GEOHYDROLOGY AND REGIONAL GROUND-WATER FLOW OF THE COASTAL LOWLANDS AQUIFER SYSTEM IN PARTS OF LOUISIANA, MISSISSIPPI, ALABAMA, AND FLORIDA--A PRELIMINARY ANALYSIS

By Angel Martin, Jr., and C.D. Whiteman, Jr.

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MANUEL LUJAN, JR., Secretary

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Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
P.O. Box 66492
Baton Rouge, LA 70896

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CONVERSION FACTORS AND ABBREVIATIONS

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

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
million cubic feet per day (Mft^3/d)	0.005856	cubic meter per second (m^3/s)
inch (in.)	25.4	millimeter (mm)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
square mile (mi^2)	2.59	square kilometer (km^2)
mile (mi)	1.609	kilometer (km)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 X °C + 32.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

The Coastal Lowlands aquifer system of Louisiana, Mississippi, Alabama, and Florida consists of alternating, discontinuous beds of sand, gravel, silt, and clay of Miocene age and younger. The sediments thicken and dip toward the Gulf of Mexico and are highly heterogeneous.

The Coastal Lowlands aquifer system has been subdivided into five regional aquifers defined on the basis of water-level and pumpage data largely from heavily pumped areas. These aquifers from youngest to oldest are: the upper Pleistocene aquifer, the lower Pleistocene-upper Pliocene aquifer, the lower Pliocene-upper Miocene aquifer, the middle Miocene aquifer, and the lower Miocene aquifer. Electric logs of 279 wells were analyzed to construct maps of aquifer thickness, sand and clay content, and dissolved-solids concentrations of interstitial water. Analysis of the hydraulic characteristics of the regional aquifers indicates that the upper Pleistocene aquifer has the highest lateral hydraulic conductivity and the lower Miocene aquifer has the lowest.

A six-layer finite-difference ground-water flow model was used to investigate and quantify the regional ground-water flow of the Coastal Lowlands aquifer system. The model was calibrated to match 1980 steady-state conditions. Results indicate that pumpage from the Coastal Lowlands aquifer system exerts a major effect on the system under 1980 conditions; about 66 percent of the water that entered the flow system was discharged by pumpage. Regional ground-water flow under predevelopment conditions was primarily from recharge areas in central and southeastern Louisiana and southwestern Mississippi toward discharge areas along the gulf coast and in the major river valleys. Pumping for industry, public supply, and irrigation has produced cones of depression that distort or reverse the predevelopment flow pattern.

INTRODUCTION

The Gulf Coast Regional Aquifer-System Analysis (RASA) study described by Grubb (1984) is one of a series of federally funded studies by the U.S. Geological Survey designed to improve our knowledge of major aquifer systems in the United States (Chase and others, 1983). This report describes the development of a conceptual model of ground-water flow in the eastern part of the Coastal Lowlands aquifer system, development of a digital flow model to simulate ground-water flow in the aquifer system, and use of the model to quantify flow in the aquifer system under steady-state conditions. The Coastal Lowlands aquifer system consists of all aquifers of Miocene age and younger occurring in the Gulf Coastal Plain and the Mississippi Embayment of Texas, Louisiana, Mississippi, Alabama, and western Florida (Grubb, 1984). This study addresses only that part of the Coastal Lowlands aquifer system east of the Texas-Louisiana border. Models of other components of the regional aquifer system are being developed, as well as a large-scale regional model of the entire Gulf Coast aquifer system. Concurrent development of the models allows input and output to be shared and compared to insure compatibility of the final models.

The study area in Louisiana, Mississippi, Alabama, and Florida covers about 68,500 mi² (square miles) of which about 58,400 mi² is land and inland water bodies, with the remainder offshore in the Gulf of Mexico. The area extends from the Texas-Louisiana border at the Sabine River to the Escambia River in the western Florida panhandle (fig. 1). The southern boundary of the study area extends from a short distance inland to more than 40 mi (miles) offshore, while the arcuate northern boundary extends northward to near Jackson, Miss. Land-surface altitude ranges from near sea level along the coast to more than 500 ft (feet) above sea level in southwestern Mississippi and 400 ft in west-central Louisiana.

Climate in the study area is subtropical. Average annual temperatures range from about 18.5 °C in the north to more than 20.5 °C along the coast (U.S. Weather Bureau, 1980a). Average annual rainfall ranges from about 48 in. (inches) in the northern and western parts of the study area to more than 65 in. in coastal areas of Louisiana and Alabama.

Previous regional studies of the Mississippi Embayment and the Gulf Coastal Plain were used to establish the broad geologic and hydrologic framework of the study area. Statewide, multicounty, and multiparish reports were used to define the framework. (See Selected References.) Where necessary, and particularly in heavily stressed areas, local and single county or parish studies were used to complete the definition of the hydrologic framework.

Detailed lithologic interpretations of 279 electric logs of wells were used to divide the aquifer system into five regional aquifers and to determine sand and clay bed thickness within each aquifer. In addition, the electrical properties (spontaneous potential and resistance) of each sand bed more than 20 ft thick were recorded for estimation of the concentration of dissolved solids in interstitial water. Water-level, water-use, and aquifer-test data were compiled from files of the U.S. Geological Survey for use in the digital ground-water flow model.

As part of the data collection and analysis performed for this study, four reports have been published that describe ground-water levels in aquifers within the Coastal Lowlands aquifer system in Louisiana. The published reports show water levels for 1980 in the Pleistocene aquifers (Martin and Whiteman, 1985a), the Evangeline and equivalent aquifers (Martin and Whiteman, 1985b), and the Catahoula aquifer in the Catahoula Sandstone of Miocene age (Martin and Whiteman, 1986), and water levels for 1984 in the Jasper and equivalent aquifers (Martin and others, 1988). In addition, reports have been published showing geohydrologic sections in northern Louisiana (Whiteman and Martin, 1984) and statistical analyses of aquifer-test results in Louisiana (Martin and Early, 1987).

GEOHYDROLOGY

Geologic Setting

The study area is in the Gulf Coastal Plain physiographic province (Fenneman, 1983). It lies along the northern side of the gulf coast geosyncline and across the axis of the Mississippi structural trough (fig. 1). The area is characterized by off-lapping, coastward thickening wedges of fluvial, deltaic, and marine sediments. The last major transgression of the sea across the area occurred during Eocene and Oligocene time, when extensive beds of clay, silt, and lime were deposited to form the Jackson and Vicksburg Groups. The southern edge of the outcrop-subcrop area of the Jackson and Vicksburg Groups delineates the northern boundary of the study area shown in figure 1. Deltaic processes have been dominant during deposition of the sediments above the Jackson and Vicksburg Groups. Advancing deltaic fronts pushed the shoreline and its associated beach, dune, and lagoonal deposits seaward while blankets of fluvial sediments were deposited on the coastal plain inland, and extensive marine deposits formed offshore. The entire sequence of sediments above the Jackson and Vicksburg Groups has been named the Coastal Lowlands aquifer system (Grubb, 1984). The undifferentiated sequence of clay, silt, and lime beds of the Jackson and Vicksburg Groups below the Coastal Lowlands aquifer system has been named the Vicksburg-Jackson confining unit.

The Aquifer System

The Coastal Lowlands aquifer system consists primarily of alternating beds of sand and gravel, silt, and clay. Gravel is common in the northern part of the study area but becomes finer and less common southward. Grain size of the sand also decreases southward, grading to sandy clay or silt and finally to clay. Lime and marl occur in the lower part of the aquifer system and are more common throughout the marine section to the east. A distinctive feature of the sediments is their heterogeneity. Major lithologic changes occur over short distances vertically and horizontally (fig. 2). Individual sand beds can rarely be traced for more than a few miles, and even the most extensive sand beds cannot be traced with certainty for more than 30 to 50 mi. Dip of individual beds is southerly, ranging from about 10 to 50 ft/mi (feet per mile) in the outcrop area and shallow subsurface. Dip increases to the south and with increasing depth to well over 100 ft/mi at depths of more than 3,000 ft in the southern part of the study area.

The geopressured zone (a zone of abnormally high fluid pressure) occurs within the sediments comprising the Coastal Lowlands aquifer system in the southern part of the study area. Movement of fluids between the geopressured zone and the normally pressured overlying sediments is believed to be relatively small compared to the movement of fluids in the normally pressured sediments (Grubb, 1986, p. 4). Where geopressure occurs within the sediments making up the Coastal Lowlands aquifer system, the top of the geopressured zone is considered to be the base of the flow system. Thickness of the Coastal Lowlands aquifer system as thus defined ranges from zero along the northern edge of the outcrop area to more than 18,000 ft near the Louisiana coast south of New Orleans. (See pl. 2.) The study by the RASA project staff in Austin, Texas, is considering ground-water flow in all of the Coastal Lowlands aquifer system above the geopressured zone (pls. 1 and 2).

This study is confined to that part of the Coastal Lowlands aquifer system containing water with no more than 10,000 mg/L (milligrams per liter) average dissolved solids (freshwater to moderately saline water). Water with more than 10,000 mg/L dissolved solids is considered to be remnant saltwater, either connate or from ancient transgressions of the sea, and not part of the modern ground-water flow system. The total thickness of the ground-water flow system, as defined for this study, ranges from zero along the northern edge to slightly over 5,000 ft in southeastern Louisiana (fig. 3). Figures 4 and 5 show the total thickness of sand and the percentage of sand in the flow system. Maximum sand thickness increases from zero along the northern edge of the aquifer system to almost 3,000 ft in southeastern Louisiana. Sand thickness decreases in the southern part of the study area because saltwater occurs at progressively shallower depths south of the line of maximum sand thickness. Sand content of the flow system ranges from less than 10 percent to more than 90 percent.

Predevelopment flow of water in the Coastal Lowlands aquifer system was primarily from north to south (fig. 2). Most recharge entered the aquifers in the upland terrace areas of south-central and southeastern Louisiana and southwestern Mississippi. Water that was not discharged locally to streams or by evapotranspiration moved downward to the regional flow system and then toward discharge areas at lower altitudes in the coastal plain and along major stream valleys. This natural circulation of water through the aquifer system resulted in vertical differences in water levels within the aquifer system. Water levels decreased with increasing depth in the recharge areas and increased with depth in the discharge areas.

The marine and deltaic parts of the aquifers originally contained connate saltwater. Freshwater moving downdip from the recharge areas forces the saltwater ahead of it, but the downdip movement of saltwater is blocked where the sand beds pinch out or are displaced by faulting. Because the sand beds dip at angles greater than the slope of the sea floor, there is no direct connection between the sand beds and the Gulf of Mexico. Saltwater can move out of the downdip part of the sand beds only by upward leakage through overlying sediments. The present position of the freshwater-saltwater interface is the result of the interactions of the driving hydraulic head, the density of the saltwater, the permeability and porosity of the sands, and the vertical hydraulic conductivity of the sediments overlying the saltwater.

Large systems of normal faults displaced downward toward the Gulf of Mexico and numerous salt domes occur in the southern part of the study area. The faults may act as barriers to ground-water flow and affect the occurrence and movement of freshwater and salty water in the aquifer system (Rollo, 1969), but the scale of this study is too large and documented effects of the faults are too sparse to permit consideration of individual faults. For this study, it is assumed that the collective effect of the faults on the regional ground-water flow system can be treated as a reduction of the transmissivity of the aquifer system in the downdip direction. Similarly, it has been assumed that, although the salt domes displace or distort the sediments of the aquifer system, their effects are too localized to have a significant effect on the regional ground-water flow system.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

A digital quasi-three-dimensional ground-water flow model of the Coastal Lowlands aquifer system is being developed using the U.S. Geological Survey modular finite-difference model (McDonald and Harbaugh, 1988). The modular model is well documented and has been used and tested in numerous studies. In this study the modular model is used to simulate steady-state flow in a layered aquifer system where the layers are not separated by discrete confining units. The model of the Coastal Lowlands aquifer system is being used to refine estimates of the hydraulic properties of the aquifer system, to quantify ground-water flow in the aquifer system, and to investigate the effects of present and possible future development of ground water.

Model Grid

A finite-difference grid was prepared for use with the digital flow model. To facilitate data collection, data transfer, and the comparison of model results, the same grid orientation was used for the regional model and each of the more detailed component models. Figure 6 shows the relation between the regional model grid and the model grid used for this study. The regional grid uses uniform blocks 10 mi on a side, while the grids for the component models use uniform blocks 5 mi on a side. Each regional grid block contains four of the component model blocks. The grid for this study, representing an area of 136,500 mi^2 (390 X 350 mi), consists of 78 rows and 70 columns (fig. 7). Vertically, the sediments of the area are divided into five layers of variable thickness. A sixth layer is used to represent the upper boundary of the model. With six layers, the total number of blocks is 32,760. Many of the blocks are inactive because they are in areas where the aquifer represented by that layer does not exist. The total number of active blocks is 11,238.

Model Layers

Although treatment of the Coastal Lowlands aquifer system as a single heterogeneous, anisotropic aquifer is useful in developing a conceptual model of the ground-water flow system, the aquifer system must be subdivided into layers in order to use a digital model to investigate the vertical distribution of flow within the aquifer system. Attempts to correlate and map previously named aquifers led to the conclusion that no horizons above the top of the Jackson and Vicksburg Groups can be mapped across the study area. Morgan (1963, fig. 3) and Winner and others (1968, table 1) subdivided the freshwater-bearing part of the aquifer system in relatively small areas of Louisiana into zones based on water-level and water-quality data. More recently, Buono (1983) emphasized the unity of the aquifer system in southwestern Mississippi and southeastern Louisiana by naming the entire freshwater-bearing part the Southern Hills aquifer system. Buono (1983) noted that none of the previous subdivisions of the aquifer system could be applied across his study area.

The Coastal Lowlands aquifer system as defined for the gulf coast RASA studies (Grubb, 1984) includes the Southern Hills aquifer system (Buono, 1983), but is far more extensive--from the Escambia River of western Florida to the Rio Grande River at the southern border of Texas. The Coastal Lowlands aquifer system also includes the saltwater-bearing part of the flow system, which Buono (1983) excluded. Weiss and Williamson (1985) discuss the theoretical constraints and the strategy used to divide the massive coastward-thickening wedge of sediments into layers suitable for analysis by a digital ground-water flow model. The strategy consisted of selecting heavily-pumped areas (Baton Rouge, Louisiana, to the east and Houston, Texas, to the west) and establishing layers at these sites on the basis of water-level and pumpage data. Five layers were defined at each pumping center with emphasis on making the layers thinnest at the top and progressively thicker downward to provide the best resolution in the part of the flow system that contains the most freshwater and where most of the flow occurs. After the layers were defined at the pumping centers, they were extended along the strike of the beds by maintaining the thickness of each layer as the same percentage of the total aquifer system thickness as at the pumpage centers. Electric logs were checked to insure that the resulting layer breaks did not occur within a major sand bed. Where necessary, layer contacts were adjusted to coincide with the top or bottom of major sand beds.

The upper layers, representing the younger sediments, were pinched out in an updip direction to simulate the outcrop pattern in which progressively older bands of sediment are exposed in an updip direction. Similarly, the lower layers pinch out in a downdip direction to reflect the downdip transition of sandy zones to clay and shale and the rise of the top of the geopressured zone, which is treated as the base of the flow system where it occurs above the top of the Jackson and Vicksburg Groups. The resulting layers, which include the saltwater-bearing part of the aquifer system, are used in the regional model. For this study, which does not include the saltwater-bearing part of the aquifer system, each layer was truncated downdip along the line at which the average dissolved-solids content of the water in all of the sand beds in the layer exceeded 10,000 mg/L. The average dissolved-solids concentration was calculated using spontaneous potential and resistivity data from electric logs. Because the top of the geopressured zone lies well below the level at which the average dissolved-solids content of the water exceeds 10,000 mg/L, the base of the flow system for this study consists of the top of the Vicksburg-Jackson confining unit or the base of the deepest layer containing freshwater to moderately saline water (pls. 1 and 2). Figures 8 through 12 show the areal extent of each layer as defined for this study and the outcrop-subcrop area of each layer.

The five layers resulting from the subdivision of the Coastal Lowlands aquifer system described above are well suited for use with a digital flow model, but do not correspond to aquifers named and described in previous studies. To discuss the properties and characteristics of the layers, new geohydrologic unit names were developed by the RASA project staff in Austin, Texas, during the period that this report was being prepared. The names used in this report differ slightly from the newly developed names, which follow the recommendations of a report by Laney and Davidson (1987). The five regional aquifers, from youngest to oldest, are the upper Pleistocene aquifer, the lower Pleistocene-upper Pliocene aquifer, the lower Pliocene-upper Miocene aquifer, the middle Miocene aquifer, and the lower Miocene aquifer. One confining layer (the lower Miocene confining unit) was defined between the lower and middle Miocene aquifers over part of the study area. The relation of regional aquifers and geohydrologic units to model layers and to previously named aquifers is shown in table 1. It should be noted that these aquifers are defined as hydrologic units, and they may contain beds significantly younger or older than indicated by their names. Plates 1 and 2 show the regional aquifers or model layers, on west-east and north-south geohydrologic sections, respectively.

Boundary Conditions

One of the most important aspects of any model is the proper selection of boundaries. Hydrologic boundaries must be accurately represented to avoid boundary-related errors in model results. The boundaries used in the model to simulate predevelopment conditions and 1980 conditions as steady state are discussed below. Also discussed are changes that may be needed in some of the boundaries if the model is used to simulate the effects of large changes in pumpage.

The upper boundary of the model consists of a constant-head layer (layer 1) overlying the five layers representing the aquifer system. The head specified for each block of the constant-head layer is the water-table altitude at the location of that block. This layer acts as a source or sink for all water entering or leaving the flow system except that removed by pumpage. Use of a constant-head upper boundary for the present phase of modeling is justified because there has been no significant decline in the water table as a result of development through 1980. The constant-head boundary has the potential of supplying unlimited recharge from layer 1 to the underlying layers of the model. Flow through the lower face of layer 1 must be monitored during calibration of the model to insure that recharge does not reach unreasonable levels at any point. If the model is used to investigate the effects of large increases in pumpage, it may be necessary to modify this upper boundary by limiting the maximum rate of recharge.

All of the lateral boundaries of the model are no-flow boundaries. Along the northern and eastern sides of the model, the no-flow boundary in each layer is at the updip limit of the outcrop-subcrop area of the layer. The southern boundary of each layer is at the line along which the average calculated dissolved-solids concentration of the water in the sands of the aquifer represented by that layer exceeds 10,000 mg/L. As discussed in the section describing the aquifer system, water with more than 10,000 mg/L dissolved solids is not considered to be part of the modern flow system in this study.

The western boundary is no flow a short distance west of the Sabine River. From the upland areas of southeastern Texas, ground-water flowed southeastward toward the Sabine River and southward and southwestward toward the Texas coastal plain under predevelopment conditions. Under 1980 conditions, flow from the upland areas of southeastern Texas diverges, with part of the water moving southeastward to or across the Sabine River and part moving toward pumping centers near Beaumont, Texas. Under both predevelopment and 1980 conditions, the effects of the no-flow boundary would be confined to the area west of the river. The area west of the river is being modeled by the Texas District as part of a study of the Coastal Uplands and Coastal Lowlands aquifer systems of Texas and is included in this model only to minimize the

Table 1.--Relation of the regional geohydrologic units to aquifers and model layers used in this report and to previously named aquifers

Gulf coast RASA regional geohydrologic units[1]	Aquifers	Model layer number	Aquifers in Louisiana	Aquifers in Mississippi	Aquifers in Alabama	Aquifers in Florida
Zone A (Holocene-upper Pleistocene deposits)	Upper Pleistocene	2	Upland terraces "Shallow sands" Chicot "200-foot" sand of Lake Charles "500-foot" sand of Lake Charles "700-foot" sand of Lake Charles Alluvial Plaquemine Gramercy ("200-foot" sand of New Orleans) Norco ("400-foot" sand of New Orleans) Gonzales-New Orleans ("700-foot" sand of New Orleans) "400-foot" sand of Baton Rouge "600-foot" sand of Baton Rouge Atchafalaya Ponchatoula (upper)	Undifferentiated alluvial and terrace Mississippi River alluvial	Absent	Absent
Zone B (Lower Pleistocene-upper Pliocene deposits)	Lower Pleistocene-upper Pliocene	3	"1,200-foot" sand of New Orleans "800-foot" sand of Baton Rouge "1,000-foot" sand of Baton Rouge "1,200-foot" sand of Baton Rouge "1,500-foot" sand of Baton Rouge "1,700-foot" sand of Baton Rouge Ponchatoula (lower) Big Branch Kentwood Abita Covington Slidell Blounts Creek Evangeline (upper)	Terrace Citronelle	Absent	Absent
Zone C (Lower Pliocene-upper Miocene deposits)	Lower Pliocene-upper Miocene	4	"2,000-foot" sand of Baton Rouge "2,400-foot" sand of Baton Rouge Tchefuncta Hammond Zone 2 of Florida parishes and Pointe Coupee (upper) Evangeline (lower) Williamson Creek Jasper (upper)	Miocene (upper)	Alluvial Terrace Citronelle (upper)	Absent
Zone D (Middle Miocene deposits)	Middle Miocene	5	Zone 2 of Florida parishes and Pointe Coupee (lower) Zone 3 of Florida parishes and Pointe Coupee "2,800-foot" sand of Baton Rouge Amite Ramsay Franklinton Jasper (lower) Carnahan Bayou	Miocene (middle)	Citronelle (lower) Miocene (upper)	Sand and gravel (upper)
Zone E (Lower Miocene-upper Oligocene deposits)	Lower Miocene	6	Catahoula	Miocene (lower)	Miocene (lower)	Sand and gravel (lower)

[1] Grubb, 1987, figure 3.

effects of the no-flow boundary within the study area. If future simulations involve large changes in pumpage near the western boundary of the model, it may be desirable to change the boundary to specified head or head-dependent flux to better simulate the changing flow conditions near the boundary.

The lower boundary of the model is simulated as no flow. In the northern part of the model area, this boundary is the top of the thick clays of the Jackson and Vicksburg Groups. Although a small amount of water may leak upward through these clays from the underlying Eocene sediments, the maximum anticipated rate of leakage is negligible in relation to the volume of flow in the Coastal Lowlands aquifer system. In the southern part of the model area, the lower boundary of the model is at the base of the lowest layer containing water with an average dissolved-solids concentration of less than 10,000 mg/L. Where the average calculated dissolved-solids concentration of water within that layer exceeds 10,000 mg/L, the layer is truncated by a no-flow boundary and the lower boundary of the model moves up to the bottom of the layer above. This produces a stepped lower boundary with sharp discontinuities of transmissivity from high values in grid blocks representing the maximum or near-maximum thickness of the lowest layer to zero in adjacent no-flow grid blocks. (See pls. 1 and 2.) A planned future modification of the model is to smooth the lower boundary by considering the dissolved-solids concentration of water within individual sand beds of the lowest layer instead of the average value for all sand beds. Elimination of sand beds from the computation of transmissivity as they become salty will improve the representation of the transmissivity of the aquifer and of the distribution of freshwater to moderately salty water near the base of the aquifer system.

Model Input

In order to simulate ground-water flow in the aquifer system, hydraulic properties of the aquifer system, initial and boundary conditions, and pumping stresses, if any, must be supplied to the model. The entry for each property at each grid block represents an average value of the property throughout the block and is made at the center of the block, defined as the node or nodal point. Major items of data input are discussed individually below.

Layer Extent Arrays

Layer extent arrays define the active areas and boundaries of the model. Variable-head nodes represent the areas of the flow system in which the aquifer represented by the model layer exists and in which heads are free to change in response to changing stresses. Constant-head nodes represent boundaries of the flow system where head does not change with time, but through which flow into or out of the system may occur. No-flow nodes represent boundaries of the flow system through which no flow will occur under any conditions. Layer extent arrays are a direct reflection of the conceptual model of the aquifer system and were constructed during the mapping and definition of the geohydrologic framework.

Water-Table Altitudes

Water-level altitudes representing water levels in the aquifer system at the start of the simulation period are supplied for each active node of the model. Head values supplied for constant-head nodes are critical because these values affect the heads calculated by the model at variable-head nodes. For steady-state simulations, the starting head supplied to variable-head nodes is not critical. In the present model, all nodes in the upper layer of the model (layer 1) are constant head with water levels set at the altitude of the water table.

An initial attempt to generate a matrix representing the water table by digitizing a hand-contoured map of the water table was not satisfactory. Because of the sparse water-level data relative to small scale variations in land-surface altitude, about one third of the resulting water-table altitudes were above the altitude of land surface (Williams and Williamson, 1989, p. 338). The availability of a detailed data base of land-surface altitudes (Godson, 1981) with about 90 regularly-spaced entries per model block, led to the development of equations relating water-table altitude to land-surface altitude and the variability of land-surface altitude within each model block (Williams and Williamson, 1989, p. 337). The resulting equations were used to calculate water-table altitudes for each node. The calculated water-table altitudes, shown as a contour map in figure 13, are used as the water-level values in the constant-head nodes in the top layer of the model.

Transmissivity

Transmissivity is input to the model as a matrix of sand thickness and a lateral hydraulic-conductivity value for each layer. Sand thickness at each node is multiplied within the model by the hydraulic-conductivity value to compute the transmissivity for each node.

Sand Thickness

The total thickness and percentage of sand in each layer was calculated for each of 279 geophysical logs. For logs that ended within a layer, it was assumed that the missing part of the layer contained the same percentage of sand as the part shown on the log. Matrices of layer thickness, sand thickness, and percentage of sand for each active node were generated by interpolation for each model layer. The sand thickness matrices were used as input to the model. Figures 14 through 23 show maps of sand thickness and percentage of sand derived from these matrices for each model layer below the constant-head layer. Sand thickness for each layer increases from zero along the northern edge of the layer to as much as 1,600 ft in the middle Miocene aquifer (model layer 5) east of Baton Rouge, Louisiana. Percentage of sand for each layer ranges from less than 10 percent to greater than 90 percent.

Aquifer Hydraulic Conductivity

Five hundred and twenty aquifer tests from the Coastal Lowlands of Louisiana, Mississippi, and Alabama were examined to determine aquifer lateral hydraulic conductivity. These tests were of varying quality, reliability, and detail. Some were single-well tests (pumping well) not designed to measure the hydraulic characteristics of the aquifers, but to test well efficiency. Other tests, specifically designed to measure aquifer hydraulic characteristics, included the pumping well and at least one properly spaced observation well. The remaining tests can be classified as intermediate between the two previously described well groups.

Transmissivity of the aquifer was calculated using an appropriate analytical method for each aquifer test. The hydraulic conductivity of the aquifer at the location of each test was determined by dividing the calculated transmissivity by an appropriate sand thickness. For some single-well tests, the length of the screened interval within a sand bed was used for calculation of hydraulic conductivity because the tests involved low pumping rates, small well diameters, short pumping periods, and short screen lengths. Under these conditions, the calculated transmissivity value was assumed to represent only the part of the aquifer penetrated by the well screen (Meyer and others, 1975, p. 18). For other tests involving large pumping rates and long screen intervals, the entire sand-bed thickness was used for calculation of hydraulic conductivity.

The following table shows the number of aquifer tests, values for arithmetic and harmonic means of lateral hydraulic conductivity, average value of the two means, and the standard deviation about the arithmetic mean for each regional aquifer. The average value of hydraulic conductivity from the two means was used for calculating transmissivity for each model layer during initial model simulations. The arithmetic mean is affected by extreme high values. Several high values of lateral hydraulic conductivity for each regional aquifer greatly increased the arithmetic-mean values. The harmonic mean, defined as the reciprocal of the arithmetic mean of the reciprocals of the hydraulic-conductivity values, is not significantly affected by extreme high values and is always less than or equal to the arithmetic mean. The harmonic mean is affected by extreme low values. The harmonic means of aquifer hydraulic conductivity are considerably lower than the arithmetic means as shown in the following table. The averages of the arithmetic and harmonic means probably represent better estimates of lateral hydraulic conductivities of the aquifers than the arithmetic or harmonic means individually. On average, the upper Pleistocene aquifer has the highest hydraulic conductivity, whereas, the lower Miocene aquifer has the lowest. The relatively large values of standard deviation indicate the large variability of hydraulic conductivity values in each aquifer. Hydraulic conductivity is not required for model layer 1 because it is a constant-head layer.

Model layer	Aquifer	Number of aquifer tests	Hydraulic conductivity (feet per day)			
			Arith-metic mean	Harmonic mean	Average of means	Standard deviation
2	Upper Pleistocene-----	93	236	171	203	97
3	Lower Pleistocene-upper Pliocene------	84	97	43	69	100
4	Lower Pliocene-upper Miocene-------------	106	111	73	91	73
5	Middle Miocene--------	124	91	32	62	60
6	Lower Miocene---------	113	74	29	51	65

Restriction of Vertical Flow

The vertical movement of ground water between the regional aquifers is simulated in the model in terms of leakance. For this study, the leakance is defined as the vertical hydraulic conductivity of the clays within and between the regional aquifers divided by the thickness of clay between midpoints of the regional aquifers. Descriptions of the confining beds, interbedded clays, and the vertical hydraulic conductivity of the clays are given below.

Confining Units

Clays of the Jackson and Vicksburg Groups form the Vicksburg-Jackson confining unit (Grubb, 1984, p. 15) at the base of the Coastal Lowlands aquifer system. This confining unit is modeled as an impermeable (no flow) lower boundary of the flow system and is not an active element of the model.

A thick sequence of clay and silt in the lower part of the Coastal Lowlands aquifer system can be mapped beneath parts of southwestern and south-central Louisiana. This clay separates the lower Miocene aquifer from the middle Miocene aquifer and has been named the lower Miocene confining unit and is referred to as the zone E confining unit by Grubb (1987, p. 105-113). The lower Miocene confining unit would normally be treated in the model as a distinct confining unit; but because of its relatively small areal extent within the study area, it was treated as a special case of the interbedded clays within model layers as described below.

Interbedded Clays

Extensive confining clay beds do not occur within the Coastal Lowlands aquifer system, but large water-level differences do occur vertically within the flow system. Some provision must be made in the model to restrict vertical flow between layers to duplicate the observed water-level differences. The method, successfully applied in other regional aquifer studies, adopted for this model was to treat the interbedded clays between vertically adjacent nodes as being equivalent to a single clay bed (Bredehoeft and Pinder, 1970). The equivalent clay thickness was computed by adding one-half the aggregate clay thickness of the upper layer to one-half the aggregate clay thickness of the lower layer. Where the lower Miocene confining unit was present in southern Louisiana, its thickness was added to the equivalent clay thickness of the adjoining layers. Use of the equivalent clay thickness introduces an areal variability into the leakance between model layers that corresponds to the conceptual model of the flow system. There will be relatively low restriction to vertical flow in areas where the aquifers represented by the model layers contain little clay, and relatively high restriction to vertical flow where the aquifers contain a high percentage of interbedded clay.

Vertical Hydraulic Conductivity of Clays

Few data exist to define the vertical hydraulic conductivity of the clays which restrict vertical flow between aquifers. No aquifer tests are known from the area that were designed, or are adequate, to permit calculation of vertical leakage across clay beds. Laboratory measurements were made on two core samples of clay from a test well in the Baton Rouge, Louisiana, industrial district (Whiteman, 1980, table 4). The values of vertical hydraulic conductivity measured for these cores, 1.1×10^{-6} ft/d (feet per day) for a core at 450 ft and 1.7×10^{-5} ft/d from a core at 2,115 ft, are within the ranges of laboratory values reported by Gabrysch and Bonnet (1974, table 2) for clay cores from the Coastal Lowlands aquifer system in Texas. Because the vertical hydraulic conductivity of the mixture of clays, silts, and sandy clays making up the equivalent clay thickness was expected to be higher than the laboratory values measured on relatively pure clays, a single value of 2.0×10^{-5} ft/d was initially assigned for all nodes in all layers of the model.

Ground-Water Pumpage

Ground-water pumpage data were obtained from published reports and existing files in two basic formats: distributed pumpage and point pumpage. Distributed pumpage, such as for irrigation or rural-domestic use, is collected by county or parish and is rarely related to specific wells or sites. The distributed pumpage for each county or parish was divided among model nodes in the developed, non-urban areas of that county or parish (D.J. Ackerman, U.S. Geological Survey, written commun., 1985). Because most distributed pumpage is from relatively shallow wells, the distributed pumpage was usually assigned to the uppermost aquifer. In the few cases where distributed pumpage from deep wells formed a significant part of the total pumpage from a county or parish, the pumpage was divided between the aquifers involved. Point pumpage, from municipal or industrial wells or well fields, is collected by well or by site. This pumpage can be assigned, based on well depth, directly to the model nodes from which the water is withdrawn. Total pumpage from the modeled area in 1980 was about 252.4 Mft^3/d (million cubic feet per day) or 1,888 Mgal/d (million gallons per day). By aquifer and model layer, the pumpage was:

Aquifer	Model layer	Pumpage	
		Mft^3/d	Mgal/d
Upper Pleistocene------------------	2	166.9	1,248.5
Lower Pleistocene-upper Pliocene---	3	16.0	119.7
Lower Pliocene-upper Miocene-------	4	21.8	163.1
Middle Miocene---------------------	5	37.4	279.8
Lower Miocene----------------------	6	10.3	77.0

Figures 24 through 28 show the areal distribution of pumpage by aquifer. Pumpage of about 95 Mft^3/d from the upper Pleistocene aquifer (model layer 2) in southwestern Louisiana for rice irrigation constitutes about 38 percent of the pumpage from the entire aquifer system. Concentrated withdrawals from pumping centers occur from all aquifers. The least pumpage, about 10.3 Mft^3/d or 4 percent of the total pumpage, is from the lower Miocene aquifer (model layer 6).

No recharge or waste injection wells were included in the model. Although brine, produced in conjuction with oil and gas, and some liquid industrial wastes are disposed of through injection wells, most of the injection occurs into saltwater-bearing sands that are not included in this model. No significant recharge of freshwater through wells occurs in the area.

CALIBRATION OF THE MODEL

Calibration is the process in which model parameters and boundary conditions are adjusted to reduce the difference between model-simulated results and field observations to an acceptable level. Calibration may be based on matching water levels, hydraulic gradients, drawdowns, flow rates, volumetric budgets, or any combination of these. This model was calibrated by matching model-simulated water levels for 1980, treated as steady state, to measured 1980 water levels. Measured water levels were assigned to model blocks on the basis of the location and depth of the wells. If multiple water levels were available from a single well, the mean of the water levels was used. If more than one well was located in a model block, a weighted mean water level was computed based on the distance of each well from the node.

The entire Coastal Lowlands aquifer system was not under steady-state conditions in 1980. For example, water levels in the Alexandria area, Louisiana, were declining due to increases in pumpage. In Lake Charles and Baton Rouge, Louisiana, water levels were recovering due to decreases in pumpage. The rate at which these water levels were changing was not considered to be significant in relation to the horizontal and vertical scale of the aquifer system simulated. Transient simulations starting with predevelopment conditions will be done at a later date for calibration of the storage coefficient of the aquifer system and to calibrate the model over varying time periods. The 1980 steady-state calibration will be compared with transient calibration results to test the validity of the 1980 steady-state calibration.

Thus far, only the leakance of the confining beds and the transmissivities of the aquifers have been adjusted in the calibration process. Care was taken to insure that these parameters were adjusted within reasonable ranges based on values from field observations, information from previous studies, and results from the regional model being calibrated by the project staff in Austin, Texas. Initially, uniform parameter adjustments were made over the full areal extent of each layer. As expected, adequate calibration could not be obtained using uniform parameter adjustments, so subareas within each layer were delineated and used in subsequent calibration simulations.

Table 2 shows the range of uniform values of vertical and lateral hydraulic conductivity tested for each model layer and the range of values used in the subareas of each layer for the simulation that gave the best match of measured water-level altitudes, water-level gradients, and large cones of depression. Maps of the model-simulated water-level altitudes for the simulation using the ranges of values in table 2 producing the best simulated results are shown in figures 29 through 33. Hand-contoured maps of measured water-level altitudes (figs. 34-38) were compared to the simulated water-level altitudes to prepare difference maps (figs. 39-43). Both the selection of measurements to be used and the contouring of the maps of measured water-level altitudes are subjective and responsible for some of the errors indicated by the difference maps. Vertical differences in water levels within an aquifer may occur anywhere in the study area, but are most common and largest in the outcrop areas and near pumping centers. Because of the inherent errors resulting from the subjectivity involved in their preparation, the difference maps were used in calibration of the model only as guides to areas needing attention and to monitor the effects of changes made during calibration.

Model-simulated water-level altitudes were compared to measured water-level altitudes from individual model blocks after each simulation. Figure 44 is a histogram showing the difference between the model-simulated and measured water-level altitudes for the best simulation. In this comparison, model layer 2 shows the best fit of simulated to measured water-level altitudes with 292 of 349 simulated water-level altitudes within 20 ft of the measured water-level altitudes. Model layer 5 shows the poorest fit, with 21 of 276 simulated water-level altitudes differing by more than 100 ft from the measured values.

The root-mean-square error (RMSE) and the mean error were calculated for each model layer after each simulation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (h_i^s - h_i^m)^2}{N}}$$

where h^s is the model-simulated water level, h^m is the measured water level, and N is the number of water-level pairs compared. Minimizing the RMSE by adjusting the model input parameters gives values of the parameters which produce simulated water-level altitudes best fitting the measured values. The mean errors indicate whether the model-computed water-level altitudes for each layer, taken as a whole, are higher or lower than the measured water-level altitudes.

Table 2.--Ranges of values of vertical and lateral hydraulic conductivity used in model calibration

Aquifer	Model layer	Vertical hydraulic conductivity (feet per day)		Lateral hydraulic conductivity (feet per day)	
		Uniform values tested	Values in subareas of calibrated model	Uniform values tested	Values in subareas of calibrated model
(Constant-head upper boundary)---	1	$1 \times 10^{-3} - 2 \times 10^{-5}$	$1.1 \times 10^{-1} - 5.5 \times 10^{-6}$	(a)	(a)
Upper Pleistocene---	2	$1 \times 10^{-3} - 1 \times 10^{-6}$	$1.4 \times 10^{-2} - 2.1 \times 10^{-4}$	50-170	42.5-170
Lower Pleistocene-upper Pliocene----	3	$1 \times 10^{-3} - 2 \times 10^{-5}$	$2.75 \times 10^{-3} - 1.1 \times 10^{-4}$	50-170	85 -170
Lower Pliocene-upper Miocene-----	4	$1 \times 10^{-3} - 2 \times 10^{-5}$	$3.0 \times 10^{-3} - 7.5 \times 10^{-5}$	20- 89	45
Middle Miocene------	5	$1 \times 10^{-3} - 1 \times 10^{-6}$	$4.0 \times 10^{-4} - 1.0 \times 10^{-6}$	20- 97	20 - 40
Lower Miocene-------	6	(b)	(b)	10- 38	19

[a] Hydraulic conductivity is not required for model layer 1 because it is a constant-head layer.

[b] Vertical hydraulic conductivity is not required for model layer 6 because the bottom of this layer is the lower boundary of the model and is simulated as no flow.

Mean error and RMSE for each layer for the model-simulated water levels shown in figures 29 through 33 are:

Layer	Mean error (feet)	Root-mean-square error (feet)
2	5.36	14.64
3	11.29	34.68
4	6.09	39.75
5	-7.65	57.86
6	12.13	45.96

Comparisons of the maps showing simulated (figs. 29-33) and measured (figs. 34-38) water-level altitudes show that the model reproduced regional hydraulic gradients and large cones of depression resulting from large withdrawals with reasonable accuracy.

Flow rates and volumetric budgets of the aquifer system cannot be measured independently with enough accuracy to be used directly in the calibration of the model. Model-simulated nodal flow rates and volumetric budgets provide useful qualitative checks on model results. For example, if simulated recharge rates or flows between model layers are unreasonably high in any part of the model area, the model cannot be considered to be adequately calibrated even though simulated and measured water-level altitudes agree closely.

MODEL RESULTS

Following calibration of the model as described in the preceding section, pumpage was removed and another simulation was made to represent predevelopment conditions. The resulting water-level altitudes are shown as maps in figures 45 through 49. These maps cannot be compared directly with maps of measured water-level altitudes as was done with the simulation representing 1980 water levels because too few predevelopment water levels are available. Harris (1904) published numerous water levels, many measured in 1903, for relatively shallow wells in coastal Mississippi and in southern Louisiana. Most of the well locations and water-level altitudes given by Harris (1904) are approximations. Some additional measurements are available from the records of wells drilled in the late 1800's and early 1900's. Although several hundred wells had been drilled in southern Louisiana by 1903, flowing and pumping yields were relatively low and water levels measured in 1903 were probably within a few feet of the predevelopment level. Because of the uncertainties in the measured data, statistical comparisons were not made between the simulated and measured predevelopment water levels, but visual comparisons indicated reasonable agreement.

Flow of water into and out of the constant-head upper layer of the model under predevelopment conditions is shown in figure 50. Flow out of the constant-head layer (positive) represents recharge to the aquifer system and flow into the layer (negative) represents discharge from the aquifer system. Recharge is concentrated in the uplands of west-central and northern-southeast Louisiana and southwestern Mississippi. Discharge occurs in the low-lying coastal plain and marshes of southern Louisiana, Mississippi, and Alabama and along the alluvial valleys of the major rivers of the area. Figures 51 through 55 are flow-vector plots showing the rate and direction of flow within each regional aquifer. Also shown are the areas where each aquifer receives recharge from (downward flow) or discharges to (upward flow) the overlying aquifer or the constant-head boundary. These figures indicate that predevelopment flow in the Coastal Lowlands aquifer system was primarily from recharge areas in the northern part of the study area toward discharge areas along the coast and in the major river valleys. Drainage of water from the aquifer system to the Mississippi River valley was greatest to the central and western parts of the valley, not to the present course of the Mississippi River along the eastern side of the valley.

Figure 56 is a schematic north-south cross section of the aquifer system showing the vertical distribution of flow between the constant-head upper layer and the outcrop of each of the aquifers and the distribution of flow within the aquifer system. The flow rates shown are for the areal extent of the aquifer system. Figure 56 shows that most of the flow under predevelopment conditions occurs in the upper part of the aquifer system. Of a total inflow to the aquifer system of 202.4 Mft^3/d, 70.2 Mft^3/d (about 35 percent) circulates within the upper Pleistocene aquifer (layer 2), and 63.4 Mft^3/d (about 31 percent) circulates within the outcrop areas of the older aquifers (layers 3-6). Most of the water entering an aquifer in its outcrop area circulates and is discharged locally within the outcrop area. Only 68.8 Mft^3/d (about 34 percent) of the water entering the aquifers in the outcrop areas moves downdip beyond the outcrop area or downward to a deeper aquifer to become part of the deep regional circulation under predevelopment conditions.

Areal and vertical distribution of ground-water flow in the aquifer system under 1980 conditions, treated as steady state, is shown in figures 57 through 63. Withdrawal of water from the aquifer system at the 1980 rate causes most of the area of southwestern and coastal Louisiana and the coastal areas of Mississippi, Alabama, and western Florida to change from areas of discharge to areas of recharge (fig. 57). Over the area of the model, recharge with 1980 pumpage increases to 379.7 Mft^3/d (nearly twice the predevelopment rate) and natural discharge is reduced to 127.3 Mft^3/d (about 63 percent of the predevelopment rate). (See fig. 58.) Pumpage of 252.4 Mft^3/d accounts for about 66 percent of the total discharge from the aquifer system, with pumpage from the upper Pleistocene aquifer (layer 2) of 166.9 Mft^3/d amounting to about 44 percent of the total discharge.

Figures 59 through 63 show the rate and direction of flow within each regional aquifer under 1980 conditions. Also shown are the areas where each aquifer receives recharge from (downward flow) or discharges to (upward flow) the overlying aquifer or the constant-head boundary. Comparison with the predevelopment flow-vector plots (figs. 51-55) indicates that regional flow in the Coastal Lowlands aquifer system in 1980 remains primarily north to south and toward the major rivers. However, the flow fields have been significantly affected by heavy pumpage in all regional aquifers. This is especially evident in the upper Pleistocene aquifer in southwestern Louisiana near Lake Charles and in southeastern Louisiana in the New Orleans area. Regional flow lines in these areas have been altered or reversed since predevelopment time.

NEED FOR MODEL REFINEMENT

More model simulations will be made to improve the match between measured and simulated water-level altitudes. These simulations will involve further modification of the leakance of the confining units and the transmissivities of the aquifers, as well as possible modification of boundary conditions such as the location of the downdip no-flow boundary. As mentioned in the discussion of the lower boundary of the model, it is planned to smooth the lower boundary of the model by thinning the lowest active layer downdip as saltwater occurs at progressively higher levels within the aquifer represented by that layer. Transient simulations calibrated by matching long-term water-level changes will be used to determine aquifer storage coefficients and to refine the calibration of the model made in steady-state simulations. Simulations will be made to study the effects of changes in pumpage from the Coastal Lowlands aquifer system on water levels, hydraulic gradients, and flows. Sensitivity analysis will be done to determine the sensitivity of the model to the hydraulic characteristics of the aquifers and confining units, changes in pumping stresses, and boundary conditions. Sensitivity analysis provides insight into the probable accuracy of projections made by the model and may indicate where additional work to improve the model is needed or would be most productive.

SUMMARY AND CONCLUSIONS

The Coastal Lowlands aquifer system of Louisiana, Mississippi, Alabama, and Florida is an off-lapping sequence of fluvial, deltaic, and marine deposits of Miocene age and younger. The aquifer system consists of alternating, discontinuous beds of sand, gravel, silt, and clay that thicken and dip southward toward the Gulf of Mexico. The sediments are highly heterogeneous with few individual sand beds that can be traced for more than a few miles. The aquifer system is underlain by the Vicksburg-Jackson confining unit, a marine clay sequence of the Jackson and Vicksburg Groups.

The Coastal Lowlands aquifer system is subdivided into five regional aquifers. Electric logs of 279 wells were analyzed to construct maps of aquifer thickness, sand and clay content, and dissolved-solids concentrations of interstitial water. The regional aquifers were defined on the basis of water-level and pumpage data from heavily pumped areas and extended into lesser-developed areas by extrapolating aquifer thicknesses. The aquifers, from youngest to oldest are the upper Pleistocene aquifer, the lower Pleistocene-upper Pliocene aquifer, the lower Pliocene-upper Miocene aquifer, the middle Miocene aquifer, and the lower Miocene aquifer. In this study, the base of the ground-water flow system is defined as the shallower of either the top of the Vicksburg-Jackson confining unit or the bottom of the deepest layer overlying the confining unit containing water with no more than 10,000 mg/L average dissolved solids.

Sand thickness in the flow system increases from zero along the northern edge of the aquifer system to almost 3,000 ft in a small area in southeastern Louisiana. Sand content ranges from less than 10 percent to greater than 90 percent.

Hydraulic characteristics of the regional aquifers were determined from analysis of aquifer-test data. The analysis indicates that on average the upper Pleistocene aquifer has the highest lateral hydraulic conductivity (203 ft/d) and the lower Miocene aquifer has the lowest (51 ft/d).

A six-layer finite-difference ground-water flow model is being used to investigate and quantify the regional flow of the Coastal Lowlands aquifer system. The model is being calibrated by steady-state simulation to match 1980 conditions. The model in its present state generally reproduces the ground-water hydraulic gradients and the major cones of depression shown by maps of measured water-level altitudes. Results indicate that pumpage is a major control on flow in the aquifer system under 1980 conditions; about 66 percent of the water entering the flow system is discharged by pumpage. Pumping for industry, public supply, and irrigation under 1980 conditions produced cones of depression that distorted or reversed the predevelopment flow pattern. Total pumpage from the modeled area in 1980 was about 252.4 Mft^3/d. Pumpage of about 95 Mft^3/d from the upper Pleistocene aquifer of southwestern Louisiana for rice irrigation produced the most widespread cone of depression and constitutes about 38 percent of pumpage from the entire aquifer system. The least pumpage, about 10.3 Mft^3/d or 4 percent of the total pumpage, is from the lower Miocene aquifer.

Removal of pumpage from the model allows simulation of predevelopment conditions. Regional flow of ground water in the Coastal Lowlands aquifer system under predevelopment conditions was primarily from recharge areas in the uplands of central Louisiana and southwestern Mississippi toward discharge areas along the coast and in the major river valleys. Results indicate that under predevelopment conditions most of the flow occurred in the upper part of the aquifer system. About 35 percent (70.2 Mft^3/d) of the total flow in the aquifer system (202.4 Mft^3/d) circulated in model layer 2, representing the upper Pleistocene aquifer, and about 31 percent (63.4 Mft^3/d) circulated in the outcrop areas of layers 3 through 6, representing the older regional aquifers.

Planned model refinement includes making additional steady-state simulations to improve the calibration of the model to 1980 conditions. Other work will include transient simulations to improve estimates of aquifer storage coefficients, sensitivity analysis to determine probable accuracy of projections based on model results, and simulations to project the effects of present and possible alternative pumping rates and distributions on water levels in the future.

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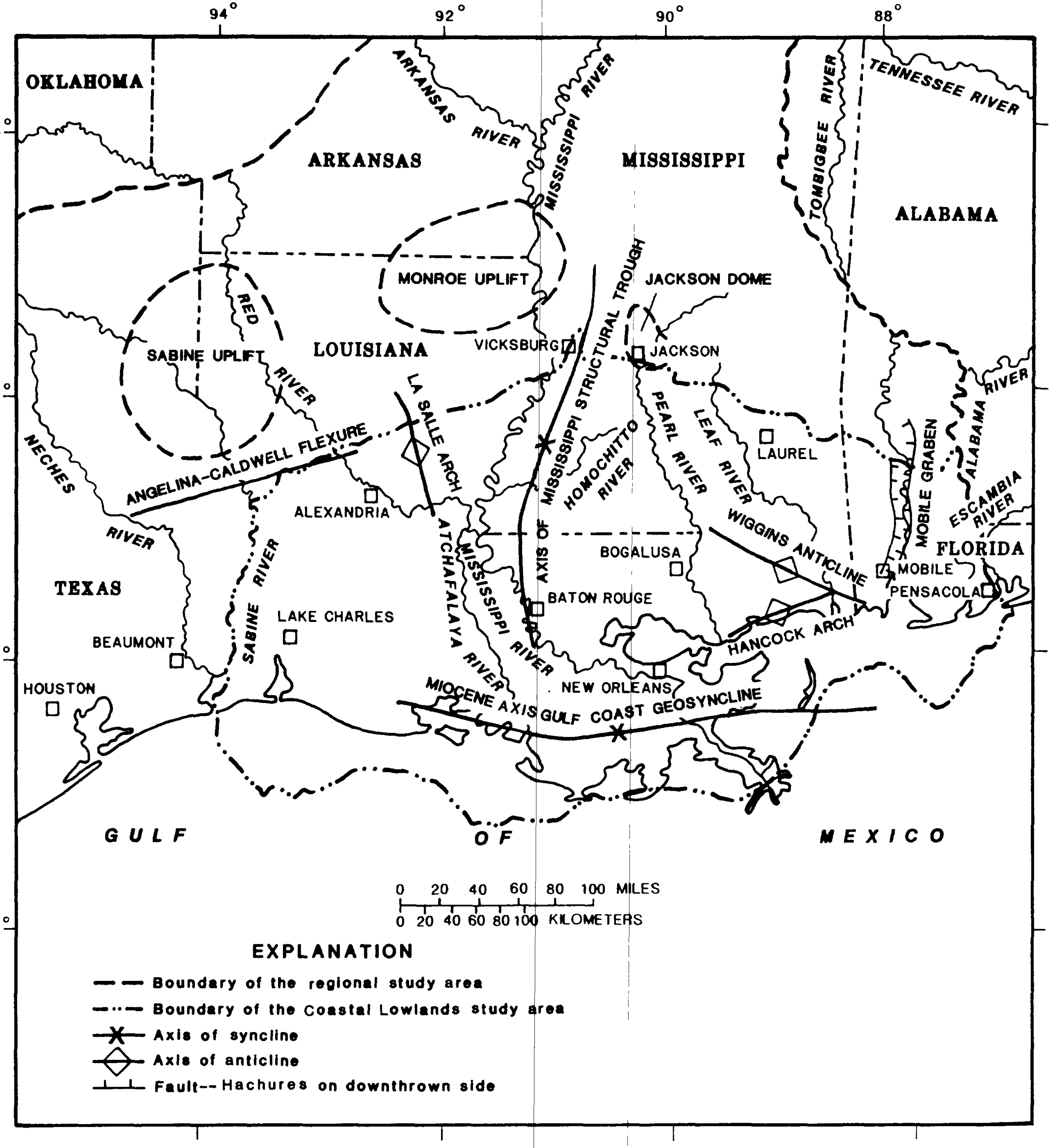

Figure 1.--Location of the study area and major structural features in and near the study area.

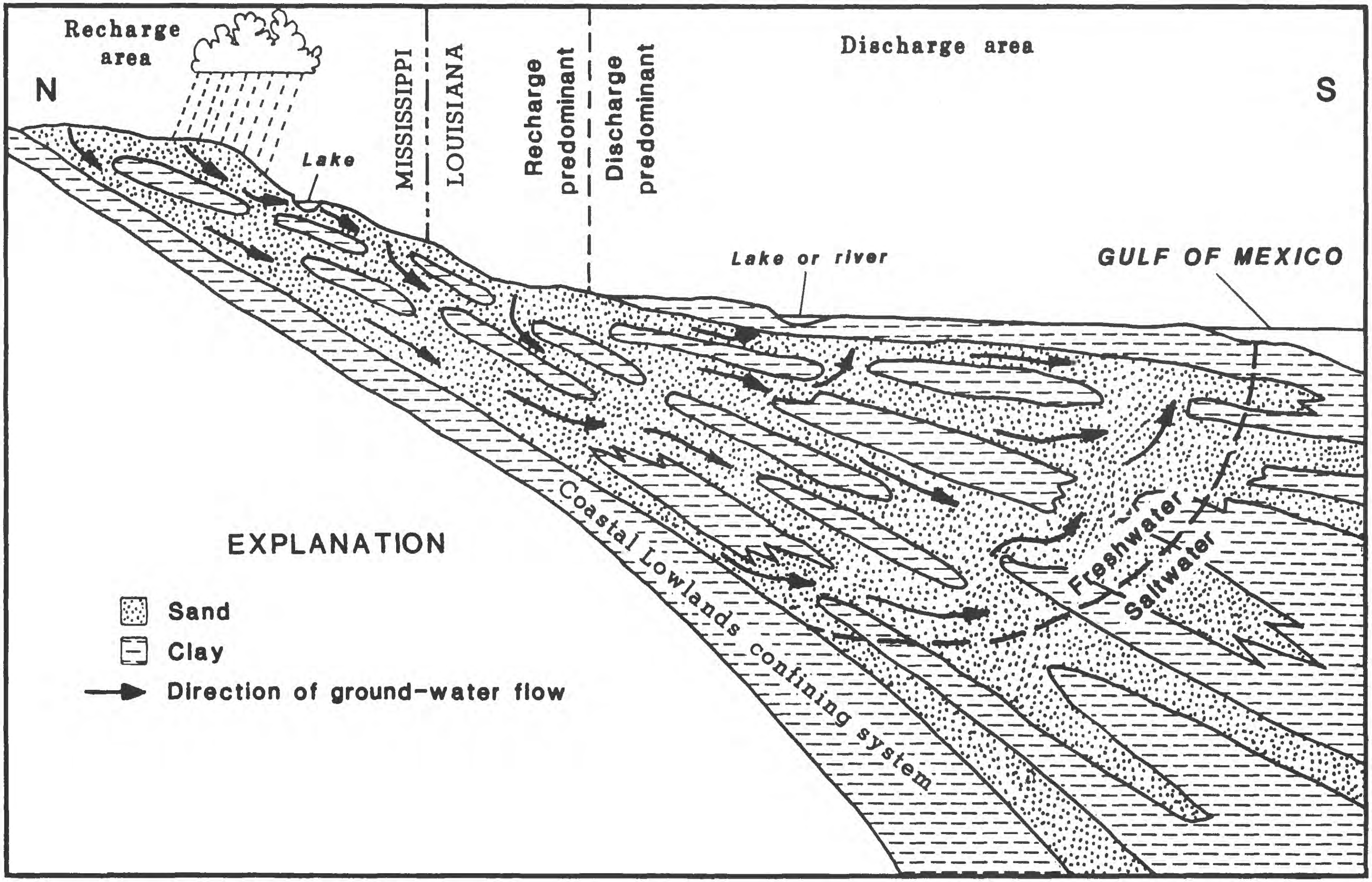

Figure 2.--Generalized north-south geohydrologic section from southwestern Mississippi to the Gulf of Mexico.

Figure 3.--Total thickness of the ground-water flow system.

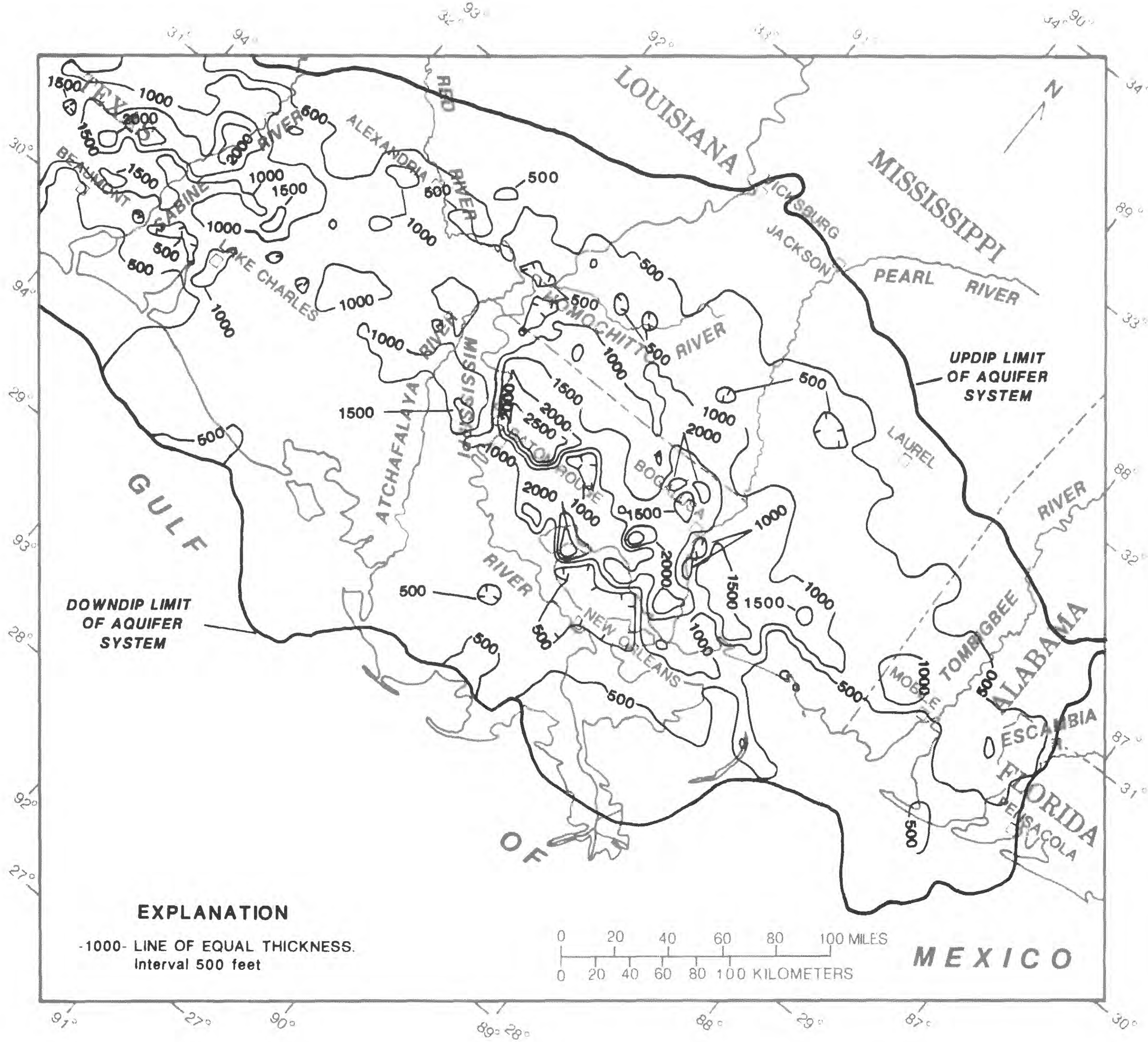

Figure 4.--Total thickness of sand in the ground-water flow system.

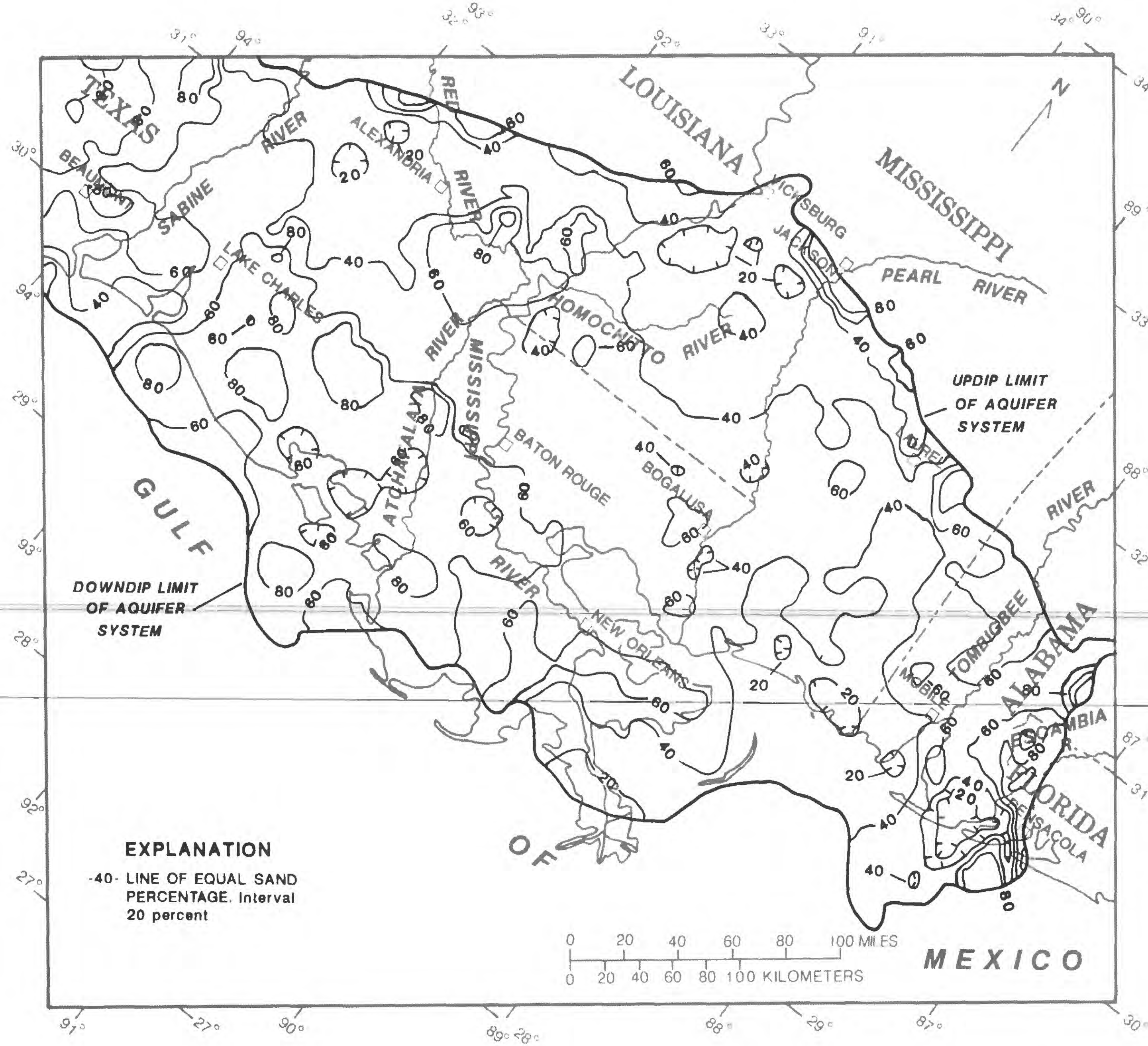

Figure 5.--The percentage of sand in the ground-water flow system.

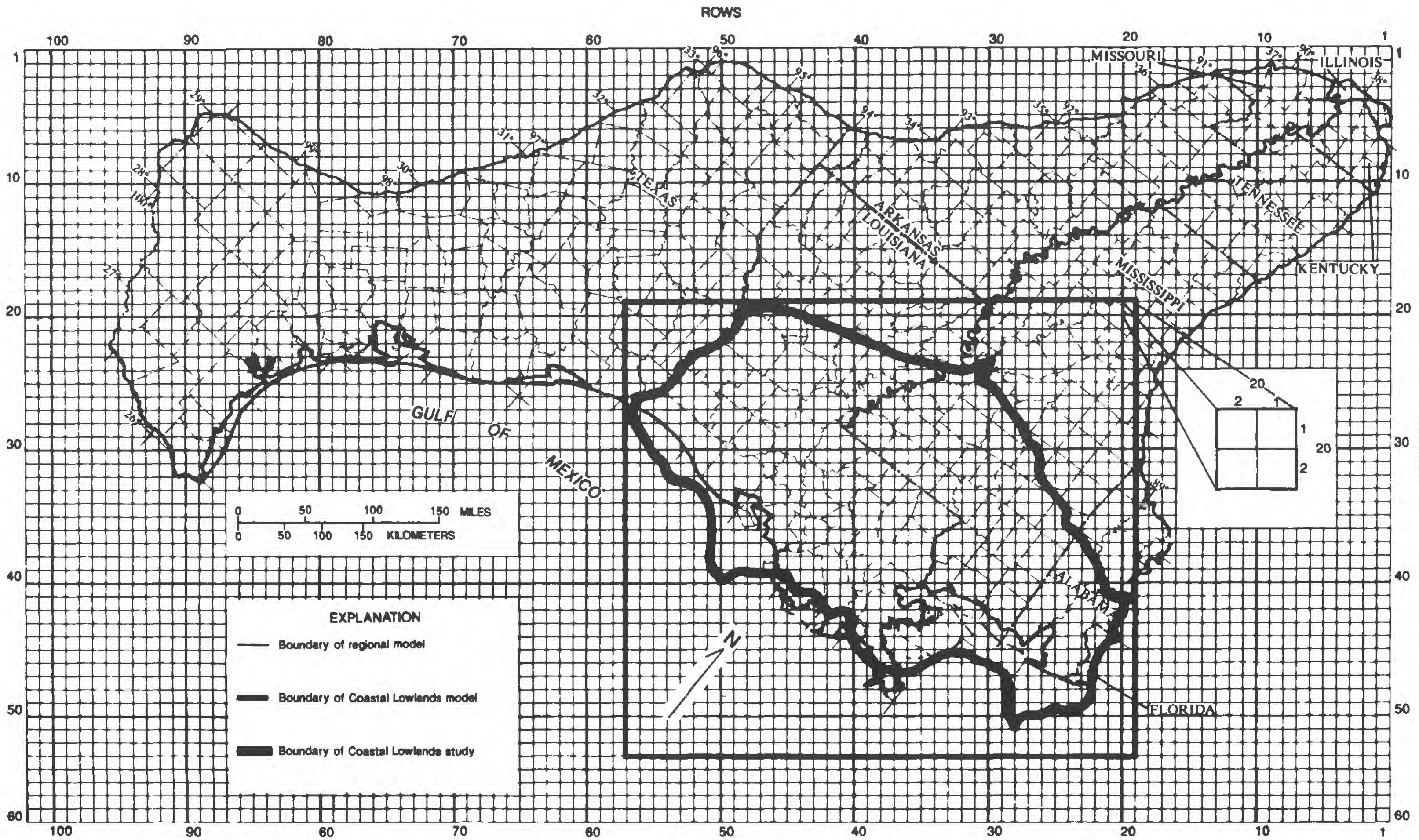

Figure 6.--The finite-difference grid for the Regional Aquifer-System Analysis model showing the relation of the Coastal Lowlands model to the regional model.

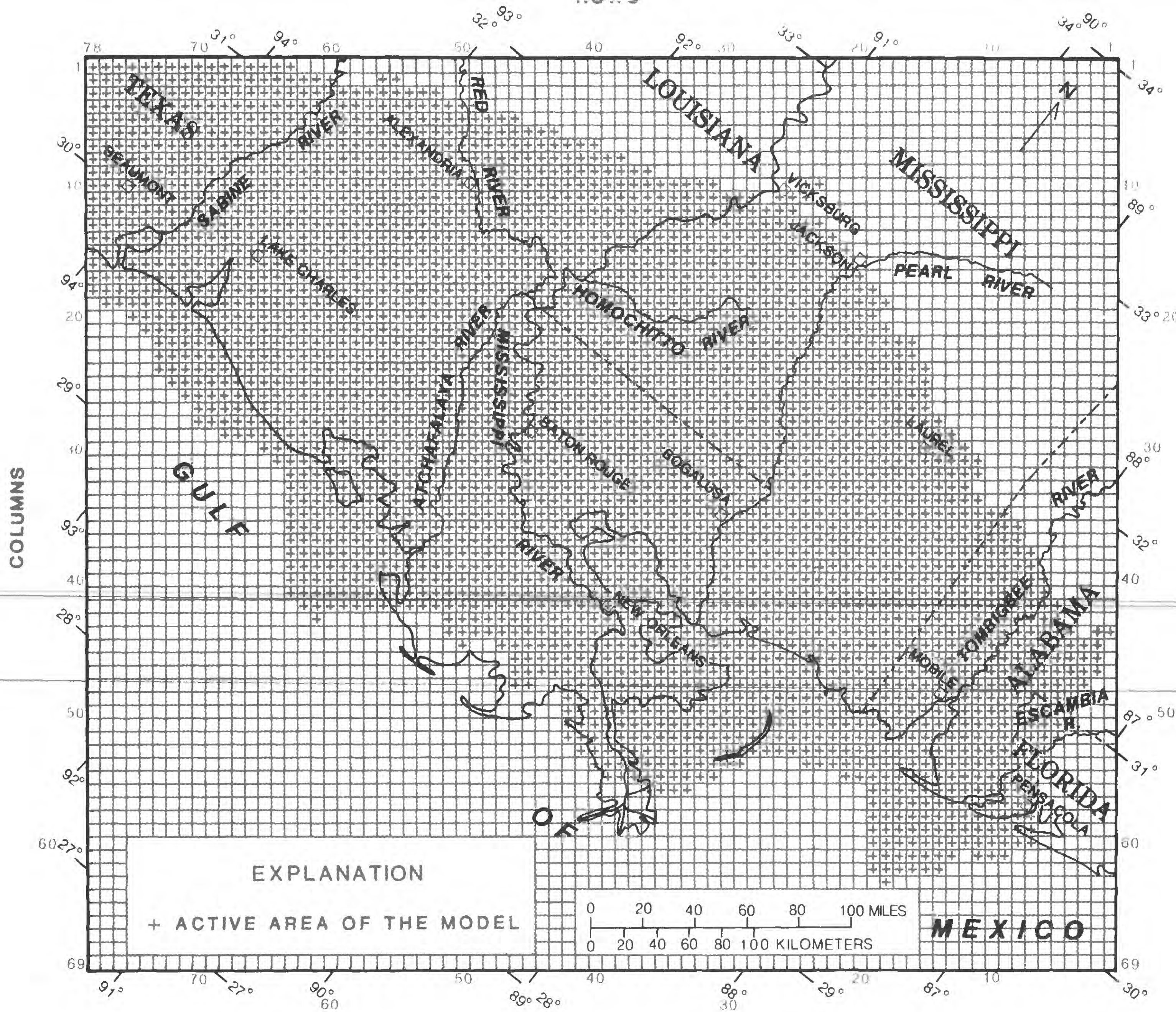

Figure 7.--Finite-difference grid with the active area of the model.

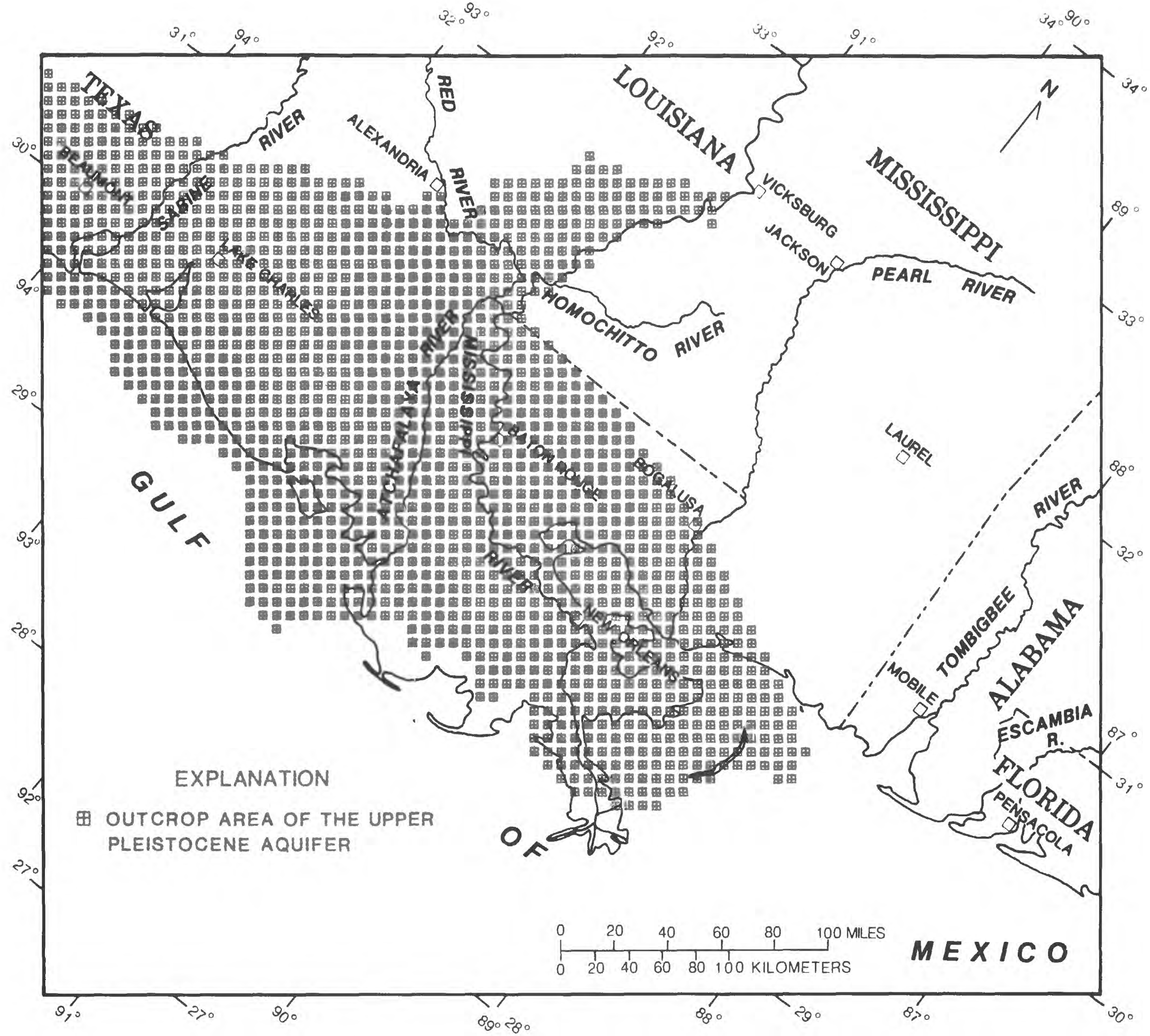

Figure 8.--Areal extent of the upper Pleistocene aquifer (model layer 2).

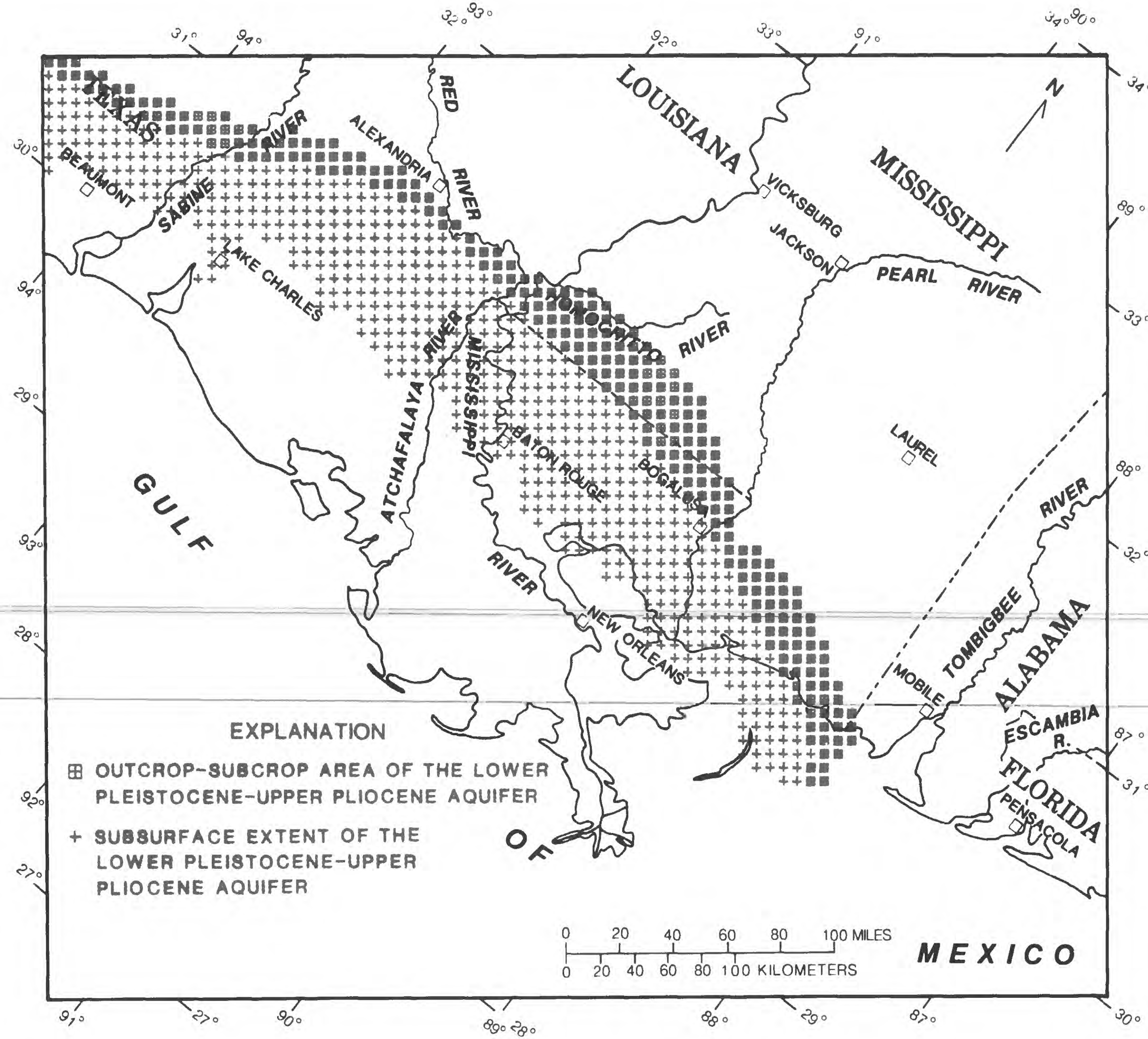

Figure 9.--Areal extent and outcrop-subcrop area of the lower Pleistocene-upper Pliocene aquifer (model layer 3).

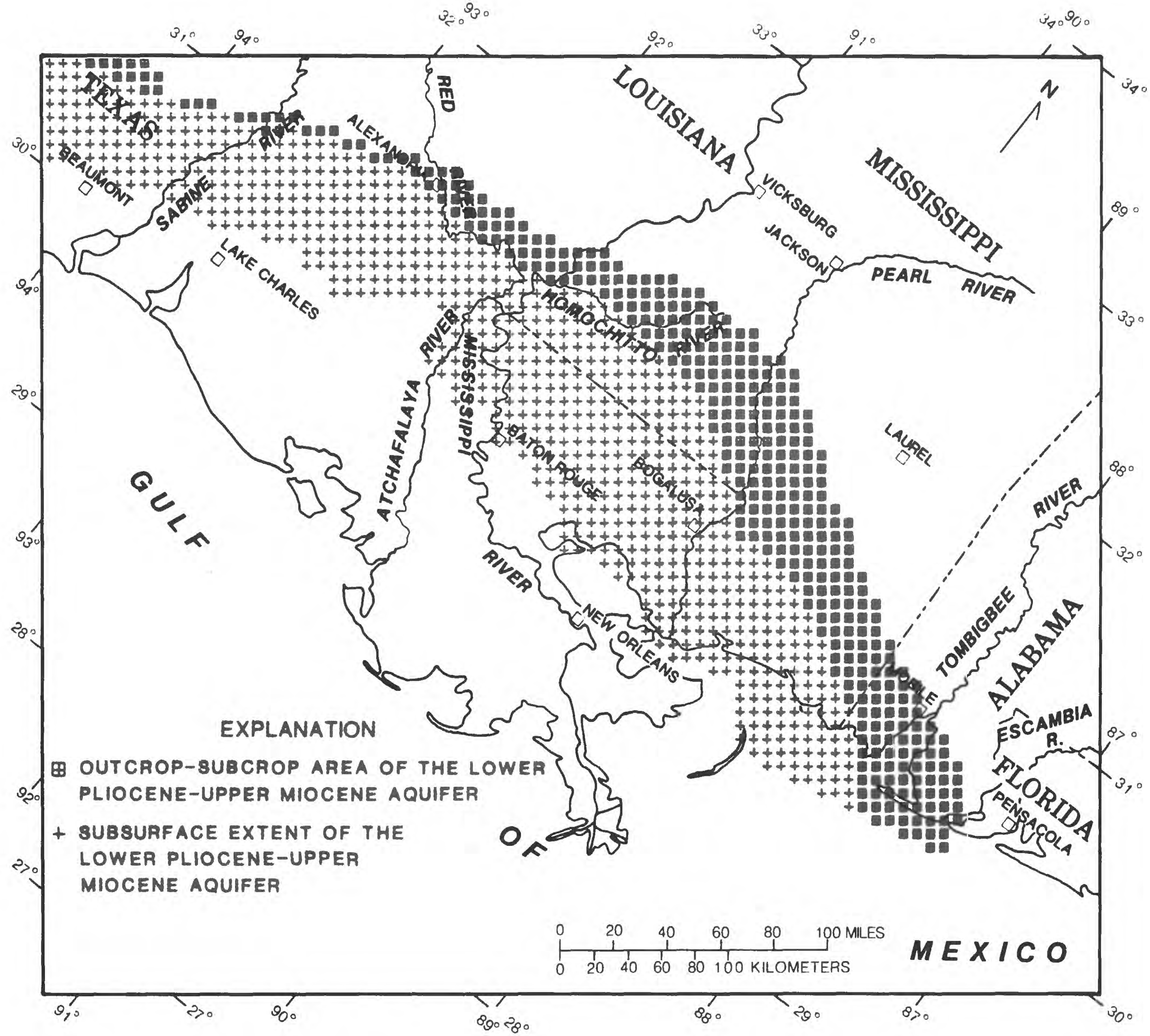

Figure 10.--Areal extent and outcrop-subcrop area of the lower Pliocene-upper Miocene aquifer (model layer 4).

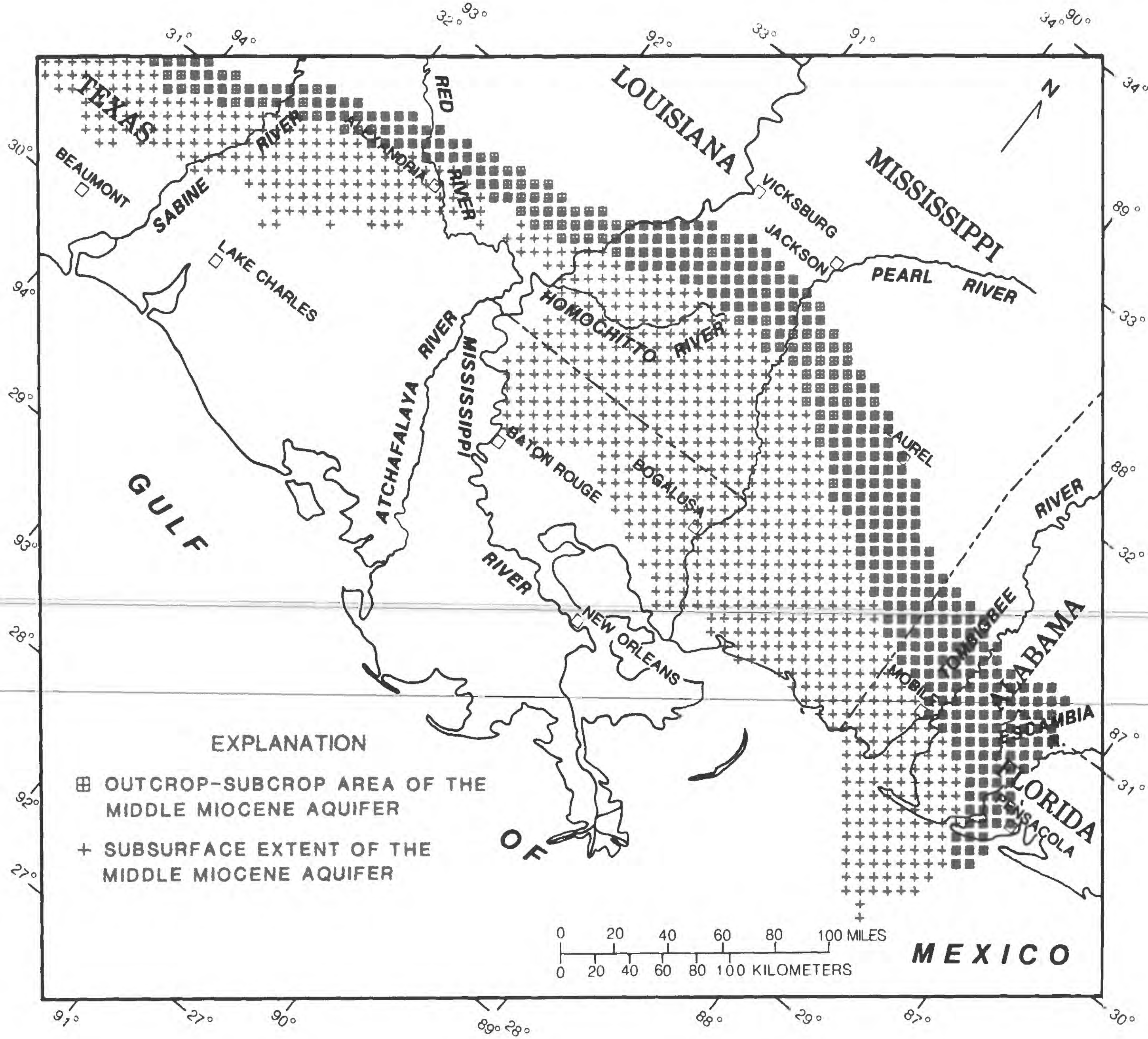

Figure 11.--Areal extent and outcrop-subcrop area of the middle Miocene aquifer (model layer 5).

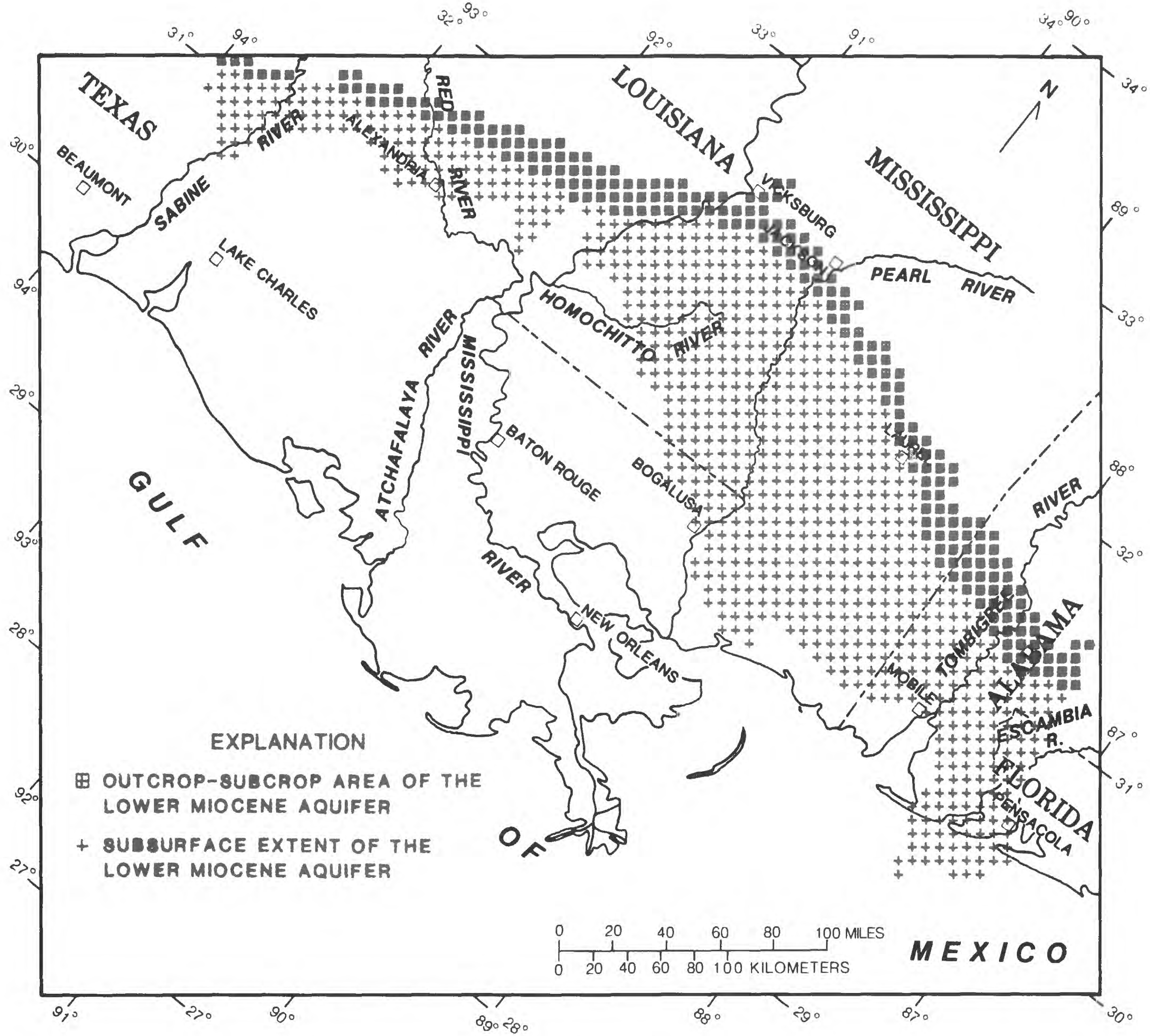

Figure 12.--Areal extent and outcrop-subcrop area of the lower Miocene aquifer (model layer 6).

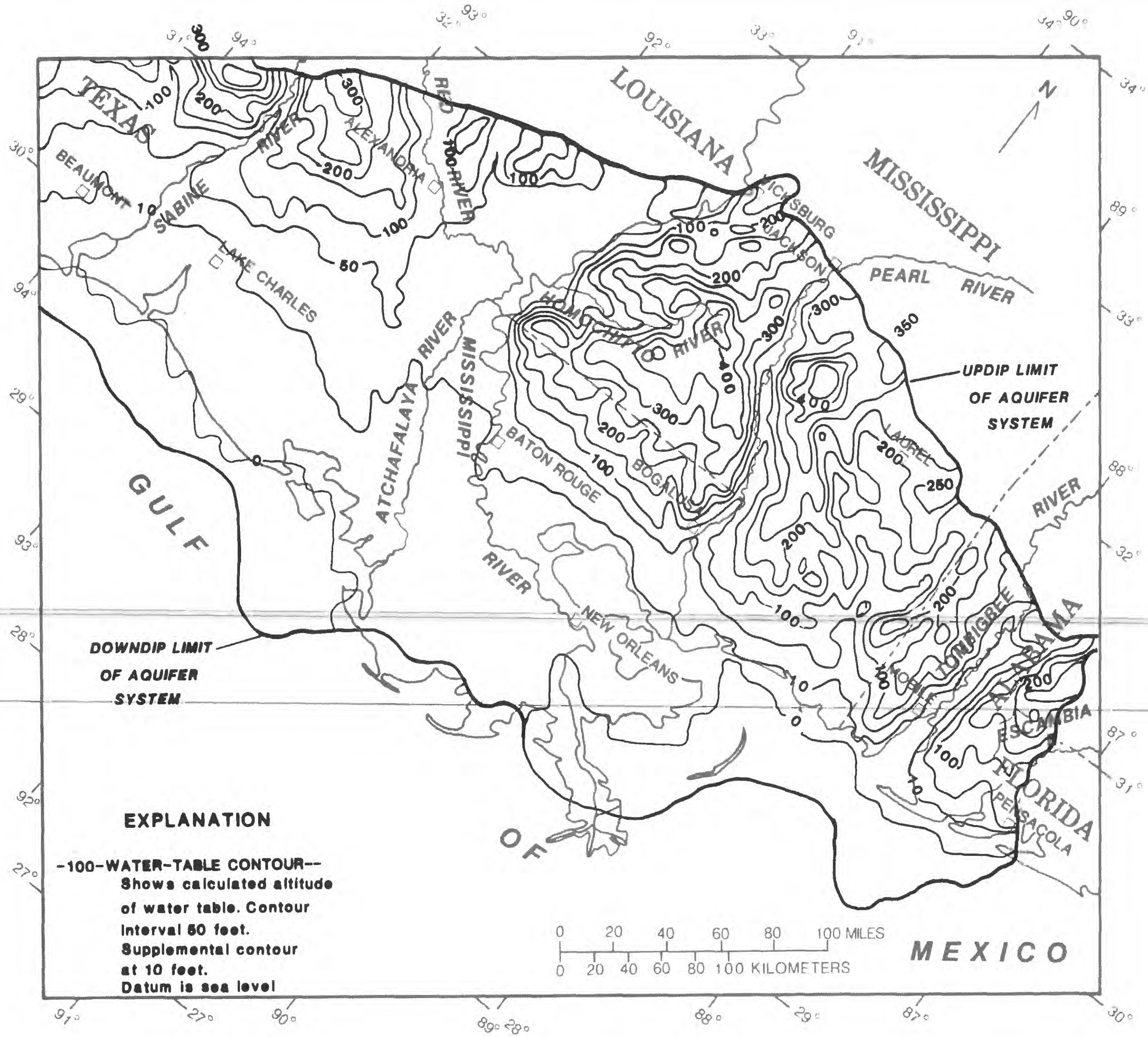

Figure 13.--The calculated altitude of the water table.

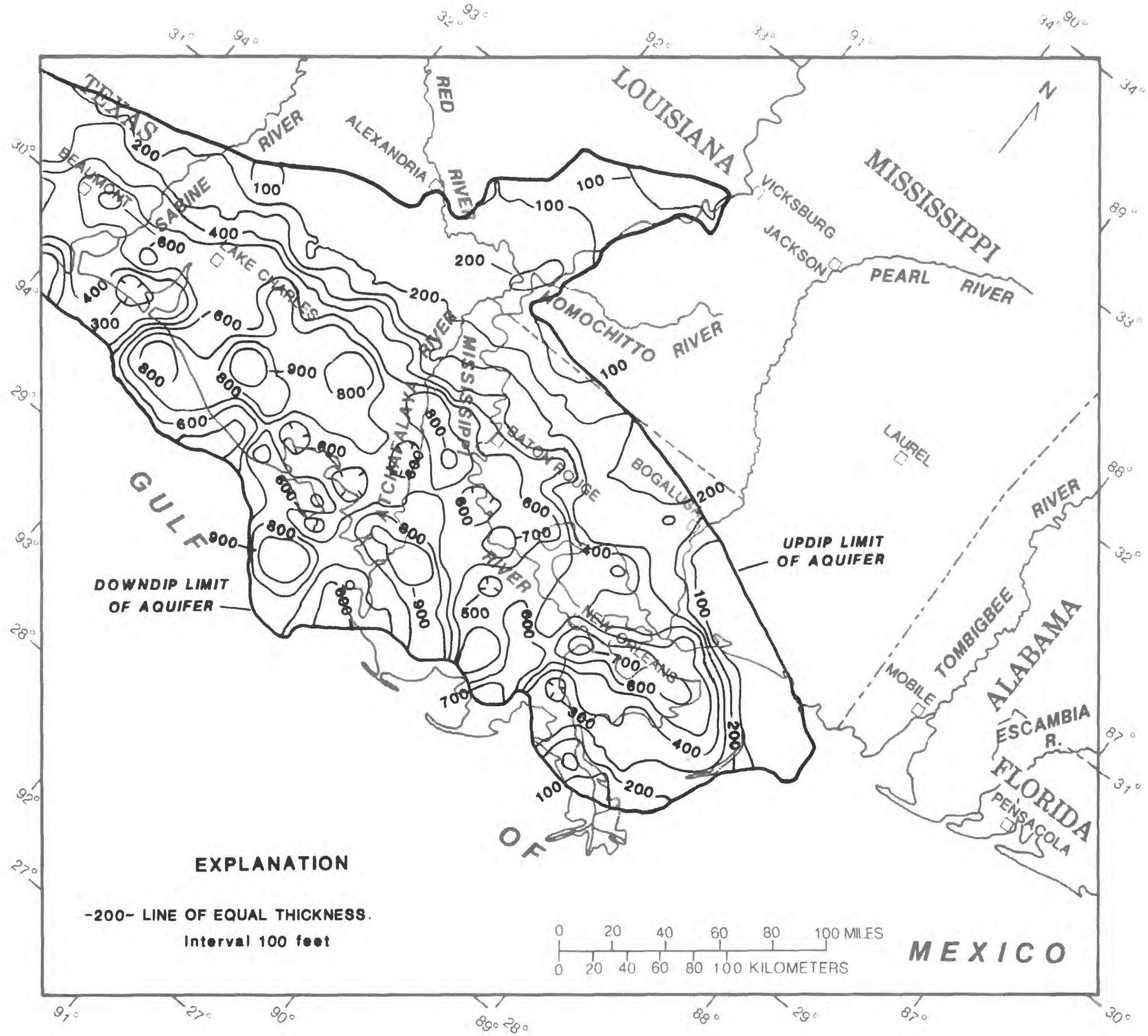

Figure 14.--Total thickness of sand in the upper Pleistocene aquifer (model layer 2).

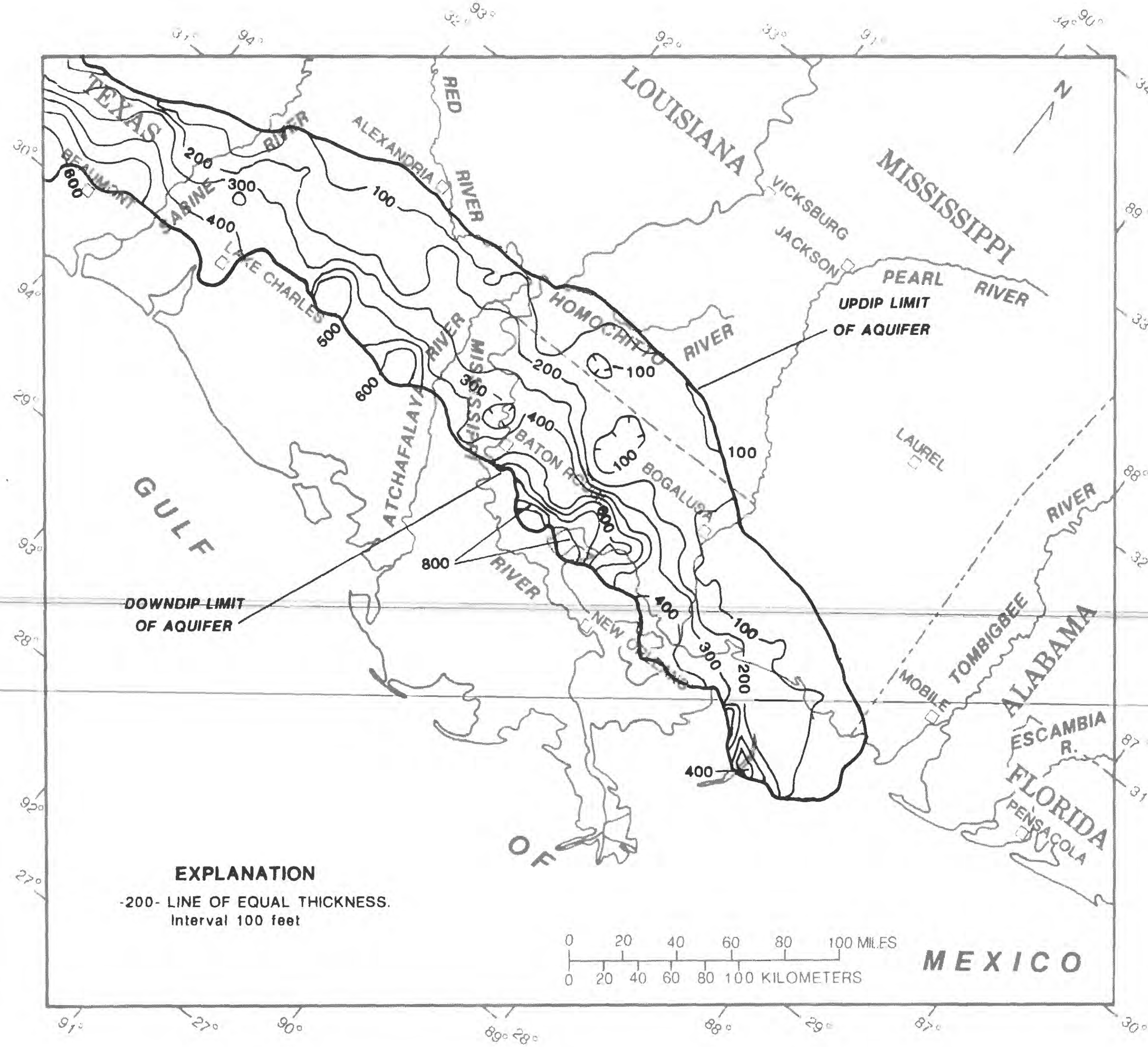

Figure 15.--Total thickness of sand in the lower Pleistocene-upper Pliocene aquifer (model layer 3).

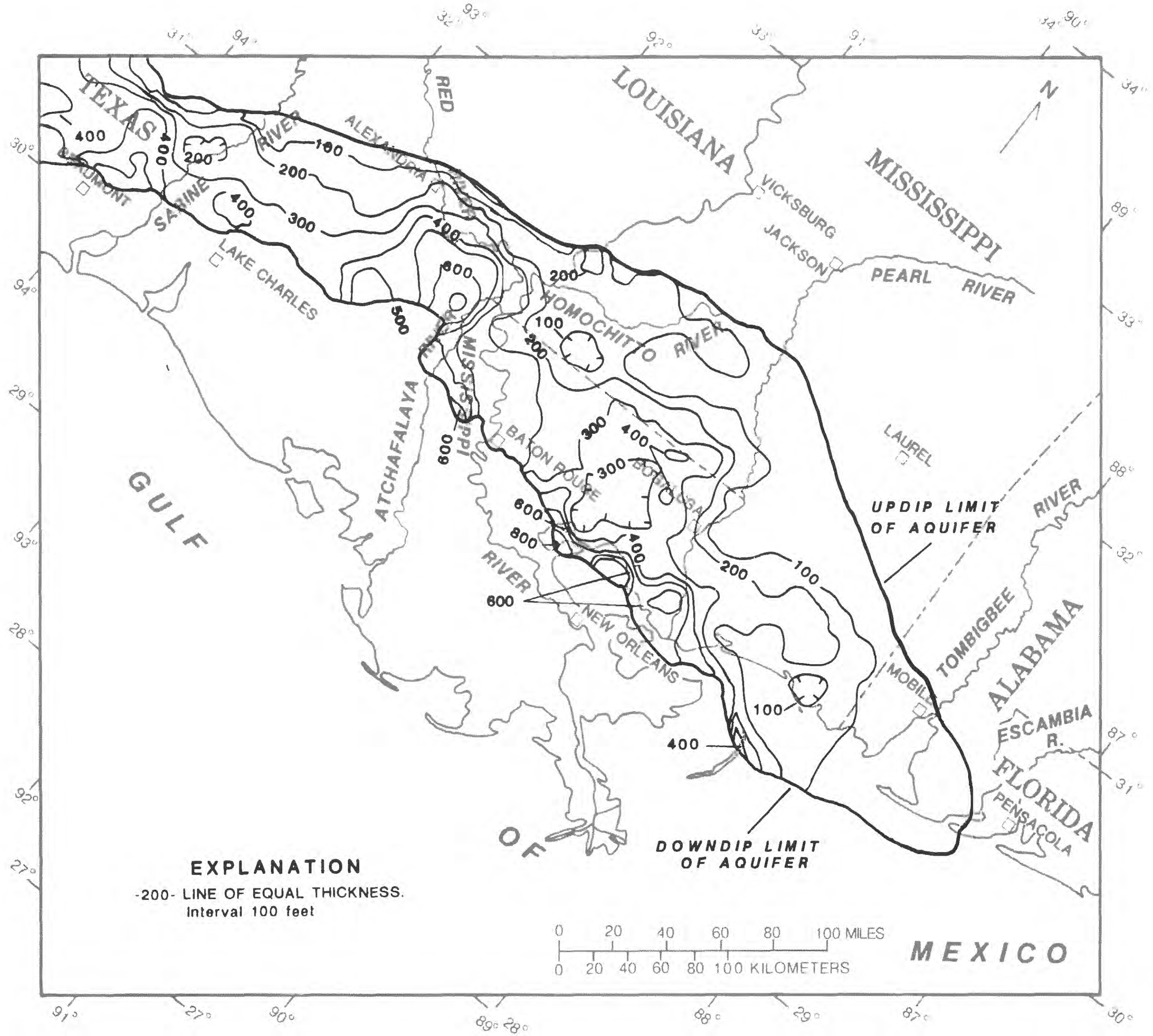

Figure 16.--Total thickness of sand in the lower Pliocene-upper Miocene aquifer (model layer 4).

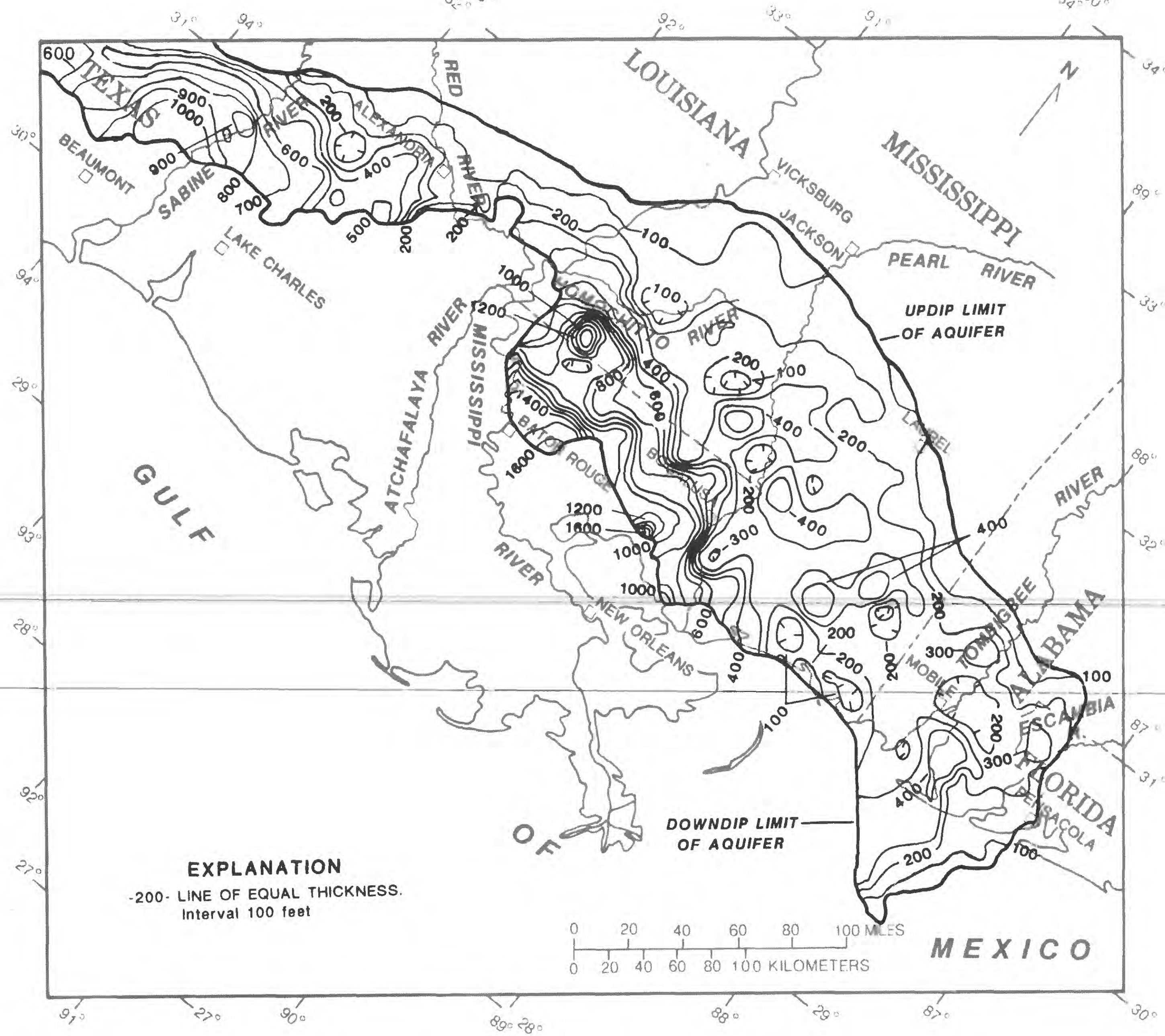

Figure 17.--Total thickness of sand in the middle Miocene aquifer (model layer 5).

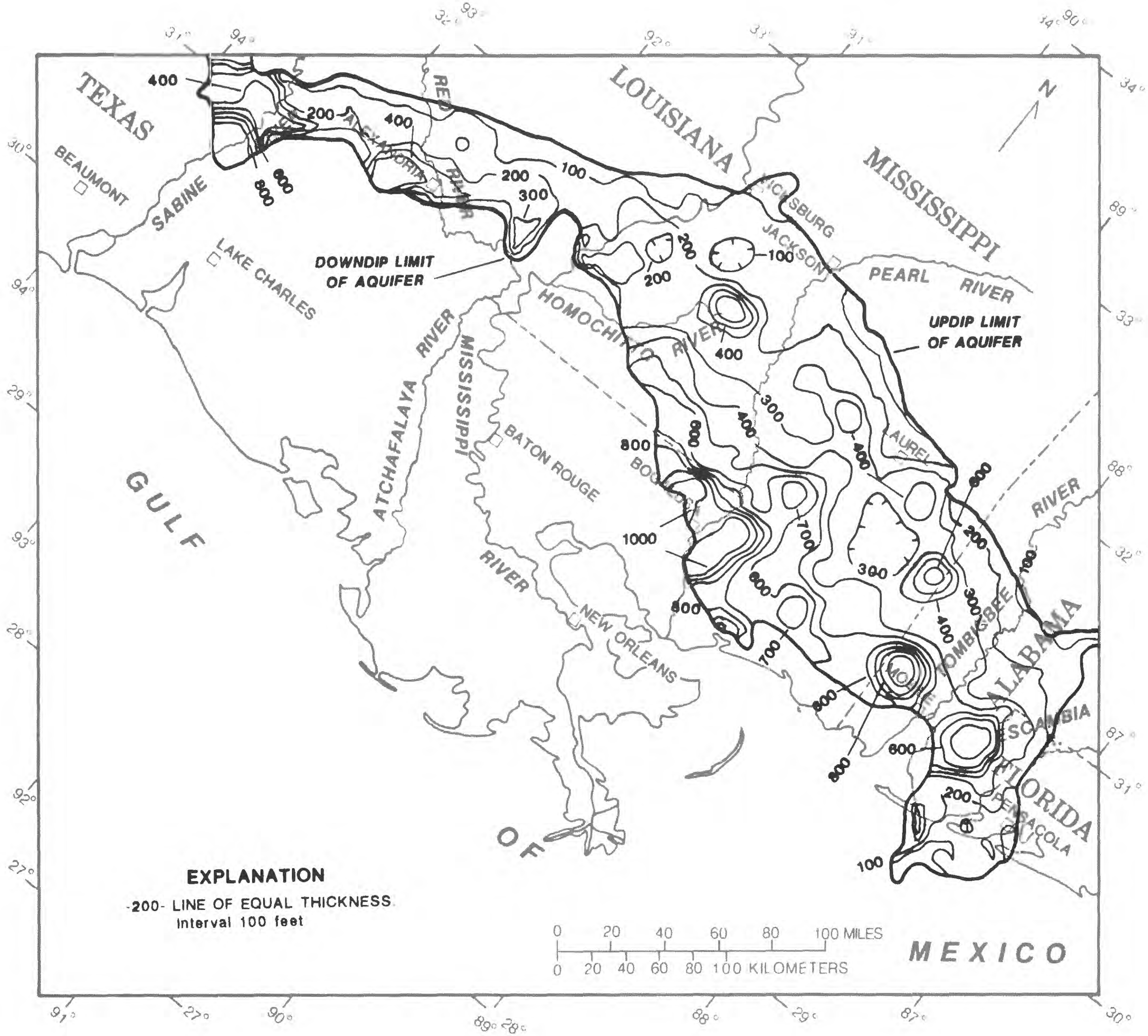

Figure 18.--Total thickness of sand in the lower Miocene aquifer (model layer 6).

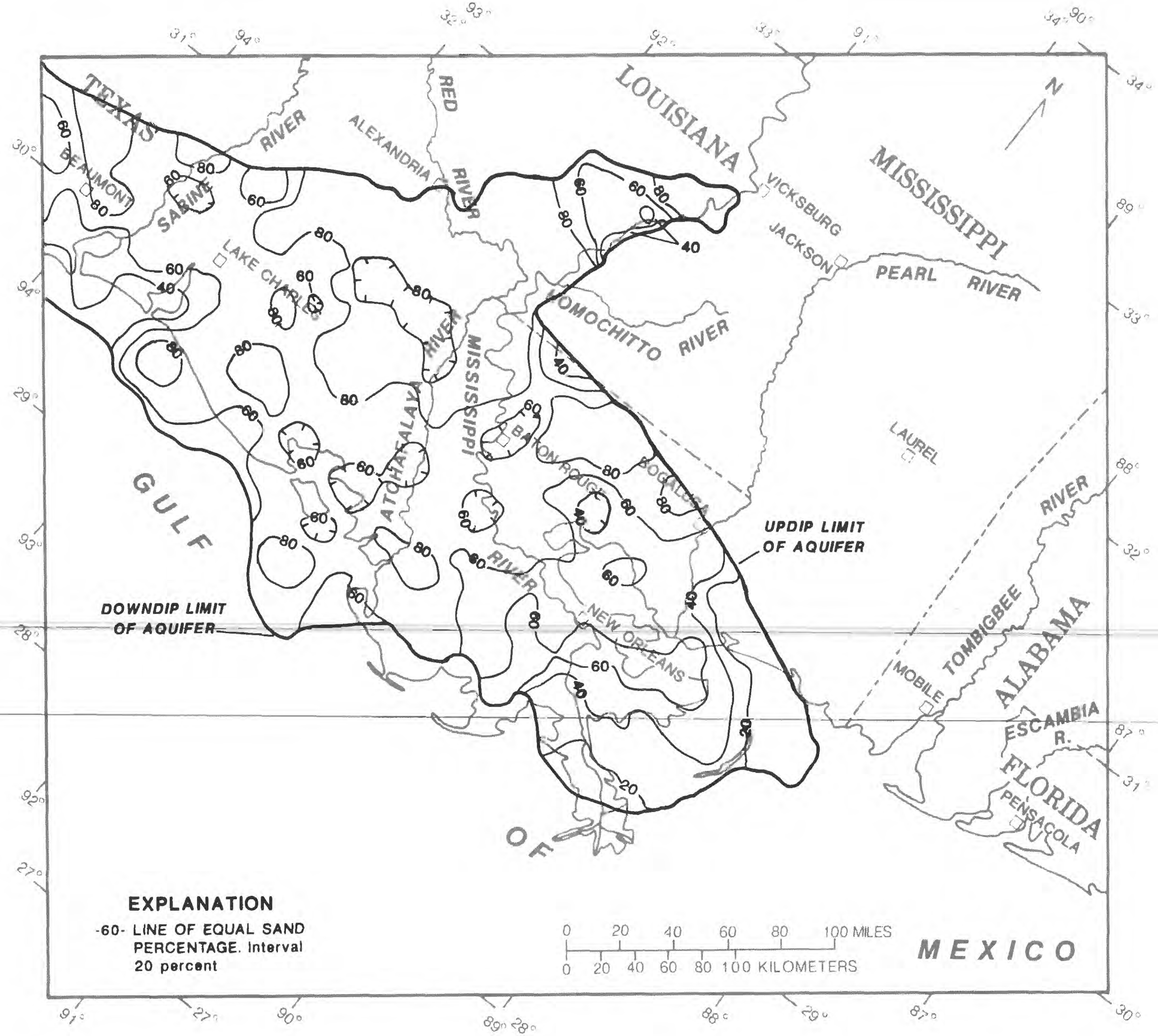

Figure 19.--Percentage of sand in the upper Pleistocene aquifer (model layer 2).

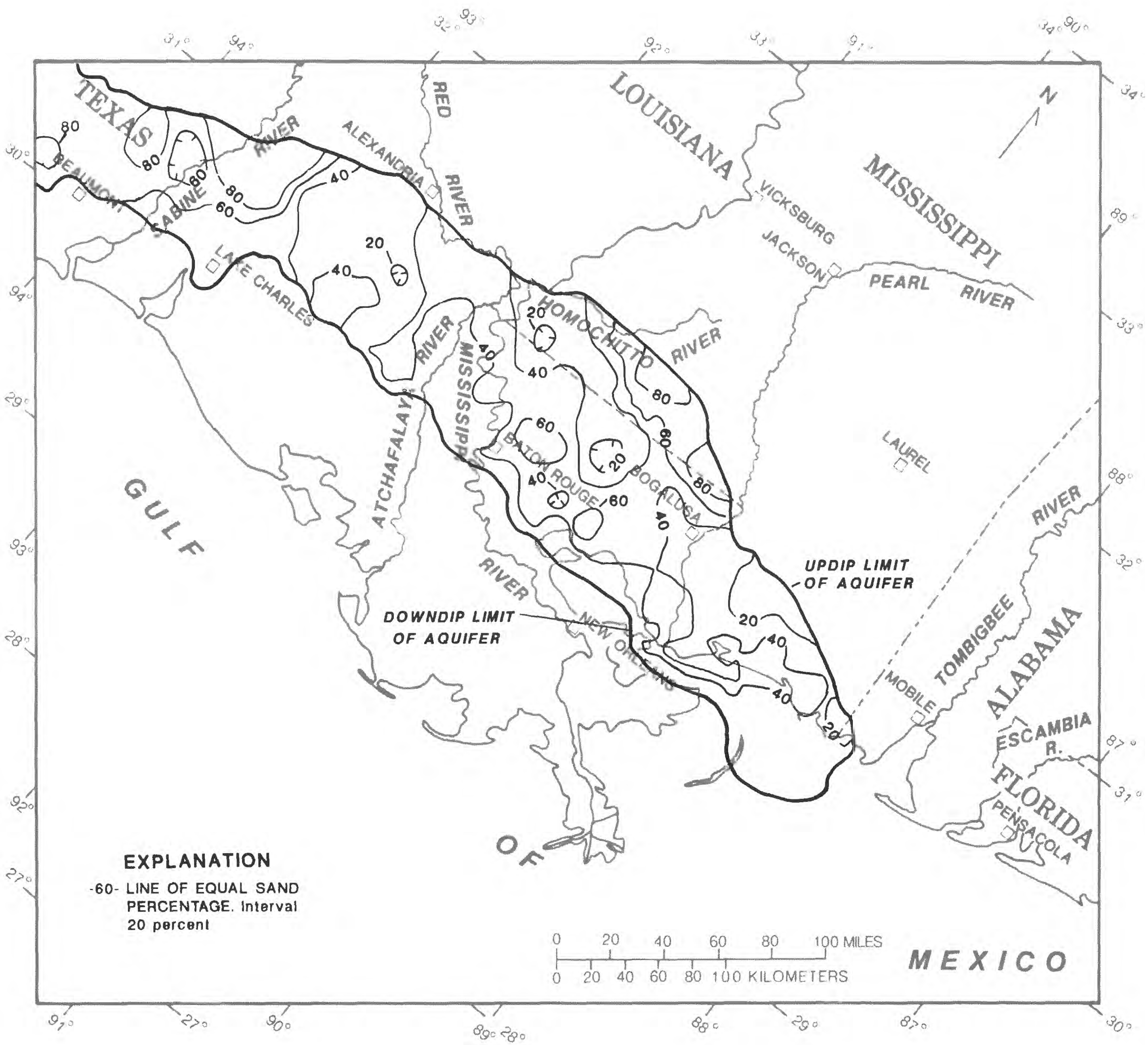

Figure 20.--Percentage of sand in the lower Pleistocene-upper Pliocene aquifer (model layer 3).

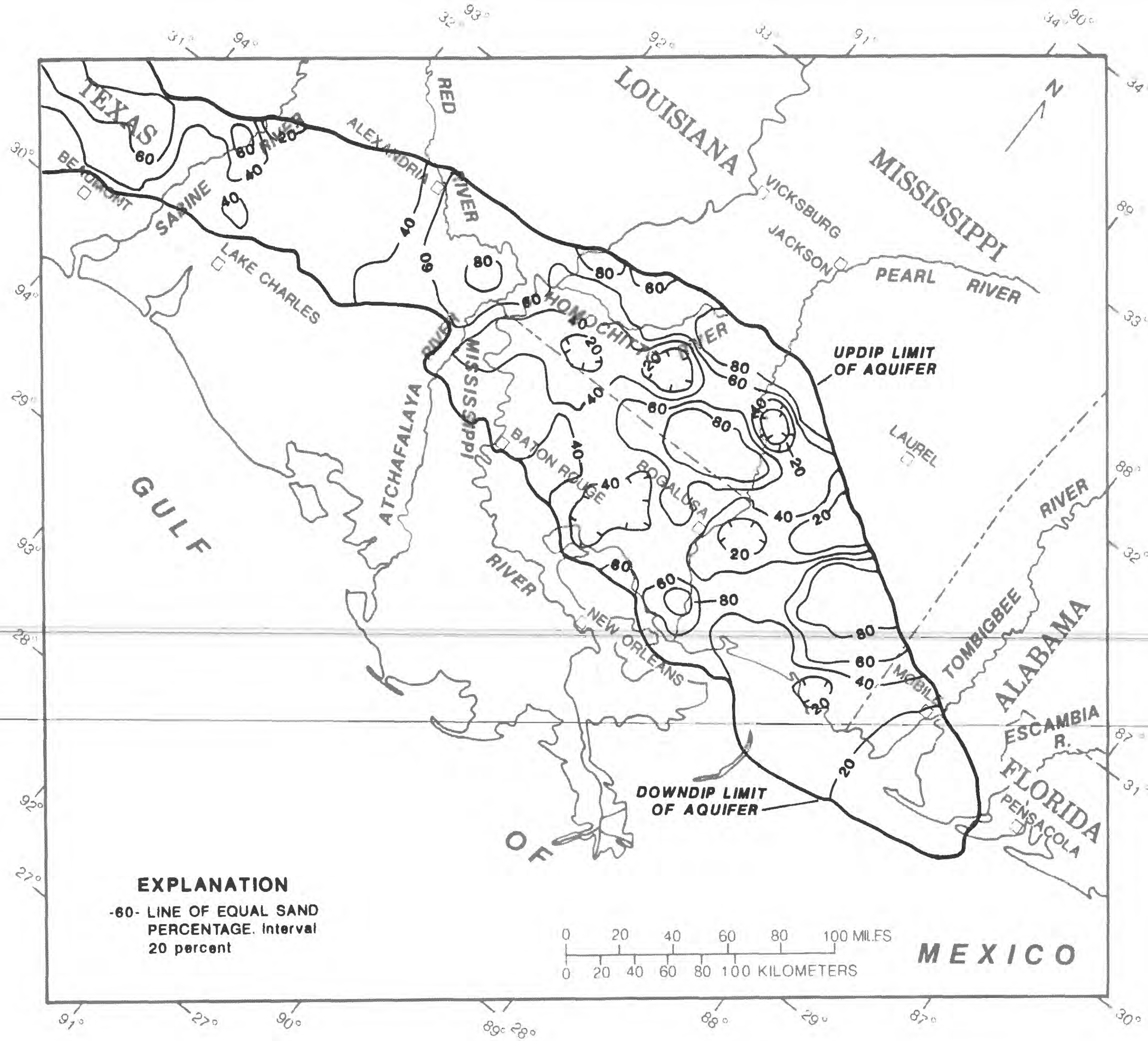

Figure 21.--Percentage of sand in the lower Pliocene-upper Miocene aquifer (model layer 4).

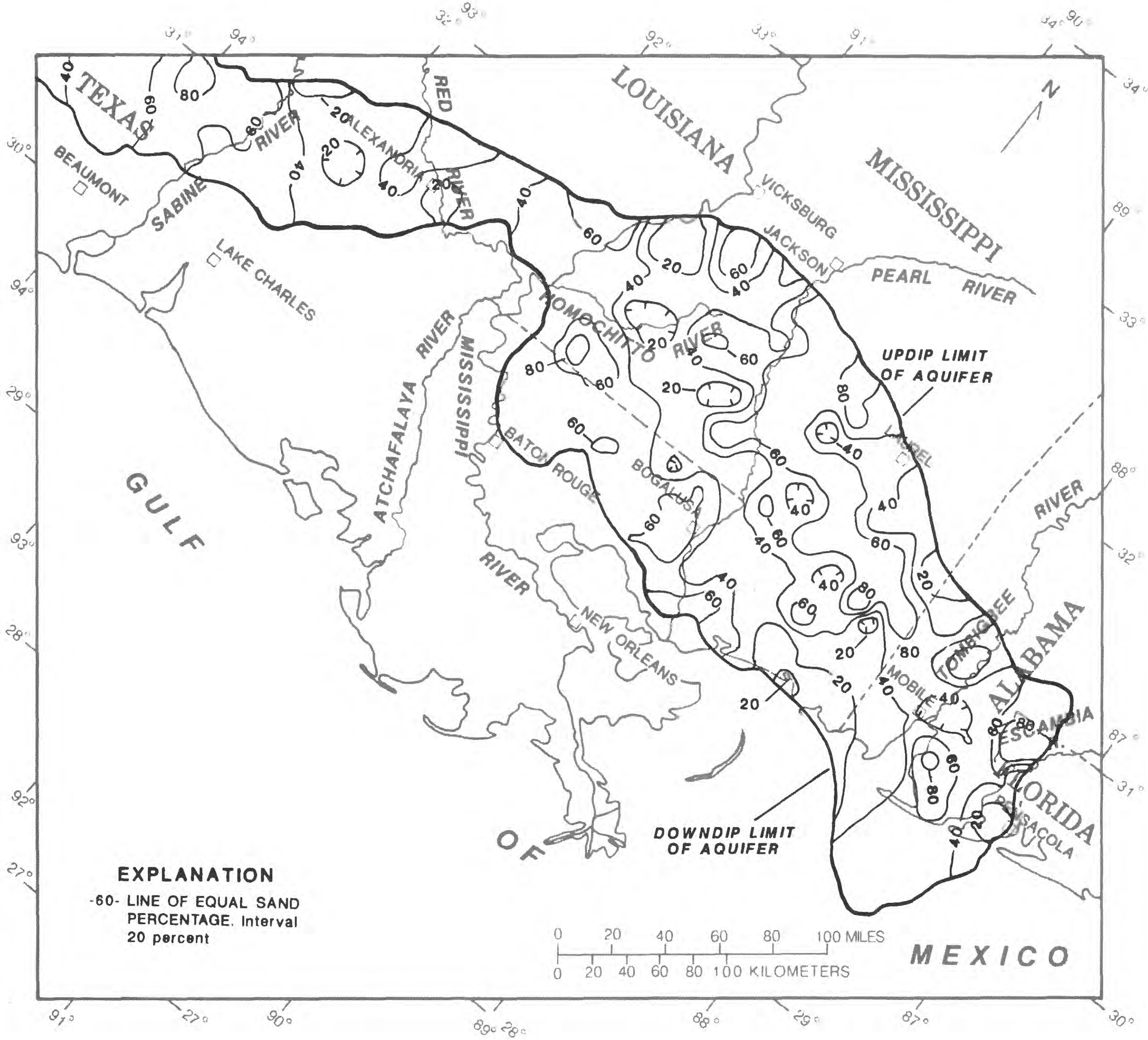

Figure 22.--Percentage of sand in the middle Miocene aquifer (model layer 5).

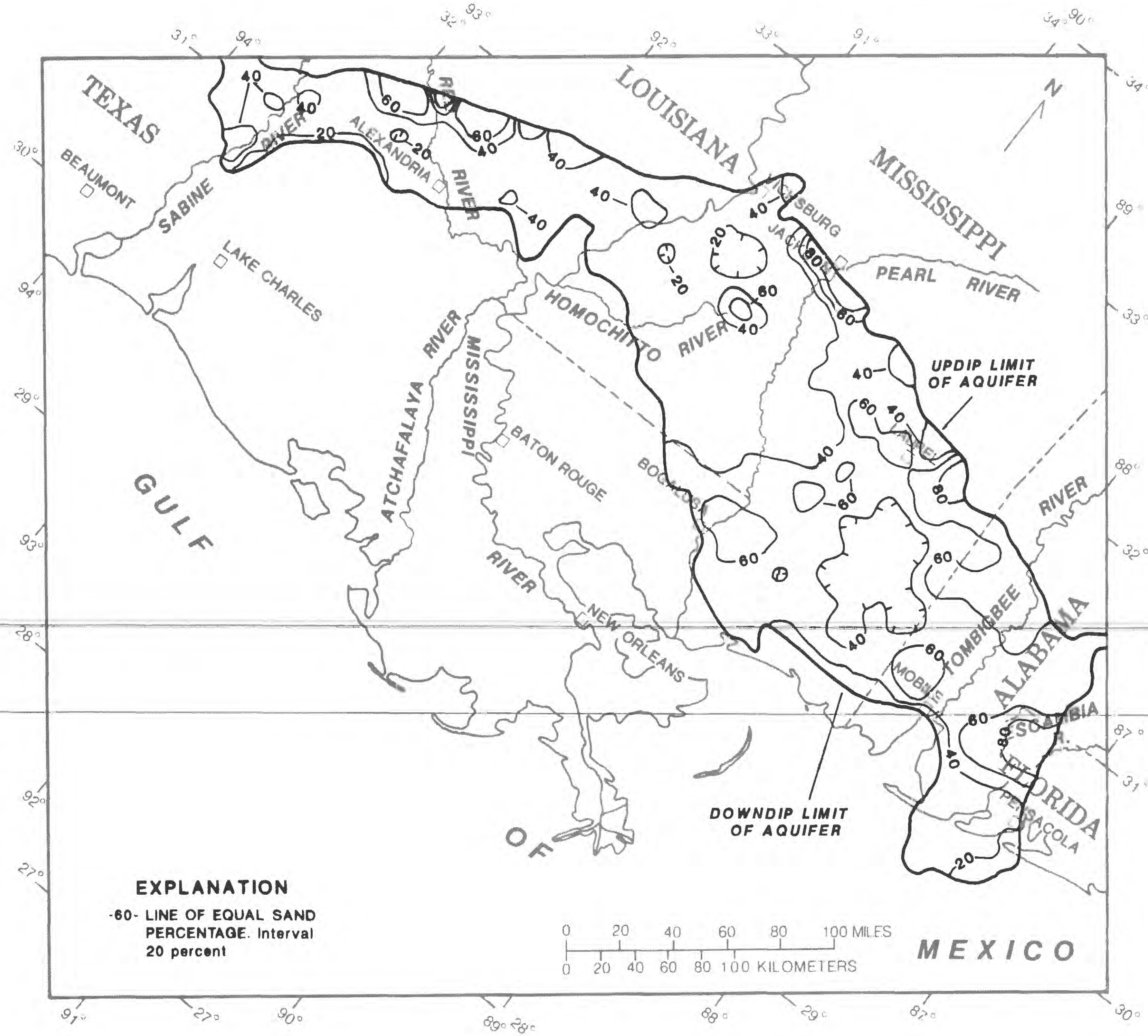

Figure 23.--Percentage of sand in the lower Miocene aquifer (model layer 6).

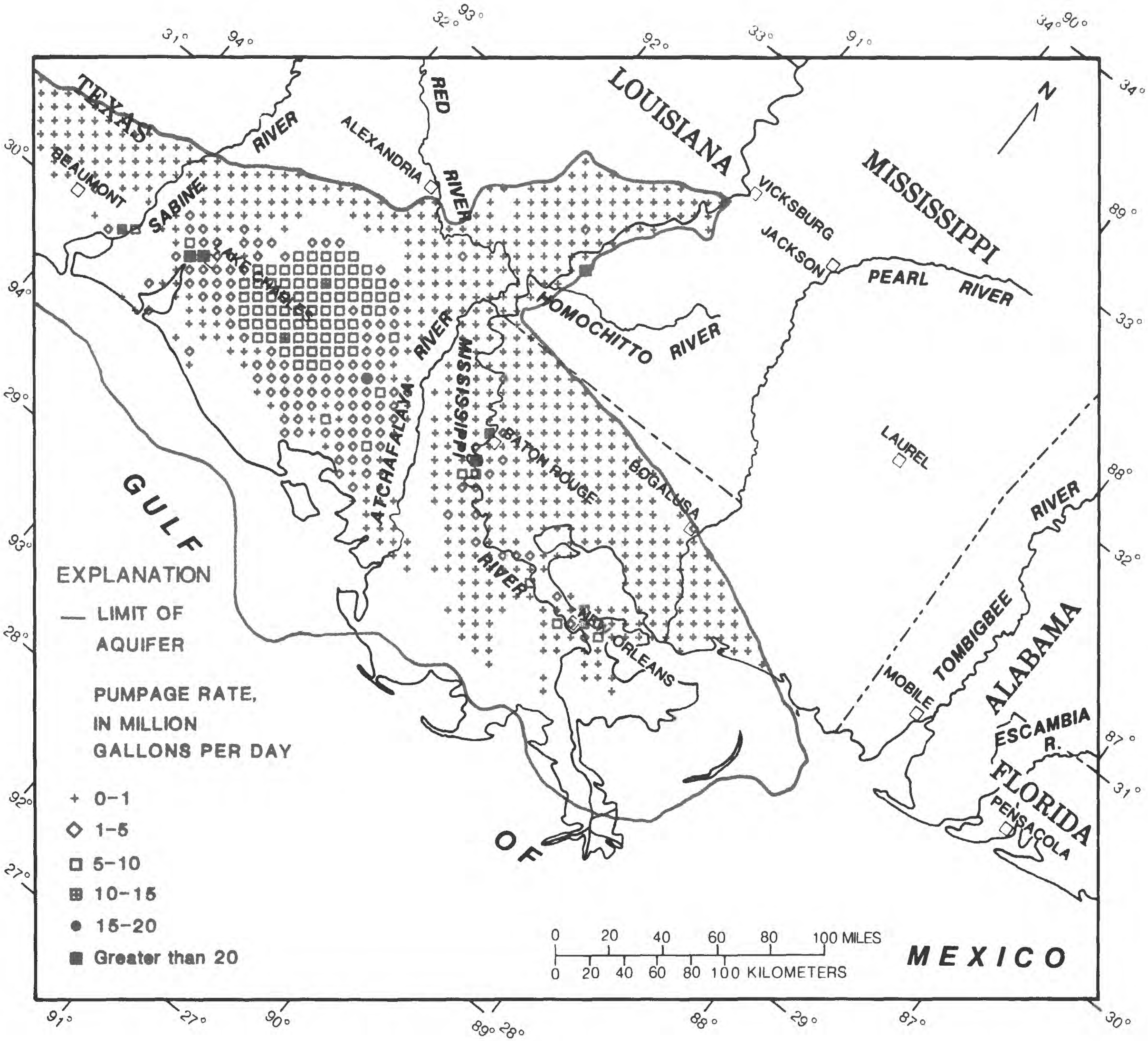

Figure 24.--Areal distribution of pumpage from the upper Pleistocene aquifer (model layer 2).

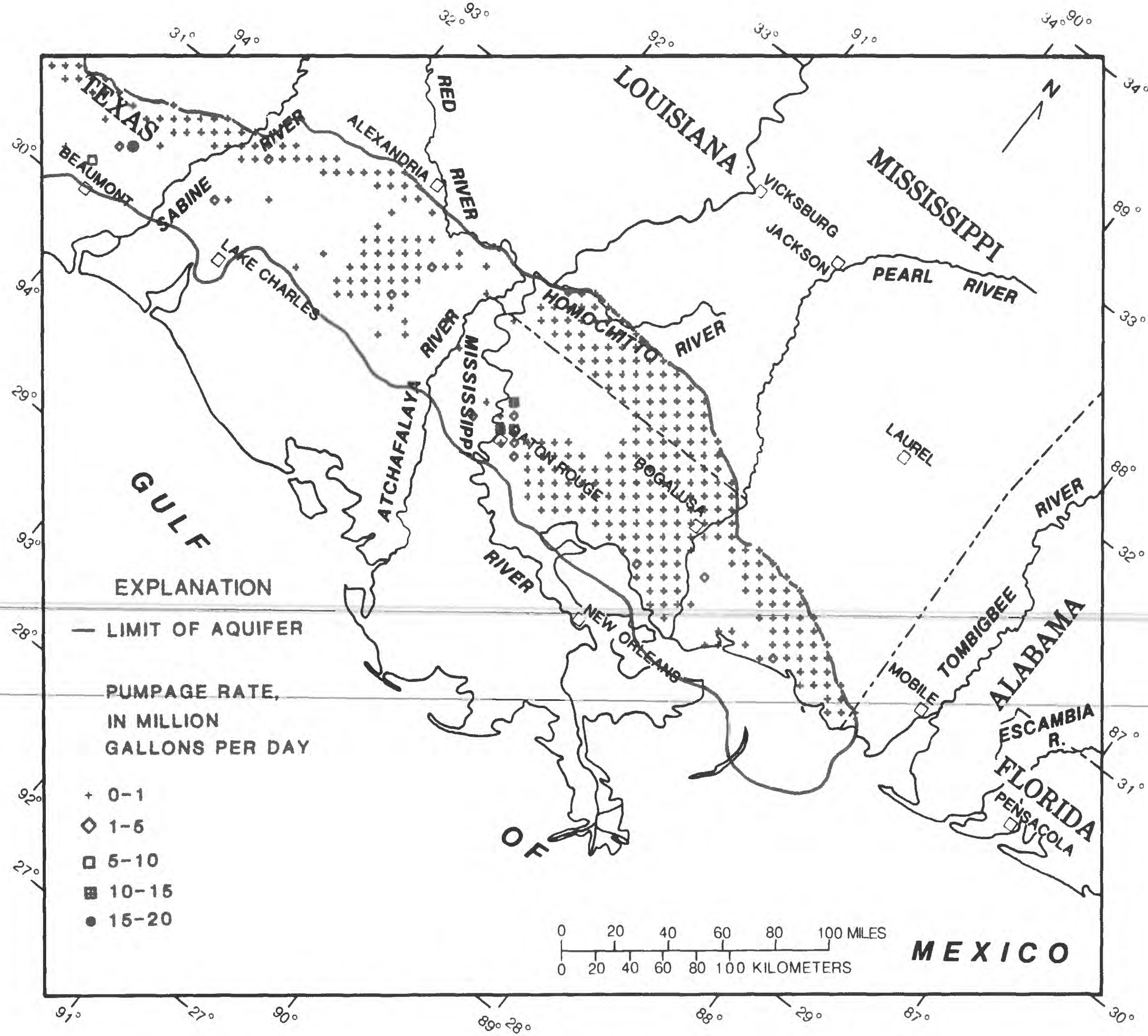

Figure 25.--Areal distribution of pumpage from the lower Pleistocene-upper Pliocene aquifer (model layer 3).

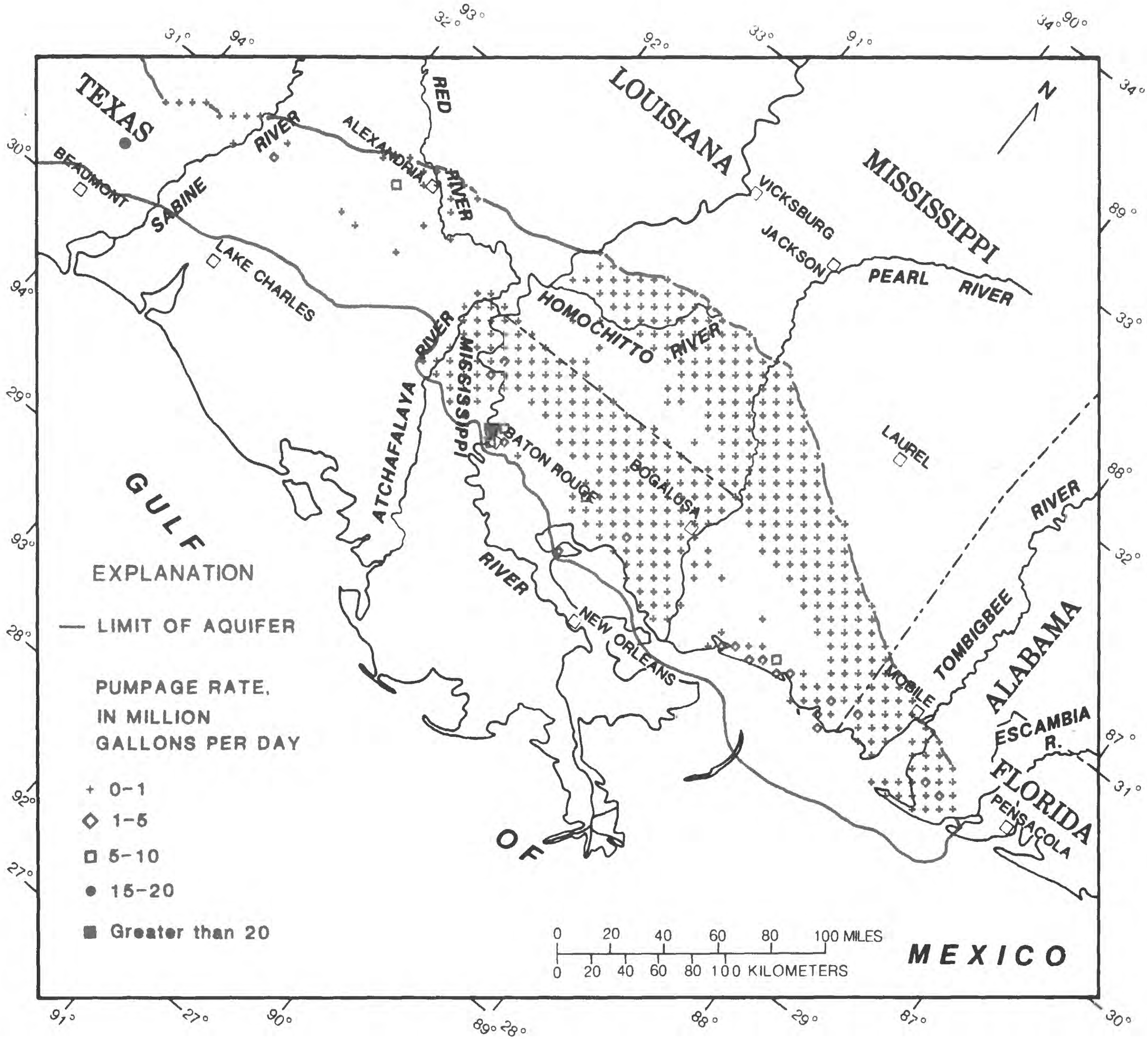

Figure 26.--Areal distribution of pumpage from the lower Pliocene-upper Miocene aquifer (model layer 4).

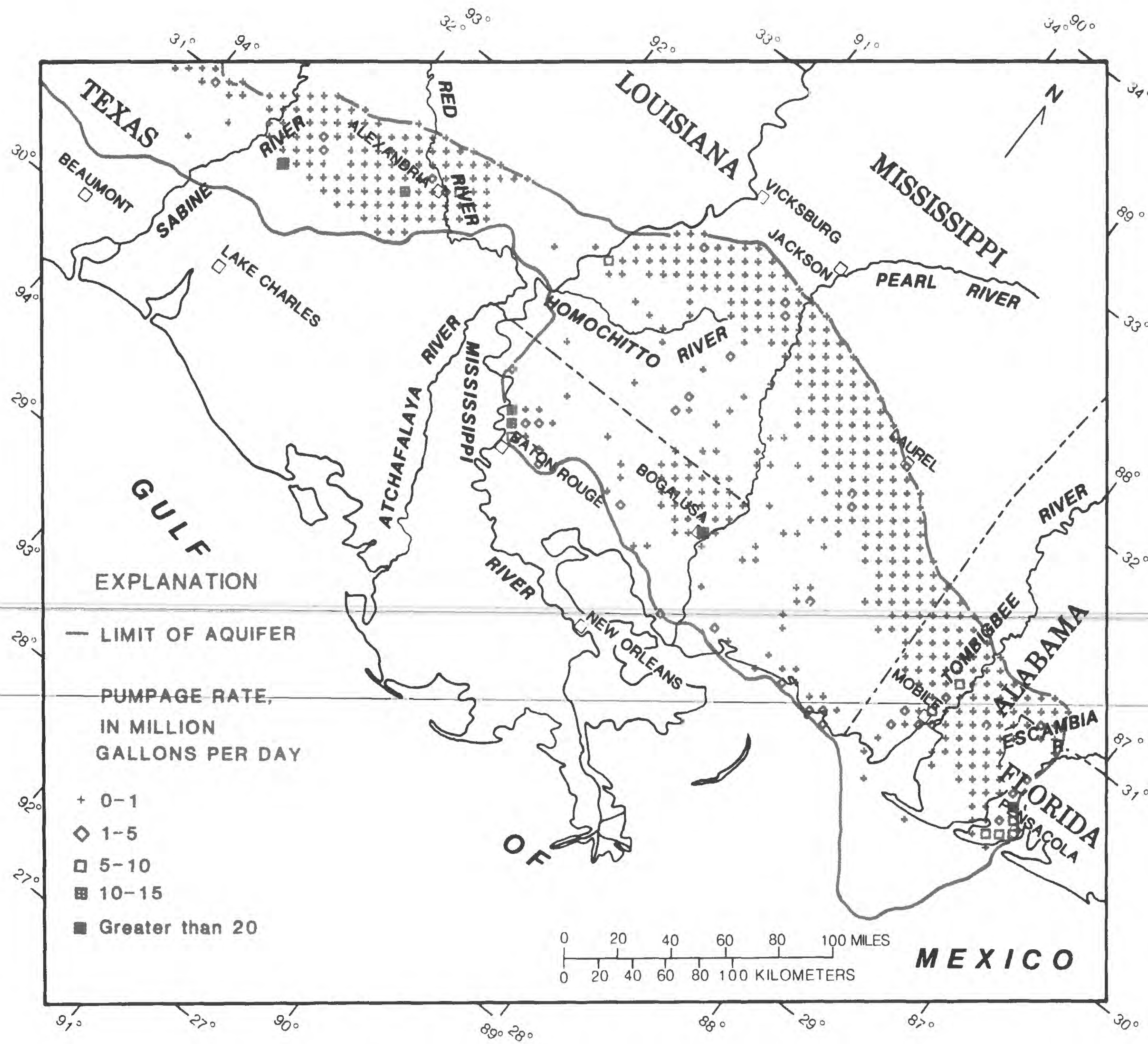

Figure 27.--Areal distribution of pumpage from the middle Miocene aquifer (model layer 5).

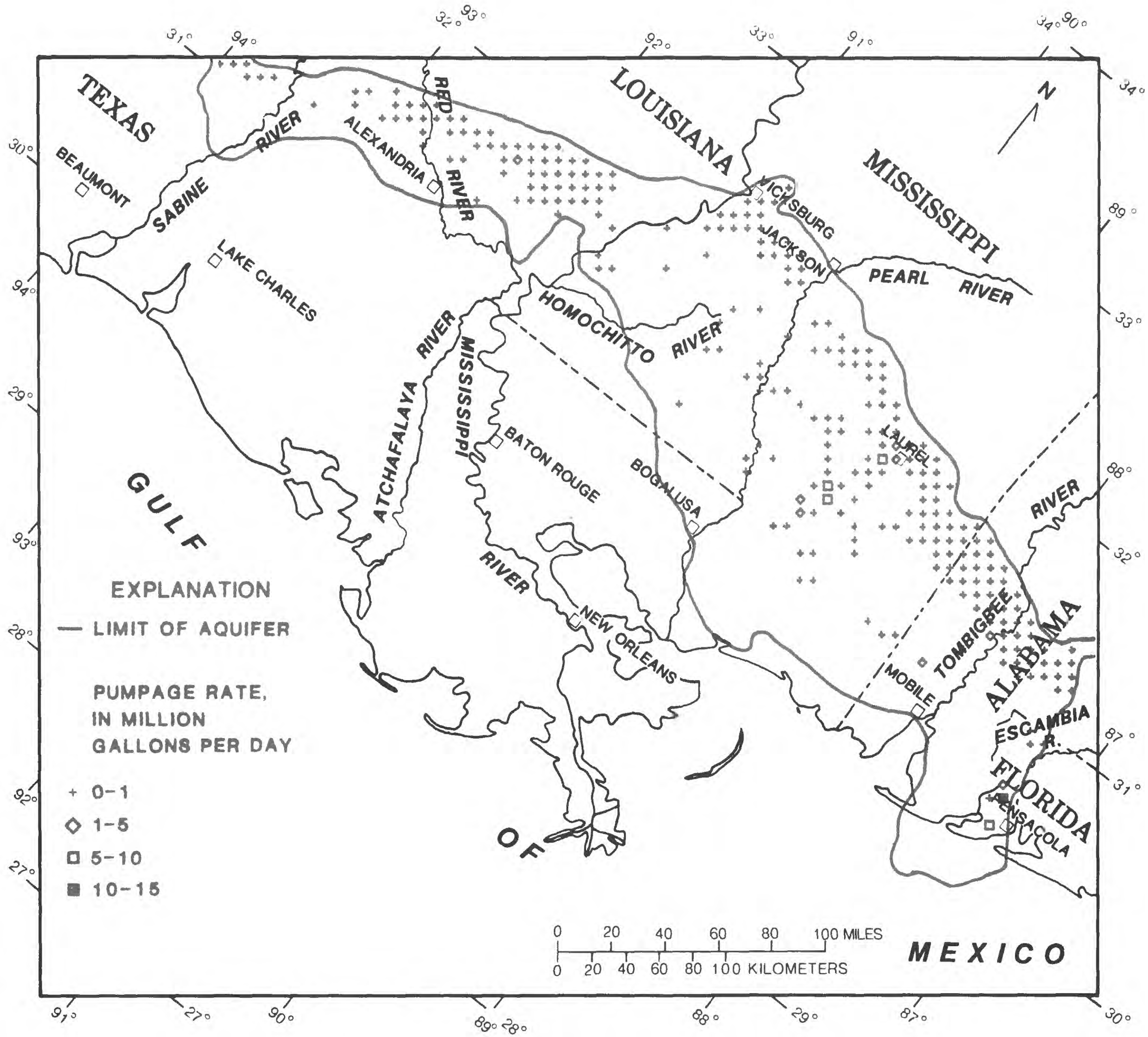

Figure 28.--Areal distribution of pumpage from the lower Miocene aquifer (model layer 6).

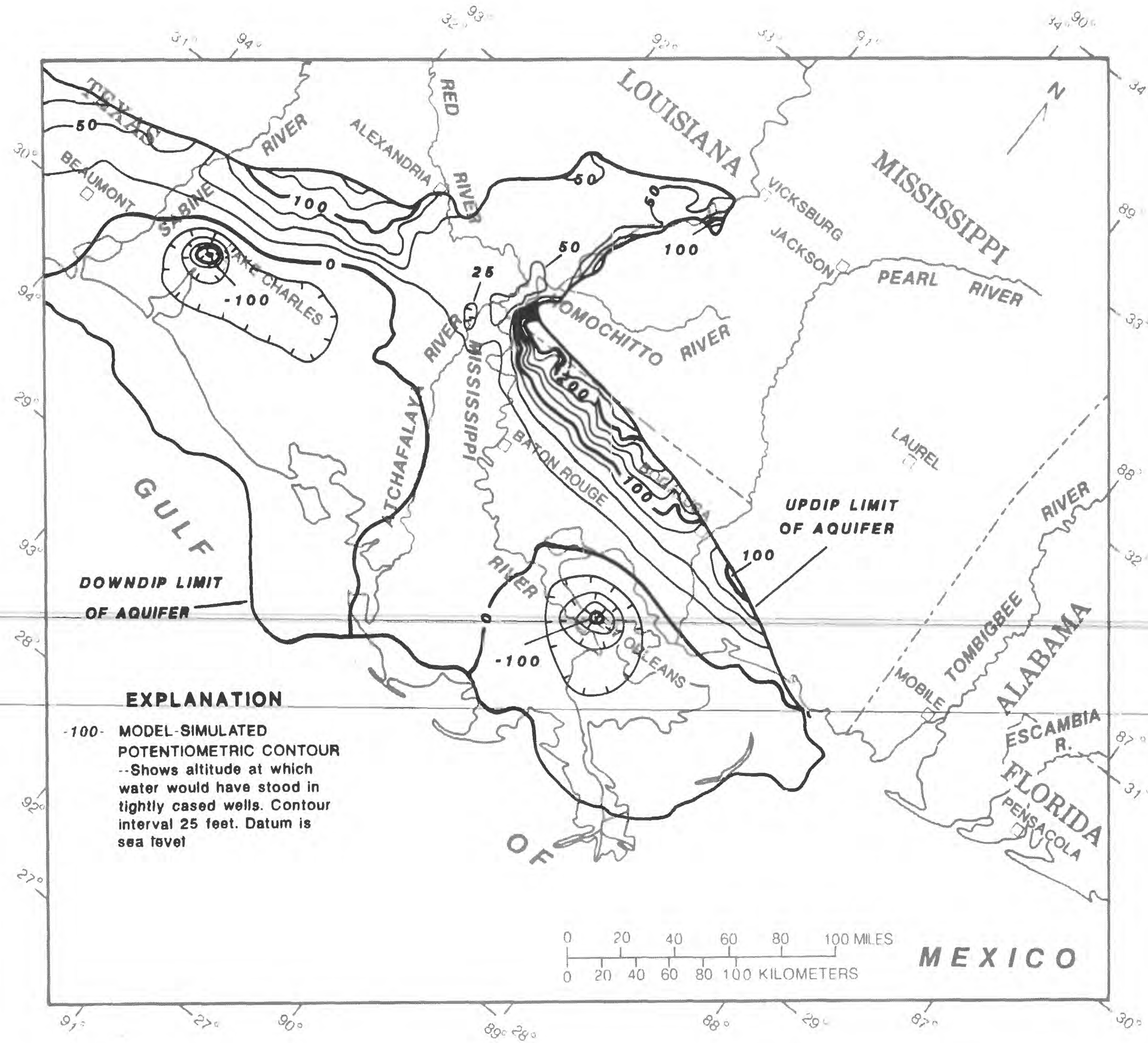

Figure 29.--Model-simulated water-level altitudes for 1980 of the upper Pleistocene aquifer (model layer 2).

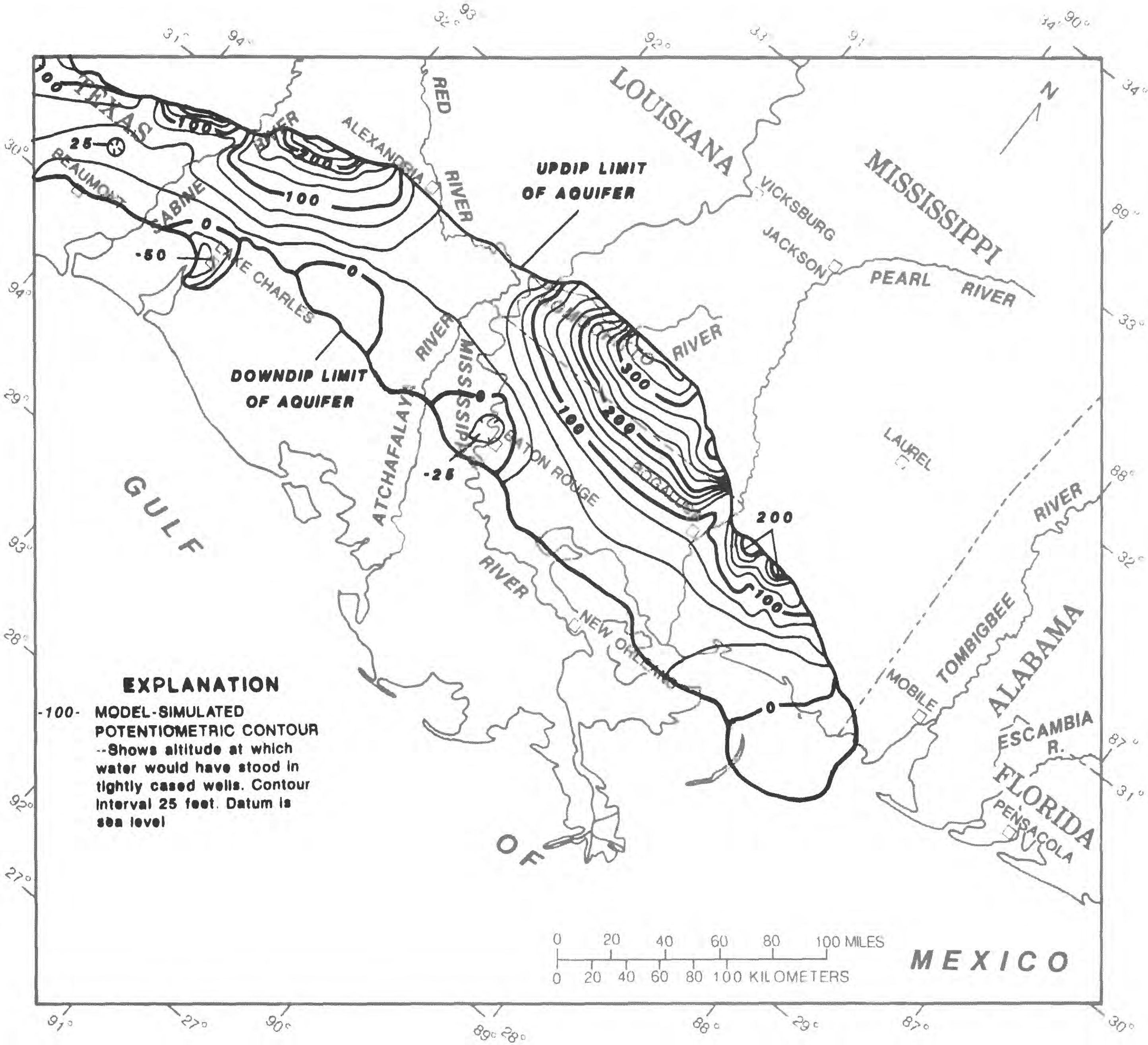

Figure 30.--Model-simulated water-level altitudes for 1980 of the lower Pleistocene-upper Pliocene aquifer (model layer 3).

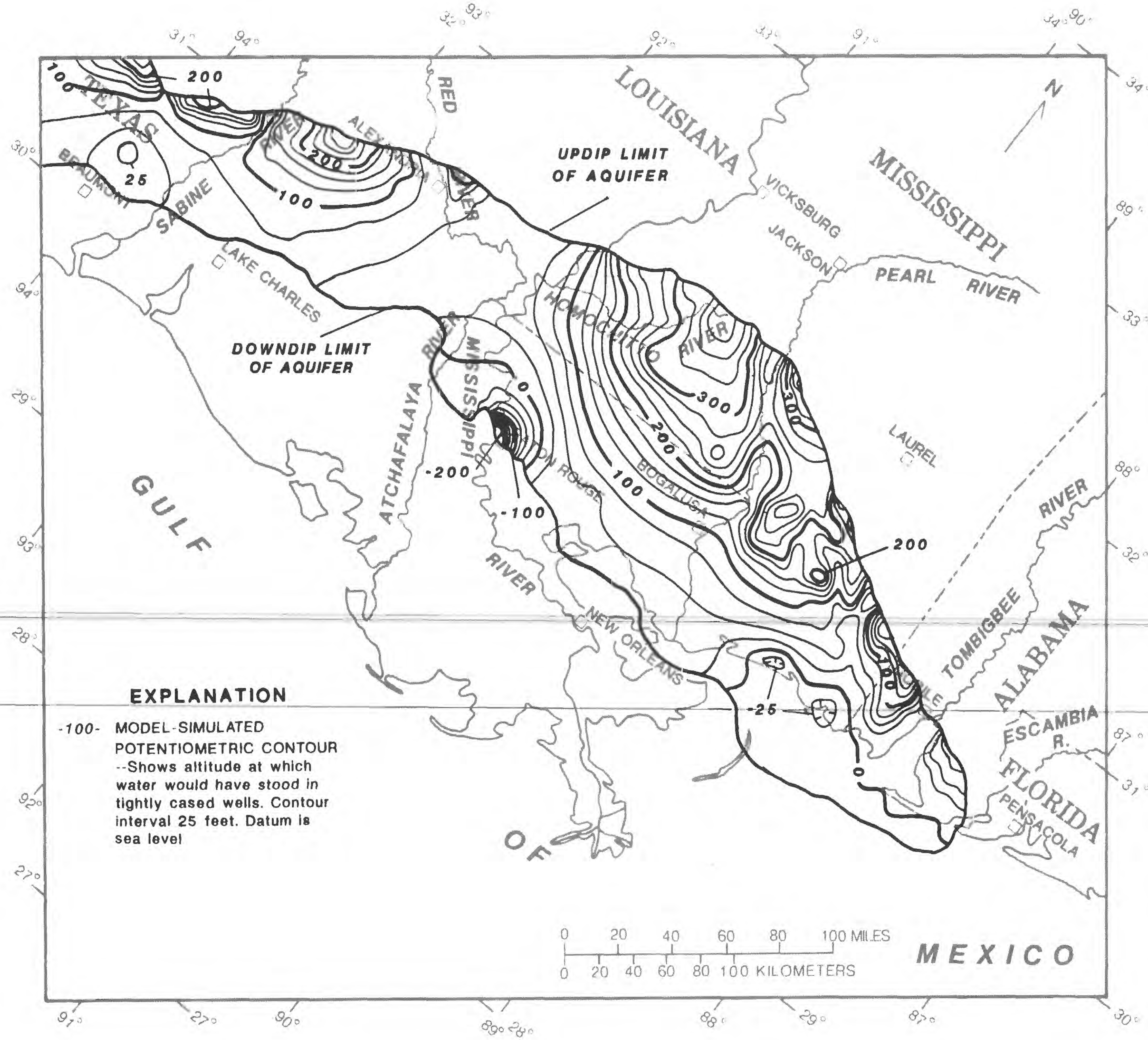

Figure 31.--Model-simulated water-level altitudes for 1980 of the lower Pliocene-upper Miocene aquifer (model layer 4).

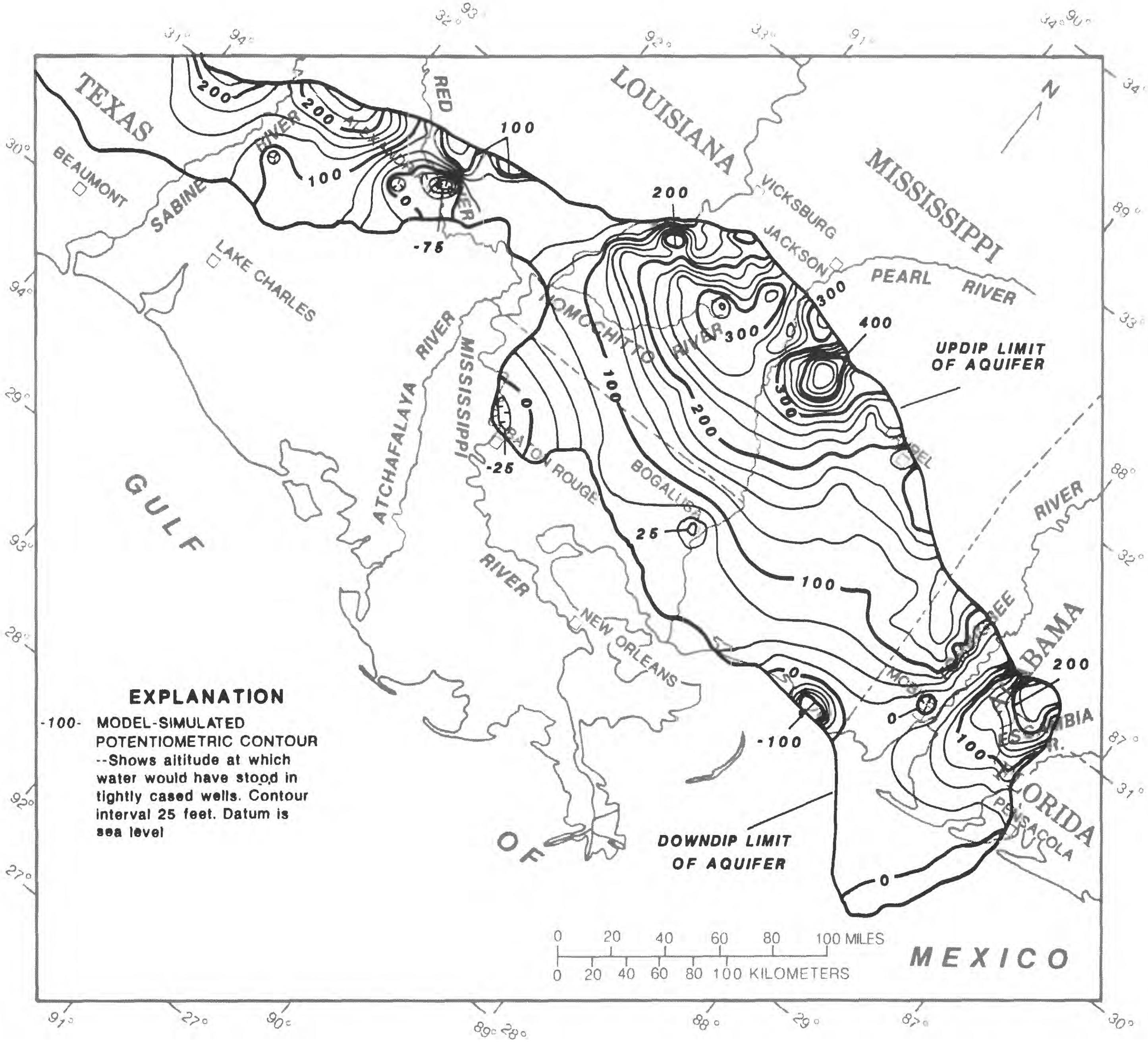

Figure 32.--Model-simulated water-level altitudes for 1980 of the middle Miocene aquifer (model layer 5).

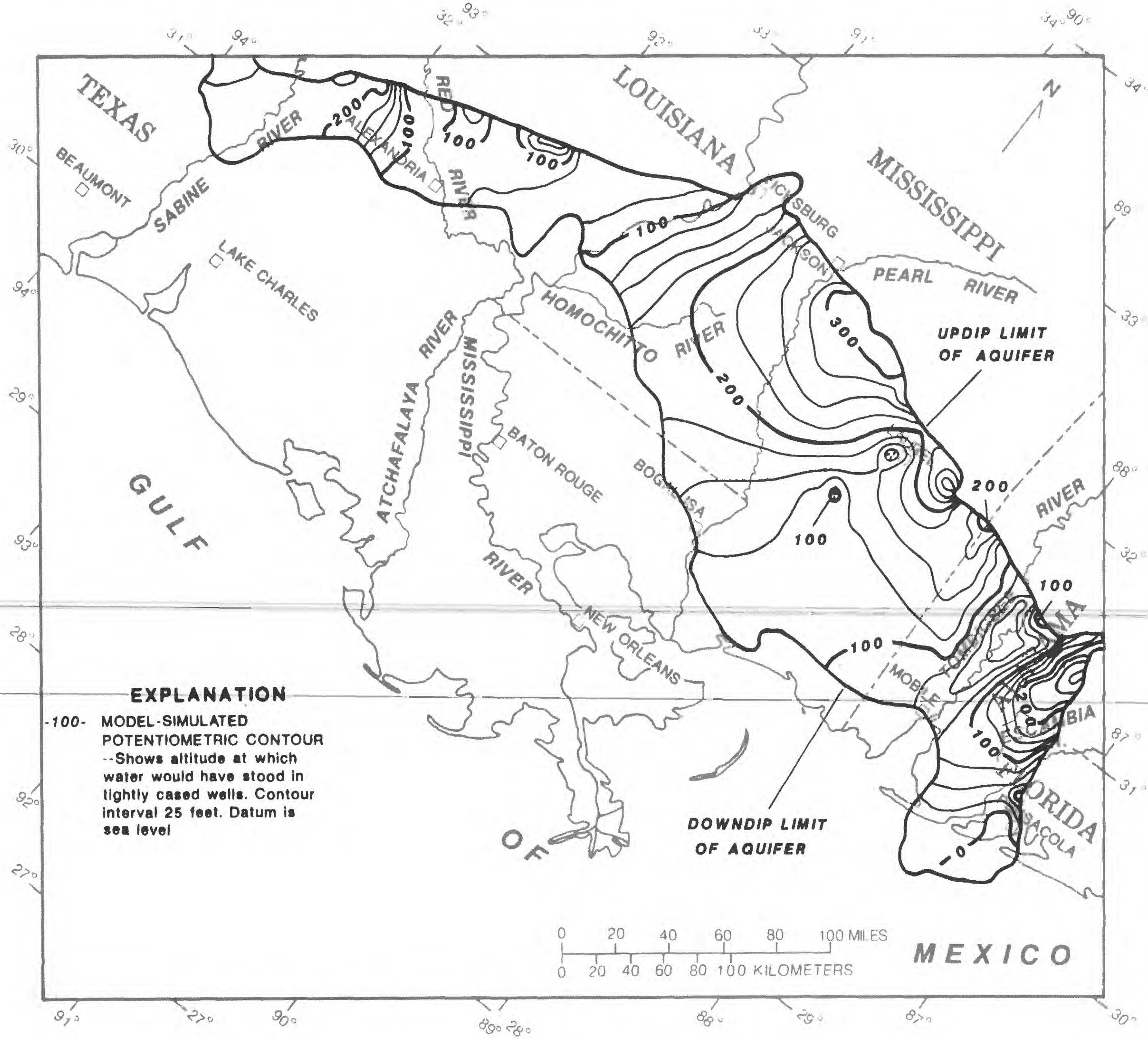

Figure 33.--Model-simulated water-level altitudes for 1980 of the lower Miocene aquifer (model layer 6).

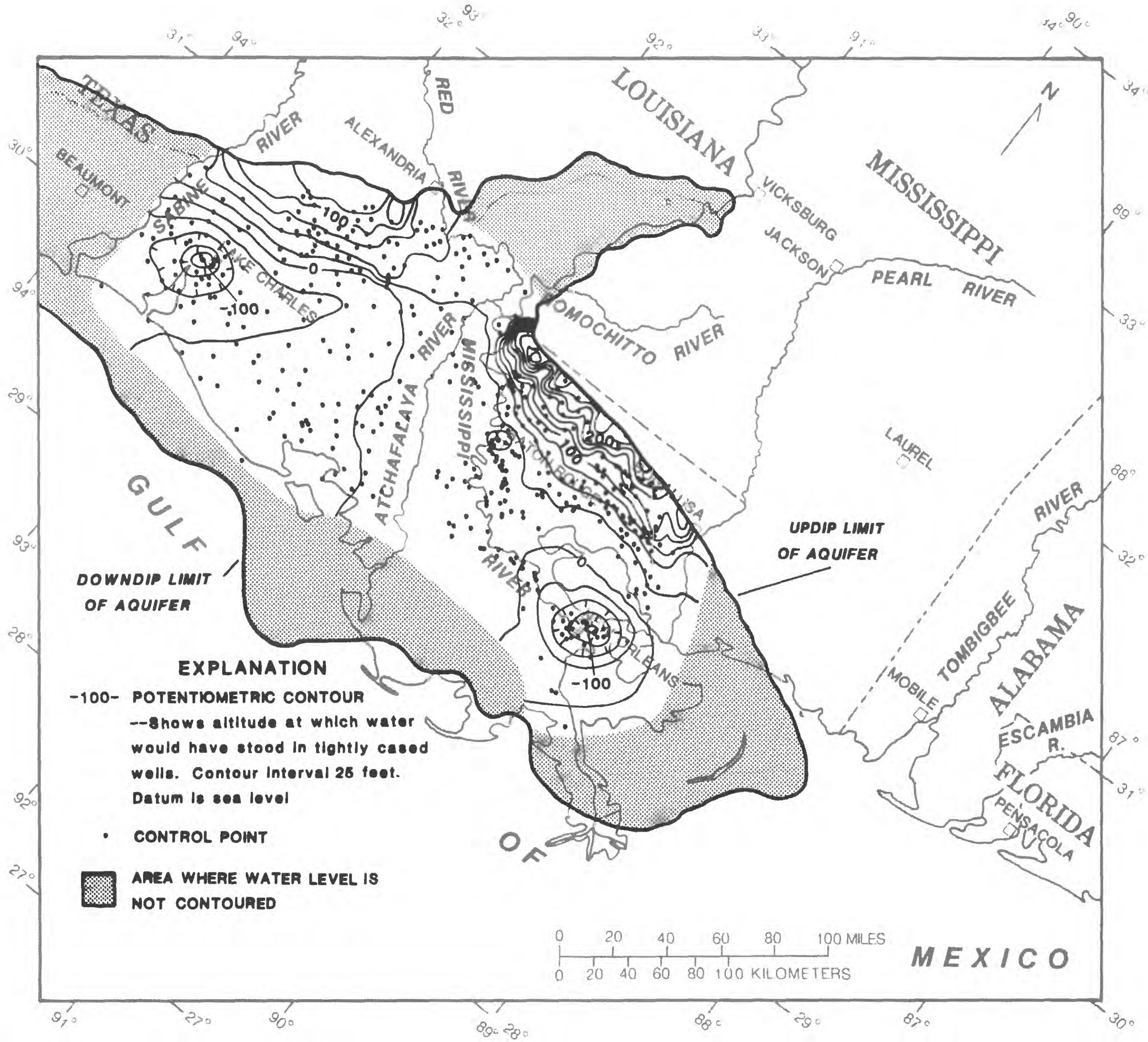

Figure 34.--Measured 1980 water-level altitudes of the upper Pleistocene aquifer.

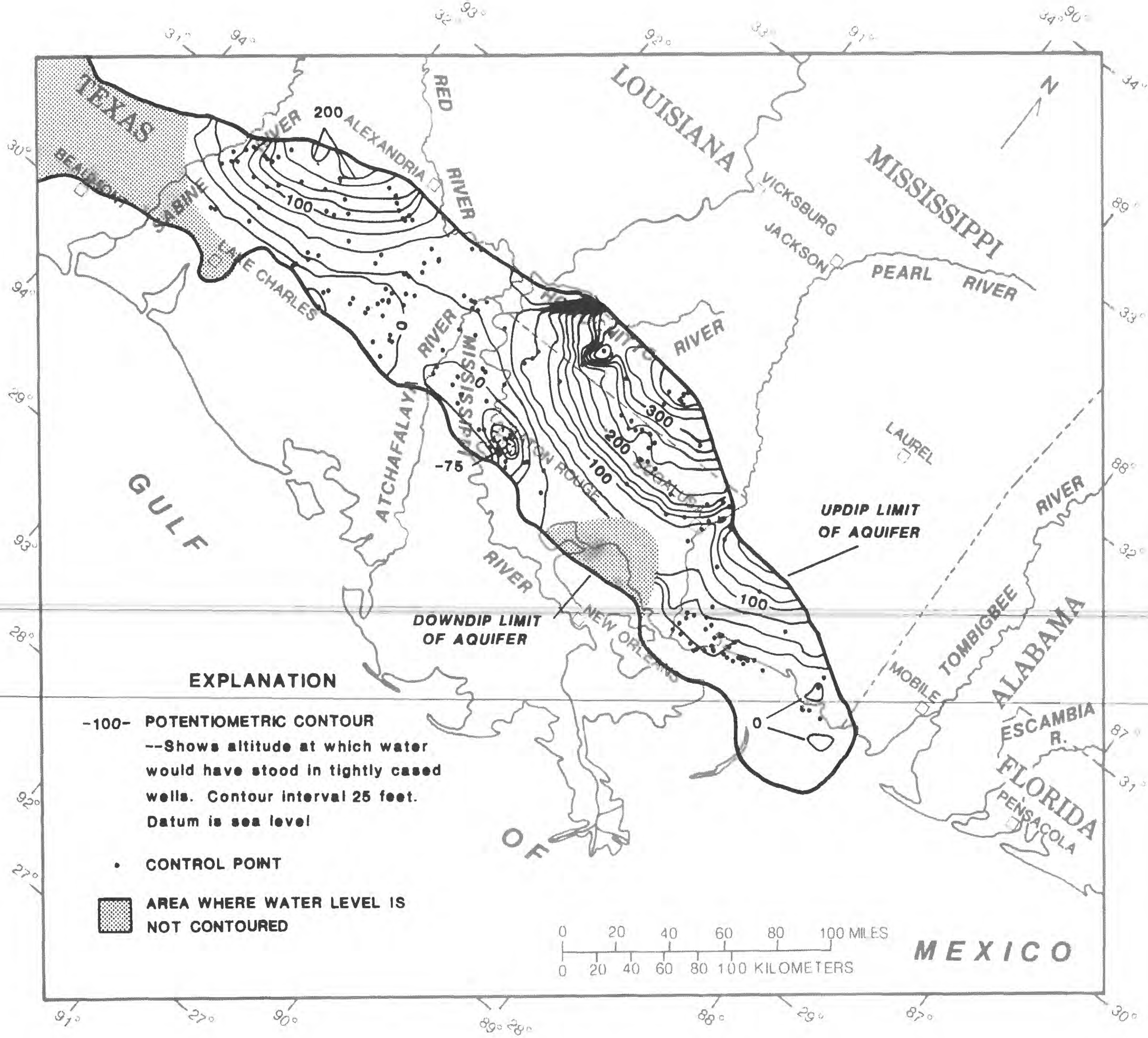

Figure 35.--Measured 1980 water-level altitudes of the lower Pleistocene-upper Pliocene aquifer.

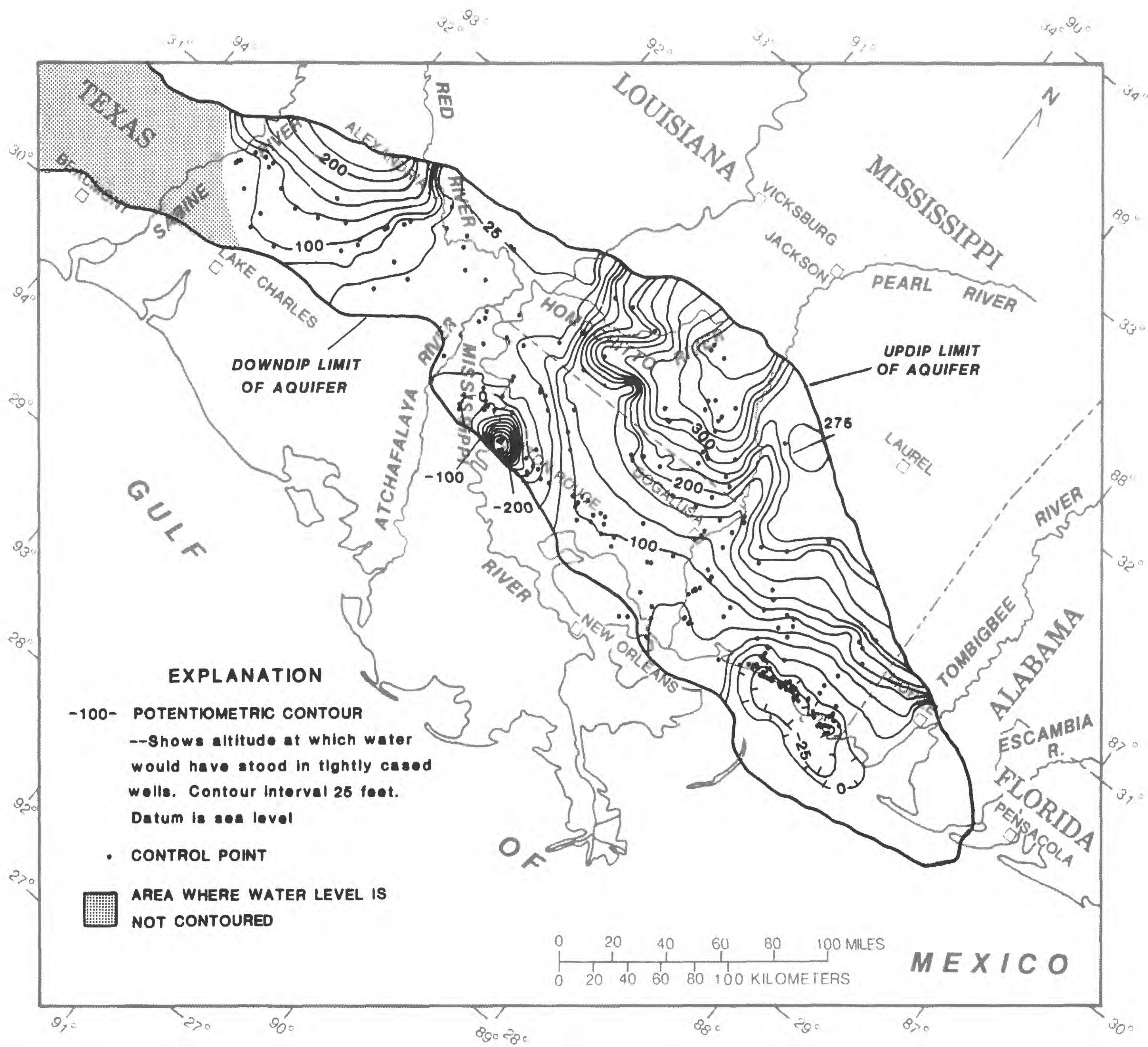

Figure 36.--Measured 1980 water-level altitudes of the lower Pliocene-upper Miocene aquifer.

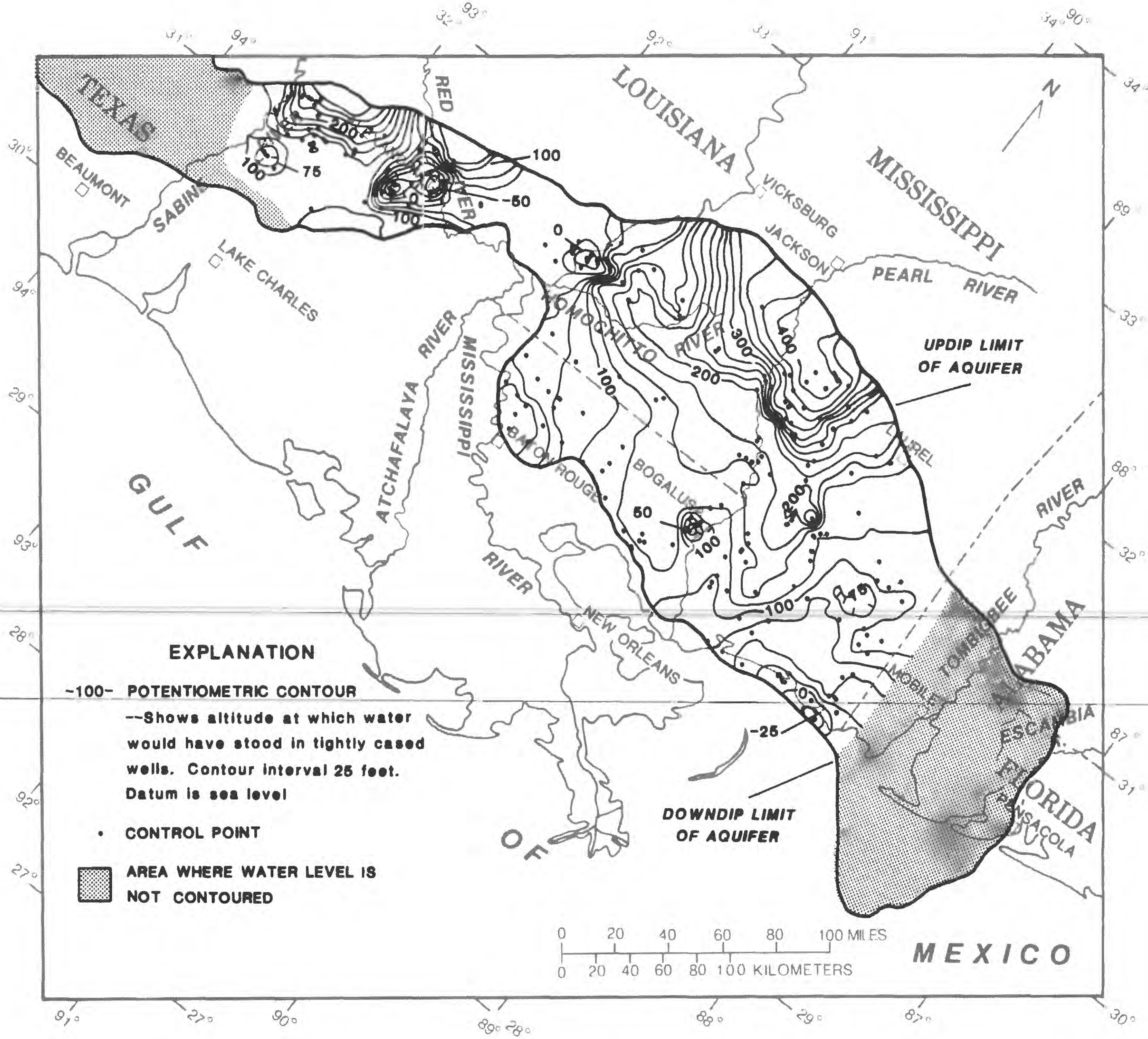

Figure 37.--Measured 1980 water-level altitudes of the middle Miocene aquifer.

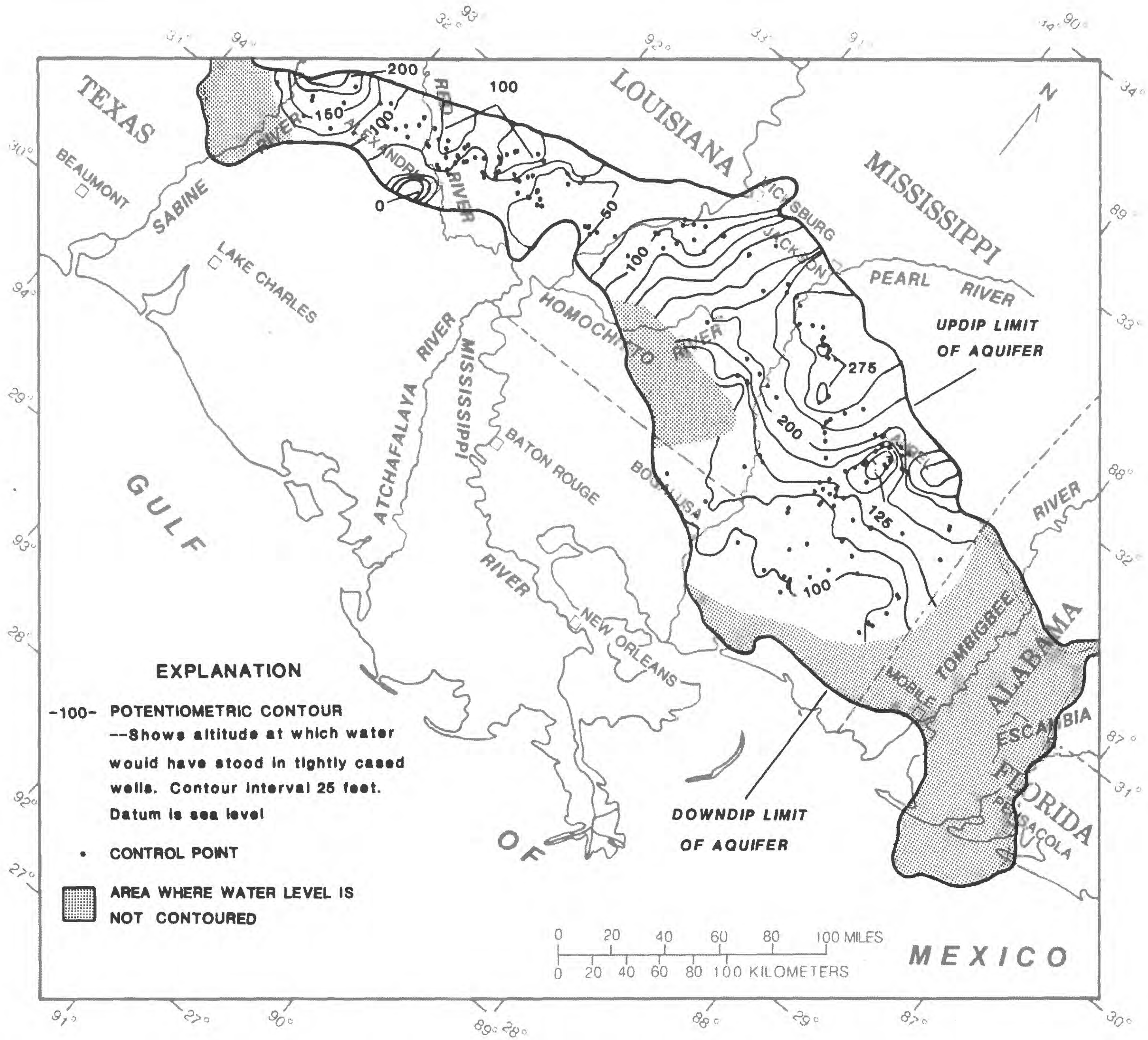

Figure 38.--Measured 1980 water-level altitudes of the lower Miocene aquifer.

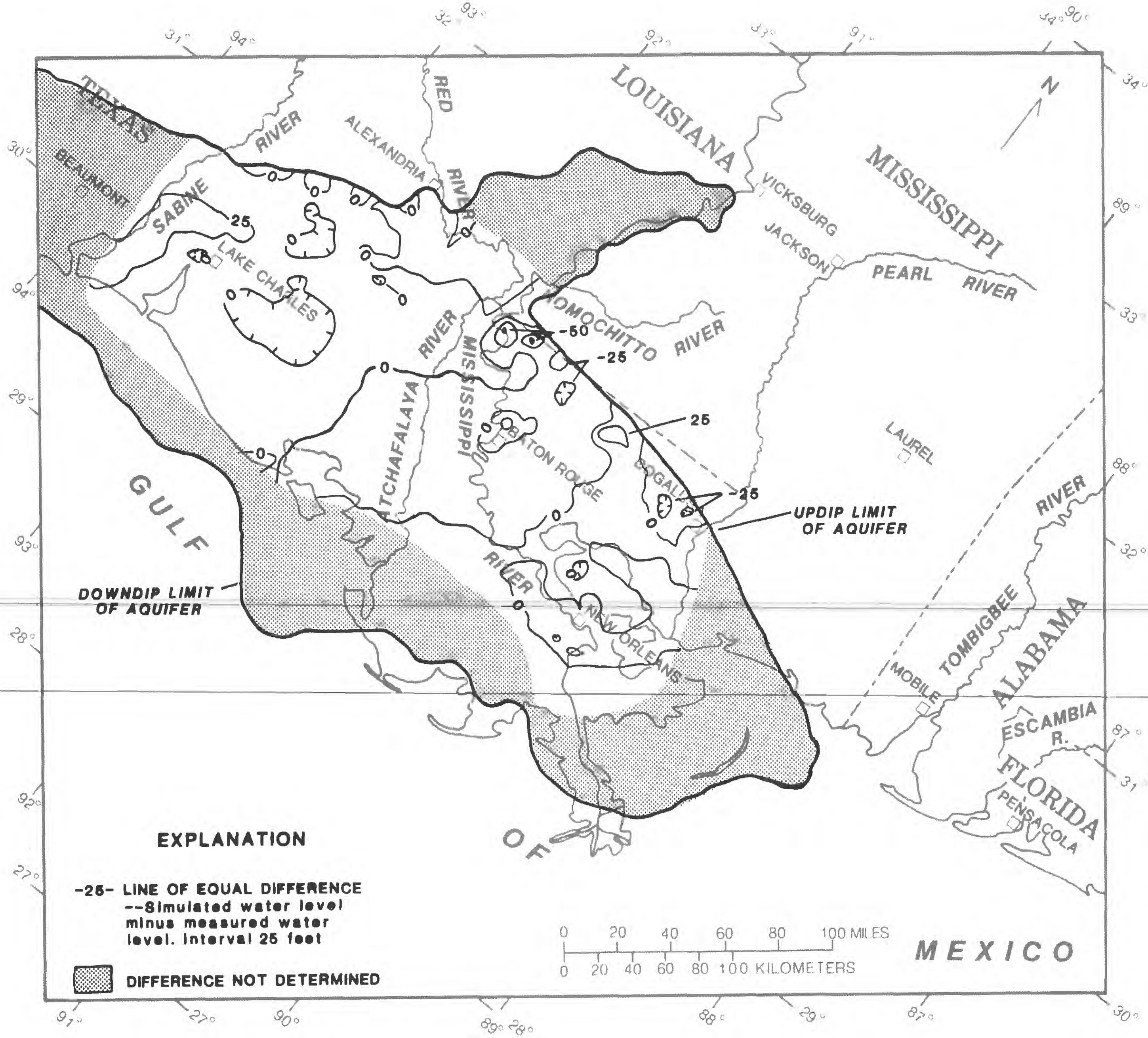

Figure 39.--Difference between model-simulated and measured water-level altitudes for 1980 of the upper Pleistocene aquifer (model layer 2).

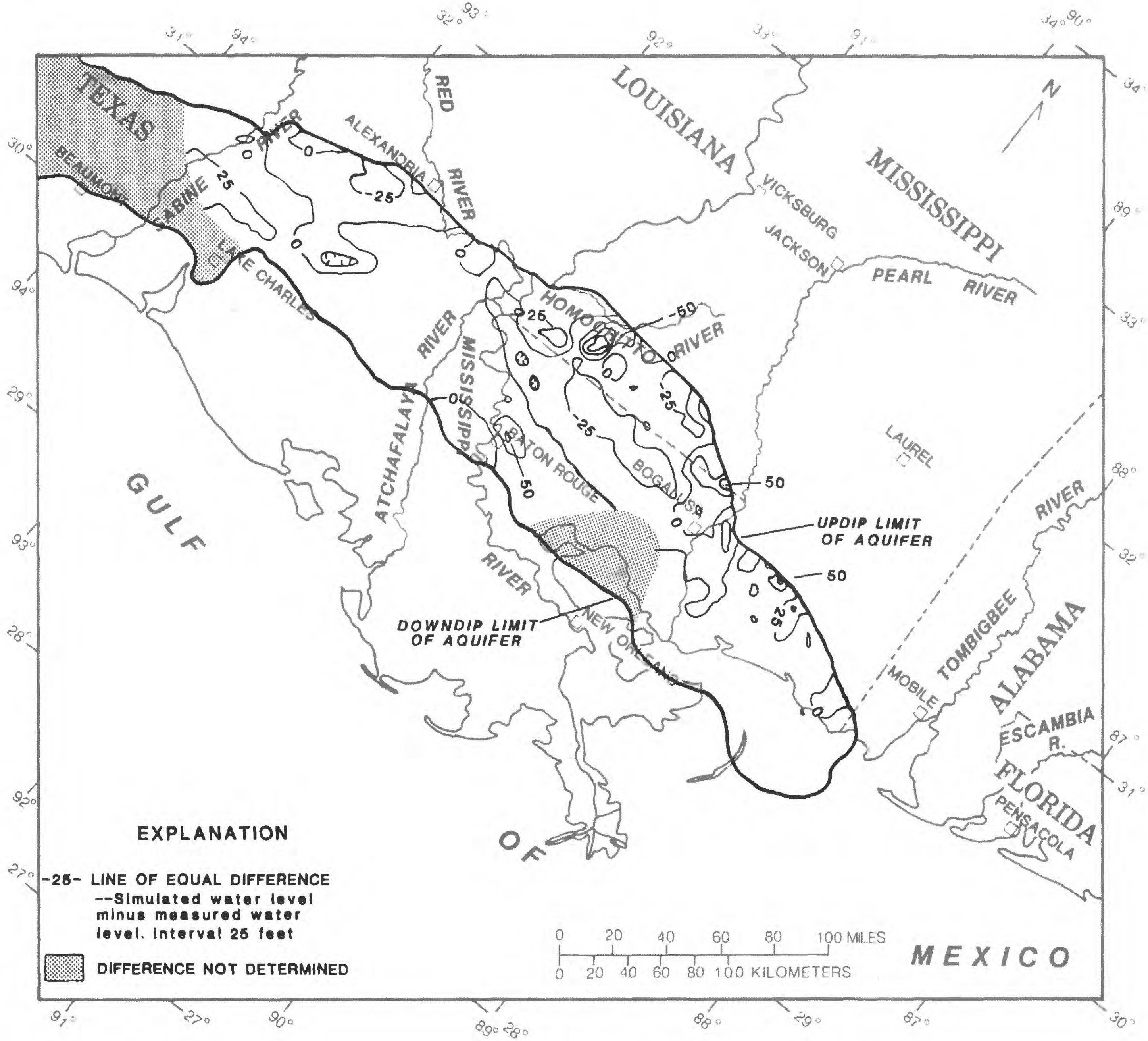

Figure 40.--Difference between model-simulated and measured water-level altitudes for 1980 of the lower Pleistocene-upper Pliocene aquifer (model layer 3).

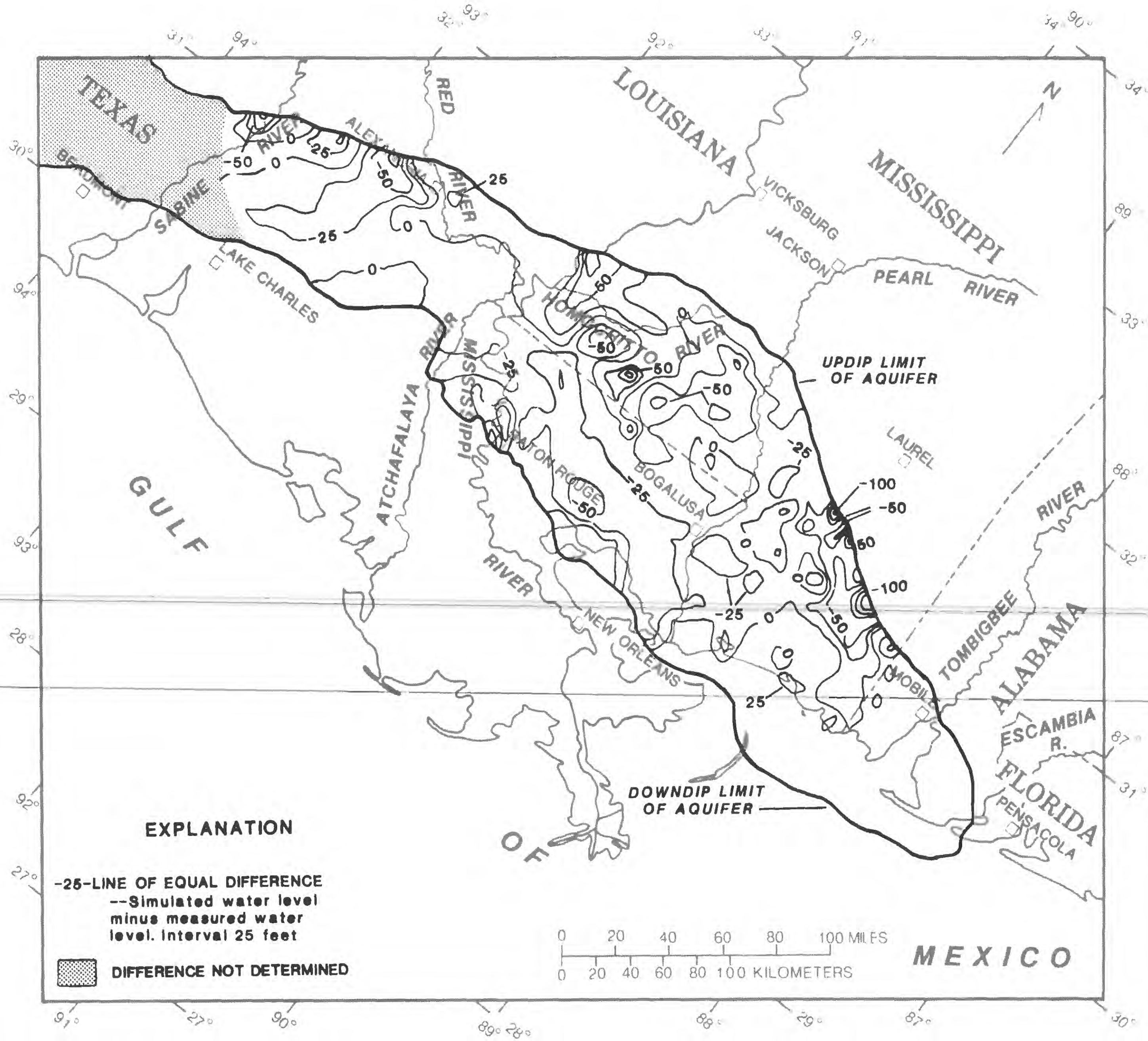

Figure 41.--Difference between model-simulated and measured water-level altitudes for 1980 of the lower Pliocene-upper Miocene aquifer (model layer 4).

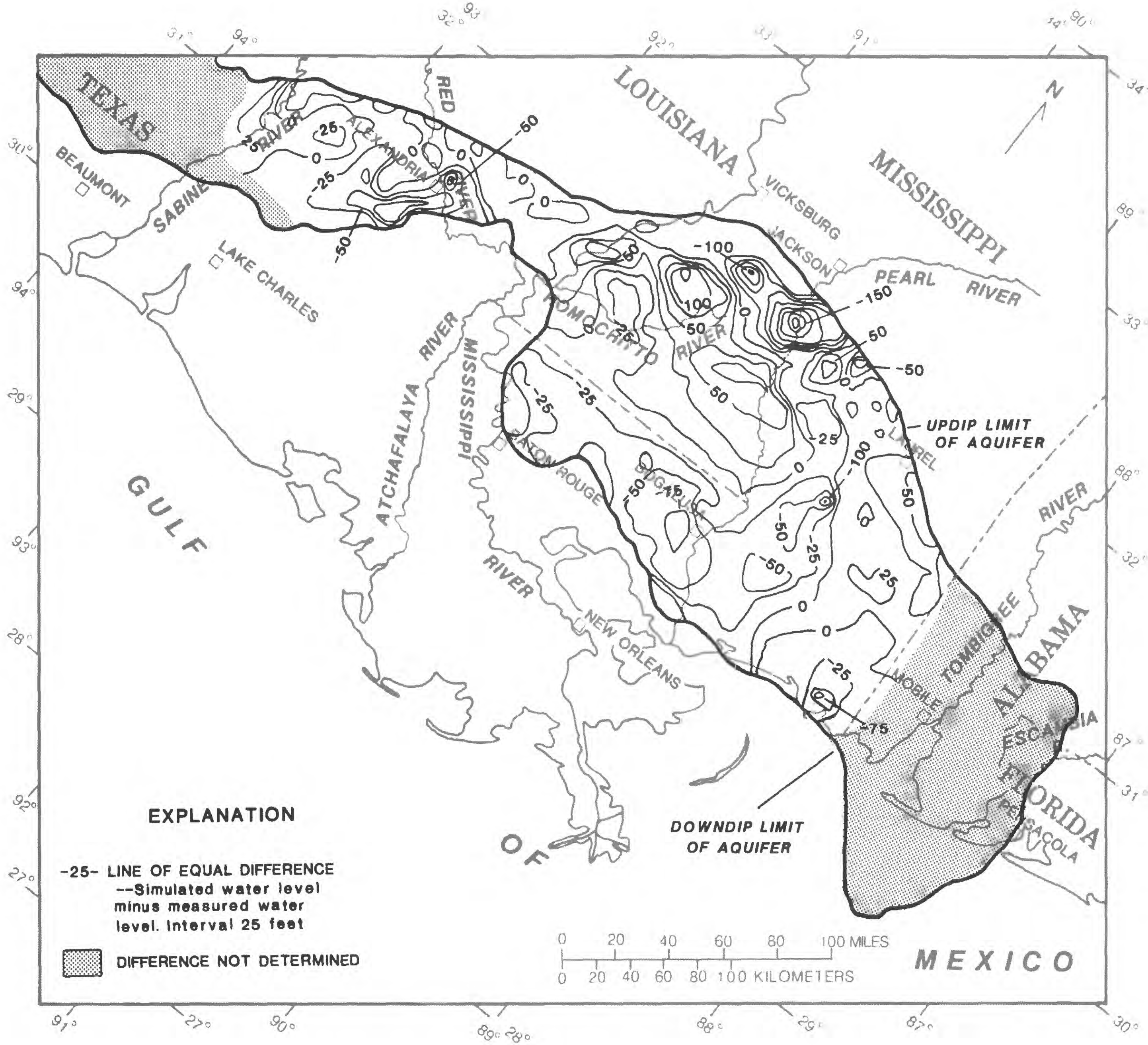

Figure 42.--Difference between model-simulated and measured water-level altitudes for 1980 of the middle Miocene aquifer (model layer 5).

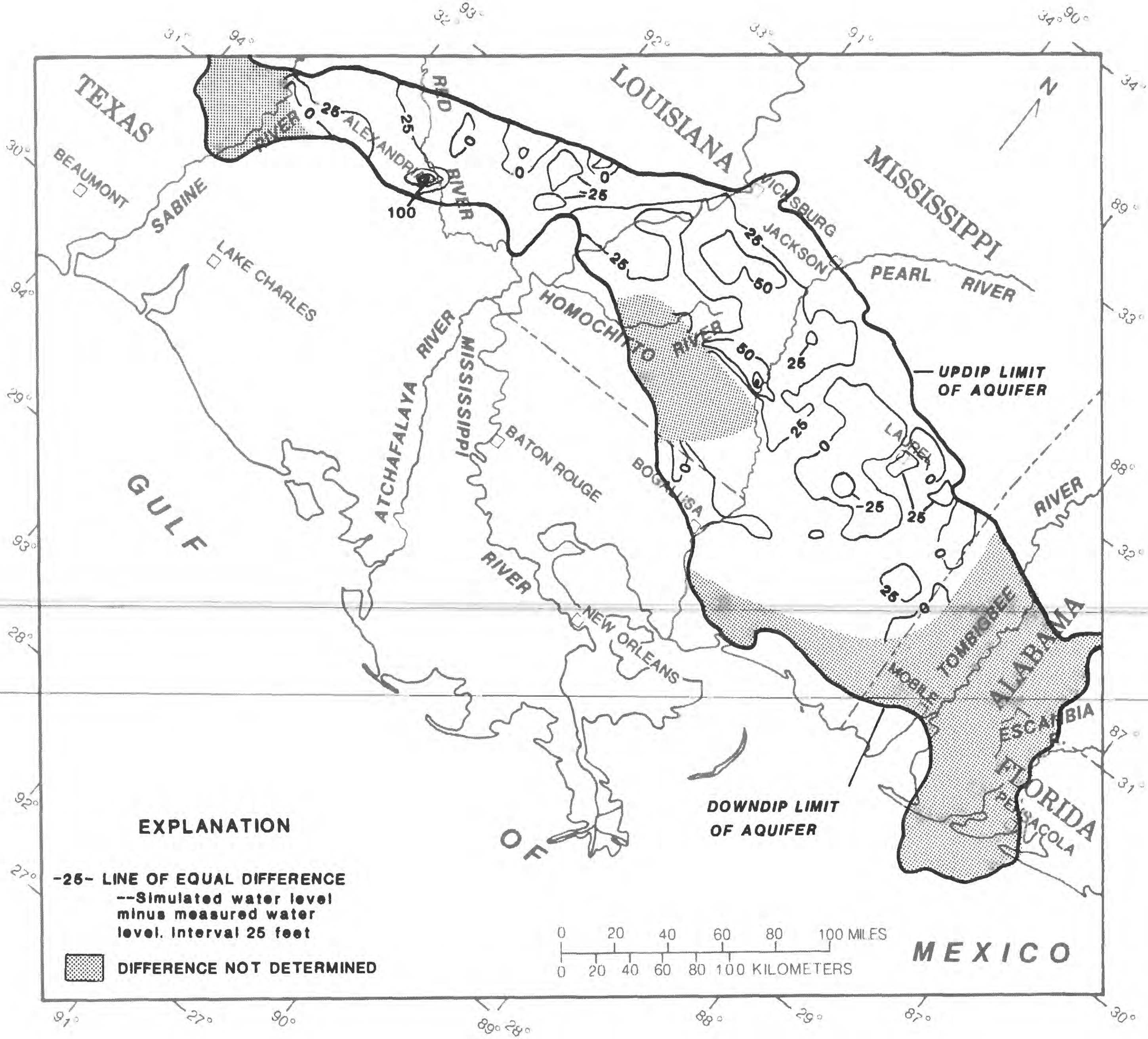

Figure 43.--Difference between model-simulated and measured water-level altitudes for 1980 of the lower Miocene aquifer (model layer 6).

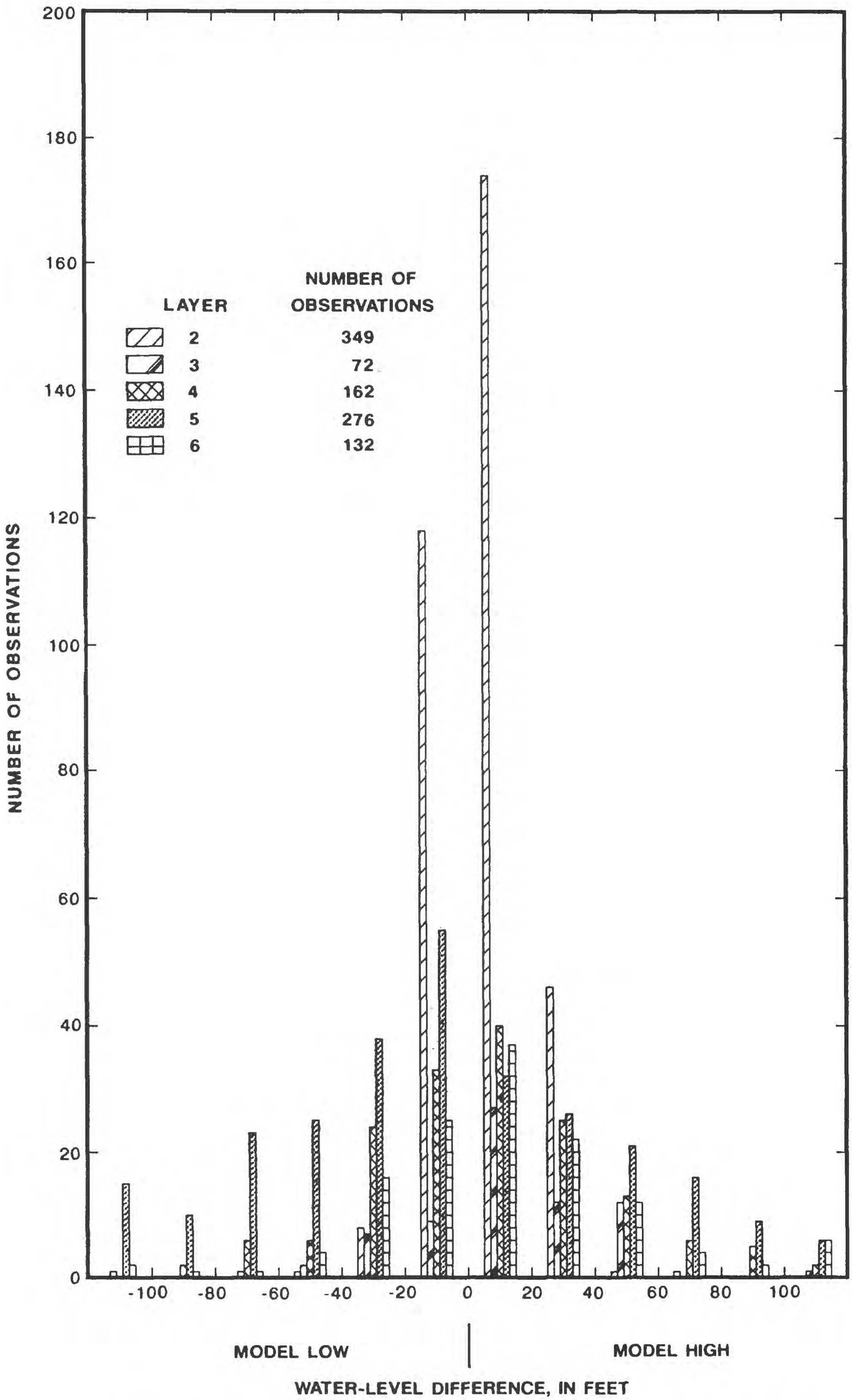

Figure 44.--The difference between model-simulated and measured water-level altitudes.

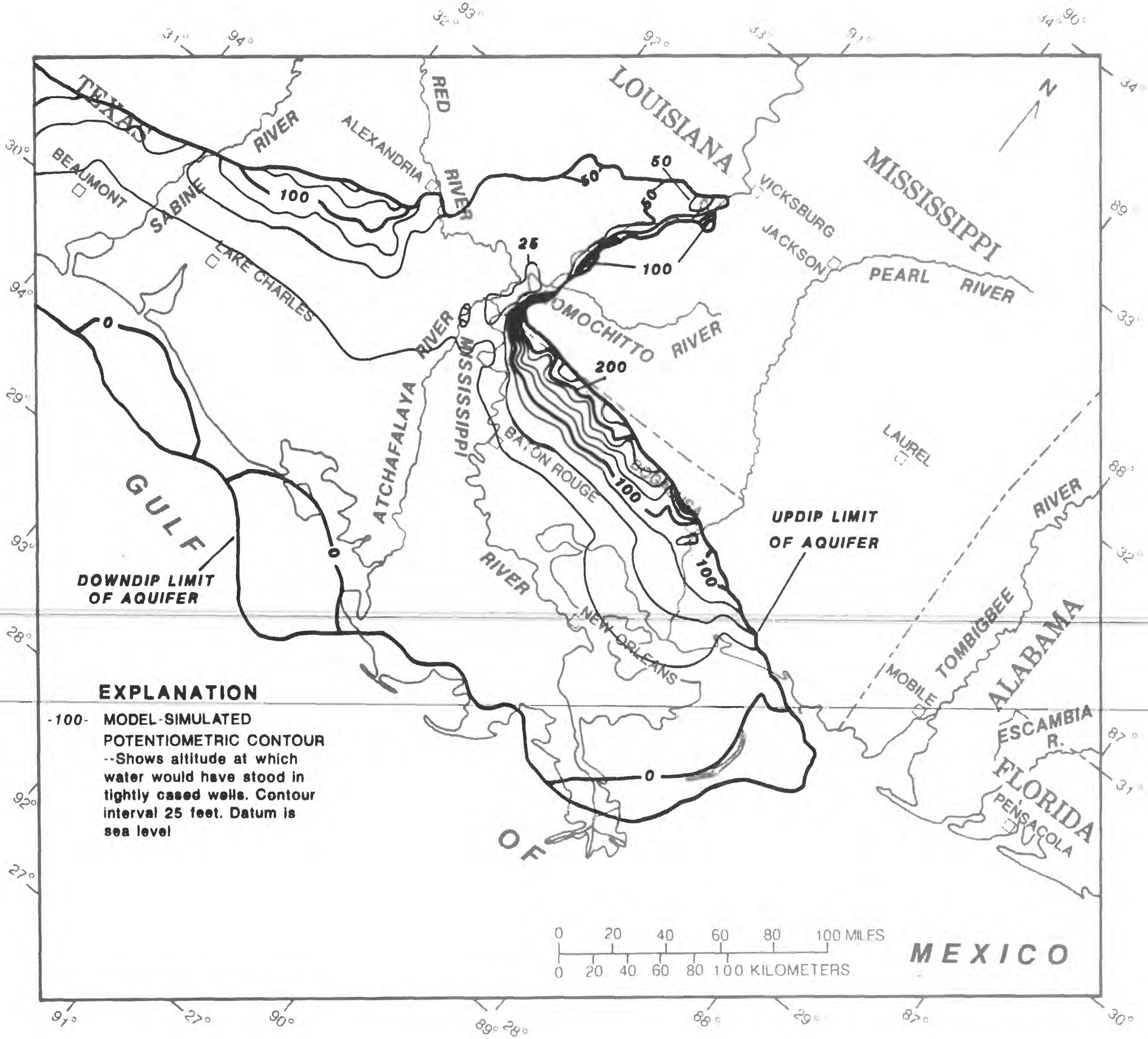

Figure 45.--Model-simulated predevelopment water-level altitudes of the upper Pleistocene aquifer (model layer 2).

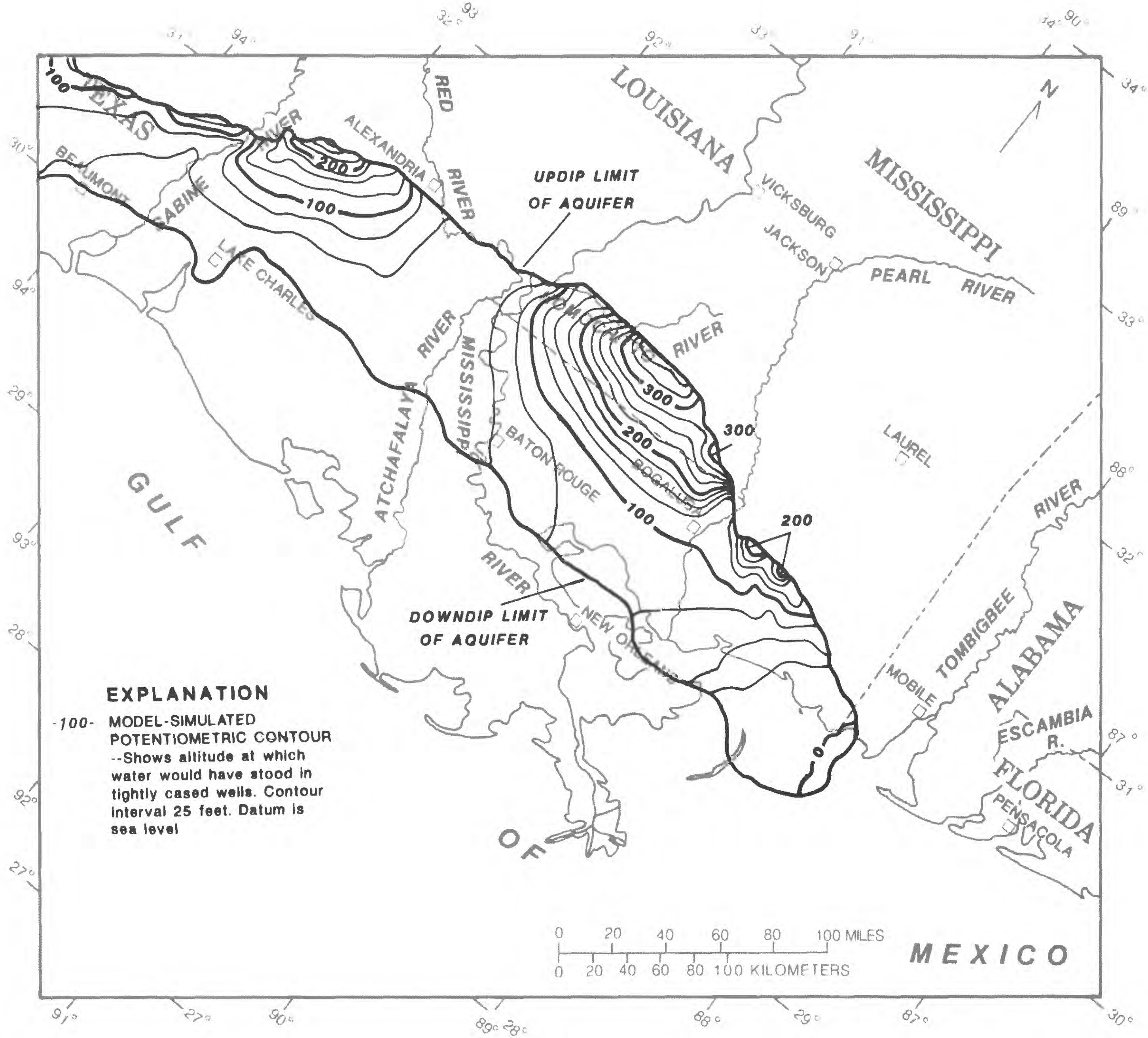

Figure 46.--Model-simulated predevelopment water-level altitudes of the lower Pleistocene-upper Pliocene aquifer (model layer 3).

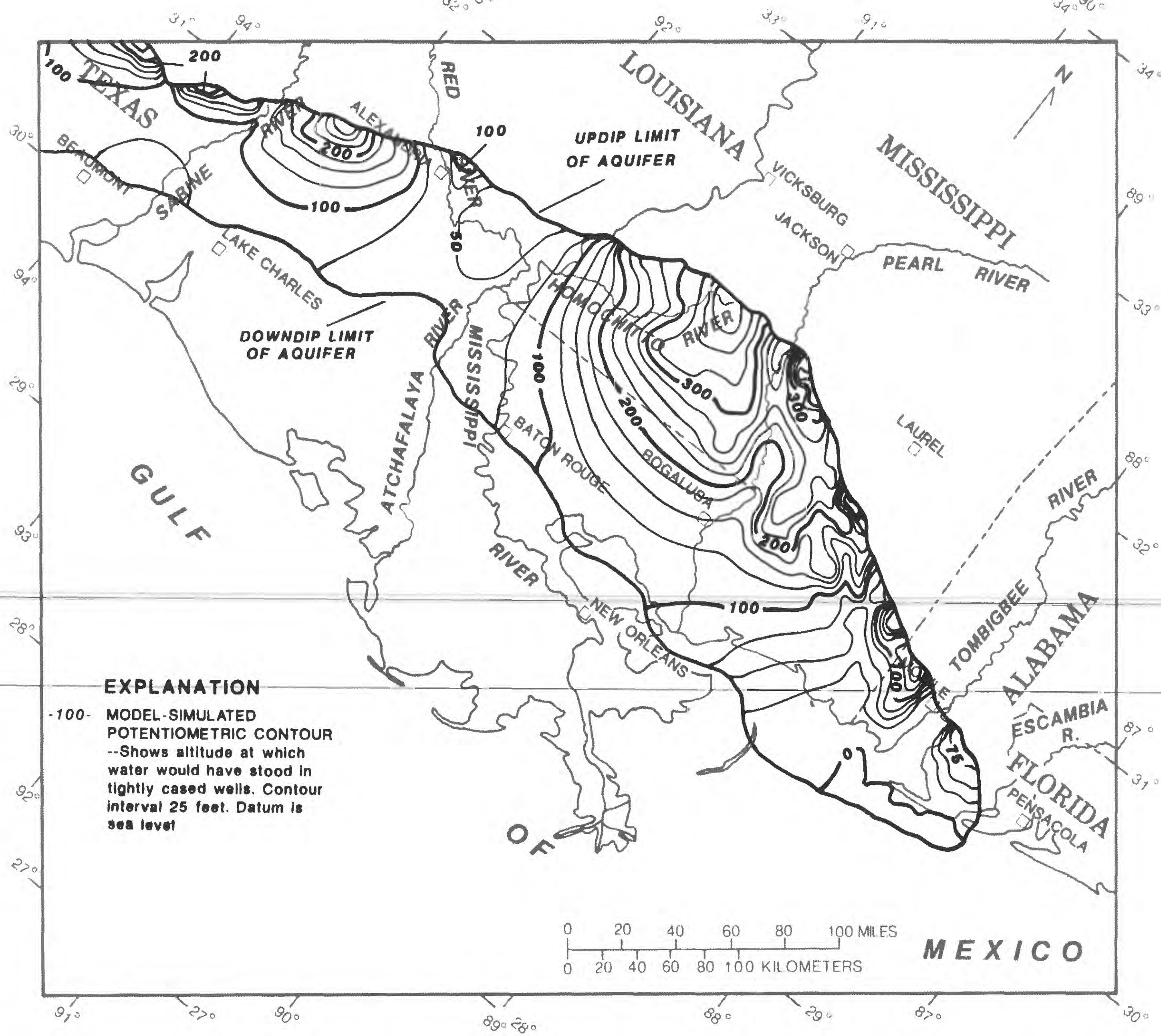

Figure 47.--Model-simulated predevelopment water-level altitudes of the lower Pliocene-upper Miocene aquifer (model layer 4).

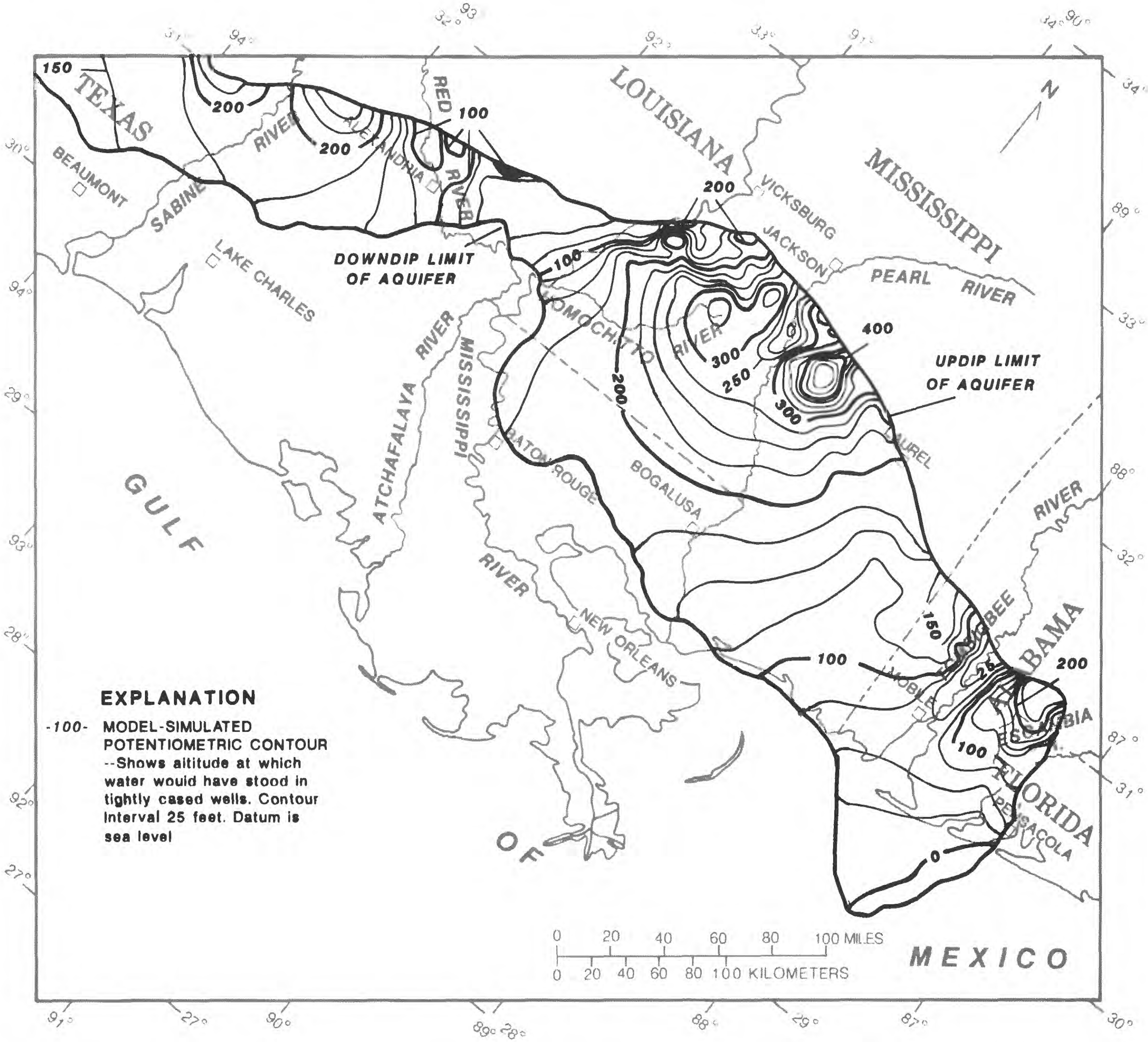

Figure 48.--Model-simulated predevelopment water-level altitudes of the middle Miocene aquifer (model layer 5).

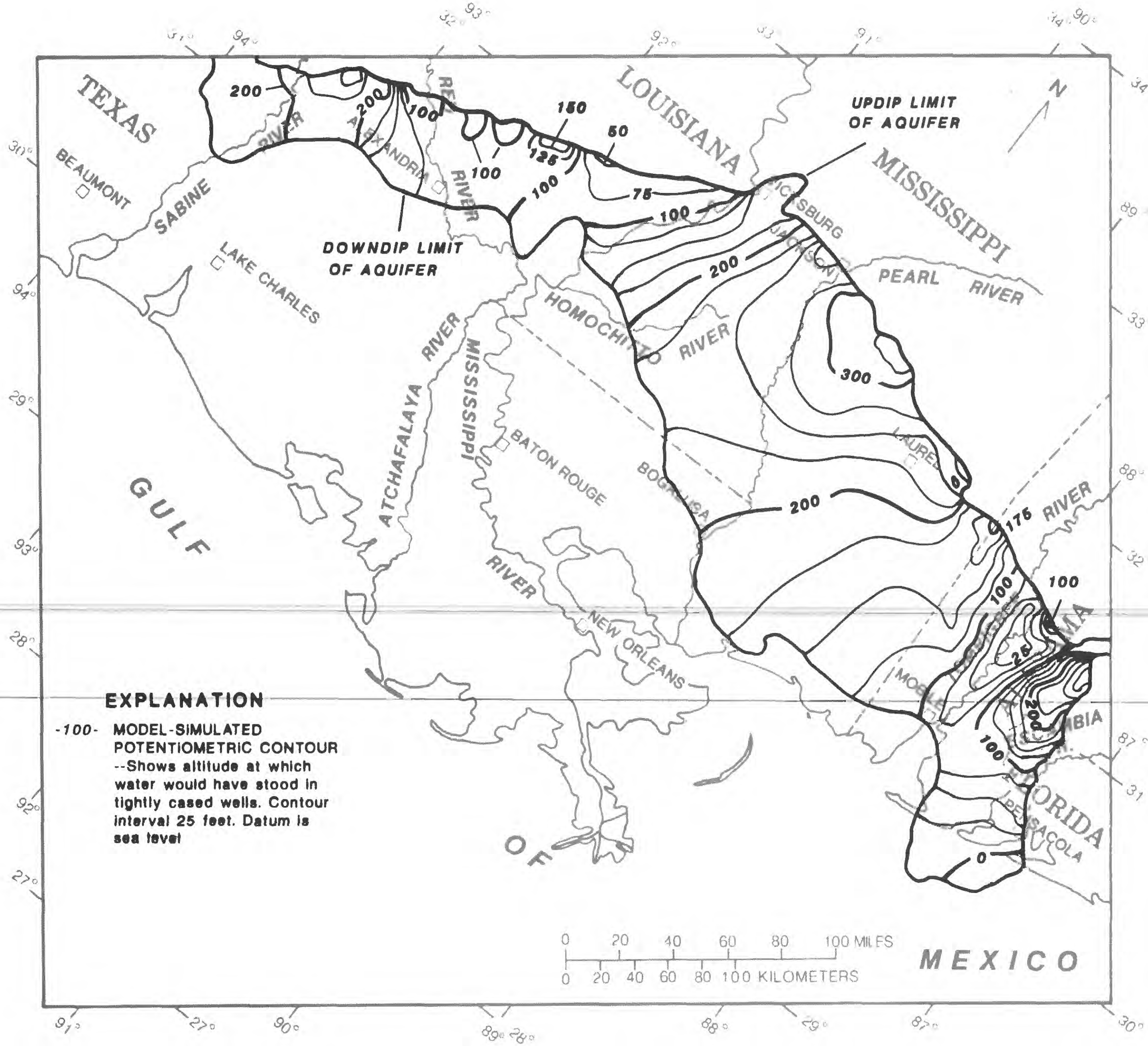

Figure 49.--Model-simulated predevelopment water-level altitudes of the lower Miocene aquifer (model layer 6).

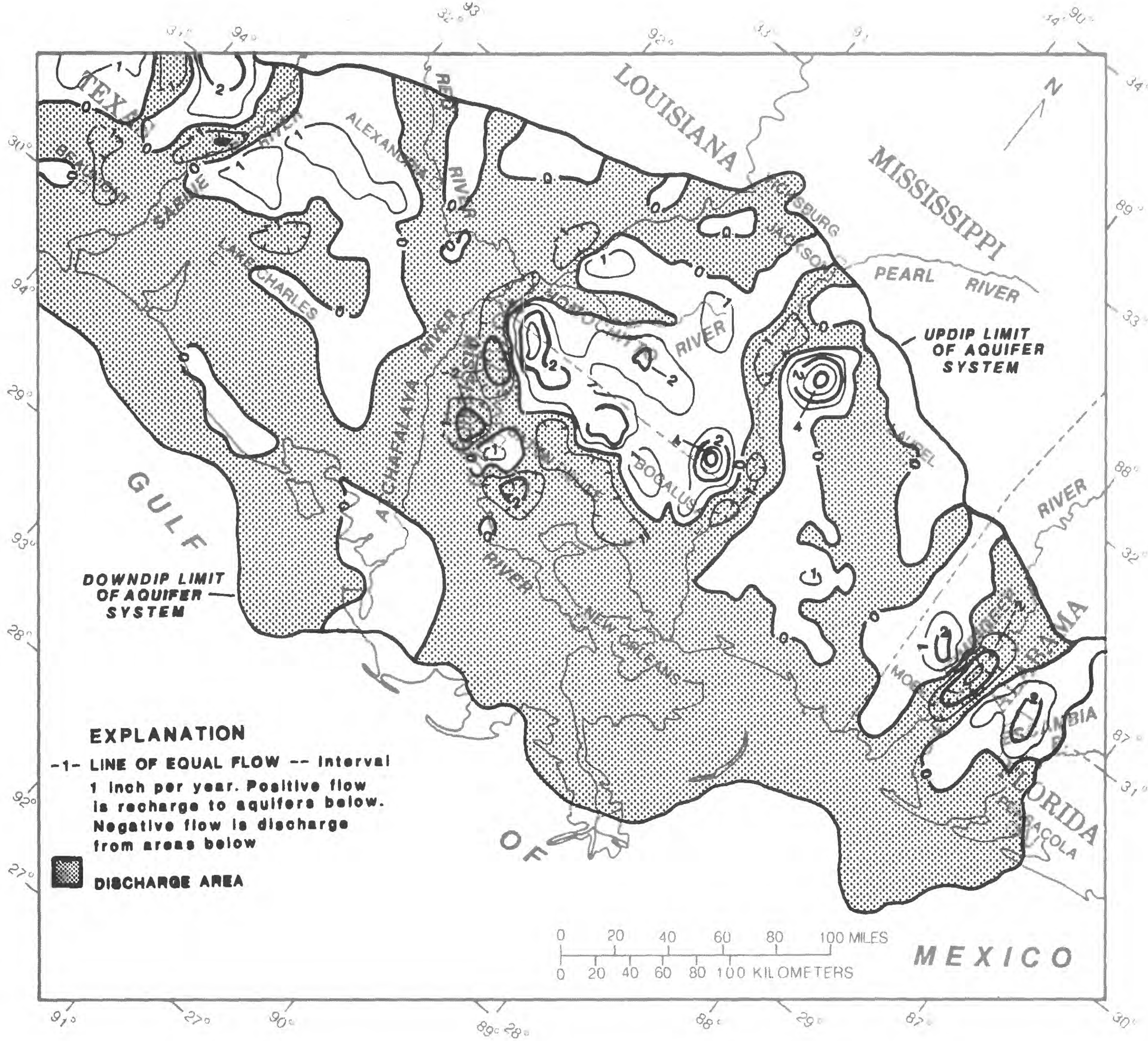

Figure 50.--Areal distribution of flow through the constant-head upper boundary (model layer 1) of the Coastal Lowlands aquifer system under predevelopment conditions.

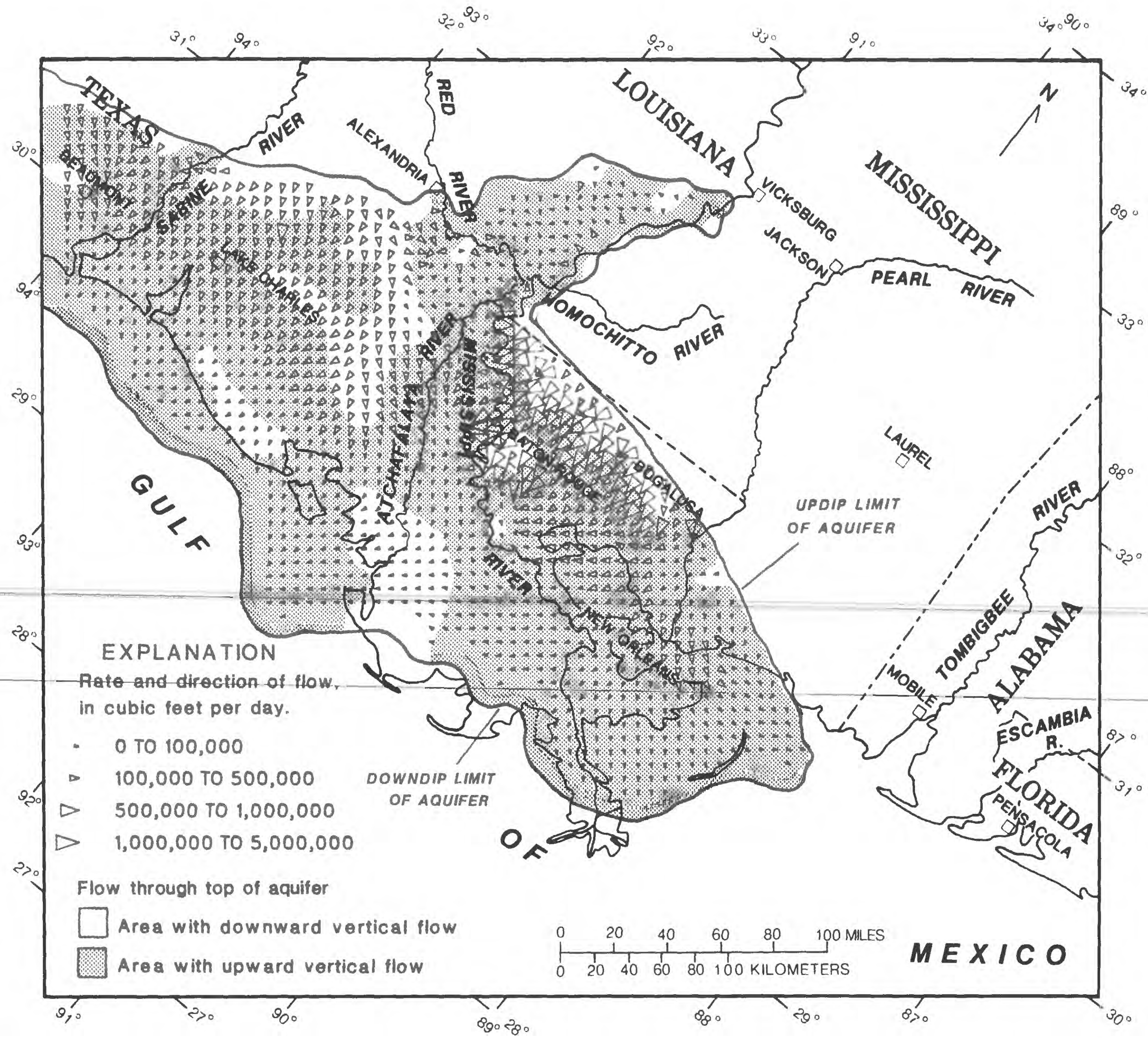

Figure 51.--Ground-water flow under predevelopment conditions in the upper Pleistocene aquifer (model layer 2).

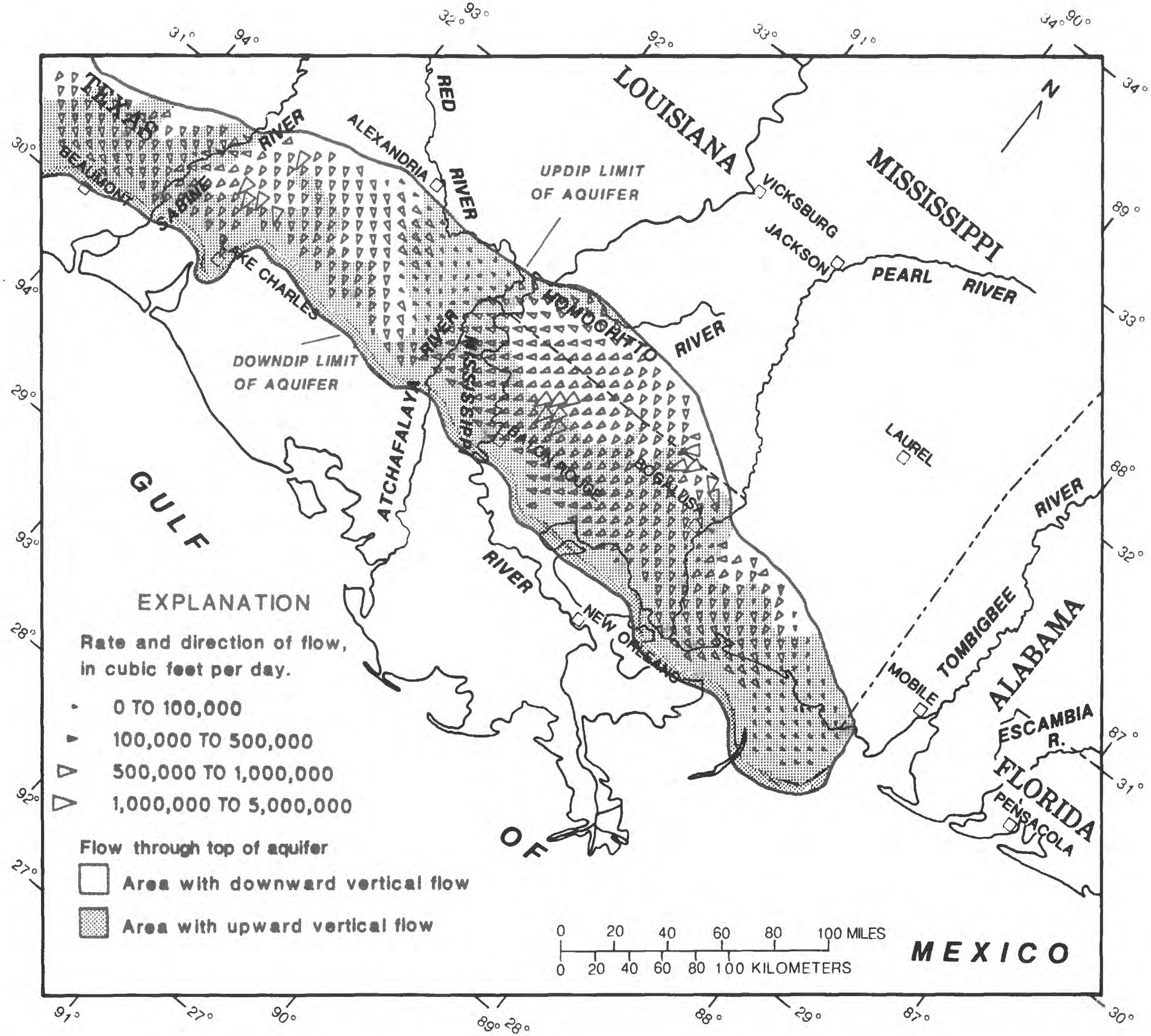

Figure 52.--Ground-water flow under predevelopment conditions in the lower Pleistocene-upper Pliocene aquifer (model layer 3).

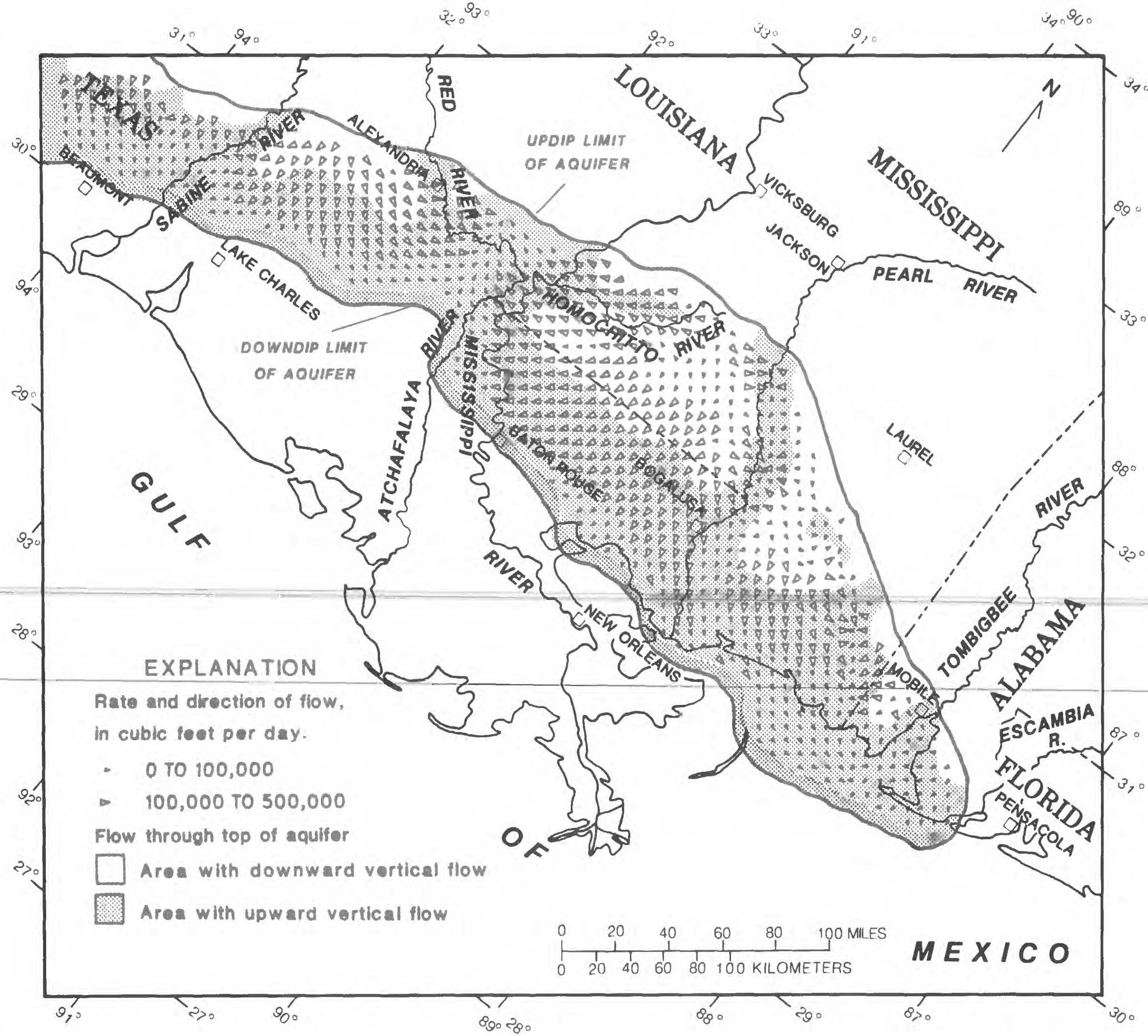

Figure 53.--Ground-water flow under predevelopment conditions in the lower Pliocene-upper Miocene aquifer (model layer 4).

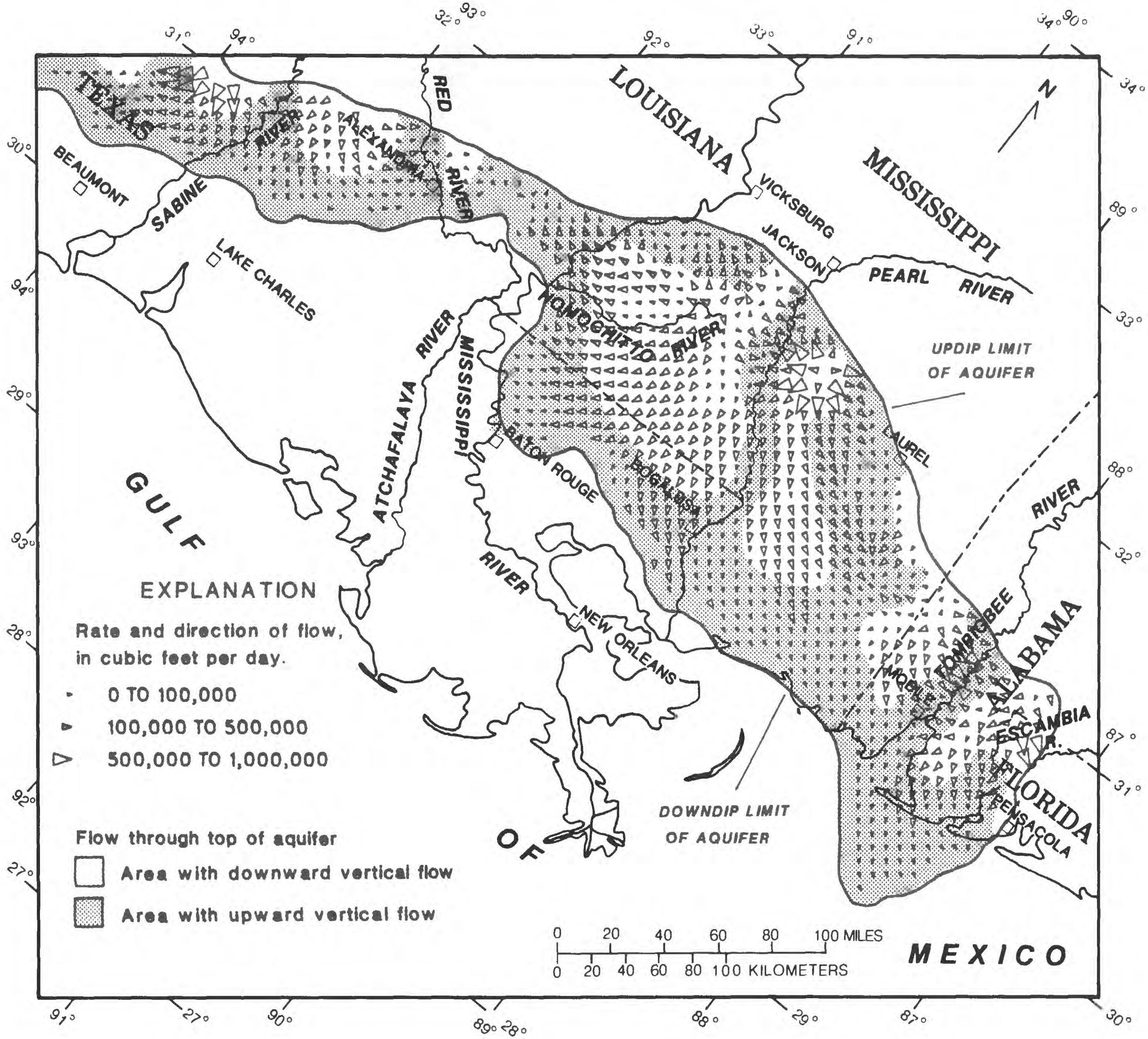

Figure 54.--Ground-water flow under predevelopment conditions in the middle Miocene aquifer (model layer 5).

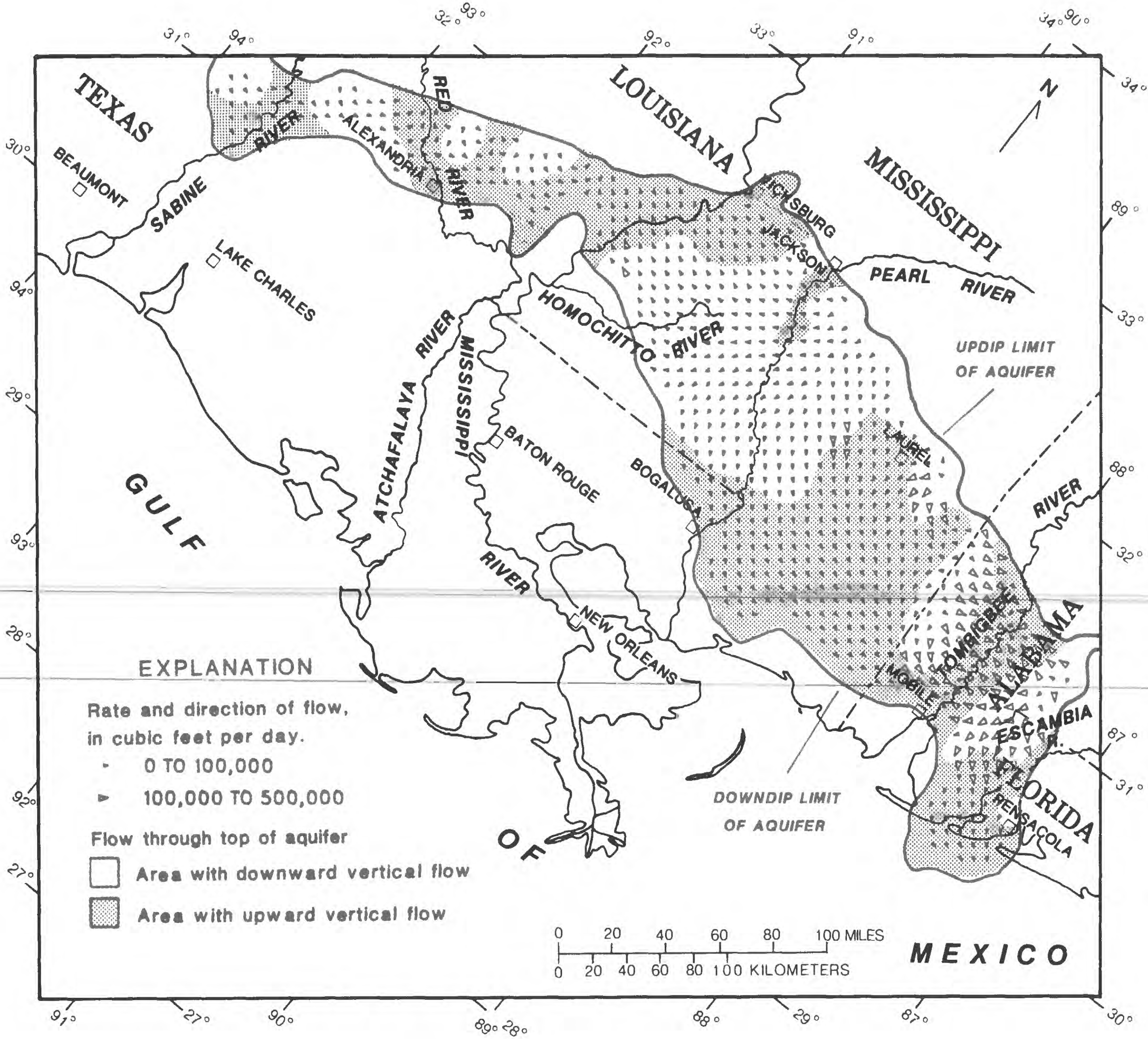

Figure 55.--Ground-water flow under predevelopment conditions in the lower Miocene aquifer (model layer 6).

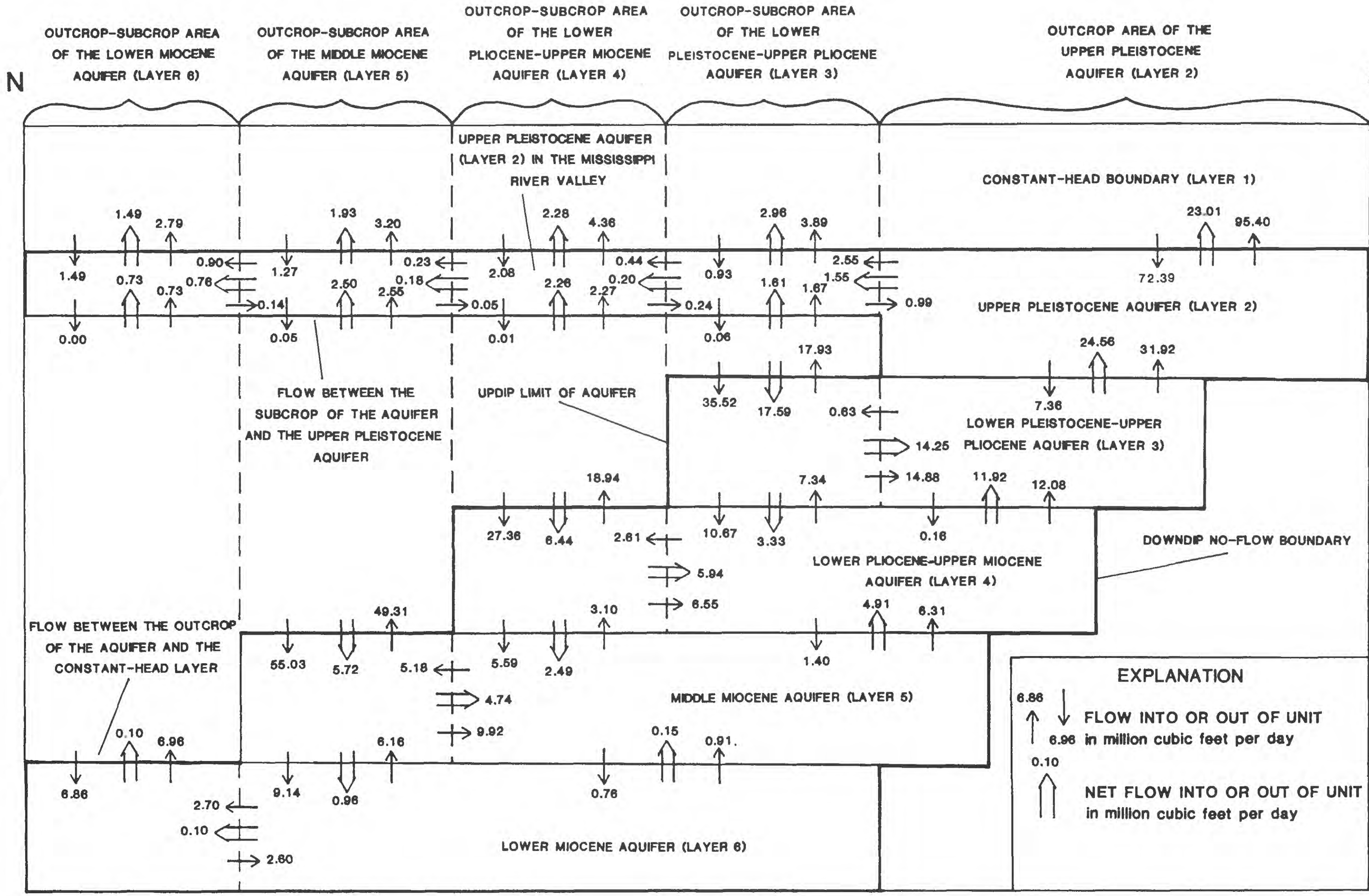

Figure 56.--Schematic north-south cross section of the Coastal Lowlands aquifer system showing the distribution of flow between and within layers under predevelopment conditions.

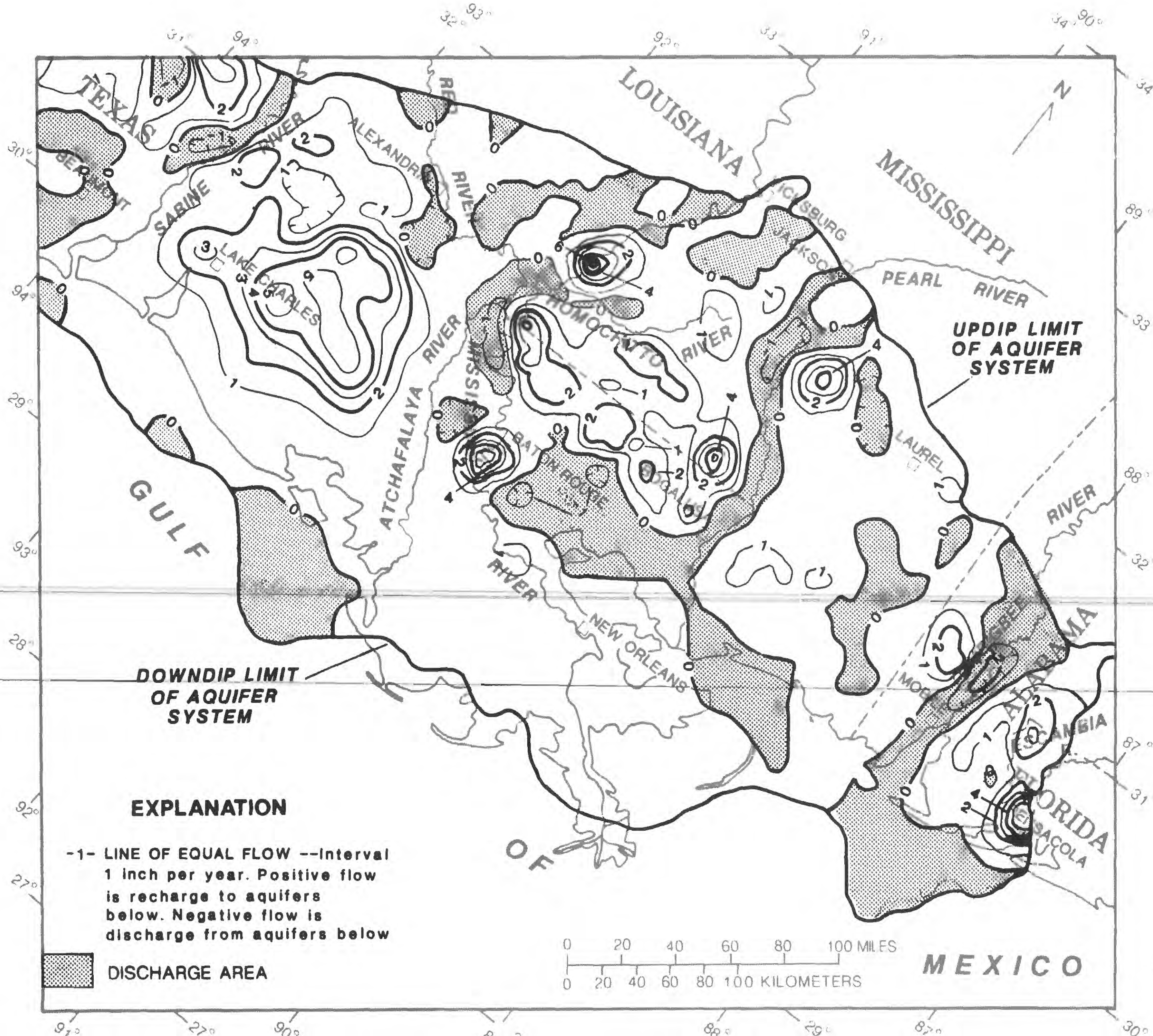

Figure 57.--Areal distribution of flow through the constant-head upper boundary (model layer 1) of the Coastal Lowlands aquifer system under 1980 conditions, treated as steady state.

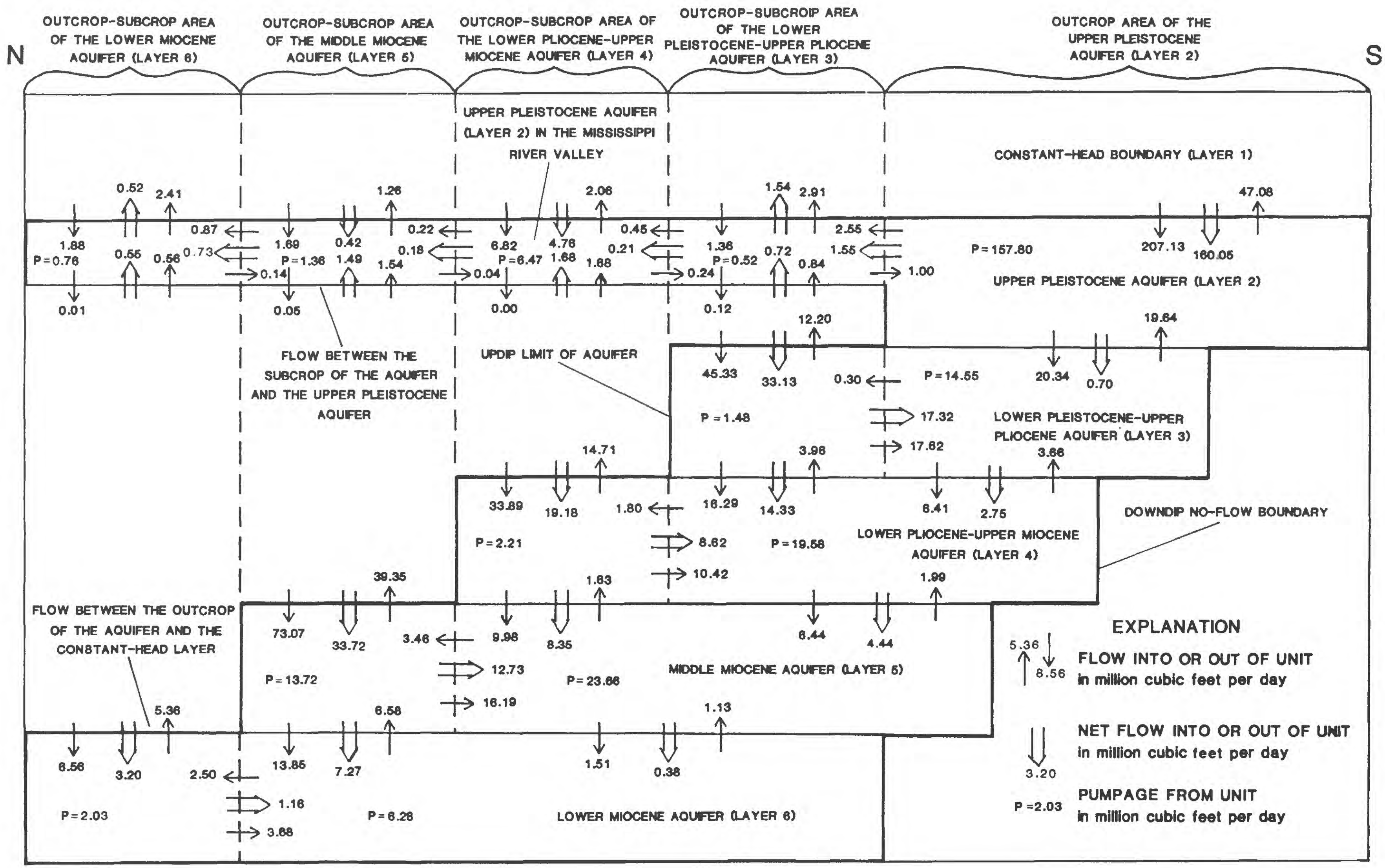

Figure 58.--Schematic north-south cross section of the Coastal Lowlands aquifer system showing the distribution of flow between and within layers under 1980 conditions, treated as steady state.

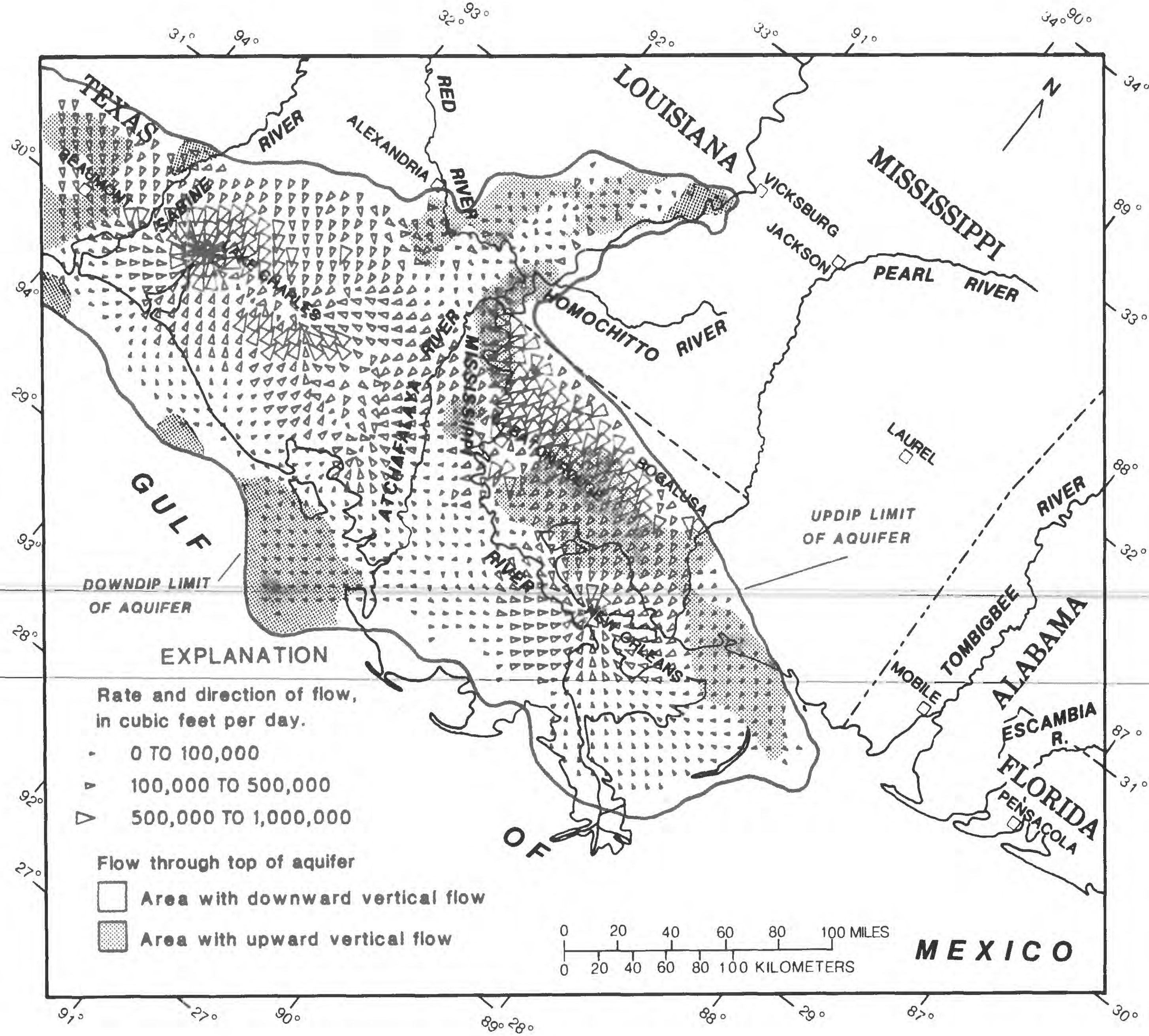

Figure 59.--Ground-water flow under 1980 conditions, treated as steady state, in the upper Pleistocene aquifer (model layer 2).

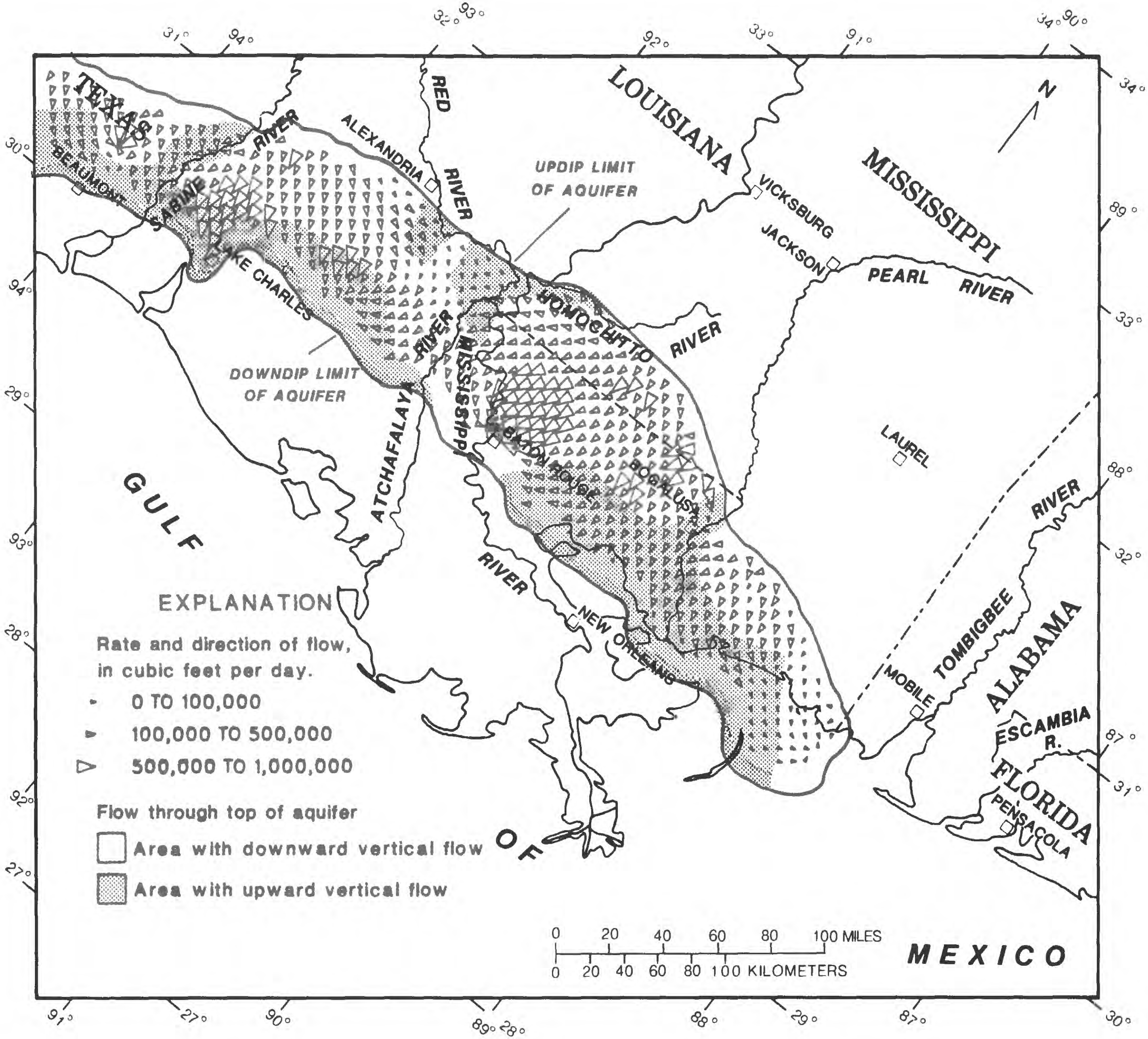

Figure 60.--Ground-water flow under 1980 conditions, treated as steady state, in the lower Pleistocene-upper Pliocene aquifer (model layer 3).

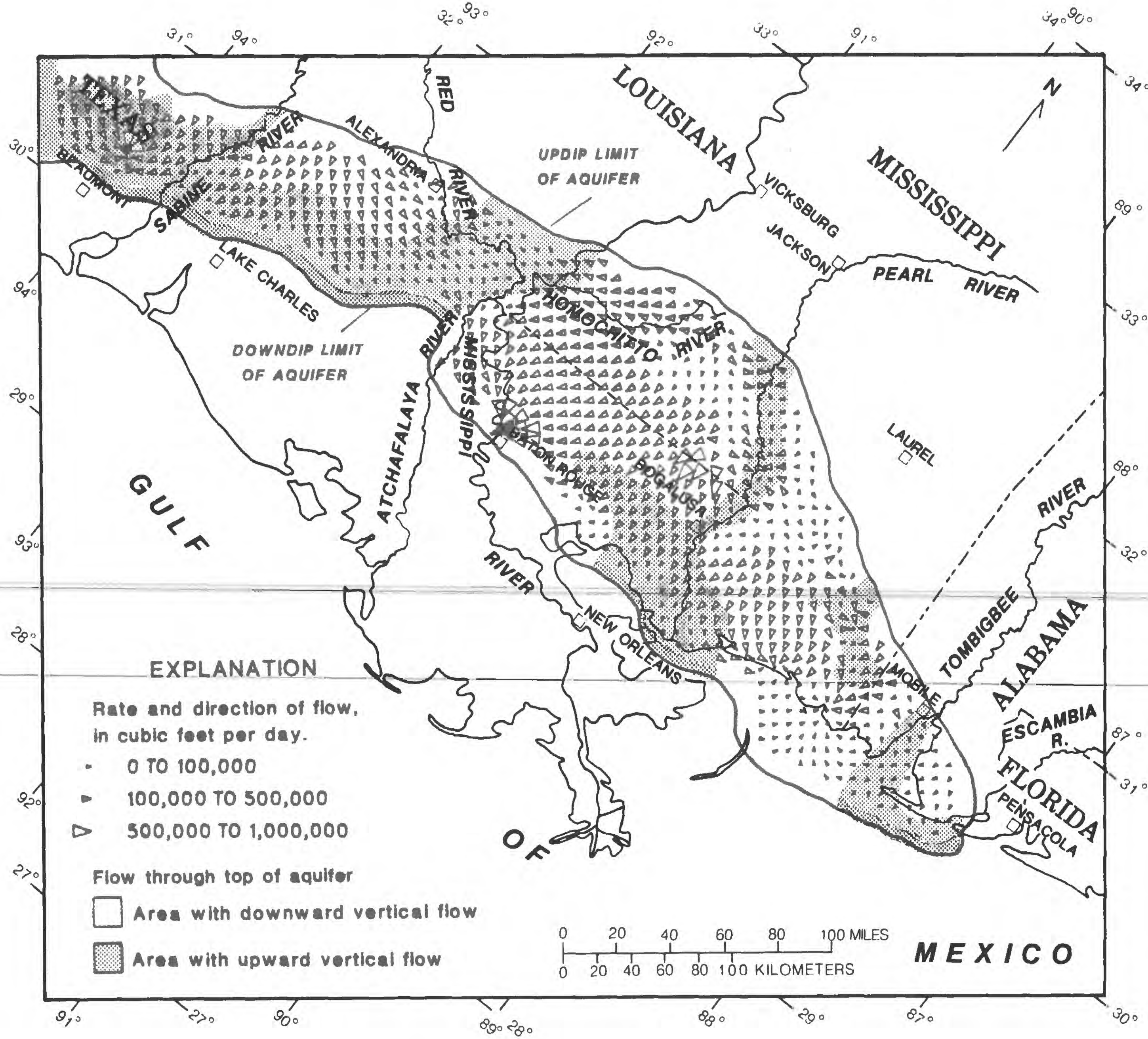

Figure 61.--Ground-water flow under 1980 conditions, treated as steady state, in the lower Pliocene-upper Miocene aquifer (model layer 4).

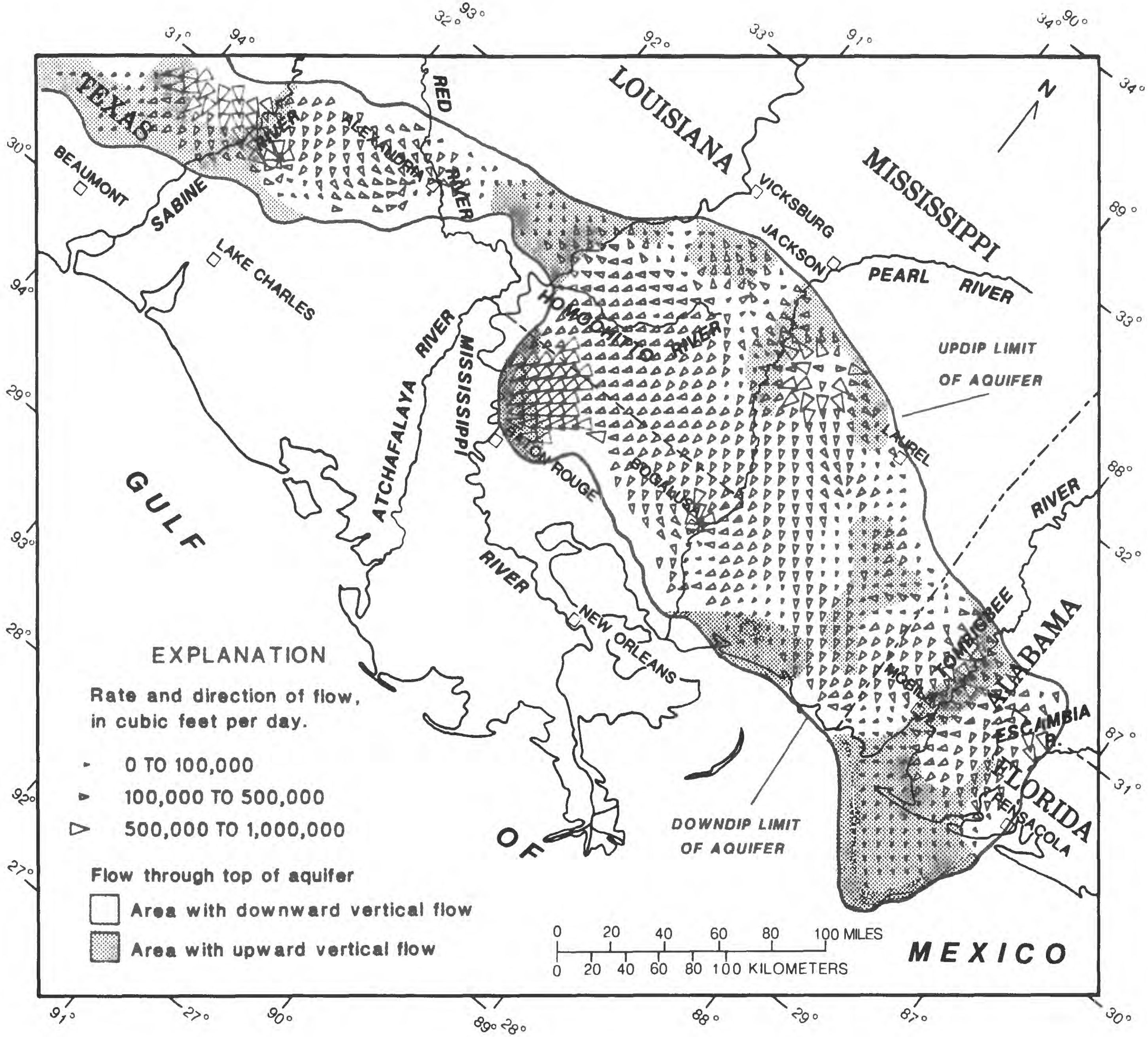

Figure 62.--Ground-water flow under 1980 conditions, treated as steady state, in the middle Miocene aquifer (model layer 5).

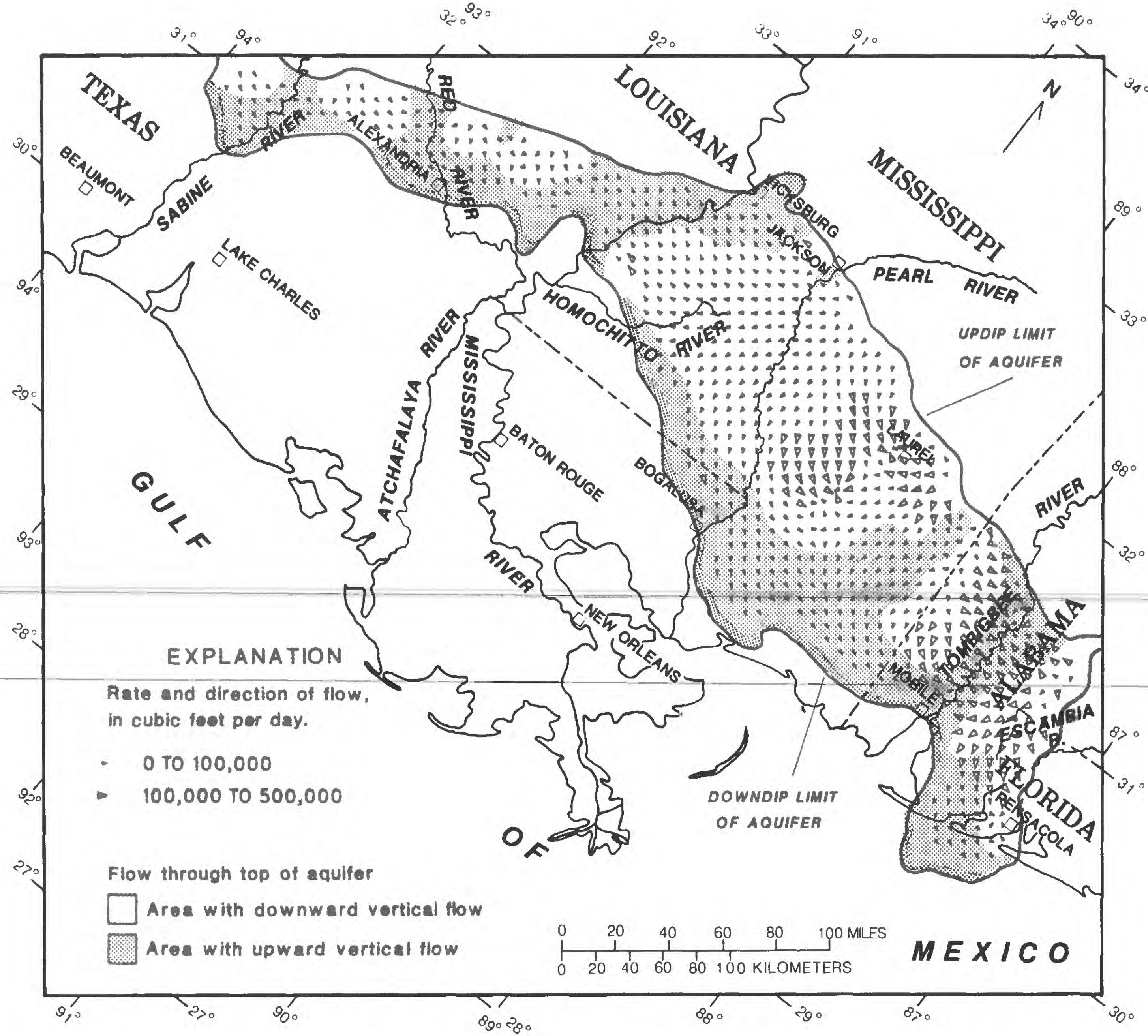

Figure 63.--Ground-water flow under 1980 conditions, treated as steady state, in the lower Miocene aquifer (model layer 6).