HYDROGEOLOGY AND SIMULATION OF GROUND-WATER FLOW IN THE EUTAW-McSHAN AQUIFER AND IN THE TUSCALOOSA AQUIFER SYSTEM IN NORTHEASTERN MISSISSIPPI

By Eric W. Strom and Michael J. Mallory

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U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 710, Federal Building
100 W. Capitol Street
Jackson, Mississippi 39269

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot	0.3048	meter
foot per day	0.3048	meter per day
foot per year	0.3048	meter per year
foot per mile	0.1894	meter per kilometer
inch	25.4	millimeter
inch per year	25.4	millimeter per year
mile	1.609	kilometer
million gallons per day	0.04381	cubic meter per second
cubic foot per second	0.02832	cubic meter per second
million cubic feet per day	0.3278	cubic meter per second
square mile	2.590	square kilometer
foot squared per day	0.0929	meter squared per day

Temperature in degrees Fahrenheit (^{o}F) can be converted to degrees Celsius (^{o}C) as follows: $^{o}C = (^{o}F-32)/1.8$.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum 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.

The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness. In this report, the mathematically reduced form, foot squared per day, is used for convenience.

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ABSTRACT

The Eutaw-McShan aquifer and Tuscaloosa aquifer system in northeastern Mississippi were investigated to better understand the hydrogeology and the ground-water flow in and between the aquifers. A model was developed to simulate ground-water flow for prepumping and pumping conditions, and model simulations projected the possible effects of increased ground-water withdrawals. The aquifers studied, from youngest to oldest, are the Eutaw-McShan, Gordo, Coker, massive sand, and the Lower Cretaceous aquifers. Most water withdrawn for public and industrial water use in northeastern Mississippi is from the Eutaw-McShan aquifer and Tuscaloosa aquifer system.

The finite-difference computer code MODFLOW was used to simulate the ground-water flow system. The model grid covers 33,440 square miles, primarily in northeastern Mississippi, but includes parts of northwestern Alabama, southwestern Tennessee, and eastern Arkansas. The model was vertically discretized into six layers. Each grid cell was dimensioned 1 mile on a side.

A comparison of the simulated predevelopment and 1992 potentiometric surfaces for the aquifers shows an overall water-level decline. Simulated water levels declined an average of 53 and 44 feet in the confined parts of the Eutaw-McShan and Gordo aquifers, respectively. However, the area near Tupelo had a significant rise in water levels due to decreased pumpage from the Eutaw-McShan and Gordo aquifers compared to the simulated potentiometric surface for 1978.

Projection simulations were made using 1993 pumpage for 20 years. Simulated water levels rose an average of 3.4 and 2.3 feet in the confined parts of the Eutaw-McShan and Gordo aquifers, respectively, from simulated 1992 water levels. The overall simulated rise in water-levels in the Eutaw-McShan and Gordo aquifers is the result of reduced 1992 pumpage due to development of surface-water sources at Tupelo. Projection simulations were also made with a 1.5-, 3-, and 5-percent annual increase of 1993 pumpage for 20 years. Projection simulations made with a 5-percent annual increase of 1993 pumpage indicated simulated water levels declined an average of 41 and 38 feet in the confined parts of the Eutaw-McShan and Gordo aquifers, respectively, from simulated 1992 water levels.

INTRODUCTION

Ground water from the Eutaw-McShan aquifer and Tuscaloosa aquifer system is an important resource in the counties of northeastern Mississippi, supplying most of the water used for industrial, municipal, and commercial purposes. Since World War II, the rate of withdrawal from the multiaquifer system generally has increased each year, resulting in large water-level declines at major pumping centers. Continued population growth, combined with increasing industrial and agricultural water demand, could result in continued water-level decline, coalesced cones of depression in the potentiometric surfaces, and subsequent changes in water quality. The potentially adverse effects of increased withdrawal are a major concern to ground-water users and those involved in managing the water resources of northeastern Mississippi. The Tombigbee River Valley Water Management District (TRVWMD) and the Mississippi Department of Environmental Quality, Office of Land and Water Resources (OLWR), are concerned about the effects that increased pumpage may have on an already stressed ground-water system. In 1987, the Mississippi State Water Permit Board declined to issue additional permits for water wells in the City of Tupelo (J.H. Hoffmann, OLWR, written commun., 1993).

In May 1990, the U.S. Geological Survey, in cooperation with the TRVWMD and the OLWR, began an investigation of the Eutaw-McShan aquifer and Tuscaloosa aquifer system in northeastern Mississippi to better understand the hydrogeology and the flow of water in and between the aquifers. As part of the investigation, a model was developed to simulate ground-water flow for prepumping and pumping conditions and used to project the possible effects of increased ground-water withdrawals.

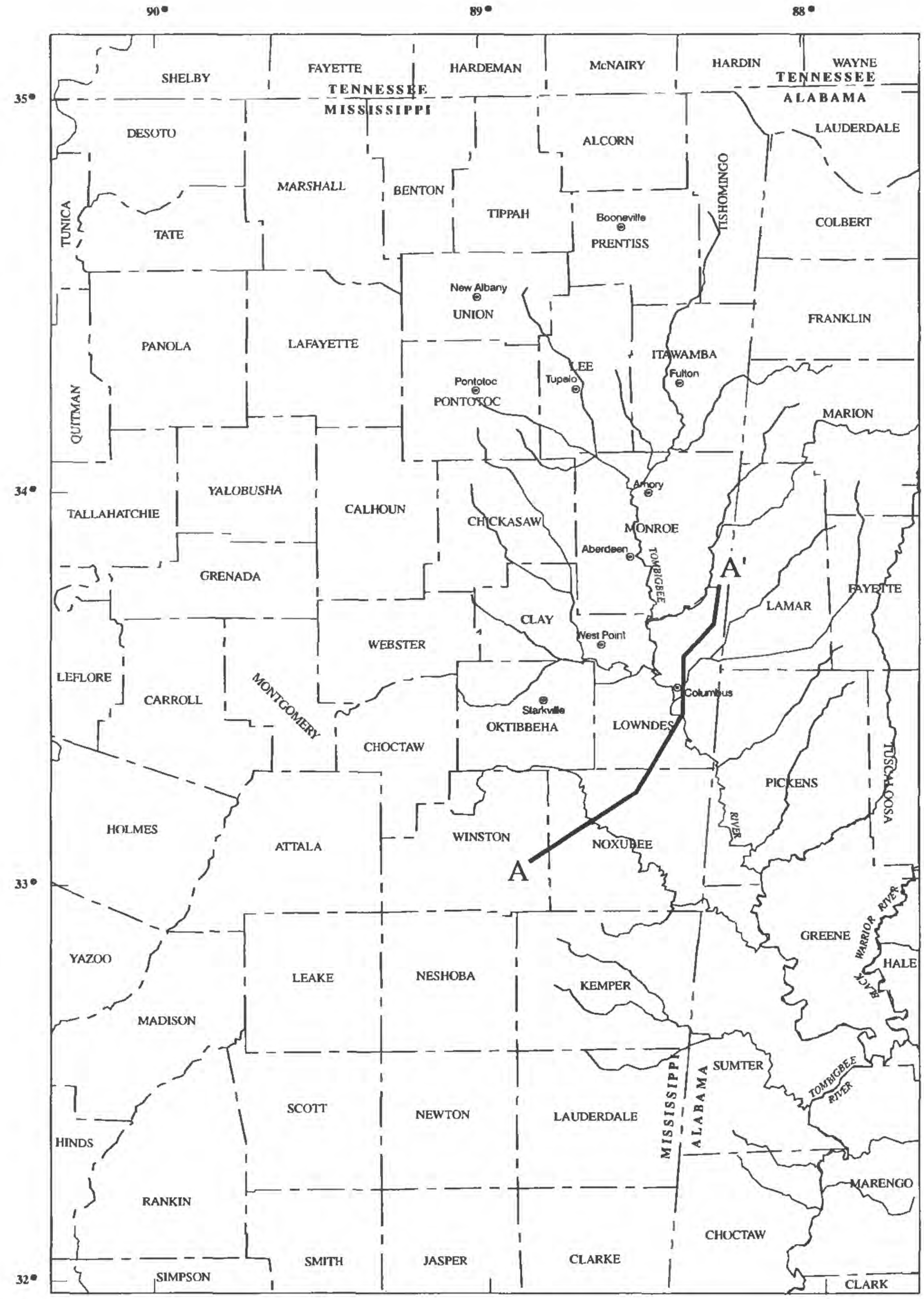
Purpose and Scope

The purpose of this report is to describe the hydrogeology and simulate ground-water flow in the Eutaw-McShan aquifer and in the Tuscaloosa aquifer system in northeastern Mississippi. The report includes descriptions of the aquifers; of a numerical ground-water flow model used to simulate the aquifers; and of model simulated effects of increased ground-water withdrawals for 5, 10, and 20 years. This report is intended to aid the public and Federal, State, and local water-supply and water-management agencies in planning ground-water use.

General Setting of the Study Area

The study area covers 33,440 square miles, primarily in northeastern Mississippi, but includes parts of northwestern Alabama, southwestern Tennessee, and eastern Arkansas (fig. 1). The area includes the extent of the Eutaw-McShan and Tuscaloosa aquifers and adjacent areas that affect ground-water flow and availability of water in northeastern Mississippi.

The study area is within the Gulf Coastal Plain physiographic province, mainly on the eastern flank of the Mississippi embayment subprovince (Fenneman, 1938). Regionally, the study area is topographically highest in the northeastern part, and topographically lowest in the southeastern and western parts (fig. 2). The major surface-water drainages influencing flow in the Eutaw-McShan and Tuscaloosa aquifers are the Tombigbee and Black Warrior Rivers (fig. 1). The climate of the study area is semitropical and humid, with a mean annual air temperature between 62 and 64 degrees Fahrenheit (Boswell, 1963). Annual precipitation averages about 52 inches (National Oceanic and Atmospheric Administration, 1981).



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 10 20 MILES
0 10 20 KILOMETERS

EXPLANATION

A —— A′ TRACE OF GEOLOGIC SECTION

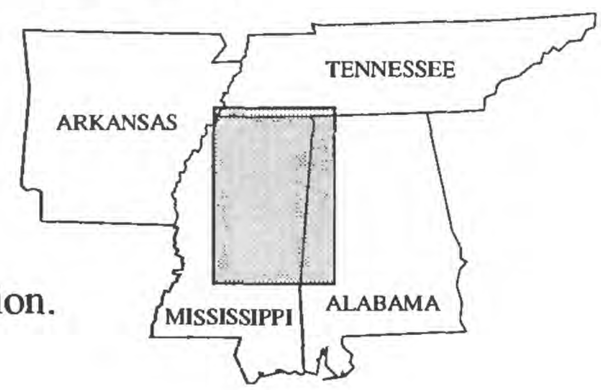


Figure 1. Location of study area and trace of geologic section.

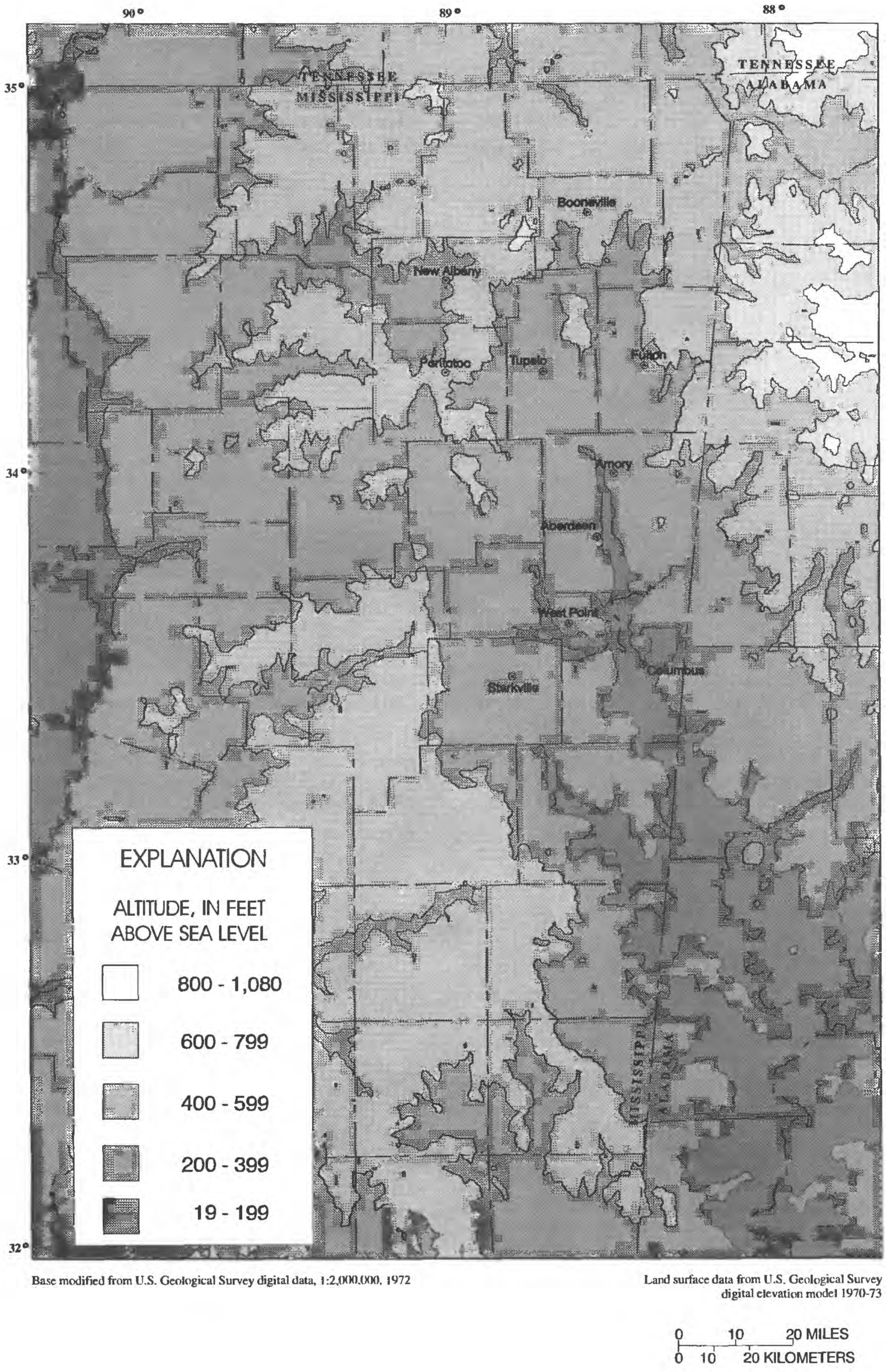


Figure 2. Average land-surface altitude in each square mile of the study area.

Previous Investigations

Reports from previous investigations were published by the U. S. Geological Survey; the Mississippi Department of Environmental Quality, Office of Land and Water Resources; the Mississippi Geological Survey; the Mississippi Board of Water Commissioners; the Mississippi Research and Development Center; other State and Federal agencies; and others. Relevant investigations of the geology and hydrology have been reported by Boswell (1963, 1977, 1978), Boswell and others (1965), Cushing (1966), Hardeman (1966), Moore (1969), Gandl (1982), Davis (1987) and Mallory (1993). Appraisals of the ground-water resources and water-use data have been reported by Crider and Johnson (1906), Stephenson and others (1928), Lang and Boswell (1960), Wasson and Thomson (1970), Newcome (1971), Callahan (1979), Wasson (1986), Slack and Darden (1991), and Oakley and Burt (1992). Potentiometric maps of the aquifers include Wasson (1980a, 1980b), Darden (1984, 1985), Goldsmith (1990, 1991), Everett and Jennings (1994), Hardin and Everett (1994), and Phillips and Hoffmann (1994). Digital computer ground-water flow model studies including all or parts of the study area are reported by Gardner (1981), Kernodle (1981), Planert and Sparkes (1985), and Mallory (1993).

Acknowledgments

The authors would like to thank Ernest H. Boswell, Jo F. Everett, David L. Hardin, James H. Hoffmann, Stephen P. Jennings, and Patricia A. Phillips (Office of Land and Water Resources) for the analyses of most of the borehole-geophysical log information used this study, and for review of the manuscript.

HYDROGEOLOGY

The Eutaw-McShan aquifer and Tuscaloosa aquifer system are part of the larger Southeastern Coastal Plain aquifer system, which is composed primarily of clastic sediments of Cretaceous and Tertiary age. The Eutaw-McShan aquifer and the Tuscaloosa aquifer system are typical of Cretaceous aquifers of the Southeastern Coastal Plain aquifer system, and are described in the following section. The section includes discussions of the geologic setting, hydrogeologic units, ground-water movement, and ground-water withdrawal.

Geologic Setting

The geologic setting of the study area is described by Cushing and others (1964) as resulting from subsidence that may have begun during the late Paleozoic Era and continued through the Cretaceous Period. This subsidence formed the basins of the Gulf Coast geosyncline, and of the southward plunging syncline of the Mississippi embayment. However, most of the syncline of the Mississippi embayment was not formed by the end of the Paleozoic Era. It was during the Jurassic Period of the Mesozoic Era when evidence of a sedimentary basin became observable. By the end of the Cretaceous Period the Mississippi embayment had formed the approximate size and shape of today. Since the Cretaceous Period, cyclic transgression and regression of the sea have subsequently deposited an assorted, but ordered array of sediments within the Mississippi embayment in northeastern Mississippi. The nature of the sediments is directly related to past depositional environments, which in turn are related to fluctuations of sea level and the shifting of the shoreline. The sediments include gravel, sand, clay, chalk, and marl of fluvial-deltaic, continental and marginal-marine origins. Older geologic units crop out in northeastern Mississippi, and sequentially younger units are present at land surface to the west and south toward the axis of the Mississippi embayment. The dip of the Cretaceous units generally is toward the axis of the embayment, averaging about 40 feet per mile (Boswell and others, 1965), and the sediments generally become thicker downdip. Geologic units that crop out in the study area range in age from the Quaternary to Devonian Periods. The sediments that form the Eutaw-McShan and Tuscaloosa aquifers were deposited during the Cretaceous Period. A geologic section showing the northeast to southwest dip, and the relation between the geologic units, is shown in figure 3.

Description of the Hydrogeologic Units

The five aquifers studied, from youngest to oldest, are the Eutaw-McShan aquifer, the Gordo, Coker, and massive sand aquifers of the Tuscaloosa Group, and the Lower Cretaceous aquifer. Geologic and hydrologic data provided most of the necessary information for the interpretation and conceptualization of the multiaquifer system. About 600 borehole-geophysical logs and drillers' information, combined with pertinent stratigraphic and hydrologic data, were used to provide the basis for the identification, definition, and correlation of areally extensive hydrogeologic units. The OLWR completed most of the borehole-geophysical log analysis, including interpretation of sand and clay thickness data used in this report. Additional information used in this report pertaining to the physical boundaries of the individual aquifers and intervening confining units are reported by Boswell (1963), Boswell and others (1965), Cushing (1966), Hardeman (1966), Moore (1969), Boswell (1978), Gandl (1982), Wasson (1986), Davis (1987), and Mallory (1993). Hydraulic characteristics of aquifers and confining units were initially estimated from analyses of borehole-geophysical and lithologic logs of water wells and test holes, data on the specific capacity of water wells, and aquifer tests. A generalized hydrogeologic section showing the northeast to southwest dip, and the relation between the aquifers, is shown in figure 4.

Eutaw-McShan Aquifer

The Eutaw-McShan aquifer includes sediments of the Eutaw and McShan Formations (fig. 5). In Mississippi these formations are considered a single aquifer because the sands are hydraulically connected; however, intervening beds of clay and silt may result in localized small vertical head gradients.

The Eutaw-McShan aquifer crops out primarily in the northeastern part of Mississippi and northwestern part of Alabama within the study area (fig. 6). The northern and northwestern extent of the aquifer is the depositional extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile westward toward the axis of the Mississippi embayment in the northern part, and dips southwestward in the southern part.

The upper part of the Eutaw-McShan aquifer has a finer grain size and a larger silt content than the rest of the aquifer and is called the Tombigbee Sand Member. The Tombigbee Sand Member produces little water. The remainder of the Eutaw-McShan aquifer mainly consists of thin beds of fine to medium glauconitic sand (Boswell, 1963). Analysis of well-log data indicates that total sand thickness within the study area ranges from about 1 foot in the eastern part of the outcrop area to more than 300 feet in the southwestern part and southern part of the study area. The sand is thinnest near the outcrop and generally thickens downdip. An average horizontal hydraulic conductivity value of 12 feet per day, based on the results of 50 aquifer tests, was reported by Slack and Darden (1991).

The Eutaw-McShan aquifer receives recharge from precipitation in the outcrop area. Smaller amounts of recharge also come from overlying and underlying aquifers (Mallory, 1993). Water-level data indicate that discharge from the aquifer is to topographic lows in the outcrop area, and to the Tombigbee and Black Warrior Rivers from upward leakage through units of the Selma

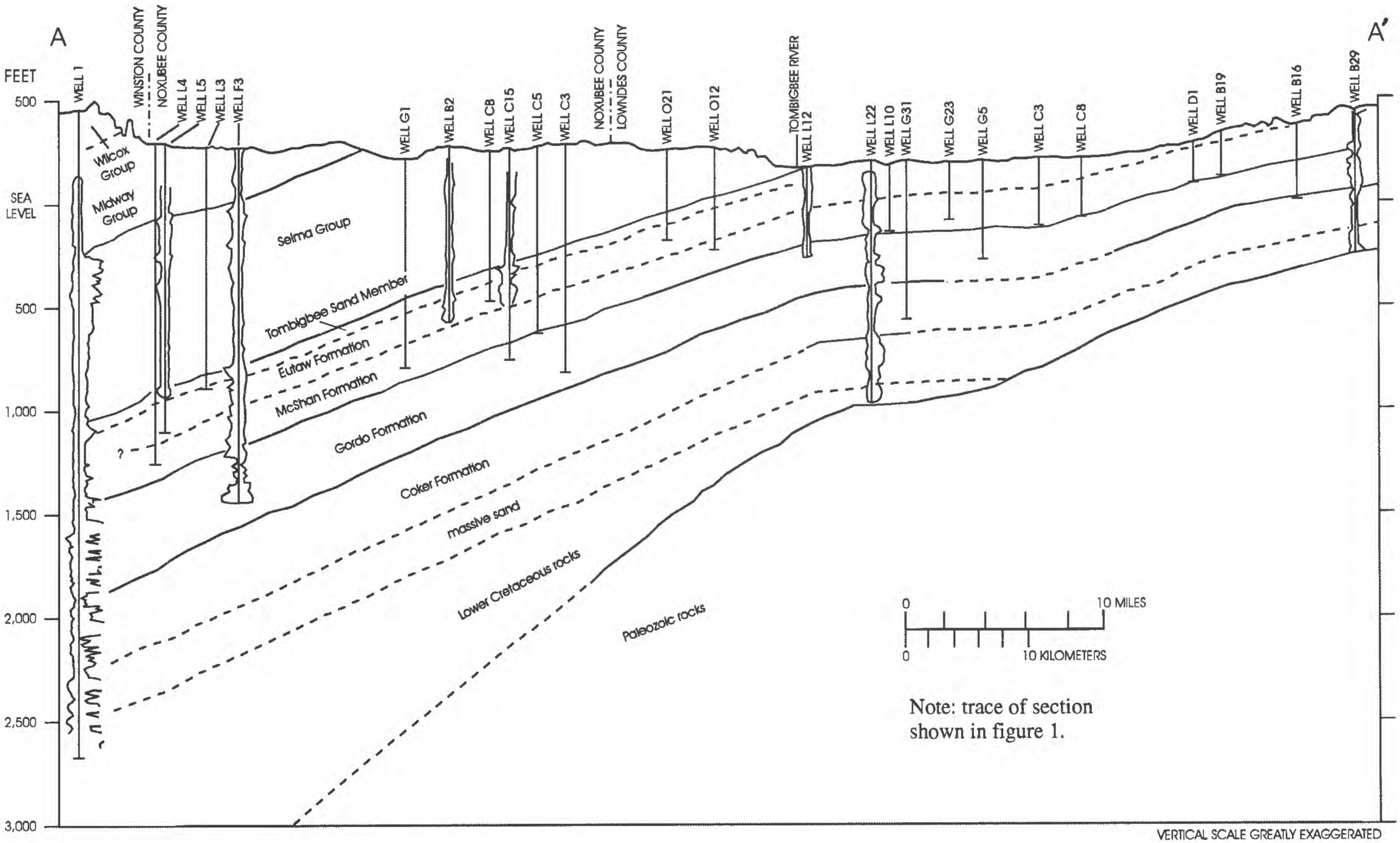


Figure 3. Geologic section showing the northeast to southwest dip and relation of geologic units in northeastern Mississippi (modified from Boswell, 1963).

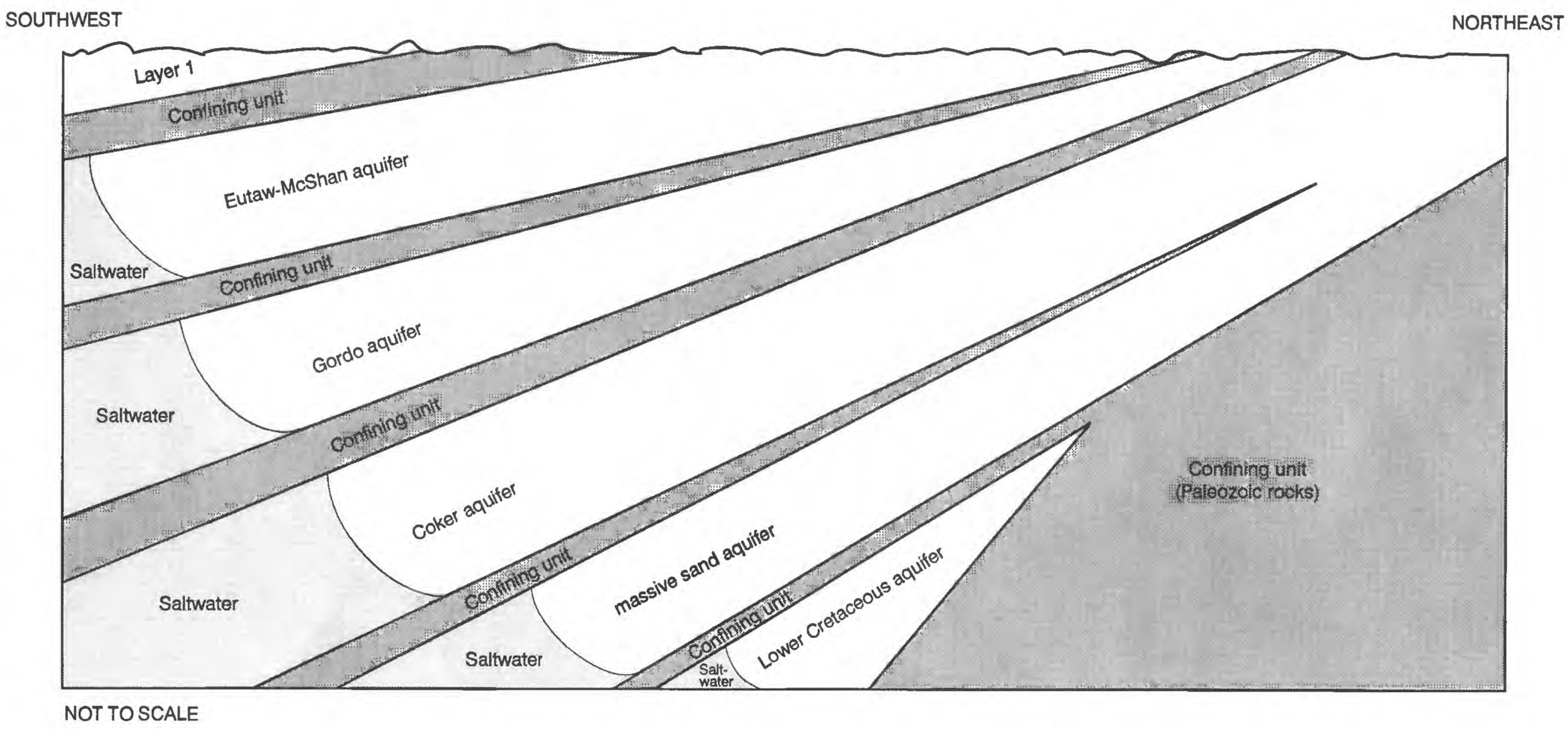


Figure 4. Diagrammatic hydrogeologic section showing the northeast to southwest dip and relation of hydrogeologic units in the study area.

Erathem	System	Series	Group	Geologic unit	Principal aquifer or aquifer system	Model layers
Cenozoic		Paleocene	Wilcox Group	Hatchetigbee Formation		
				Tuscahoma Formation		
				Wilcox Group, middle part		
				Nanafalia Formation	Lower Wilcox aquifer	
				Fearn Springs Member		
				Wilcox Group, lower part		
			Midway Group	Naheola Formation		
				Porters Creek Clay		
				Matthews Landing Marl Member		
Mesozoic	Cretaceous	Upper Cretaceous	Selma Group	Prairie Bluff Chalk		1
				and Owl Creek Formation		
				Ripley Formation	Ripley aquifer	
				Demopolis Chalk		
				Coffee Sand	Coffee Sand aquifer	
				Mooreville Chalk		
				Arcola Limestone Member		
				Eutaw Formation	Eutaw-McShan aquifer	2
				Tombigbee Sand Member		
				Lower Eutaw Formation		
				McShan Formation		
			Tuscaloosa Group	Gordo Formation	Gordo aquifer (Tuscaloosa aquifer system)	3
				Coker Formation	Coker aquifer (Tuscaloosa aquifer system)	4
				Massive sand	Massive sand aquifer (Tuscaloosa aquifer system)	5
		Lower Cretaceous		Undifferentiated	Lower Cretaceous aquifer (Tuscaloosa aquifer system)	6
Paleozoic				Undifferentiated	Paleozoic aquifer system	

Figure 5. Geologic units and principal aquifers in the study area (modified from Slack and Darden, 1991).

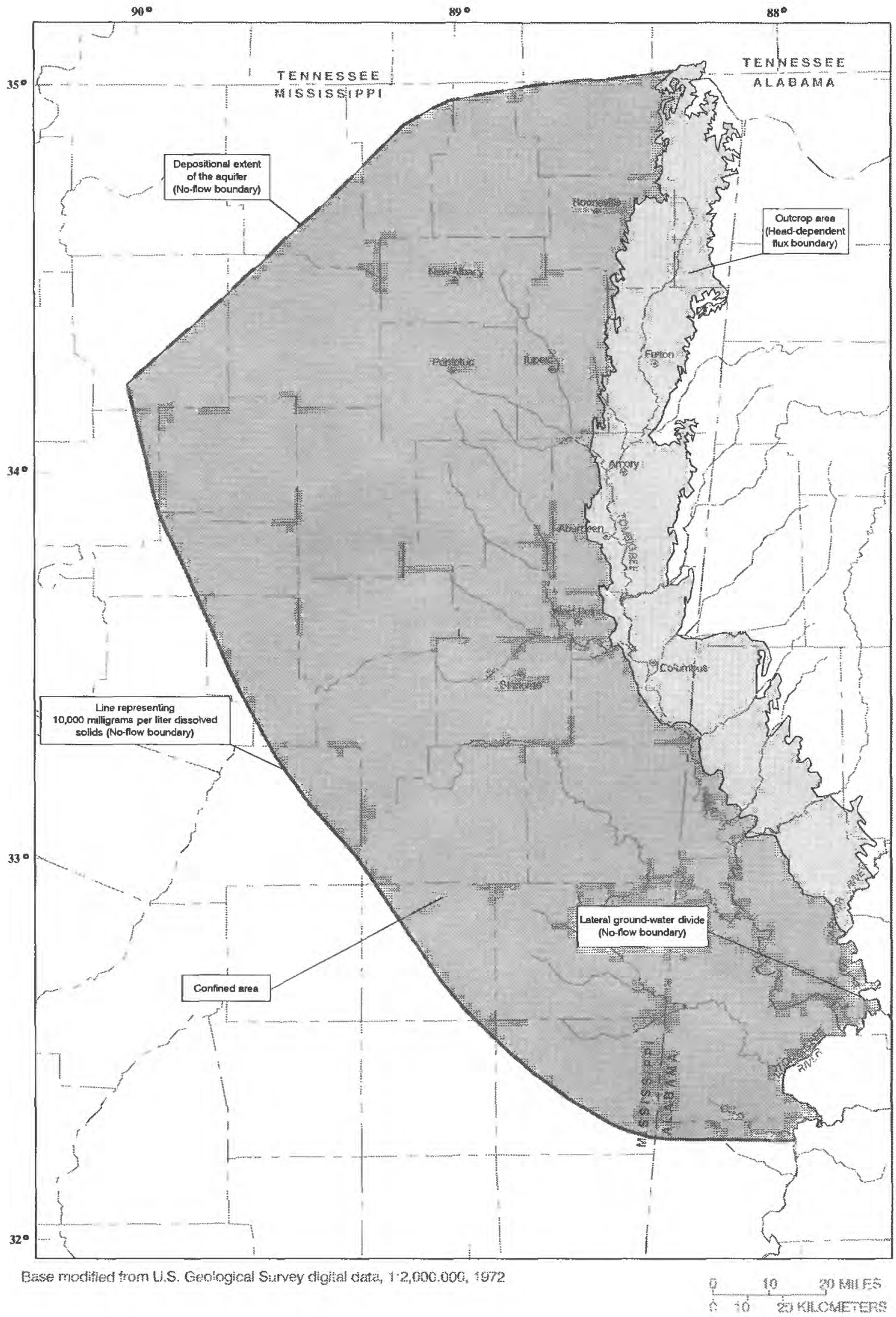


Figure 6. Extent of the Eutaw-McShan aquifer.

Group (Wasson, 1980a; Gardner, 1981). The aquifer also discharges water to the Gordo aquifer in parts of the updip area (J.H. Hoffmann, oral commun., 1994), and to wells screened in the aquifer.

The units overlying the Eutaw-McShan aquifer in the study area, from youngest to oldest, are the Wilcox Group; the Naheola Formation, Porters Creek Clay, and Clayton Formation of the Midway Group; and the Owl Creek Formation, Prairie Bluff Chalk, Ripley Formation, Demopolis Chalk, Coffee Sand, and Mooreville Chalk of the Selma Group (fig. 5). The Coffee Sand aquifer overlies the Eutaw-McShan aquifer, and is in turn overlain by the Ripley and lower Wilcox aquifers. The Eutaw-McShan is separated from the Coffee Sand by the Mooreville Chalk south of an approximate east-west line at about the latitude of the Union and Pontotoc County boundary (fig. 1). North of this line the Mooreville Chalk is absent and the Eutaw-McShan aquifer is in contact with the Coffee Sand aquifer. However, data indicate that the Tombigbee Sand Member is very fine grained in this area and effectively acts as a confining unit, hydraulically separating the Eutaw-McShan and Coffee Sand aquifers (S.P. Jennings, oral commun., 1994). The Eutaw-McShan aquifer is separated from the overlying Ripley and Wilcox aquifers by thick sequences of clay and chalk in the Selma and Midway Groups.

Tuscaloosa Aquifer System

The Tuscaloosa aquifer system consists of the Gordo, Coker, and massive sand aquifers of the Tuscaloosa Group, and a Lower Cretaceous aquifer of undifferentiated sediments (fig. 5). These aquifers are confined by intervening clay and silt, but regionally maintain a hydraulic continuity and, therefore, constitute a system (Boswell, 1978). Most of the available data for the Tuscaloosa aquifer system is for the Gordo aquifer. Few data are available for describing the hydrogeology of the deeper parts of the Tuscaloosa aquifer system.

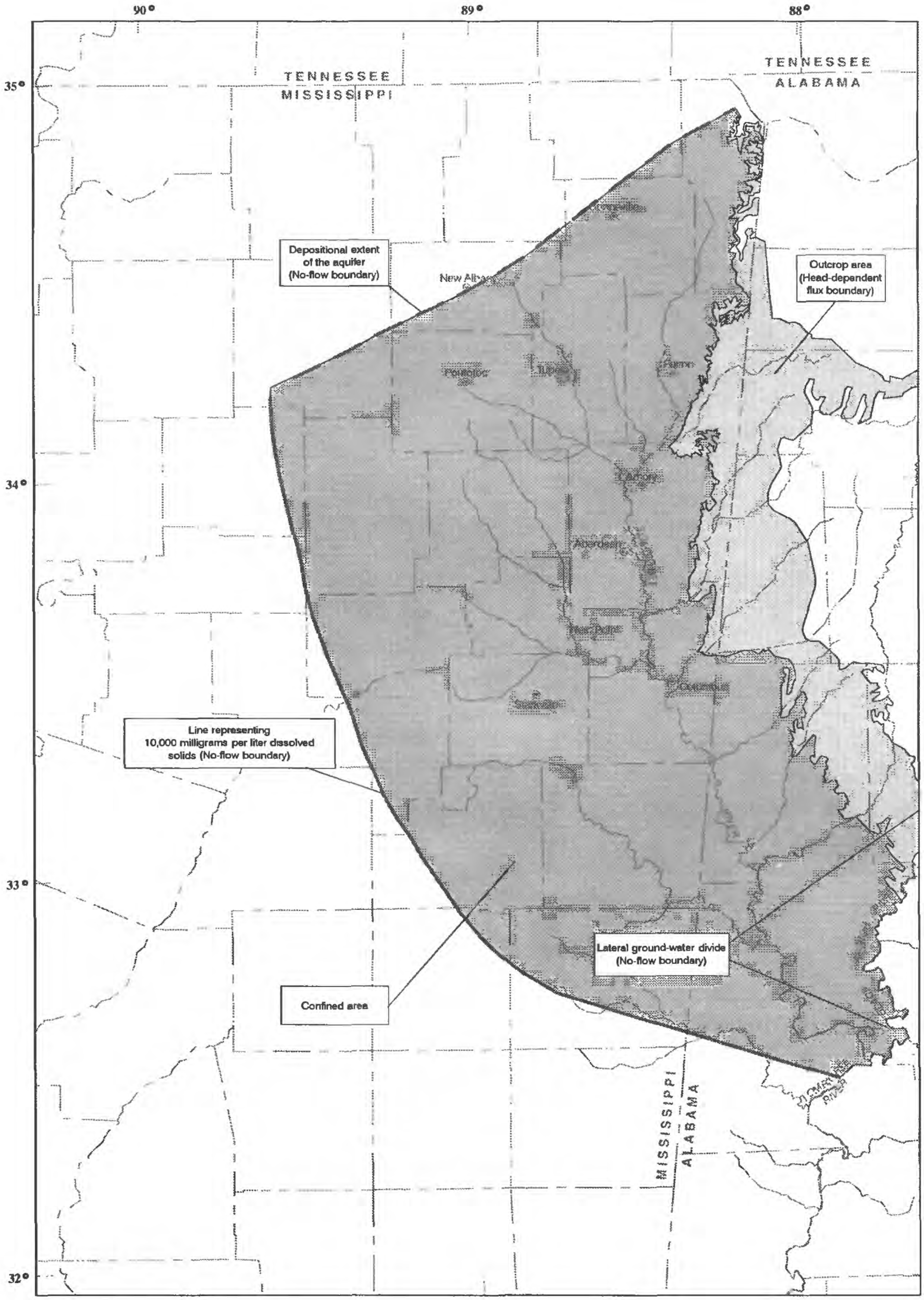
Gordo Aquifer

The Gordo aquifer crops out in extreme northeastern Mississippi and in northwestern Alabama (fig. 7). The northern and northwestern extent of the aquifer is the depositional extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile westward toward the axis of the Mississippi embayment in the northern part of the study area, and dips southwestward in the southern part.

The lower part of the Gordo aquifer generally is composed of coarse quartz sand and chert gravel, and the upper part is interbedded sand and clay (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot in the eastern part of the outcrop area to more than 350 feet in the southwestern part and southern part of the study area. The sand is thinnest near the outcrop and generally thickens downdip. An average horizontal hydraulic conductivity value of about 48 feet per day, based on the results of 33 aquifer tests, was reported for the aquifer (Slack and Darden, 1991).

The Gordo aquifer receives recharge from precipitation in the outcrop area. Recharge also enters the aquifer from overlying and underlying aquifers (Mallory, 1993). Water-level data indicate that discharge from the aquifer is to topographic lows in the outcrop area, and to the Eutaw-McShan aquifer in the Tombigbee and Black Warrior River valley areas (Wasson, 1980b; Gardner, 1981). Available water-level data indicate that the aquifer also discharges water to the Eutaw-McShan aquifer in parts of the downdip area, to the Coker aquifer in the updip area (J.H. Hoffmann, oral commun., 1994), and to wells screened in the aquifer.

The Gordo aquifer is confined beneath the overlying Eutaw-McShan aquifer by clay and silt. Well-log data indicate that total clay thickness of the confining unit in the study area ranges from



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 10 20 MILES
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Figure 7. Extent of the Gordo aquifer.

about 1 foot in the eastern part of the outcrop area to about 200 feet in the southwestern part and southern part of the study area. The confining unit is thinnest near the outcrop and generally thickens downdip.

Coker Aquifer

The Coker aquifer does not crop out in Mississippi, but does crop out in the adjacent northwestern part of Alabama (fig. 8). The northern and northwestern extent of the aquifer is the depositional extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile toward the southwest.

The Coker aquifer is composed of interbedded gray shale and lenticular beds of fine to medium sand (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot in the eastern part of the outcrop area to more than 350 feet in the southwestern part and southern part of the study area. The sand is thinnest near the outcrop and generally thickens downdip. The average horizontal hydraulic conductivity value for the aquifer is about 100 feet per day based on limited aquifer test results (W.T. Oakley, USGS, oral commun., 1994).

The Coker aquifer receives recharge from precipitation in the outcrop area. Recharge also enters the aquifer from overlying and underlying aquifers (Mallory, 1993). Water-level data indicate that discharge from the aquifer is to topographic lows in the outcrop area. Limited available water-level data indicate that the aquifer also may discharge water to the Gordo aquifer in the downdip area, and to the massive sand aquifer in the updip area (J.H. Hoffmann, oral commun., 1994), in addition to wells screened in the aquifer.

The Coker aquifer is confined from the overlying Gordo aquifer by clay and silt. Well-log data indicate that total clay thickness within the study area for the confining unit ranges from about 1 foot in part of the outcrop area to about 200 feet in the southern part of the study area. The confining unit is thinnest near the outcrop and generally thickens downdip.

Massive Sand Aquifer

The massive sand aquifer is often considered a lower part of the Coker aquifer. The easternmost limit of the massive sand aquifer is assumed coincident with the Coker aquifer in this study (fig. 9). However, a clay confining unit thickens away from the outcrop area and effectively separates the two aquifers in the downdip area. The northern and northwestern extent of the aquifer is the depositional extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile toward the southwest.

The massive sand aquifer predominantly contains nonmarine medium to coarse, brown to white quartz sand, commonly with a lower chert and quartz pea gravel (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot in the eastern part of the study area to more than 350 feet in the western part. The sand is thinnest near the easternmost extent of the aquifer and generally thickens downdip. The average horizontal hydraulic conductivity value for the aquifer is estimated to be 200 feet per day based on limited aquifer test results (W.T. Oakley, oral commun., 1994).

The massive sand aquifer does not crop out and is recharged by leakage from the Coker aquifer in its outcrop area because the upper confining unit is relatively thin in that region. Water-level data for the massive sand aquifer are limited, but it is generally assumed that the massive

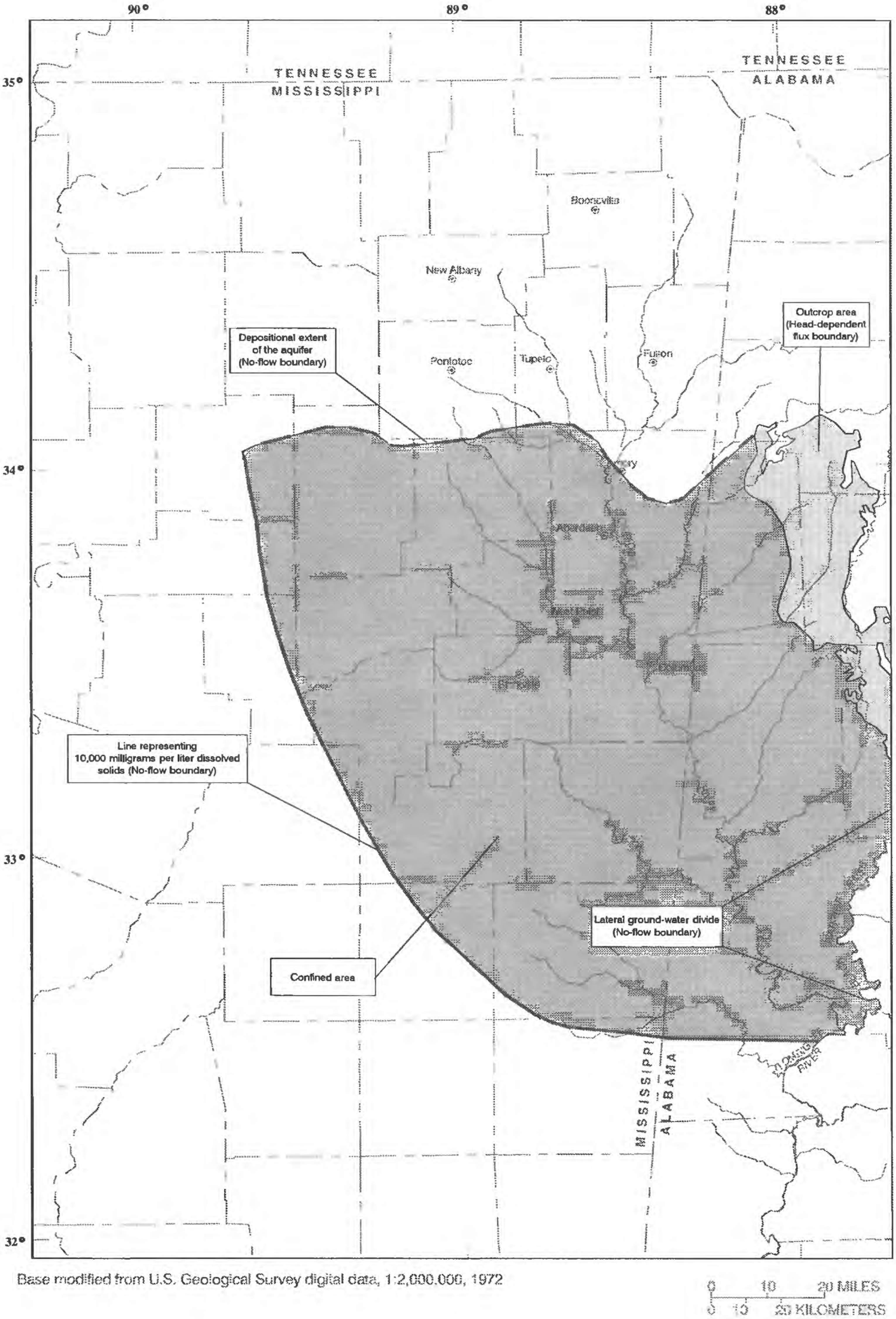


Figure 8. Extent of the Coker aquifer.

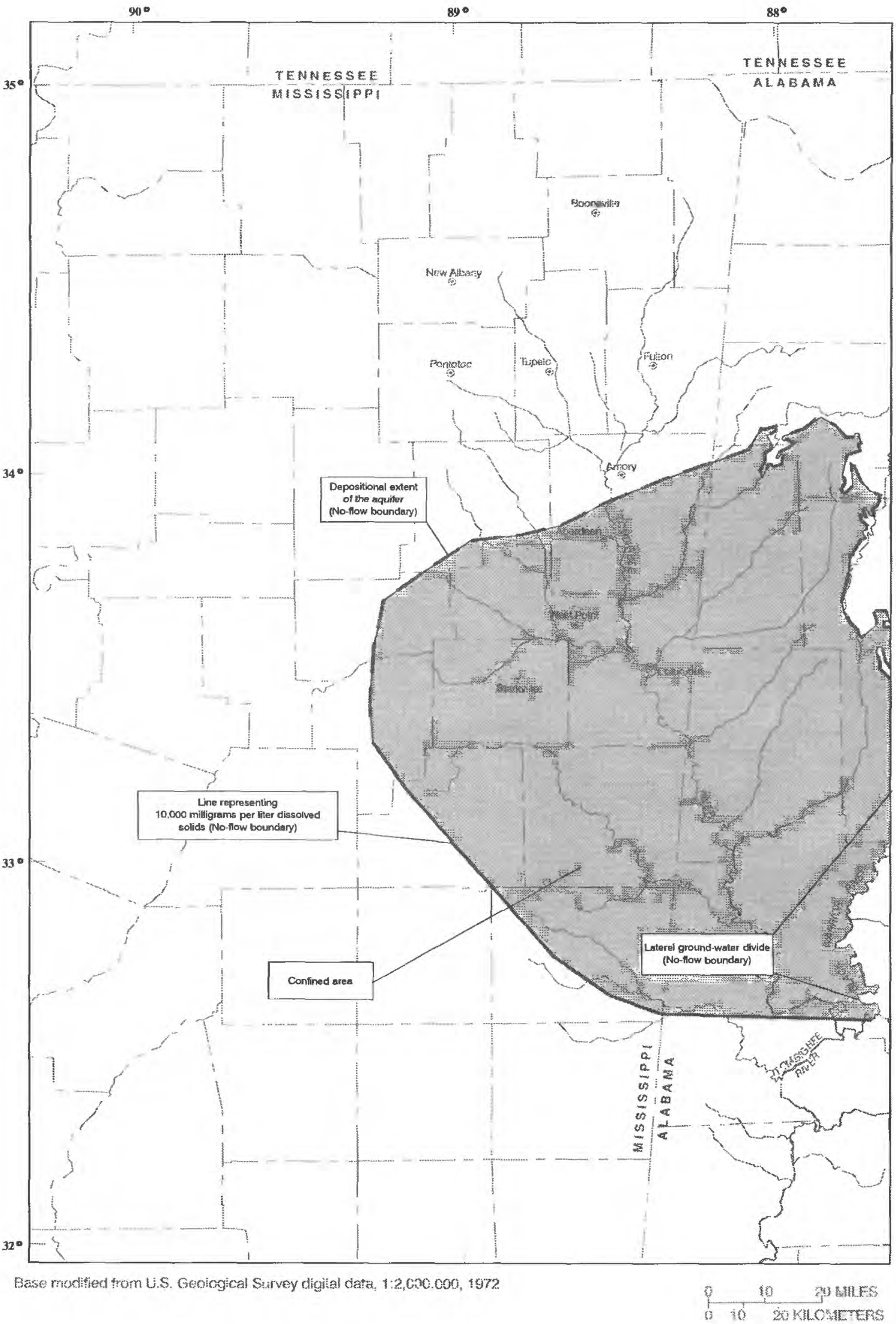


Figure 9. Extent of the massive sand aquifer.

sand may also receive recharge in the downdip area from the underlying Lower Cretaceous aquifer (J.H. Hoffmann, oral commun., 1994). Water may be discharged from the massive sand aquifer to the Coker aquifer in the downdip area, and to the Lower Cretaceous aquifer in the updip area (J.H. Hoffmann, oral commun., 1994), in addition to wells screened in the aquifer.

The massive sand aquifer is separated from the overlying Coker aquifer by clay and silt in most of the study area. Well-log data indicate that total clay thickness within the study area for the confining unit ranges from about 1 foot in the eastern part of the study area to more than 200 feet in the southern part of the study area. The confining unit is thinnest near the eastern limit of the aquifer and generally thickens downdip.

Lower Cretaceous Aquifer

The Lower Cretaceous aquifer does not crop out in Mississippi and the study area. To the north and northeast, the aquifer pinches out against Paleozoic rock. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations (fig. 10). The aquifer dips about 35 to 40 feet per mile toward the southwest.

The Lower Cretaceous aquifer consists of shale, clay, sand, gravel, and calcareous strata (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot where it pinches out against Paleozoic rocks in the northeast, to about 1,000 feet along the west, southwest, and southern edge of the study area. The sand is thinnest near the northeastern extent of the aquifer and generally thickens downdip. The average horizontal hydraulic conductivity value for the aquifer is estimated to be 200 feet per day (W.T. Oakley, oral commun., 1994).

Although water-level data do not exist for the Lower Cretaceous aquifer, it is logical to assume that the aquifer receives recharge from the massive sand aquifer in the updip area; discharge from the aquifer probably is to the massive sand aquifer in the downdip region, but there probably is only minor exchange (J.H. Hoffmann, oral commun., 1994).

The Lower Cretaceous aquifer is confined from the overlying massive sand aquifer by clay and silt. Well-log data indicate that total clay thickness within the study area for the confining unit ranges from about 1 foot in the northeastern part to almost 150 feet in the southern part. The confining unit is thinnest near the northeastern limit of the aquifer and generally thickens downdip.

Ground-Water Movement

A potentiometric surface map of an aquifer shows altitudes above sea level at which water would stand in tightly cased wells. The map also indicates the general direction of ground-water flow, because ground water moves from areas of high potentiometric head to areas of low potentiometric head. Potentiometric surface maps for the Eutaw-McShan and Gordo aquifers based on 1992 water-level measurements (figs. 11 and 12) indicate some ground water enters the deeper confined part of the aquifers from the northernmost counties in the outcrop area, and flows in an arcuate path toward the southeastern part of the aquifers. Flow also moves locally toward cones of depression in the potentiometric surface formed by large pumping centers. Water-level data indicate that flow in the southeastern part of Eutaw-McShan and Gordo aquifers is upward through the overlying confining units, discharging water into the Tombigbee River valley (Wasson, 1980a,b; Everett and Jennings, 1994; Phillips and Hoffmann, 1994). A major discharge area also exists for the Eutaw-McShan and Gordo aquifers around the confluence of the Tombigbee and Black Warrior River valleys (Gardner, 1981). Vertical head gradients indicate

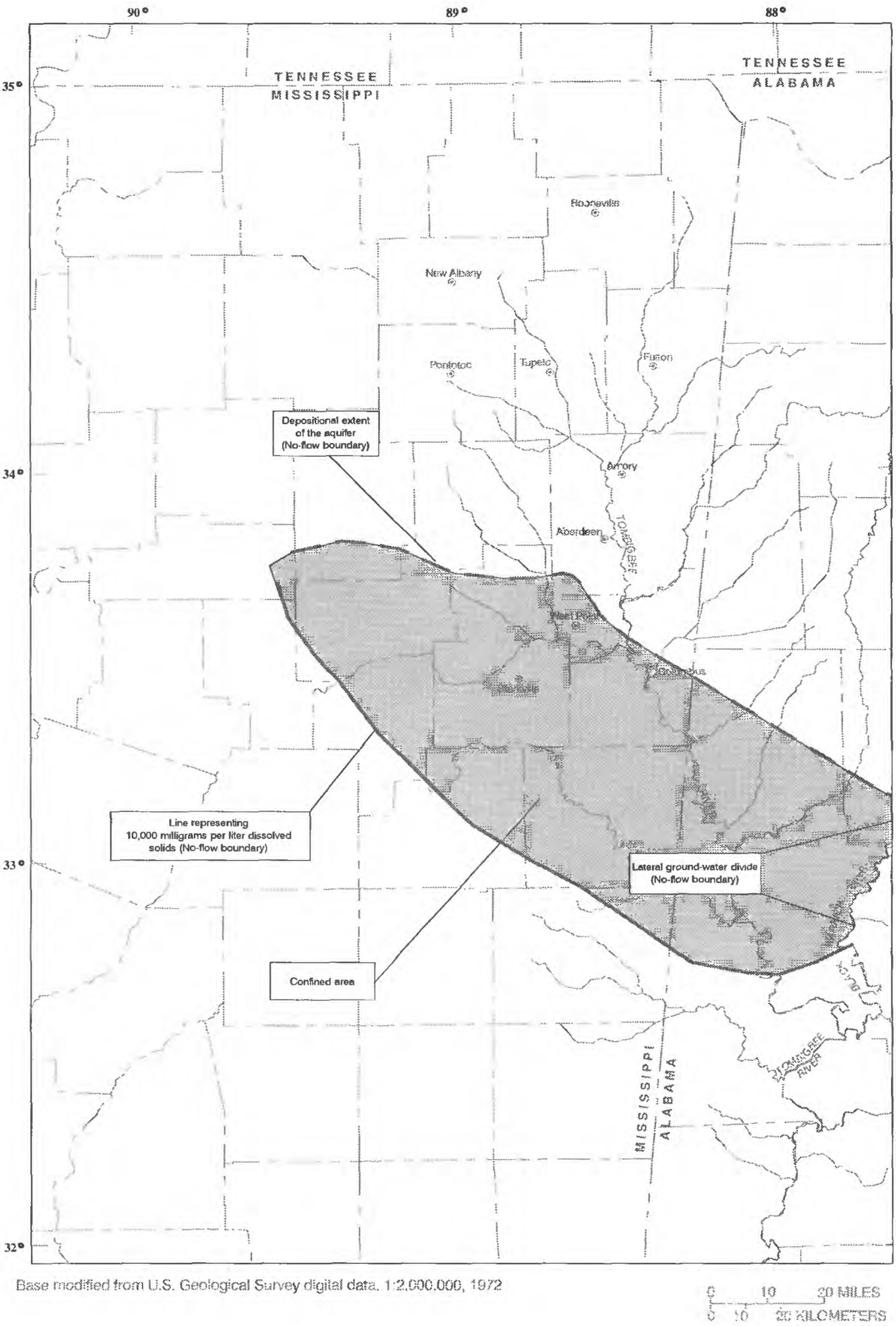
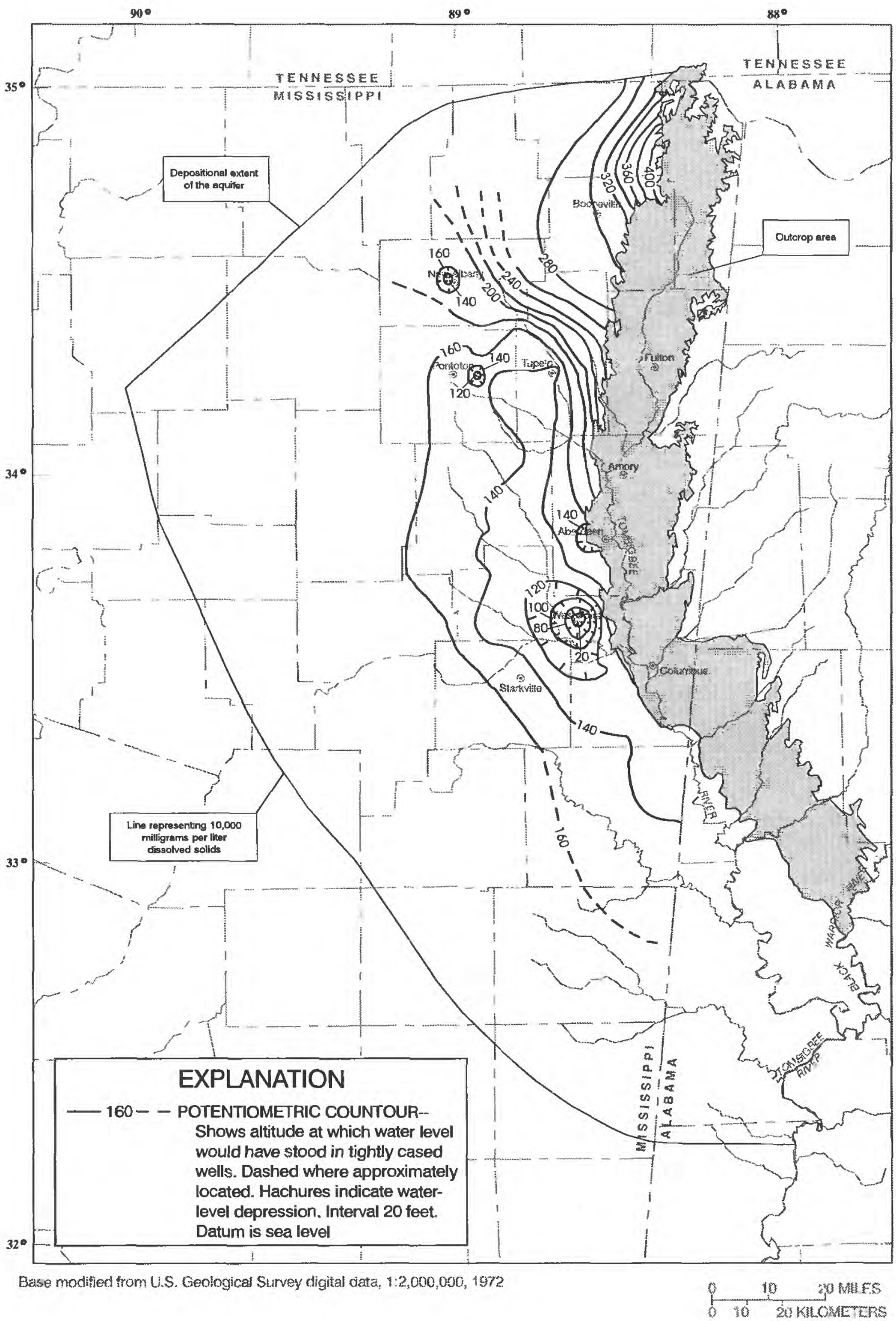


Figure 10. Extent of the Lower Cretaceous aquifer.



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

Figure 11. Potentiometric surface map of the Eutaw-McShan aquifer based on 1992 water-level measurements (modified from Everett and Jennings, 1994).

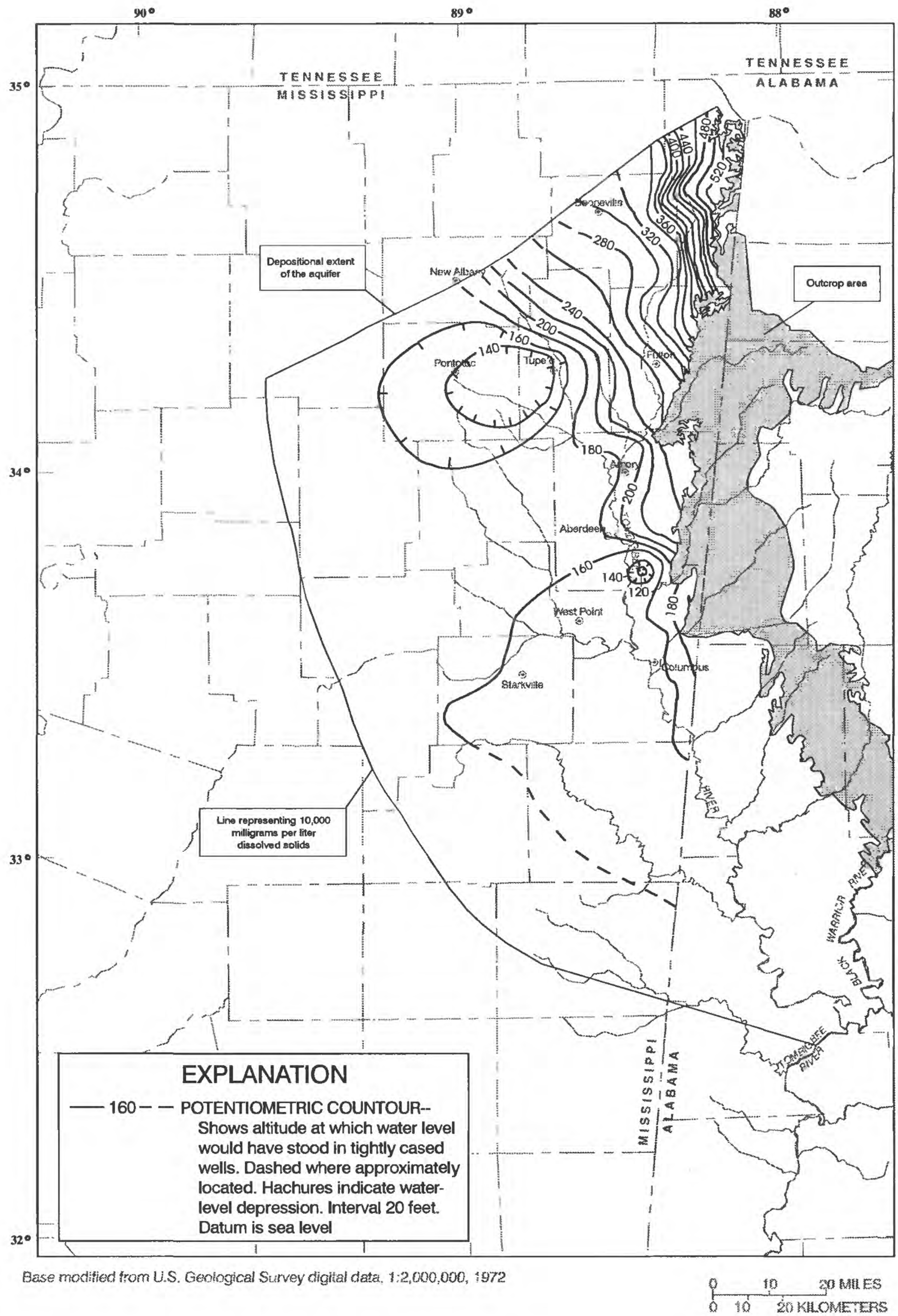


Figure 12. Potentiometric surface map of the Gordo aquifer based on 1992 water-level measurements (modified from Phillips and Hoffmann, 1994).

some flow enters the Eutaw-McShan aquifer from the overlying Coffee Sand aquifer (J.H. Hoffmann, oral commun., 1994). Some water may also enter and leave the Eutaw-McShan aquifer in the far northeastern counties of Mississippi from an underlying Paleozoic aquifer of fractured rock (S.P. Jennings, oral commun., 1994). However, the Eutaw-McShan aquifer does not transmit water efficiently in this area, and any exchange of water probably has a minor effect on the aquifer. Ground-water movement in the aquifer outcrop areas is from topographic highs to topographic lows. Limited water-level data in the Coker and massive sand aquifers indicate that the regional flow patterns are similar to those of the overlying aquifers, and it is assumed that any flow within the Lower Cretaceous aquifer would have the same regional flow pattern as that in the overlying aquifers of the system.

Ground-Water Withdrawal

Most water withdrawn for public and industrial water use in northeastern Mississippi is from the Eutaw-McShan aquifer and from the Tuscaloosa aquifer system. Ground-water use has generally been increasing since World War II, although Tupelo has begun to use surface-water sources. Cones of depression in the potentiometric surfaces of the Eutaw-McShan and Gordo aquifers have recovered in some areas, such as Tupelo in Lee County, as a result of decreasing ground-water withdrawal. In most other areas the cones of depression in the potentiometric surfaces have stabilized or are increasing in size.

Relatively large withdrawals from the Eutaw-McShan aquifer have historically occurred at Booneville in Prentiss County, at New Albany in Union County, at Pontotoc in Pontotoc County, at Tupelo in Lee County, at Aberdeen in Monroe County, and at West Point in Clay County (fig. 1). In 1992, about 14 million gallons per day was withdrawn from the Eutaw-McShan aquifer in and around the pumping centers listed above.

Relatively large withdrawals from the Gordo aquifer have historically occurred at Booneville in Prentiss County, at Pontotoc in Pontotoc County, at Tupelo in Lee County, at Fulton in Itawamba County, at Amory and industries south of Aberdeen in Monroe County, at West Point in Clay County, at Starkville in Oktibbeha County, and at Columbus and industries south of Columbus in Lowndes County (fig. 1). In 1992, about 33 million gallons per day was withdrawn from the Gordo aquifer in and around the pumping centers listed above.

Analysis of borehole-geophysical logs by the OLWR indicates that much of the water previously thought to have been withdrawn from the Coker aquifer was actually from the underlying massive sand aquifer (J.H. Hoffmann, oral commun., 1994). As a result, relatively little water is now (1994) thought to have been withdrawn from the Coker aquifer. Instead, the massive sand aquifer has relatively large withdrawals at Aberdeen in Monroe County, and at Columbus and industries south of Columbus in Lowndes County (fig. 1). In 1992, about 16 million gallons per day was withdrawn from the massive sand aquifer. No significant withdrawal is thought to have occurred from the Lower Cretaceous aquifer within the study area.

SIMULATION OF GROUND-WATER FLOW

A quasi-three-dimensional, numerical model of ground-water flow was developed. The analysis of water flow was made using results from the model simulations representing the Eutaw-McShan aquifer and Tuscaloosa aquifer system. Included in this section is a description of the model, simulations of 1992 and predevelopment ground-water flow conditions, projected effects of increased ground-water withdrawals, and model limitations.

Model Description

Anisotropic and heterogeneous three-dimensional flow of ground-water, assumed to have constant density, may be described by the partial-differential equation:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z}) - W = S_s\frac{\partial h}{\partial t}$$

where

K_{xx}, K_{yy}, and K_{zz} = components of the hydraulic conductivity tensor,

S_s = specific storage,

W = source or sink term,

h = potentiometric head,

t = time.

The finite-difference computer code MODFLOW (McDonald and Harbaugh, 1988) numerically approximates this equation, and was used to simulate the Eutaw-McShan aquifer and Tuscaloosa aquifer system. Published data and data from field investigations were collected and reviewed prior to model input. Data analysis included determining the geologic framework of the aquifer system to be modeled. The aquifers were simulated as separate layers and discretized into two-dimensional finite-difference grids. Applying the field data to the grid required matching parameter values to the scale of the model. After determining the grid size, the hydraulic characteristics for aquifers and confining units were applied to the model.

Grid Design

The model grid covers 33,440 square miles, primarily in northeastern Mississippi, but includes parts of northwestern Alabama, southwestern Tennessee, and eastern Arkansas (fig. 13). The focus of the study is northeastern Mississippi; however, parts of other States are included to simulate the boundary conditions. The model grid was oriented north-south because no predominant axes of transmissivity for the aquifers were indicated by the data. A lateral anisotropy ratio of one was used in the simulations. Each grid layer consists of 220 rows and 152 columns. The model was vertically discretized into six layers resulting in a total of 200,640 grid cells in the model. Layer 1 represents the closest potential water-bearing units overlying layer 2 --the Coffee Sand, Ripley, and lower Wilcox aquifers, and surficial deposits. Layers 2, 3, 4, 5, and 6 represent the Eutaw-McShan, Gordo, Coker, massive sand, and Lower Cretaceous aquifers, respectively. Each grid cell was dimensioned 1 mile on a side to allow a broader areal range of use for the model, because areas of interest may change, and because the distribution of input data used to determine structure and thicknesses for the aquifers was of a matching scale in several areas.

Boundaries

Model boundaries determine where and how much water enters and leaves the model; therefore, the selection of boundaries for the aquifers is a major concern in any modeling effort. The selection of model boundaries for the aquifers in this model were based on information reported by Boswell (1963); Boswell and others (1965); Cushing (1966); Hardeman (1966); Moore (1969); Boswell (1978); Gandl (1982); Wasson (1986); Davis (1987); E.H. Boswell,

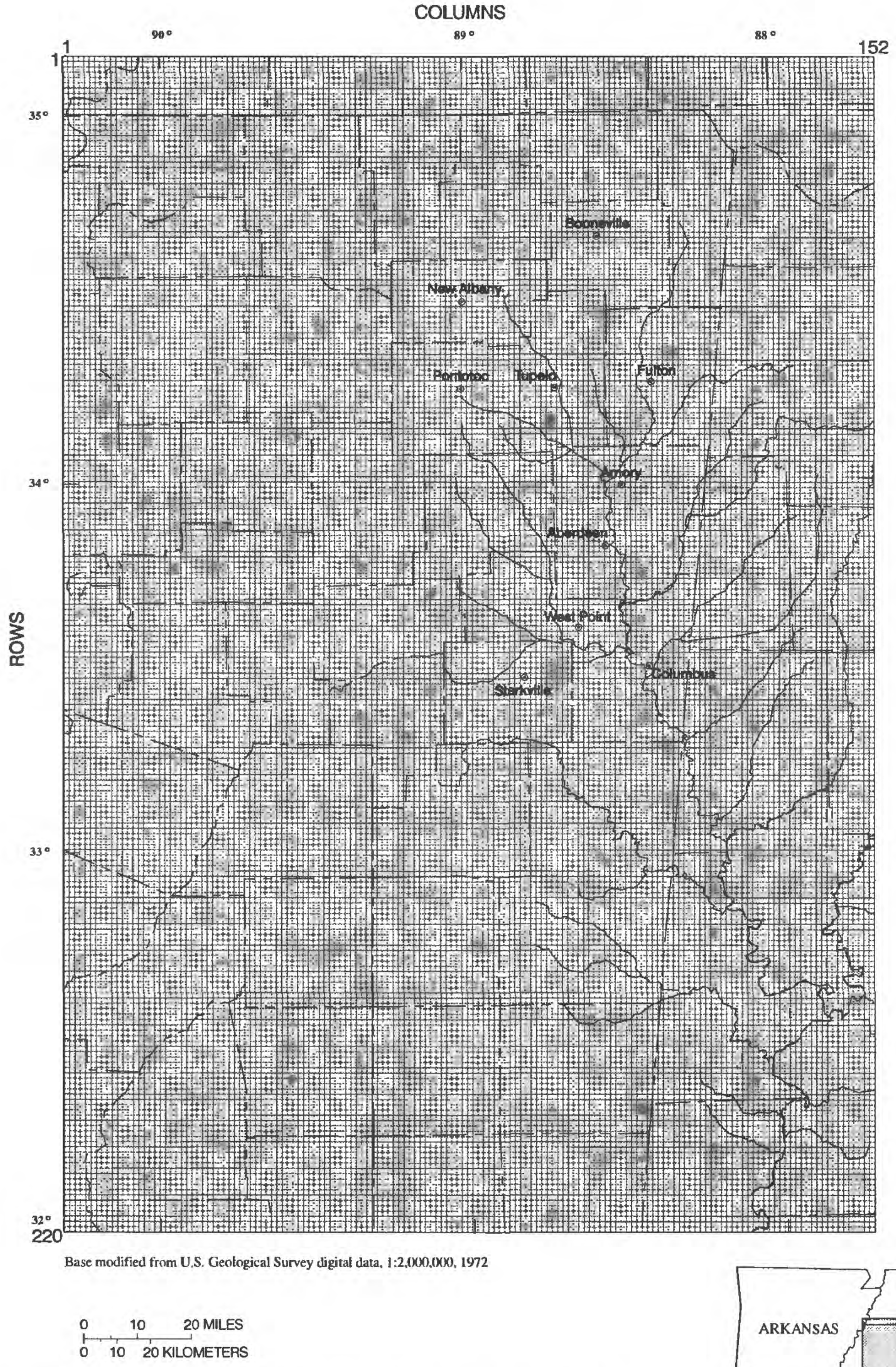


Figure 13. Finite-difference grid used in the numerical model of the Eutaw-McShan and Tuscaloosa aquifers.

J.F. Everett, D.L. Hardin, J.H. Hoffman, S.P. Jennings, and P.A. Phillips (OLWR, oral commun., 1993).

An upper constant-head boundary (layer 1) overlies the Eutaw-McShan aquifer (layer 2). The upper boundary (layer 1) represents the overlying water-bearing units above the Eutaw-McShan aquifer (fig. 14). To the north, the heads in layer 1 represent those in the Coffee Sand aquifer and a small area of the overlying Ripley aquifer immediately south of the Coffee Sand. The heads along the western part of layer 1 represent heads of the lower Wilcox aquifer. South of the Coffee Sand heads, along the eastern part of layer 1, the heads represent water levels in surficial water bearing deposits overlying chalk and clay. However, most of layer 1 is separated from the Eutaw-McShan (layer 2) by thick confining units, and flow is limited by the low vertical hydraulic conductivity of the confining units.

The downdip extent of freshwater (defined for the purposes of this study as a concentration of 10,000 milligrams per liter of dissolved solids) represents no-flow lateral boundaries for all of the aquifers simulated in the model (figs. 6-10). A no-flow boundary at this location assumes a stable downdip freshwater-saltwater interface, which appears reasonable because the downdip extent of freshwater for the aquifers has remained nearly stationary since reported by Gandl (1982). For many of the aquifers, the region where the dissolved-solids concentrations are between 1,000 and 10,000 milligrams per liter is relatively small, which also implies little mixing and flow parallel to the freshwater-saltwater interface. If flow were across the interface in the downdip direction, flow would eventually move upward at some point to discharge; flow upward is unlikely because the confining units above the Eutaw-McShan thicken to the southwest in the downdip direction to more than 1,500 feet near the freshwater-saltwater interface. Any significant upward flow would have to be through secondary structural features, such as faults. The freshwater-saltwater interface has been similarly treated as a no-flow boundary in the Southeastern Coastal Plain aquifers in Mississippi by Mallory (1993) and Arthur (1994).

The northern boundaries of all of the aquifers are the depositional limits of the sediments, and are simulated as no-flow boundaries (figs. 6-10). The southeastern boundaries of the aquifers are also simulated as no-flow boundaries. The southeastern boundaries are at a lateral ground-water flow divide formed by the Tombigbee and Black Warrior Rivers. Water-level data indicate that these rivers, particularly near their confluence, are major discharge areas for the Eutaw-McShan and Gordo aquifers, with all lateral flow converging from both the east and the west, being captured by the river channels (Gardner, 1981). Consequently, no lateral flow moves across the Tombigbee and Black Warrior Rivers. Water is discharged upward by leakage through the confining units. Although no water-level data are available for the Coker, massive sand, and Lower Cretaceous aquifers in this area, regional flow patterns are assumed to be similar throughout the Tuscaloosa aquifer system (Mallory, 1993; J.H. Hoffmann, oral commun., 1993), and a lateral ground-water flow divide is also simulated for these aquifers--with flow moving upward by leakage as a result of vertical head gradients with the overlying aquifers. In all of the aquifers except the Eutaw-McShan, the eastern grid-line boundary formed by the eastern edge of the model grid (figs. 6-10) was simulated as a lateral no-flow boundary because the eastern edge of the grid in this area was chosen to approximate the ground-water and surface-water flow divide between the Tombigbee and Black Warrior River drainage basins.

The outcrop areas of the Eutaw-McShan, Gordo, and Coker aquifers are simulated with head-dependent flux boundaries (figs. 6-8). An average of about 52 inches per year of precipitation falls on these outcrop areas. Only a small fraction of this amount enters the ground-water flow system as recharge. Some of the water that enters the ground-water flow system travels only a short distance before being discharged locally; in terms of the digital model, much of this localized flow is invisible at the one-mile grid discetization. The model simulations represent only the

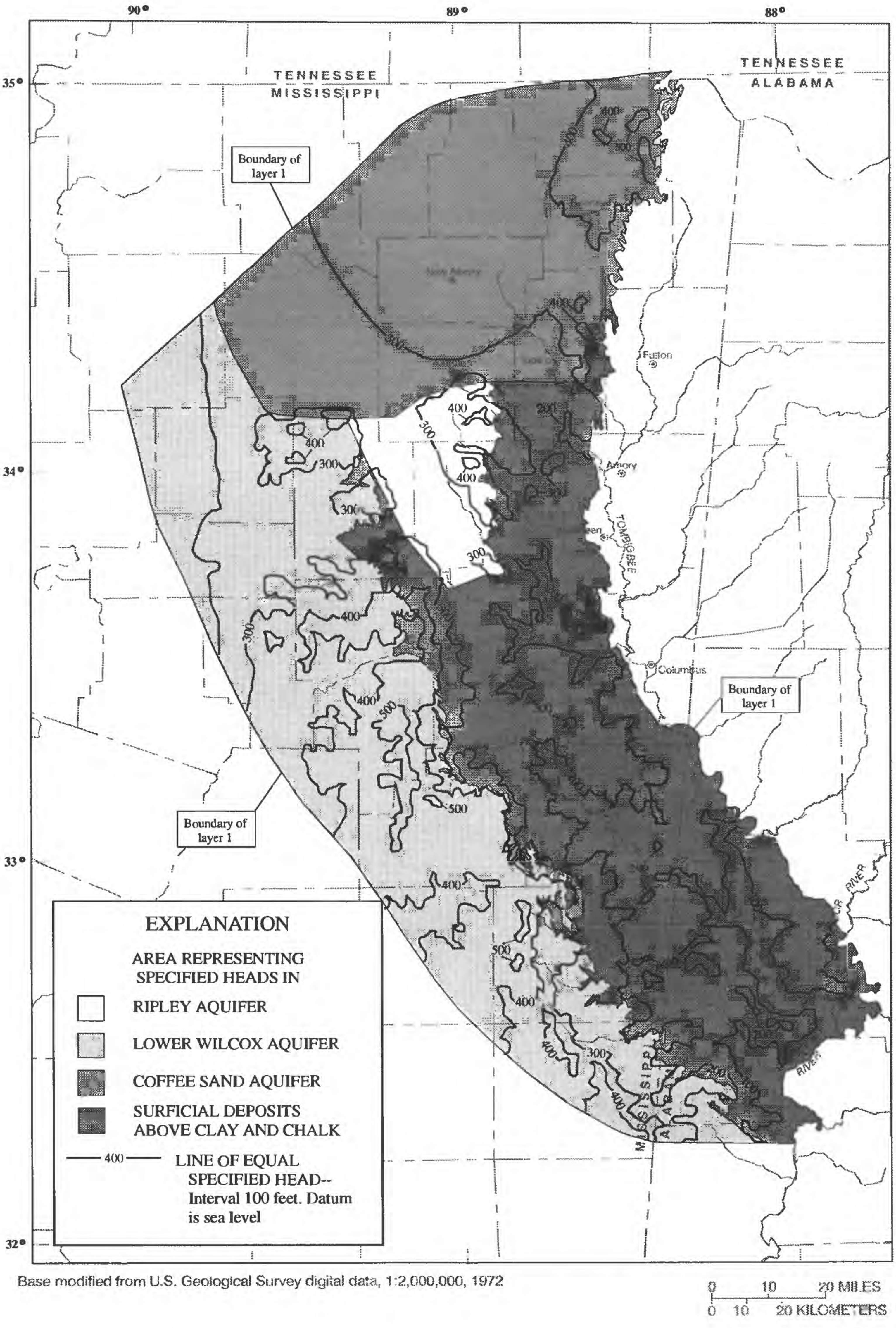


Figure 14. Specified heads for model layer 1 (upper boundary).

intermediate and regional scale flow system. Because allocations of total recharge between local, intermediate, and regional flow systems is difficult to accurately determine, recharge in the digital model was simulated by head-dependent flux nodes throughout the outcrop areas. This was implemented using the river package in MODFLOW (McDonald and Harbaugh, 1988). The large base flows observed in even small streams in the outcrop area indicate that recharge in the precipitation rich environment is more than sufficient to provide all the recharge that the aquifers can accept, and that much of the potential recharge is rejected by the aquifers and diverted into surface runoff. The minimum land-surface altitude in each outcrop grid cell, which approximates stream baseflow-level, represents the driving head for the river package. This method of representing the outcrop areas allowed a better understanding of the distribution of recharge to the aquifer system, derived during the process of model calibration.

The massive sand and Lower Cretaceous aquifers do not crop out, and the northeastern boundaries which represent the depositional limits of the aquifers are simulated with no-flow boundaries (figs. 9-10). The massive sand aquifer has been considered a lower part of the Coker aquifer, but in this study they are simulated as separate aquifers because a confining unit separates them in much of the modeled area. The lateral eastern extent of the massive sand is assumed to be coincident with the lateral eastern extent of the Coker aquifer.

The lower model boundary is a no-flow boundary. This boundary represents relatively impermeable underlying Paleozoic units.

Transmissivity, Horizontal Hydraulic Conductivity, and Storage Coefficient

Sand thickness data from borehole-geophysical logs were used to construct the transmissivity grids for the aquifers. Sand thicknesses represented the total sand thickness for the aquifer at the well site. The sand thickness data for each aquifer were gridded and contoured (figs. 15-19). For the Eutaw-McShan and Gordo aquifers, hydraulic conductivities reported from aquifer tests (Slack and Darden, 1991) were plotted, gridded, and contoured. The hydraulic conductivity grids were multiplied by the corresponding gridded sand thickness data to generate the initial transmissivity grids for the Eutaw-McShan and Gordo aquifers. Horizontal hydraulic conductivity data for the Coker, massive sand and Lower Cretaceous aquifers were insufficient to produce areally variable hydraulic conductivity grids. For these aquifers, reported (Slack and Darden, 1991) and estimated (W.T. Oakley, oral commun., 1994) average values of hydraulic conductivity were multiplied by the corresponding sand thickness grids to generate the initial transmissivity grids. Transmissivities for the aquifers are highly variable in the modeled area because the sand thickness generally ranges from about a foot near and within the outcrop areas, to several hundred feet near the west and southwestern boundaries. The final transmissivity grids used in the model are shown in figures 20-24.

Few storage coefficient data are available for the aquifers in the model area and reported values (Boswell and others, 1965; Slack and Darden, 1991) are somewhat variable. A constant value of 0.0001 was used in the model for all of the aquifers. This value is typical for a medium-grained sand aquifer under confined conditions (Driscoll, 1989).

Leakance

Leakance values are used by the model to calculate a vertical conductance for each cell. Leakance values incorporate both vertical hydraulic conductivity and confining unit thickness into a single term. A thorough discussion on the use and formulation of the leakance values may be found in McDonald and Harbaugh (1988). Confining unit thicknesses determined from borehole-geophysical logs were used to make the leakance grids for the model. The confining units are mostly composed of clay and silt. The upper confining unit overlying the Eutaw-McShan

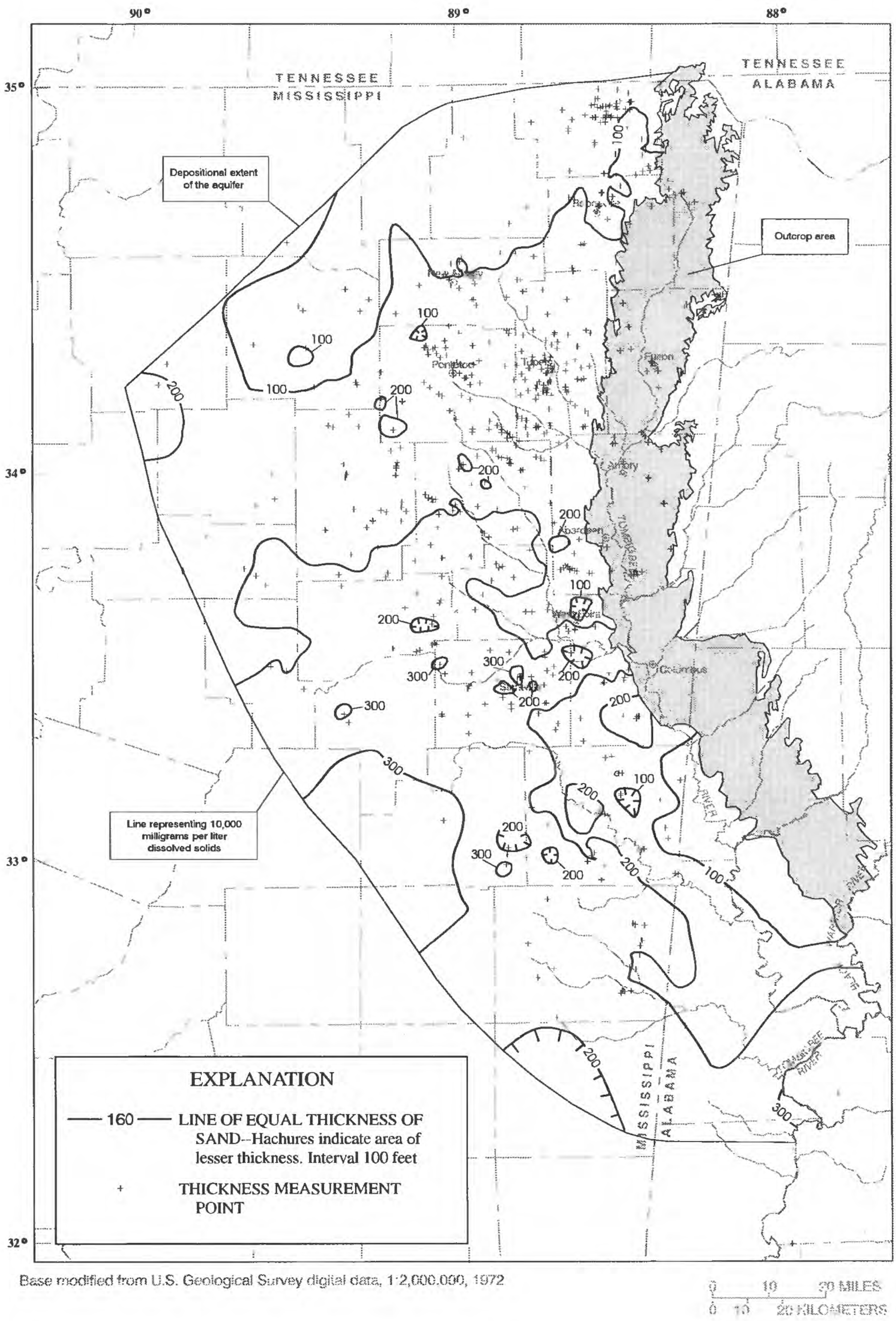


Figure 15. Total sand thickness of the Eutaw-McShan aquifer and location of measurements.

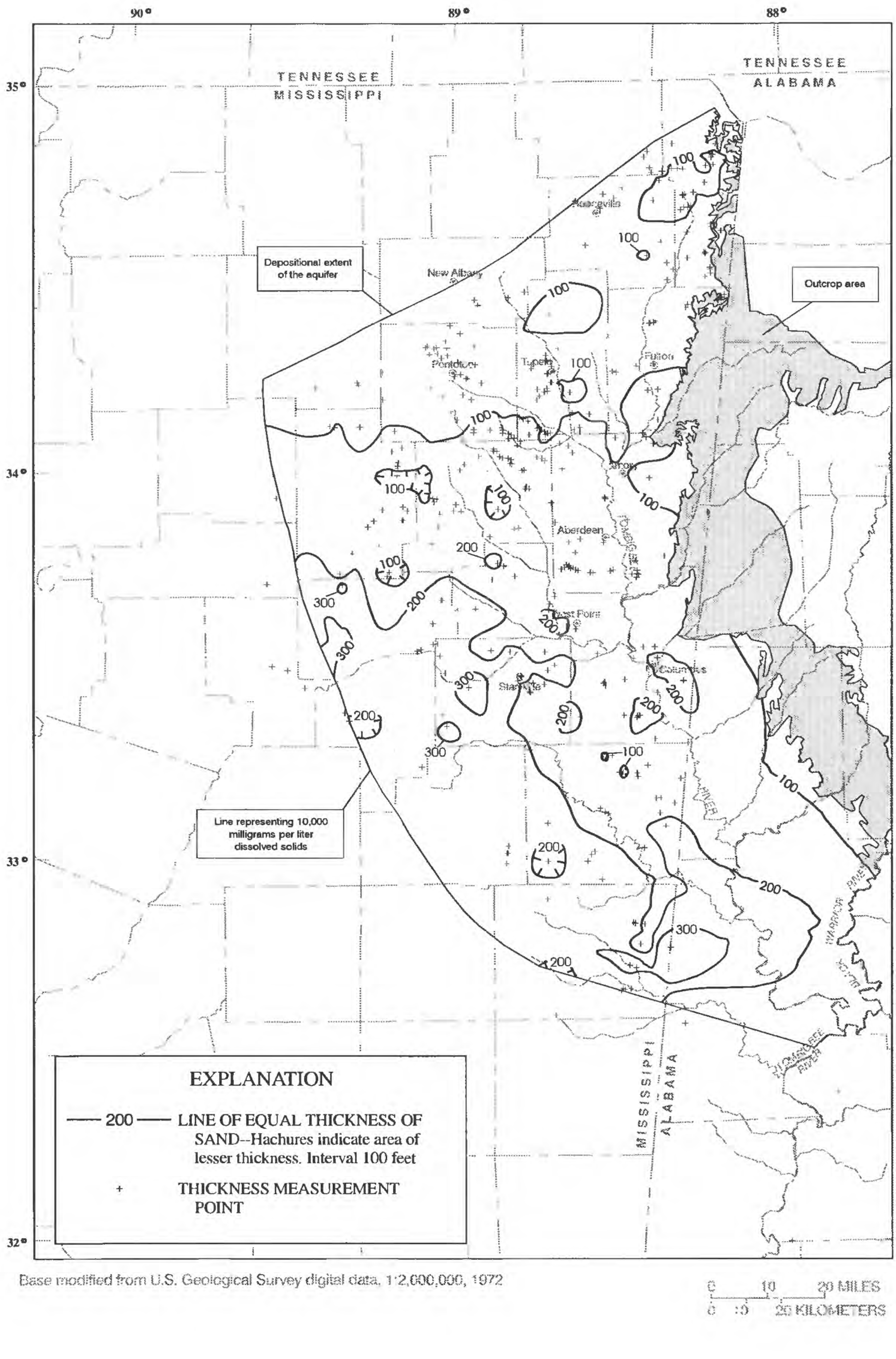


Figure 16. Total sand thickness of the Gordo aquifer and location of measurements.

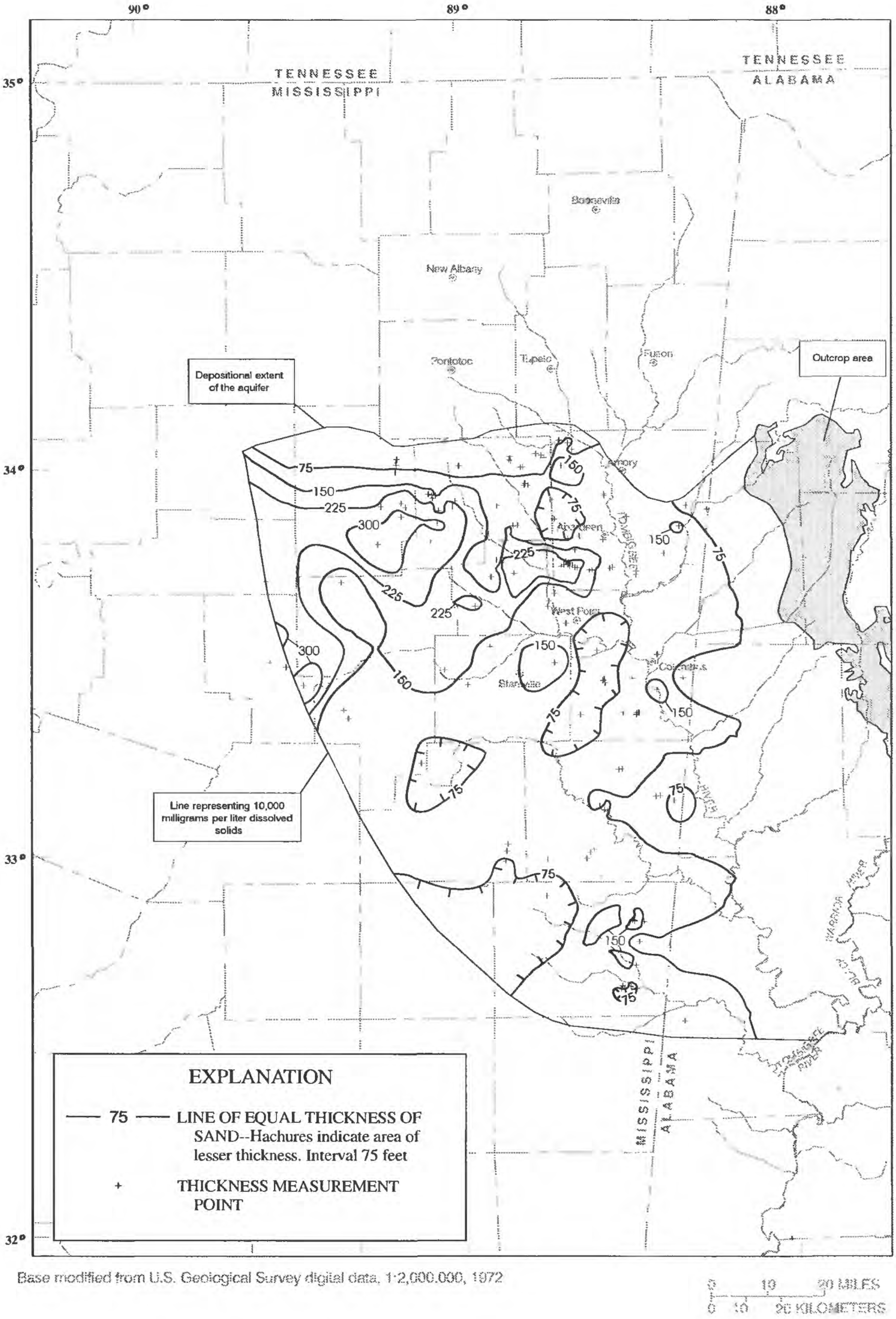


Figure 17. Total sand thickness of the Coker aquifer and location of measurements.

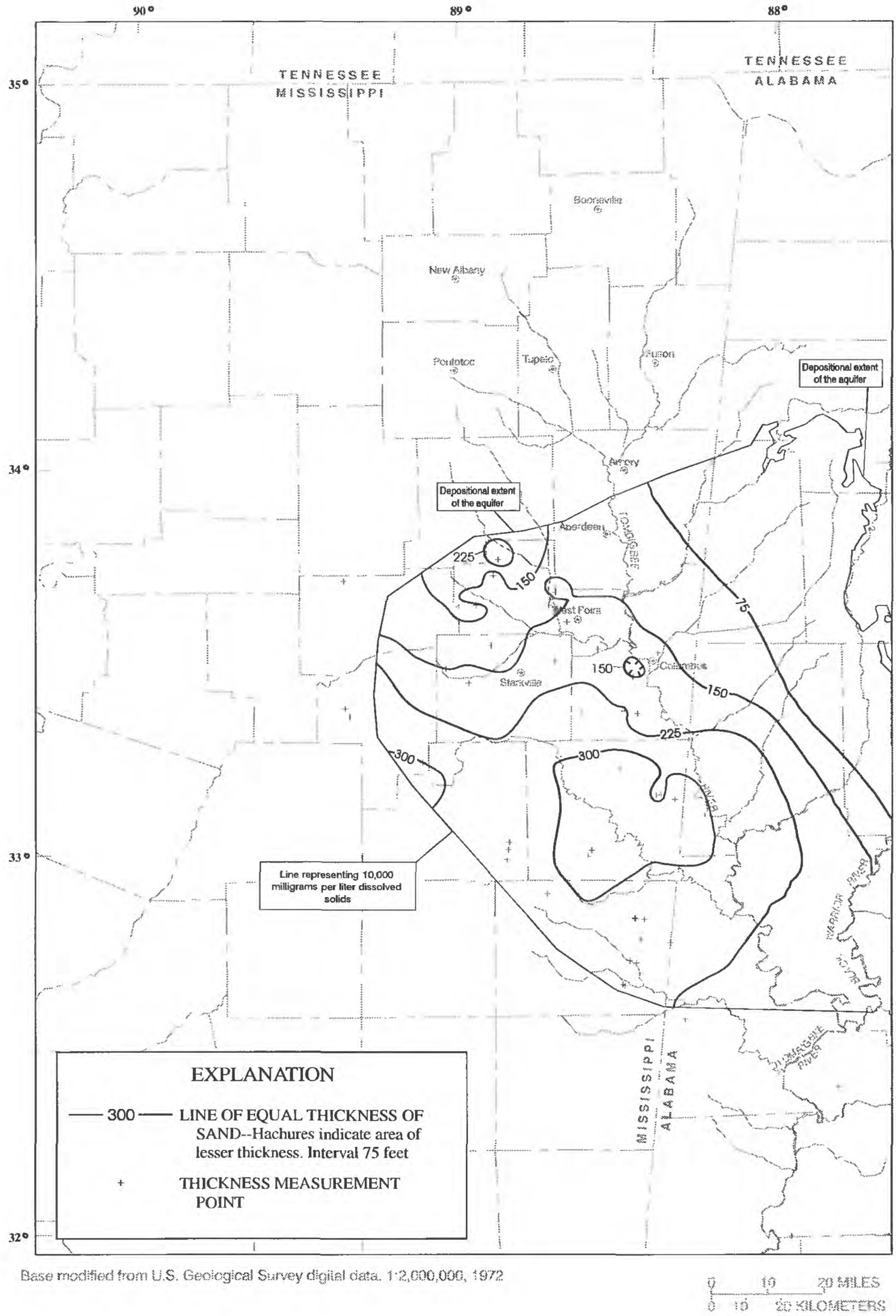


Figure 18. Total sand thickness of the massive sand aquifer and location of measurements.

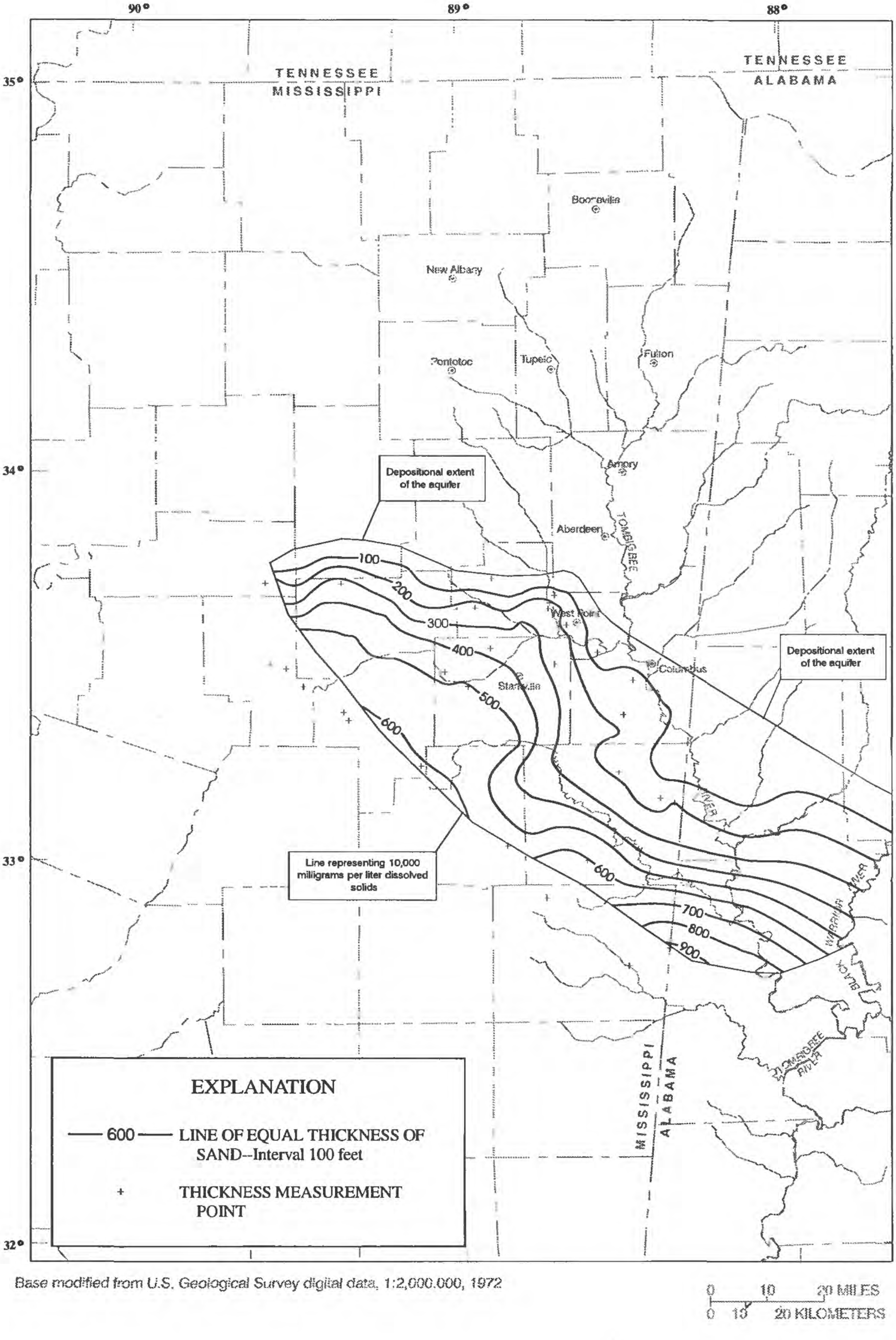


Figure 19. Total sand thickness of the Lower Cretaceous aquifer and location of measurements.

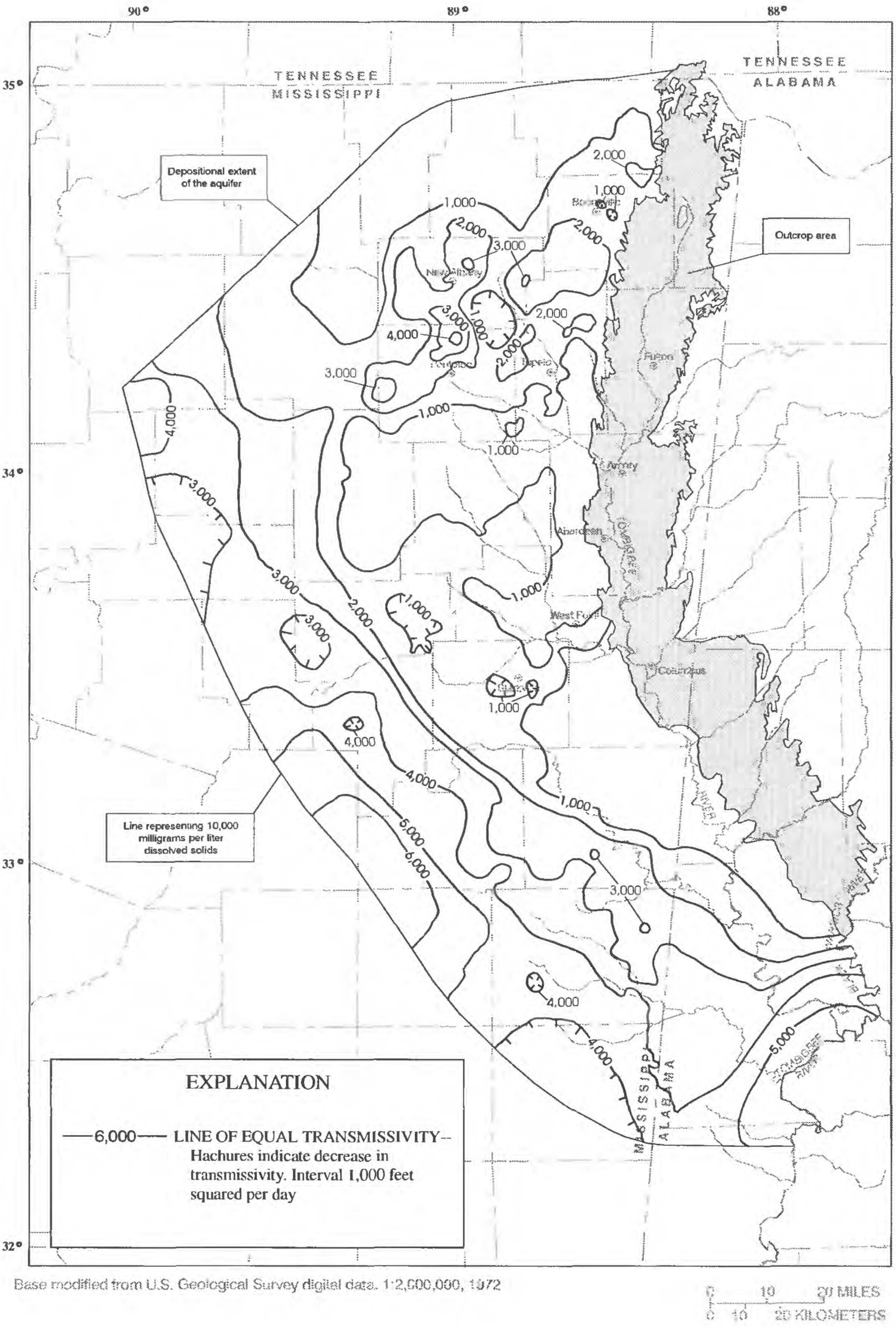


Figure 20. Transmissivity of the Eutaw-McShan aquifer used in model simulations.

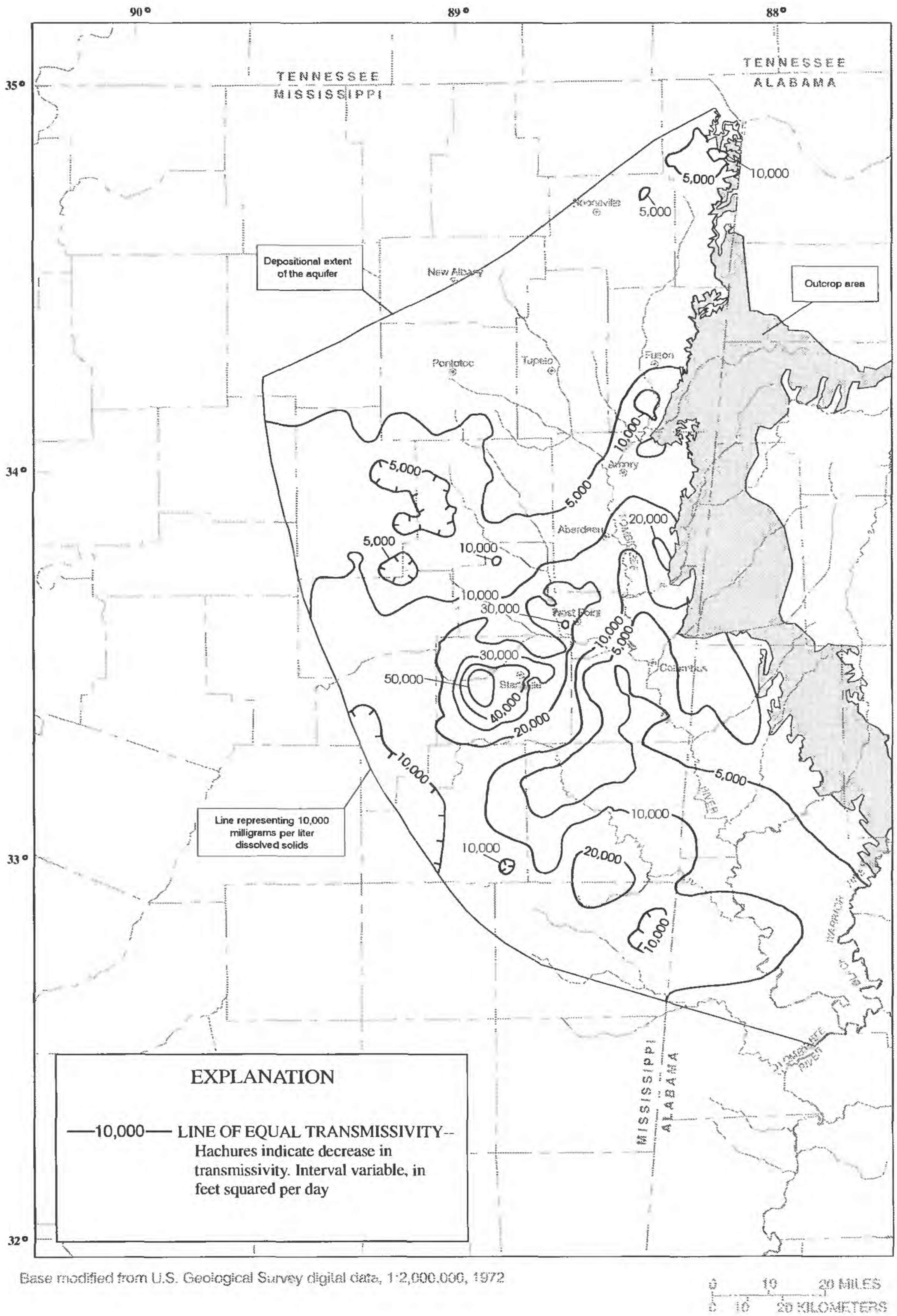


Figure 21. Transmissivity of the Gordo aquifer used in model simulations.

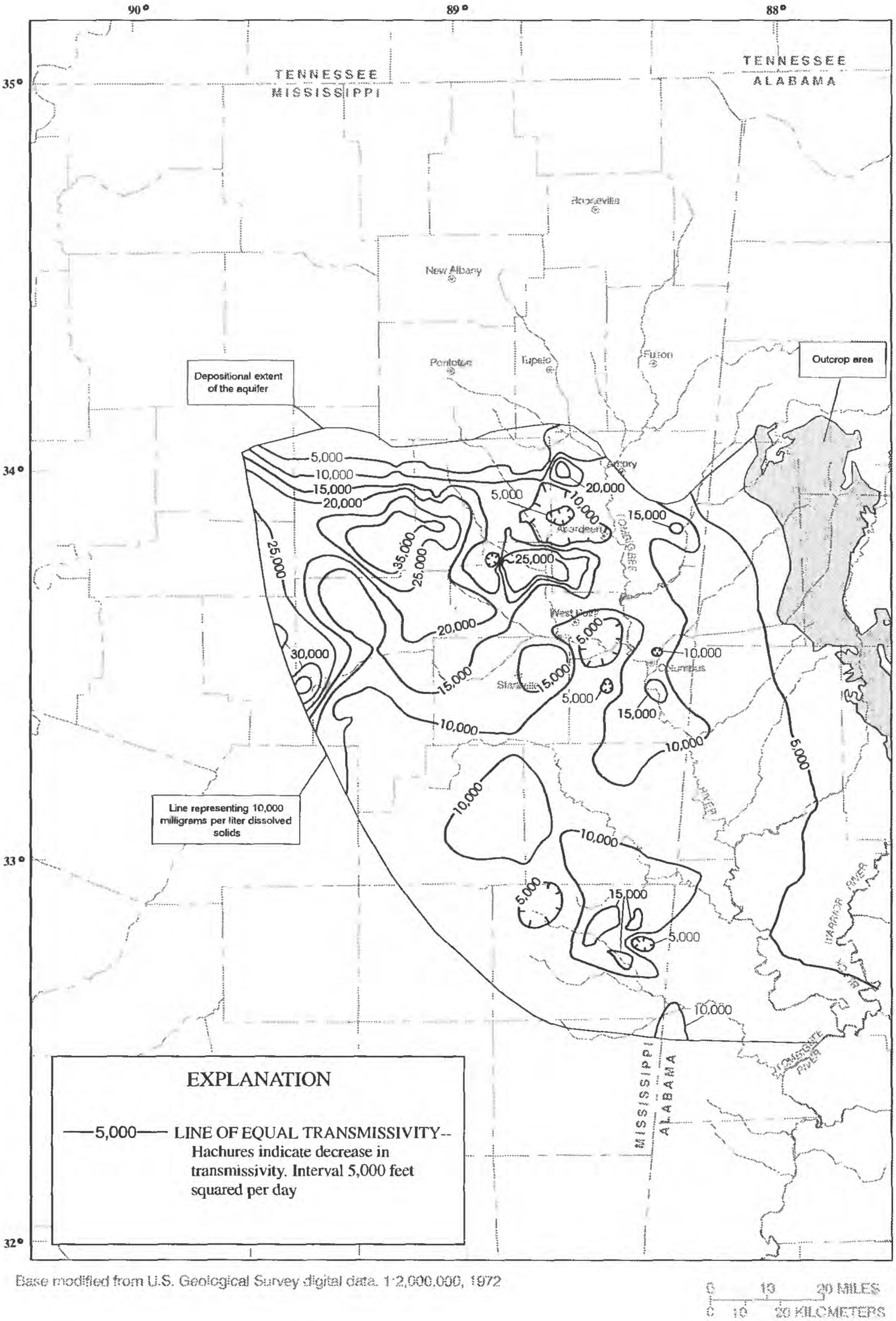


Figure 22. Transmissivity of the Coker aquifer used in model simulations.

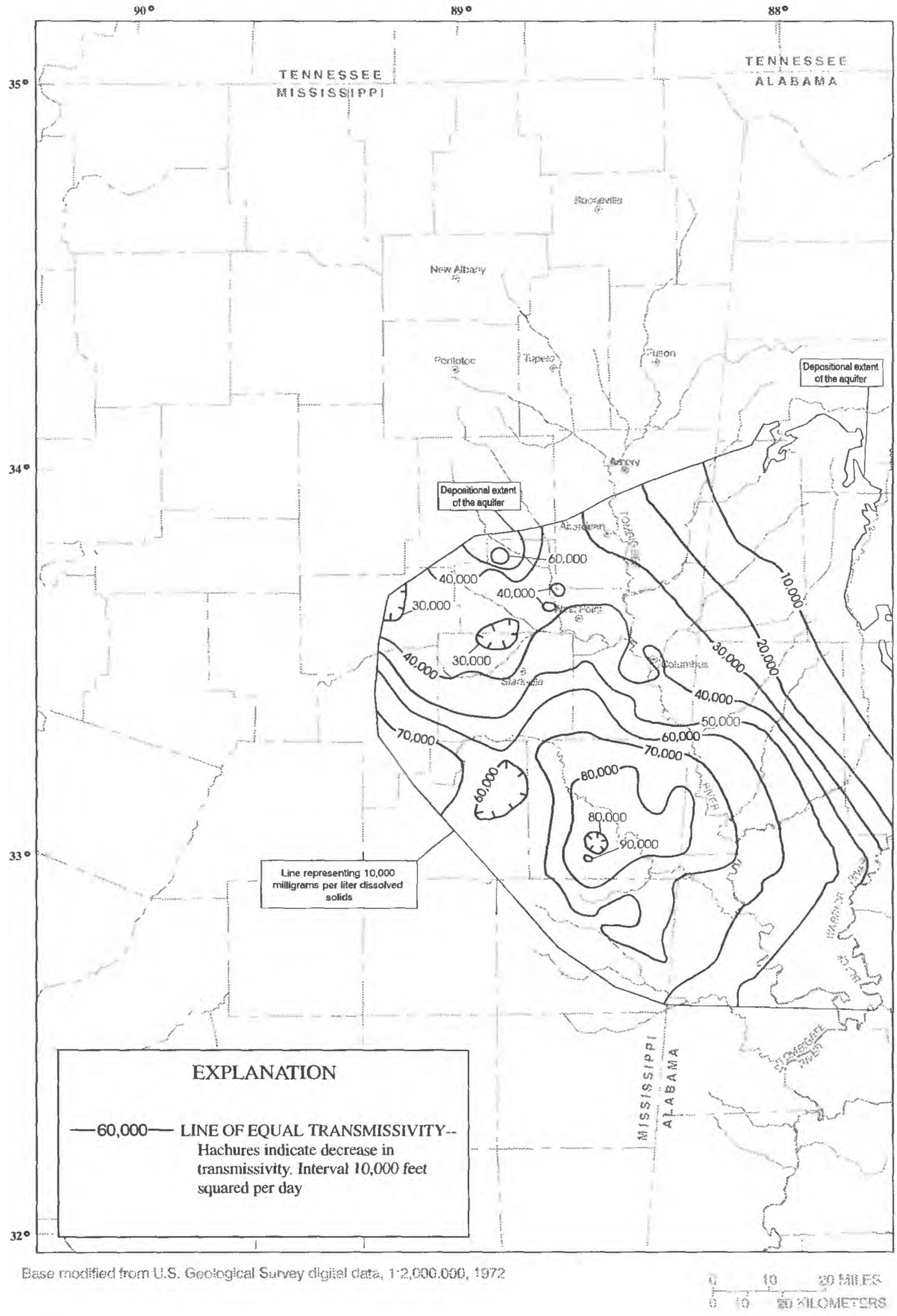


Figure 23. Transmissivity of the massive sand aquifer used in model simulations.

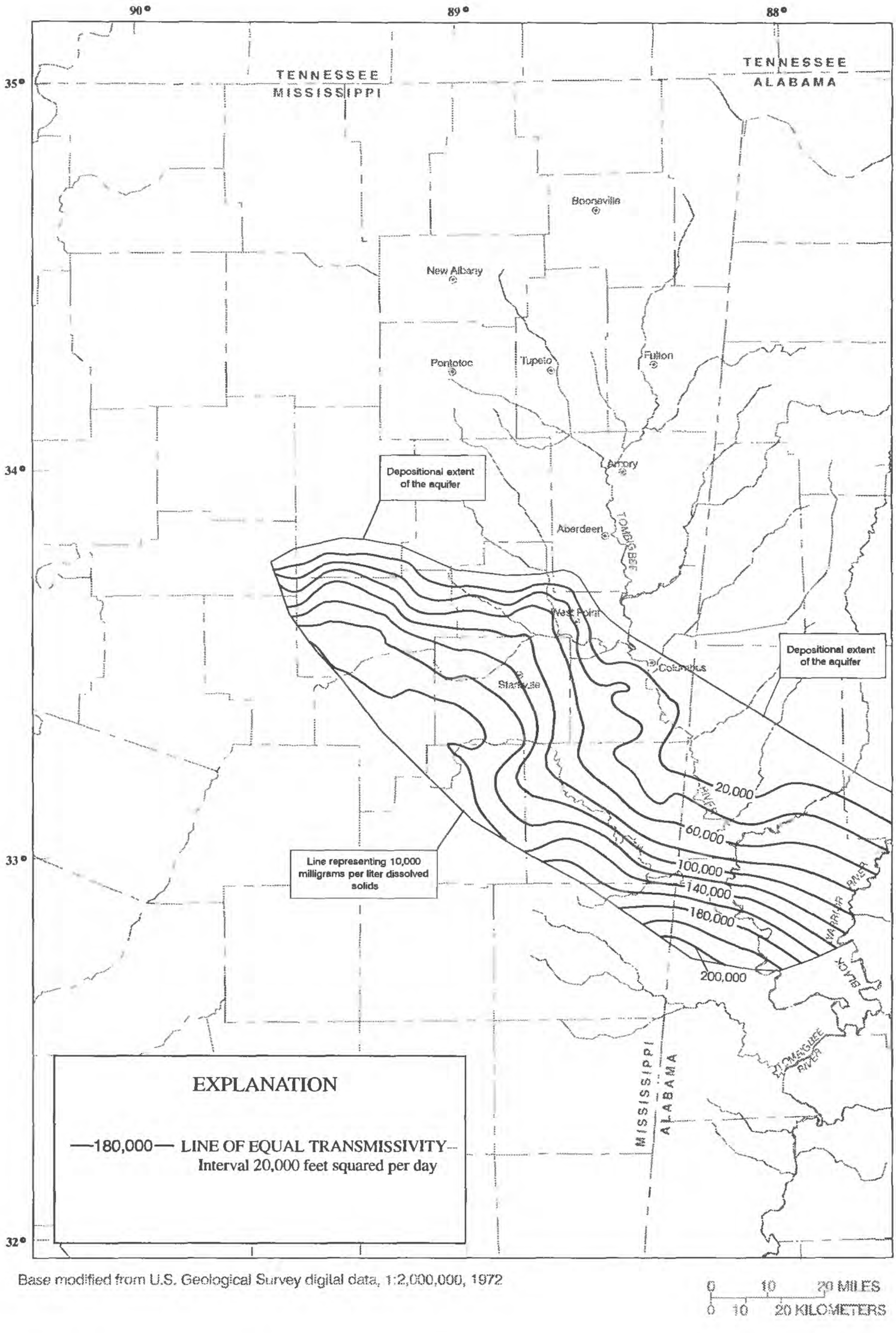


Figure 24. Transmissivity of the Lower Cretaceous aquifer used in model simulations.

aquifer represents the distance to the nearest overlying aquifer or distance to land surface if no aquifer is present. For the Gordo, Coker, massive sand, and Lower Cretaceous aquifers, the confining unit represents the total clay thickness separating each aquifer from the overlying aquifer. These data were then gridded and contoured (figs. 25-29). Limited information on vertical hydraulic conductivity is available for the confining units. A constant vertical hydraulic conductivity value of 0.00001 foot per day initially was assumed for all of the confining units. This value is based on ranges of 0.00001 to 0.000001 reported by Planert and Sparkes (1985) for the clay layer separating the Eutaw-McShan and Gordo aquifers in Marengo County, Alabama (fig. 1), and on horizontal hydraulic conductivity values for clay (Domenico and Schwartz, 1990) reduced to account for anisotropy between vertical and horizontal flow in a layered medium. The initial leakance grids were then generated by dividing the average vertical hydraulic conductivity value of 0.00001 foot per day by the confining unit grids. The final leakance grids used in the model are shown in figs. 30-34.

Strategy of Calibration

The calibration strategy was to initially vary the best known parameters as little as possible, and vary the poorly known or unknown values the most to achieve the best overall agreement between simulated and measured water levels. Model calibration was based on transient conditions because few water-level data representing predevelopment, steady-state conditions for the aquifers modeled are available. The calibrated parameters determined during transient simulations were used for determining simulated heads for predevelopment, steady-state conditions.

During the calibration process many of the initial input parameters required adjustment to some degree to achieve a best fit between simulated and measured water-levels. The initial transmissivity grids were modified during model calibration to produce calibrated transmissivity grids for all of the aquifers. The resultant values of modeled horizontal hydraulic conductivity and values determined from aquifer tests, or estimated, are listed in table 1. The aquifer test values for the Eutaw-McShan and Gordo aquifers are based on aquifer tests reported by Slack and Darden (1991). Fewer data are available for the other aquifers. Values reported for the Coker and massive sand aquifers are based on tests (Slack and Darden, 1991) and on estimates (W.T. Oakley, oral commun., 1994). The value reported for the Lower Cretaceous aquifer is estimated (W.T. Oakley, oral commun., 1994) because no aquifer tests have been made on the aquifer in the modeled area.

Table 1. Average model calibrated and estimated values of horizontal hydraulic conductivity

Aquifer	Average model calibrated value of horizontal hydraulic conductivity (feet per day)	Average test or estimated value of horizontal hydraulic conductivity (feet per day)
Eutaw-McShan	12	12
Gordo	49	48
Coker	100	100
Massive sand	250	200
Lower Cretaceous	250	200

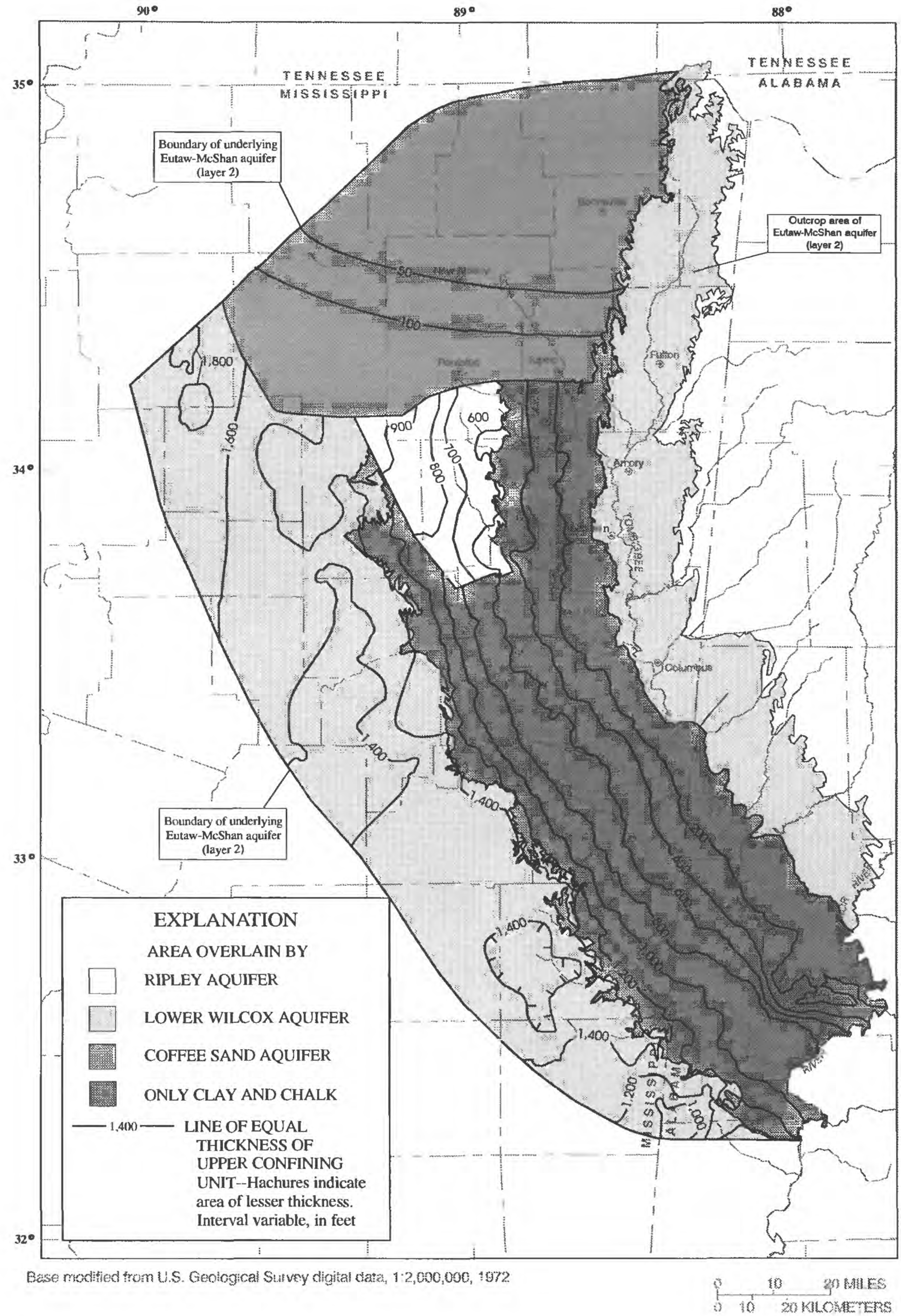


Figure 25. Thickness of upper confining unit overlying the Eutaw-McShan aquifer used in model simulations.

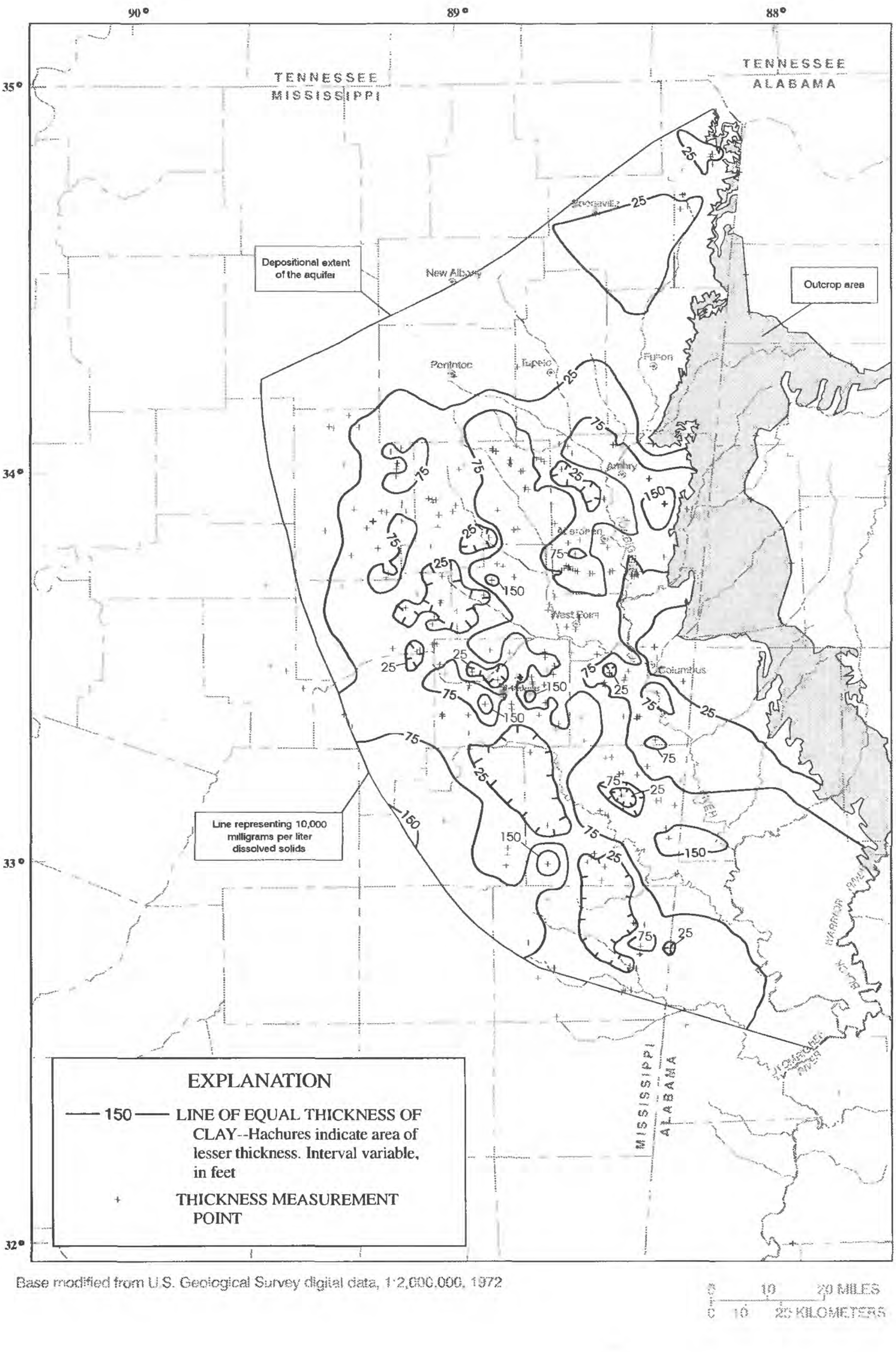


Figure 26. Total clay thickness of the Gordo aquifer and location of measurements.

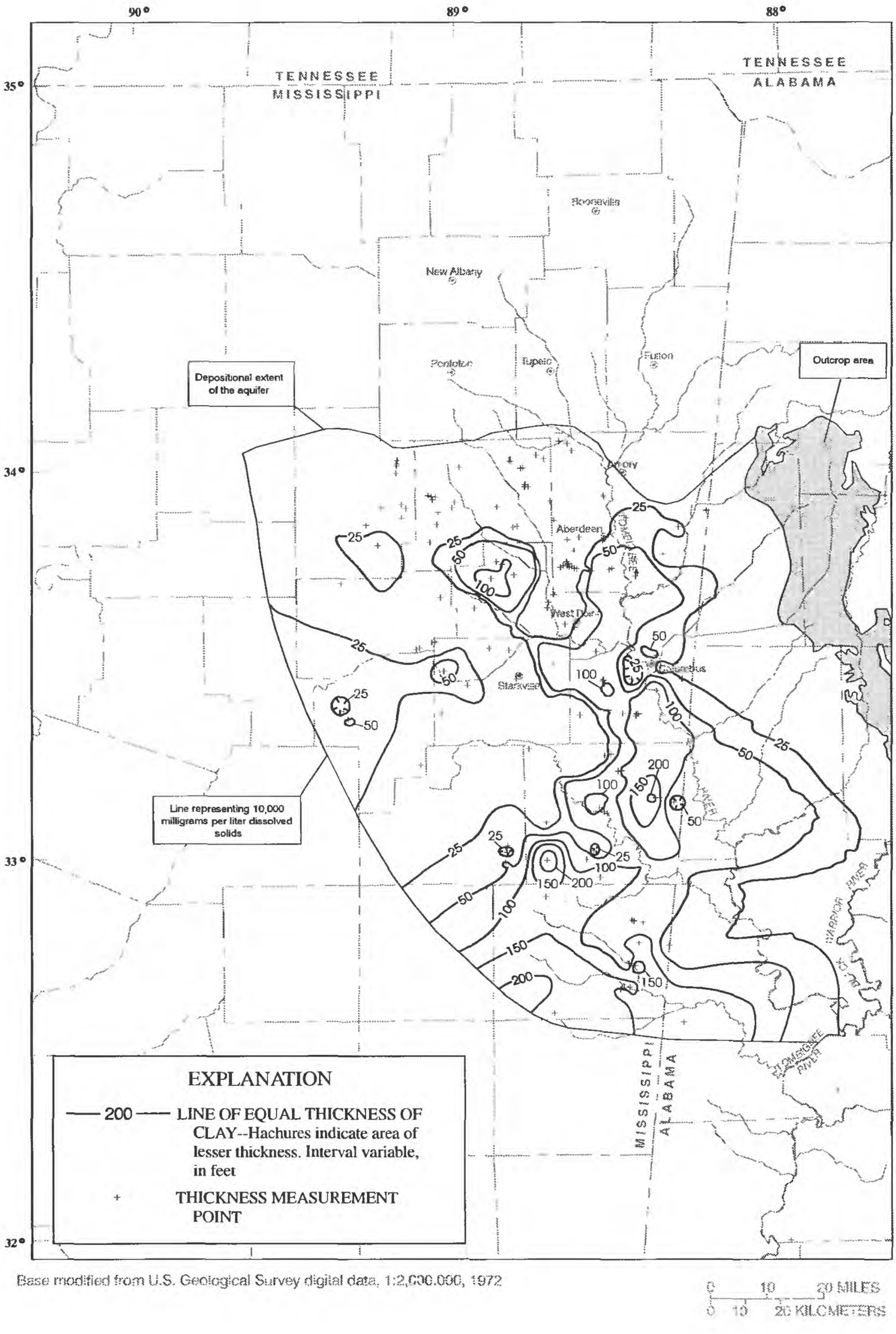


Figure 27. Total clay thickness of the Coker aquifer and location of measurements.

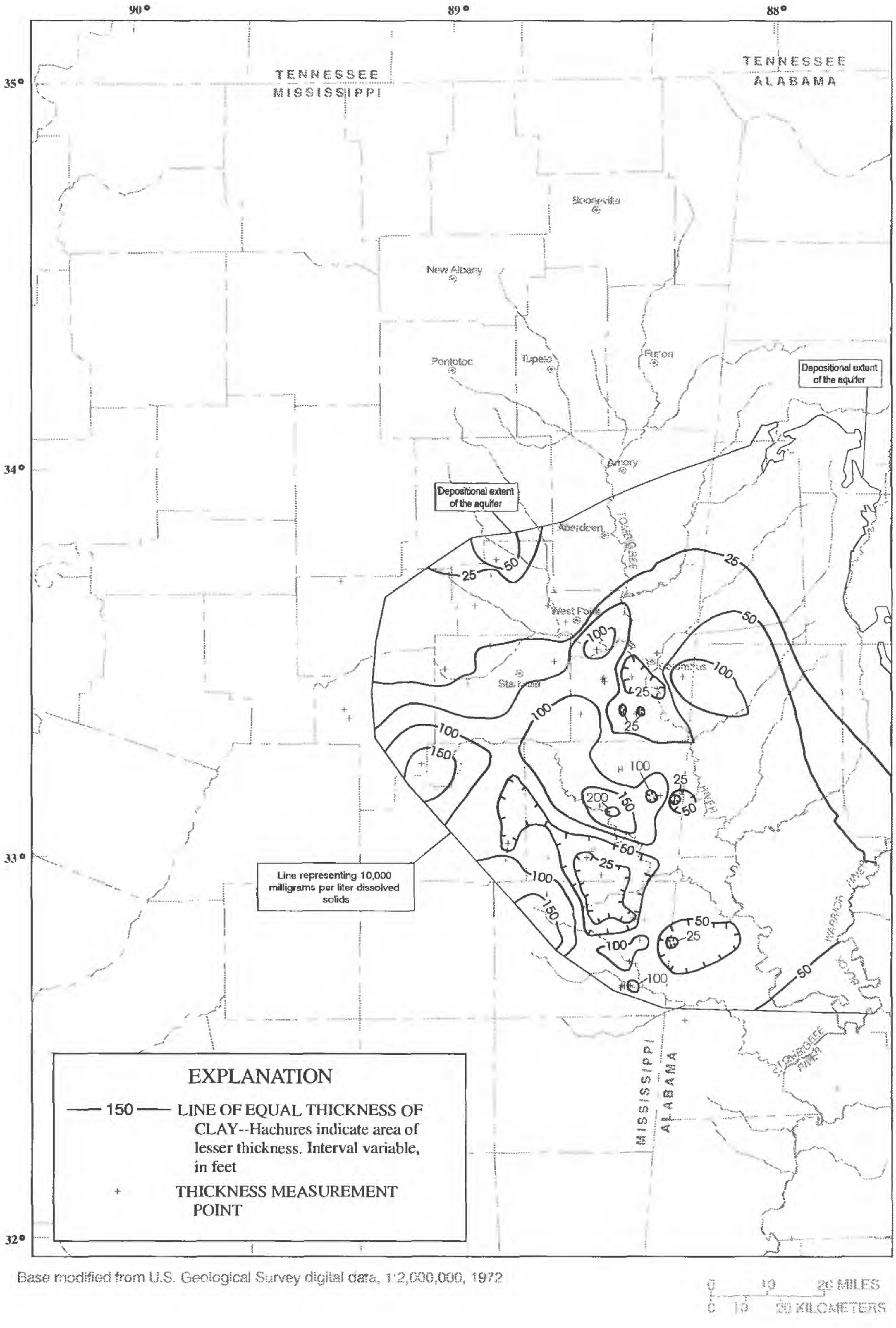


Figure 28. Total clay thickness of the massive sand aquifer and location of measurements.

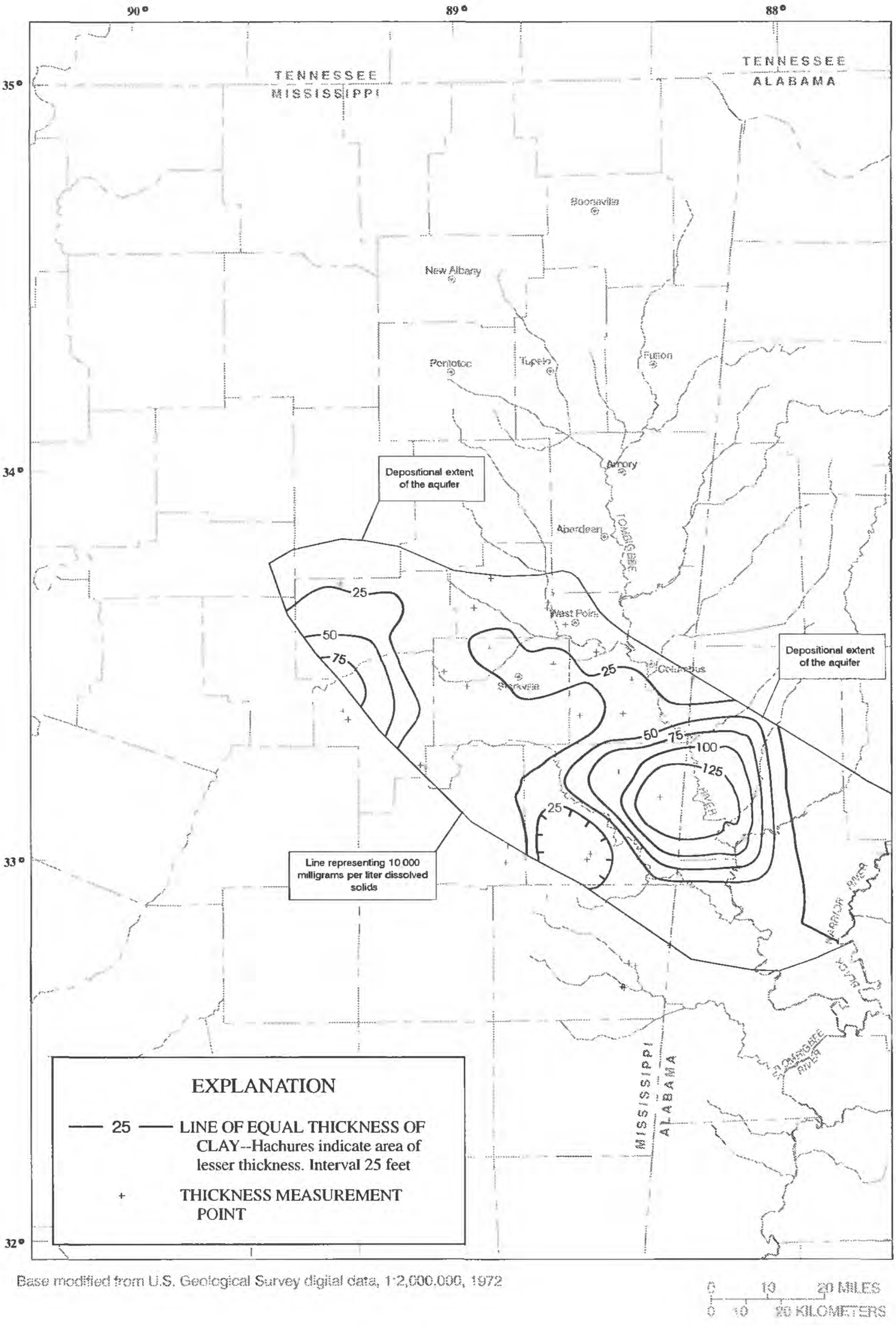


Figure 29. Total clay thickness of the Lower Cretaceous aquifer and location of measurements.

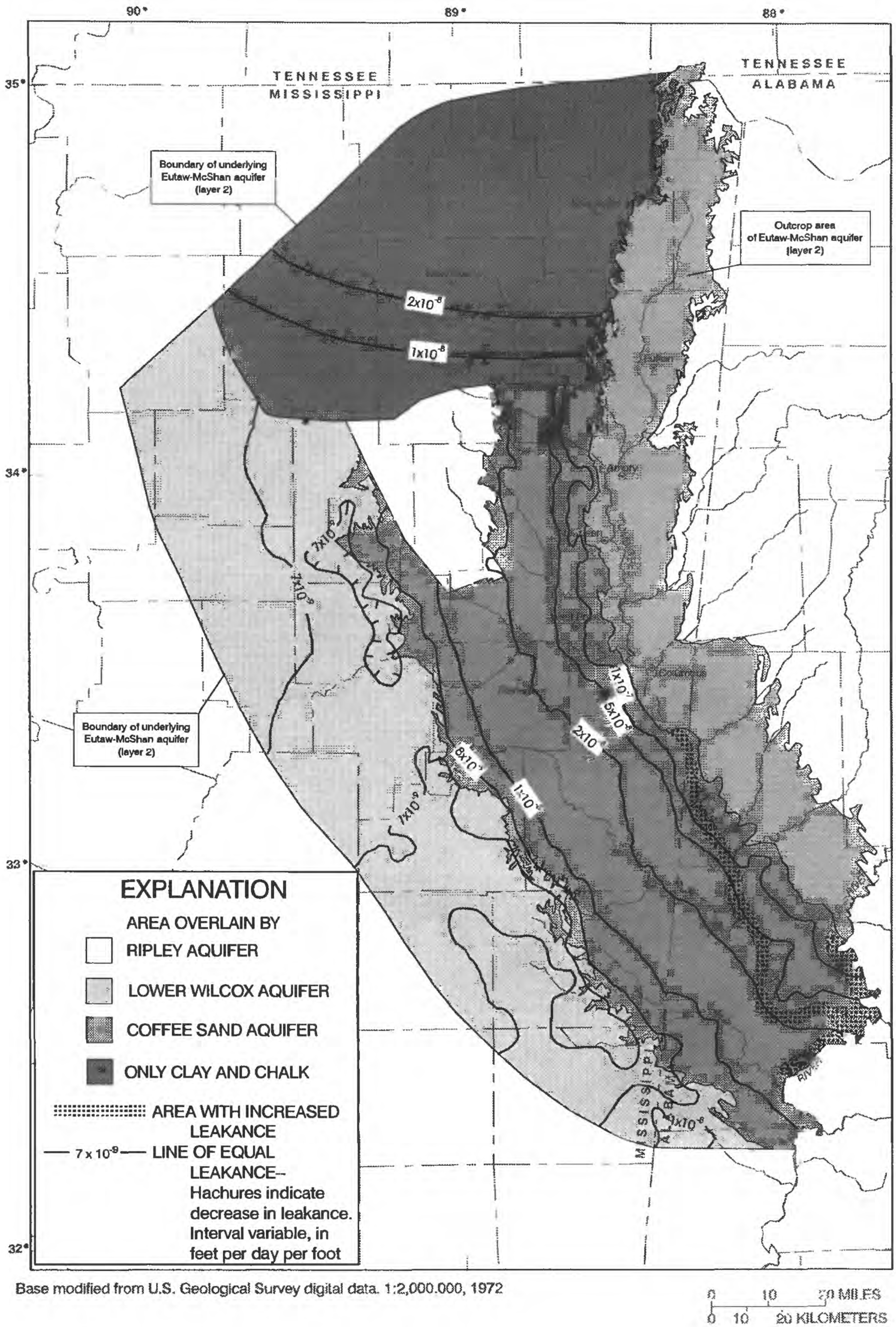


Figure 30. Leakance of confining unit between the Eutaw-McShan aquifer and overlying units used in the model simulations.

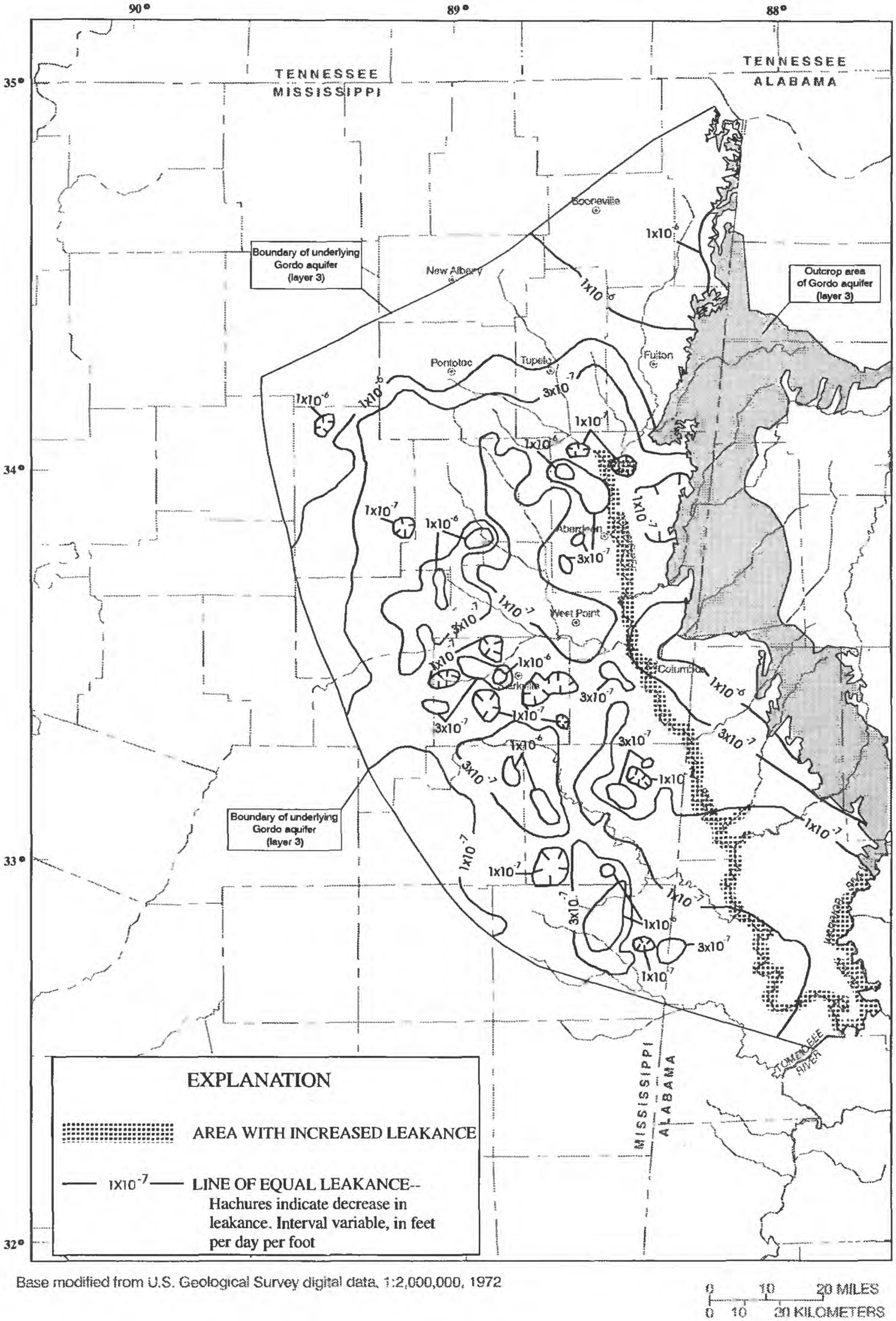


Figure 31. Leakance of confining unit between the Gordo aquifer and the overlying Eutaw-McShan aquifer used in model simulations.

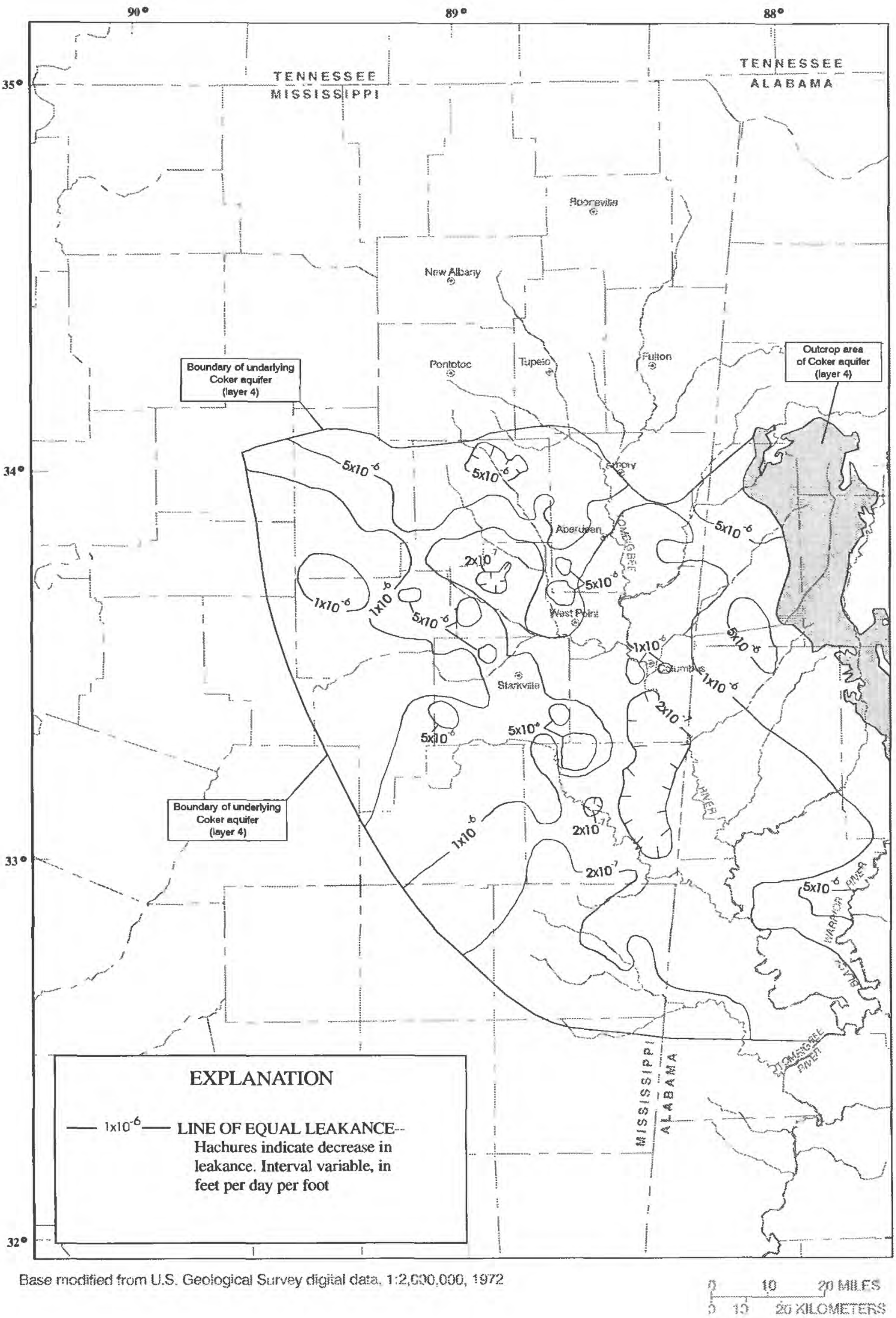


Figure 32. Leakance of confining unit between the Coker aquifer and the overlying Gordo aquifer used in the model simulations.

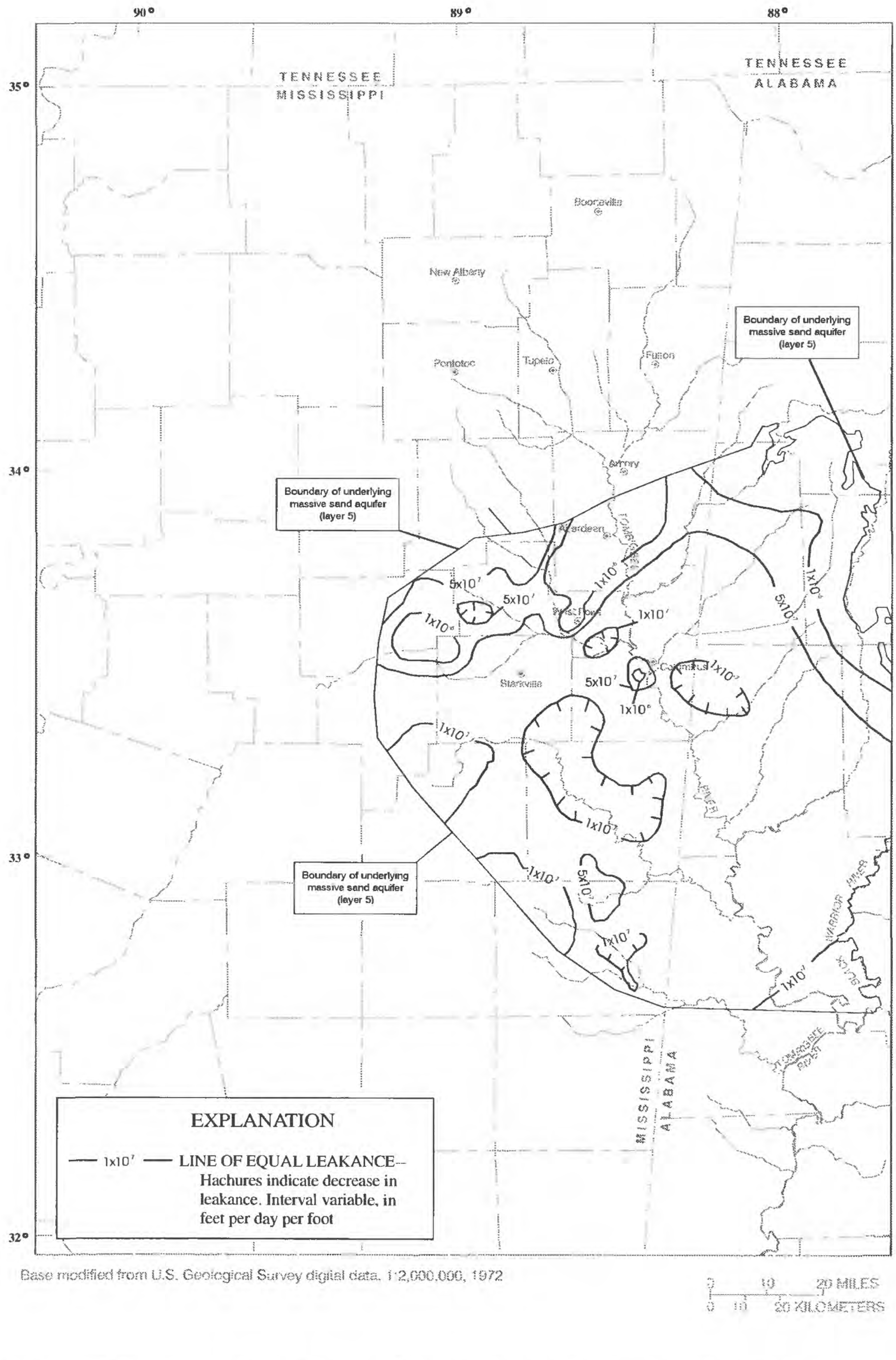


Figure 33. Leakance of confining unit between the massive sand aquifer and the overlying Coker aquifer used in the model simulations.

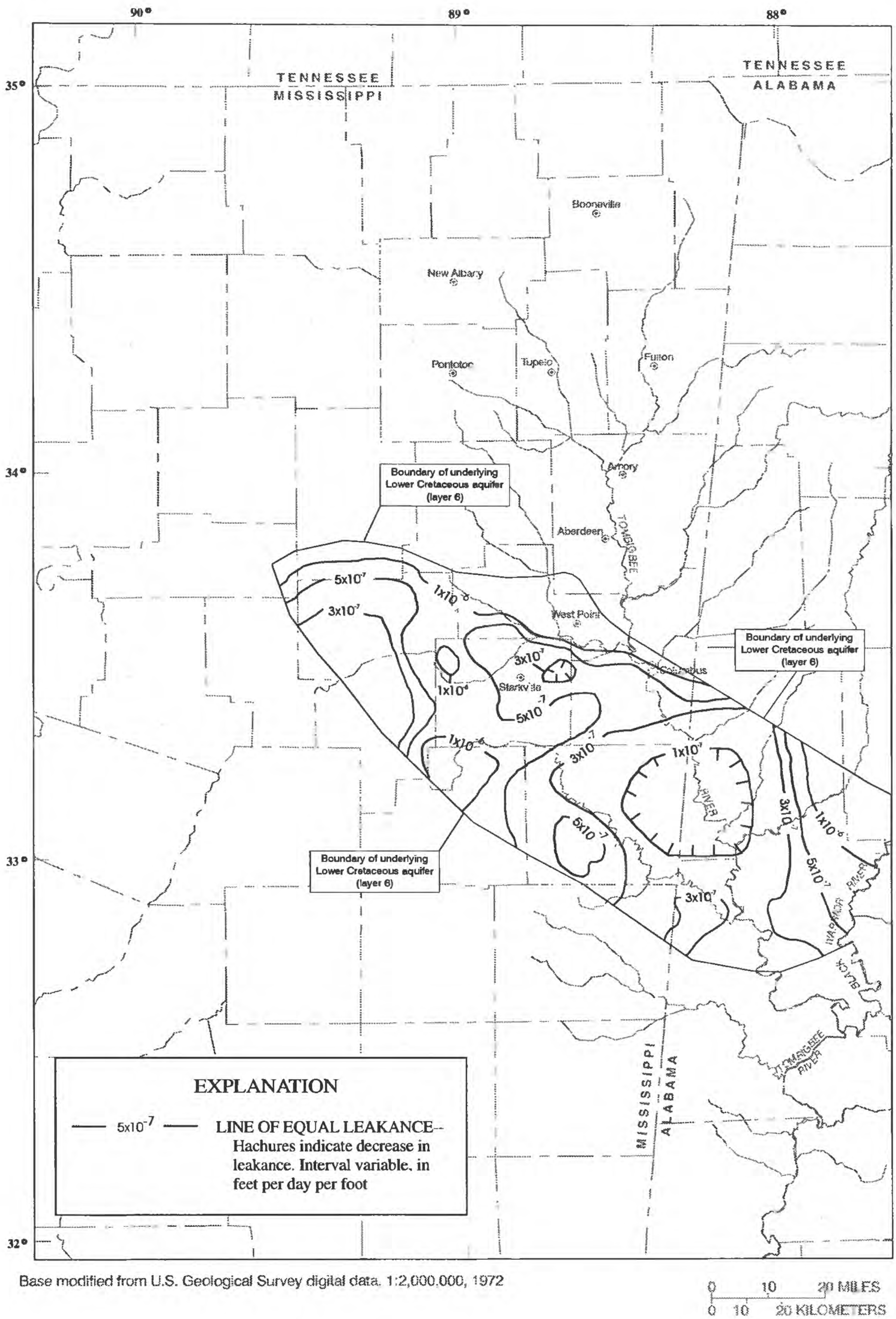


Figure 34. Leakance of confining unit between the Lower Cretaceous aquifer and the overlying massive sand aquifer used in model simulations.

Four changes were made to the initial leakance grids during model calibration. One change was made in the confining interval between the Eutaw-McShan and the Coffee Sand aquifers (fig. 25). In the northern part of this area the confining Mooreville Chalk is absent. However, the Tombigbee Sand Member is very fine grained in this area and acts as a confining unit; therefore, the confining thickness in this area represents the Tombigbee Sand Member.

Two other changes were made, one along the Tombigbee River and the other in the area of the confluence of the Tombigbee and Black Warrior Rivers (figs. 30-31). Water-level data indicate that these two areas are major discharge areas for the Eutaw-McShan and Gordo aquifers (Gardner, 1981). The vertical conductances were increased from one to two orders of magnitude in these areas during model calibration. Seismic surveys indicate faulting along parts of the river reaches in this area (Gardner, 1981). Faults and other structural features may increase vertical flow in this area (Mallory, 1993).

The fourth change made was an increase in the vertical hydraulic conductivity value for the confining unit separating the Gordo and Coker aquifers. The value was increased from 0.00001 to 0.000021 foot per day during model calibration.

Simulations were made under transient conditions for nine pumping (stress) periods that began January 1, 1900, and ended on December 31, 1992. Each pumping period consisted of one time-step. The length of the pumping periods and their corresponding dates are listed in table 2. The pumping periods were chosen to represent large changes in pumpage; however, to some degree the pumping periods also indicate times at which pumpage and water-level data were available. The pumpage used during each pumping period is shown in figure 35.

The effect of the Tennessee-Tombigbee Waterway on the ground-water flow system was also simulated. The waterway consists of a series of canals, locks, dams and divide cuts that connect the Tennessee and Tombigbee Rivers. Pool elevations in the canal sections were used as driving heads for the simulation. Sections of the waterway were completed at different times; however, the waterway was simulated as being completed at design pool elevation at the beginning of pumping period 6 in 1979.

Table 2. Pumping periods used in the model of the Eutaw-McShan and Tuscaloosa aquifers

Pumping period	Length of time (years)	Date
1	40	1900-39
2	20	1940-59
3	10	1960-69
4	5	1970-74
5	4	1975-78
6	6	1979-84
7	5	1985-89
8	2	1990-91
9	1	1992-92

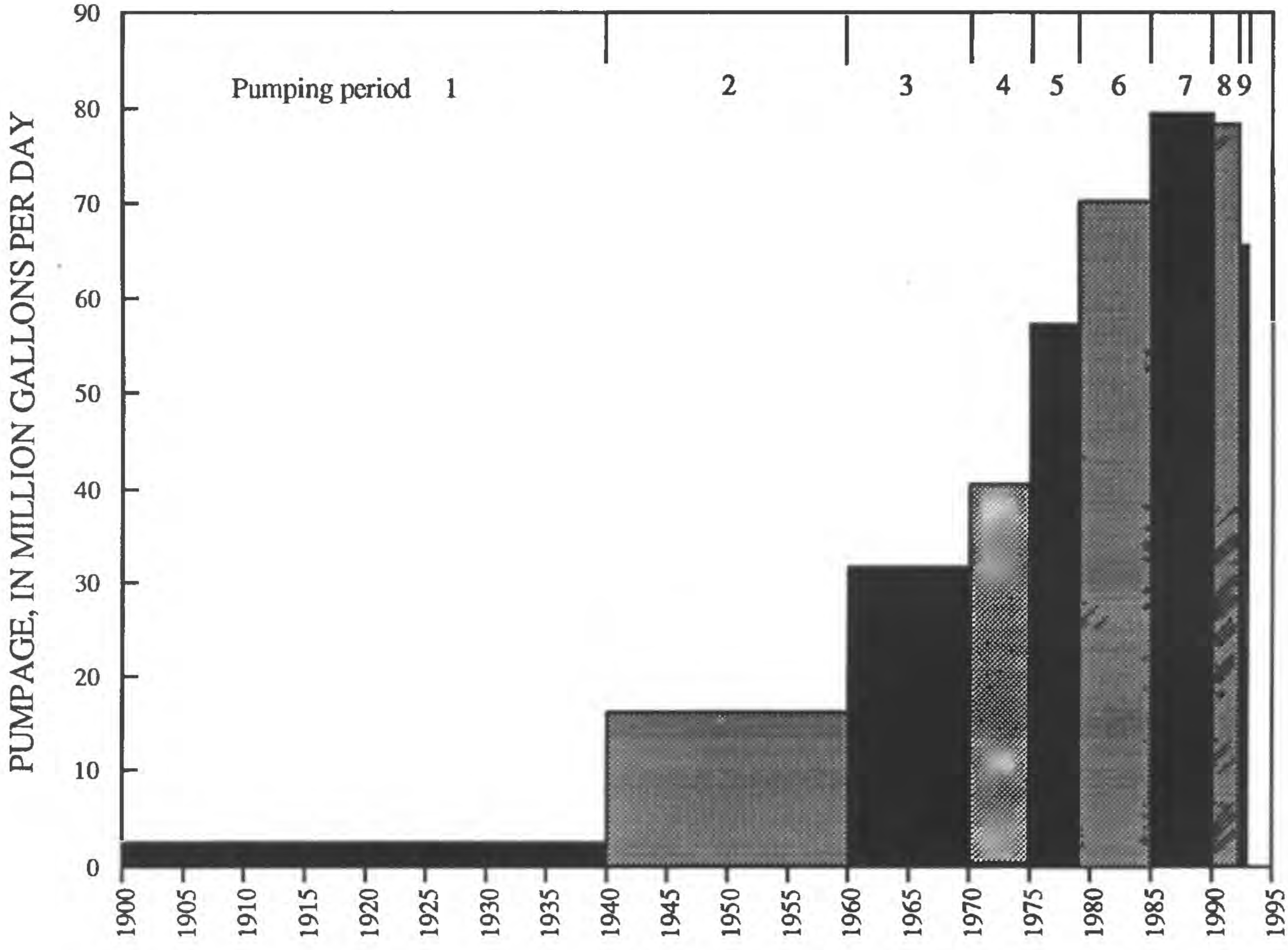


Figure 35. Total pumpage used for each pumping period simulated in the model of the Eutaw-McShan and Tuscaloosa aquifers.

Published water-level data are available for the Eutaw-McShan and Gordo aquifers at the end of pumping period 5 in 1978 (Wasson, 1980a,b), and at the end of pumping period 9 in 1992 for the Eutaw-McShan (Everett and Jennings, 1994), Gordo (Phillips and Hoffmann, 1994), and Coker and massive sand (Hardin and Everett, 1994) aquifers. A total of 569 water-level measurements from published reports provided the primary calibration values for the simulations. These water-level measurements are separated by 14 years, which is helpful in model verification. Potentiometric maps for intermediate periods (Darden, 1984 and 1985; Goldsmith, 1990 and 1991) were also analyzed. The total number of water-level measurements used to calibrate each aquifer and the root-mean-square error of the simulated heads are listed in table 3. The root-mean-square error, or RMS, is defined as the square-root of the sum of the square of the differences between measured and simulated values of head divided by the total number of points used, or:

$$\mathrm{RMS} = \sqrt{\frac{\sum(\text{measured head} - \text{simulated head})^2}{\text{total number of points}}}$$

Table 3. Root-mean-square error of simulated head in the aquifers for 1978 and 1992

Aquifer	Number of water-level measurements (1978)	Root-mean-square error of simulated heads, in feet (1978)	Number of water-level measurements (1992)	Root-mean-square error of simulated heads, in feet (1992)
Eutaw-McShan	104	13.0	167	16.2
Gordo	67	16.2	198	19.0
Coker	--	--	14	11.8
Massive sand	- -	--	19	5.4

The simulated potentiometric surfaces for 1978 are shown in figs. 36 and 37 for the Eutaw-McShan and Gordo aquifers. Few water-level measurements are available for the Coker and massive sand aquifers for 1978 (pumping period 5), and no measurements are available for the Lower Cretaceous aquifer in the modeled area. Although water-level data for the Coker and massive sand aquifers for 1992 (pumping period 9) were matched, no water-level measurements were available for other pumping periods which precluded verification. However, water levels from a long-term observation well are available for the massive sand aquifer in Noxubee County, and simulated and measured heads are in close agreement (fig. 38). The Lower Cretaceous aquifer was simulated primarily to provide a realistic lower boundary for the system. Because no water-level data are available for the Lower Cretaceous aquifer and only estimates of hydraulic parameters (W.T. Oakley, oral commun., 1994) are available, calibration of this model layer was not possible. Therefore, potentiometric maps are not shown for the Lower Cretaceous aquifer in this report.

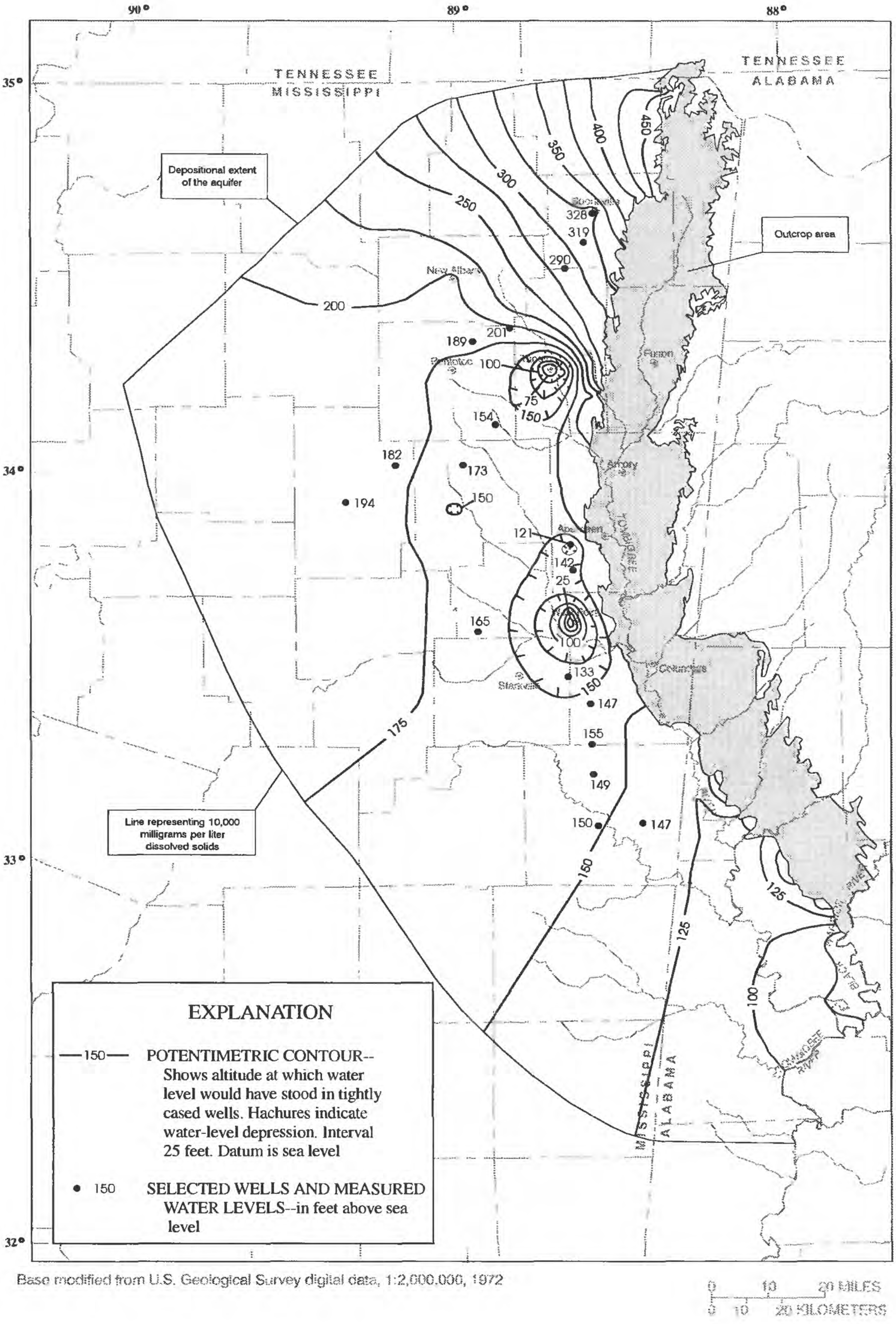


Figure 36. Simulated 1978 potentimetric surface of the Eutaw-McShan aquifer.

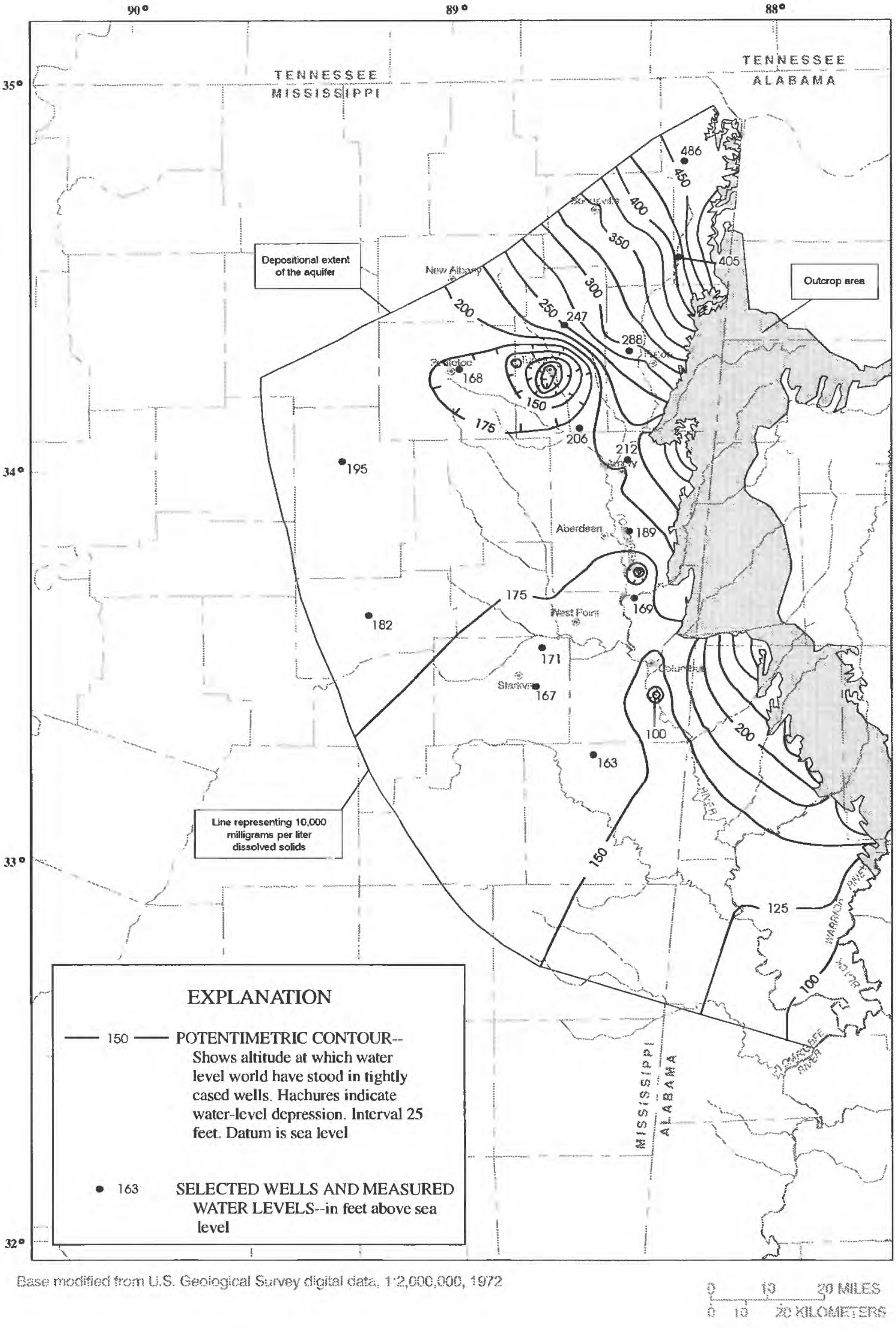


Figure 37. Simulated 1978 potentiometric surface of the Gordo aquifer.

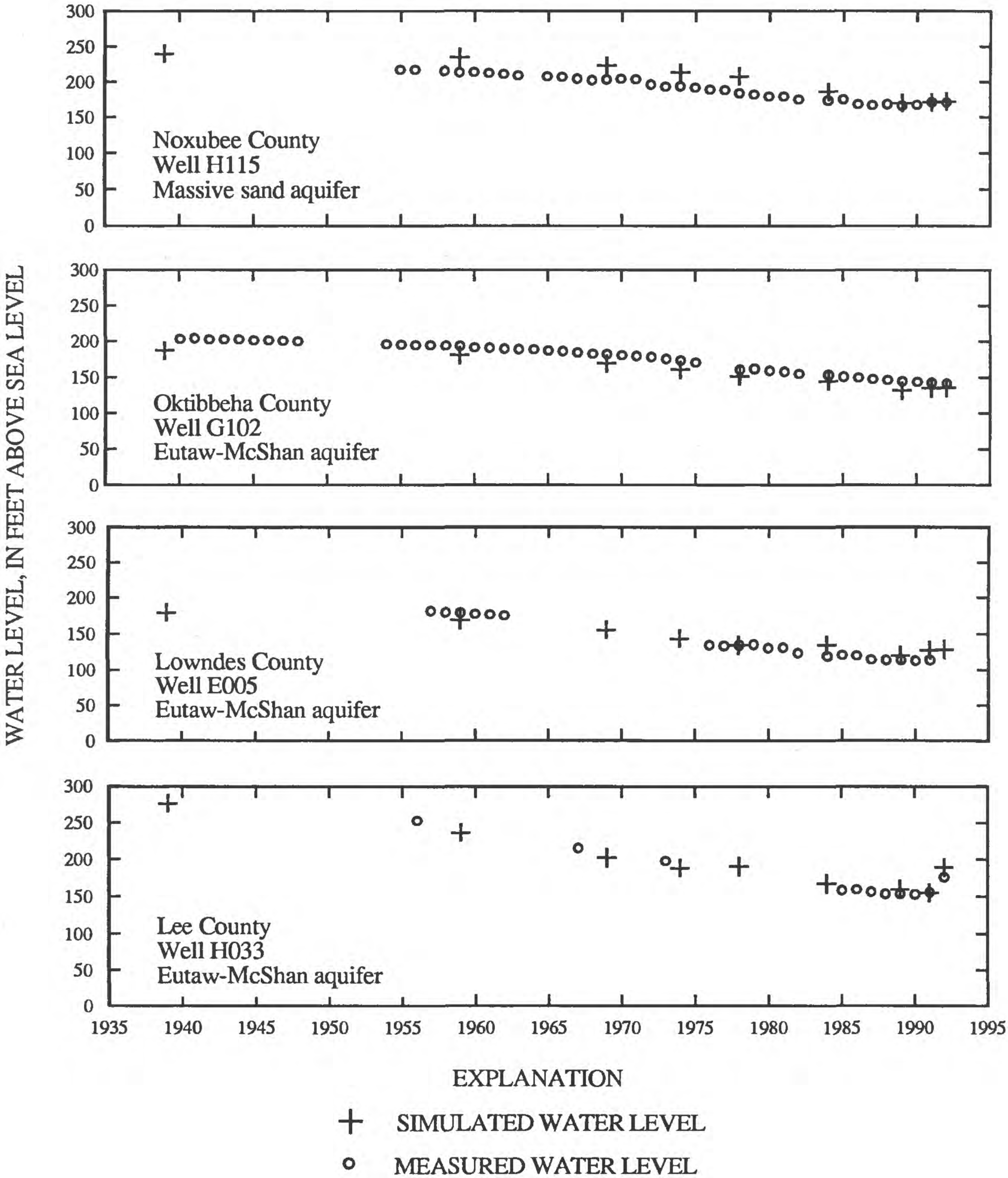


Figure 38. Simulated and measured water levels for selected observation wells screened in the massive sand and Eutaw-McShan aquifers (location of wells shown in figures 41 and 44).

Hydrographs of water levels in observation wells show how the water levels at a site change through time. Four hydrographs for the Eutaw-McShan aquifer, three for the Gordo aquifer, and one for the massive sand aquifer are shown in figs. 38-39 (well locations are shown in figs. 41-42 and fig. 44). The hydrographs represent water levels in pumping centers as well as in outlying areas. The hydrographs were made using the last measured value for each year to best correspond with the simulated values. The hydrographs of wells screened in the Eutaw-McShan and Gordo aquifers in Lee County show a recovery of water levels at Tupelo after 1990 due to a decrease in pumpage. The difference between the simulated and measured water level for 1991 at well H042 (fig. 39) may indicate a lag in model response time. Water levels also fluctuated for well H042 in 1991, ranging from 57 to 126 feet above sea level. The hydrographs of wells outside of Lee County show a general long-term trend of declining water levels.

Sensitivity Analysis

The sensitivity of the model to an input parameter can be tested by varying only the parameter of interest over a range of values and monitoring the response of the model by determining the root-mean-square error of the simulated heads compared to the measured heads. The model's sensitivity to changes in transmissivity, pumpage, vertical hydraulic conductivity, and recharge conductance were tested by increasing and decreasing the values by a uniform factor. The root-mean-square error for the system was determined by weighting all the aquifers and stress periods for which data exist by the total number of calibration points. The weighting process consisted of dividing the number of wells available for a given aquifer and stress period (table 3) by the total number of wells (569) and multiplying the value by the root-mean-square error to get a weighted error. The weighted error for each aquifer and stress period were summed to determine the total error for the system. The results of this analysis (fig. 40) indicate that the model is more sensitive to decreases than to increases in transmissivity from the calibrated value, more sensitive to increases than to decreases in pumpage from the calibrated value, more sensitive to increases than to decreases in vertical hydraulic conductivity from the calibrated value, and shows little sensitivity to changes in recharge conductance over the range of tested values. Model calibration also indicated relatively little sensitivity to changes in the storage coefficients.

Simulation of Predevelopment Ground-Water Flow Conditions

Simulations of predevelopment ground-water flow conditions were made by using hydraulic input parameters determined during transient model calibration in a steady-state analysis. The simulated predeveloped potentiometric surface for the Eutaw-McShan aquifer is shown in figure 41. The model is constructed to simulate heads under confined conditions; therefore simulated heads for the aquifer outcrop areas are not presented. Heads in the aquifer generally are highest to the northeast and lowest to the southeast. This trend is a general reflection of the topography which is also highest to the northeast and lowest to the southeast in the model area (fig. 2). Regional ground-water flow is from the northeast to the southeast along an arcuate path. Ground water from the northernmost part of the outcrop area enters the basal part of the aquifer. As ground water moves from the outcrop area southward, flow is captured by the Tombigbee River. In the extreme southeastern part of the area, flow moves upward through the confining unit into the Tombigbee and Black Warrior Rivers.

The simulated predevelopment overlying Eutaw-McShan aquifer (fig. 41) and the underlying Coker (fig. 43) and massive sand (fig. 44) aquifers. The Gordo aquifer generally has higher heads than the Eutaw-McShan aquifer along much of the Tombigbee River, in the discharge area and downdip area to the southeast, and in some of the more northeastern counties. The Coker aquifer generally has higher heads than the overlying Gordo aquifer in the downdip areas, and the

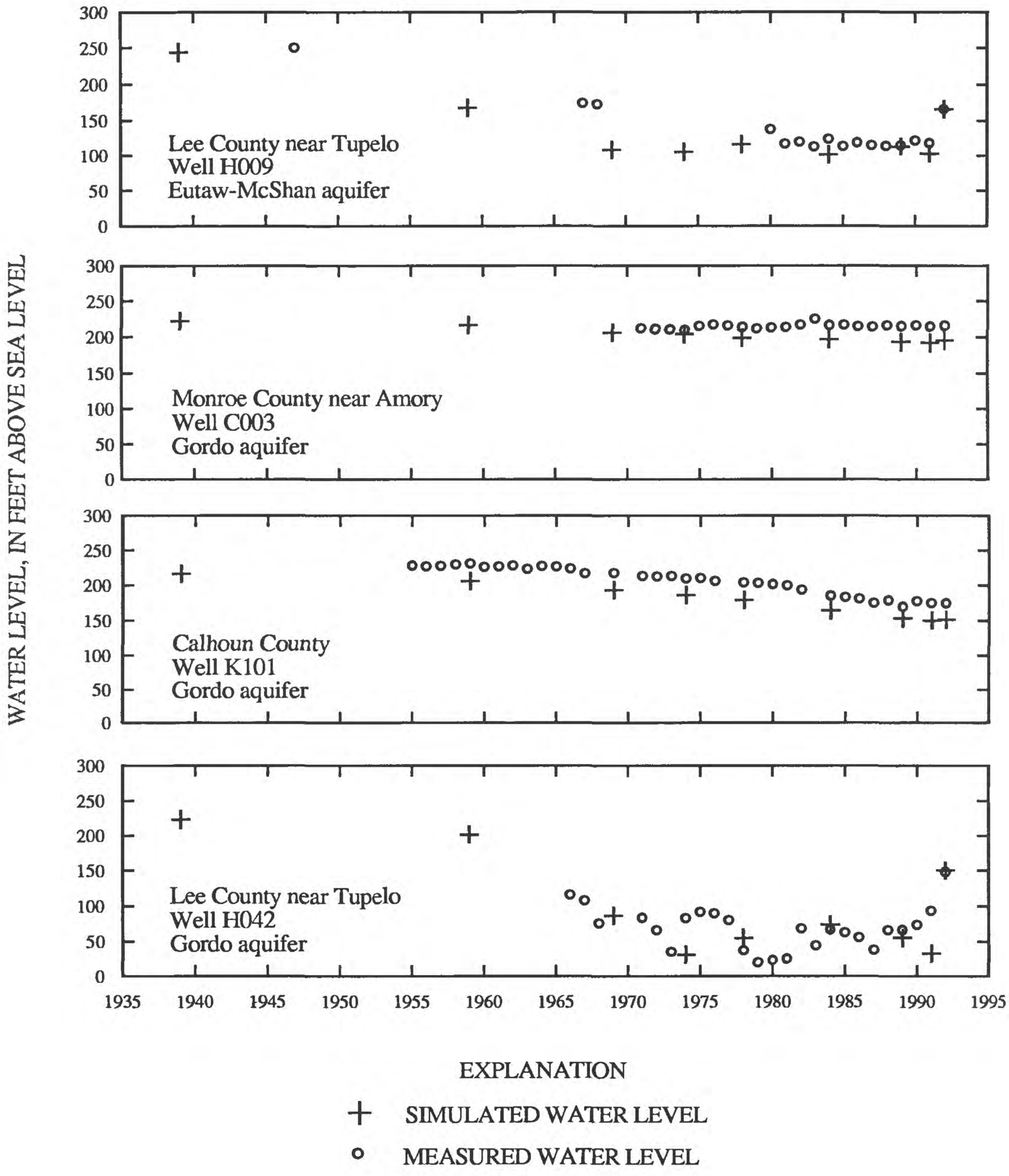


Figure 39. Simulated and measured water levels for selected observation wells screened in the Eutaw-McShan and Gordo aquifers (location of wells shown in figures 41 and 42).

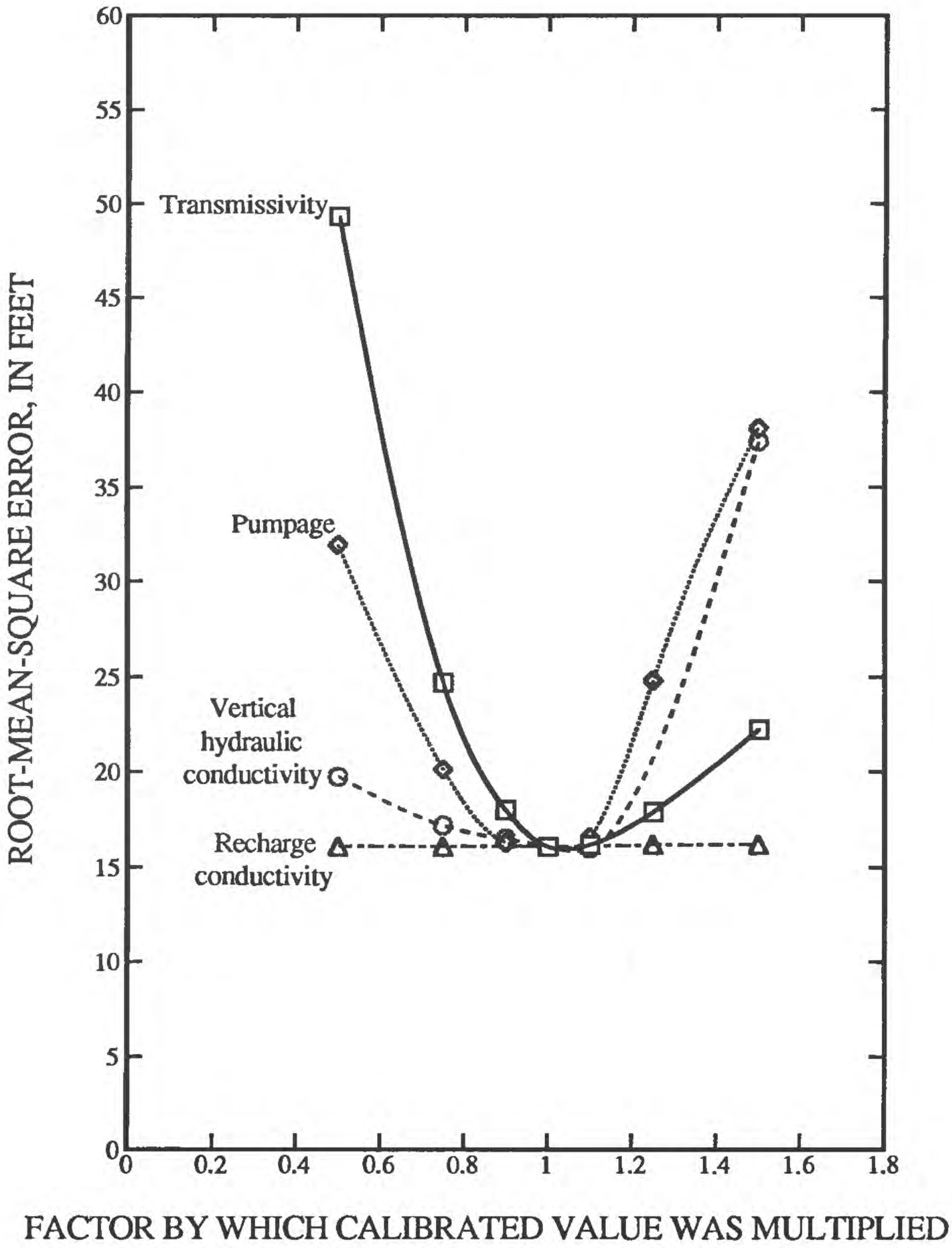


Figure 40. Sensitivity of the model of the Eutaw-McShan and Tuscaloosa aquifers to changes in aquifer parameters.

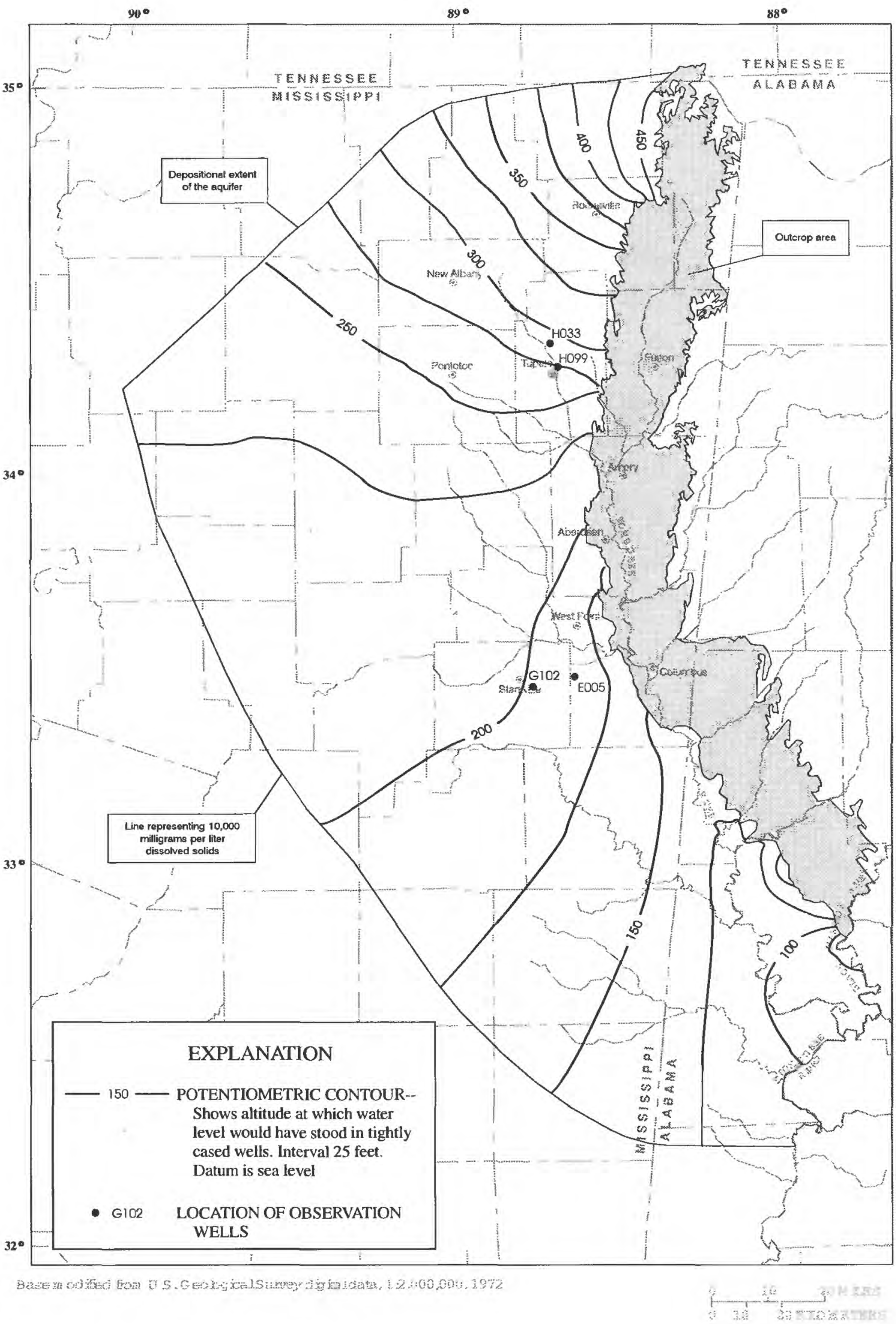


Figure 41. Simulated predevelopment potentiometric surface of the Eutaw-McShan aquifer.

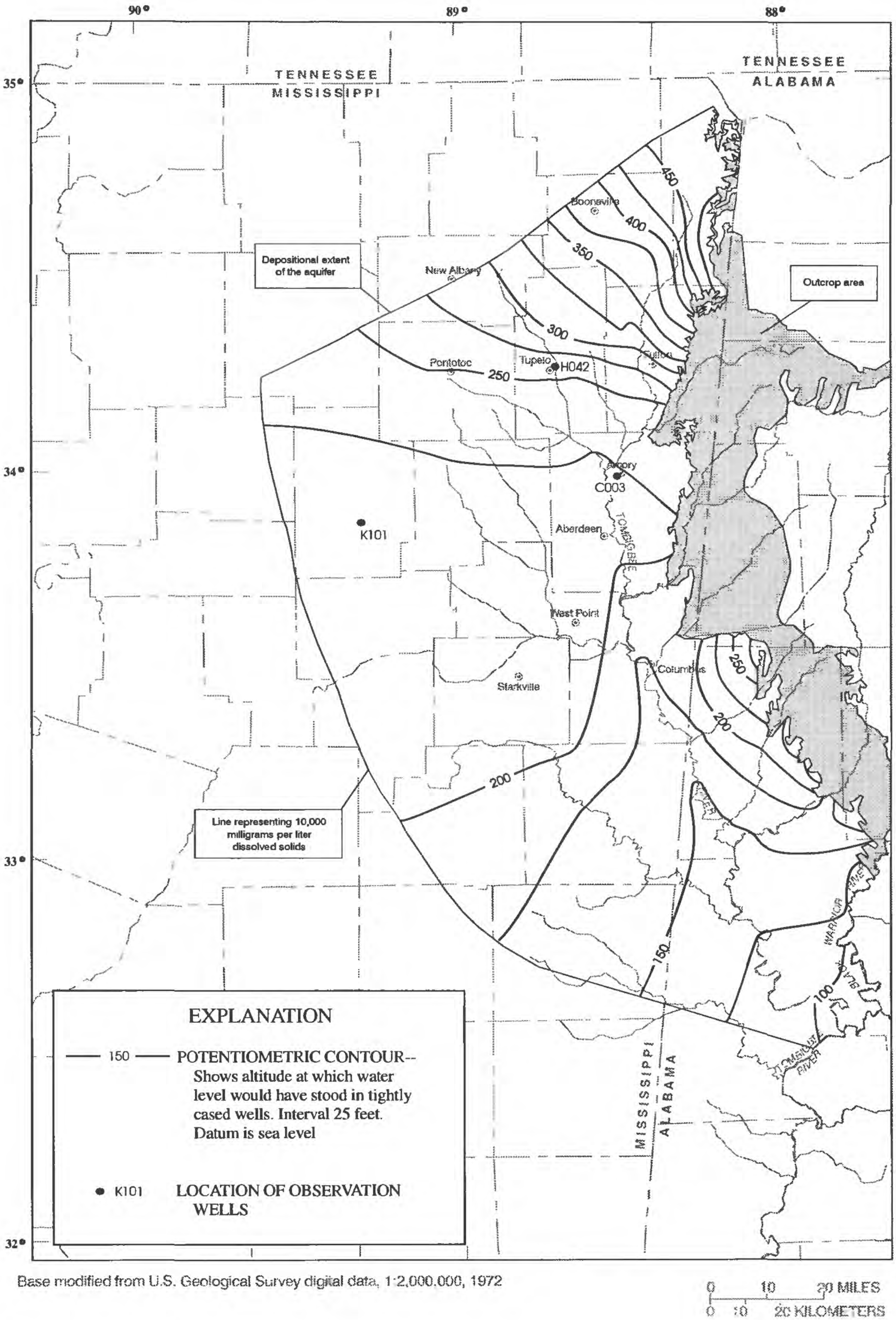
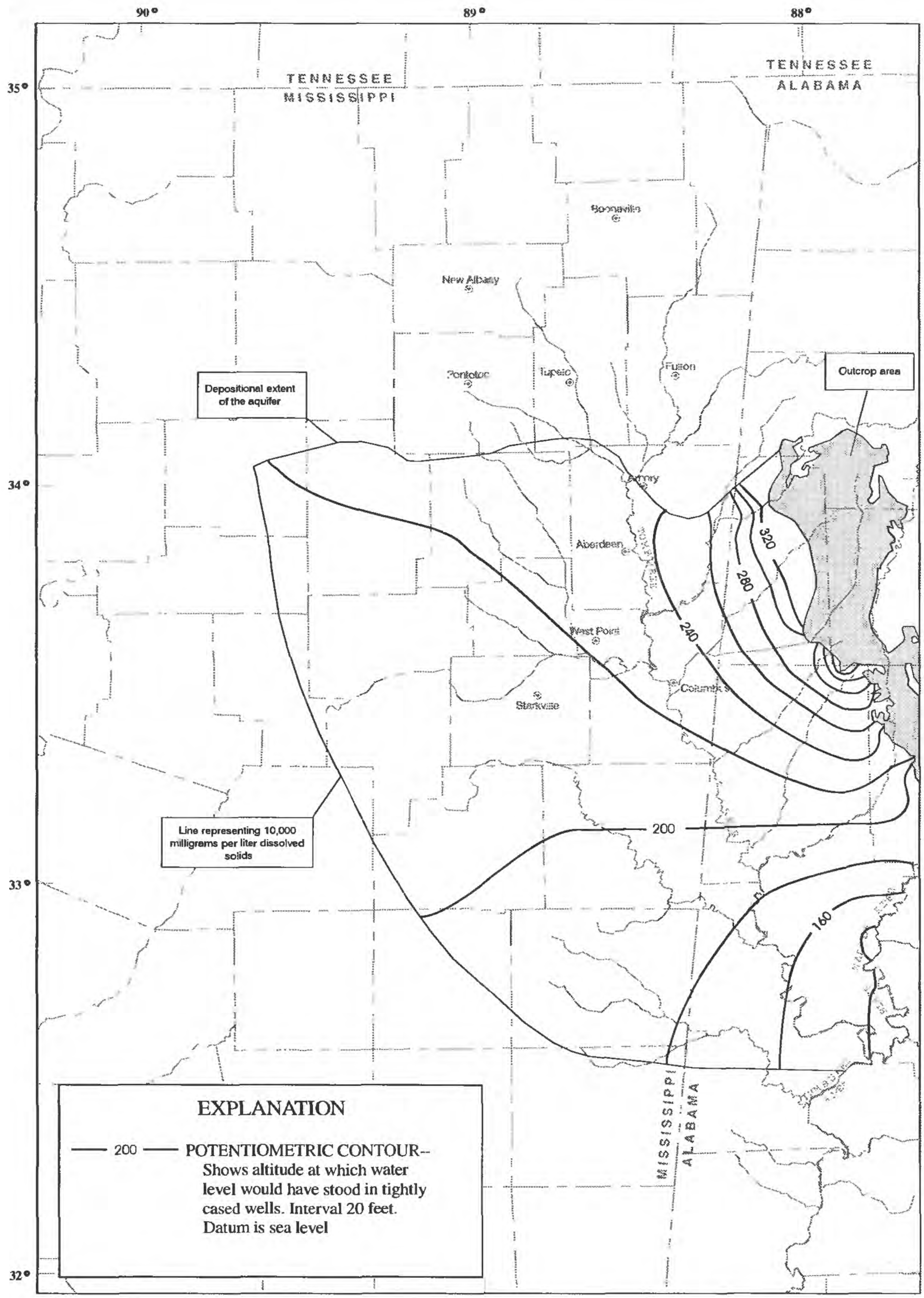


Figure 42. Simulated predevelopment potentiometric surface of the Gordo aquifer.



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

Figure 43. Simulated predevelopment potentiometric surface of the Coker aquifer.

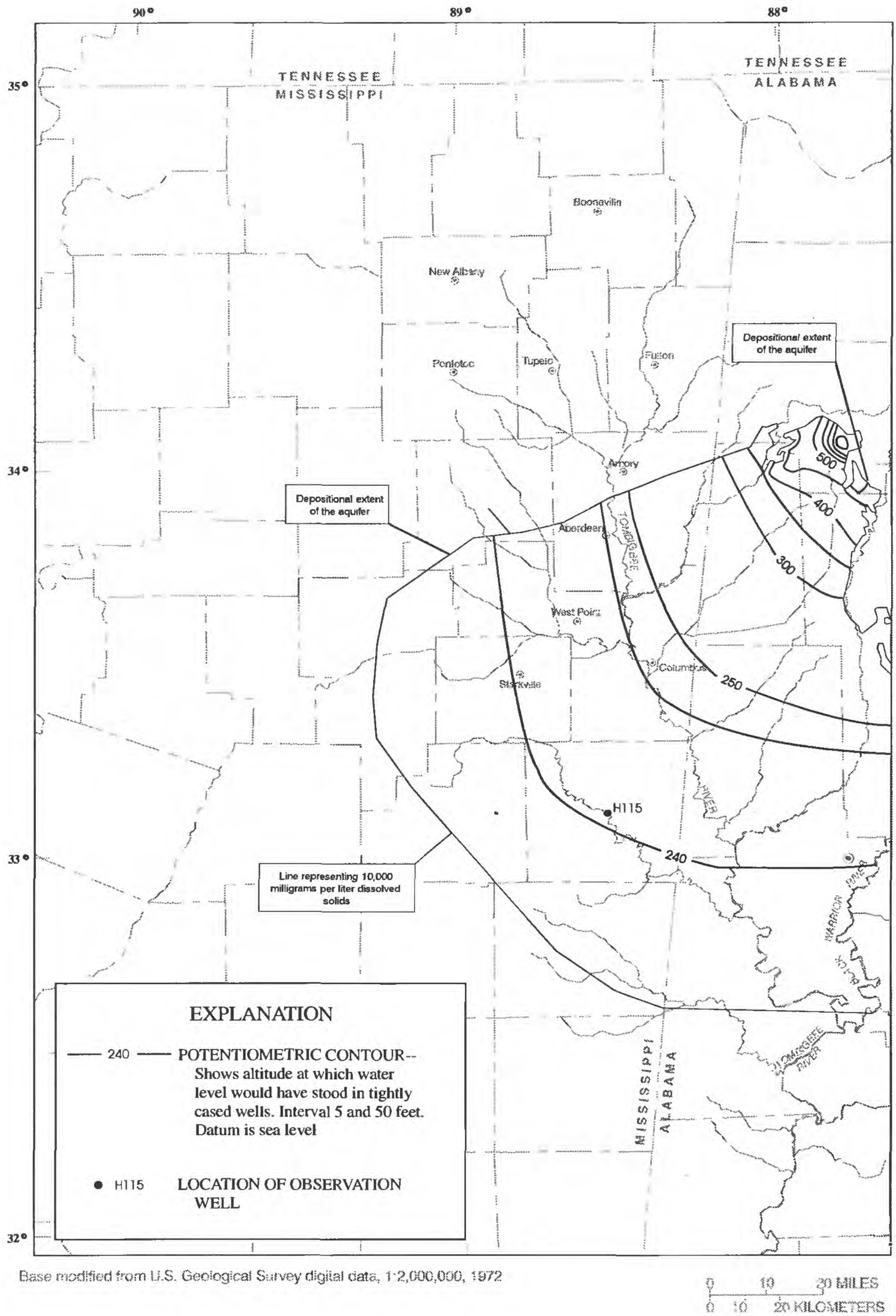


Figure 44. Simulated predevelopment potentiometric surface of the massive sand aquifer.

massive sand aquifer generally has higher heads than the overlying Coker aquifer in the downdip areas.

Distribution of areas of simulated predevelopment recharge and discharge output from the model in the outcrop areas are shown in figure 45. Areas of recharge are mainly at topographic highs, and areas of discharge are mainly at topographic lows. The net recharge rate to all the aquifers in the outcrop areas is about 23 cubic feet per second.

Lateral flow through and vertical leakage between the aquifers depends on several factors, including transmissivity within the aquifers, leakance of the confining units, and the altitude of the potentiometric surfaces of the aquifer. Flow between aquifers and flow into and out of the outcrop areas are shown in figure 46 for simulated predevelopment conditions. About 225.2 cubic feet per second entered the Eutaw-McShan aquifer from the outcrop area, about 7.9 cubic feet per second entered from overlying units, and about 52.3 cubic feet per second entered from the underlying Gordo aquifer. About 229.9 cubic feet per second flowed from the Eutaw-McShan aquifer at the outcrop area, about 30.9 cubic feet per second flowed into overlying units (mainly along Tombigbee and Black Warrior Rivers), and about 24.6 cubic feet per second flowed into the underlying Gordo aquifer.

About 415.5 cubic feet per second entered the Gordo aquifer from the outcrop area, and about 47.6 cubic feet per second entered from the underlying Coker aquifer. About 408.6 cubic feet per second flowed from the Gordo aquifer at the outcrop area, and about 26.8 cubic feet per second flowed into the underlying Coker aquifer.

About 176.7 cubic feet per second entered the Coker aquifer from the outcrop area, and about 23.7 cubic feet per second entered from the underlying massive sand aquifer. About 155.9 cubic feet per second flowed from the Coker aquifer at the outcrop area, and about 23.7 cubic feet per second flowed into the underlying massive sand aquifer. Only about 0.7 cubic foot per second of flow was exchanged between the massive sand and Lower Cretaceous aquifers.

Simulation of 1992 Ground-Water Flow Conditions

Simulation of 1992 ground-water flow conditions was made using hydraulic parameters determined during transient model calibration. The simulated 1992 surfaces for the Eutaw-McShan and Gordo aquifers (figs. 47-48) may be compared with the 1992 potentiometric surfaces based on water-level measurements (figs. 11-12). A comparison of the simulated predevelopment (fig. 41) and 1992 (fig. 47) potentiometric surfaces for the Eutaw-McShan aquifer shows an overall decline in head. Simulated water levels declined an average of about 53 feet in the confined part of the Eutaw-McShan aquifer. Areas in Clay, Chickasaw, Lee, Pontotoc, and Union Counties have water-level declines of more than 100 feet. However, the area near Tupelo had a significant rise in water levels due to decreased pumpage compared to the simulated potentiometric surface for the aquifer in 1978 (fig. 36).

A comparison of the simulated predevelopment (fig. 42) and 1992 (fig. 48) potentiometric surfaces for the Gordo aquifer also shows an overall decline in head. Simulated water levels declined an average of about 44 feet in the confined part of the Gordo aquifer. Areas in Lee, Pontotoc, and Union Counties have water-level declines of more than 100 feet. However, the area near Tupelo and areas in Lowndes County had significant rises in water levels due to decreased pumpage compared to the simulated potentiometric surface for the aquifer in 1978 (fig. 37).

A comparison of the simulated predevelopment (figs. 43-44) and 1992 (figs. 49-50) potentiometric surfaces for the Coker and massive sand aquifers also show an overall decline in

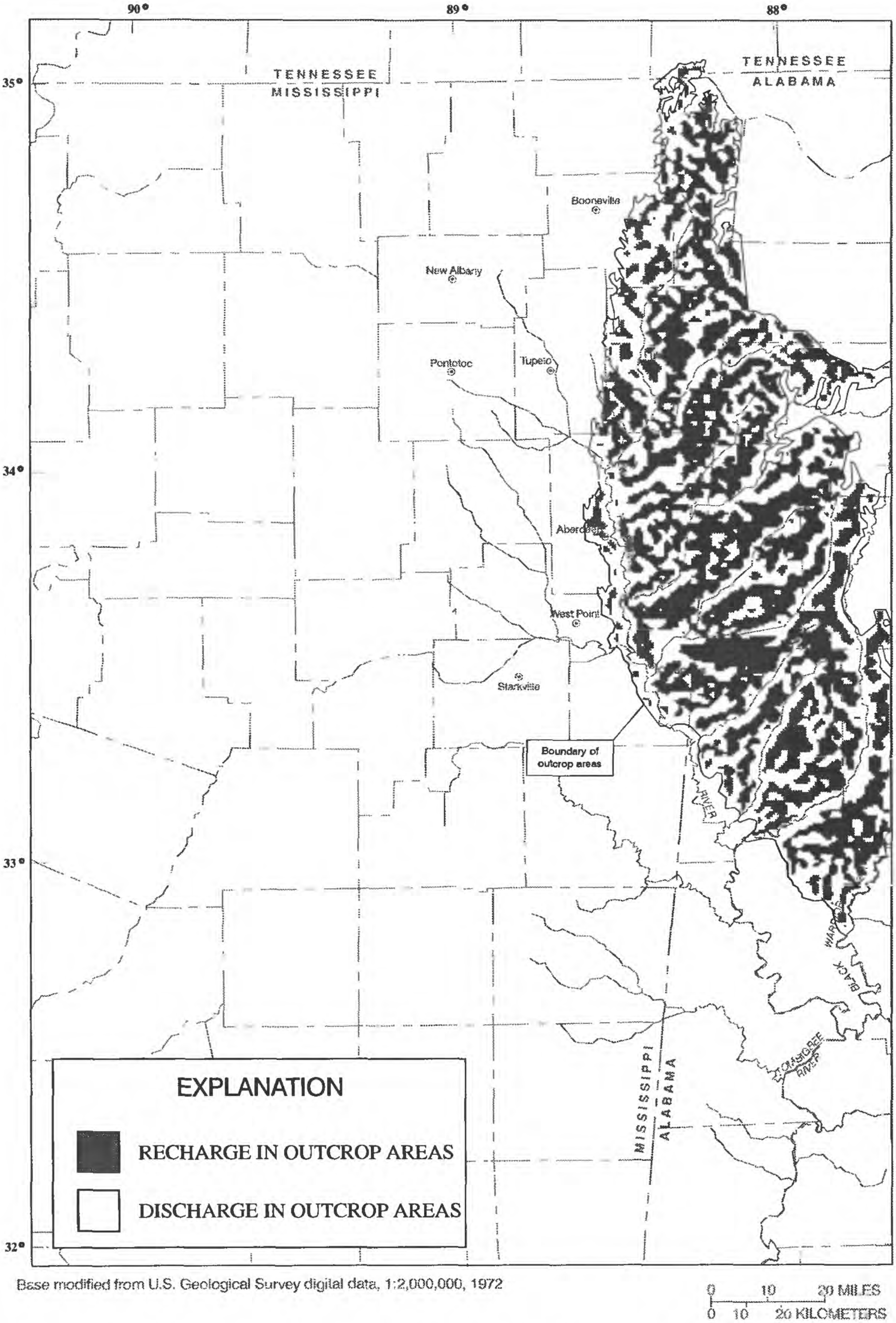


Figure 45. Model output of areas of simulated predevelopment recharge and discharge in aquifer outcrops.

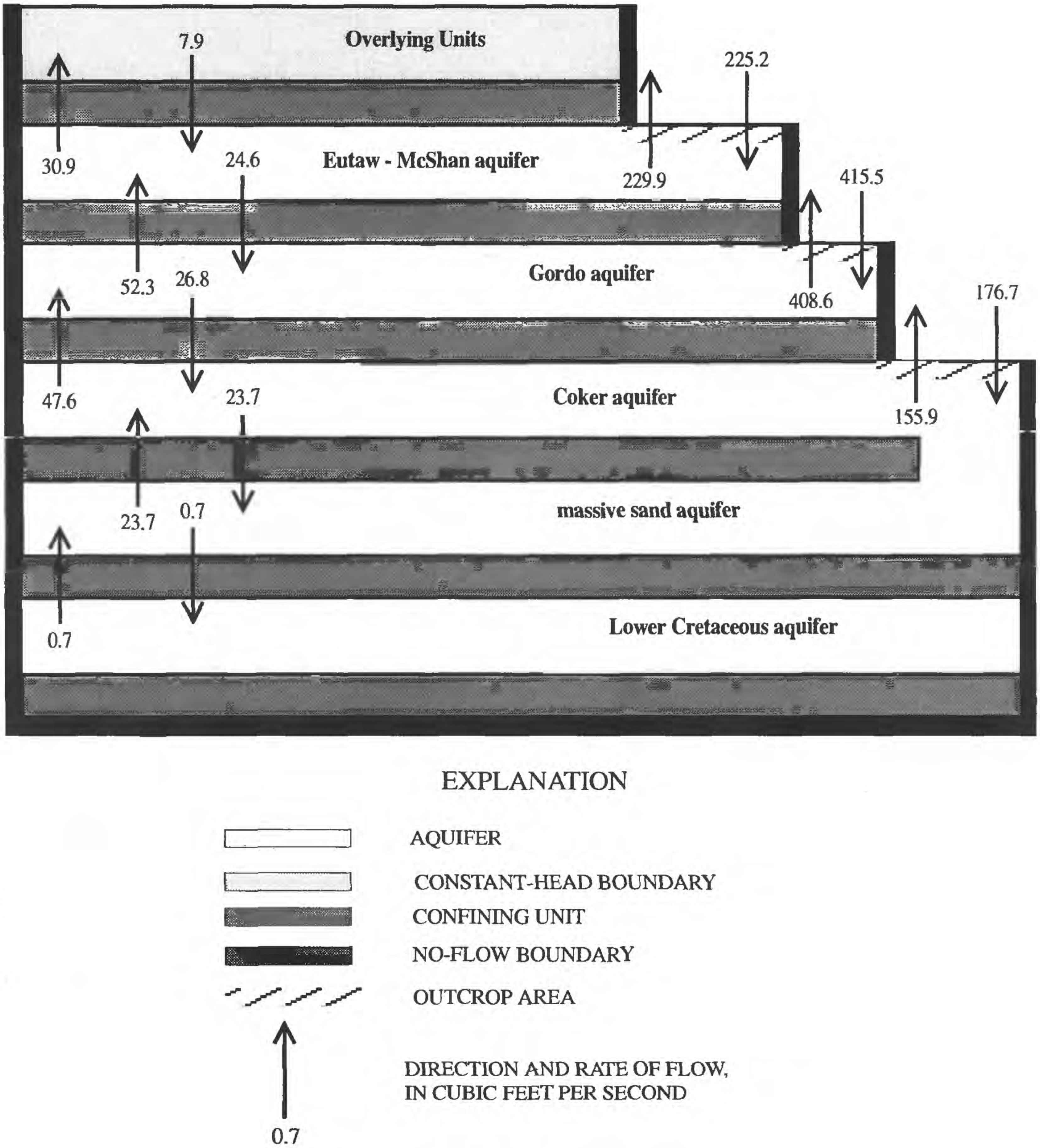


Figure 46. Simulated predevelopment flow rates for the aquifers in the model area.

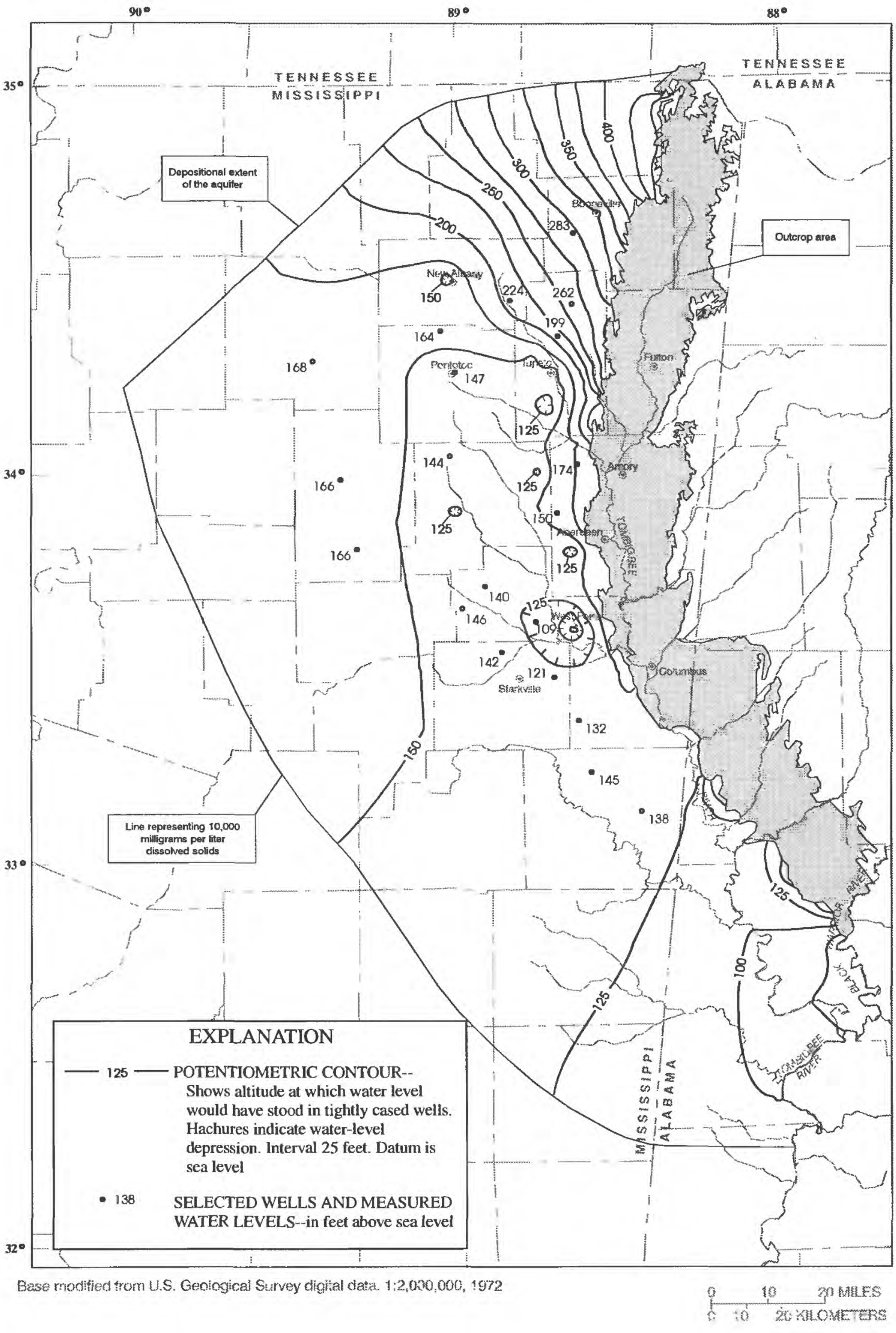


Figure 47. Simulated 1992 potentiometric surface of the Eutaw-McShan aquifer.

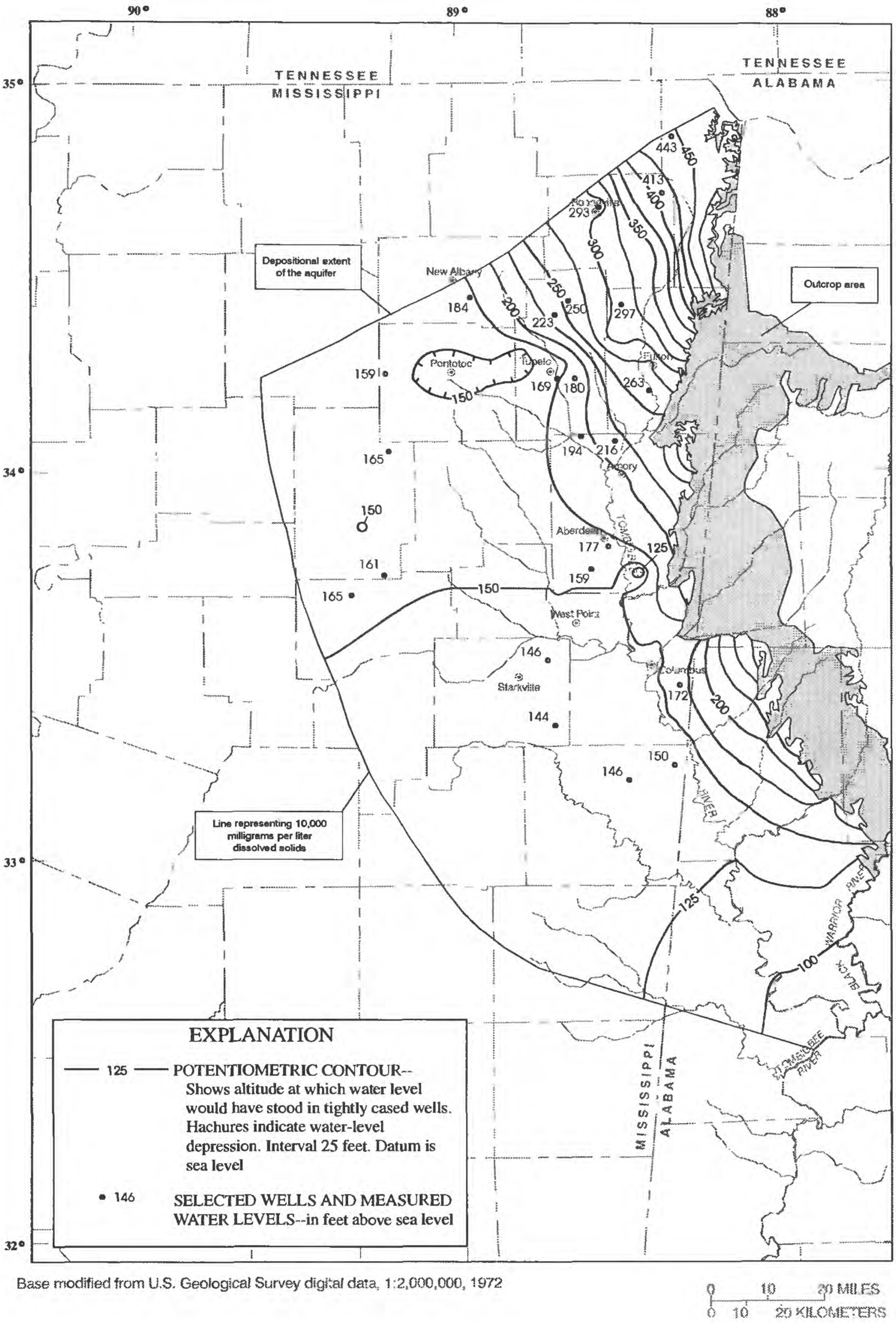


Figure 48. Simulated 1992 potentiometric surface of the Gordo aquifer.

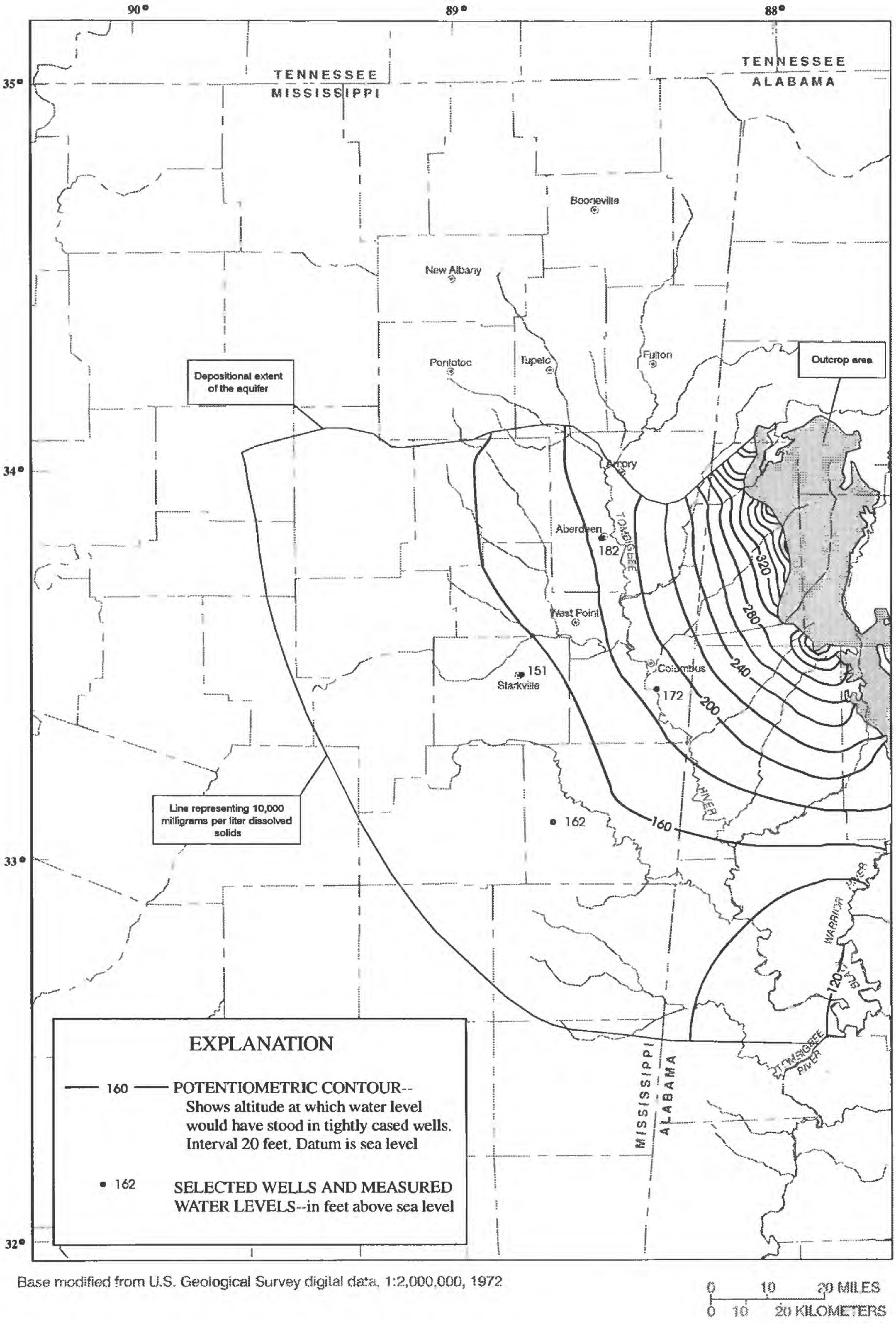


Figure 49. Simulated 1992 potentiometric surface of the Coker aquifer.

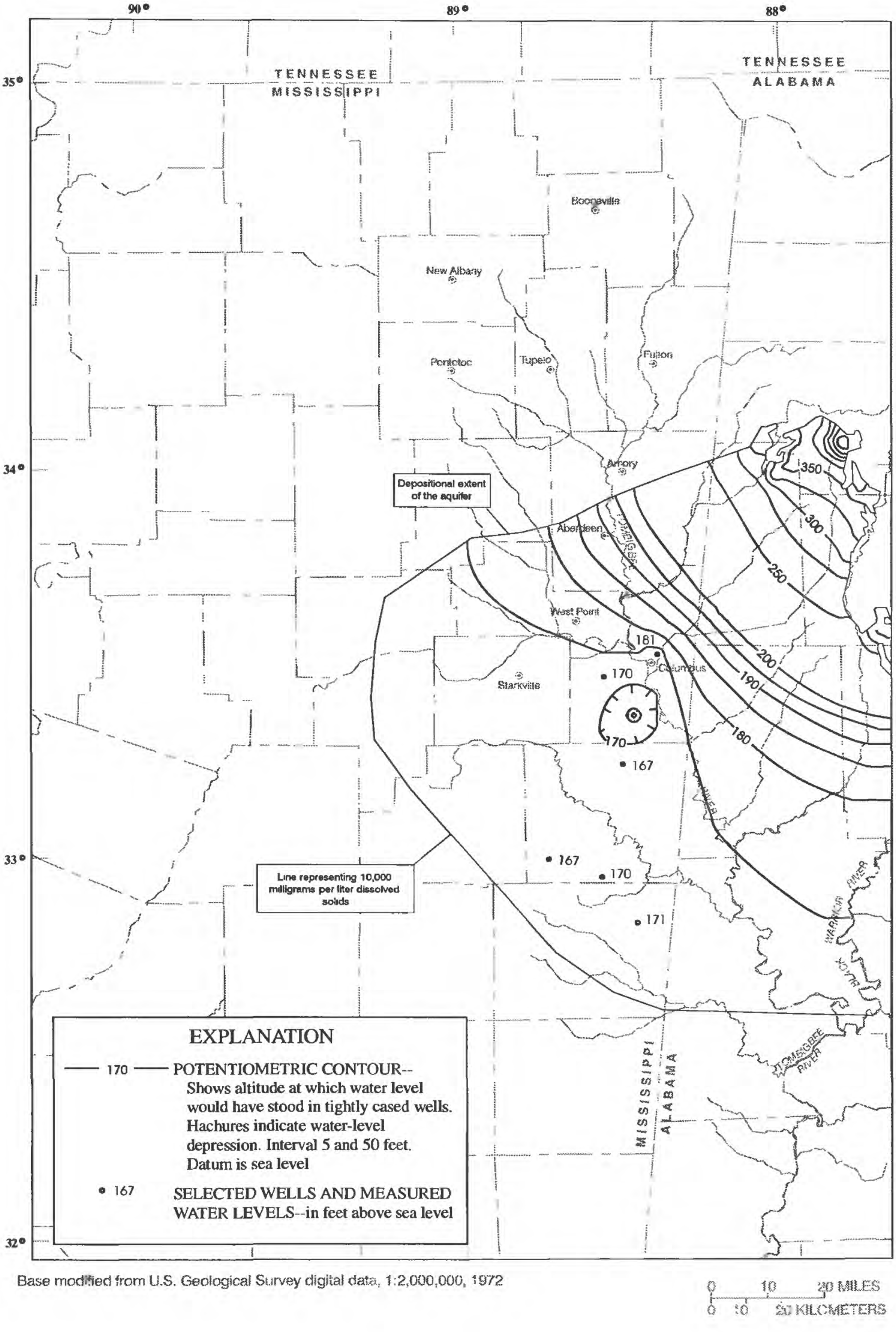


Figure 50. Simulated 1992 potentiometric surface of the massive sand aquifer.

head. Simulated water-levels declined about 42 and 60 feet for the confined parts of the Coker and massive sand aquifers, respectively.

Distribution of areas of simulated 1992 recharge and discharge output from the model in the outcrop areas are shown in figure 51. Areas of recharge are mainly at topographic highs and areas of discharge are mainly at topographic lows. The net recharge rate to all the aquifers in the outcrop areas is about 116.4 cubic feet per second. A localized area of mainly increased discharge exists in the northern part of the outcrop area when compared to the predevelopment recharge and discharge areas (fig. 45) due to the simulated effects of the Tennessee-Tombigbee Waterway.

Lateral flow through and vertical flow between the aquifers and flow into and out of the outcrop areas is shown in figure 52 for simulated 1992 conditions. About 244.6 cubic feet per second entered the Eutaw-McShan aquifer from the outcrop area, about 12.9 cubic feet per second entered from overlying units, and about 29.7 cubic feet per second entered from the underlying Gordo aquifer. About 213.0 cubic feet per second flowed from the Eutaw-McShan aquifer at the outcrop area, about 23.3 cubic feet per second flowed into overlying units (mainly along Tombigbee and Black Warrior Rivers), and about 27.2 cubic feet per second flowed into the underlying Gordo aquifer. About 22.1 cubic feet per second was removed from the Eutaw-McShan aquifer by pumping, and about 1.6 cubic feet per second was removed from storage.

About 428.5 cubic feet per second entered the Gordo aquifer from the outcrop area, and about 38.5 cubic feet per second entered from the underlying Coker aquifer. About 374.8 cubic feet per second flowed from the Gordo aquifer at the outcrop area, and about 33.4 cubic feet per second flowed into the underlying Coker aquifer. About 53.7 cubic feet per second was removed from the Gordo aquifer by pumping, and about 2.6 cubic feet per second was removed from storage.

About 172.6 cubic feet per second entered the Coker aquifer from the outcrop area, and about 11.4 cubic feet per second entered from the underlying massive sand aquifer. About 141.5 cubic feet per second flowed from the Coker aquifer at the outcrop area, and about 37.5 cubic feet per second flowed into the underlying massive sand aquifer. Only about 0.1 cubic foot per second was removed from the Coker aquifer by pumping, and about 0.2 cubic foot per second entered the aquifer as a gain in storage. The Coker aquifer had a significant overall decrease in pumpage (about 0.35 cubic foot per second in 1978 to about 0.1 cubic foot per second in 1992) which is probably responsible for the simulated recovery.

About 1.1 cubic feet per second of flow entered the massive sand aquifer from the underlying Lower Cretaceous aquifer, and about 1.3 cubic feet per second flowed from the massive sand aquifer into the Lower Cretaceous aquifer. About 25.5 cubic feet per second was removed from the massive sand aquifer by pumping, and about 0.4 cubic foot per second was removed from storage. No pumpage has occurred from the Lower Cretaceous aquifer, and about 0.2 cubic foot per second was removed from storage.

Projected Effects of Increased Ground-Water Withdrawals

The calibrated model was used to make simulations for four different pumping rates and for time periods of 5, 10, and 20 years. The initial pumpage used for the projections represents 1993 values. These values are similar to the 1992 values used for the last pumping period (9) of the model; however, a few of the wells used in the 1992 pumpage data were abandoned, and several new wells were developed in 1993. The projection simulations incorporate these new data. The first projection assumes no annual increase in pumpage, the second a 1.5-percent annual increase, the third a 3-percent annual increase, and the fourth a 5-percent annual increase. Results for the Eutaw-McShan and Gordo aquifers are presented because only these aquifers had enough

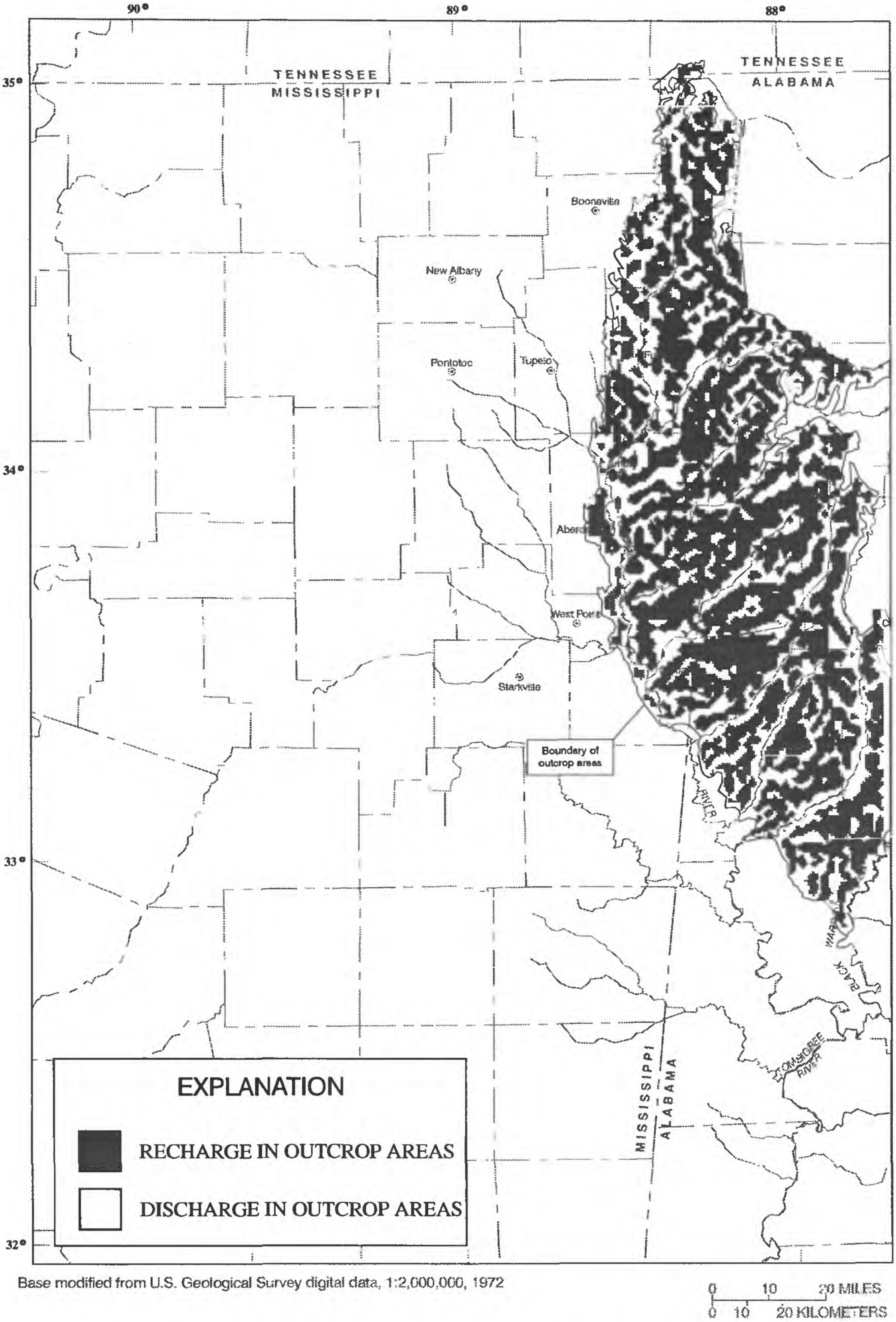


Figure 51. Model output of areas of simulated 1992 recharge and discharge in aquifer outcrops.

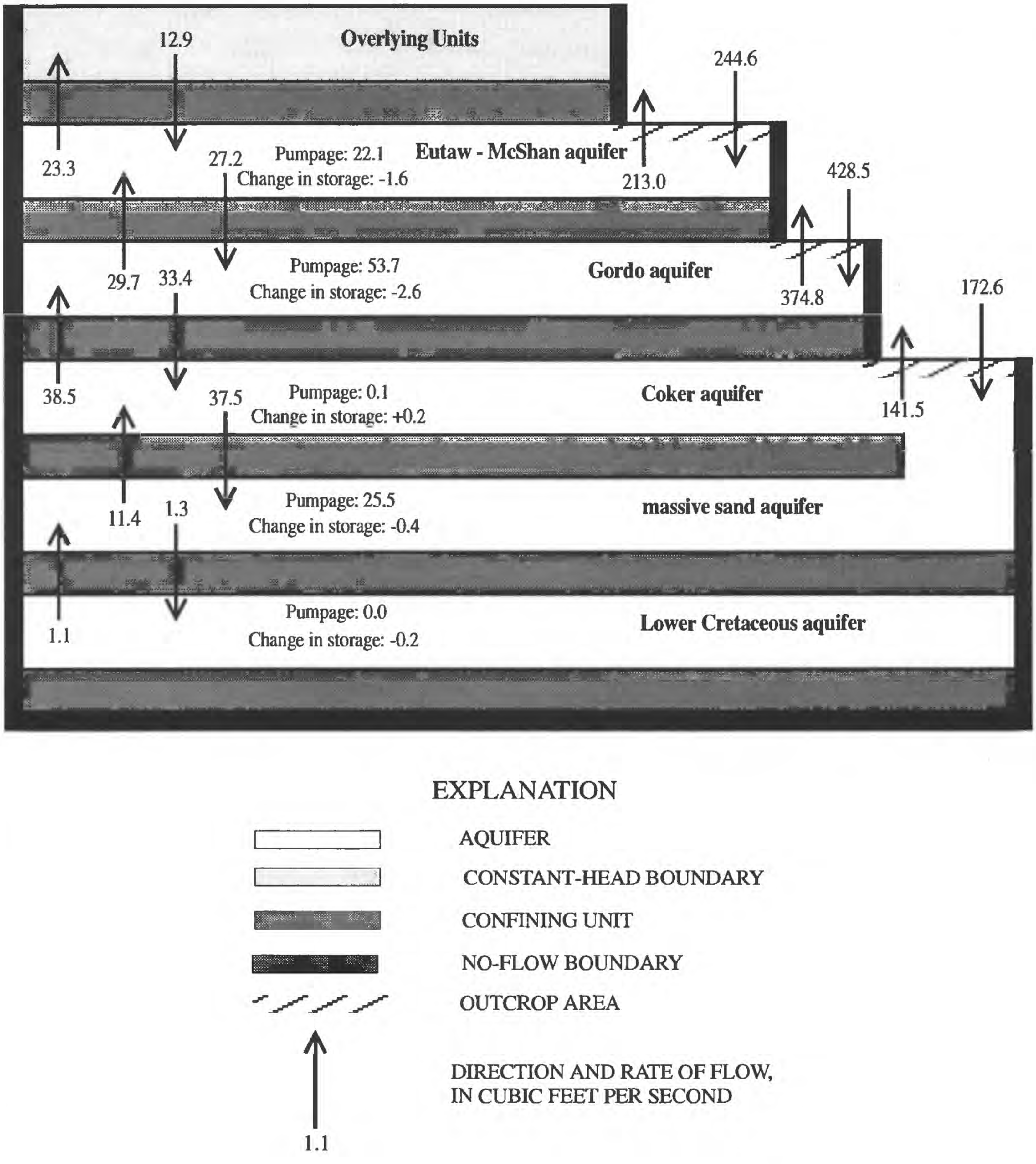


Figure 52. Simulated 1992 flow rates for the aquifers in the model area.

historical data for verification during the calibration process. The simulated results are presented as hydrographs at Tupelo and West Point for the Eutaw-McShan and Gordo aquifers, and as potentiometric surface maps for the aquifers after 20 years with the 0-percent annual change and the 5-percent annual increases in pumpage.

1993 Pumpage for 20 Years

Projection simulations were made using 1993 pumpage for 20 years. Analysis of the flow budget indicates that only a small amount of water is released from storage after 20 years. Water levels in the confined part of the Eutaw-McShan aquifer rose an average of about 3.4 feet from simulated 1992 levels. The maximum water-level rise was about 45 feet, a few miles west of Tupelo. The overall simulated rise in water levels in the Eutaw-McShan aquifer is the result of reduced 1992 pumpage due to development of surface-water sources at Tupelo.

The Gordo aquifer had an average simulated water-level rise in the confined part of the aquifer of about 2.3 feet from 1992 levels. The maximum simulated rise in water levels in the Gordo aquifer was about 30 feet, a few miles west of Tupelo. The overall simulated rise in water levels in the Gordo aquifer is also the result of reduced 1992 pumpage due to development of surface-water sources at Tupelo. Projected water levels at Tupelo (fig. 53) show the general trend of continued water-level recovery eventually reaching a fairly stable level for both aquifers after 20 years. Projected water levels at West Point (fig. 54) show the general trend of a fairly stable level for both aquifers. The simulated potentiometric surfaces for the aquifers after 20 years of pumpage (figs. 55-56) also show that the major water-level change is near the Tupelo area when compared to the 1992 potentiometric surfaces (figs. 47-48).

Annual 1.5-Percent Increase of 1993 Pumpage for 20 Years

Projection simulations were made with a 1.5-percent annual increase of 1993 pumpage for 20 years. Water levels in the confined part of the Eutaw-McShan aquifer declined an average of about 7 feet from simulated 1992 levels. However, water levels rose a maximum of about 25 feet from simulated 1992 levels near the Tupelo area as a result of the reduced 1992 pumpage. Water levels in the Eutaw-McShan aquifer had a maximum decline of about 26 feet from simulated 1992 values near West Point, and declined 15 to 20 feet at Aberdeen, and in east-central Chickasaw County.

The Gordo aquifer had an average simulated water-level decline in the confined part of the aquifer of about 7 feet from 1992 levels. However, water levels in the Gordo aquifer rose a maximum of about 12 feet above simulated 1992 levels after 20 years of simulation near the Tupelo area as a result of the reduced 1992 pumpage. Water levels in the Gordo aquifer declined about 15 to 20 feet from simulated 1992 values near Booneville, Starkville, West Point, and in south-central Monroe County. Projected water levels at Tupelo (fig. 53) show the general trend of continued water-level recovery for about 5 years, followed by water-level declines for both aquifers. Simulated water levels at West Point (fig. 54) show the general trend of declining water levels for both aquifers.

Annual 3-Percent Increase of 1993 Pumpage for 20 Years

Projection simulations were made with a 3-percent annual increase of 1993 pumpage for 20 years. Water levels in the confined part of the Eutaw-McShan aquifer declined an average of about 19 feet from simulated 1992 levels. Water levels declined in the Eutaw-McShan aquifer about 40 to 45 feet from simulated 1992 values near Aberdeen, New Albany, Pontotoc, south of Tupelo, and in east-central and northeastern Chickasaw County. Water levels declined more than 55 feet from simulated 1992 values at West Point.

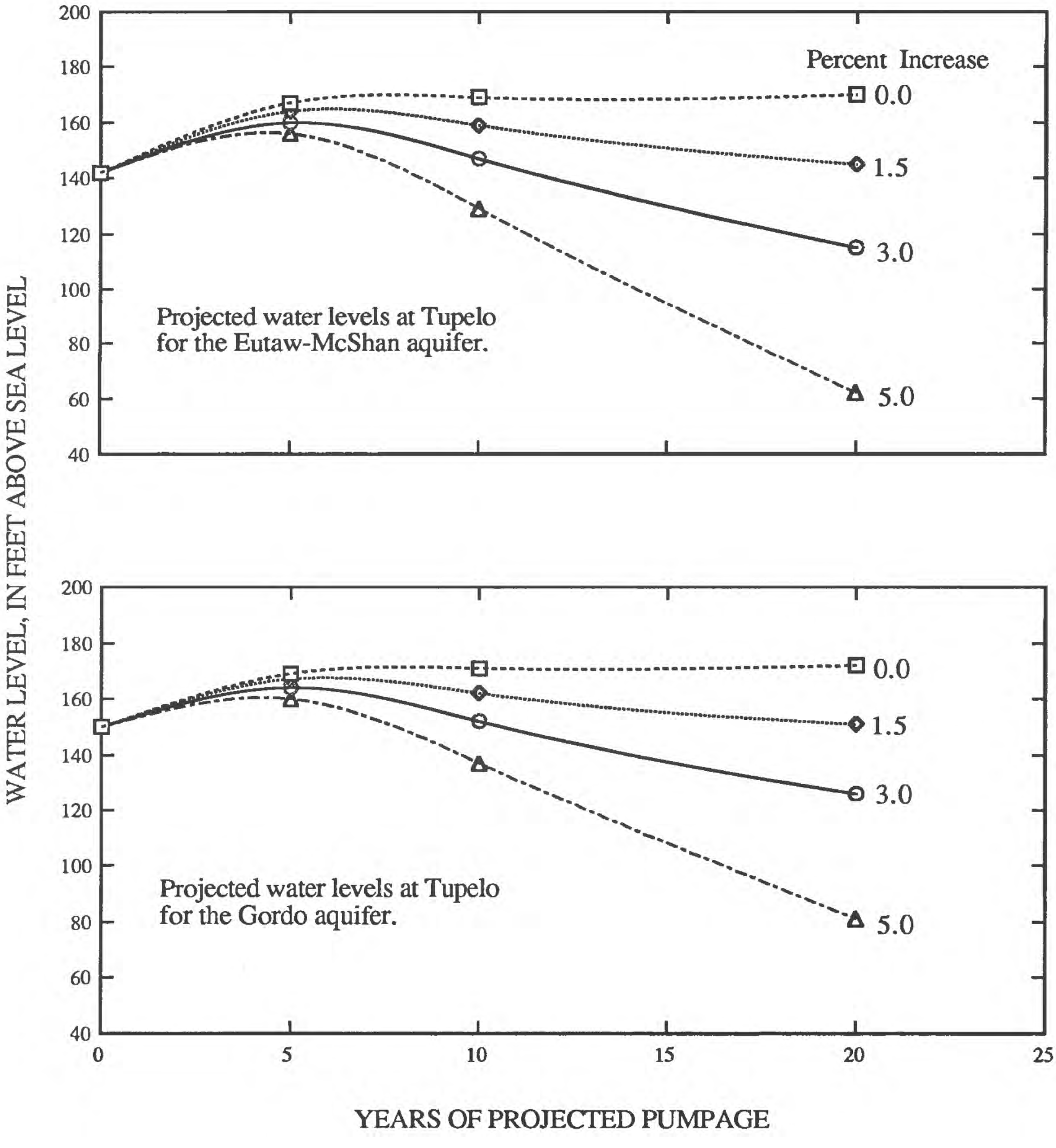


Figure 53. Projected water levels at Tupelo for the Eutaw-McShan and Gordo aquifers with various annual percentage increases of 1993 pumping rates.

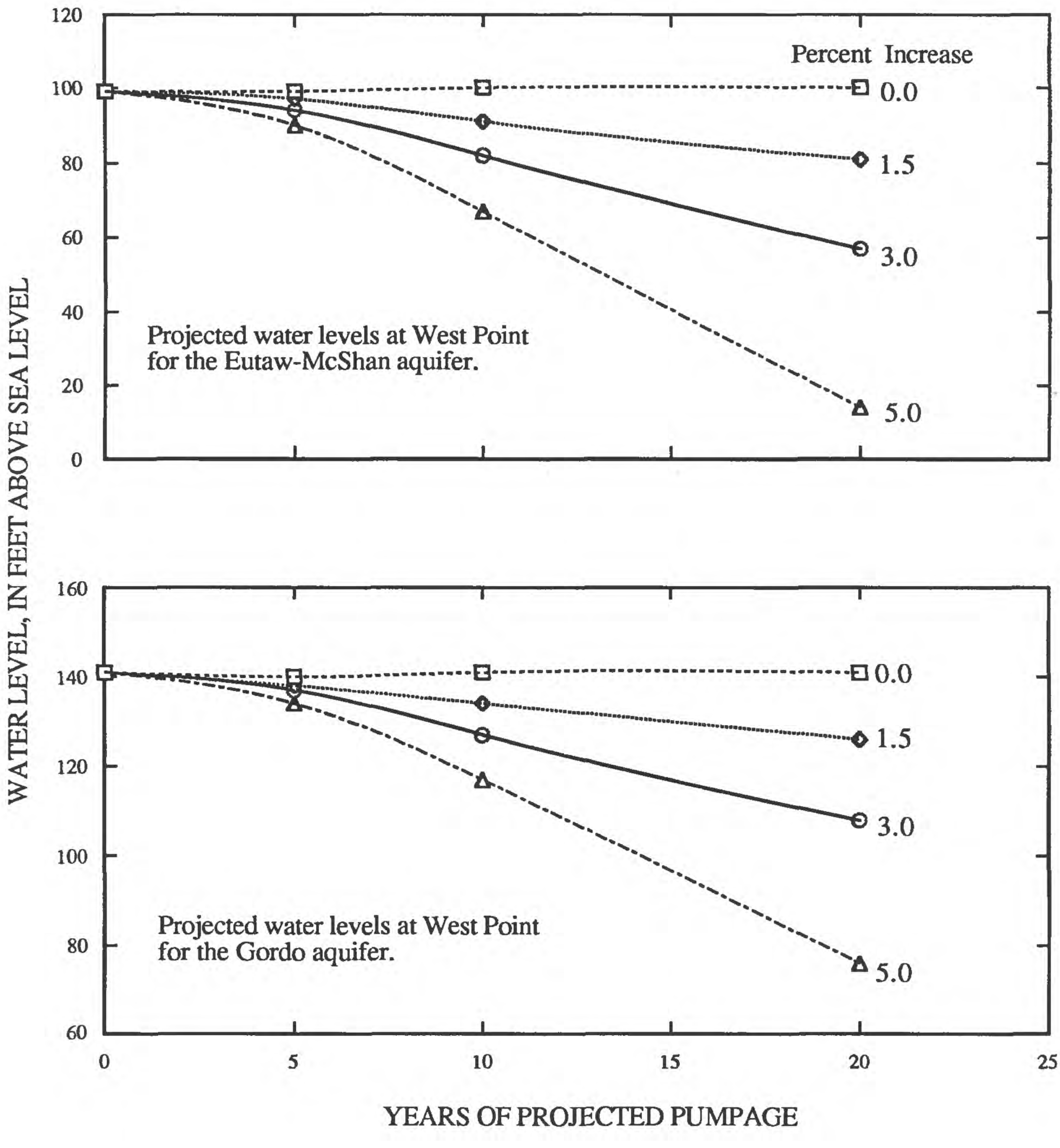


Figure 54. Projected water levels at West Point for the Eutaw-McShan and Gordo aquifers with various annual percentage increases of 1993 pumping rates.

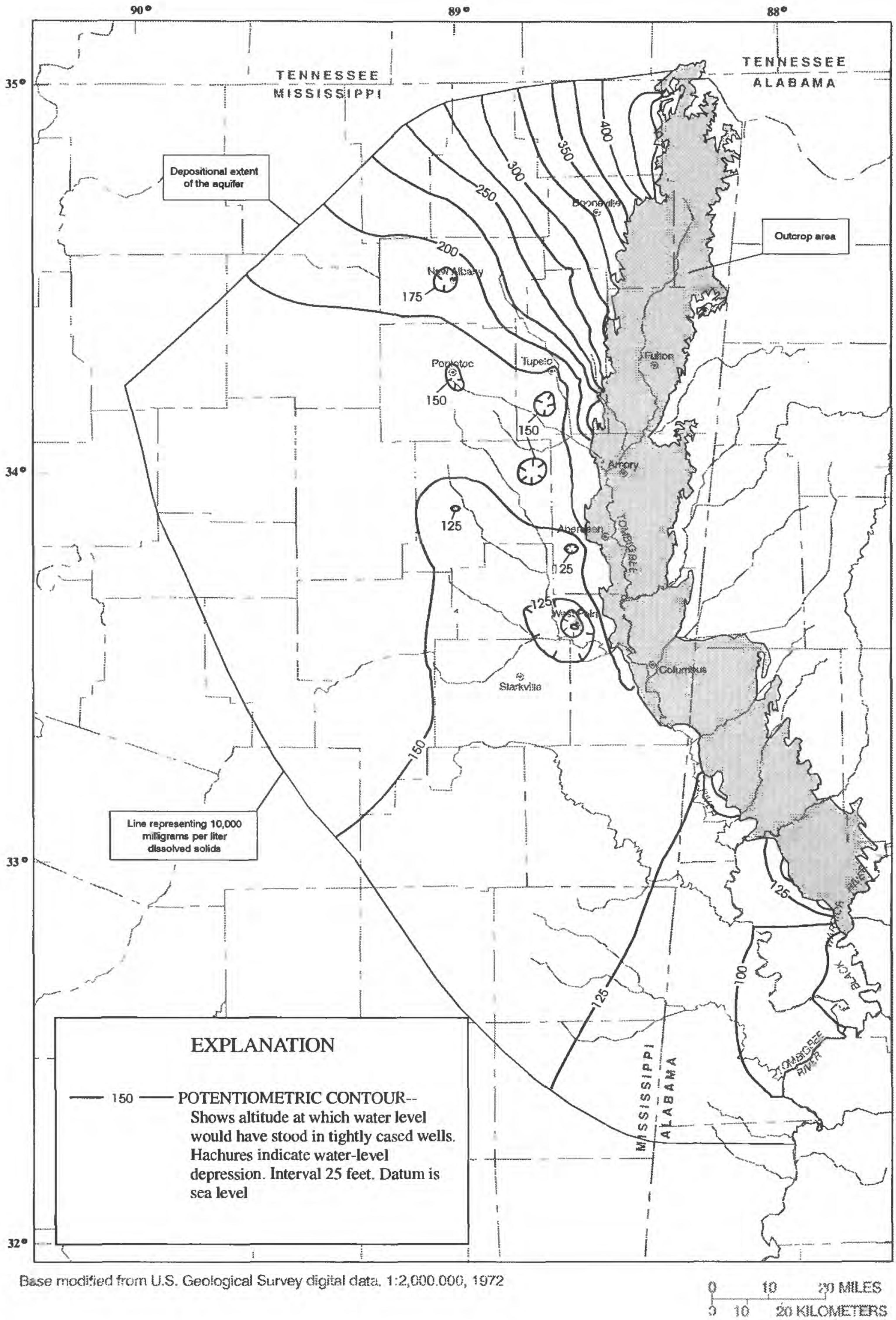
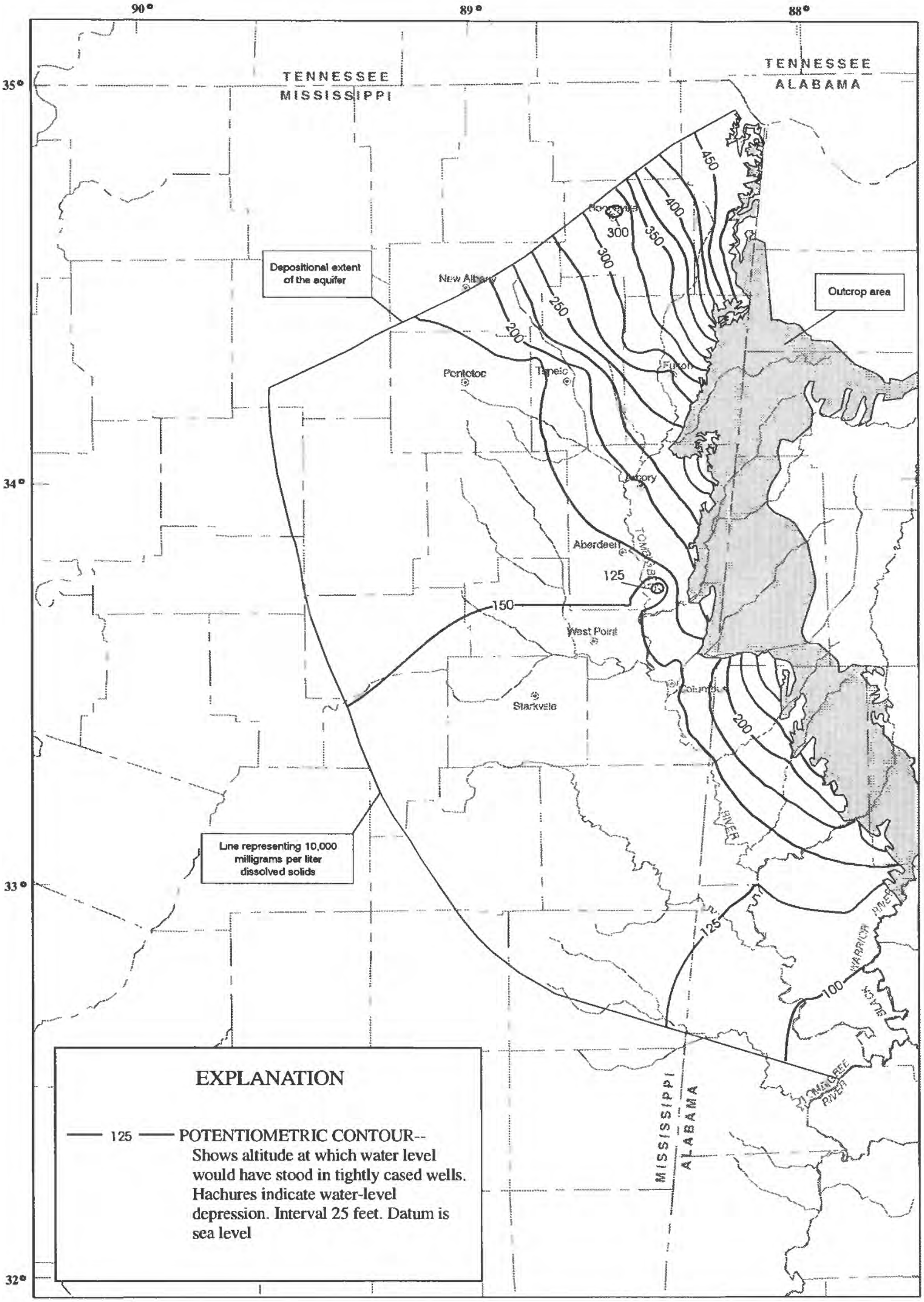


Figure 55. Simulated potentiometric surface of the Eutaw-McShan aquifer after 20 years at 1993 pumpage.



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 10 20 MILES
0 10 20 KILOMETERS

Figure 56. Simulated potentiometric surface of the Gordo aquifer after 20 years at 1993 pumpage.

The Gordo aquifer had an average simulated water-level decline in the confined part of the aquifer of about 18 feet from 1992 levels. Water levels declined in the Gordo aquifer more than 30 feet from simulated 1992 values throughout much of Clay and Oktibbeha Counties, and at Pontotoc. Water levels declined more than 50 feet from simulated 1992 values at Aberdeen and at Booneville. Projected water levels at Tupelo (fig. 53) show the general trend of continued water-level recovery for about 5 years, followed by water-level declines for both aquifers. Projected water levels at West Point (fig. 54) show the general trend of declining water levels for both aquifers.

Annual 5-Percent Increase of 1993 Pumpage for 20 Years

Projection simulations were made with a 5-percent annual increase of 1993 pumpage for 20 years. Water levels in the confined part of the Eutaw-McShan aquifer declined (fig. 57) an average of about 41 feet from simulated 1992 levels (fig. 47). Water levels declined in the Eutaw-McShan aquifer about 80 to 90 feet from simulated 1992 levels near Aberdeen, New Albany, Pontotoc, south of Tupelo in Lee County, and in east-central and northeastern Chickasaw County. Water levels declined more than 110 feet from simulated 1992 values at West Point.

The Gordo aquifer had an average simulated water-level decline in the confined part of the aquifer (fig. 58) of about 38 feet from 1992 levels (fig. 48). Water levels declined in the Gordo aquifer more than 60 feet below simulated 1992 values throughout much of Clay and Oktibbeha Counties and at Pontotoc. Water levels declined more than 70 feet from simulated 1992 values at Pontotoc and far west-central Lee County. Water levels declined more than 100 feet from simulated 1992 levels at Aberdeen and at Booneville. Projected water levels at Tupelo (fig. 53) show the general trend of continued water-level recovery for about 5 years, followed by water-level declines for both aquifers. Projected water levels at West Point (fig. 54) show the general trend of declining water levels for both aquifers.

Model Limitations

The accuracy of ground-water models is limited by assumptions made in the formulation of the governing flow equations, and in the development of an individual model. Models are also limited by cell size, number of layers, boundary conditions, time discretization, hydraulic values, accuracy of calibration, verification data, and parameter sensitivity. The model may be calibrated and verified, but the calibrated parameter values may not be unique in satisfying a particular distribution of head.

The model developed in this study is suitable for analyzing ground-water flow on a regional scale. Detailed site specific analysis is limited by cell size. The model calculates an average head for the entire cell area (1 square mile), and may not be a good approximation for the water level in an individual well. The transmissivity and other hydraulic data for an aquifer are constant in each 1-square-mile grid.

The model should not be used for analysis near any of the lateral boundaries, including the outcrop areas (which are head dependent flux boundaries). The stable freshwater-saltwater interface boundary used in the downdip areas of the aquifers would not be valid if pumping wells were placed nearby. The model is not designed to predict any movement of the freshwater-saltwater interface, or any change in water quality.

North of the Tupelo area the Eutaw-McShan aquifer is overlain by the Coffee Sand aquifer (fig. 14). Ground-water flow in the Coffee Sand aquifer was not actively modeled. The Coffee Sand aquifer was simulated as part of the overlying constant head boundary of layer 1. Flow

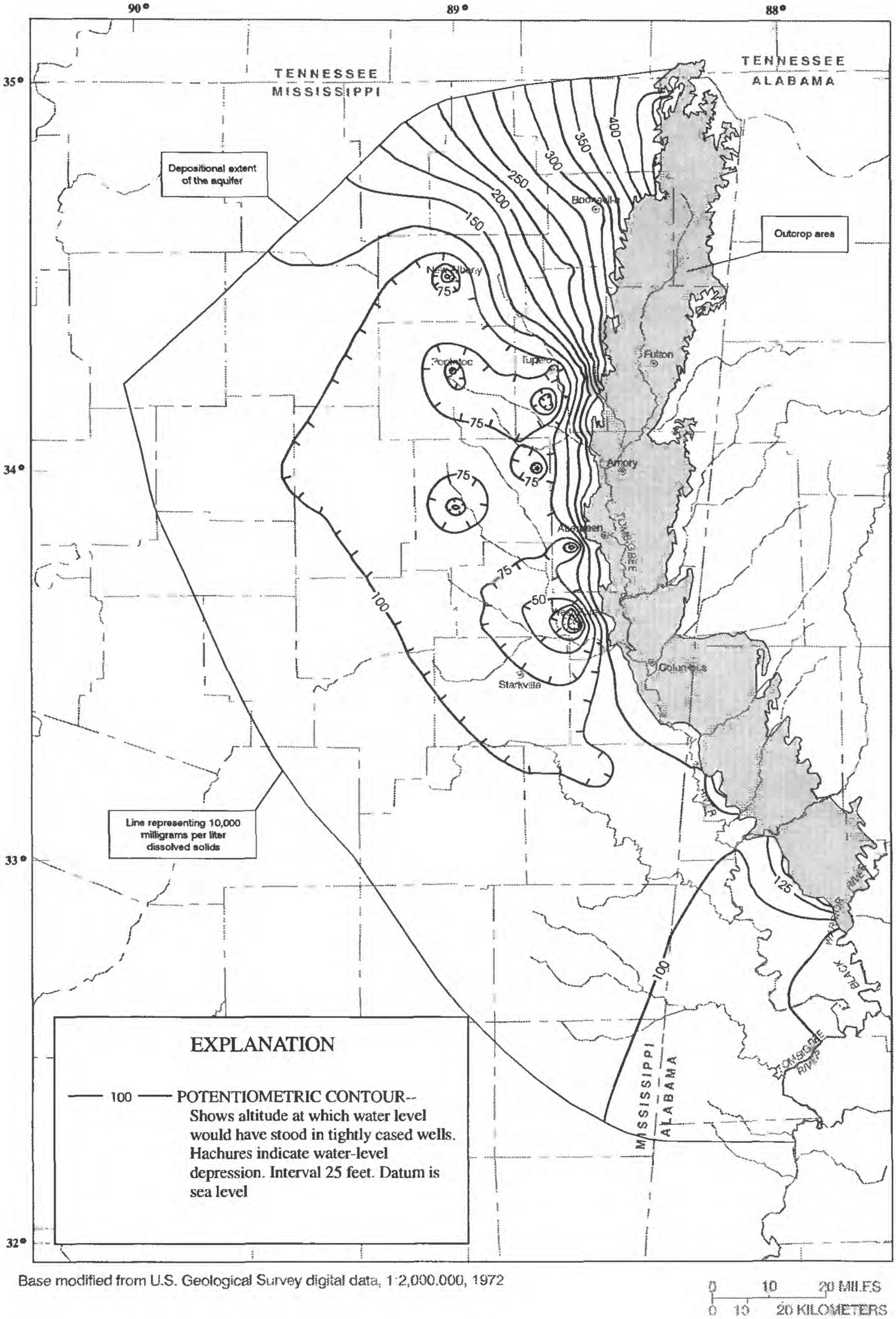


Figure 57. Simulated potentiometric surface of the Eutaw-McShan aquifer after 20 years with a 5-percent annual increase of 1993 pumpage.

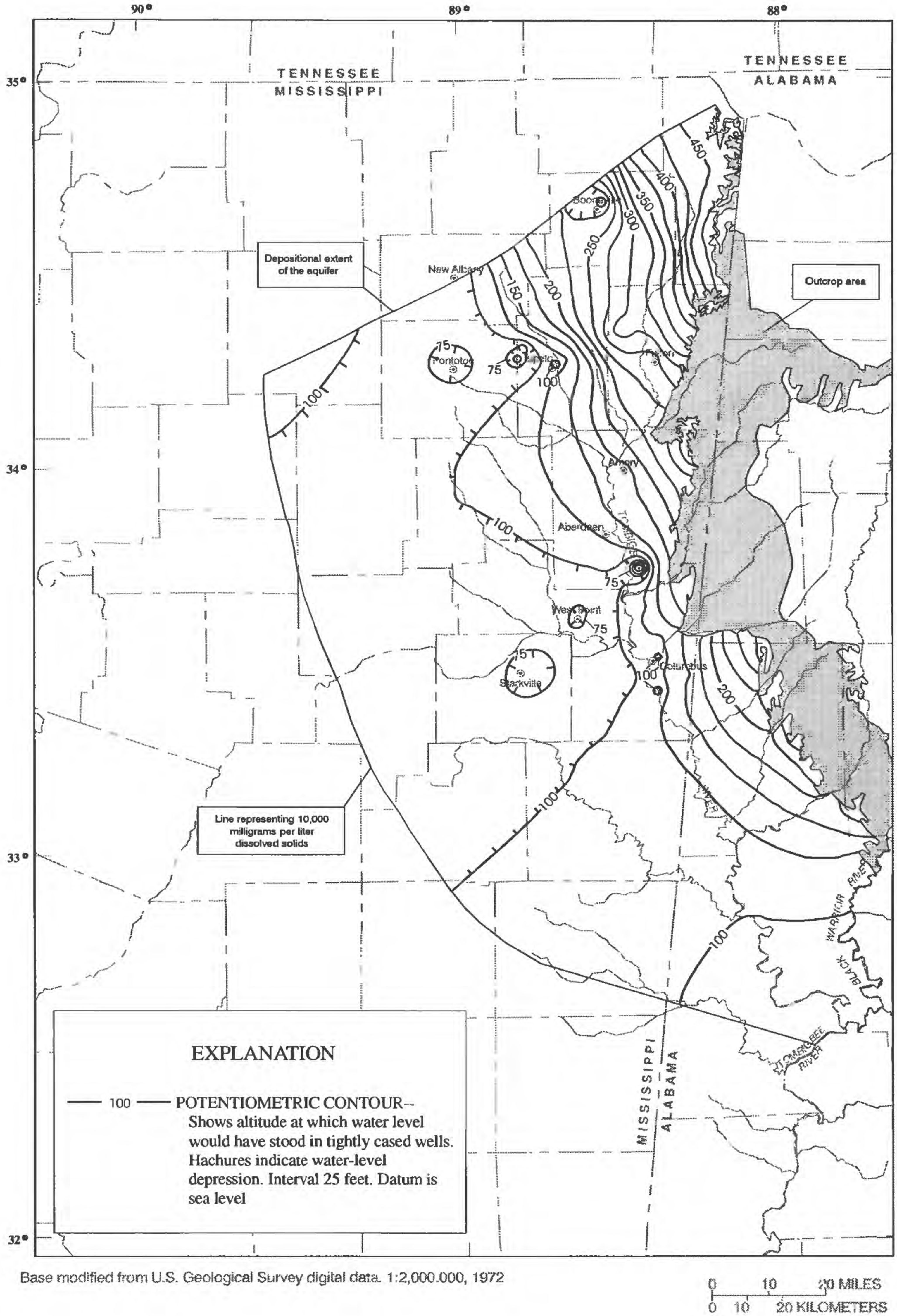


Figure 58. Simulated potentiometric surface of the Gordo aquifer after 20 years with a 5-percent annual increase of 1993 pumpage.

between the Eutaw-McShan and the overlying boundary is determined by the vertical hydraulic conductance of the confining unit, and the head difference between the upper boundary and the Eutaw-McShan aquifer (fig. 25). However, the Coffee Sand aquifer is the closest overlying aquifer to the Eutaw-McShan, and does contribute flow. The simulated amount of flow and the magnitude of the vertical hydraulic conductance terms was determined during model calibration. The parameters determined, however, are not unique and the model should be used cautiously in simulating the Eutaw-McShan aquifer where it is overlain by the Coffee Sand aquifer.

Simulated water-levels were lower than measured water levels at West Point for the 1978 pumping period and higher than measured water levels for the 1992 pumping period. Inaccurate water-use data may be the cause for the difference at West Point, but differences between measured and simulated water levels in 1992 may also be caused by numerous nearby wells being pumped while water-level measurements were made (J.H. Hoffmann, oral commun., 1994). Another possible cause for the difference might be an error in the estimation of the hydraulic connection between the Eutaw-McShan and Gordo aquifers.

There are numerous water-level measurements for the Eutaw-McShan and Gordo aquifers through time, so adequate data are available for calibration and verification. Lack of historical water-level data for the Coker and massive sand aquifers, however, precludes verification. Therefore, simulation results for the Coker and massive sand aquifers should used cautiously. The Lower Cretaceous aquifer was modeled to simulate the lower boundary of the flow system. The Lower Cretaceous aquifer model results should not be used to make definitive water-resource management decisions until data concerning the aquifer become available to verify the model results. The model results for predevelopment conditions should only be used to illustrate general trends because the results cannot be verified.

The sand and clay thickness maps are based on total thicknesses for the unit derived from borehole-geophysical log analyses that were gridded and contoured. In some areas, sand and clay thicknesses for the aquifers can vary greatly over short lateral distances. Although the maps are based on the best available data, they are subject to interpretation and may not reflect the actual sand or clay thickness at a specific site--especially where control points are sparse.

Pumpage data used in the model represented pumpage estimates for the major public and industrial supply wells in the model area. Sensitivity analysis indicated that pumpage could be increased or decreased about 20 percent and would cause only about a 3- to 4-foot difference in the overall root-mean-square error in water levels. However, large inaccuracies in estimated pumpage would require recalibration of the model.

The projection simulations are based on 1993 pumpage estimates and well locations and may be used to estimate possible regional trends in water levels and flow patterns. As new pumpage and water-level data become available, the model may be recalibrated to incorporate the new data and remain a useful tool indefinitely.

SUMMARY

The U.S. Geological Survey, in cooperation with the Tombigbee River Valley Water Management District and the Mississippi Department of Environmental Quality, Office of Land and Water Resources, conducted an investigation of the Eutaw-McShan aquifer and Tuscaloosa aquifer system in northeastern Mississippi to better understand the hydrogeology and the flow of water in and between the aquifers. As part of the investigation, a model was developed to simulate ground-water flow for prepumping and pumping conditions and used to project the possible effects of increased ground-water withdrawals.

The five aquifers studied, from youngest to oldest, are the Eutaw-McShan, Gordo, Coker, massive sand, and the Lower Cretaceous aquifers. The Eutaw-McShan aquifer includes sediments of the Eutaw and McShan Formations. In Mississippi these formations are considered a single aquifer because the sands are hydraulically connected; however, intervening beds of clay and silt may result in localized small vertical head gradients. The Tuscaloosa aquifer system consists of the Gordo, Coker, and massive sand aquifers of the Tuscaloosa Group, and a Lower Cretaceous aquifer of undifferentiated sediments. These aquifers are confined by intervening clay and silt, but regionally maintain a hydraulic continuity. Most of the available data for the Tuscaloosa aquifer system is for the Gordo aquifer.

Most water withdrawn for public and industrial water use in northeastern Mississippi is from the Eutaw-McShan aquifer and Tuscaloosa aquifer system. Ground-water use has generally been increasing since World War II, although Tupelo has begun to use surface-water sources. Cones of depression in the potentiometric surfaces of the Eutaw-McShan and Gordo aquifers have recovered in some areas, such as Tupelo in Lee County, as a result of decreasing ground-water withdrawal. In most other areas the cones of depression in the potentiometric surfaces have stabilized or are increasing in size.

The finite-difference computer code MODFLOW was used to simulate the Eutaw-McShan aquifer and Tuscaloosa aquifer system. The model grid covers 33,440 square miles. The focus of the study is northeastern Mississippi; however, parts of other States are included to simulate the boundary conditions. The model was vertically discretized into six layers.

A comparison of the simulated predevelopment and 1992 potentiometric surfaces for the Eutaw-McShan, Gordo, Coker, massive sand, and Lower Cretaceous aquifers shows an overall decline in head. Simulated water levels declined an average of about 53 feet in the confined part of the Eutaw-McShan aquifer, about 44 feet in the confined part of the Gordo aquifer, and about 42 and 60 feet for the confined parts of the Coker and massive sand aquifers, respectively. Water levels declined more than 100 feet in the Eutaw-McShan aquifer in parts of Clay, Chickasaw, Lee, Pontotoc, and Union Counties. In the Gordo aquifer, water levels declined more than 100 feet in parts of Lee, Pontotoc, and Union Counties. However, the area near Tupelo (Eutaw-McShan and Gordo aquifers) and areas in Lowndes County (Gordo aquifer) have significant rises in water levels due to decreased pumpage compared to the simulated potentiometric surface for the aquifer in 1978.

Projection simulations were made using 1993 pumpage for 20 years. Analysis of the flow budget indicates that only a small amount of water is released from storage after 20 years. Water levels in the confined part of the Eutaw-McShan aquifer rose an average of about 3.4 feet from simulated 1992 levels. The maximum water-level rise was about 45 feet, a few miles west of Tupelo. The Gordo aquifer had an average simulated water-level rise in the confined part of the aquifer of about 2.3 feet from 1992 levels. The maximum simulated rise in water levels in the Gordo aquifer was about 30 feet, a few miles west of Tupelo. The overall simulated rise in water

levels in the Eutaw-McShan and Gordo aquifers is the result of reduced 1992 pumpage due to development of surface-water sources at Tupelo.

Projection simulations were also made with a 1.5-, 3-, and 5-percent annual increase of 1993 pumpage for 20 years. With a 1.5-percent increase, water levels declined an average of about 7 feet in the confined part of the Eutaw-McShan aquifer, and about 7 feet in the confined part of the Gordo aquifer. With a 3-percent increase, water levels declined an average of about 19 feet in the confined part of the Eutaw-McShan aquifer, and about 18 feet in the confined part of the Gordo aquifer. With a 5-percent increase, water levels declined an average of about 41 feet in the confined part of the Eutaw-McShan aquifer, and about 38 feet in the confined part of the Gordo aquifer.

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