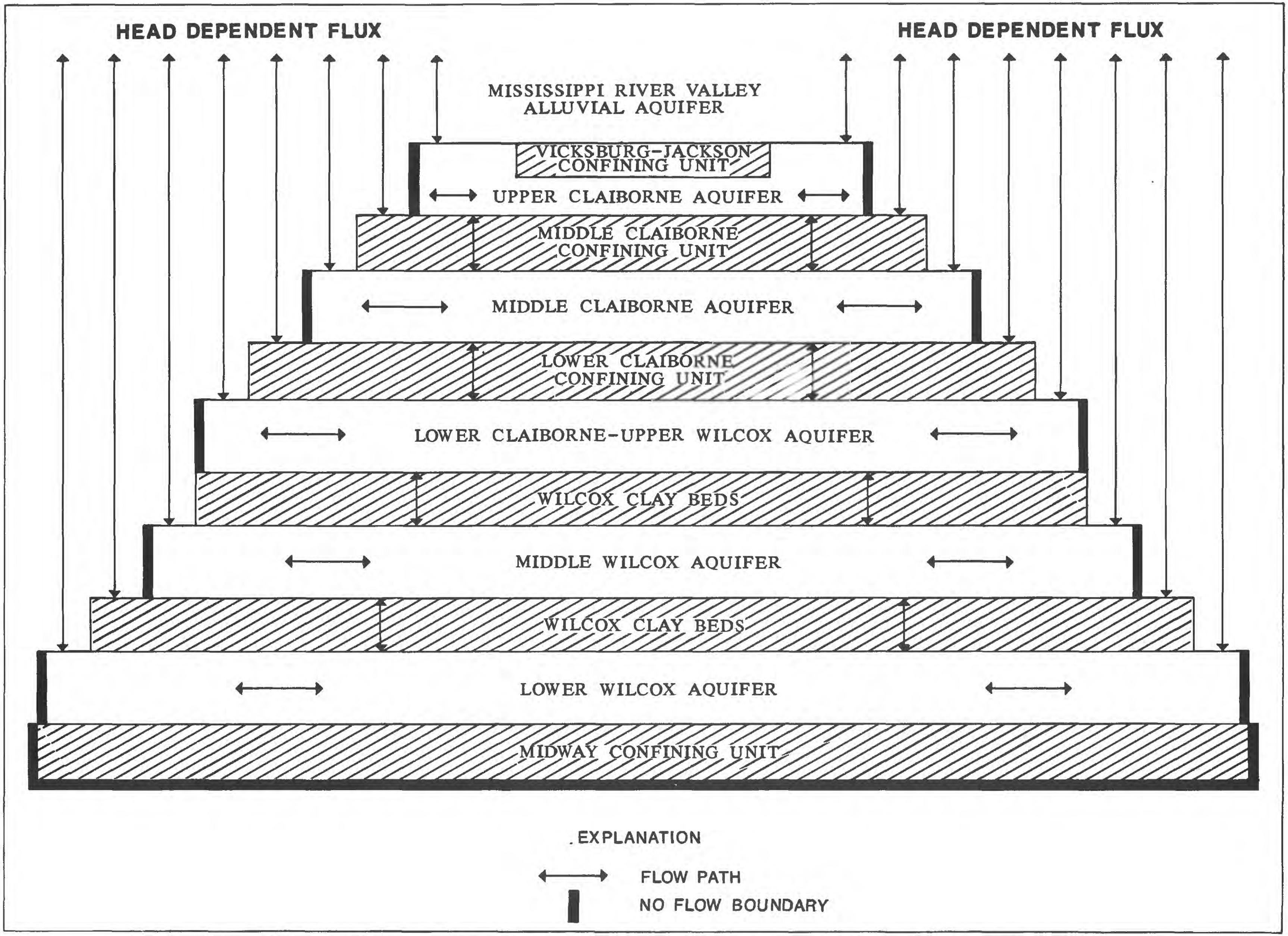

Figure 34.--Generalized west to east geohydrologic model section.

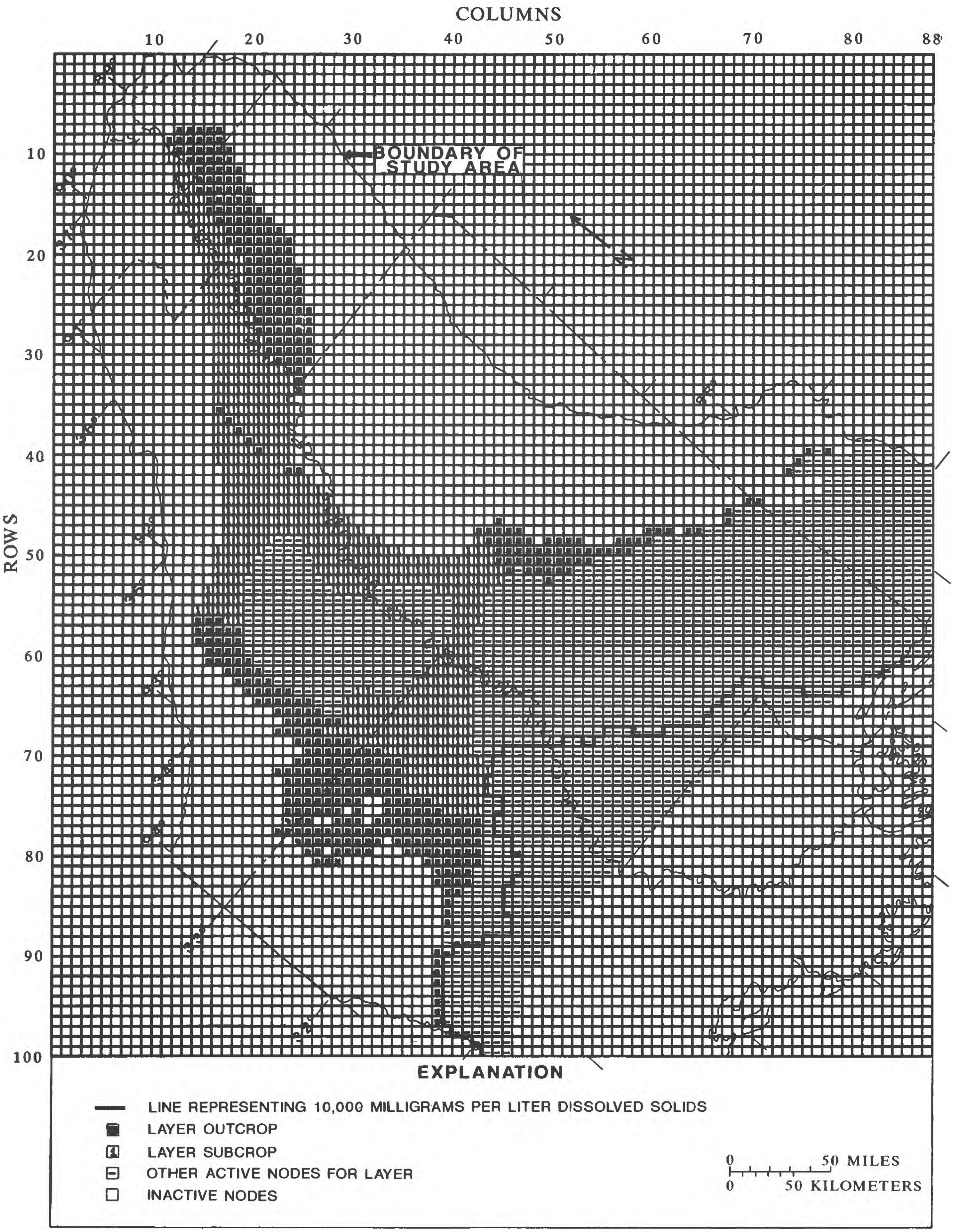

Figure 35.--Extent of model layer 1, upper Claiborne aquifer.

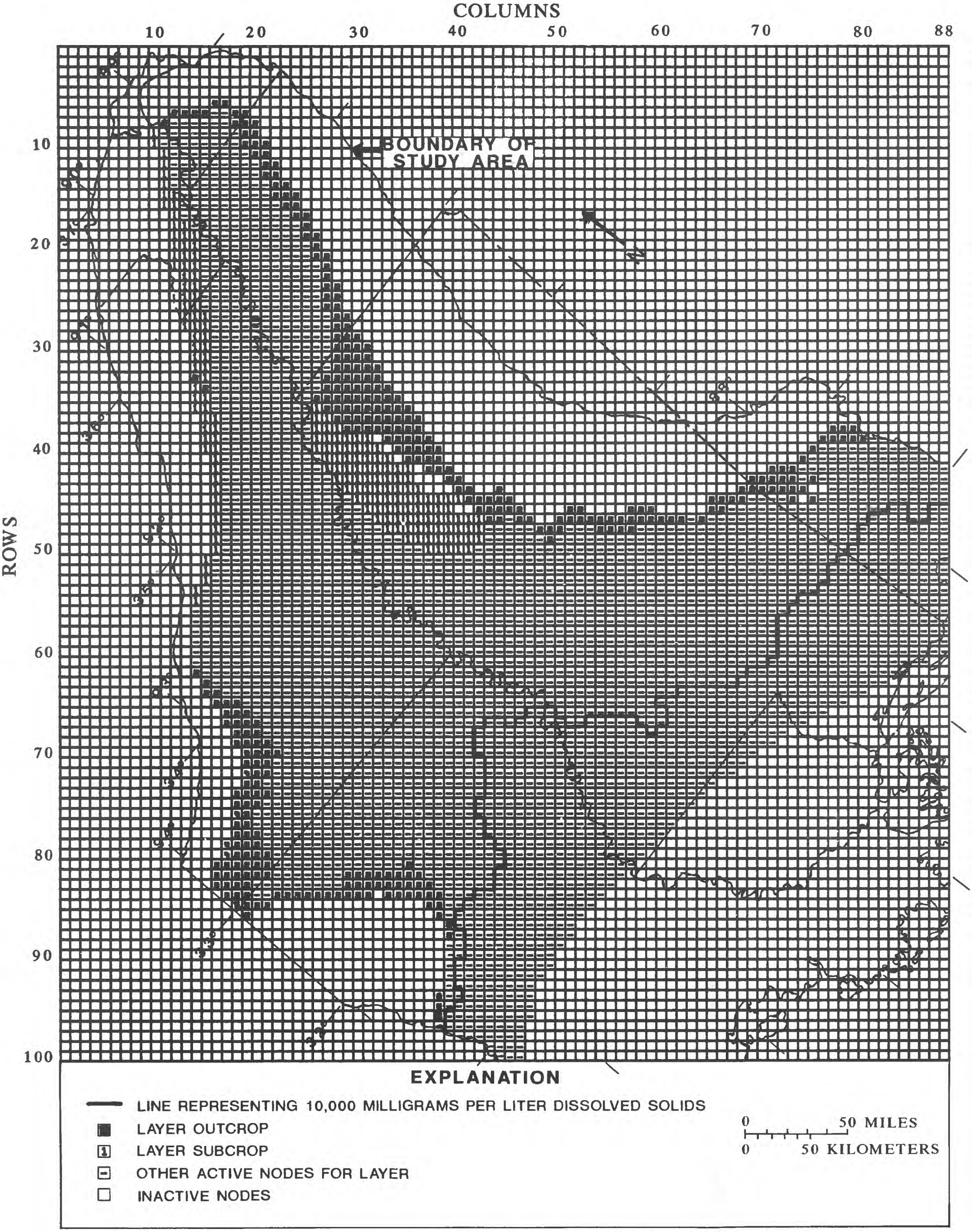

Figure 36.--Extent of model layer 2, middle Claiborne aquifer.

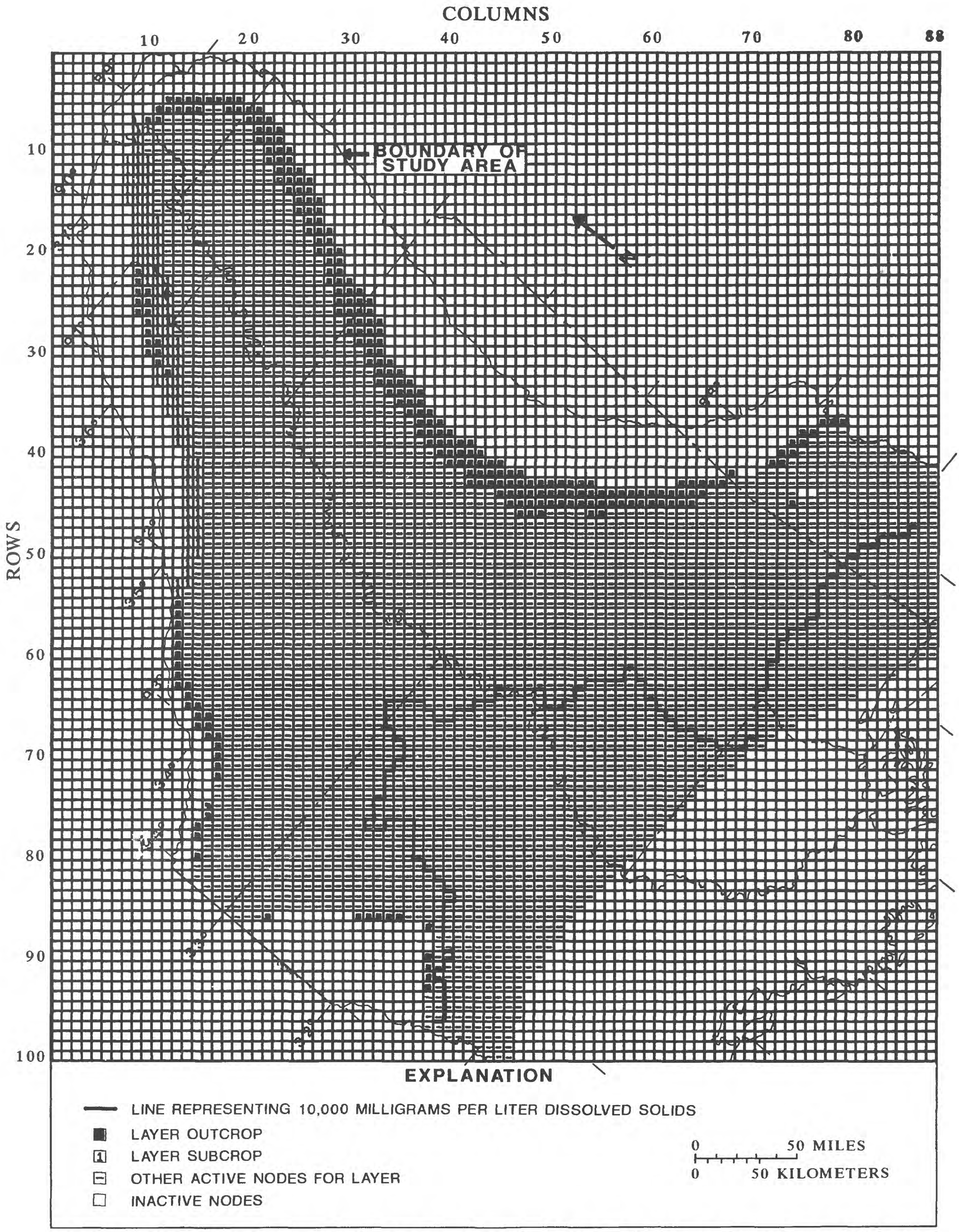

Figure 37.--Extent of model layer 3, lower Claiborne-upper Wilcox aquifer.

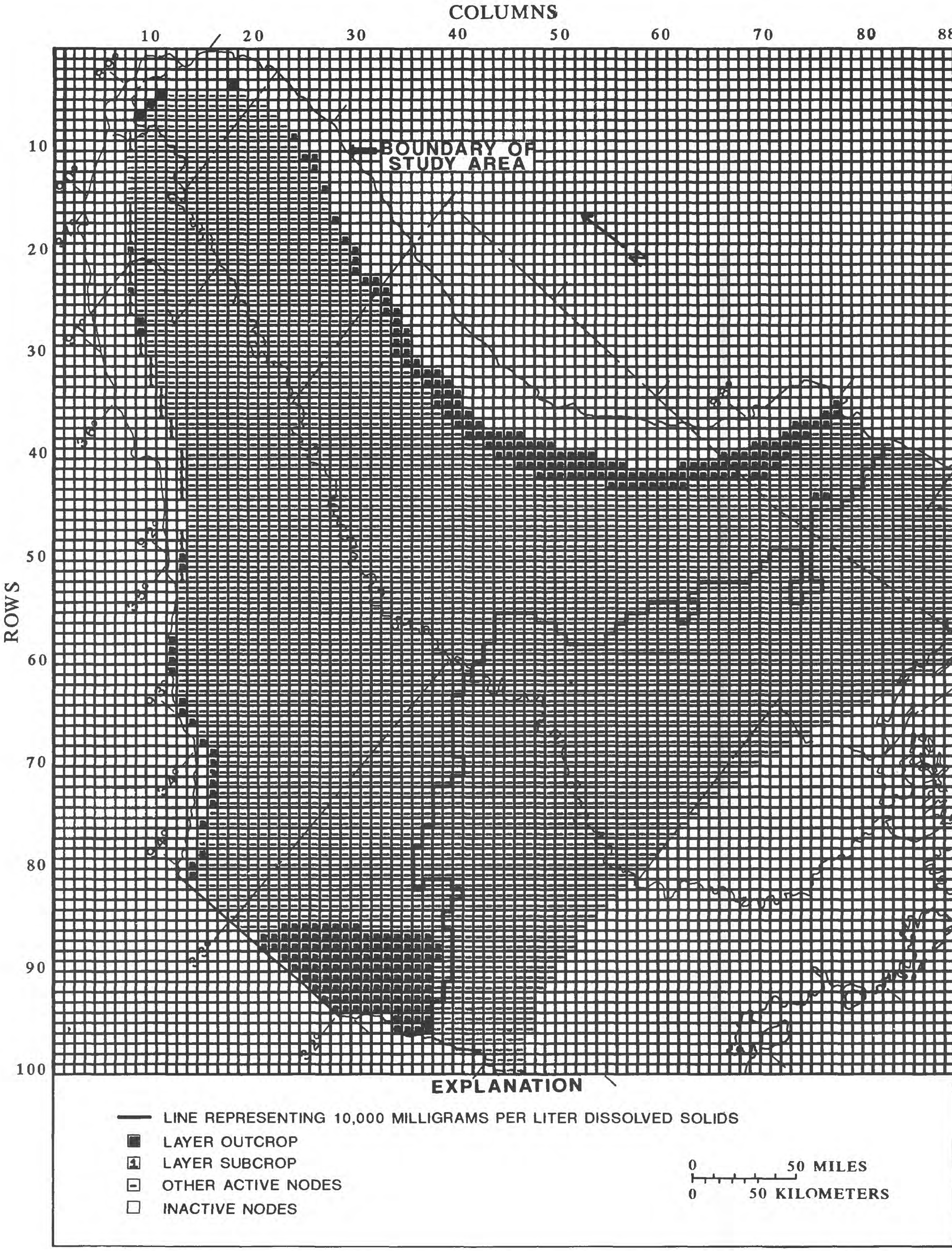

Figure 38.--Extent of model layer 4, middle Wilcox aquifer.

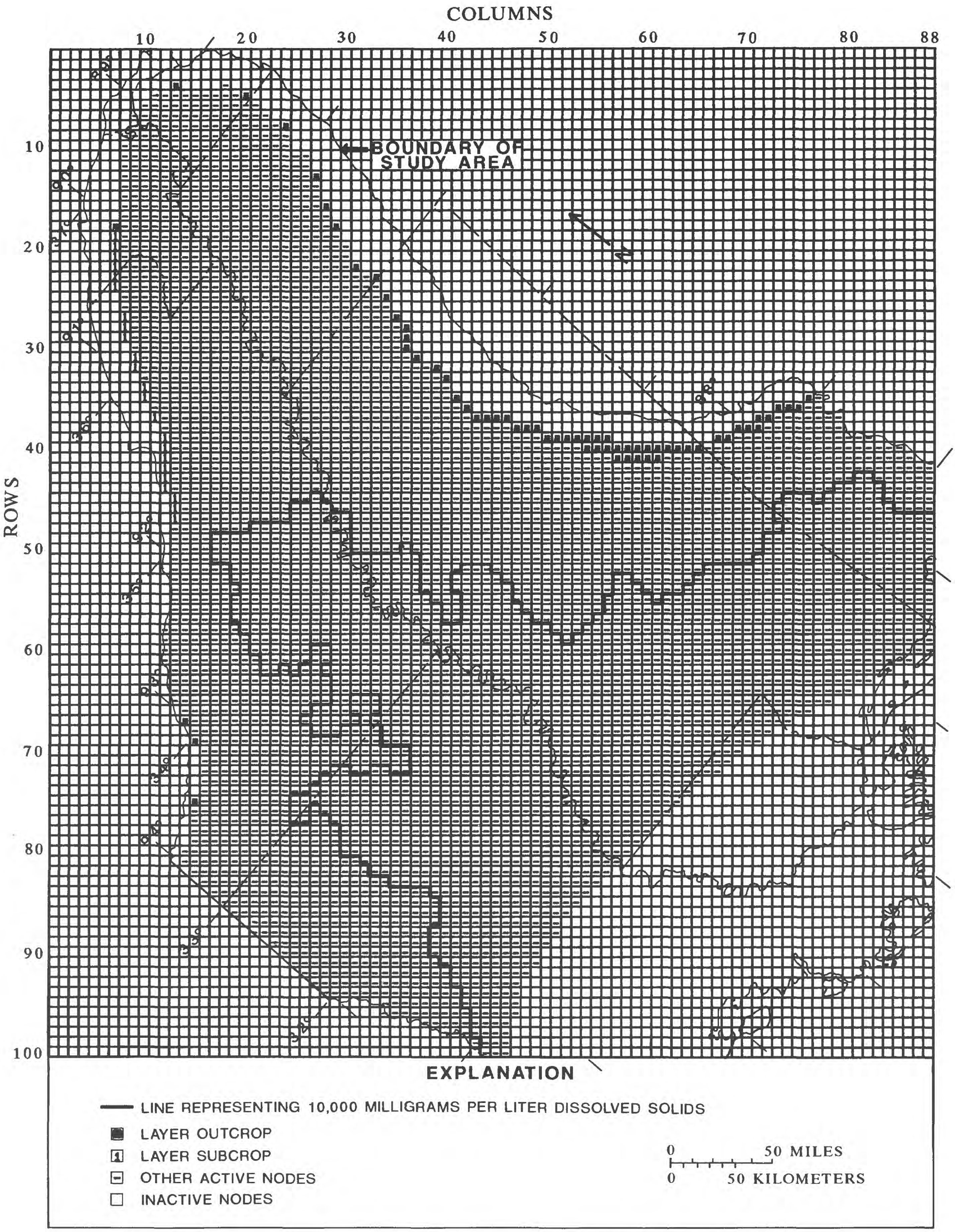

Figure 39.--Extent of model layer 5, lower Wilcox aquifer.

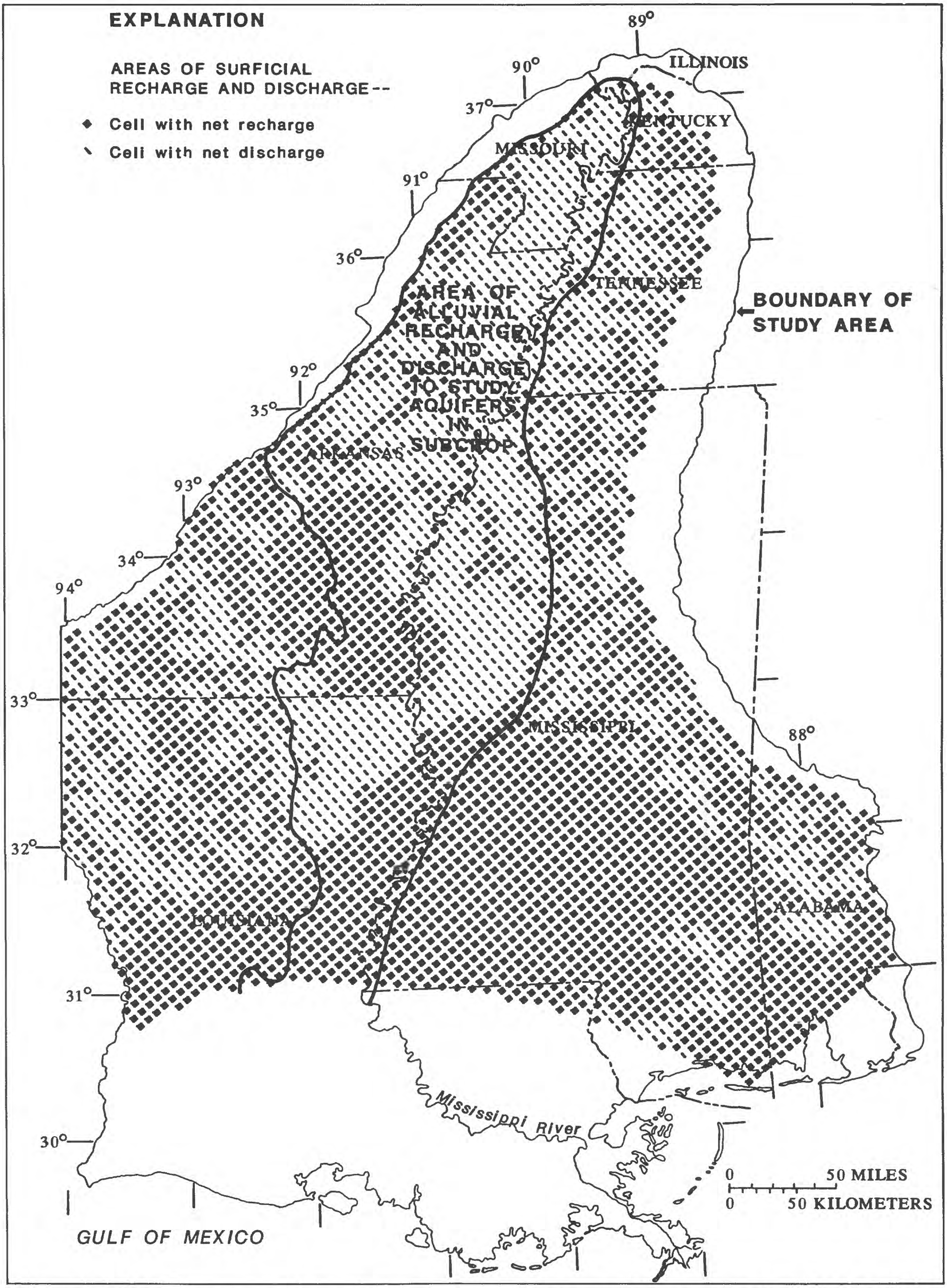

Figure 40.--Areas of recharge and discharge from model simulation using predevelopment conditions.

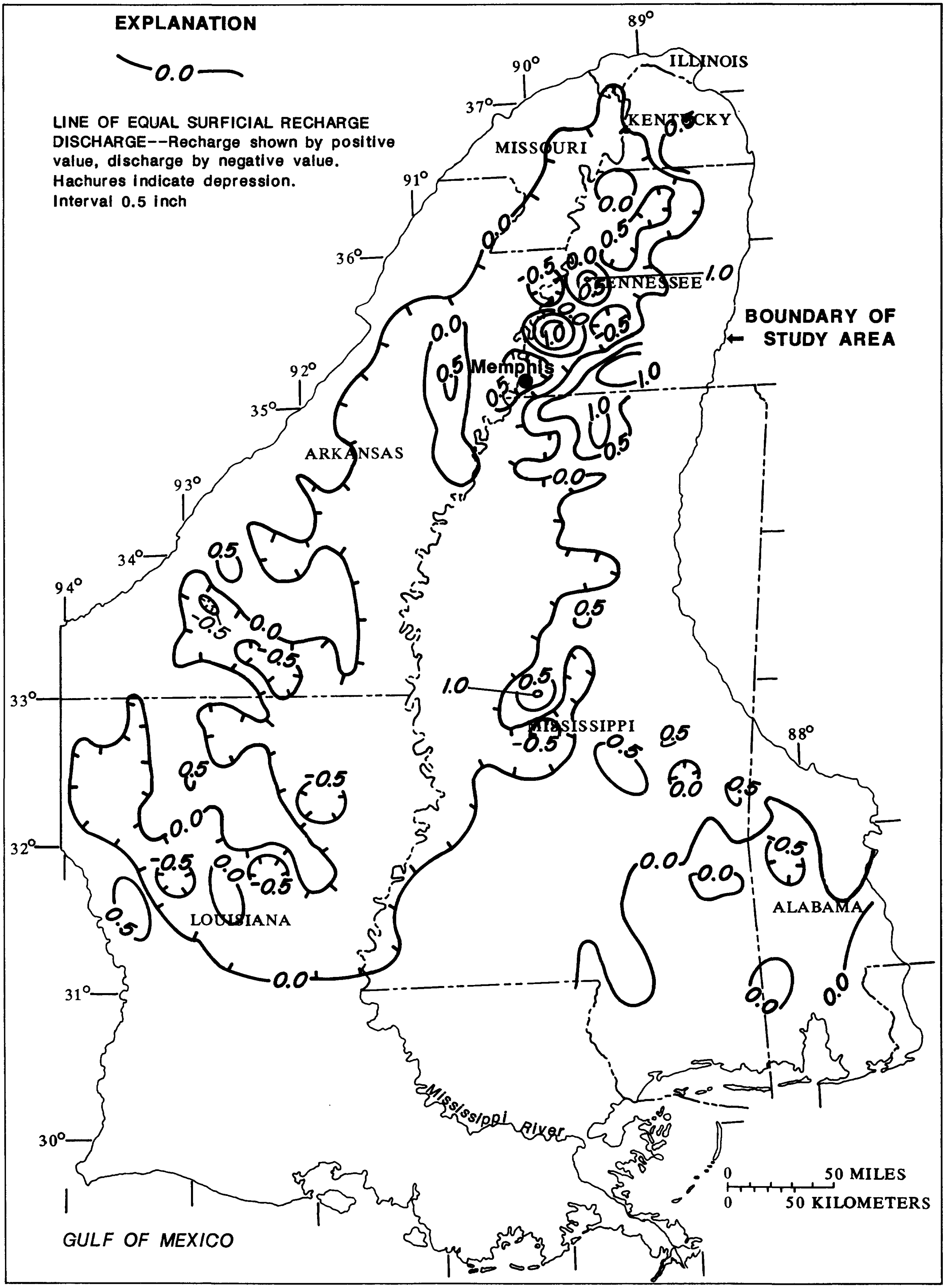

Figure 41.--Model simulated predevelopment recharge to and discharge from the Mississippi embayment aquifer system.

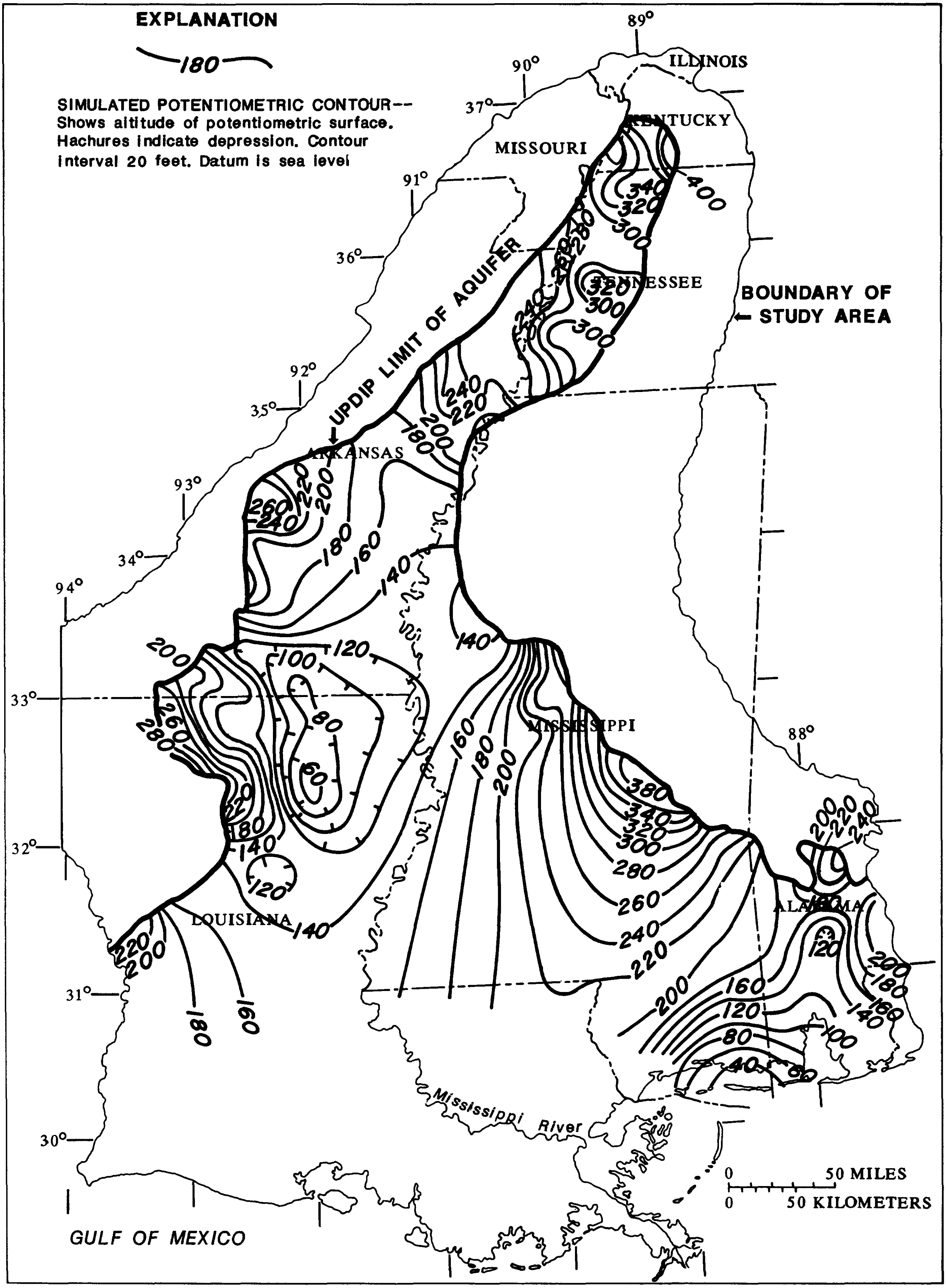

Figure 42.--Potentiometric surface of upper Claiborne aquifer using model-generated heads representing predevelopment conditions.

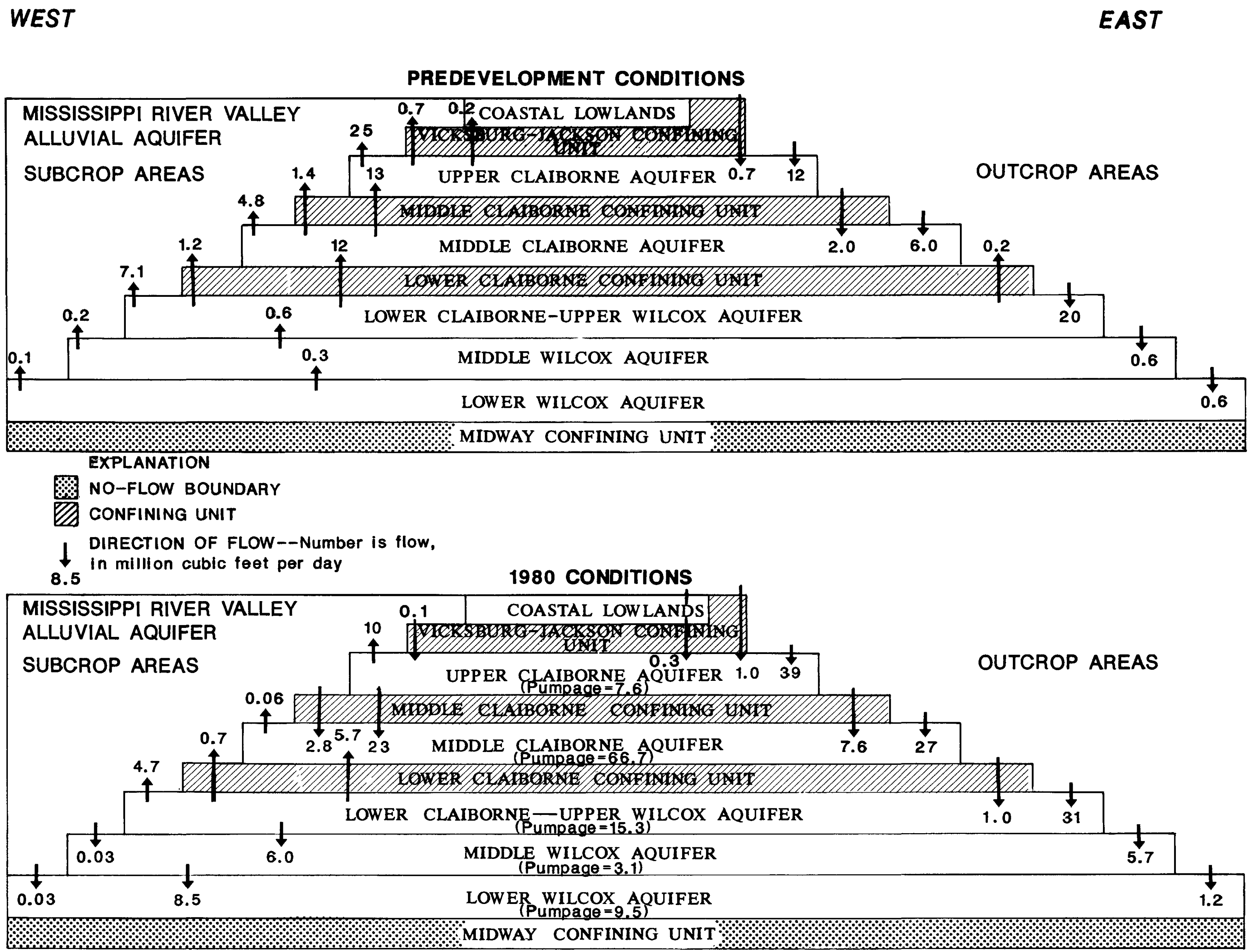

Figure 43.--Summary of model simulated flow assuming predevelopment and 1980 conditions.

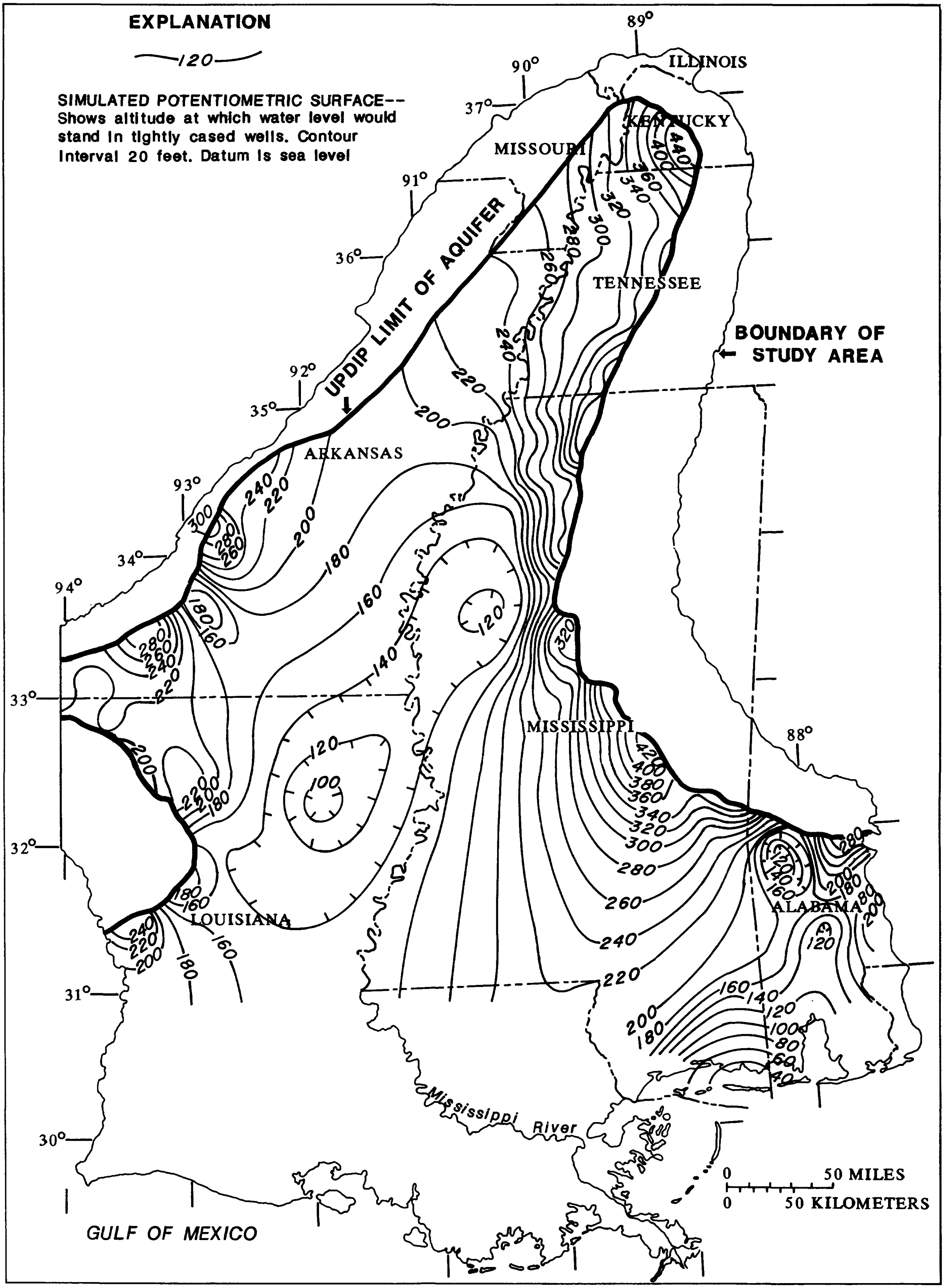

Figure 44.--Potentiometric surface of middle Claiborne aquifer using model-generated heads representing predevelopment conditions.

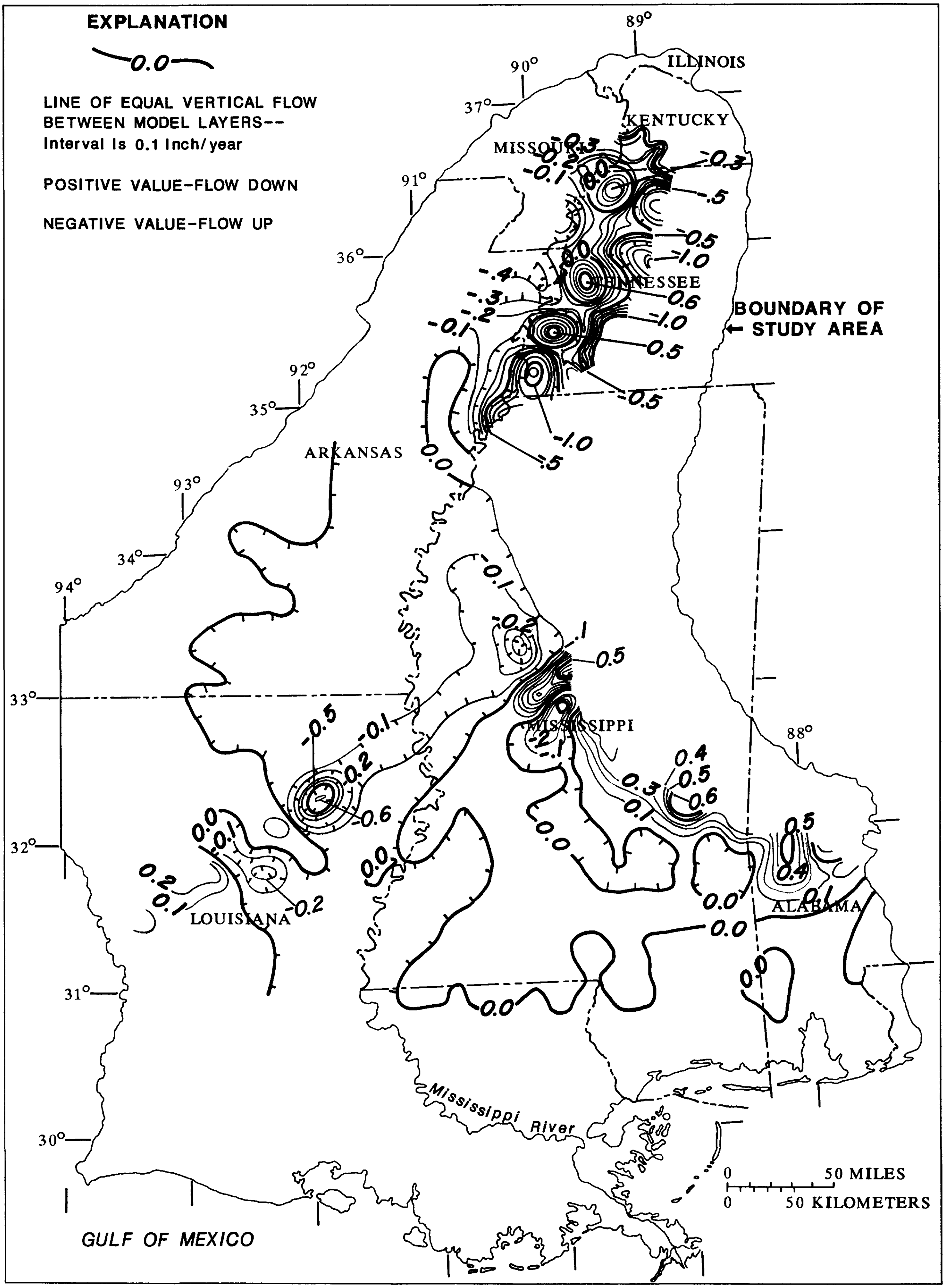

Figure 45.--Model simulated predevelopment vertical flow between upper Claiborne and middle Claiborne aquifers.

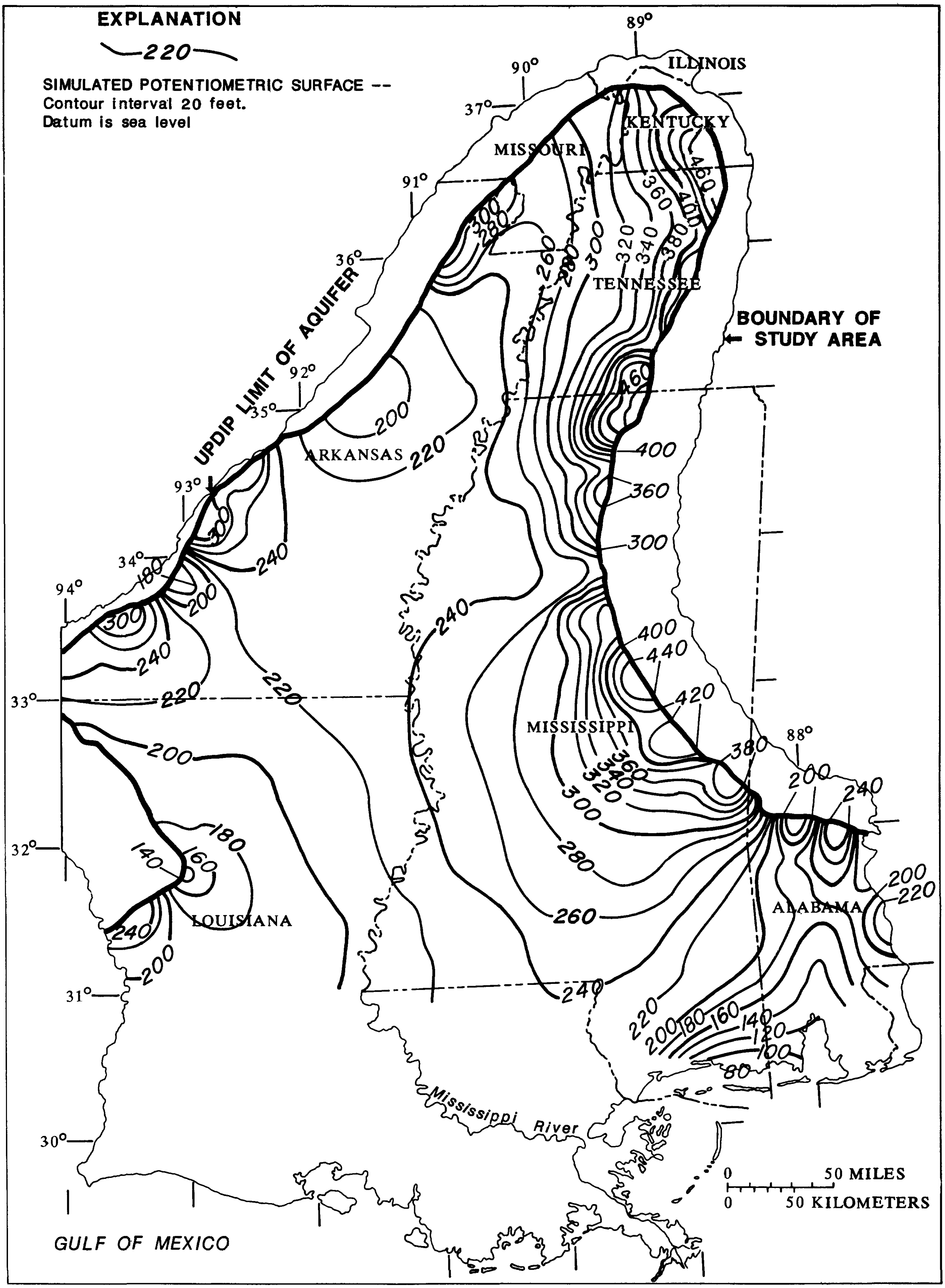

Figure 46.--Potentiometric surface of lower Claiborne-upper Wilcox aquifer using model-generated heads representing predevelopment conditions.

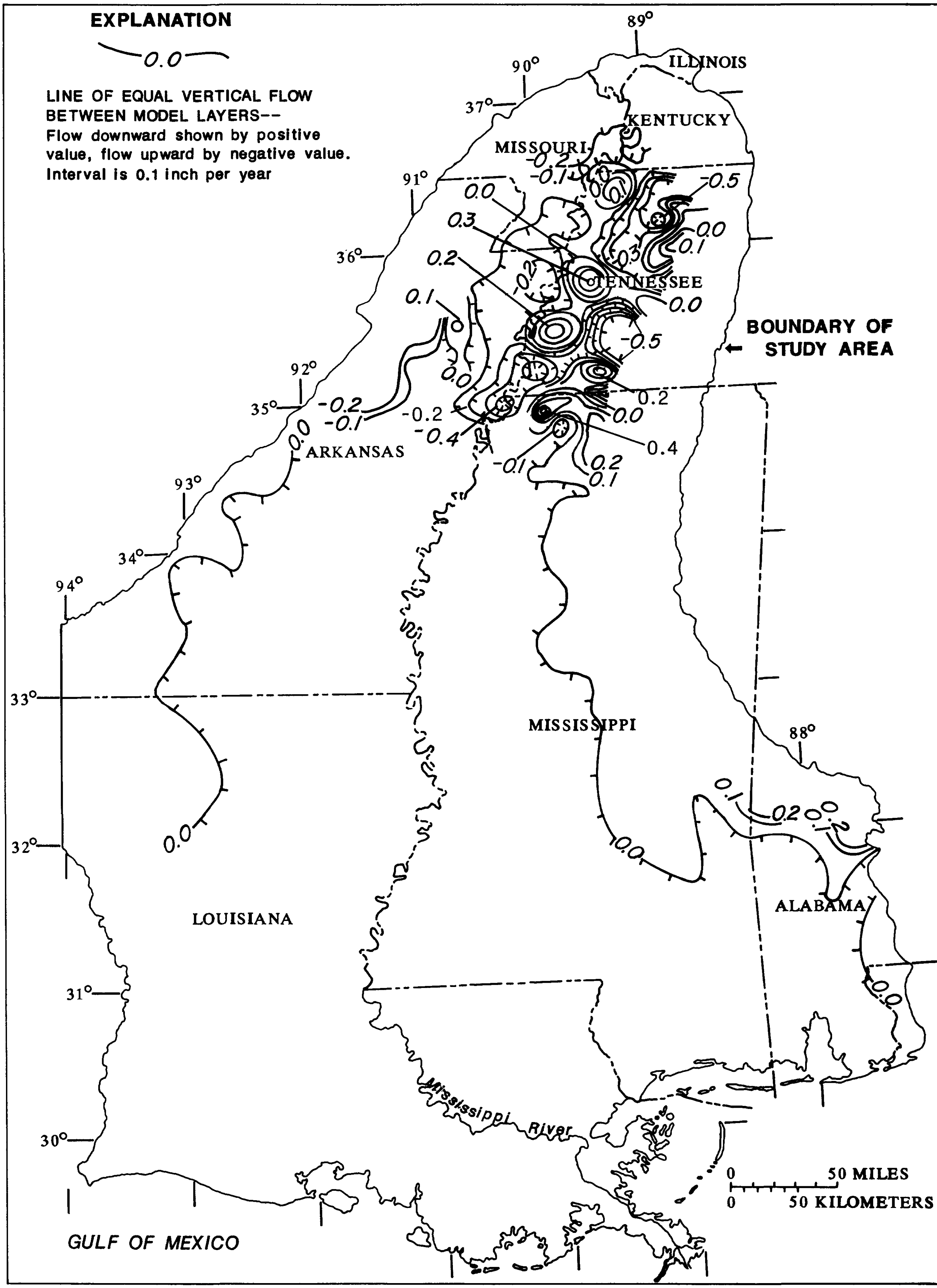

Figure 47.--Model simulated predevelopment vertical flow between middle Claiborne and lower Claiborne-upper Wilcox aquifers.

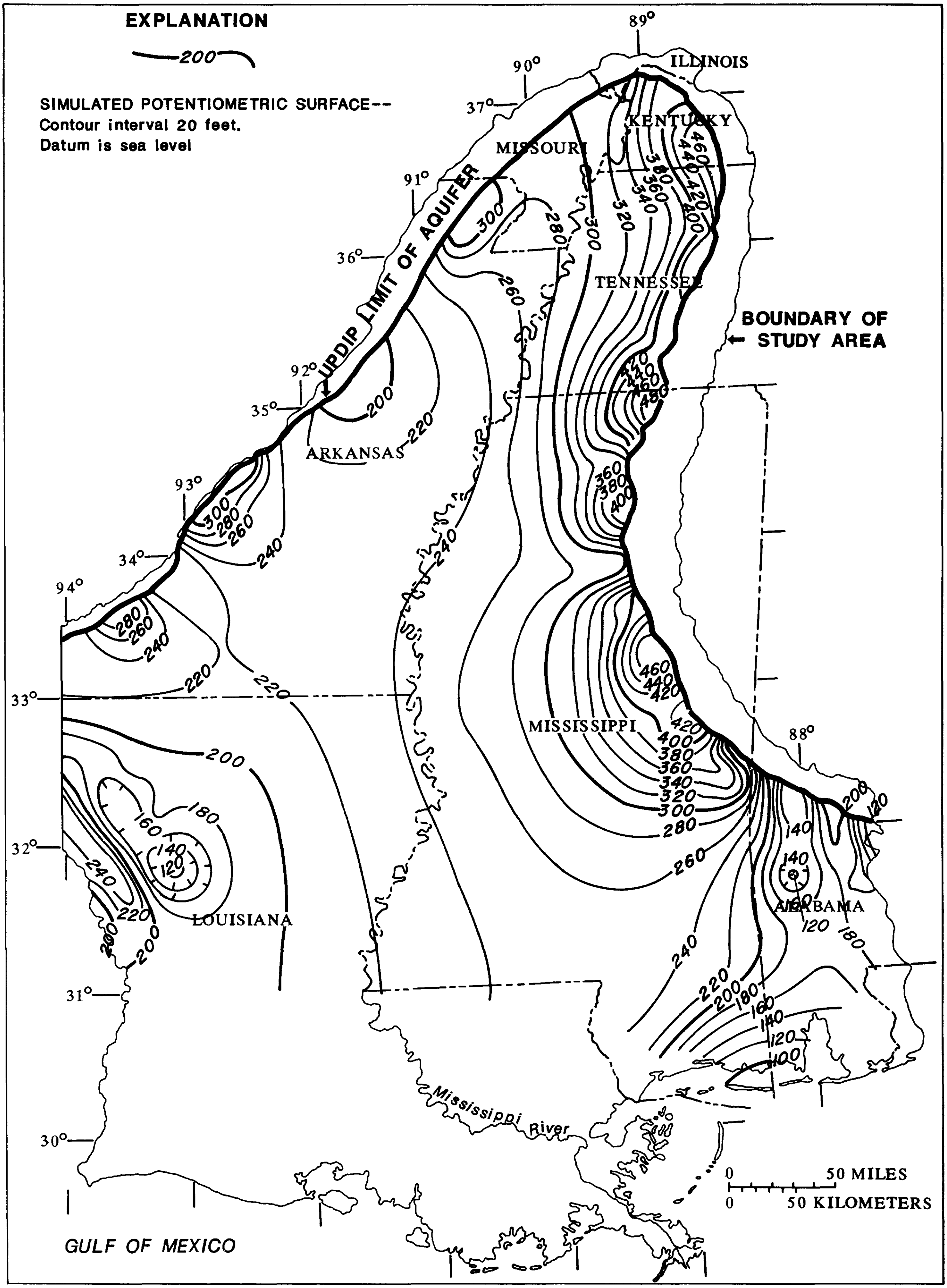

Figure 48.--Potentiometric surface of middle Wilcox aquifer using model-generated heads representing predevelopment conditions.

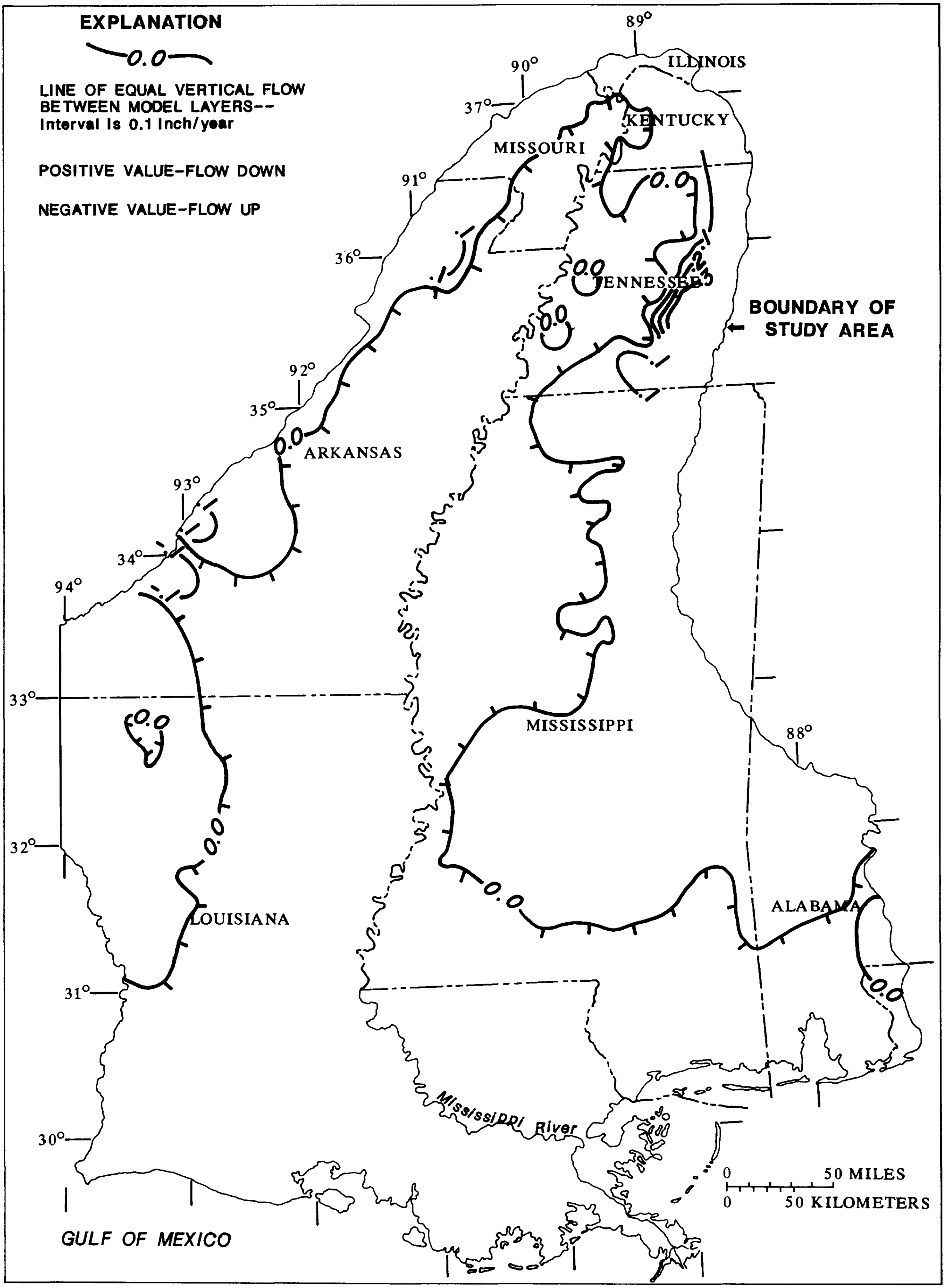

Figure 49.--Model simulated predevelopment vertical flow between lower Claiborne-upper Wilcox and middle Wilcox aquifers.

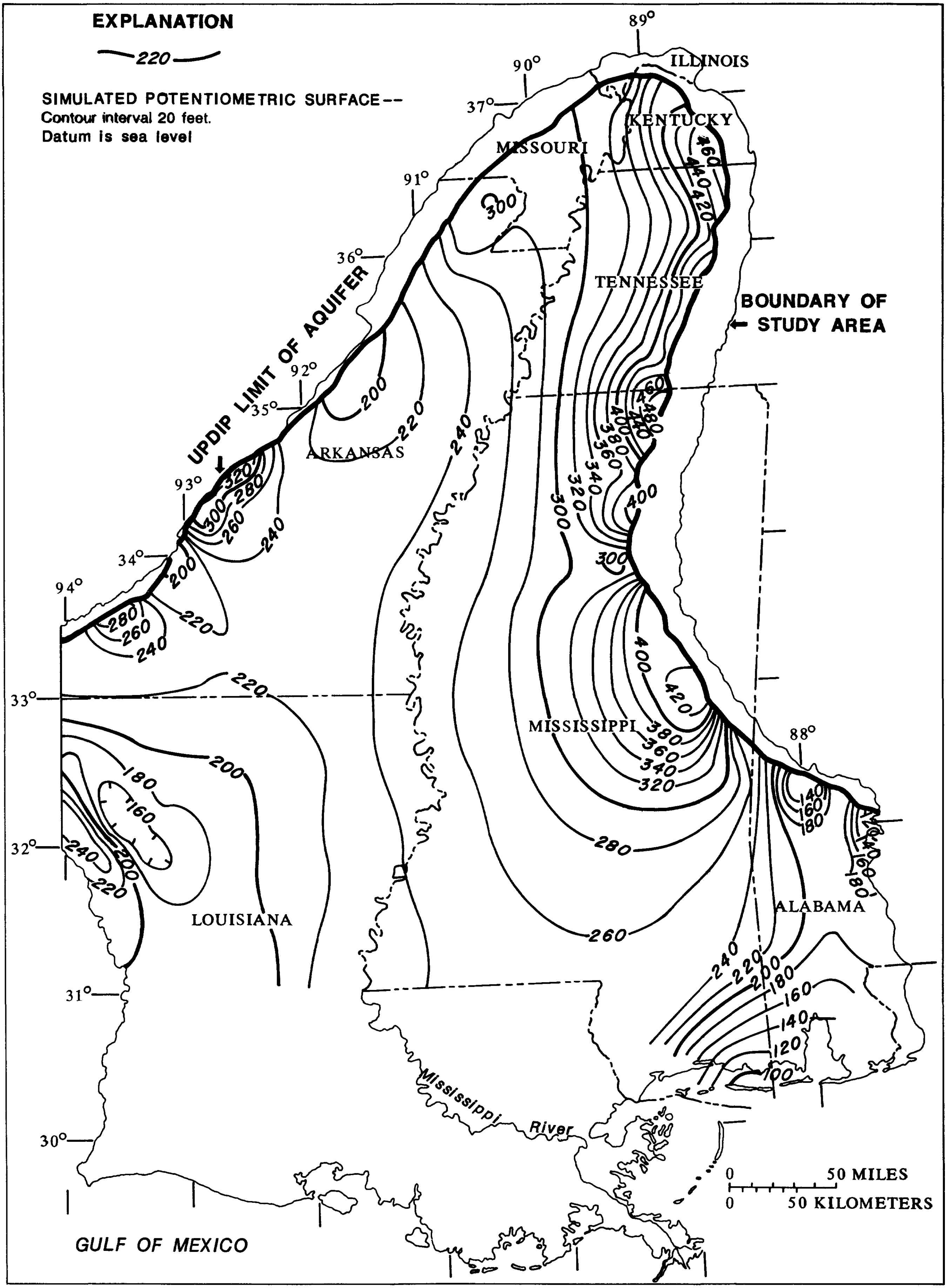

Figure 50.--Potentiometric surface of lower Wilcox aquifer using model-generated heads representing predevelopment conditions.

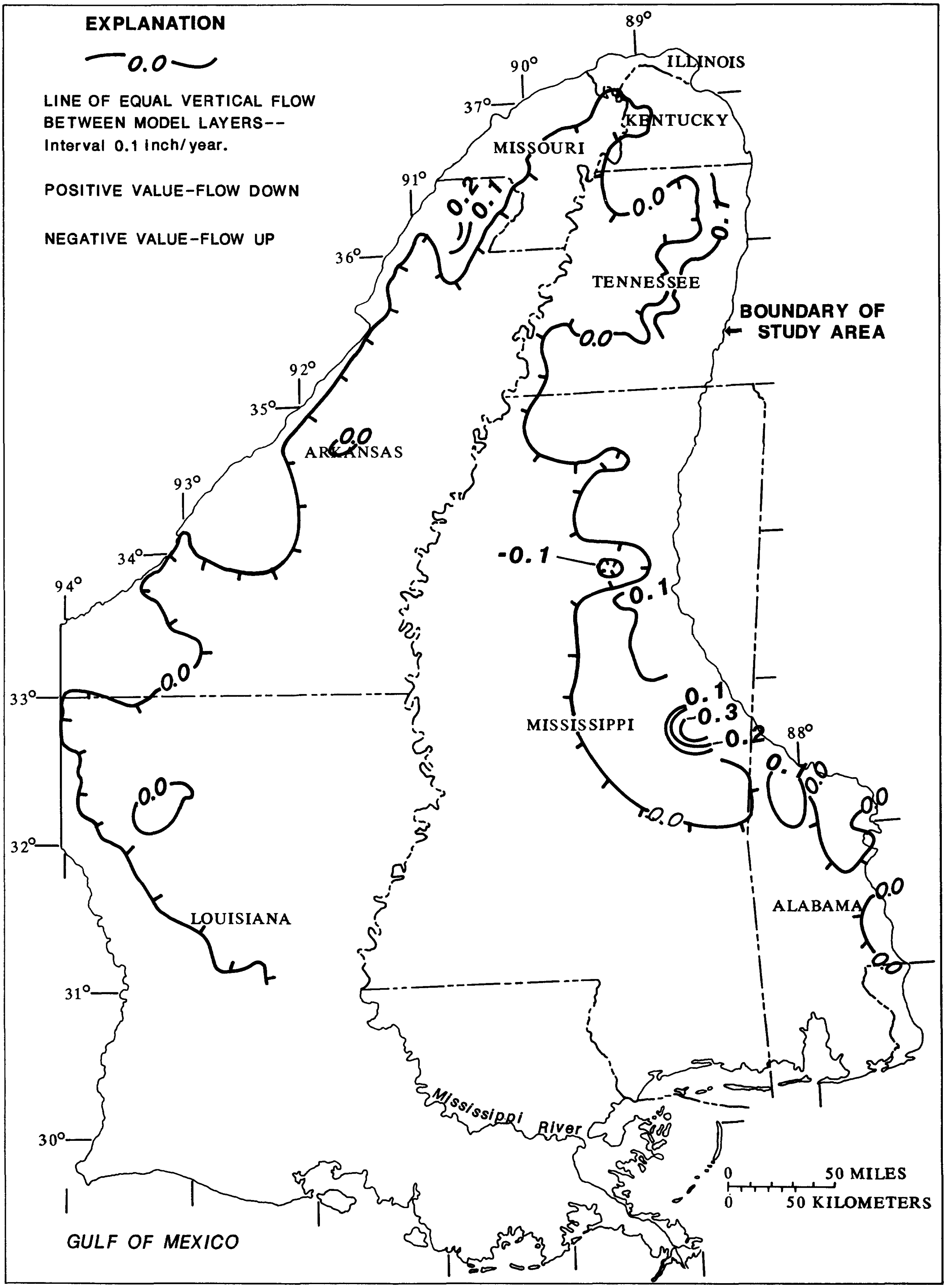

Figure 51.--Model simulated predevelopment vertical flow between middle Wilcox and lower Wilcox aquifers.

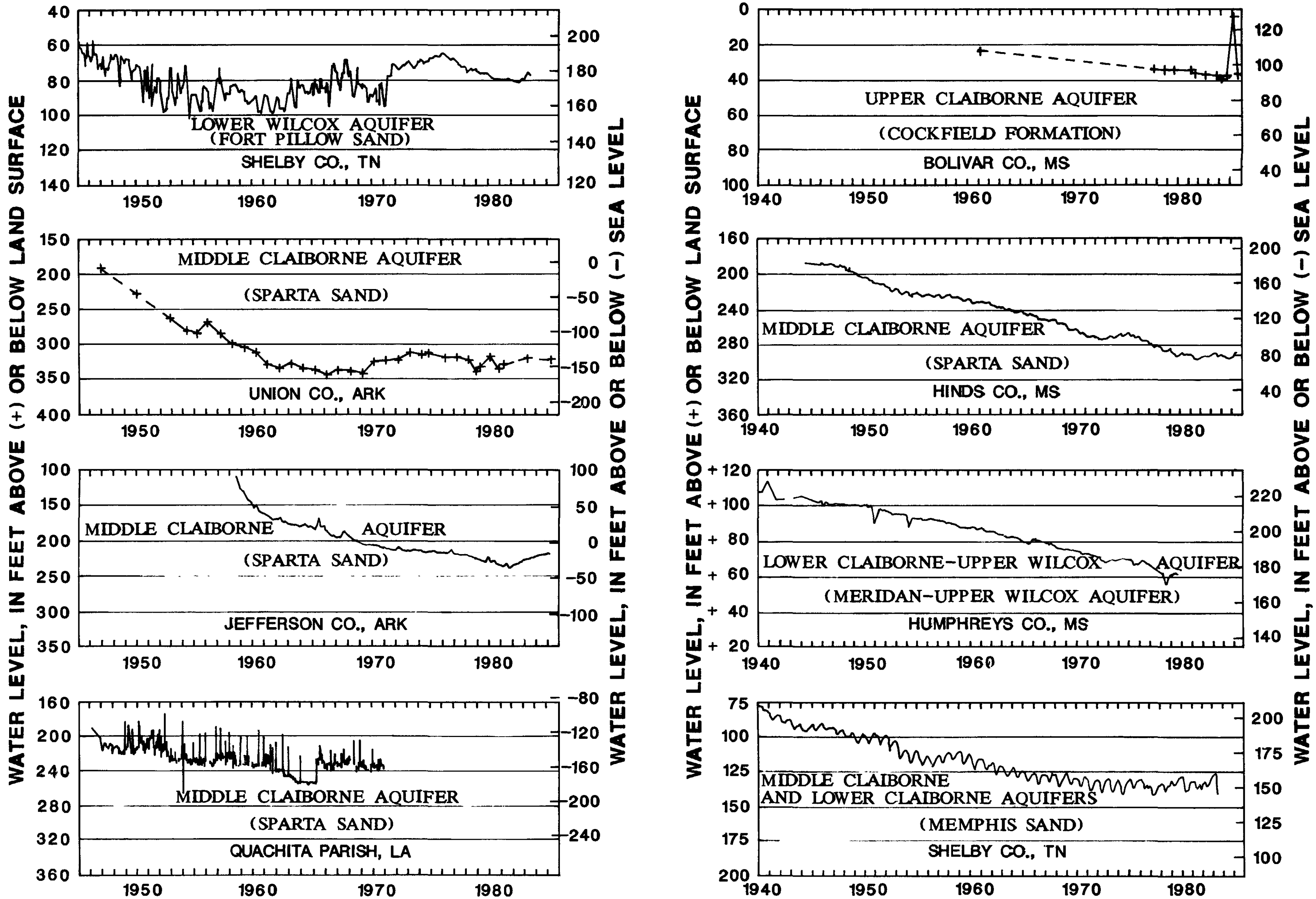

Figure 52.--Observation well hydrographs in areas of significant pumpage in the Mississippi embayment aquifer system.

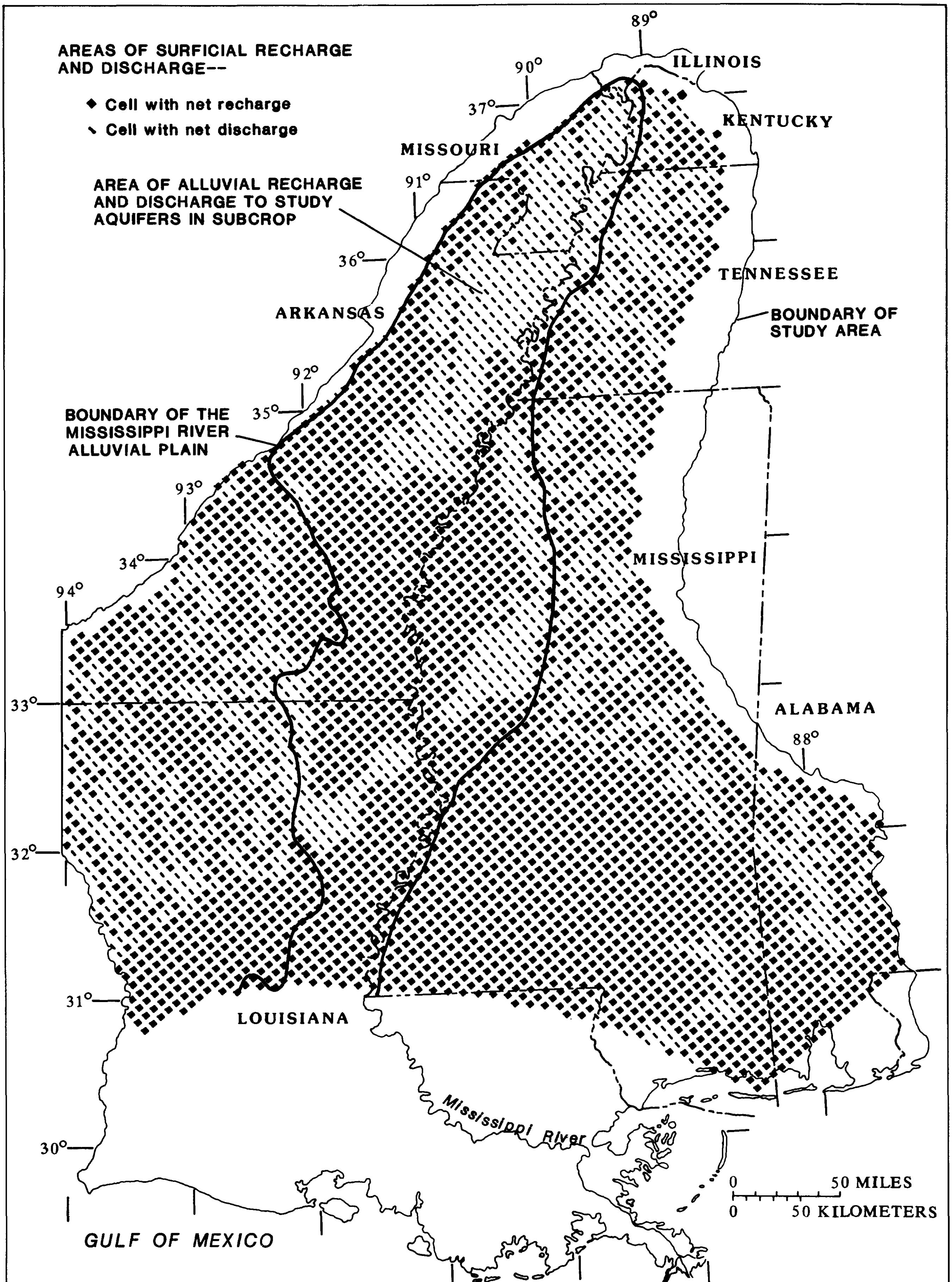

Figure 53.--Areas of surficial recharge and discharge from model simulation using 1980 pumpage.

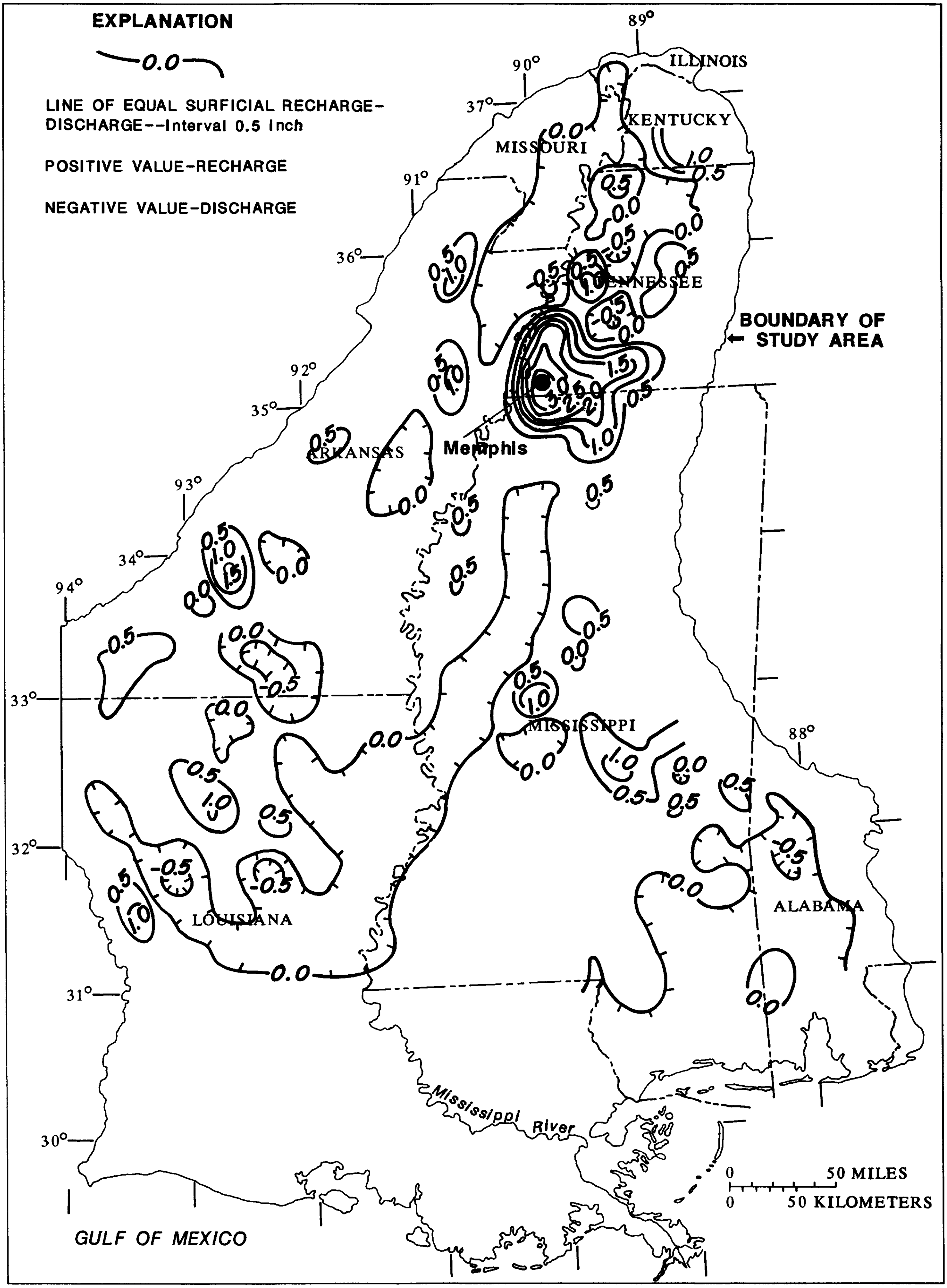

Figure 54.--Model simulated 1980 surficial recharge to and discharge from the Mississippi embayment aquifer system.

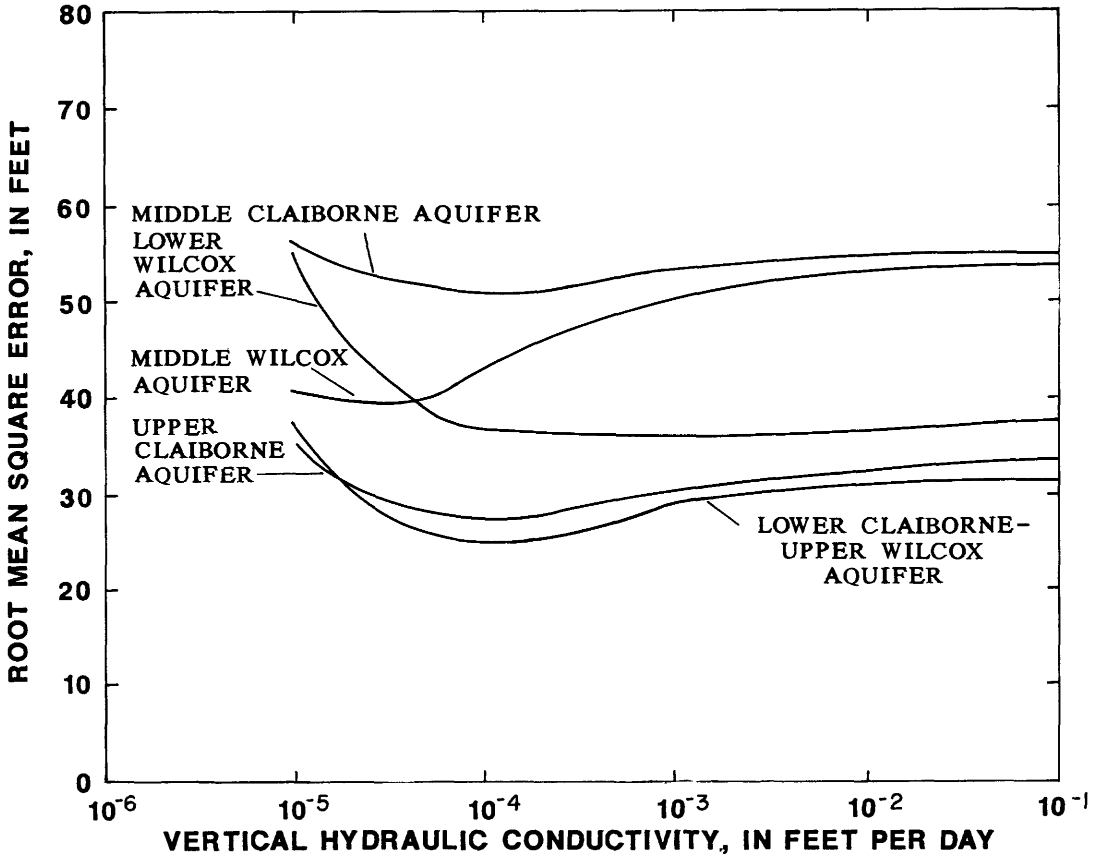

Figure 55.--Model sensitivity to vertical hydraulic conductivity in aquifer outcrop.

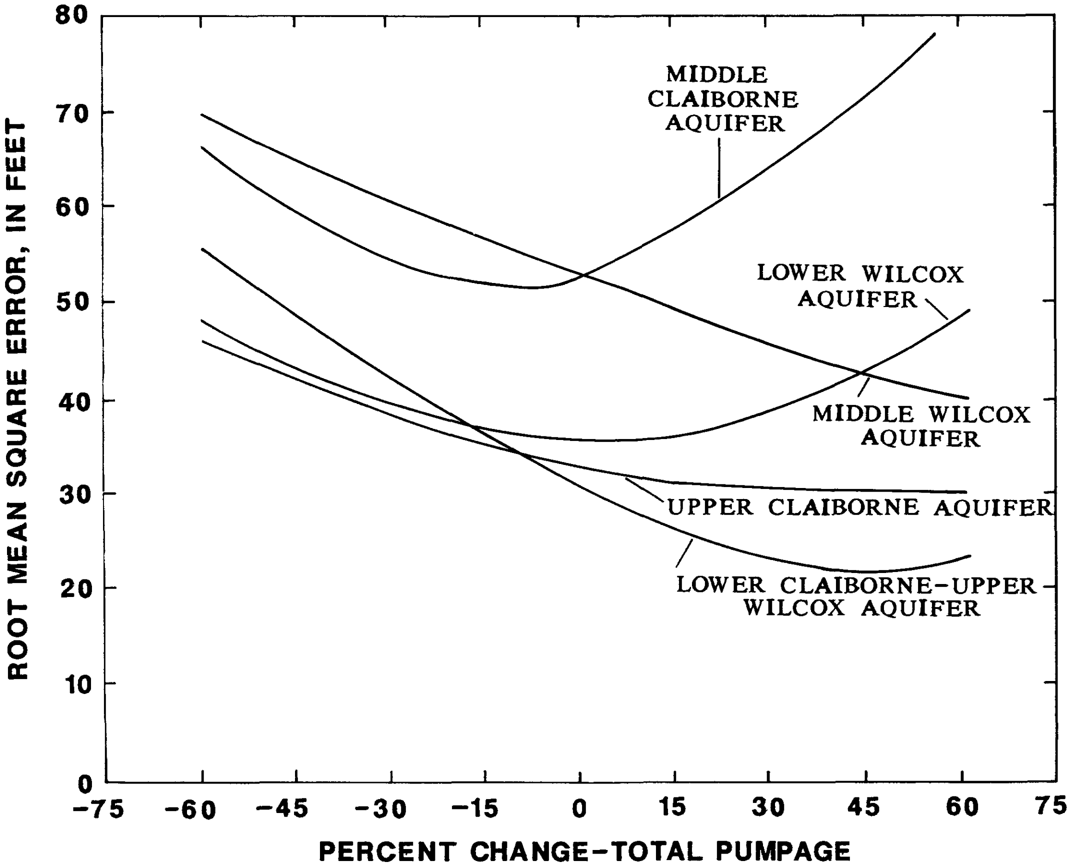

Figure 56.--Model sensitivity to pumpage.

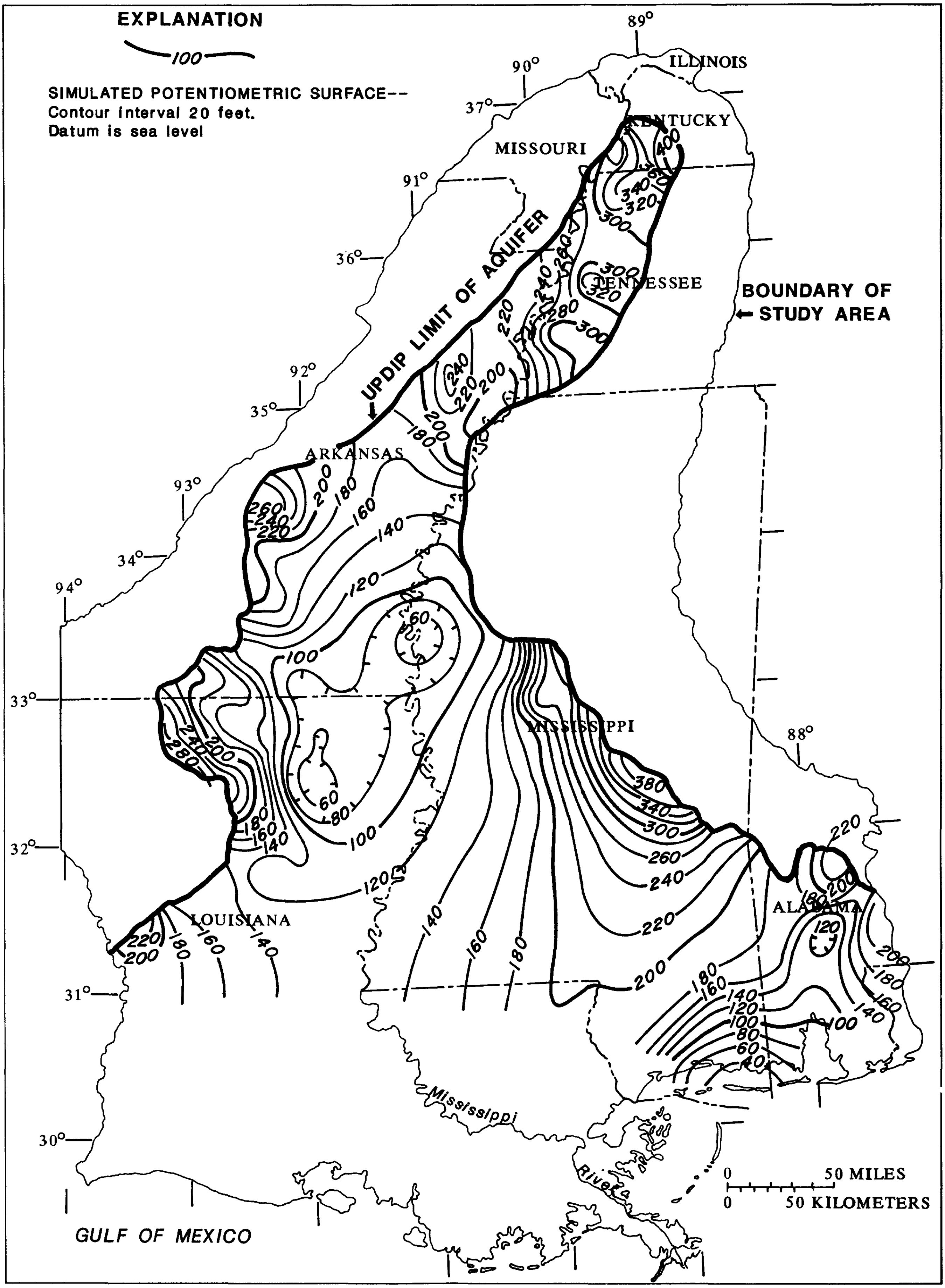

Figure 57.--Potentiometric surface of upper Claiborne aquifer using model-generated heads representing 1980 pumpage.

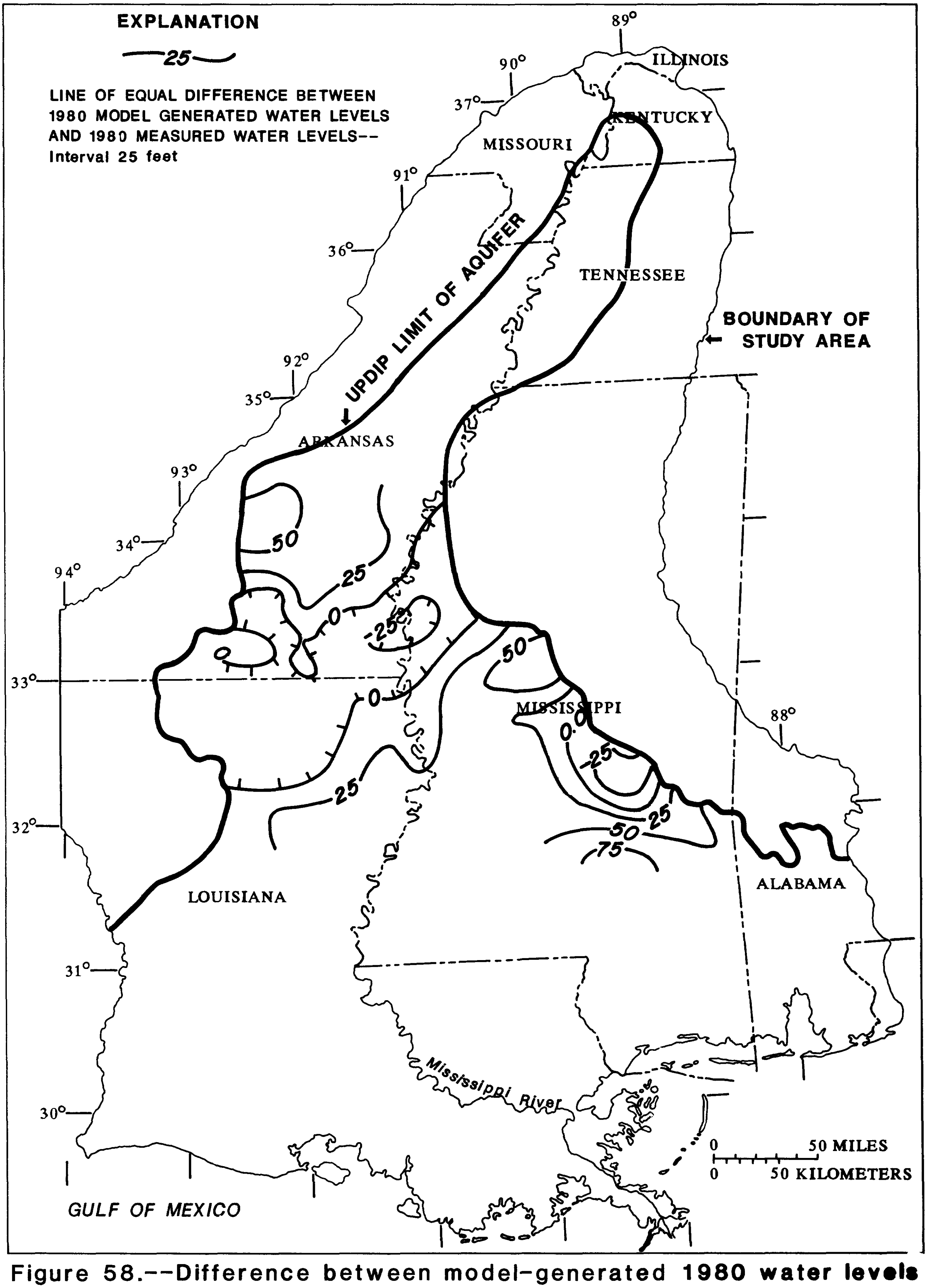

Figure 58.--Difference between model-generated 1980 water levels and measured 1980 water levels in upper Claiborne aquifer.

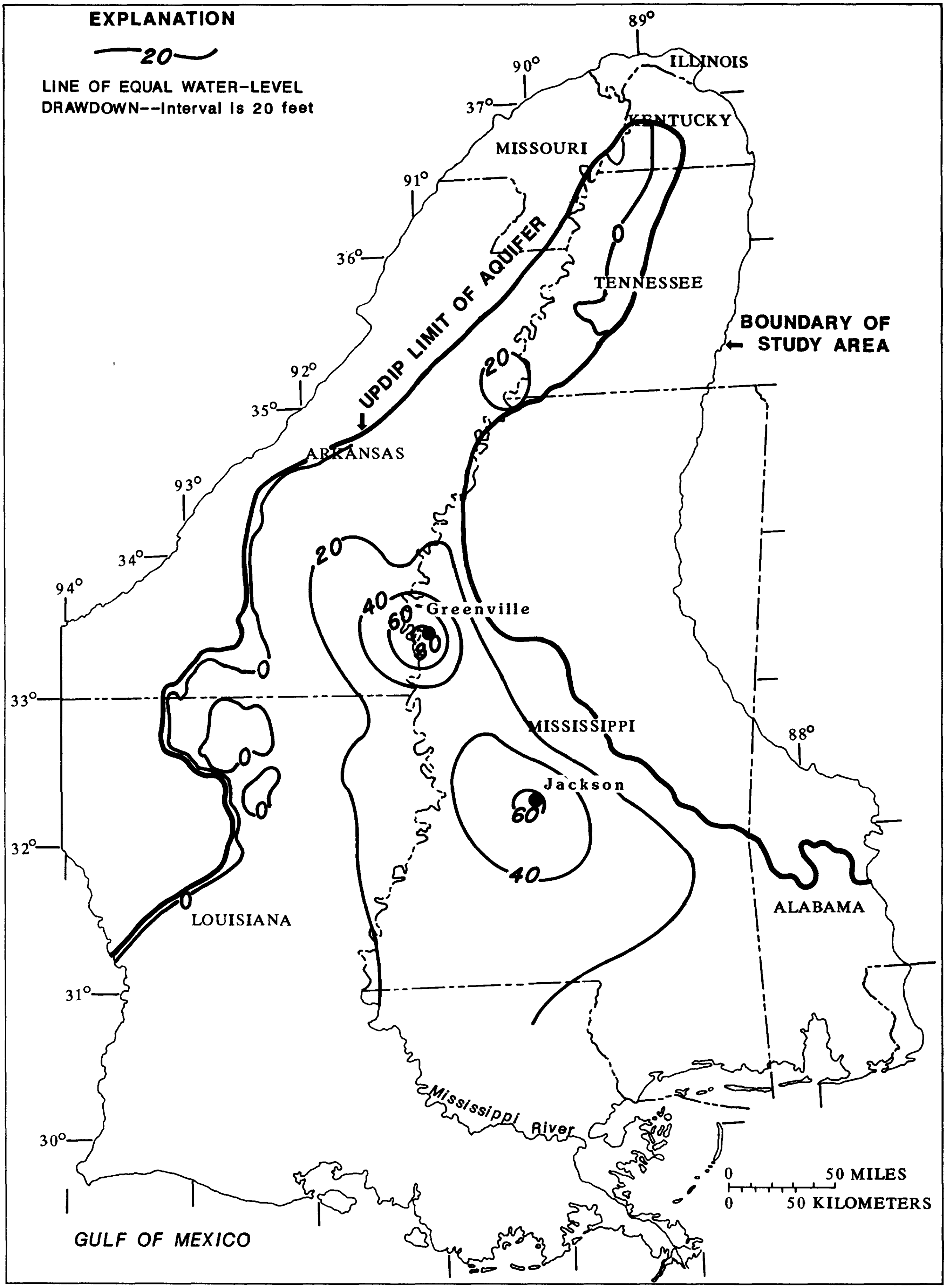

Figure 59.--Model-generated drawdown from predevelopment conditions in upper Claiborne aquifer using 1980 pumpage.

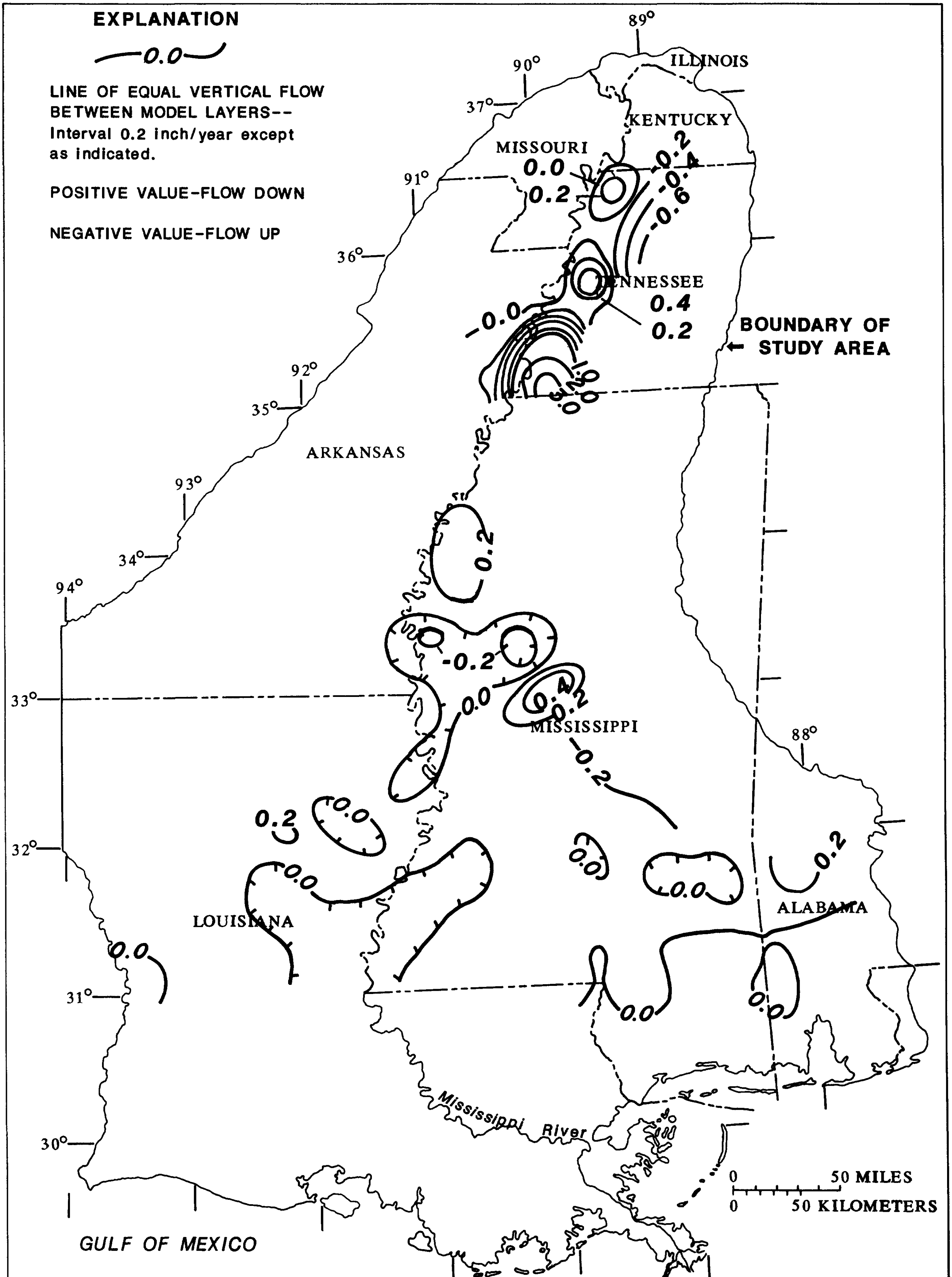

Figure 60.--Model simulated vertical flow between upper Claiborne and middle Claiborne aquifers with 1980 pumpage.

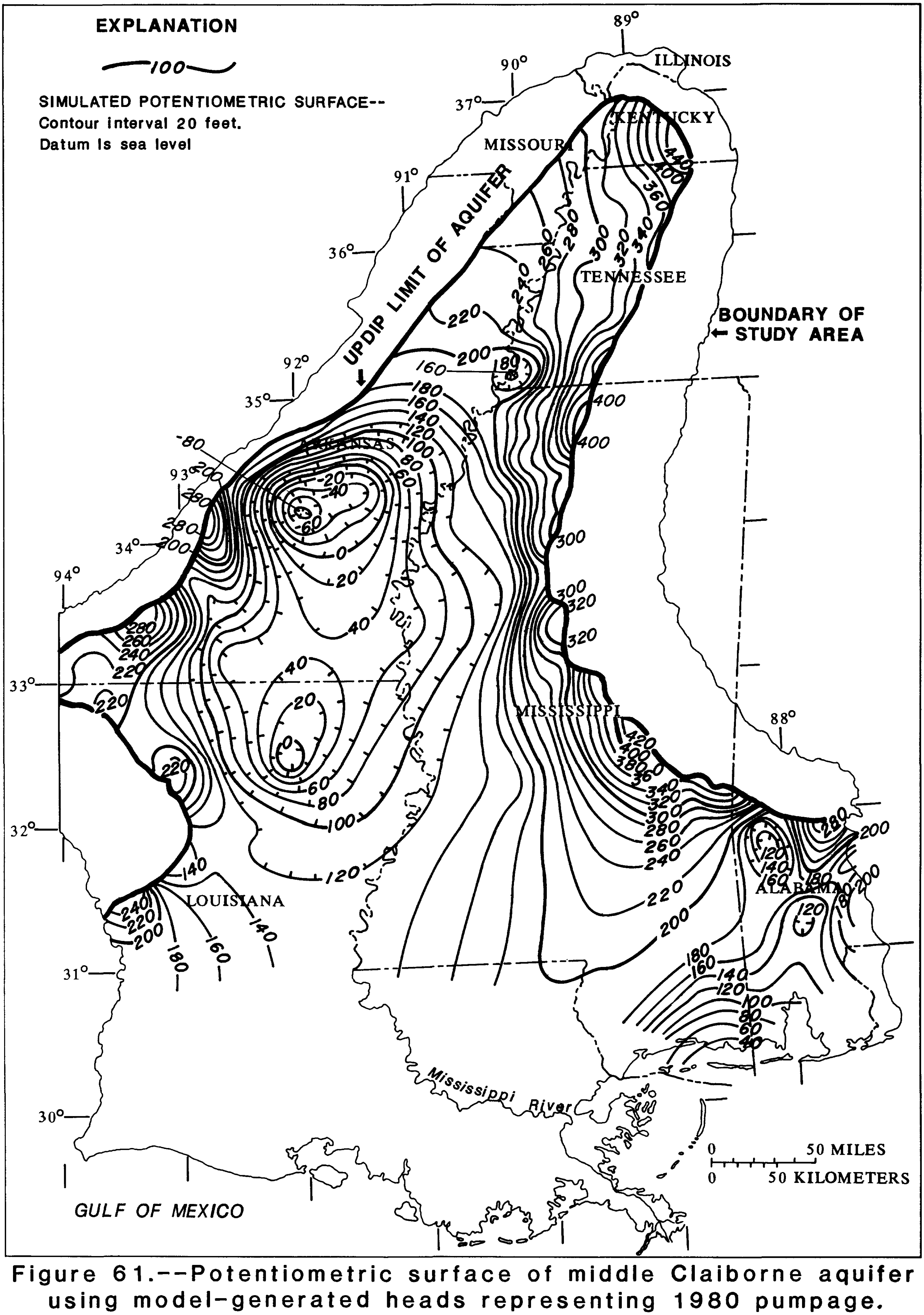

Figure 61.--Potentiometric surface of middle Claiborne aquifer using model-generated heads representing 1980 pumpage.

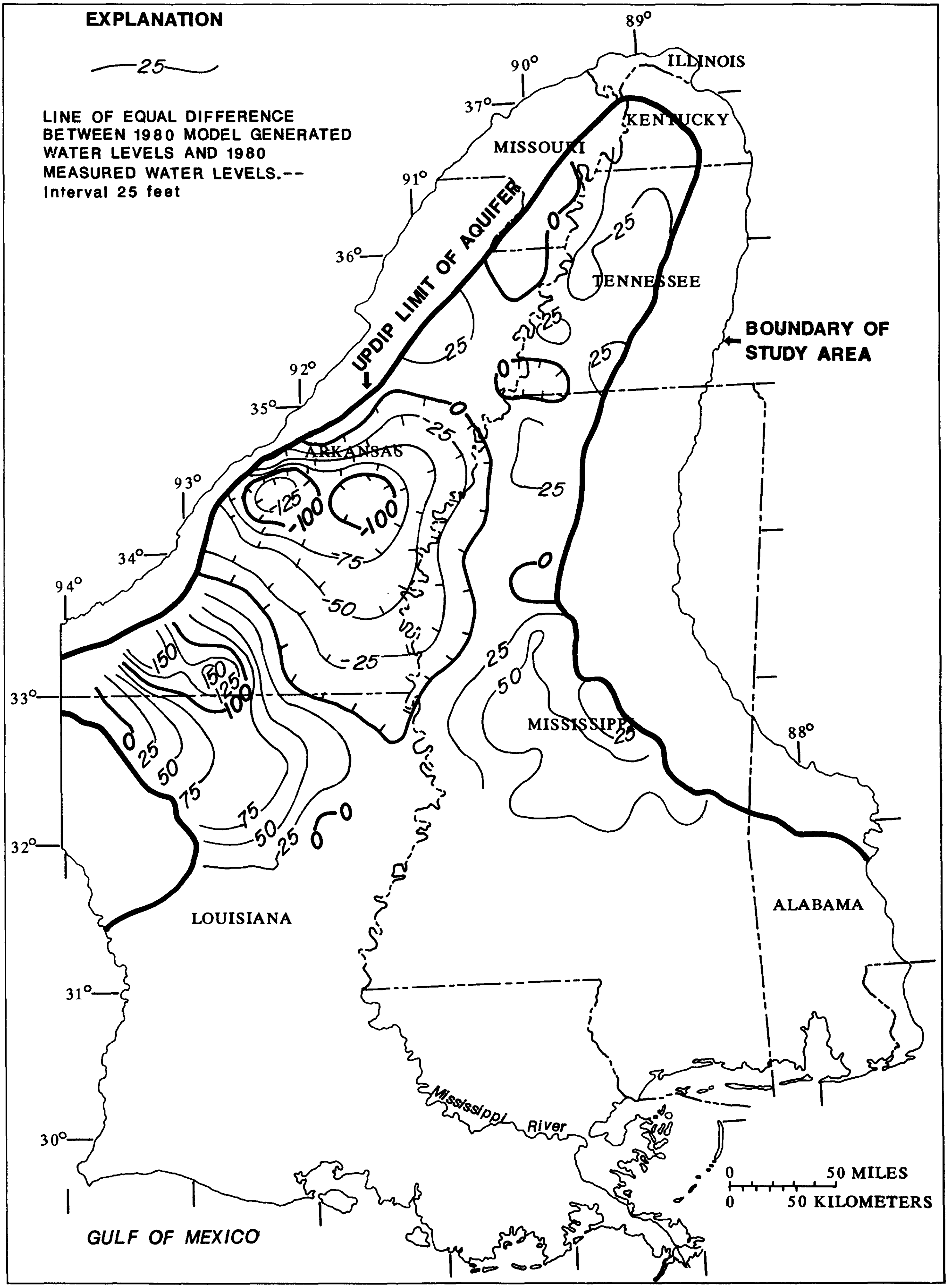

Figure 62.--Difference between model-generated 1980 water levels and measured 1980 water levels in middle Claiborne aquifer.

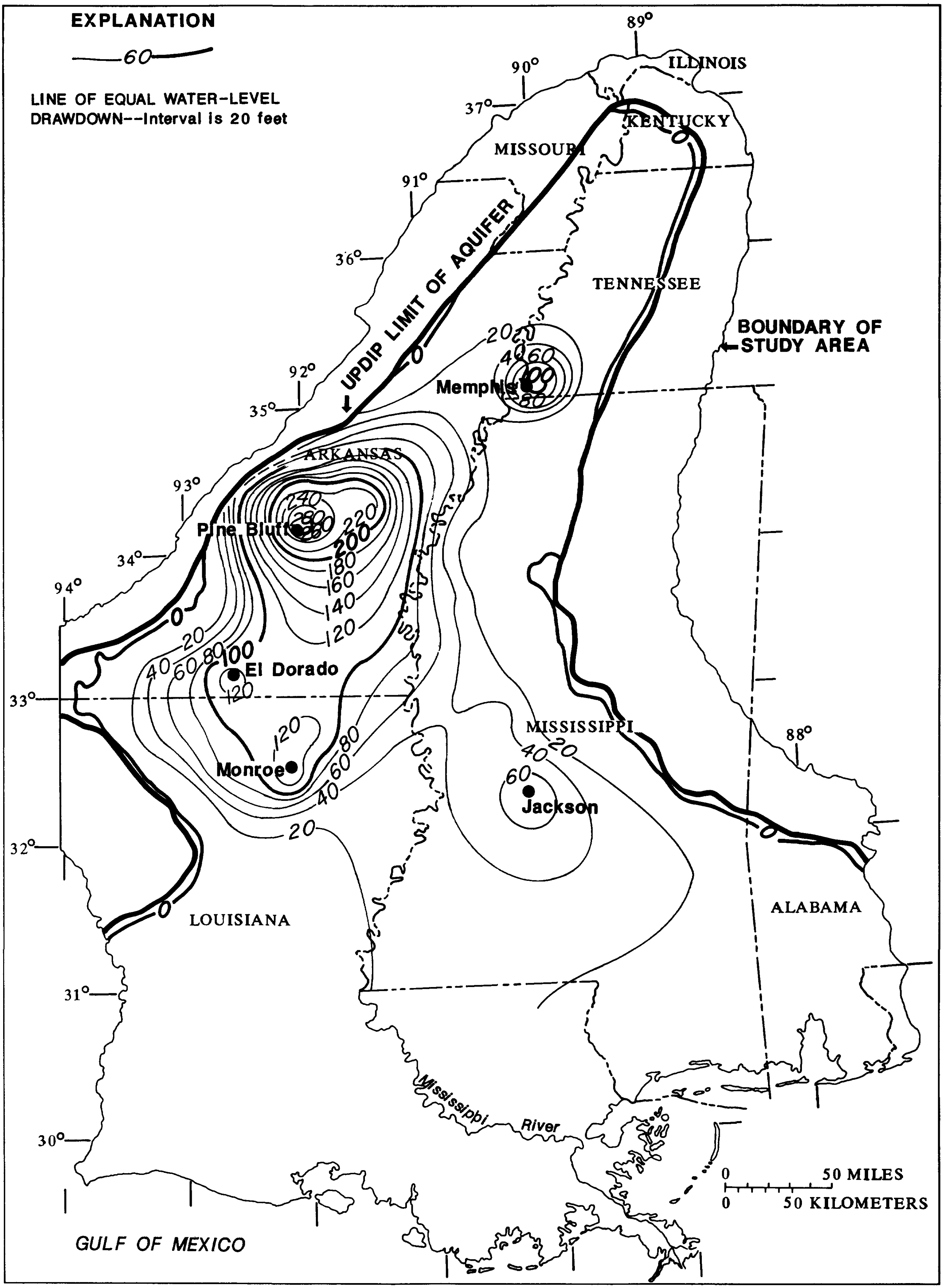

Figure 63.--Model-generated drawdown from predevelopment conditions in middle Claiborne aquifer using 1980 pumpage.

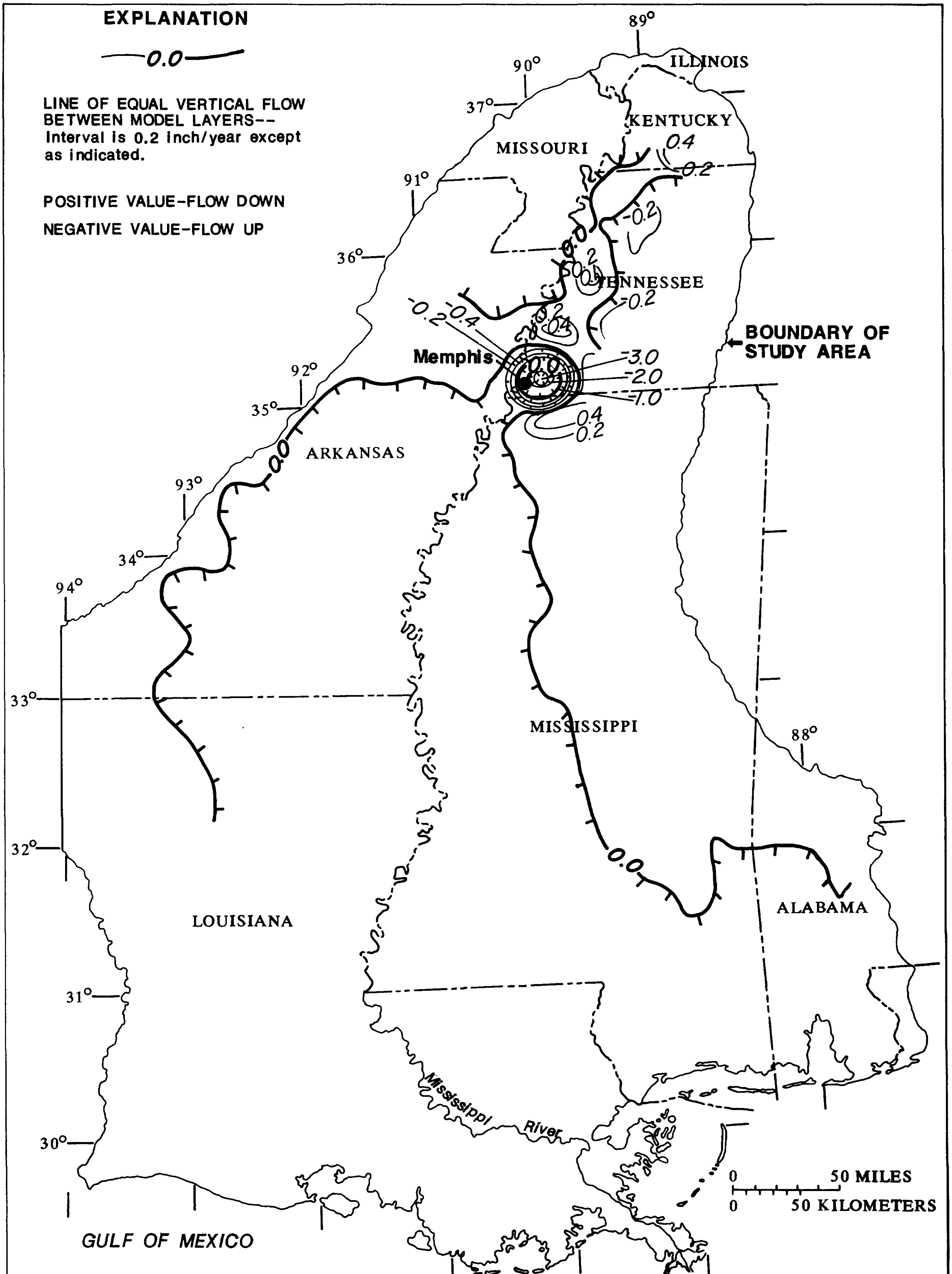

Figure 64.--Model simulated vertical flow between middle Claiborne and lower Claiborne-upper Wilcox aquifers with 1980 pumpage.

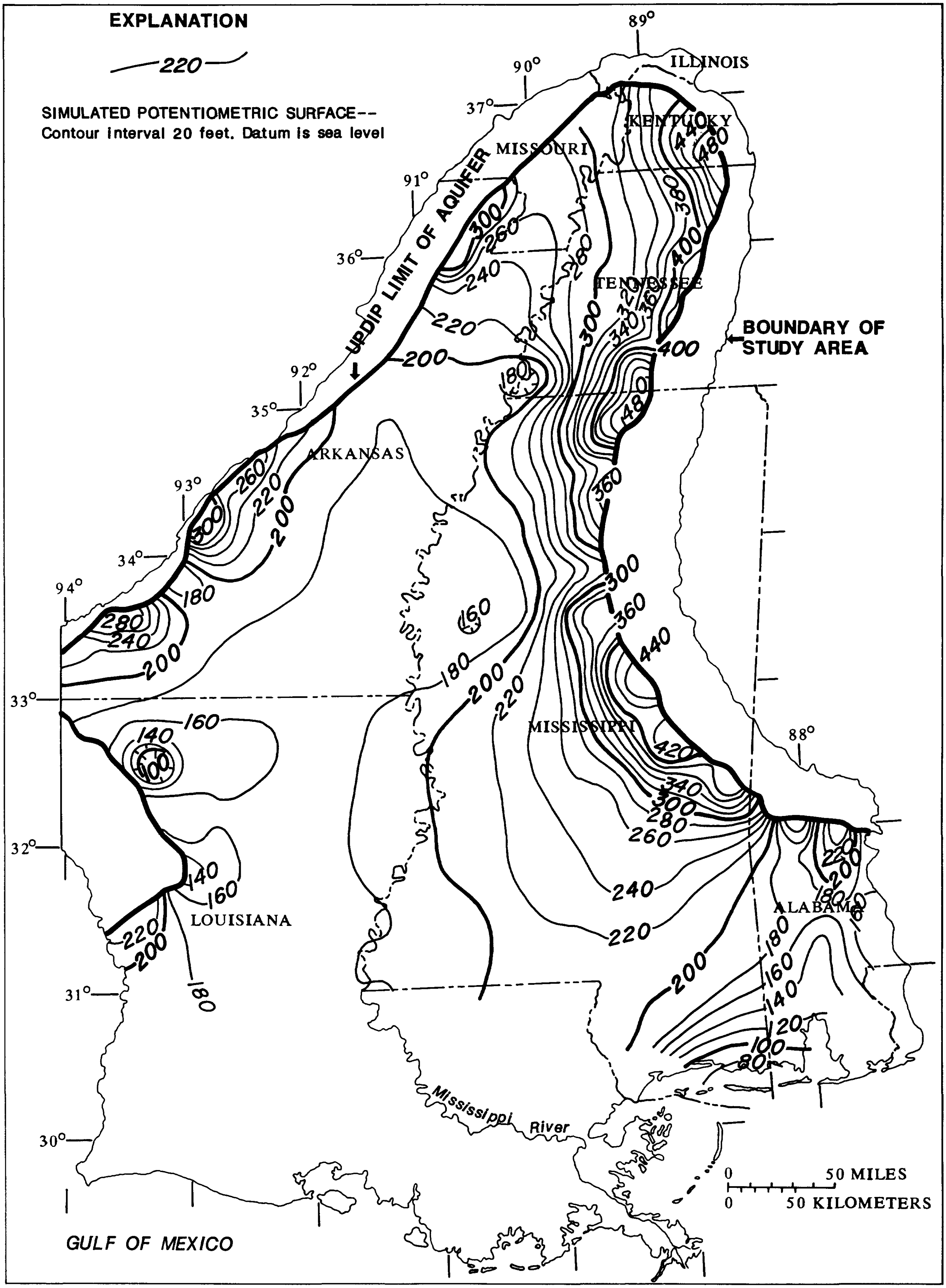

Figure 65.--Potentiometric surface of lower Claiborne-upper Wilcox aquifer using model-generated heads representing 1980 pumpage.

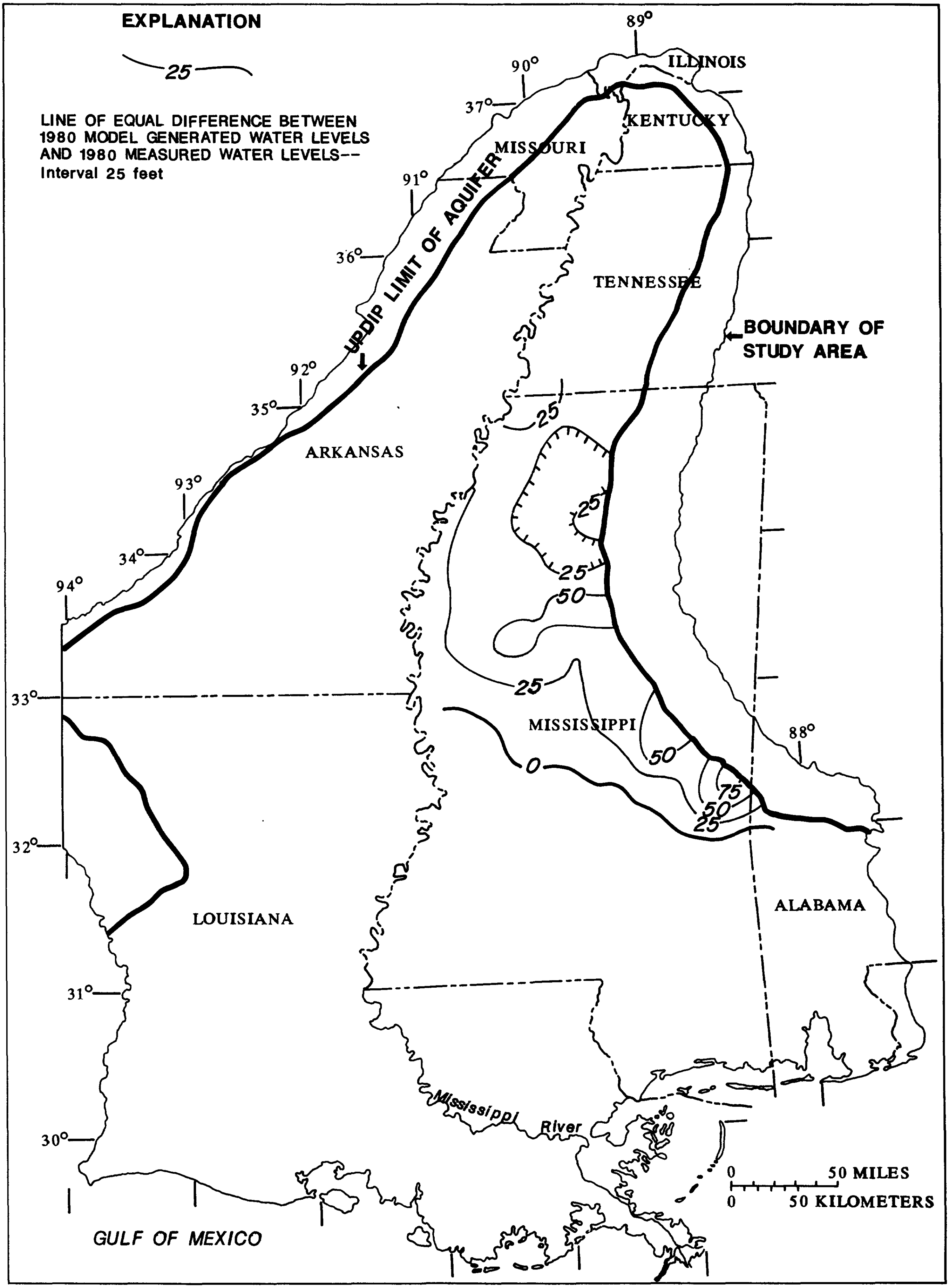

Figure 66.--Difference between model-generated 1980 water levels and measured 1980 water levels in lower Claiborne-upper Wilcox aquifer.

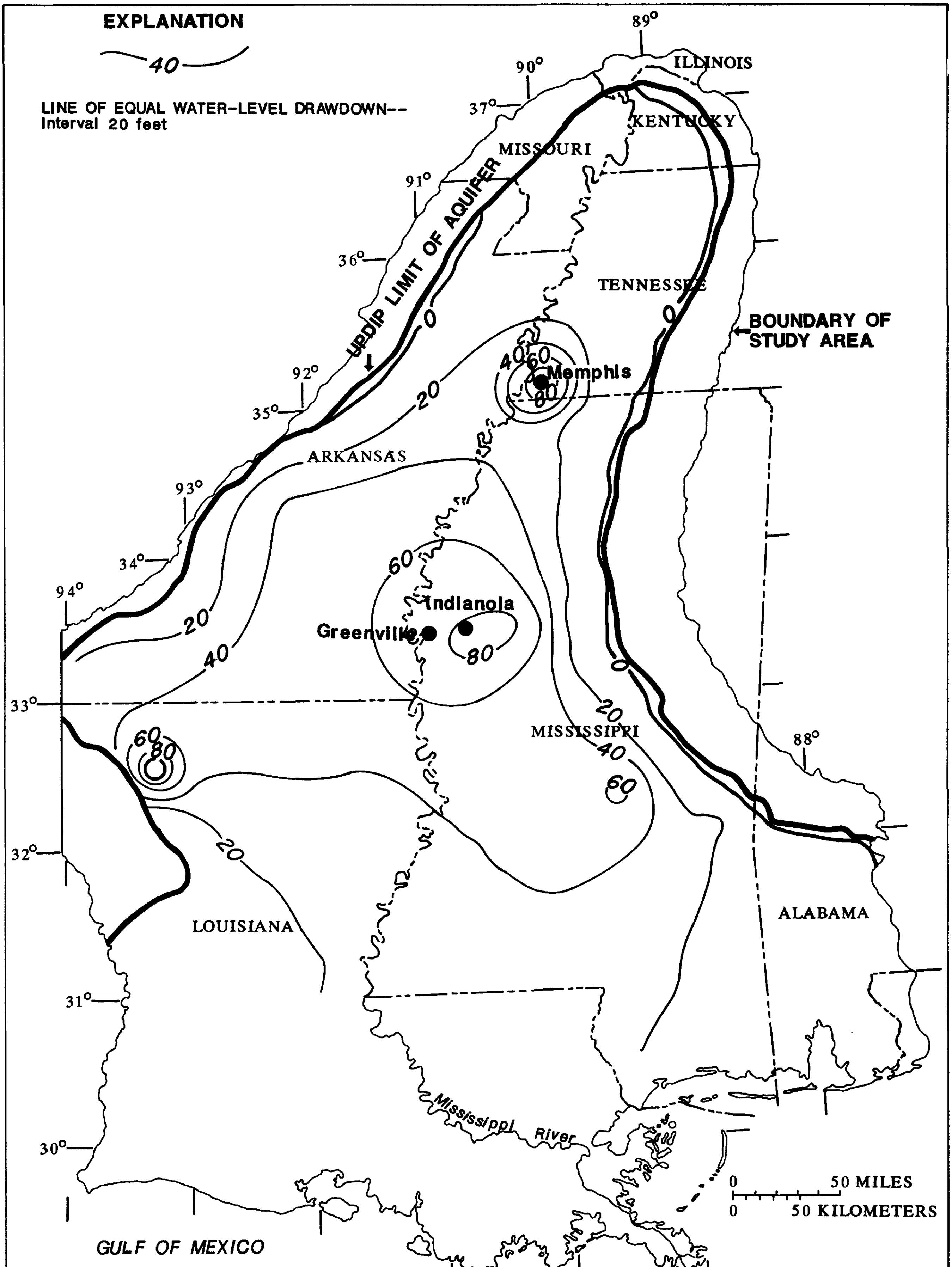

Figure 67.--Model-generated drawdown from predevelopment conditions in lower Claiborne-upper Wilcox aquifer using 1980 pumpage.

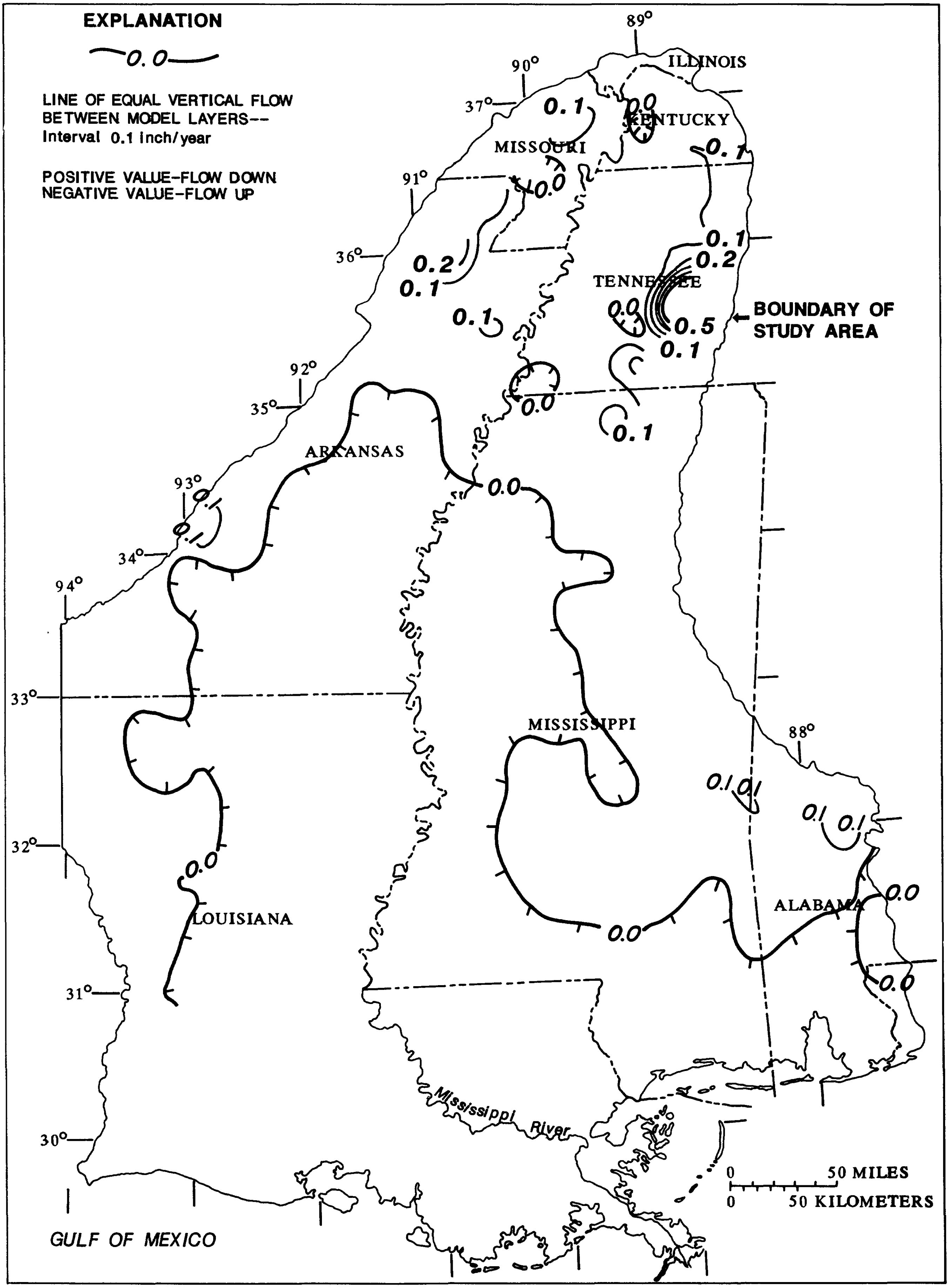

Figure 68.--Model simulated vertical flow between lower Claiborne-upper Wilcox and middle Wilcox aquifers using 1980 pumpage.

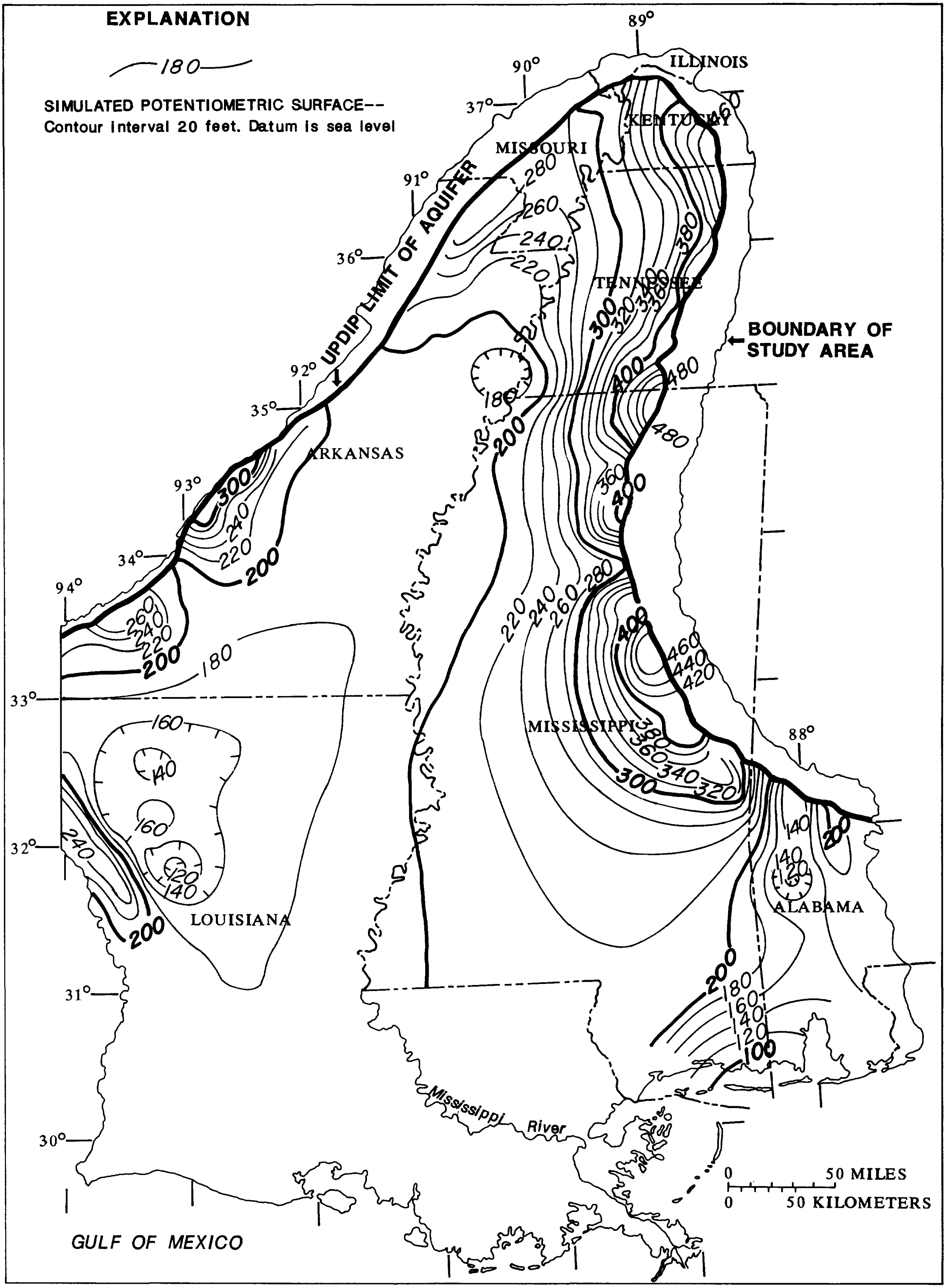

Figure 69.--Potentiometric surface of middle Wilcox aquifer using model-generated heads representing 1980 pumpage.

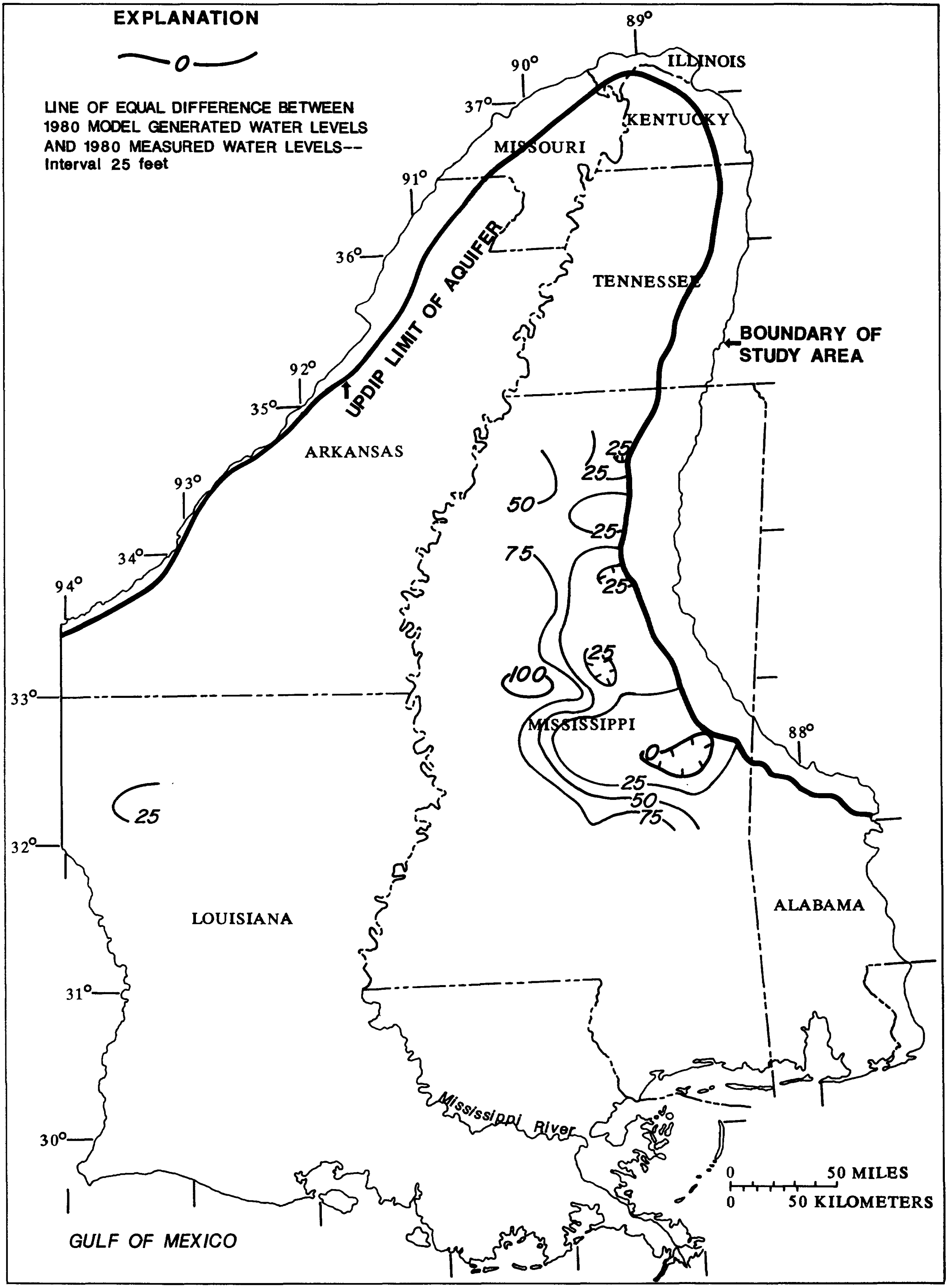

Figure 70.--Difference between model-generated 1980 water levels and measured 1980 water levels in middle Wilcox aquifer.

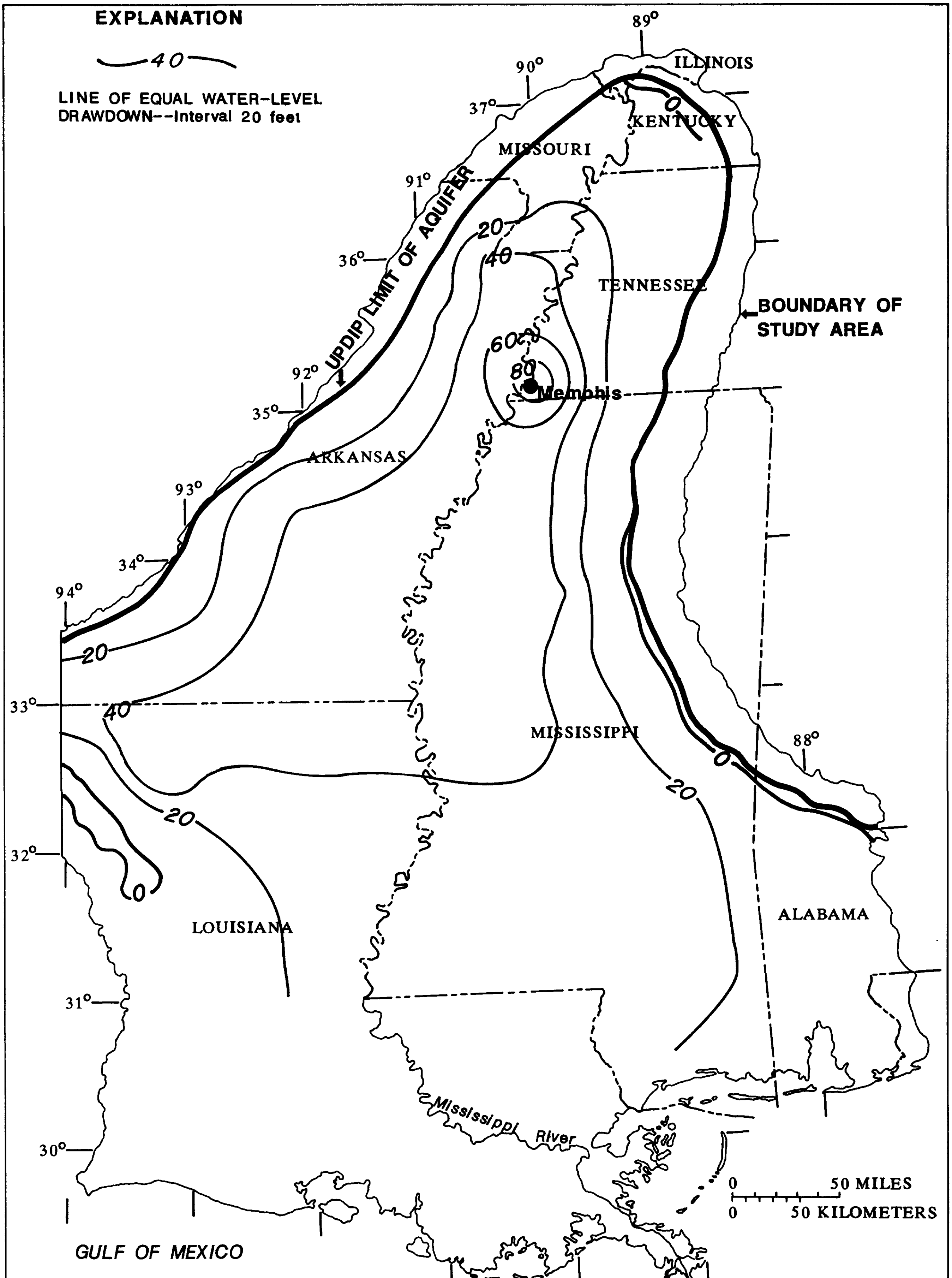

Figure 71.--Model-generated drawdown from predevelopment conditions in middle Wilcox aquifer using 1980 pumpage.

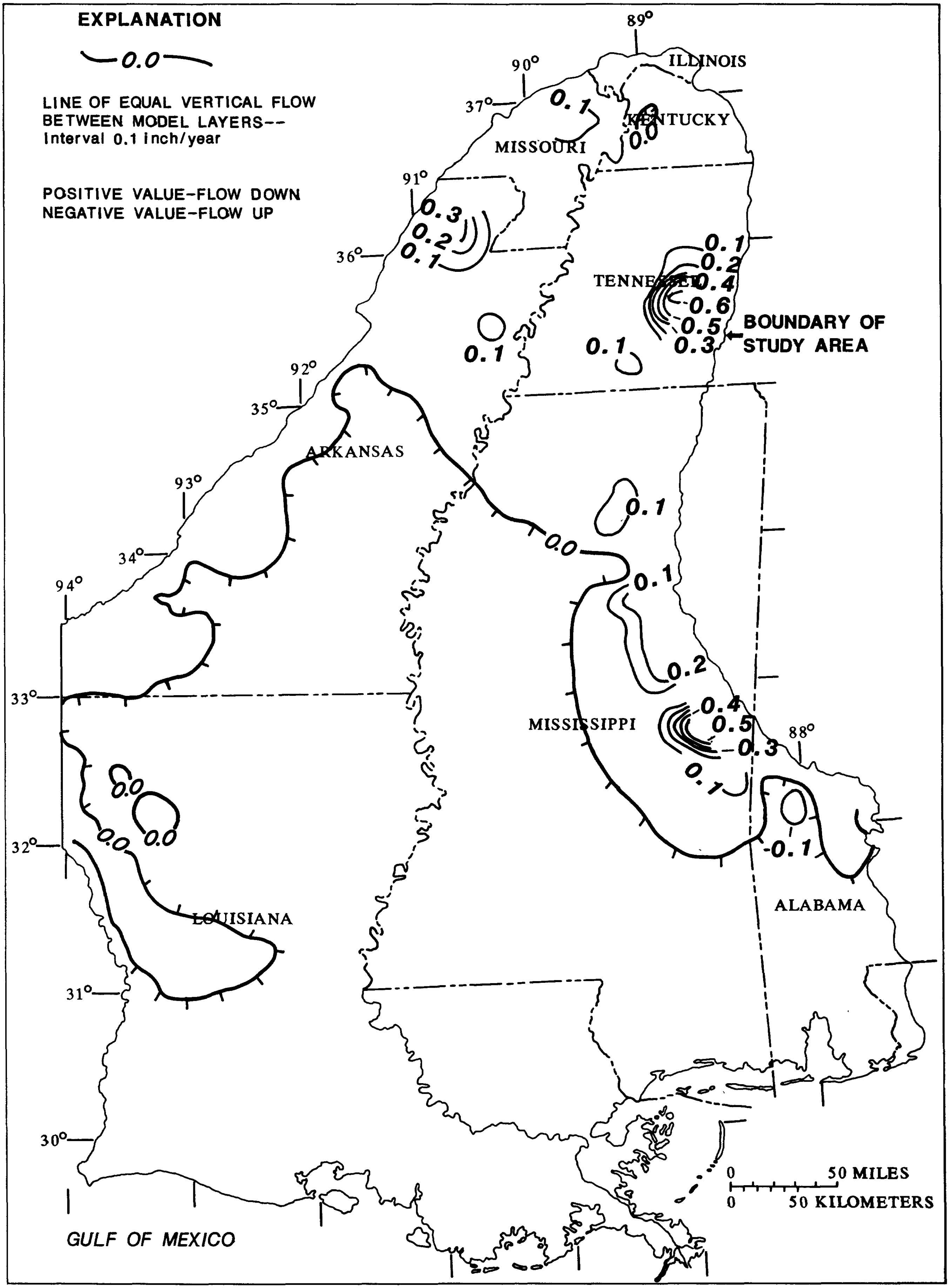

Figure 72.--Model simulated vertical flow between middle Wilcox and lower Wilcox aquifers with 1980 pumpage.

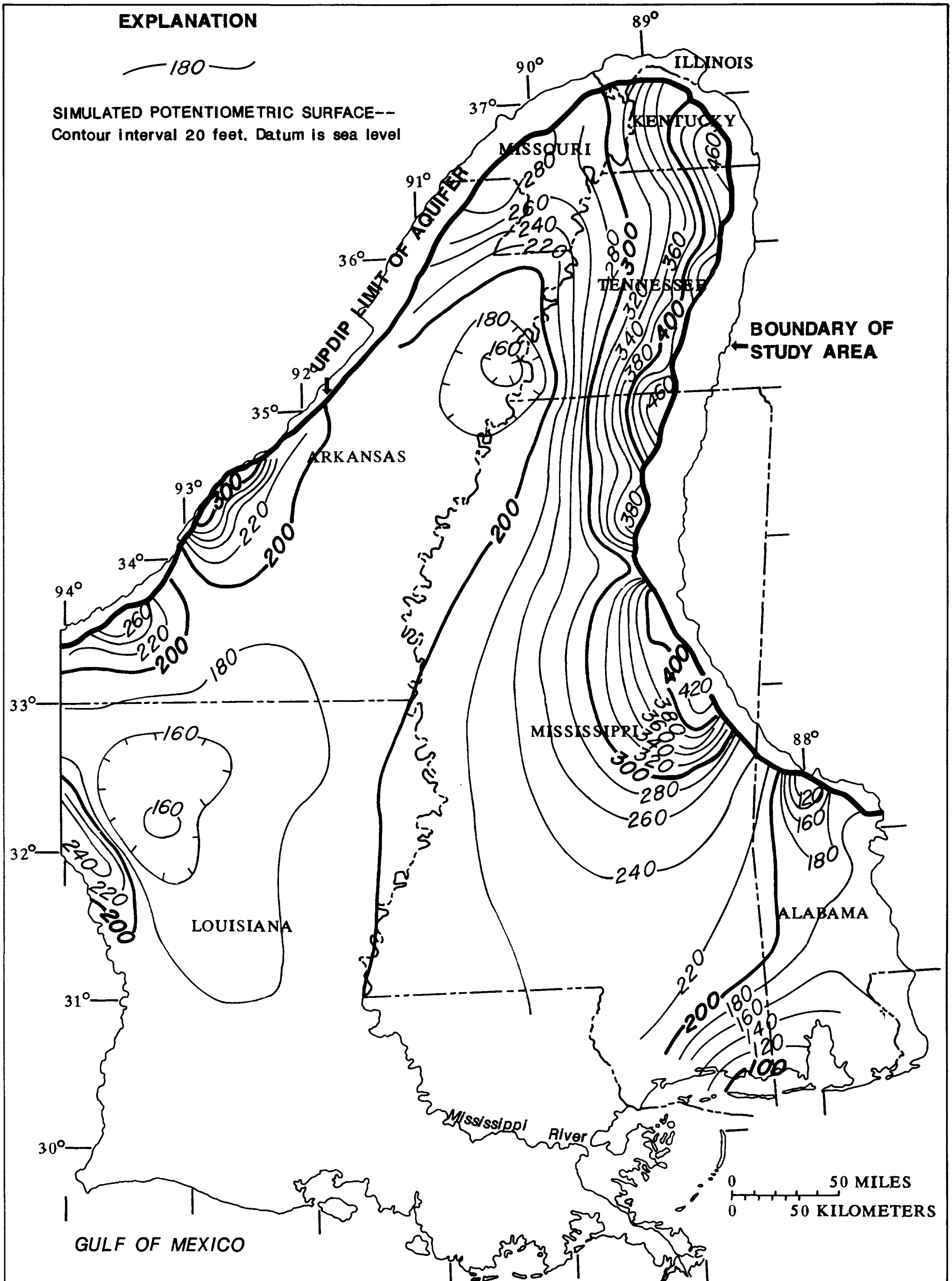

Figure 73.--Potentiometric surfce of lower Wilcox aquifer using model-generated heads representing 1980 pumpage.

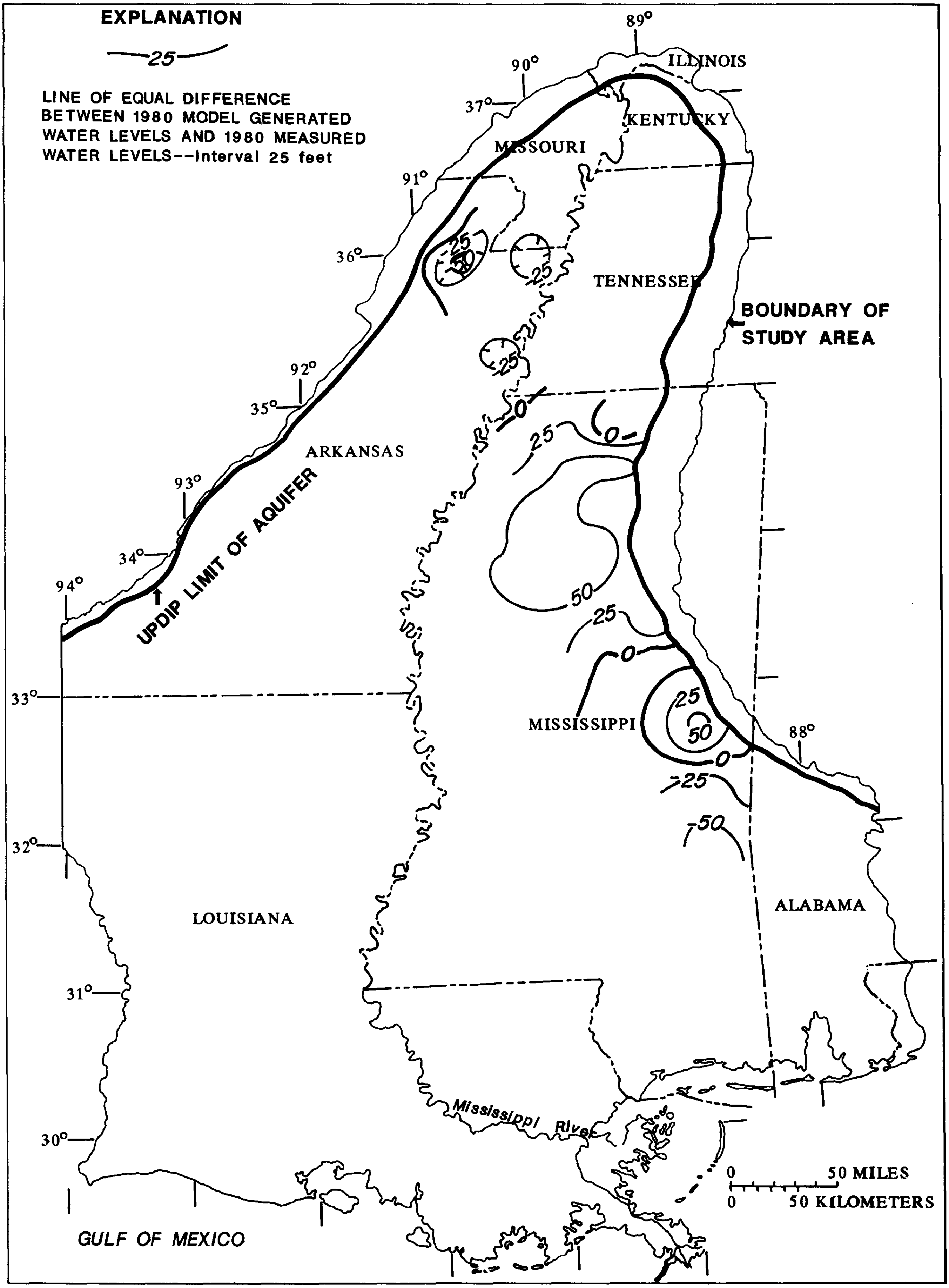

Figure 74.--Difference between model-generated 1980 water levels and measured 1980 water levels in lower Wilcox aquifer.

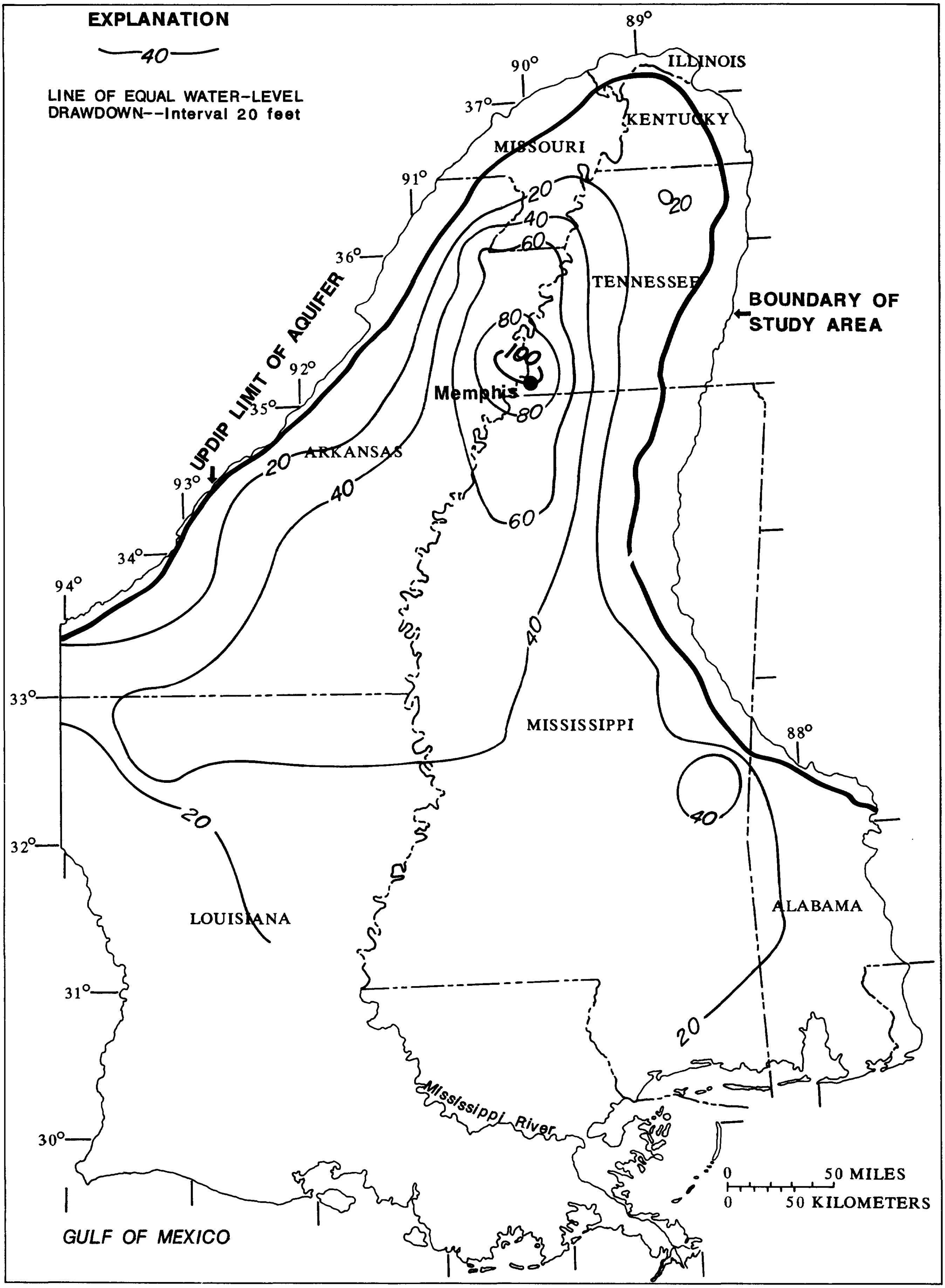

Figure 75.--Model-generated drawdown from predevelopment conditions in lower Wilcox aquifer using 1980 pumpage.

Table 1. -- Generalized correlation chart of hydrogeologic and geologic units of Tertiary age in the Mississippi embayment aquifer system.

[--, not present; Fm, Formation; Gr, Group; Mt, Mountain]

Hydrogeologic unit	Group	Missouri	Kentucky	Arkansas		Tennessee	Louisiana	Mississippi
				Southern	Northeastern			
Vicksburg-Jackson confining unit	Vicksburg	--	--	--	--	--	Vicksburg Fm	Vicksburg Gr undivided
	Jackson	Jackson Fm	Jackson Fm	Jackson Gr undivided	Jackson Gr undivided	Jackson Fm	Jackson Gr undivided	Jackson Gr undivided
Upper Claiborne aquifer	Claiborne	Cockfield Fm	Cockfield Fm	Cockfield Fm	Cockfield Fm	Cockfield Fm	Cockfield Fm	Cockfield Fm
Middle Claiborne confining unit		Cook Mt Fm	Cook Mt Fm	Cook Mt Fm	Cook Mt Fm	Cook Mt Fm	Cook Mt Fm	Cook Mt Fm
Middle Claiborne aquifer		Memphis Sand	Memphis Sand	Sparta Sand	Memphis Sand	Memphis Sand	Sparta Sand	Sparta Sand
Lower Claiborne confining unit				Cane River Fm			Cane River Fm	Zilpha Clay
Lower Claiborne-upper Wilcox aquifer				Carrizo Sand, upper sands in Wilcox Gr			Carrizo Sand , upper sands in Wilcox Gr	Winona Sand, sand in Tallahatta Fm, upper sand in Wilcox Gr
Middle Wilcox aquifer	Wilcox	Middle Sand in Wilcox Gr	Middle Sand in Wilcox Gr	Middle Sand in Wilcox Gr	Middle Sand in Wilcox Gr	Middle Sand in Wilcox Gr	Middle Sand in Wilcox Gr	Middle Sand in Wilcox Gr
Lower Wilcox aquifer		Lower Sand in Wilcox Gr , Fort Pillow Sand	Lower Sand in Wilcox Gr	Lower Sand in Wilcox Gr	Lower Sand in Wilcox Gr	Lower Sand in Wilcox Gr, Fort Pillow Sand	Lower Sand in Wilcox Gr	Lower Sand in Wilcox Gr
Midway confining unit	Midway	Midway Gr undivided	Midway Gr undivided	Midway Gr undivided	Midway Gr undivided	Midway Gr undivided	Midway Gr undivided	Midway Gr undivided

NOTE: See Table 1, Hosman and Weiss, 1988, for detailed correlation chart.

Table 2.--*Ranges of conductivity and transmissivity from selected aquifer tests in the study area.*

[no., number; ft/d, feet per day; ft^2/d, feet squared per day]

	Upper Claiborne aquifer	Middle Claiborne aquifer	Lower Claiborne-upper Wilcox aquifer	Middle Wilcox aquifer	Lower Wilcox aquifer
			ARKANSAS		
Conductivity, in ft/d					
No. Tests	1	7	--	2	--
Mean	65	172	--	49	--
Maximum	65	297	--	64	--
Minimum	65	45	--	33	--
Transmissivity, in ft^2/d					
No. Tests	1	47	2	5	4
Mean	6,283	7,668	486	14,963	17,780
Maximum	6,283	21,124	497	31,818	20,722
Minimum	6,283	535	475	2,580	13,636
			LOUISIANA		
Conductivity, in ft/d					
No. Tests	61	81	6	85	--
Mean	42	49	11	13	--
Maximum	330	167	19	79	--
Minimum	2	2	4	0.5	--
Transmissivity, in ft^2/d					
No. tests	62	82	6	85	--
Mean	2,393	3,560	617	499	--
Maximum	33,000	24,733	1,123	1,938	--
Minimum	160	80	267	8	--
			MISSISSIPPI		
Conductivity, in ft/d					
No. tests	19	39	27	17	51
Mean	69	65	63	42	86
Maximum	167	167	272	154	722
Minimum	1	6	8	3	1
Transmissivity, in ft^2/d					
No. tests	19	40	27	17	51
Mean	5,358	5,960	4,754	2,536	9,343
Maximum	17,400	17,400	17,400	8,290	36,100
Minimum	80	334	800	150	42
			TENNESSEE		
Conductivity, in ft/d					
No. tests	3	1	--	--	6
Mean	81	47	--	--	69
Maximum	176	47	--	--	84
Minimum	33	47	--	--	60
Transmissivity, in ft^2/d					
No. tests	3	37	--	--	6
Mean	3,333	25,649	--	--	15,616
Maximum	6,000	58,600	--	--	19,300
Minimum	1,500	2,700	--	--	13,300