HYDROLOGY OF THE COASTAL LOWLANDS AQUIFER SYSTEM IN PARTS OF ALABAMA, FLORIDA, LOUISIANA, AND MISSISSIPPI

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

REGIONAL AQUIFER-SYSTEM ANALYSIS--GULF COASTAL PLAIN

U.S. GEOLOGICAL SURVEY
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FOREWORD

The Regional Aquifer-System Analysis (RASA) program was started in 1978 after a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent important components of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system, and accordingly transcend the political subdivisions to which investigations often have been arbitrarily limited in the past. The broad objectives for each study are to assemble geologic, hydrologic, and geochemical information; to analyze and develop an understanding of the system; and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and of any changes brought about by human activities, as well as to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA program is assigned a single Professional Paper number. Where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and will continue in numerical sequence as the interpretive products of studies become available.

Dallas L. Peck
Director

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million cubic feet per day (Mft^3/d)	0.3278	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

To convert million cubic feet per day to million gallons per day: multiply by 7.48.

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 beds of sand, gravel, silt, and clay of late Oligocene age and younger in off-lapping, coastward-thickening wedges of sediment deposited under fluvial, deltaic, and marine conditions. The sediments are highly heterogeneous. Individual sand beds generally are not traceable for more than a few miles.

This study is limited to that part of the aquifer system containing water with 10,000 milligrams per liter or less dissolved solids. Thickness of the studied part of the aquifer system ranges from a feather edge along the updip edges of the system to more than 4,000 feet in southeastern Louisiana. Sand content of the aquifer system ranges from less than 10 to greater than 80 percent, and total sand thickness exceeds 2,000 feet in southeastern Louisiana and southern Mississippi.

The coastal lowlands aquifer system was divided into five overlapping regional permeable zones, A through E, to quantify flow in the aquifer system. The permeable zones were defined on the basis of water-level data from heavily pumped areas. From youngest to oldest the zones are the: Holocene-upper Pleistocene deposits (zone A), lower Pleistocene-upper Pliocene deposits (zone B), lower Pliocene-upper Miocene deposits (zone C), middle Miocene deposits (zone D), and the lower Miocene-upper Oligocene deposits (zone E).

Prior to development, flow in the aquifer system was primarily from upland outcrop areas in southwestern Mississippi and central and southeastern Louisiana toward lowlands along the coast and in the major river valleys. Results of simulations of flow in the aquifer system using a six-layer finite-difference flow model indicate that pumpage has significantly altered the natural ground-water flow system. Pumpage from the aquifer system for all uses peaked in 1980 at about 251 million cubic feet per day (1,874 million gallons per day), then declined to about 211 million cubic feet per day (1,579 million gallons per day) by 1985. The total flow circulating within the aquifer system in 1987, about 354 million cubic feet per day, is about 62 percent greater than the predevelopment flow of 222 million cubic feet per day. A large part of the low-lying coastal area has been transformed from areas of natural discharge to areas of recharge. Throughout much of the coastal plain, flow directions have been altered and flow converges toward pumping centers.

Simulations of ground-water flow indicate that the aquifer system was near steady state in 1987, so pumpage could be continued indefinitely at the 1983-87 rate of about 1,600 million gallons per day. Results of modeling experiments conducted to evaluate the effects of future ground-water pumpage from the coastal lowlands aquifer system show that pumping at a rate 50 percent greater than the 1983-87 rate would be feasible. The upper permeable zones and the outcrop areas of the lower zones, in general, would be most favorable for intensive development based on projected drawdowns of water levels. Development of a major pumping center near the downdip limit of a permeable zone would entail risk of saltwater encroachment.

INTRODUCTION

The study described in this report was done as part of the Gulf Coast Regional Aquifer System Analysis begun in 1980 (Grubb, 1984). The study was designed to describe and quantify regional ground-water flow in the eastern part of the coastal lowlands aquifer system to understand the effects of the present level of development and the probable effects of future development.

The Gulf Coast Regional Aquifer-System Analysis is one of about 30 similar studies in the Regional Aquifer-System Analysis program conducted by the U.S. Geological Survey in support of Federal and state needs for information to improve ground-water management (Sun, 1986, p. 4). The total area of the Gulf Coast regional study is about 290,000 mi^2 and consists of all of Louisiana, and parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Mississippi, Missouri, Tennessee, and Texas.

Three regional aquifer systems are delineated in the regional study: the coastal lowlands aquifer system, the Mississippi embayment aquifer system, and the Texas coastal uplands aquifer system (Grubb, 1984). The three aquifer systems were delineated based on differences in geologic framework, distribution of fine-grained sediments, and regional ground-water flow patterns.

Five subregional studies were conducted to study in detail different parts of these aquifer systems. The regional and subregional model areas are shown on figure 1. This report describes the hydrology of the coastal lowlands aquifer system of Alabama, Florida, Louisiana, and Mississippi. The subregional studies include three aquifer systems: the coastal lowlands aquifer system of Alabama, Florida, Louisiana, and Mississippi; the Mississippi embayment aquifer system; and the Texas coastal uplands and lowlands aquifer systems; and two regional aquifers: the Mississippi River valley alluvial aquifer; and the McNairy-Nacatoch aquifer. Preliminary results of the regional study and the subregional studies have been published in numerous reports (Weeks and Sun, 1987, p. 49; Williamson and others, 1990). Final reports of both regional and subregional scope that describe the geohydrologic framework, ground-water flow, and geochemistry of the aquifers and aquifer systems are planned for release in U.S. Geological Survey Professional Paper 1416 as parallel chapters to this report.

Massive clays of minimal permeability comprising the Vicksburg-Jackson confining unit underlie the coastal lowlands aquifer system and separate it

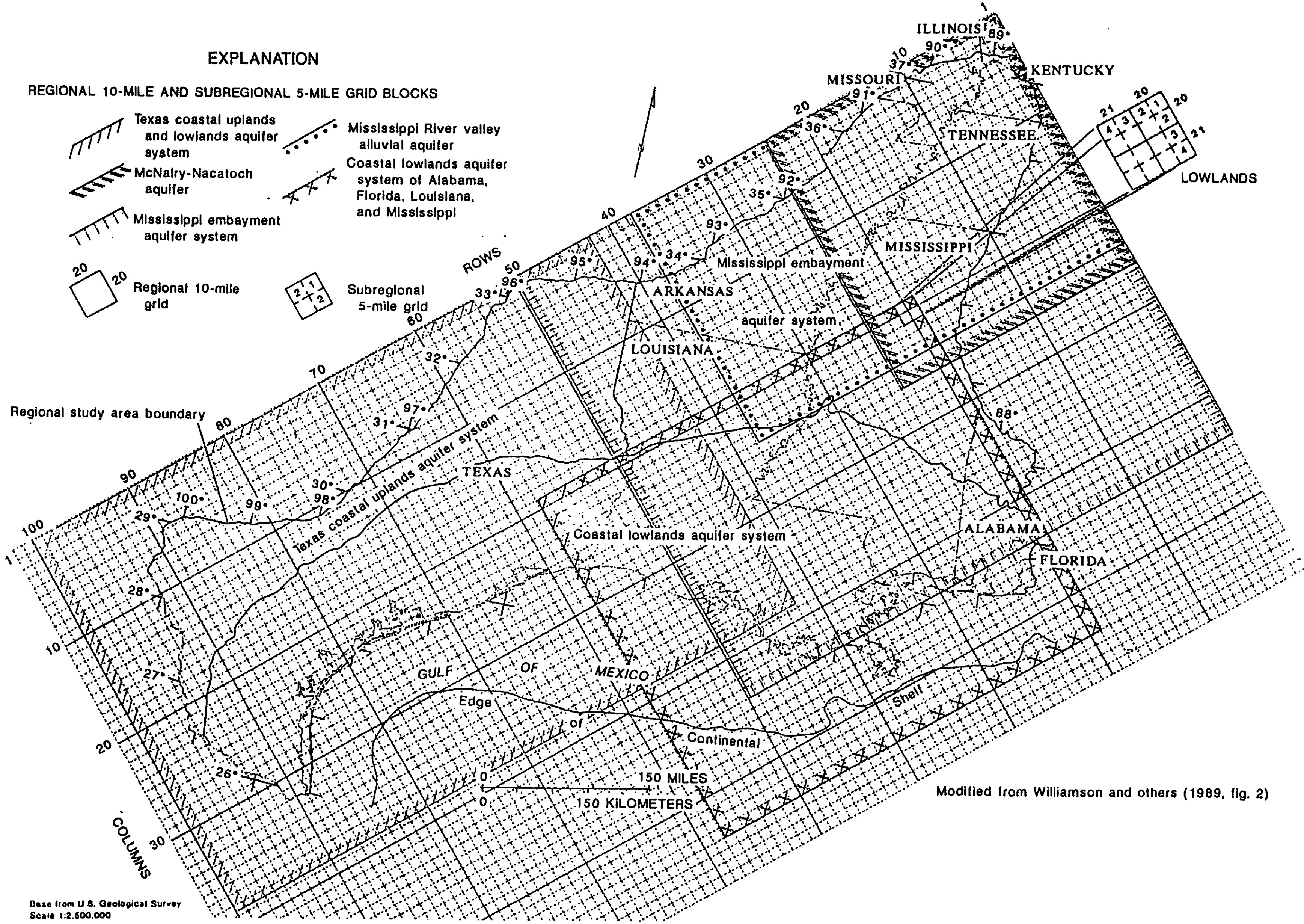


Figure 1.--Regional and subregional model areas.

from the underlying Texas coastal uplands aquifer system in Texas and the underlying Mississippi embayment aquifer system to the east. The upper 200 ft of the coastal lowlands aquifer system is equivalent to the Mississippi River valley alluvial aquifer in east-central Louisiana. The coastal lowlands aquifer system is equivalent to the Chickasawhay River aquifer of the southeastern coastal plain to the east in Alabama and Florida (Miller and Renken, 1988, p. 7).

The eastern part of the coastal lowlands aquifer system includes aquifers in deposits of late Oligocene age and younger in central and southern Louisiana, southern Mississippi, southern Alabama, and western Florida (fig. 2). This study is restricted to that part of the aquifer system containing water with dissolved-solids concentrations of 10,000 mg/L or less.

Purpose and Scope

This report presents the results and conclusions of a study of the eastern part of the coastal lowlands aquifer system. Existing data on water levels, water use, water quality, and aquifer properties were used to construct a multilayer digital model to simulate flow in the aquifer system. The report briefly describes the geohydrologic framework of the aquifer system and the development, calibration, and sensitivity analysis of a ground-water flow model, but it is primarily focused on the results of the simulations that show the natural flow of ground water throughout the regional aquifer system and the changes from the natural flow caused by development of ground-water supplies.

Previous Studies

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. 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. Previous model studies of parts of the study area were used as guides in the development of the digital ground-water flow model used in this study. (See Selected References.)

An interim report by Martin and Whiteman (1989) describes the geohydrologic framework of the aquifer system and the development of the digital ground-water flow model used to quantify flow in the aquifer system. Calibration and sensitivity analysis of the model under both steady-state and transient flow conditions are described by Martin and Whiteman (1990).

Other reports prepared as part of this study include a series of maps of the potentiometric surfaces of major aquifers in deposits of late Oligocene age and younger in Louisiana (Martin and Whiteman, 1985a; 1985b; 1986; Martin, Whiteman, and Becnel, 1988), a statistical summary of aquifer-test results for aquifers in Louisiana (Martin and Early, 1987), and a report showing two geohydrologic sections in northern Louisiana (Whiteman and Martin, 1984).

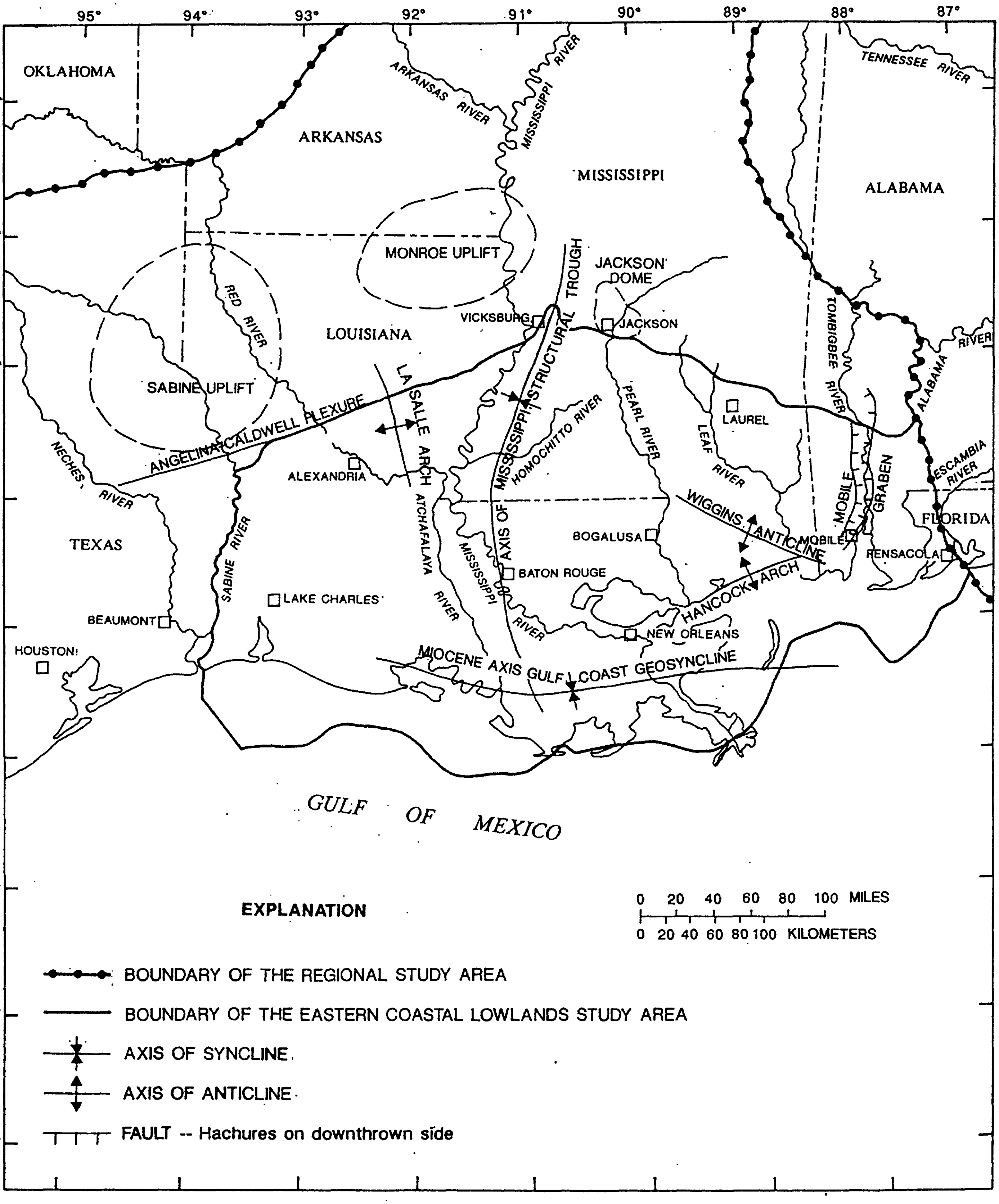


Figure 2.--Location of the study area and major structural features in and near the study area.

Physical Setting

The study area is in the eastern part of the Gulf of Mexico Coastal Plain in the southeastern United States and covers 72,700 mi^2 of which about 58,500 mi^2 is land area and inland water bodies and the rest is offshore in the Gulf of Mexico. It extends from the Sabine River, the boundary between Louisiana and Texas, on the west to the Escambia River in the Florida panhandle on the east (fig. 2). The study area extends from about 50 mi offshore to 100 mi inland at its western end, from near the coastline to 220 mi inland in the central part, and from about 25 mi offshore to 75 mi inland near its eastern end.

Physiography

Land-surface altitude in the study area ranges from more than 500 ft above sea level in southwestern Mississippi to sea level along the coast. Much of the marsh area along the Louisiana coast is at or only slightly above sea level. Several large agricultural areas in the coastal marshes and parts of the city of New Orleans lie several feet below sea level. The land surface in the study area originally consisted of a sequence of terraces sloping gently toward the coast. The older, higher terraces have been heavily dissected in the northern and eastern parts of the study area, resulting in a terrain of gently rolling to steep hills and valleys with local relief of 100 to 200 ft common. Large areas of the younger, lower terraces remain nearly undissected in the central part of the study area.

The Mississippi River and its alluvial valley are dominant features. The river and its broad, low-lying, poorly drained valley have, from the time of the earliest travelers, hindered east-west movement of people and goods while providing relatively easy and economical north-south travel by boat and barge. From the northern edge of the study area to a few miles south of Baton Rouge, La., the altitude of the alluvial valley floor is lower than the surrounding area, so the valley forms a drain for both the surface-water and the ground-water flow systems. The Mississippi River is presently flowing along the eastern side of the valley, which ranges from about 25 to 50 mi wide. This area was designated the Mississippi Alluvial Plain by Fenneman (1938).

In coastal southeastern Louisiana natural levees along the present and ancestral courses of the Mississippi River and its distributaries form the highest land. No tributaries enter the Mississippi River below Baton Rouge. The natural levees slope gently downward from crests near the stream banks to merge into surrounding backswamps and marshes. The bands of high ground formed by the natural levees range from less than 1 mi wide along smaller distributaries and near the coast to more than 20 mi wide where the modern channel of the Mississippi River emerges from the youngest of the terrace surfaces south of Baton Rouge. Almost all residential, commercial, and industrial development along the Mississippi River and its distributaries south of Baton Rouge has been along the crests of the natural levees.

Several major rivers in addition to the Mississippi River drain parts of the study area. The Sabine River forms the western boundary of the area.

The Red and Homochitto Rivers drain into the Mississippi River in the north-central part. The Pearl, Leaf, and Tombigbee Rivers drain the eastern part of the area. The Alabama and Escambia Rivers form the eastern boundary. Numerous smaller rivers, streams, and bayous drain intervening parts of the area.

Climate

The study area is characterized by long, hot, humid summers and relatively short, mild winters. Throughout the area, monthly mean temperatures are lowest in January and highest in July (fig. 3). Mean temperatures generally increase from north to south, but temperature extremes are moderated in the coastal part of the area by the effects of the Gulf of Mexico and the water surfaces exposed in lakes, streams, and marshes.

Precipitation, almost all in the form of rain, increases from northwest to southeast across the area, with the greatest amount, over 64 in., occurring a short distance inland from the coasts of Mississippi, Alabama, and Florida and inland northeast of Baton Rouge, La. (fig. 4). Although there are no pronounced wet or dry seasons, October is generally the driest month. Potential evapotranspiration, estimated by the Thornthwaite technique (Thornthwaite, 1948; Thornthwaite and Mather, 1955), generally exceeds precipitation from June through August (fig. 3). Precipitation exceeds potential evapotranspiration from November through April. Precipitation and potential evapotranspiration are generally about equal during May, September, and October.

HYDROGEOLOGIC SETTING

The coastal lowlands aquifer system consists of alternating beds of sand, gravel, silt, and clay in off-lapping, coastward-thickening wedges of sediment deposited under fluvial, deltaic, and marine conditions. The aquifer system comprises sediments of late Oligocene age and younger in the study area (Grubb, 1984) and has been described in detail by Weiss (1990).

Sediments of the coastal lowlands aquifer system are extremely heterogeneous. Changes in lithology occur over short distances laterally and vertically. Sand or gravel beds are not traceable for more than a few miles. Coarse sand and gravel are common in the northern part of the study area but become finer and less common southward, grading to sandy silt or clay and finally to clay. Lime and marl occur in the lower and eastern parts of the aquifer system. Dip of individual beds is southward, ranging from about 10 to 50 ft/mi in the outcrop and subcrop areas. Dip increases in a southerly direction and with increasing depth. Maximum dip is well over 100 ft/mi in the southern parts of the study area (Martin and Whiteman, 1989, p. 3). Total thickness of the coastal lowlands aquifer system ranges from a feather edge along the northern edge of the outcrop of the aquifers to more than 16,000 ft in southeastern Louisiana near New Orleans (Grubb, 1987, fig. 7).

The coastal lowlands aquifer system is underlain by the Jackson and Vicksburg Groups, designated the Vicksburg-Jackson confining unit (Grubb,

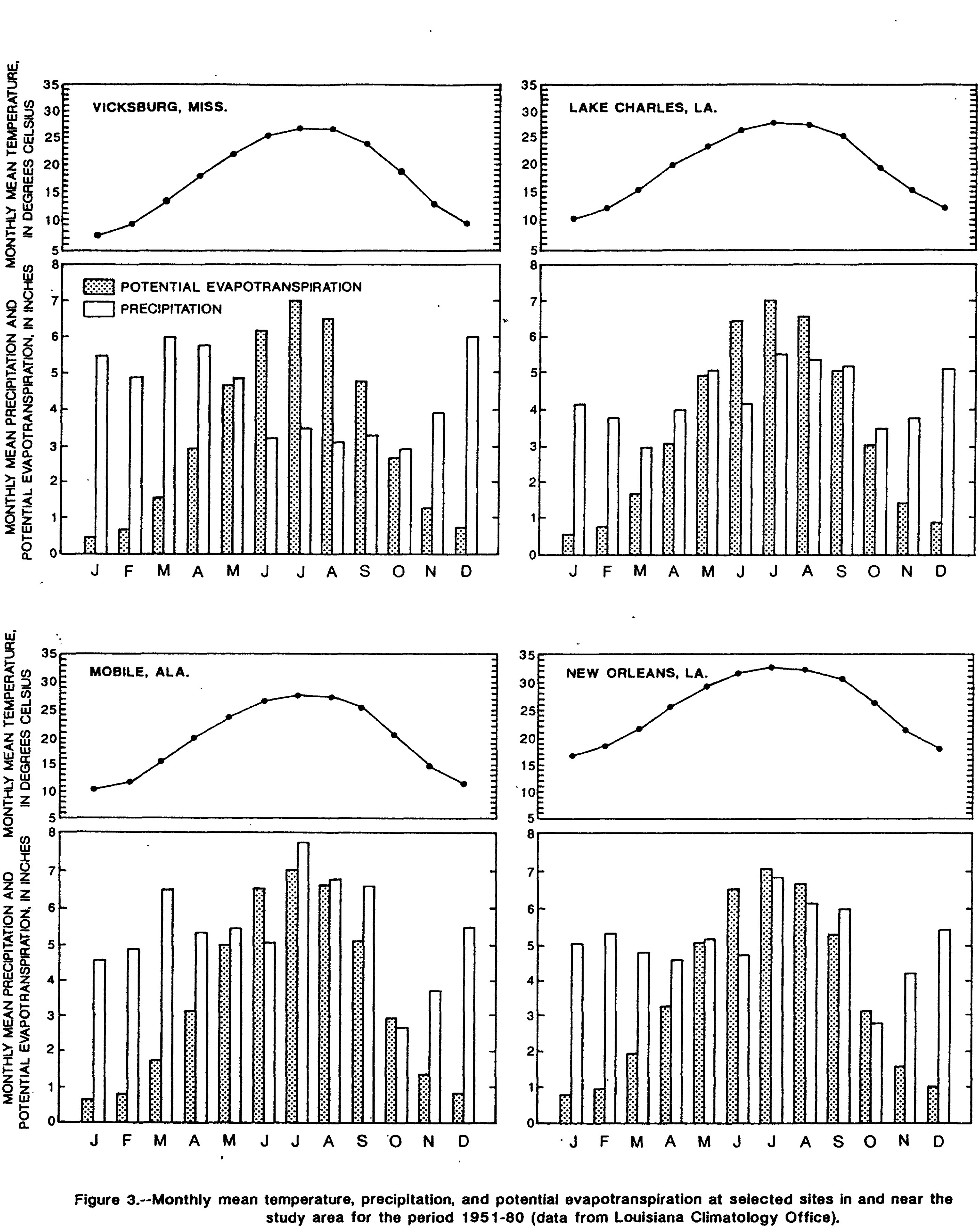


Figure 3.--Monthly mean temperature, precipitation, and potential evapotranspiration at selected sites in and near the study area for the period 1951-80 (data from Louisiana Climatology Office).

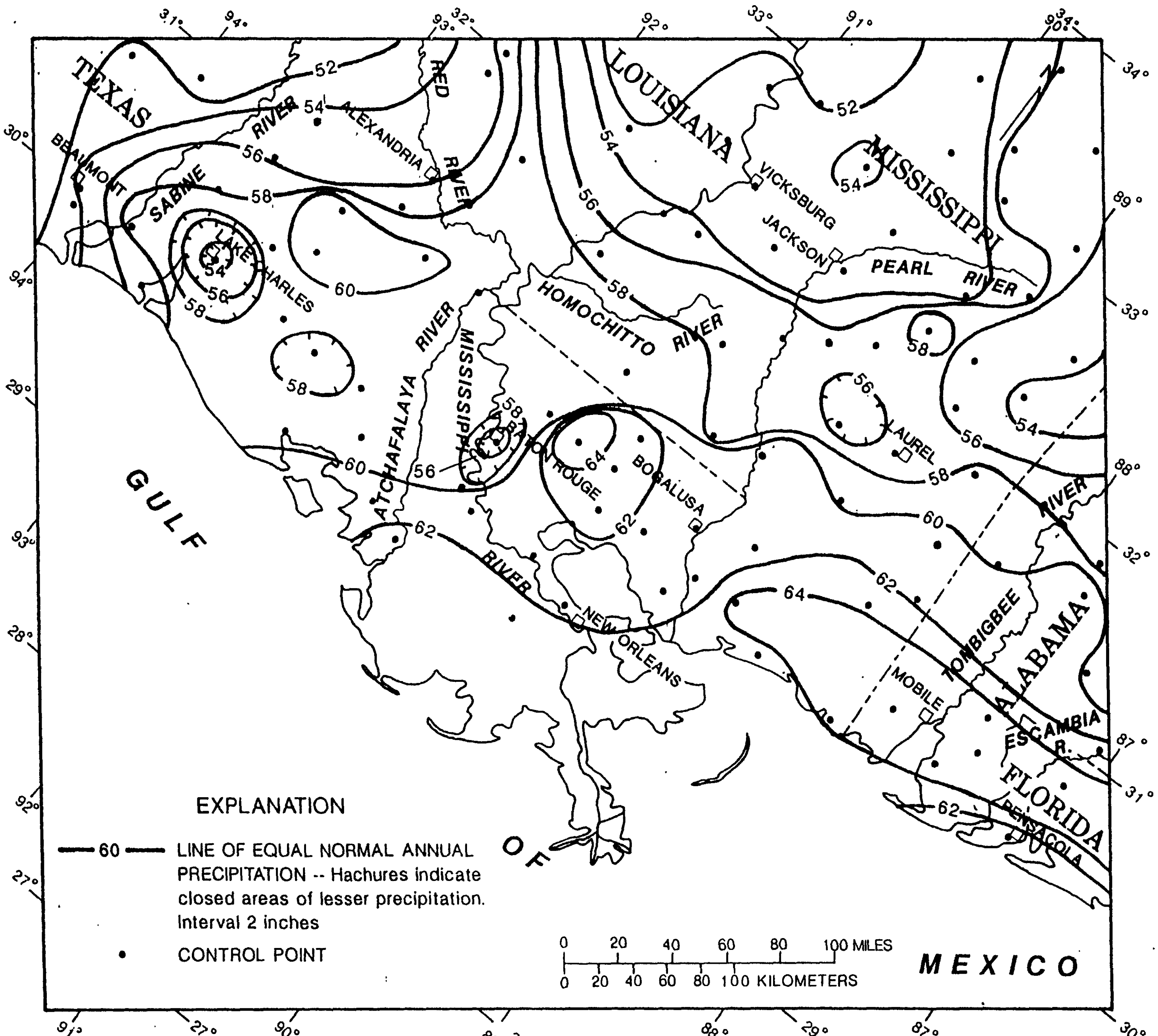


Figure 4.--Annual mean precipitation in and near the study area for the period 1951-80 (data from Louisiana Climatology Office).

1986, p. 6). The Jackson and Vicksburg Groups consist of extensive beds of clay, silt, and lime deposited during the last major transgression of the sea across the area in late Eocene and Oligocene time. Sands in the upper part of the Jackson and Vicksburg Groups, where thick and extensive enough to form aquifers, have been included in the coastal lowlands aquifer system.

Two major structural features, the north-south trending Mississippi structural trough and the east-west trending Gulf Coast geosyncline, intersect near the southern boundary of the study area (fig. 2). These two structural troughs, by controlling the location and thickness of sediment deposition, have been the dominant factors shaping the aquifer system in the study area.

Large systems of growth faults and numerous salt domes occur in the southern part of the study area. The faults displace sediments downward to the south and may act as barriers to ground-water movement in the aquifer system (Rollo, 1969). Salt domes displace sediments of the aquifer system and distort the sediments immediately around them. For this study, the collective effect of the growth fault systems has been considered as a reduction in the transmissivity of the aquifers within the system. The effects of the salt domes are thought to be too localized to have a significant effect on regional ground-water flow and were not considered in this investigation.

The geometry of the aquifer system was defined using a network of 279 electrical logs spaced 10 to 20 mi apart. Sand and gravel beds were identified on the logs and the depth, thickness, spontaneous potential, and resistivity of each bed over 20 ft thick were recorded and analyzed. Similarly, silt and clay beds were identified and their thickness and resistivity were recorded and analyzed. These data were summarized by Wilson and Hosman (1988).

A zone of abnormally high fluid pressure, the geopressured zone, occurs in the southern part of the study area within the sediments comprising the coastal lowlands aquifer system. Movement of fluids between the geopressured zone and the normally pressured overlying sediments is probably small compared to movement of fluid within the normally pressured zone (Grubb, 1986, p. 4). Where the geopressured zone occurs within the sediments of the coastal lowlands aquifer system, the top of the geopressured zone is considered to be the base of the aquifer system. (See plate 2.)

This study is restricted to the freshwater-bearing part of the coastal lowlands aquifer system; defined as that part of the system containing water with dissolved solids concentration of 10,000 mg/L or less. Water with dissolved solids concentration greater than 10,000 mg/L is not considered part of the flow system. Thus, the thickness of the part of the coastal lowlands aquifer system considered in this study is much less than that of the total aquifer system. The thickness of the freshwater-bearing part ranges from 0 ft along the northern edge of the aquifer system to more than 4,000 ft in southeastern Louisiana and southern Mississippi (fig. 5). Total sand and gravel thickness within this part of the aquifer system ranges from 0 ft along the northern edge of the aquifer system to more than 2,000 ft in southeastern Louisiana and southern Mississippi (fig. 6). The percentage of sand

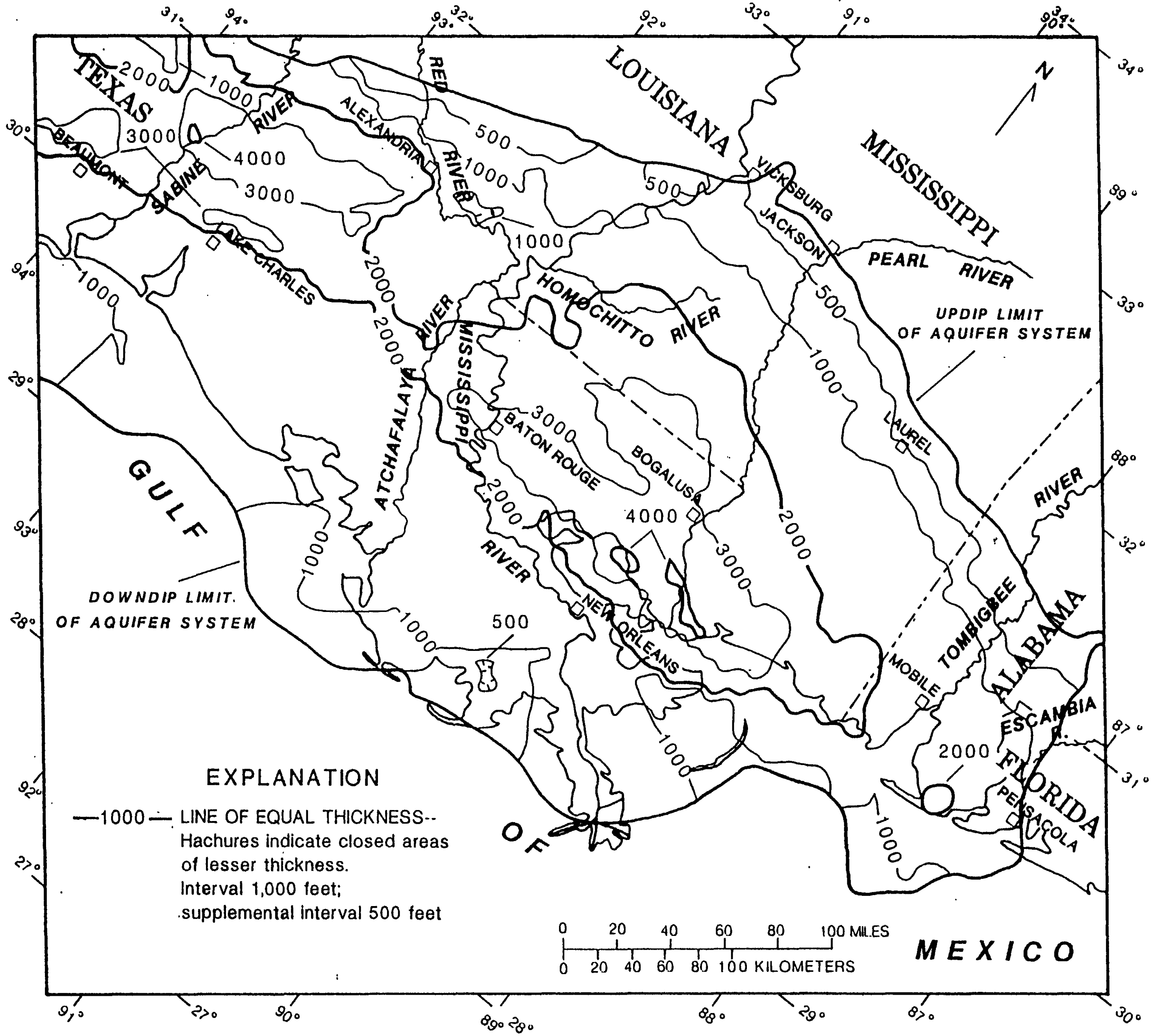


Figure 5.--Thickness of the freshwater-bearing part of the coastal lowlands aquifer system.

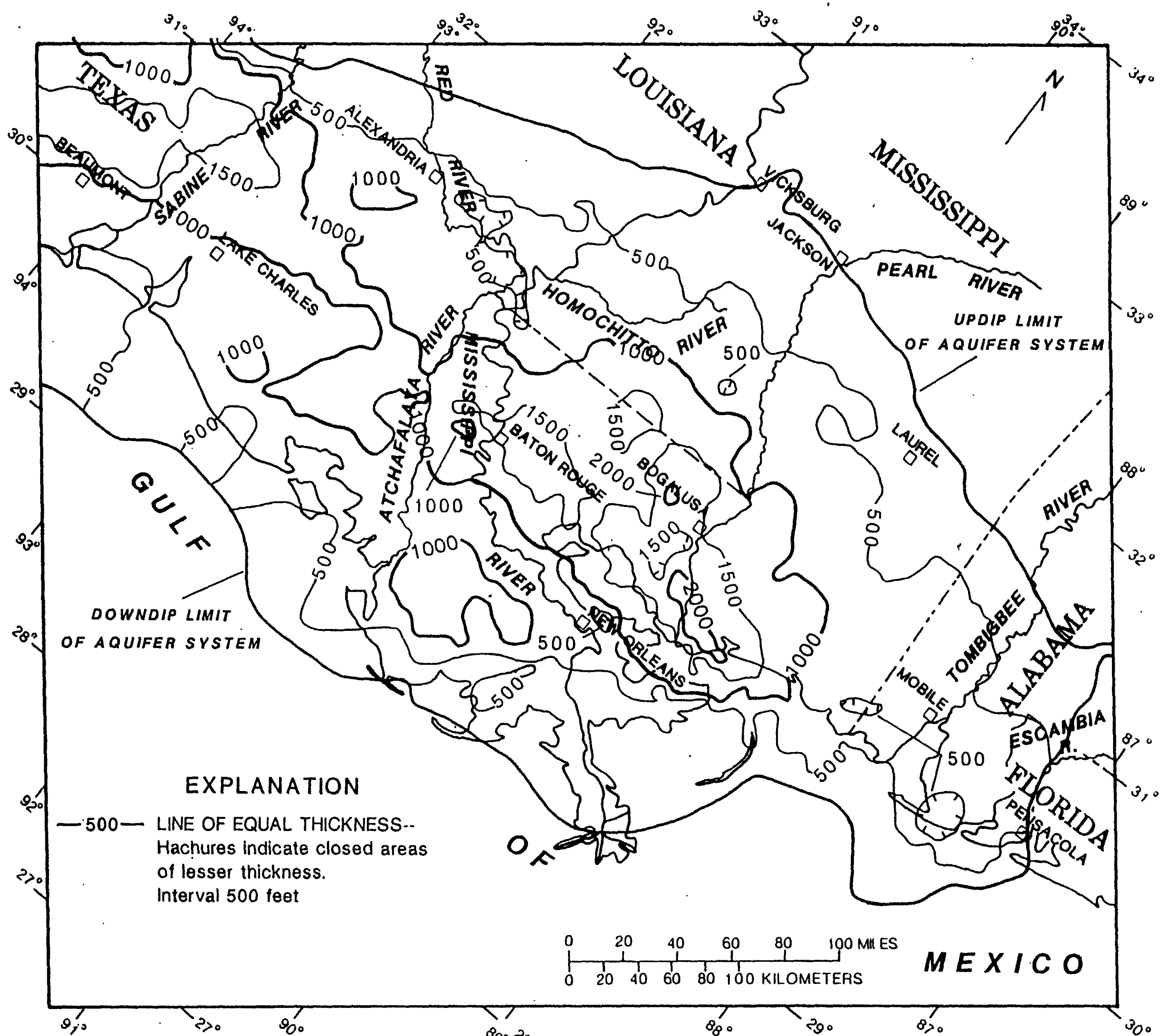


Figure 6.--Total thickness of sand and gravel in the freshwater-bearing part of the coastal lowlands aquifer system.

and gravel, and, thus, the transmissivity of a given thickness of the aquifer system, varies from less than 10 to over 80 percent (fig. 7).

Ground-water flow in the coastal lowlands aquifer system prior to development was primarily in a southerly direction from the upland terrace areas of south-central and southeastern Louisiana and southwestern Mississippi (fig. 8). Some water was discharged locally in these areas to streams or by evapotranspiration. Water not locally discharged moved downward and merged with the regional flow system to be discharged at lower altitudes along the major river valleys and near the coast. Under natural conditions water levels decreased with depth in the recharge areas and increased with depth in the discharge areas.

Saltwater occurs in the downdip marine and deltaic parts of the aquifer system. Freshwater moving downdip from the recharge areas tends to flush the saltwater ahead of it until pressures are in balance or unless movement is blocked by pinchout of the sand beds or by faulting. The sand beds offshore dip at steeper angles than the slope of the sea floor and are covered by a blanket of hundreds of feet of unconsolidated clay so there is no direct hydraulic connection between sands of the aquifer system and the Gulf of Mexico. Saltwater in the downdip part of the aquifer system may leave the system by moving vertically upward 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 (Martin and Whiteman, 1989, p. 4).

REGIONAL PERMEABLE ZONES

The coastal lowlands aquifer system was subdivided into five regional permeable zones to quantify the distribution of flow within the system (Grubb, 1987, p. 110-113). The permeable zones were defined in areas of intense pumpage such as Baton Rouge, La., and Houston, Tex., by delineating zones of similar water levels (Weiss and Williamson, 1985). Measured water levels in the zones near Baton Rouge in 1980 are shown in figure 9. After the zones were defined in the areas of heavy pumpage, they were extended along the strike of the beds by maintaining the thickness of each zone as a constant percentage of the aquifer system thickness. The zones pinch out in the updip direction, approximating the outcrop pattern in which progressively older bands of sediment are exposed in the updip direction (fig. 8). The zones were terminated downdip along the line where water in all sand beds over 20 ft thick within the zone had dissolved solids concentrations of more than 10,000 mg/L. The dissolved solids concentration was estimated from spontaneous potential and resistivity data from electric logs (Weiss, 1987).

The permeable zones represent deposits that from youngest to oldest are: Holocene-upper Pleistocene deposits (zone A), lower Pleistocene-upper Pliocene deposits (zone B), lower Pliocene-upper Miocene deposits (zone C), middle Miocene deposits (zone D), and the lower Miocene-upper Oligocene

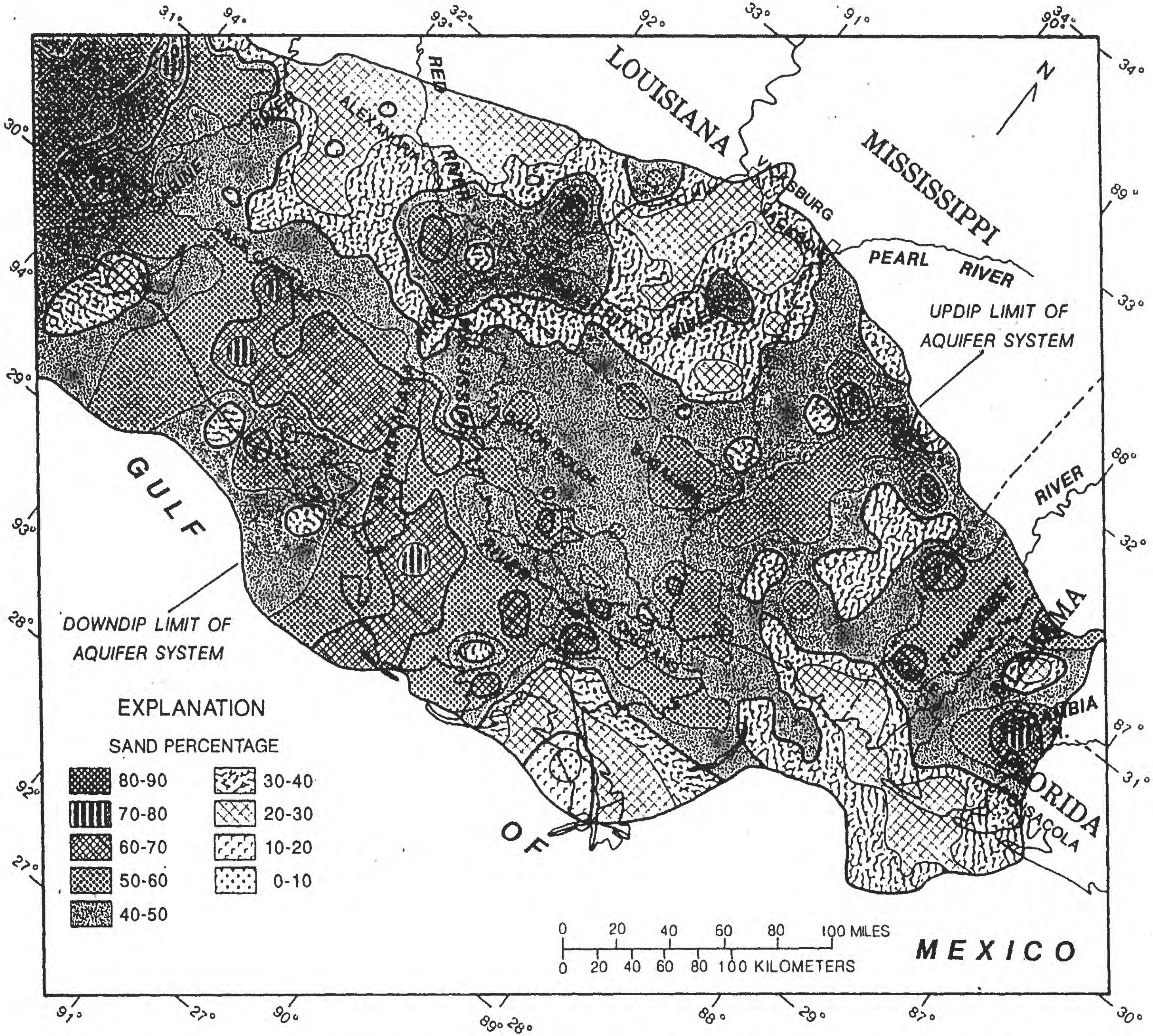


Figure 7.--Percentage of sand and gravel in the freshwater-bearing part of the coastal lowlands aquifer system.

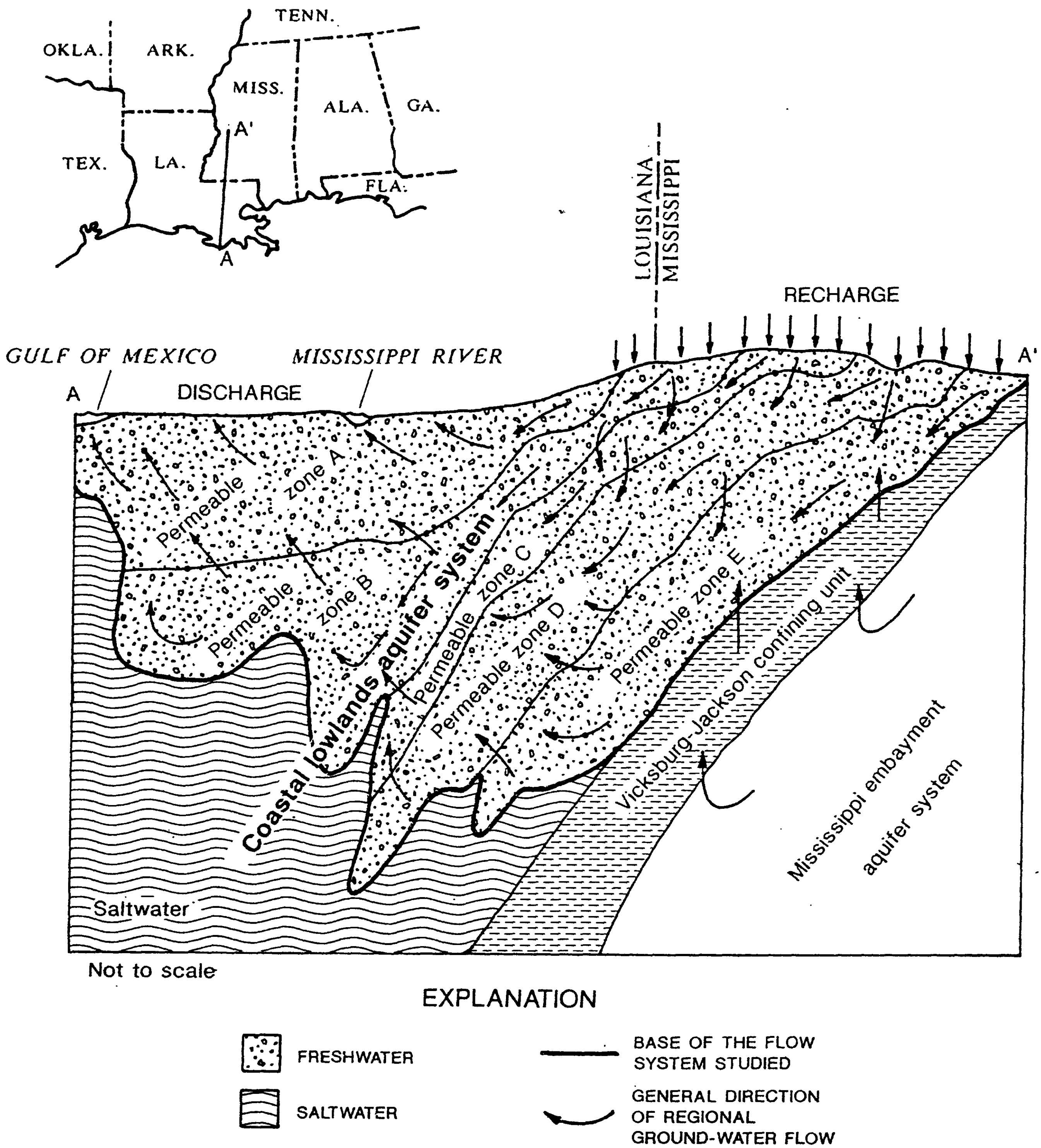


Figure 8.--Generalized hydrogeologic section showing zonation of the coastal lowlands aquifer system and direction of regional ground-water flow.

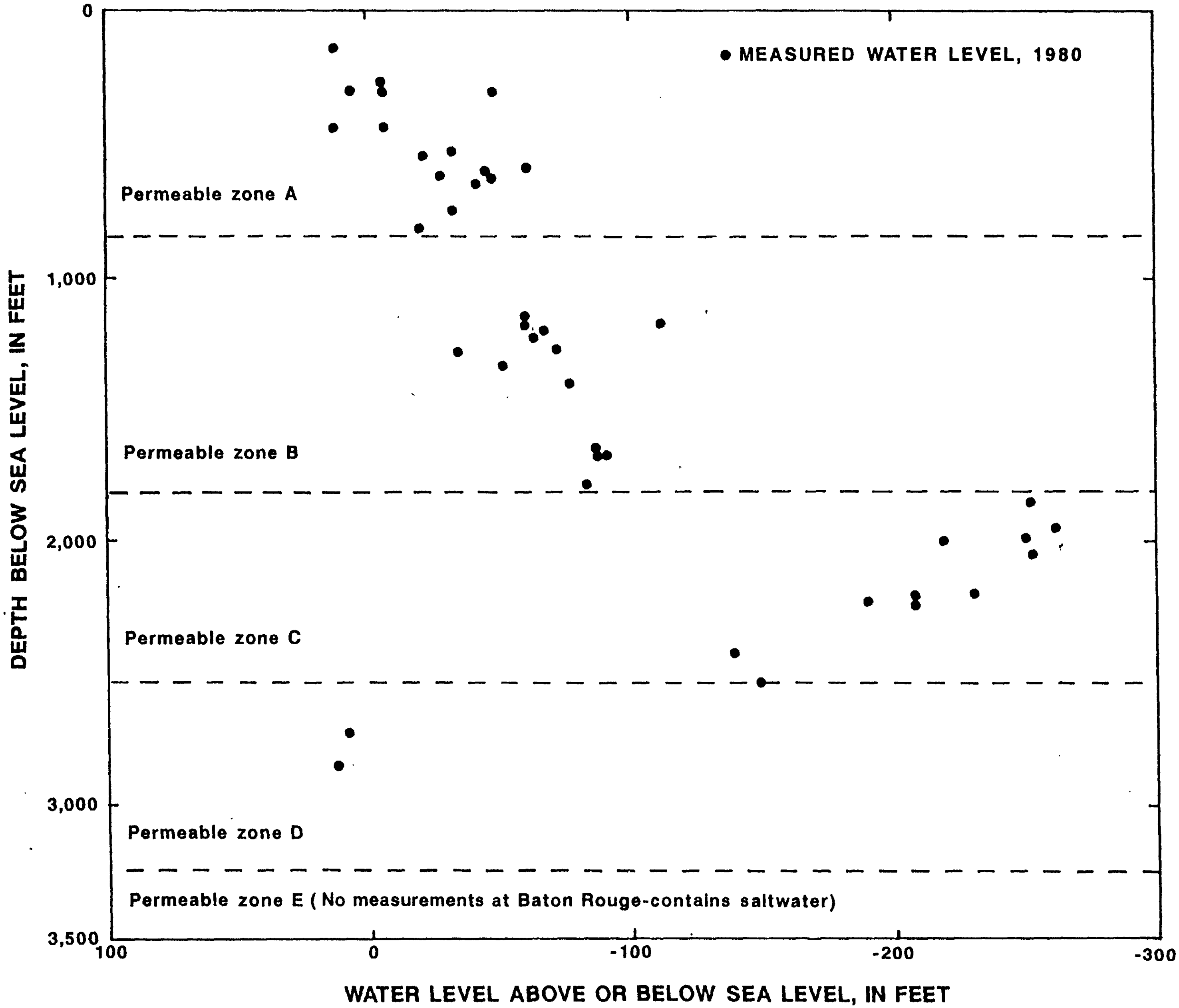


Figure 9.--Variation of water levels with depth and the zonation of the coastal lowlands aquifer system at Baton Rouge, Louisiana.

deposits (zone E). Table 1 shows the relation between the permeable zones and local aquifer names. The ages designated for the regional permeable zones are relative. The zones may contain beds that are younger or older than the indicated age. Plates 1 and 2 show the regional zones on east-west and north-south hydrogeologic sections, respectively. The areal extent of permeable zone A, the uppermost zone, and the outcrop areas of underlying zones B through E are shown in figure 10.

Hydraulic Properties of the Regional Permeable Zones

Lateral hydraulic conductivities of sand beds within the regional permeable zones were determined by examining 3,077 aquifer tests from the coastal lowlands aquifer system within the study area (A.K. Williamson, U.S. Geological Survey, written commun., 1988). The aquifer tests are clustered in areas of heavy ground-water pumpage rather than uniformly distributed. Martin and Early (1987) describe the compilation, summarization, and statistical analysis of 1,001 aquifer-test results in Louisiana which include tests of aquifers in the coastal lowlands aquifer system.

The "effective" lateral hydraulic conductivity of the permeable zones is lower than the arithmetic mean of values from aquifer tests. Clay beds separating the discontinuous sand beds within each zone disrupt the continuity of lateral flow within the zone. In addition, wells generally are completed in the most permeable, highest-yielding sand beds available at a given site, so aquifer test results typically will be biased toward the sand beds with the highest hydraulic conductivities.

The results of statistical analysis of lateral hydraulic conductivity values from all of the aquifer tests are shown in table 2. Arithmetic, geometric, and harmonic means were calculated for each permeable zone. The arithmetic mean is most affected by extreme high values, whereas the harmonic mean is most affected by extreme low values. The average of the arithmetic and harmonic means of lateral hydraulic conductivity for each zone was used as a representative value for that zone in estimating transmissivities during initial model simulations. The average of the arithmetic and harmonic means is slightly higher than the geometric mean for each zone.

Lateral hydraulic conductivity decreases from the upper to the lower permeable zones. On average, zone A, of Holocene-upper Pleistocene age, has the highest hydraulic conductivity, whereas zone E, of lower Miocene-upper Oligocene age, has the lowest. The large standard deviation about the arithmetic mean indicates the large variability of lateral hydraulic conductivity within the permeable zones.

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. To provide the restriction to vertical flow needed to produce these water-level differences, all of the clay beds (including silt and sandy clay) between the centers of adjacent permeable zones were treated as being equivalent to a single clay layer (Bredehoeft and Pinder, 1970).

Table 1.--Relation of the regional permeable zones to model layers and to previously named principal aquifers

Gulf coast RASA regional permeable zone[1]	Model layer number	Aquifers in Louisiana	Aquifers in Mississippi	Aquifers in Alabama	Aquifers in Florida
Zone A (Holocene-upper Pleistocene deposits)	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)	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)	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)	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)	6	Catahoula	Miocene (lower)	Miocene (lower)	Sand and gravel (lower)

[1] Grubb, 1987, p. 110-113; RASA, Regional Aquifer System Analysis. Because of regional structure and the way the regional permeable zones were defined, the zones cross chronostratigraphic lines in places; the greatest discrepancies occur in western Florida and southwestern Alabama, where zones D and E consist of sediments of Holocene to Middle Miocene age.

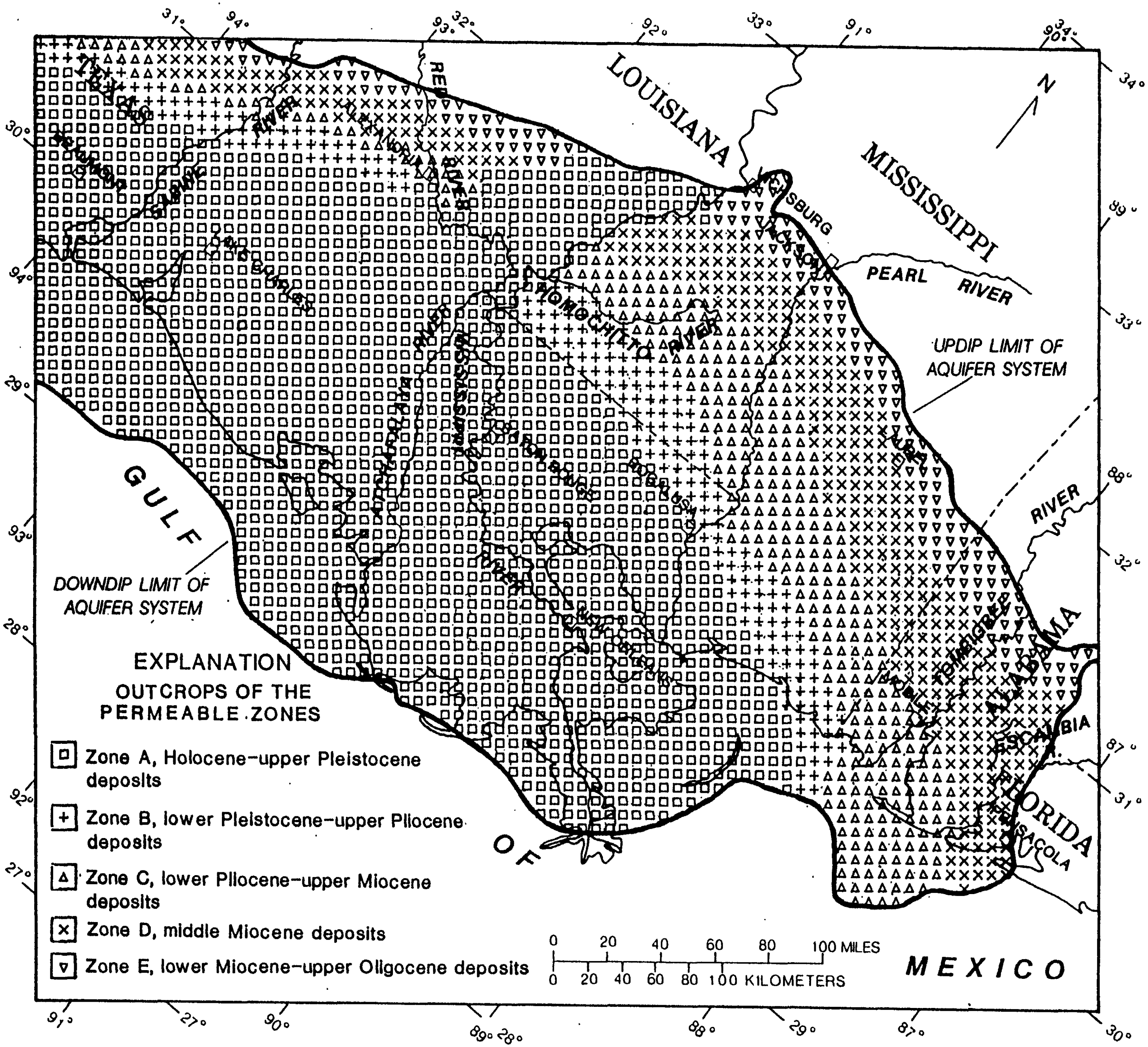


Figure 10.--The areal extent of the coastal lowlands aquifer system and the outcrop areas of the permeable zones.

Table 2.--Lateral hydraulic conductivities of sand beds within the permeable zones based on aquifer-test results

[ft/d, feet per day]

Perme-able zone	Lateral hydraulic conductivity					
	Number of aquifer tests	Arithmetic mean (ft/d)	Standard deviation (ft/d)	Harmonic mean (ft/d)	Average of harmonic and arithmetic mean (ft/d)	Geometric mean (ft/d)
A	1,126	163	152	49	106	101
B	515	97	110	19	58	51
C	487	96	99	19	58	51
D	521	78	71	18	48	42
E	428	72	55	11	42	36

Few data exist to define the vertical hydraulic conductivity of the aquifer system. None of the aquifer tests were suitable for calculation of vertical leakage across interbedded clays. Laboratory measurements of two core samples under in-situ confining pressures from test wells at Baton Rouge, La., (Whiteman, 1980, table 4) gave values of vertical hydraulic conductivity of 1.1×10^{-6} ft/d for a core from a depth of 450 ft (zone A) and 1.7×10^{-5} ft/d for a core from a depth of 2,115 ft (zone C). Laboratory measurements of clay cores from the Lake Charles industrial area (F.S. Riley, U.S. Geological Survey, written commun., 1973) gave average values of vertical hydraulic conductivity of 7.6×10^{-6} ft/d under a confining pressure equivalent to a 400 ft depth of burial and 3.8×10^{-6} ft/d under a confining pressure equivalent to a 600 ft depth of burial. The mixtures of clay, silt, and sandy clay which form the beds that account for most of the restriction of vertical flow within the coastal lowlands aquifer system would be expected to have larger vertical hydraulic conductivities than the relatively pure clays used for the laboratory tests. For initial simulations of the aquifer system, a uniform value of 2.0×10^{-5} ft/d was used for the vertical hydraulic conductivity of the clays within and between permeable zones.

Initial transient simulations specified a uniform storage coefficient of 1.0×10^{-4} for all permeable zones throughout the model. Too few values of storage coefficient were available from aquifer-test results to permit statistically valid determinations of areal or vertical variations. The uniform value of storage coefficient was later refined by calculating values for each model block. The thicknesses of sand and clay (including silt and sandy clay) in each block were multiplied by values of specific storage of 1.0×10^{-6} for sand (Lohman, 1972, p. 12) and 4.0×10^{-6} for clay (Ireland and others, 1984, table 4). This provides an areal variability in storage coefficient that reflects the areal variations in the thickness and the sand and clay content of each permeable zone.

Ground-Water Pumpage

Ground water is pumped for municipal, industrial, agricultural, and domestic use throughout most of the study area. The division of pumpage between point-type withdrawals (as defined by Mesko and others, 1990, p. 25), primarily for public supply and industrial use, and areal-type withdrawals, primarily for irrigation is shown in figure 11. Martin and Whiteman (1989, figs. 24-28) give the areal distribution of the pumpage for 1980 from each zone. The areal distribution of pumpage in 1985 from all permeable zones combined is shown in figure 12.

Table 3 summarizes pumpage from each of the permeable zones of the coastal lowlands aquifer system at five-year intervals for the period 1960-85. Throughout the period 1960-85, pumpage from permeable zone A, the youngest deposits, has ranged from 59 to 67 percent of the total pumpage from the aquifer system. Most of the water from zone A is used for rice irrigation in southwest Louisiana, but significant amounts are pumped for industrial and municipal use at Lake Charles, La., industrial use at Baton Rouge, La., and industrial and commercial use at New Orleans, La., and Natchez, Miss. Pumpage from permeable zones B through E is less concentrated than that from zone A, but significant amounts of water are withdrawn at Baton Rouge (zones B through D), Beaumont, Tex. (zones B and C), Alexandria, La. (zone D), Bogalusa, La. (zone D), and in the Pensacola, Fla. area (zones D and E).

Total pumpage from the coastal lowlands aquifer system generally increased from 1960-80, when it peaked at about 1,874 Mgal/d (251 Mft^3/d). Pumpage then declined by more than 15 percent to about 1,579 Mgal/d (211 Mft^3/d) by 1985 (table 3). Pumpage for industry and public supply peaked in 1975 (fig. 11). After 1975, declines in industrial pumpage in response to economic and environmental factors were greater than increases in pumpage for municipal use. Changes in pumpage for agriculture were primarily a result of changes in pumpage for rice irrigation in southwestern Louisiana.

Table 3.--Pumpage of water from the coastal lowlands aquifer system in the study area for the period 1960-85

[Mgal/d, million gallons per day]

Permeable zone	1960		1965		1970		1975		1980		1985	
	Rate (Mgal/d)	Percent	Rate (Mgal/d)	Percent	Rate (Mgal/d)	Percent	Rate (Mgal/d)	Percent	Rate (Mgal/d)	Percent	Rate (Mgal/d)	Percent
A	800.2	67	901.9	66	1,147.0	66	1,059.4	61	1,244.8	67	930.7	59
B	70.3	6	87.9	7	116.4	7	114.1	7	114.3	6	103.7	6
C	100.1	8	112.7	8	150.8	9	165.8	10	165.3	9	153.1	10
D	164.6	14	191.5	14	232.5	13	290.0	17	268.6	14	299.7	19
E	59.7	5	65.8	5	79.1	5	89.4	5	81.1	4	91.4	6
Total	1,194.9	100	1,359.8	100	1,725.8	100	1,718.7	100	1,874.1	100	1,578.6	100

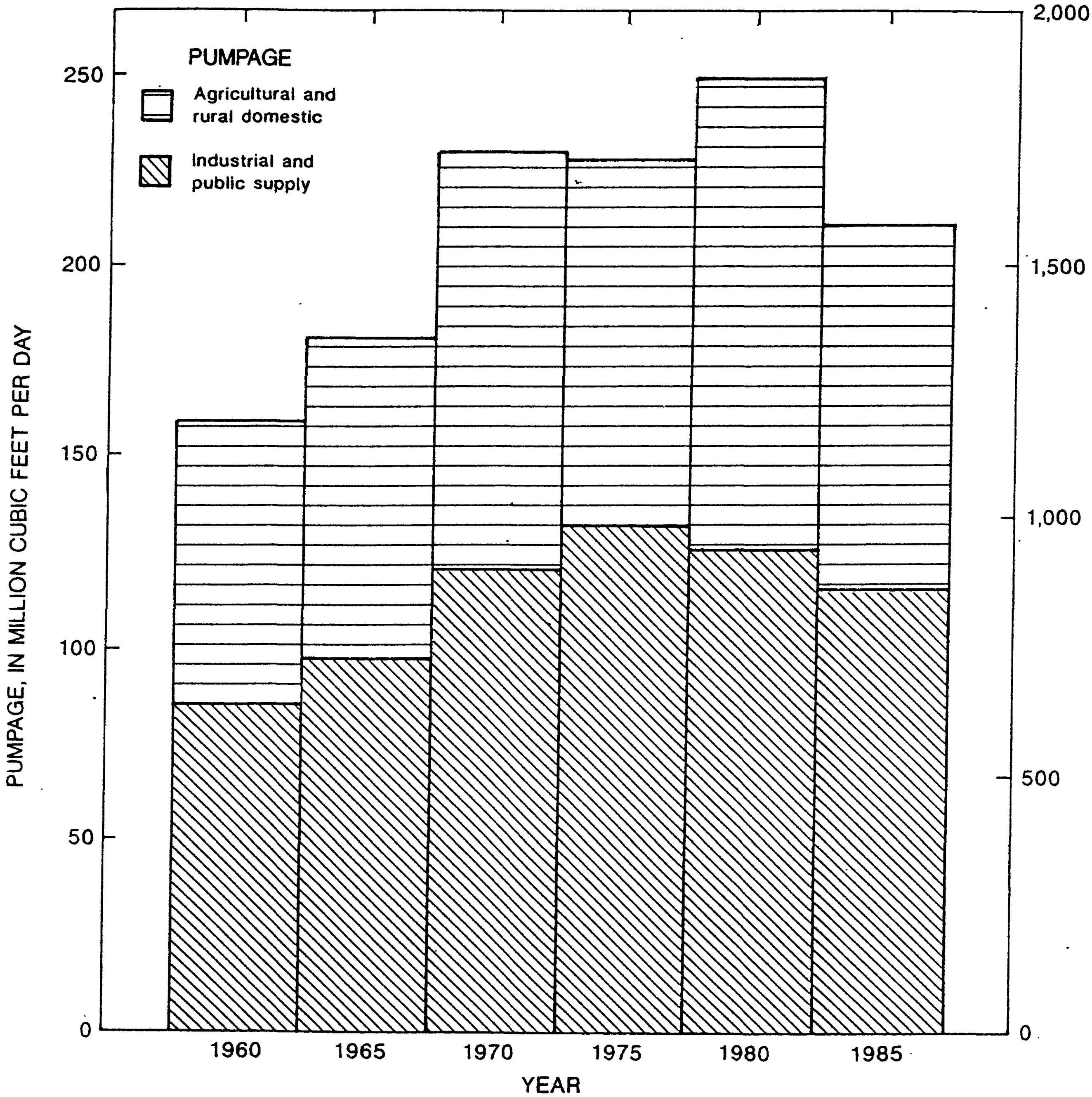


Figure 11.--Pumpage from the coastal lowlands aquifer system by major category of use, 1960-85.

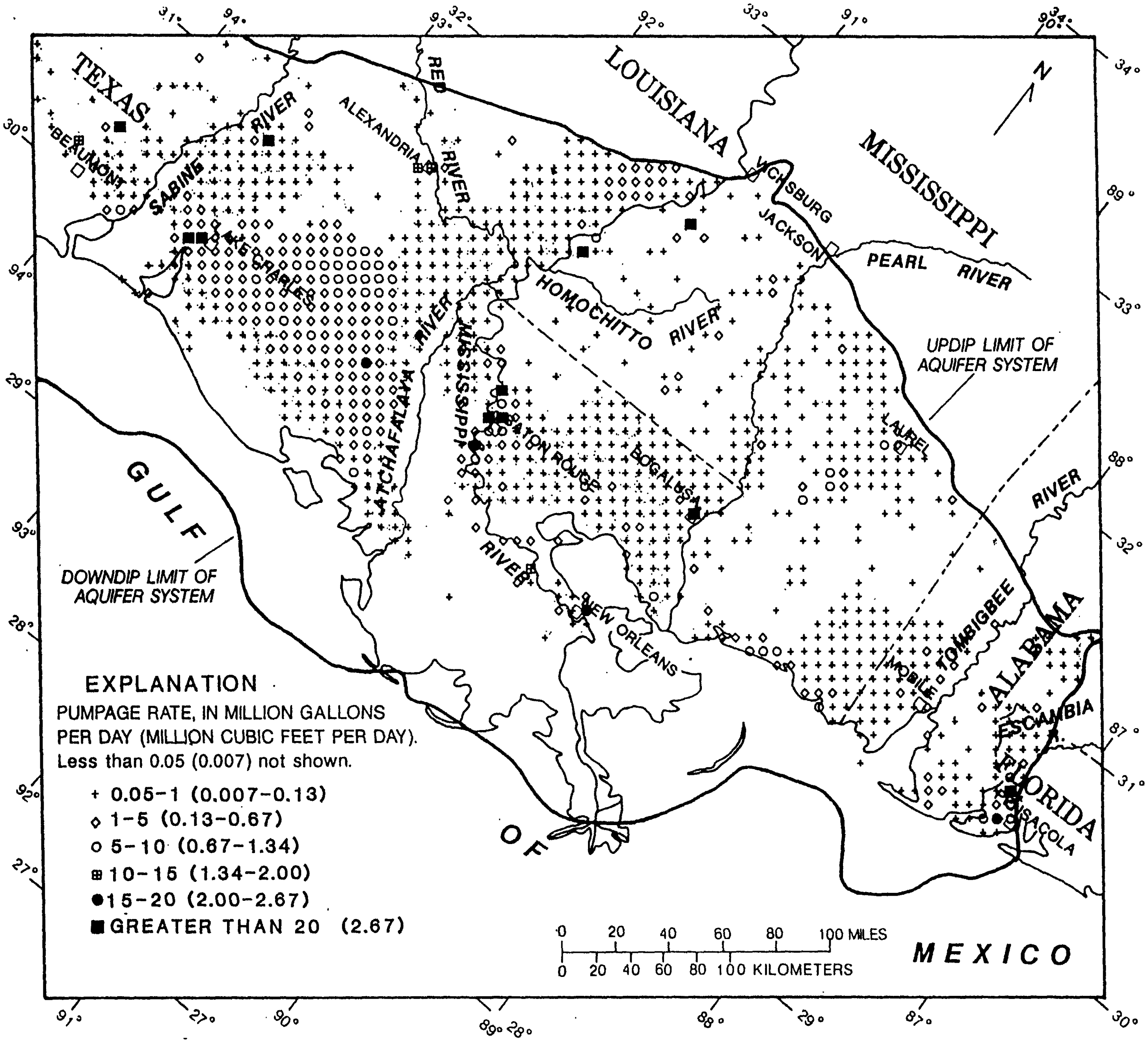


Figure 12.--Areal distribution of pumpage from the coastal lowlands aquifer system, 1985.

REGIONAL GROUND-WATER FLOW

The primary tool used to analyze regional ground-water flow in the coastal lowlands aquifer system was a six-layer finite-difference ground-water flow model. Conceptualization, construction, calibration, and sensitivity analysis of this model are described in detail by Martin and Whiteman (1989; 1990). A brief description of the model and of modifications made to the model since completion of the earlier reports is given in this report.

Model Development and Boundaries

Each permeable zone of the aquifer system is represented by a model layer (table 1) with an additional layer used as the upper boundary of the model. Model layer 1, consisting of constant-head nodes, forms an upper boundary covering all of the active area of the model. The heads of the constant-head nodes are set at the altitude of the water table. The constant-head layer represents the effects of all surficial sources of natural recharge to and discharge from the aquifer system, such as precipitation, evapotranspiration, and seepage to or from streams, lakes, and the Gulf. Use of a constant-head upper boundary for modeling is justified because there has been no significant decline in the water table as a result of ground-water pumpage through 1987. The constant-head boundary has the potential of supplying unlimited recharge from layer 1 to underlying layers. Flow downward from layer 1 was monitored during model simulation to ensure that recharge does not reach unreasonable levels at any point (Martin and Whiteman, 1990, p. 7). Model layer 2 represents the youngest part of the aquifer system, the Holocene-upper Pleistocene deposits (permeable zone A). Progressively older deposits are represented by lower model layers, with model layer 6 representing the lower Miocene-upper Oligocene deposits (permeable zone E).

The finite-difference grid and the active area of the model are shown in figure 13. A uniform grid-block (node) spacing of 5 mi was used (fig. 1). The vertical structure of the model and boundaries is shown in figure 14. Lateral boundaries in the model are predominantly no-flow. Along the northern side of the model, no-flow boundaries in each model layer simulate the updip limit of the permeable zone represented by that layer. Along the eastern side of the model, permeable beds within the aquifer extend beyond the study area but are thin and are not extensively used as a source of ground water. The potential flow across the eastern boundary is sufficiently small to permit use of a no-flow boundary without introducing significant errors at the scale of this model. Alluvial deposits of the Mississippi River, included in zone A, extend northward beyond the boundary of this model. A line of specified-flux nodes across the river valley in layer 2 at the northern edge of the model (fig. 13) simulates ground-water inflow to the model area in the alluvial deposits. The amount of flow specified for each node was determined from a model of the alluvial aquifer covering this area (fig. 1) which is described by Ackerman (1989).

The southern boundary for each model layer represents the downdip extent of water with a dissolved solids concentration of 10,000 mg/L or less in any sand bed within the layer. This is a modification of the southern boundary

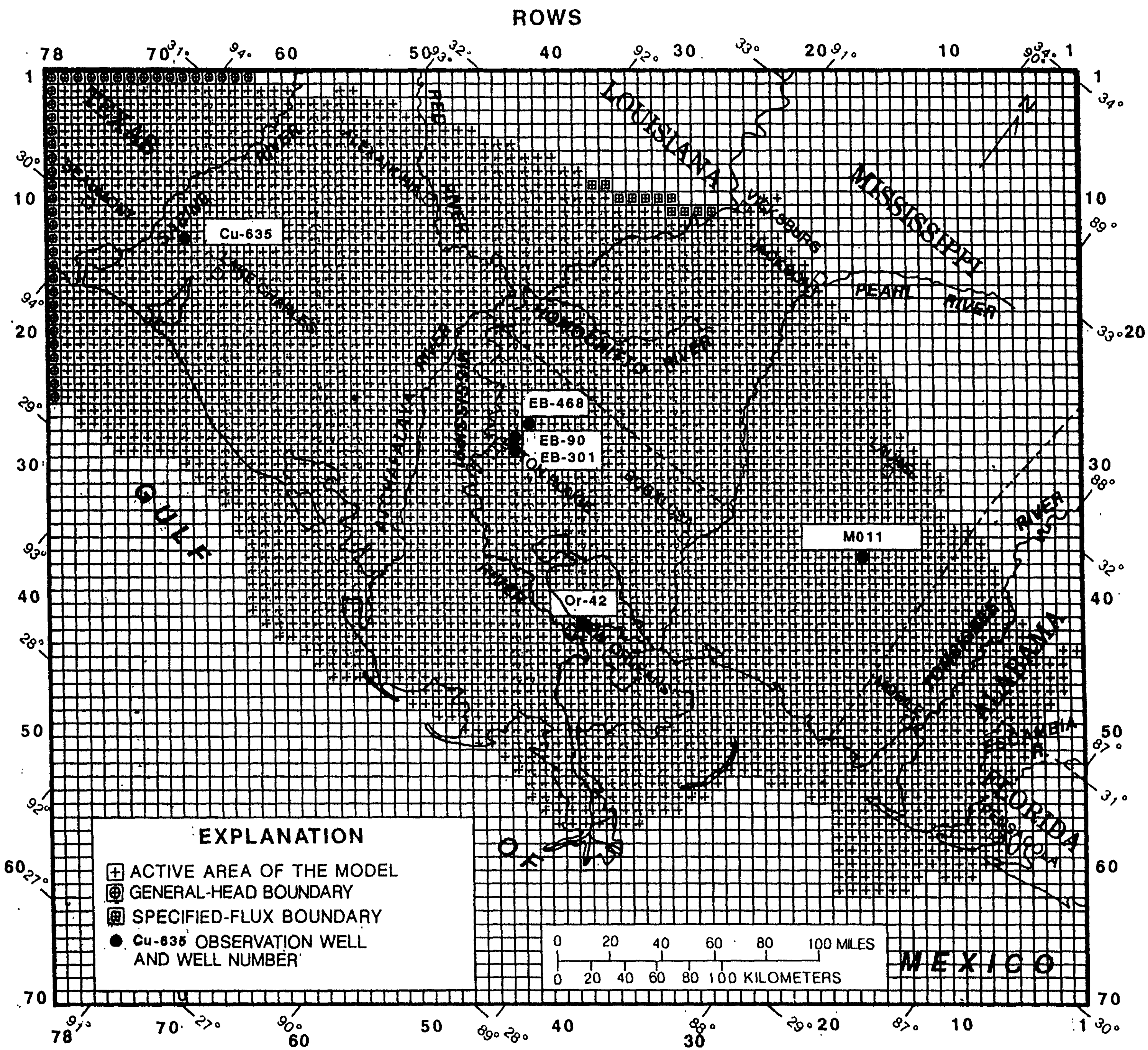


Figure 13.--Finite-difference grid, boundary conditions, the active area of the model, and location of observation wells.

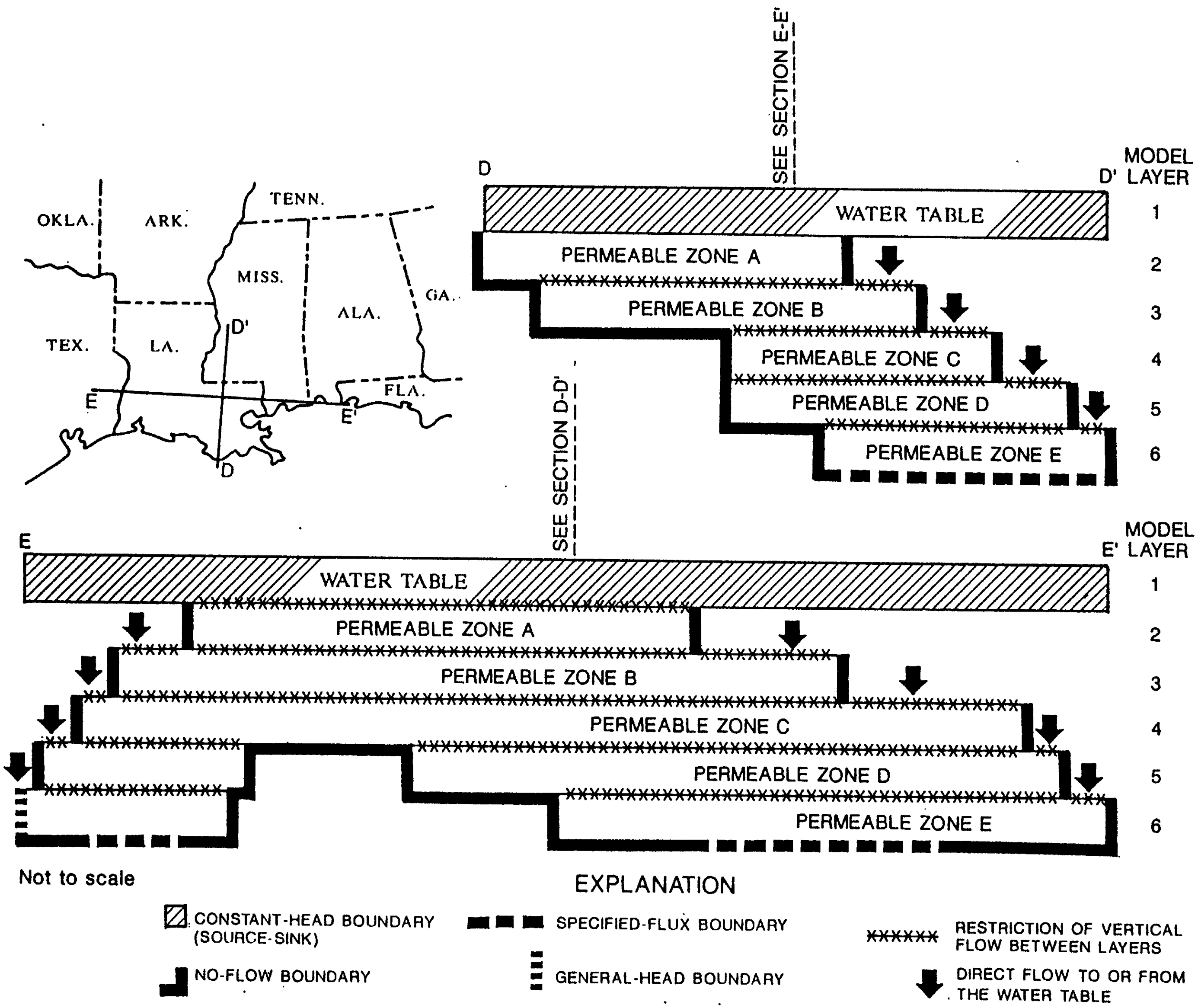


Figure 14.--North-south and east-west schematic sections through the coastal lowlands aquifer system showing vertical structure of the model including model layers and the simulated boundary conditions.

of the steady-state model described in Martin and Whiteman (1989, p. 9). The downdip boundary used in the steady-state model described in that report was determined by estimating the average dissolved solids concentration of water in all sands greater than 20 ft thick within each permeable zone. Where the average dissolved solids concentration was greater than 10,000 mg/L, the entire thickness of the zone was considered saline and not part of the active flow system. This procedure produced a boundary with abrupt cutoffs of permeable zones that did not realistically approximate the observed freshwater-saltwater interface (Martin and Whiteman, 1989, pl. 2). The modified southern boundary used in the model described in this report represents actual conditions more realistically, better simulating ground-water flow near the interface.

Assuming that no flow occurs in that part of the aquifer system with water containing more than 10,000 mg/L dissolved solids introduces some distortion to the analysis of regional ground-water flow because such water may move into the part of the aquifer system simulated in this study in response to pumpage. On a regional scale, the distortion is not significant. On a local scale, intense pumpage near the southern boundary of a permeable zone could induce saltwater encroachment. Prediction of the rate of encroachment would be adversely affected by the flow distortion, but such local effects were not addressed in this study. Flow in the entire aquifer system, including the saltwater-bearing part, is discussed in Williamson and others (1989).

No natural hydrologic boundaries are present in the coastal lowlands aquifer system on the western edge of the study area. To minimize boundary effects within the study area, the model was extended into Texas to a line between pumping centers at Lake Charles, La., and Houston, Tex. The area west of the Sabine River is included in a study of the coastal lowlands aquifer system of Texas (Ryder, 1988). In the steady-state model described in Martin and Whiteman (1989), the western boundary was treated as a no-flow boundary lying along a ground-water divide between the pumping centers. Further analysis of water-level data indicated that there was the potential for significant flow across this divide under both predevelopment (inflow to the model) and 1987 (outflow from the model) conditions. To simulate these flows, the no-flow nodes along the western boundary of the steady-state model were changed to general-head nodes (McDonald and Harbaugh, 1988, chap. 11) in model layers 2-6. Heads at the general-head boundary were determined from simulations of the coastal lowlands aquifer system in Texas (Ryder, 1988). These heads were updated at the start of each pumping period to reflect changes in water levels along the boundary through time. General-head nodes permit flow across the model boundary based on the gradient between simulated water levels at the boundary and specified water levels outside of the boundary.

The base of the model was initially treated as a no-flow boundary (Martin and Whiteman, 1989, p. 9). During the conceptualization and development of the model, flow across the thick and areally extensive clays of the Vicksburg-Jackson confining unit were assumed to be negligible. Modeling results from a parallel study of the Mississippi embayment aquifer system of Eocene age underlying the Vicksburg-Jackson confining unit indicated relatively small flows across the confining unit under conditions existing from predevelopment to 1987 (Arthur and Taylor, 1989). These flows, on the order of 0.1 to 0.7 Mft^3/d, were incorporated during calibration of the model of the coastal lowlands aquifer system (Martin and Whiteman, 1990, p. 21) by specifying flows into or out of parts of model layer 6 representing permeable zone E (fig. 14).

Model Calibration and Sensitivity Analysis

The flow model was initially calibrated to 1980 conditions treated as steady state. Although the entire model area was not at steady state in 1980, the rate at which water levels and storage were changing was not considered significant in relation to the scale of the aquifer system (Martin and Whiteman, 1989, p. 14). Calibration consisted of adjusting transmissivities of the permeable zones represented by model layers and the vertical leakances between layers that control vertical flow. Other parameters required for simulation such as water-table altitudes for the constant-head upper layer, ground-water pumpage, and specified flows across the boundaries of the model were assumed to be correct and, therefore, were not adjusted during calibration. Calibration was based on minimizing root-mean-square error (RMSE) values of the residuals between simulated and measured water levels for all permeable zones throughout the model area. Flow rates and volumetric budgets of the coastal lowlands aquifer system could not be measured independently with enough accuracy to use quantitatively in calibrating the model because errors in measurement of surface-water flow in the study area may be greater than total flow in the aquifer system. Model-computed flow rates and volumetric budgets, however, provided essential qualitative checks on model results. The model cannot be considered to be adequately calibrated if simulated flows are not within a range of expected values defined by previous studies in similar areas even though simulated and measured water levels may closely match. After steady-state calibration using 1980 pumpage (table 3), ground-water pumpage was removed from the model to simulate predevelopment conditions.

Storage coefficients were calibrated using a transient version of the model for the period from 1898 to 1987. Nine pumping periods were simulated: 1898-1917, 1918-37, 1938-57, 1958-62, 1963-67, 1968-72, 1973-77, 1978-82, and 1983-87. Although pumpage and water-level data prior to 1958 were too sparse to use statistically in calibration of the model, the first three pumping periods produce transient conditions in the simulated flow system similar to the transient conditions present in the aquifer system in 1958 at the start of the calibration period. The distribution of the water levels used for calibration to 1980 conditions is shown in Martin and Whiteman (1989, figs. 34-38). Similar distributions of water levels were used for each of the other pumping periods. The pumpages shown in table 3 were used for calibration.

The model was calibrated by matching simulated and measured water levels at the ends of pumping periods 3 through 9, from 1957-87, which coincide with periods of significant changes of ground-water development and with periods of intensive collection of pumpage and water-level data. Complete water-level data for 1987 (the end of pumping period 9) were not available when the model was calibrated, so this period was not included in the statistical evaluation of calibration results. However, pumping period 9 was included in the analysis of water-level trends in heavily pumped areas.

Initial values of storage coefficients for the transient simulation were based on the thicknesses of sand and clay present in each model block. The final values of storage coefficients resulting from the transient calibration were one half of the initial values. Initial values of transmissivity and vertical leakance derived from steady-state calibration were not significantly changed during transient calibration.

Mean error, RMSE, and standard deviation values of water-level residuals for each permeable zone and for the entire aquifer system for pumping periods 3 through 8 are shown in table 4. Values for the end of pumping period 3 (1957) are included because these water levels are the starting values for pumping period 4 (1958-62). Zone A, because of the relatively low topographic relief of its outcrop area, consistently shows the best match between simulated and measured values, whereas zones D and E show the poorest matches. The largest differences between simulated and measured water levels occur in areas of high topographic relief in the outcrops of the lower zones and near major pumping centers (Martin and Whiteman, 1990, fig. 5). These results are similar to those produced in the preliminary version of the model (Martin and Whiteman, 1989, figs. 39-43). In the outcrop areas and in areas of intense pumpage, ground-water gradients may be steep and large water-level differences may exist within a single model block making it difficult or impossible to accurately simulate measured water levels.

Hydrographs (fig. 15) show changes in measured water levels during the calibration period (1958-87) in each permeable zone and the simulated water levels at the same sites in the corresponding model layers. These show that the general water-level trends are simulated by the model.

Sensitivity analysis using both the steady-state and transient versions of the model determined the effects of varying the values of transmissivity, vertical leakance, and storage coefficient on the output of the model. These are the same properties adjusted during calibration. A detailed description of the methods and results of the sensitivity analysis is given in Martin and Whiteman (1990). Model sensitivity to changes in these values was calculated in terms of RMSE of the residuals between simulated and measured water levels. The model is generally most sensitive to changes in transmissivity and least sensitive to changes in storage coefficient. When transmissivity or vertical leakance is changed for one zone at a time, the upper part of the aquifer system, represented by permeable zone A, is most sensitive. When transmissivities or vertical leakances are changed in all zones at once, however, the deeper permeable zones (B-E) become more sensitive because flow between the constant-head upper boundary and the deeper zones is affected by the transmissivities and vertical leakances of all intervening zones. Generally, simulated water-levels are more sensitive to decreases than to increases in transmissivities and vertical leakances. Though relatively insensitive to changes in storage coefficient, the model is more sensitive to increases than to decreases.

Table 4.--Results of statistical analysis of water-level residuals of the transient calibrated model for the period 1957-82

Permeable zone	Number of observations	Mean error[1] (feet)	Root-mean-square error[2] (feet)	Standard deviation[3] (feet)
		End of Stress Period 3 - 1957		
A	301	-0.82	18.27	18.25
B	55	-17.22	33.17	28.36
C	62	-18.00	32.42	26.96
D	70	-.23	44.57	44.57
E	20	-6.00	38.05	37.57
All	508	-4.81	27.86	27.44
		End of Stress Period 4 - 1962		
A	344	3.18	18.35	18.08
B	96	7.06	30.52	29.69
C	167	-3.49	32.70	32.51
D	180	16.92	46.54	43.35
E	74	29.45	57.30	49.16
All	861	7.45	34.36	33.54
		End of Stress Period 5 - 1967		
A	283	3.87	15.25	14.75
B	121	6.94	27.86	26.98
C	252	.39	34.52	34.51
D	222	12.45	48.08	46.44
E	116	21.09	48.26	43.41
All	994	7.29	35.37	34.61
		End of Stress Period 6 - 1972		
A	348	-1.36	19.57	19.52
B	151	3.56	31.31	31.10
C	301	6.80	38.06	37.45
D	365	18.01	53.82	50.71
E	150	18.16	46.86	43.20
All	1,315	8.68	40.00	39.04
		End of Stress Period 7 - 1977		
A	348	2.24	17.70	17.56
B	43	4.97	25.38	24.89
C	71	3.65	39.55	39.38
D	64	9.16	37.15	36.00
E	29	27.30	54.47	47.13
All	555	4.74	27.58	27.17
		End of Stress Period 8 - 1982		
A	349	-0.18	14.75	14.75
B	73	7.09	33.40	32.64
C	164	6.74	40.31	39.74
D	278	2.64	55.84	55.77
E	132	19.70	46.82	42.48
All	996	4.92	39.83	39.52
		Overall Model, Stress Periods 3 through 8 - 1957-82		
A	1,973	1.11	17.45	17.30
B	539	3.41	30.49	29.45
C	1,017	1.78	36.54	35.93
D	1,179	11.61	50.90	49.10
E	521	20.39	48.92	43.99
All	5,229	5.77	35.96	34.50

1 Mean error $= \dfrac{\sum_{i=1}^{N} \left(h_i^s - h_i^m\right)}{N} = \bar{h}$

2 Root-mean-square error $= \sqrt{\dfrac{\sum_{i=1}^{N} \left(h_i^s - h_i^m\right)^2}{N}}$

3 Standard deviation $= \sqrt{\dfrac{\sum_{i=1}^{N} \left[\left(h_i^s - h_i^m\right) - \bar{h}\right]^2}{N}}$

Where h^s = simulated water level
h^m = measured water level
N = number of water-level pairs compared.

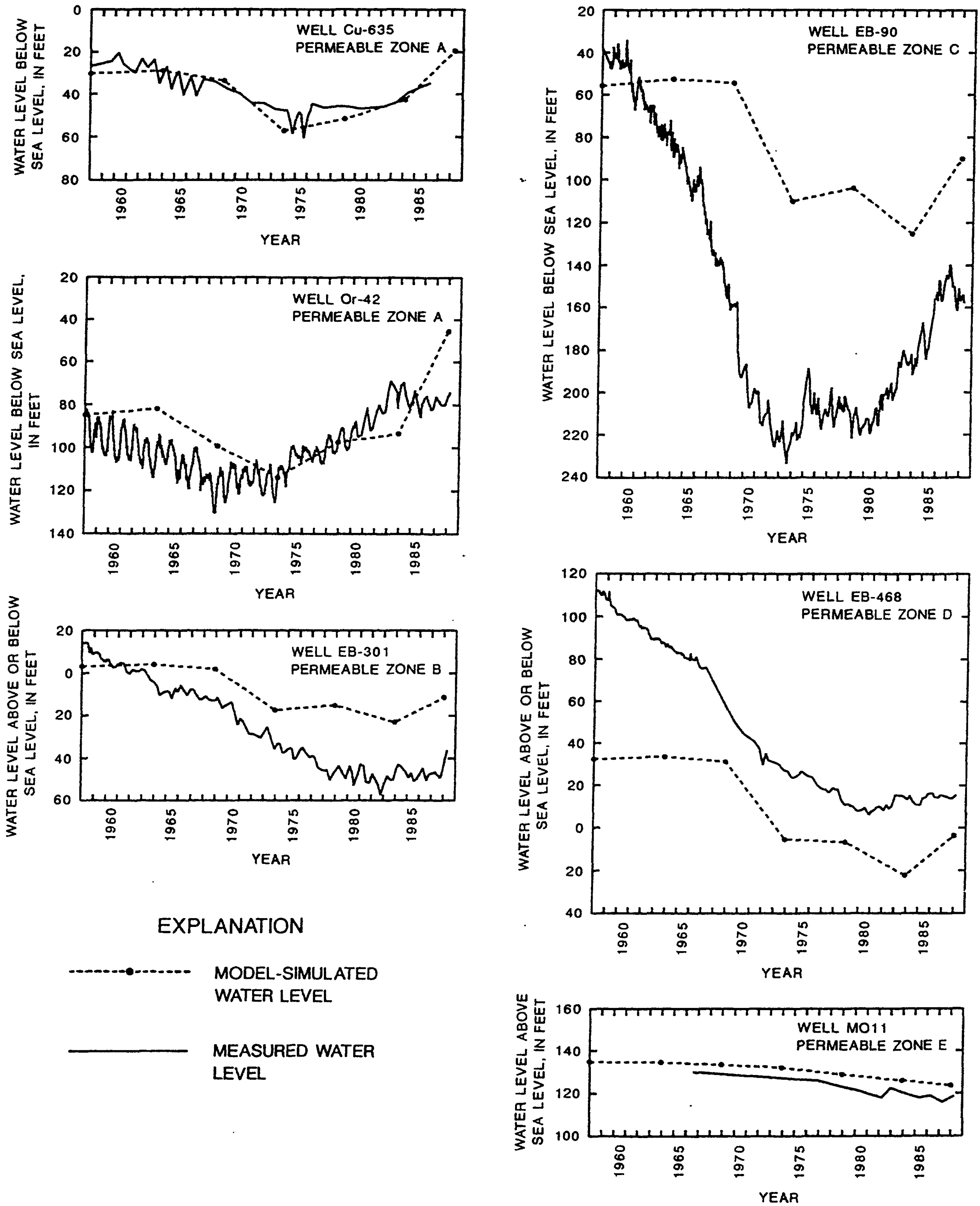


Figure 15.--Comparisons between simulated and measured water levels for the period 1958-87.

Predevelopment Flow System

Simulated results for predevelopment conditions indicate that flow in the coastal lowlands aquifer system was generally from the upland outcrop areas of southern Mississippi and central Louisiana toward the Gulf of Mexico and the major river valleys. Predevelopment water-level profiles along north-south and east-west sections are shown in figure 16. In the upland outcrop areas, water levels decrease with depth, producing relatively steep downward vertical gradients. Upward vertical gradients in discharge areas near the coast and along the major river valleys are generally smaller than the downward vertical gradients in the recharge areas because the upward flow is distributed over a larger area. Simulated predevelopment potentiometric surfaces of each zone and the vertical average water levels of all zones present in the aquifer system are shown in figures 17a-f. Average water levels are given here and in connection with later discussions of water levels to emphasize the unity of the aquifer system and to provide a convenient way of assessing the overall effects that changes in pumpage have on the aquifer system. The water levels in each zone used in computing the average values were weighted by the thickness of their respective zones.

The rate and direction of simulated ground-water flow in the aquifer system are shown in figure 18. Each of the major streams received ground-water discharge under predevelopment conditions. Drainage of water toward the Mississippi Alluvial Plain during predevelopment time was more toward the western and central parts of the valley than toward the present course of the river along the eastern side of the valley. Also shown in figure 18 are the areas where the aquifer system received recharge from (downward flow) or discharged to (upward flow) the water table. Large flows radiated from the topographically high outcrop areas.

Based on simulation, rates of recharge to and discharge from the aquifer system are shown in figure 19. Positive flow represents recharge to the aquifer system, and negative flow represents discharge from the aquifer system. The recharge and discharge rates and flows shown in this and following figures and discussed in the text include only water that remains in the aquifer system sufficiently long to cross at least one grid-block boundary and become part of the regional flow system. Large flows occur locally in the surficial part of the aquifer system that travel short distances and have little or no effect on the regional flow system. Such local flows are not included in the totals given in this report. An example of such a flow would be water that recharges the aquifer system on a hilltop and leaves the aquifer system by evapotranspiration or by discharge to a stream at the foot of the hill. Relatively large downward vertical flows occurred in and near the upland outcrop areas. More than 4 in/yr of recharge occurred in a high area in south-central Mississippi, east of the Pearl River. Recharge rates of 1 in/yr or greater occurred in the outcrop areas in the northern part of the study area. Discharge rates of up to 2 in/yr occurred along major river valleys, whereas discharge rates are less than 1 in/yr along the coast.

The total simulated flow of water circulating through the aquifer system under predevelopment conditions was about 222 Mft^3/d. The distribution of recharge to and discharge from the outcrops of the permeable zones and the

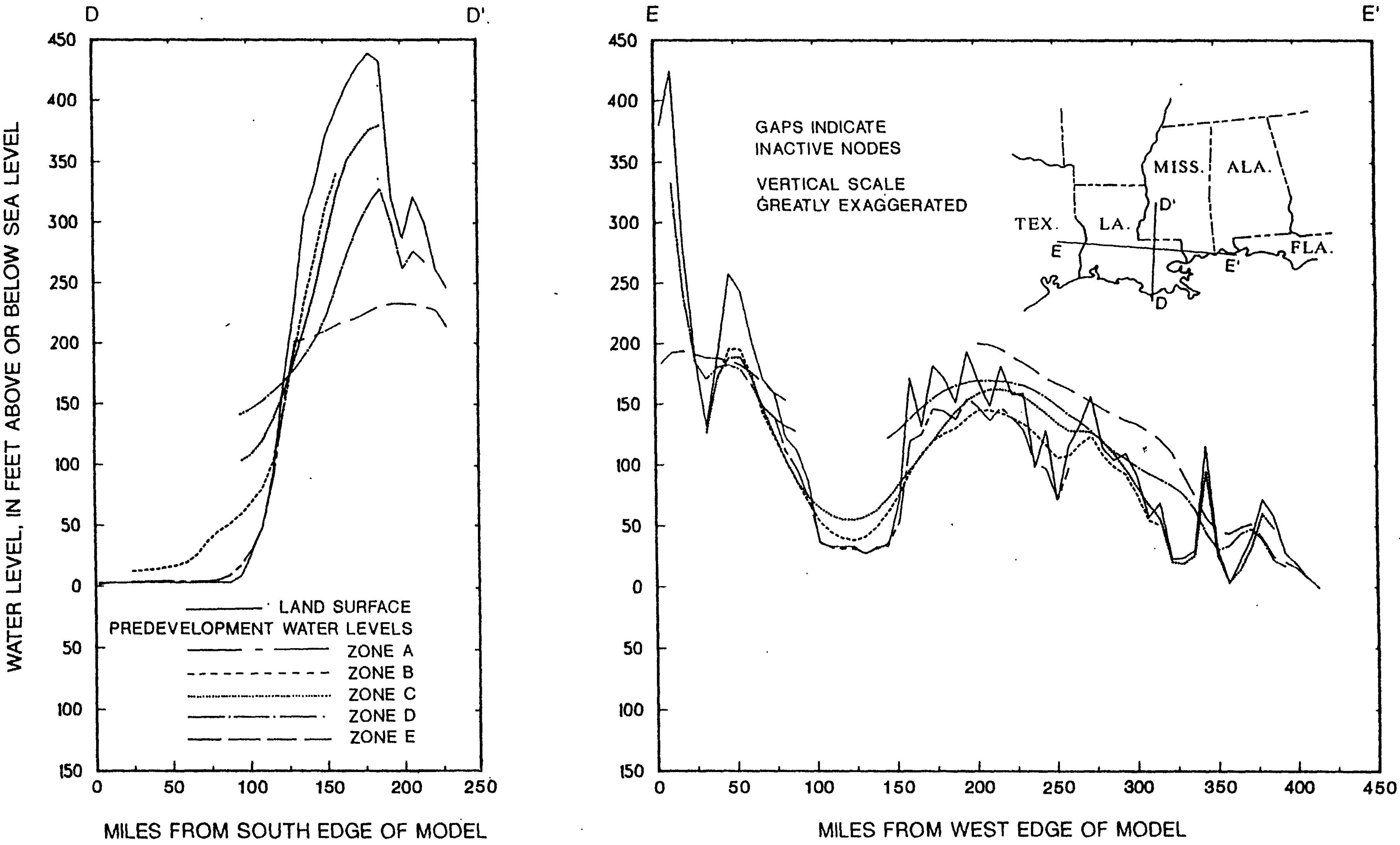


Figure 16.--Water levels in each permeable zone under predevelopment conditions.

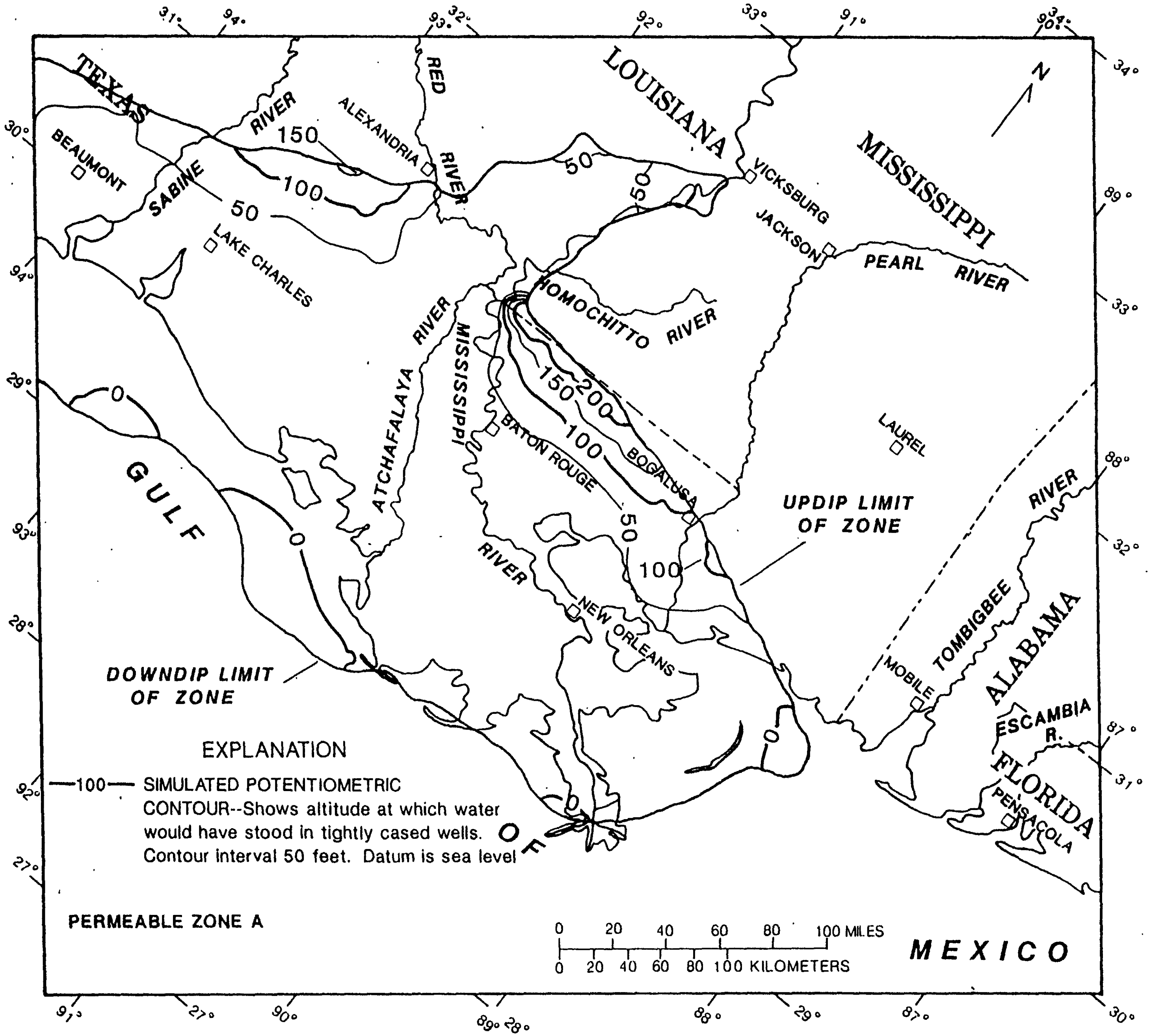


Figure 17a.--Simulated water levels under predevelopment conditions, permeable zone A.

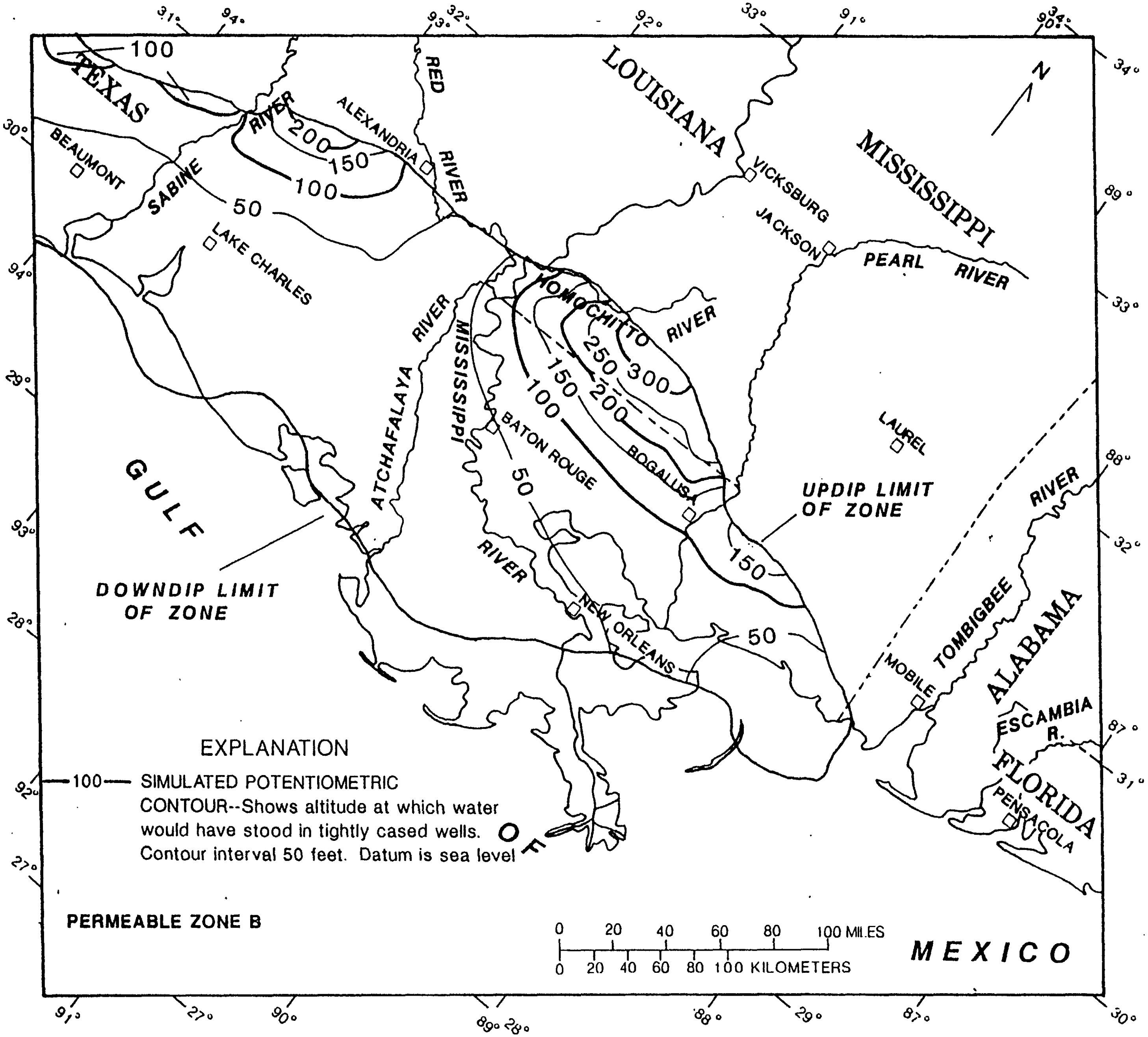


Figure 17b.--Simulated water levels under predevelopment conditions, permeable zone B.

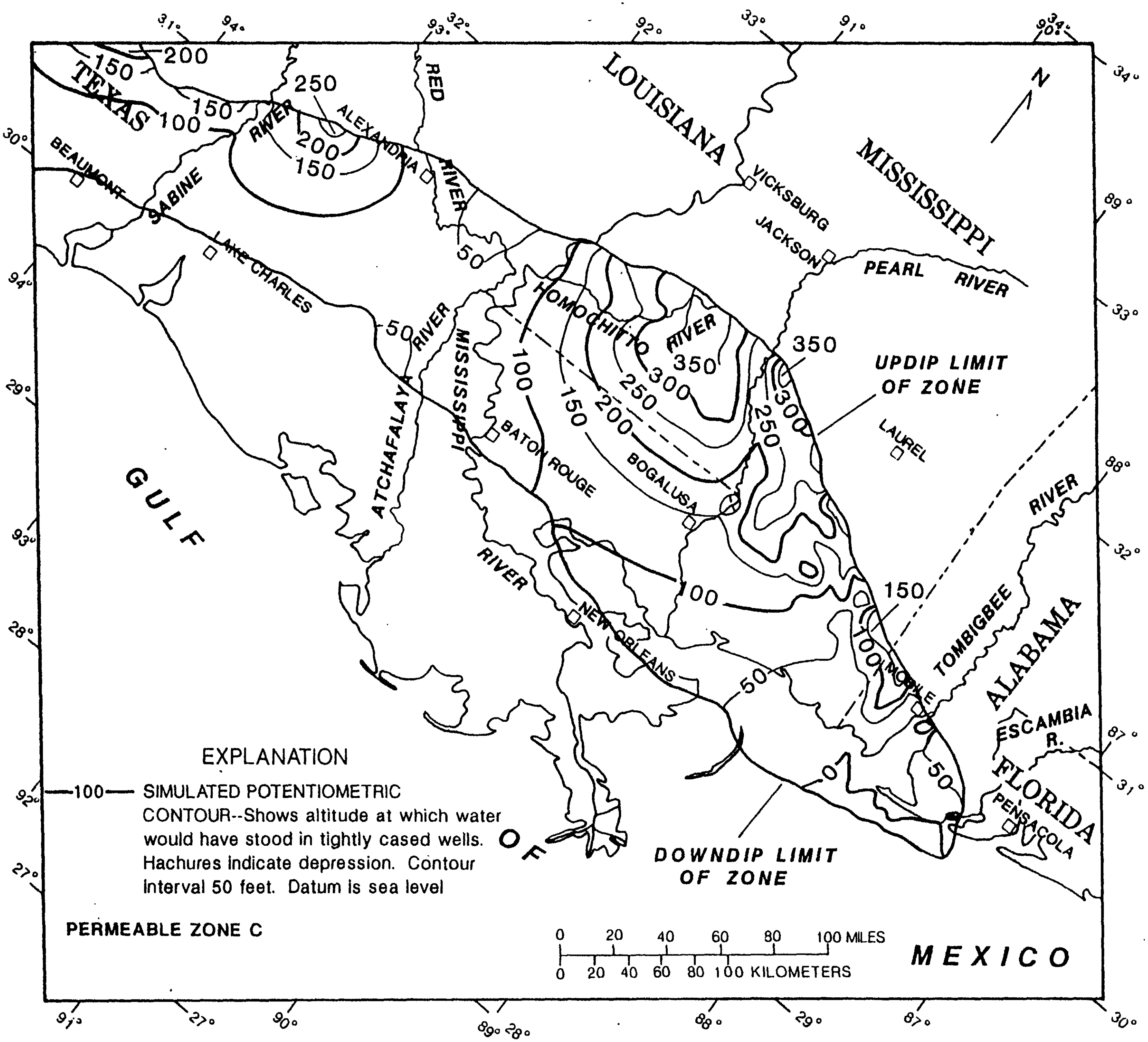


Figure 17c.--Simulated water levels under predevelopment conditions, permeable zone C.

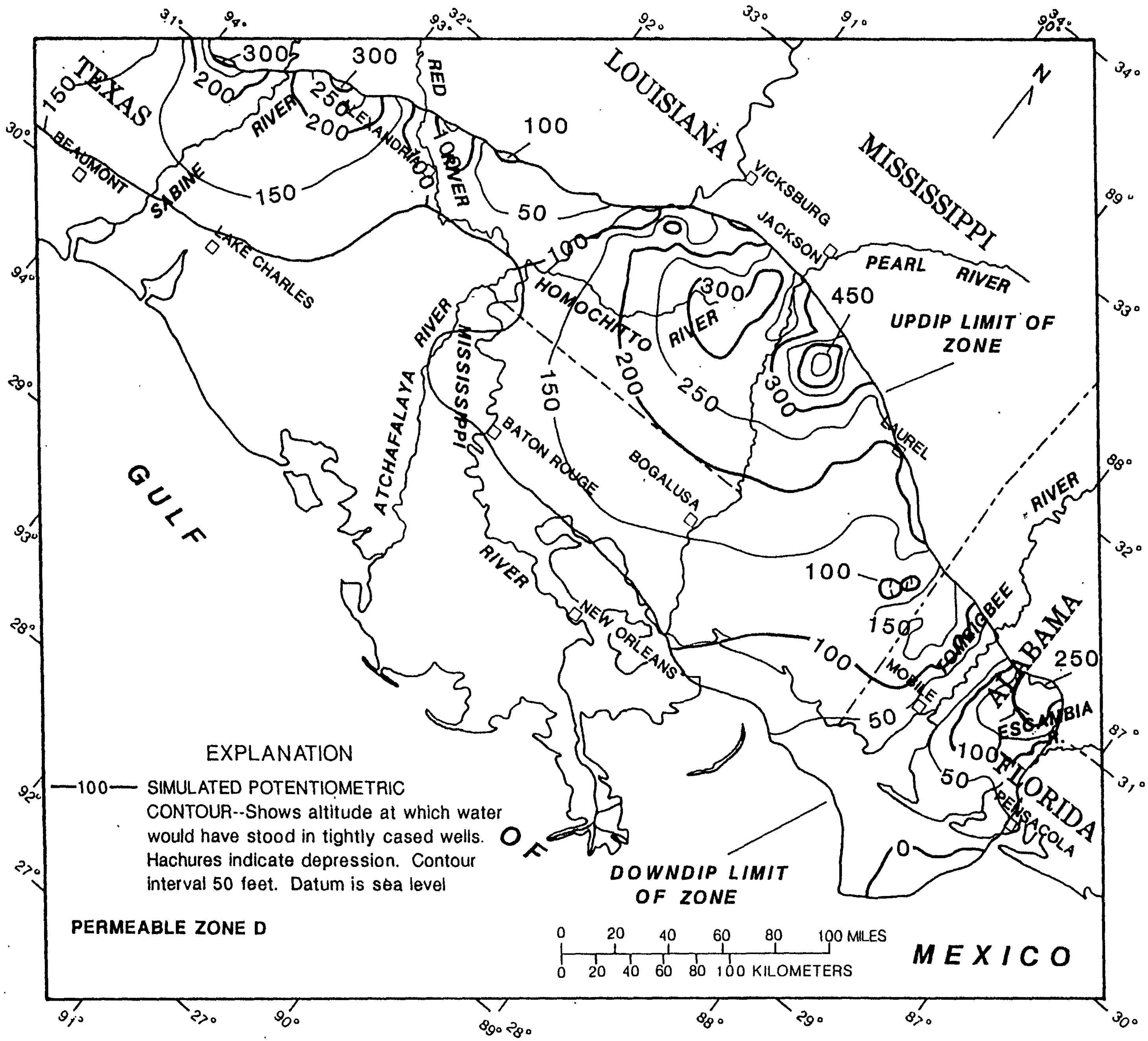


Figure 17d.--Simulated water levels under predevelopment conditions, permeable zone D.

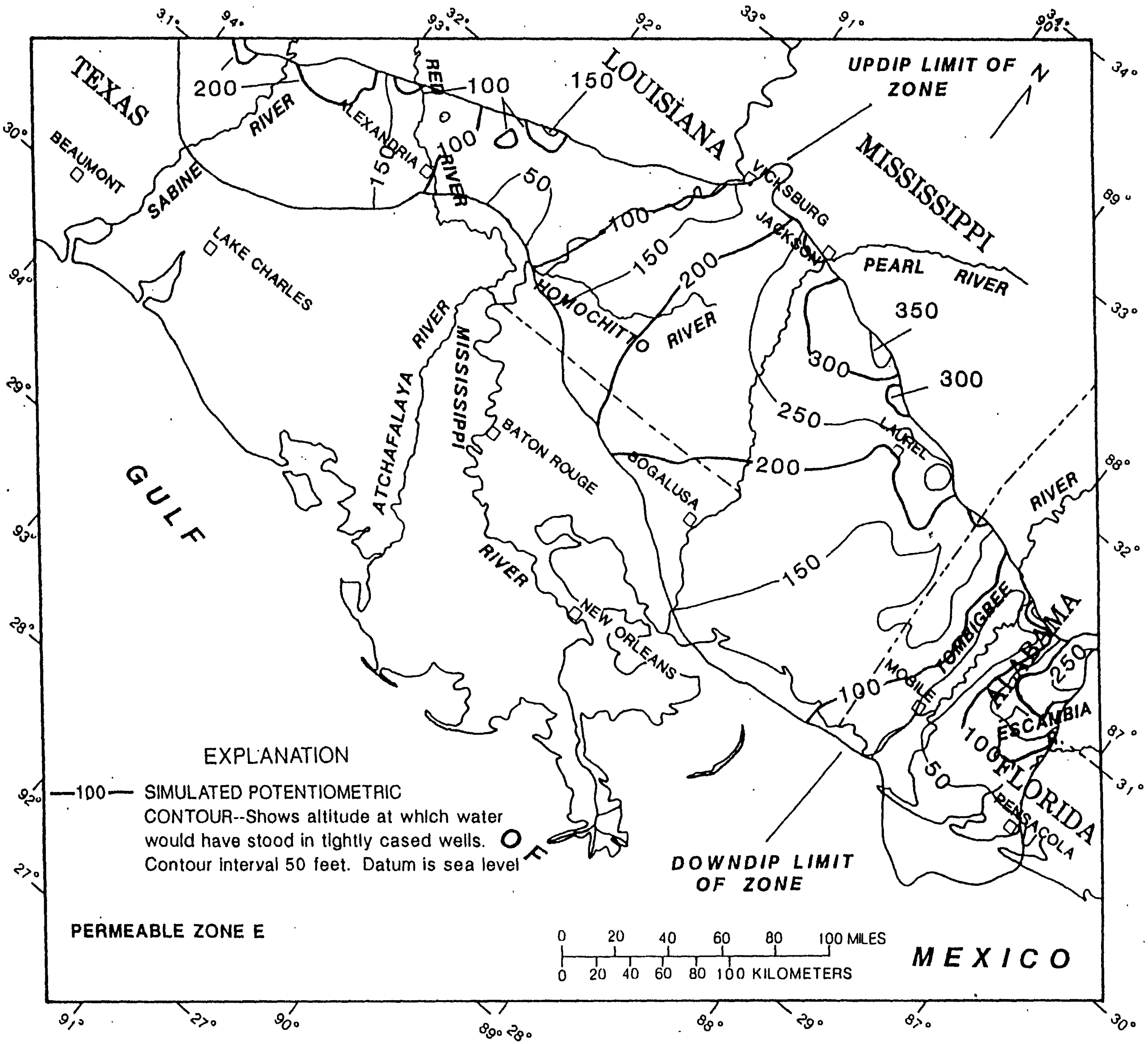


Figure 17e.--Simulated water levels under predevelopment conditions, permeable zone E.

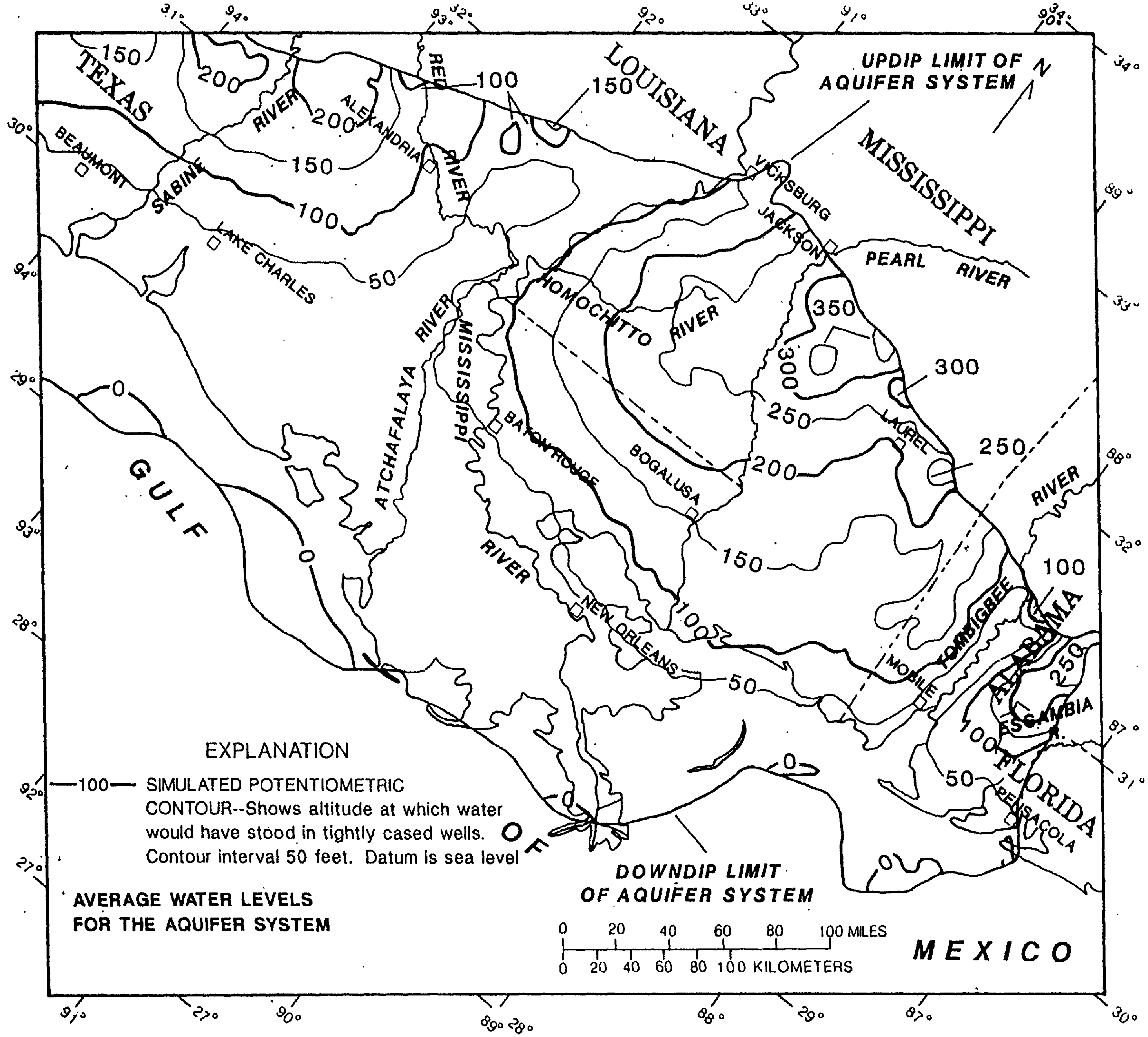


Figure 17f.--Simulated water levels under predevelopment conditions, average water levels for the aquifer system.

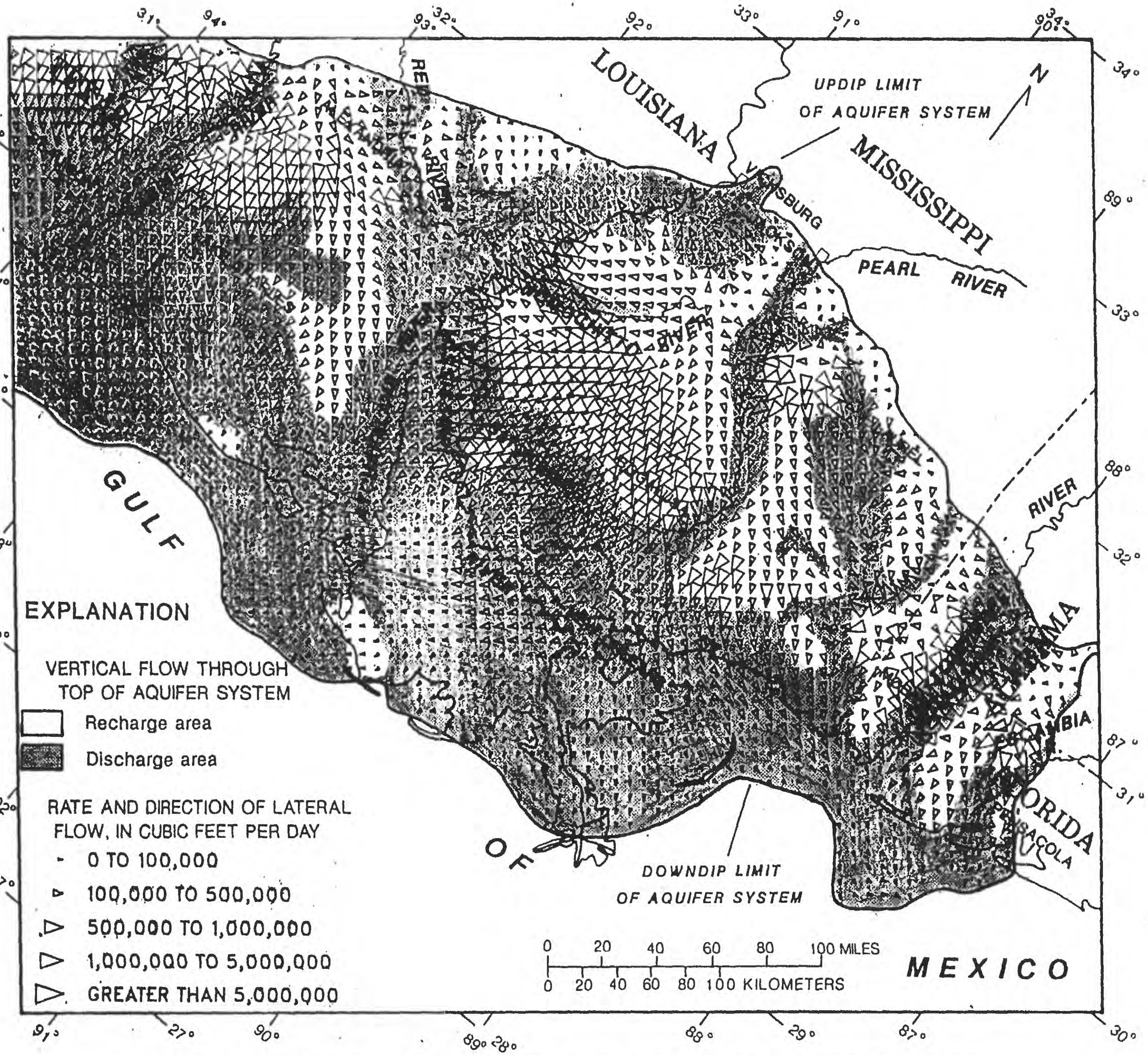


Figure 18.--Simulated ground-water flow in the aquifer system under predevelopment conditions.

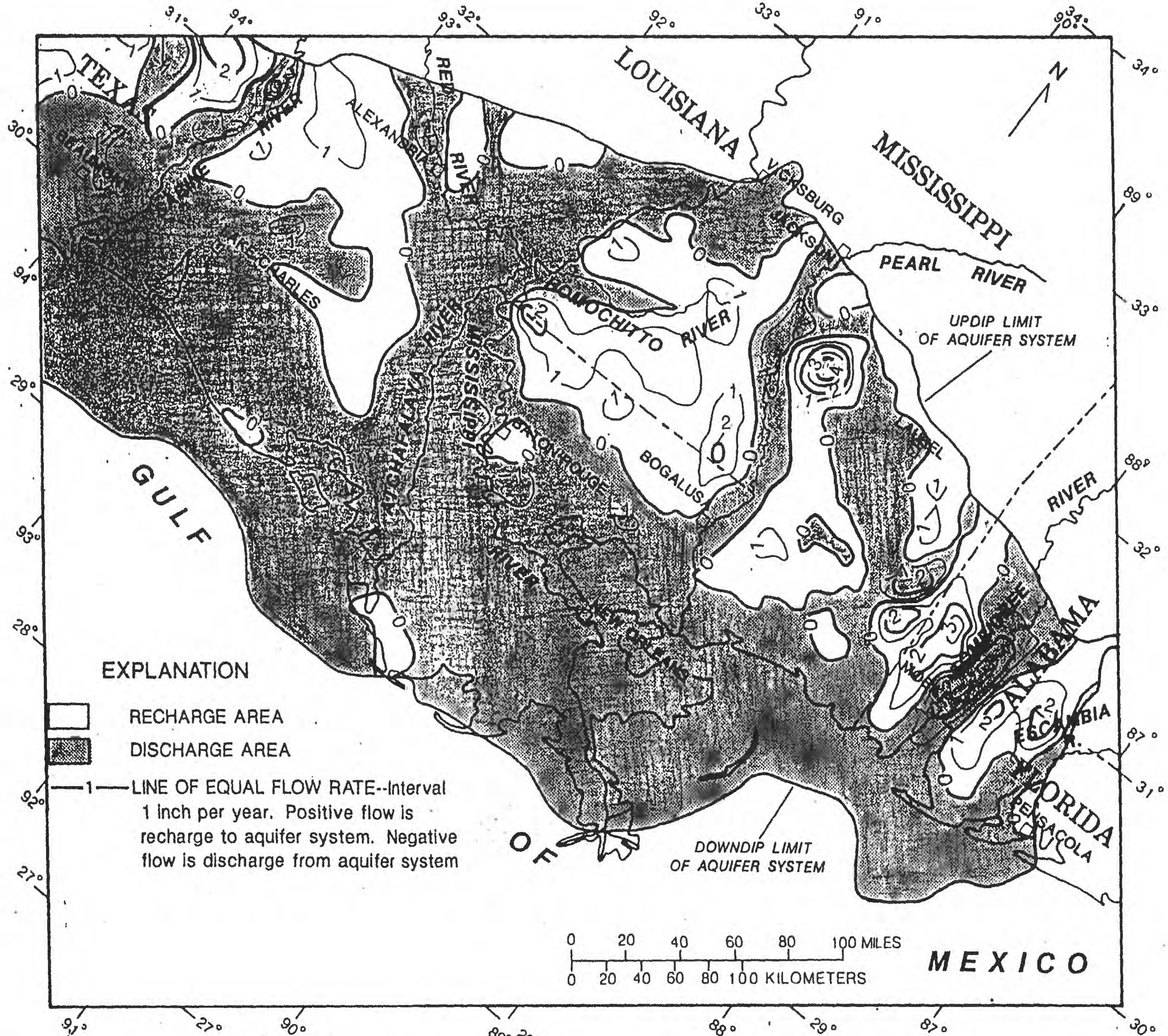


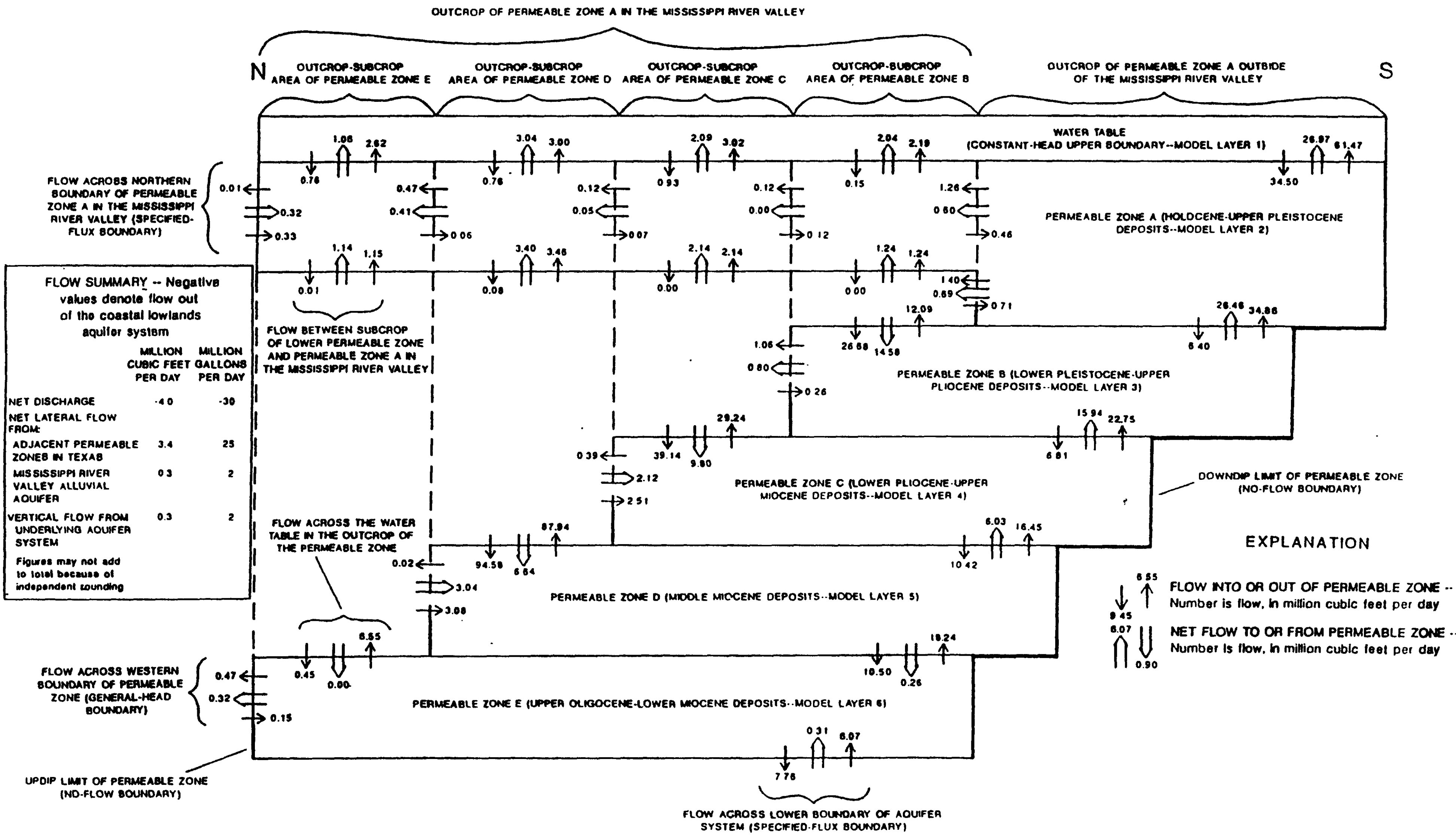
Figure 19.--Areal distribution of simulated rates of recharge to and discharge from the aquifer system under predevelopment conditions.

distribution of flow within the aquifer system are shown in figure 20. The flows shown are for the areal extent of the aquifer system within the model area. About 207 Mft^3/d (94 percent of the total simulated flow) entered the aquifer system as recharge from the surface, of which about 94.6 Mft^3/d entered the outcrop of permeable zone D. About 14.1 Mft^3/d (6 percent) enters the aquifer system laterally from adjacent aquifers in Texas and in the Mississippi River alluvial valley in northern Louisiana and vertically from the underlying Mississippi embayment aquifer system. Based on a more detailed breakdown of flows within the aquifer system than that shown in figure 20, approximately 41 percent (85 Mft^3/d) of the recharge entering the aquifer system moves downward to a lower permeable zone or downdip beneath an overlying permeable zone. About 59 percent (122 Mft^3/d) of the recharge returns to the surface as discharge without having moved beyond the outcrop area of the permeable zone it entered.

Subdivision of the Flow System

The model was divided into seven areas to investigate flow patterns and distributions in the coastal lowlands aquifer system in detail (fig. 21). The areas were chosen on the basis of factors affecting flow in the aquifer system such as topography, the outcrop pattern of the permeable zones, and drainage boundaries. Area 1, designated the southeastern Texas area, is the area west of the Sabine River in Texas. The central Louisiana area (area 2), is an area of relatively high relief where permeable zones B through E outcrop and are recharged. The southwestern Louisiana area (area 3) to the south of the central Louisiana area is an area of comparatively low relief and nearly flat natural hydraulic gradients. The Mississippi Alluvial Plain (area 4) in central and southern Louisiana is an area of low relief and generally low hydraulic gradients. The Mississippi Alluvial Plain separates the upland terraces of central Louisiana (area 2) and the low-lying coastal plain of southwestern Louisiana (area 3) from hydrogeologically comparable areas to the east. The southern Mississippi area (area 5) which is east of the Alluvial Plain consists predominantly of upland terraces in Mississippi and Alabama where permeable zones B through E outcrop and are recharged. As in the central Louisiana area, high topographic relief greatly influences hydraulic gradients. The southeastern Louisiana area (area 6) consists predominantly of low coastal plain in southeastern Louisiana and in small areas of southern Mississippi and Alabama. The area has nearly flat topographic relief and nearly flat natural hydraulic gradients. The southwestern Alabama area (area 7) is at the eastern edge of the model area, east of Mobile Bay and the Tombigbee River. The area includes sections of upland terraces and low-lying coastal plain in southwestern Alabama and western Florida.

A schematic representation of simulated flow between and within the seven areas under predevelopment conditions is shown in figure 21. Of the total of about 207 Mft^3/d of recharge, 114 Mft^3/d (55 percent) entered the aquifer system in southern Mississippi (area 5). About 39 percent (80.8 Mft^3/d) of the total discharge from the aquifer system also occurred in the southern Mississippi area. The upland terraces east and west of the Mississippi River valley (areas 2 and 5) had the greatest net recharge to the aquifer system, 5.5 Mft^3/d in central Louisiana (area 2) and 32.6 Mft^3/d in



FLOW SUMMARY -- Negative values denote flow out of the coastal lowlands aquifer system

	MILLION CUBIC FEET PER DAY	MILLION GALLONS PER DAY
NET DISCHARGE	-4 0	-30
NET LATERAL FLOW FROM:		
ADJACENT PERMEABLE ZONES IN TEXAS	3.4	25
MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER	0 3	2
VERTICAL FLOW FROM UNDERLYING AQUIFER SYSTEM	0.3	2

Figures may not add to total because of independent rounding

Figure 20.--Simulated flow between permeable zones and across boundaries of the coastal lowlands aquifer system under predevelopment conditions.

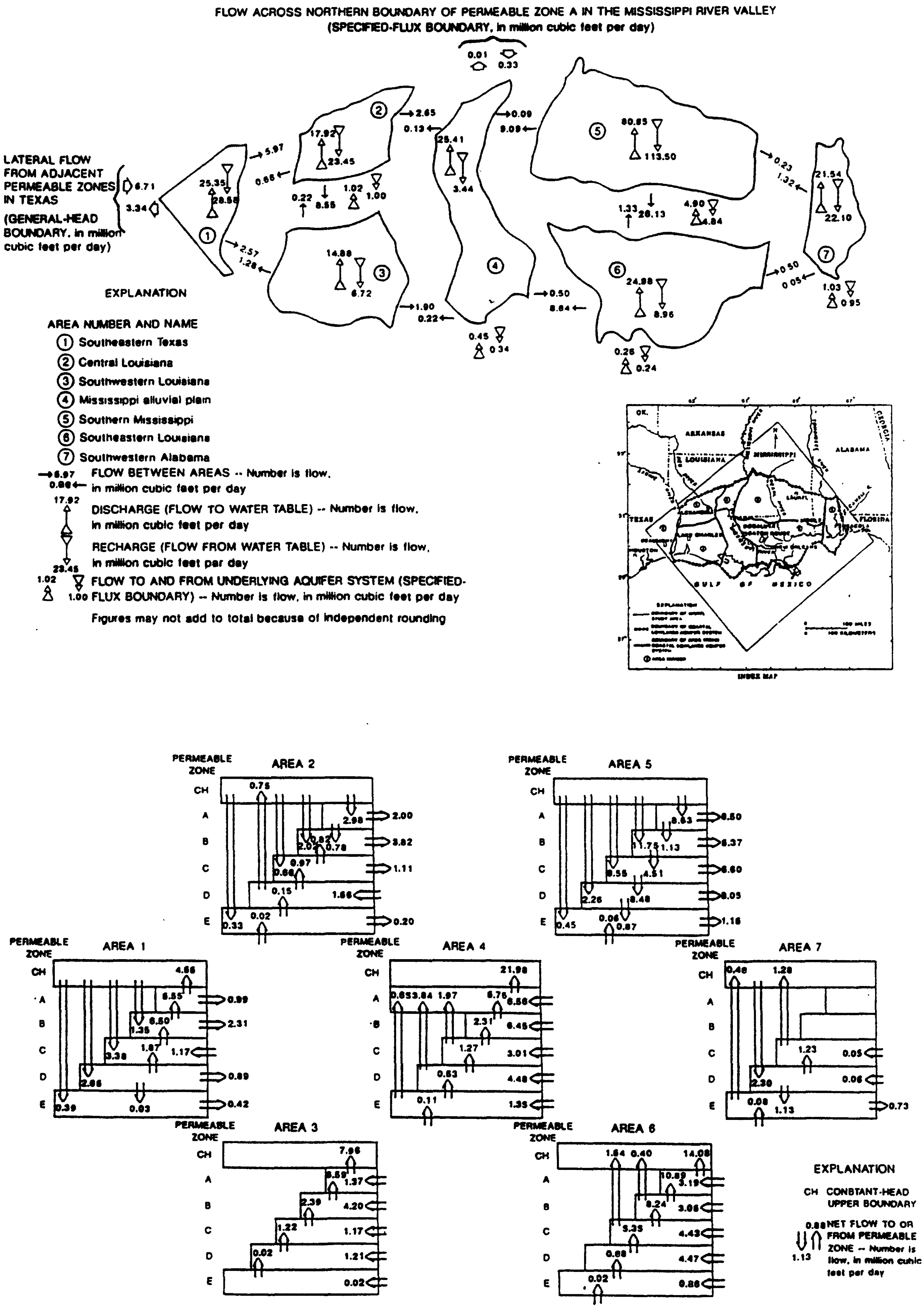


Figure 21.--Simulated flow within and between areas and across boundaries of the coastal lowlands aquifer system under predevelopment conditions.

southern Mississippi (area 5). The lower altitude coastal plain had net discharge from the aquifer system, 8.0 Mft^3/d in southwestern Louisiana (area 3) and 15.9 Mft^3/d in southeastern Louisiana (area 6). Net flow of about 21.5 Mft^3/d of water entered the Mississippi Alluvial Plain (area 4) laterally from the adjoining areas (areas 2, 3, 5, and 6, figure 21). Most of the lateral flow, about 17.3 Mft^3/d (80 percent), was westward from the southern Mississippi and southeastern Louisiana areas. Net vertical flow within the Mississippi Alluvial Plain (area 4) was upward in all permeable zones because the valley drained a large part of the aquifer system during predevelopment time. Three of the areas had net discharge, southwestern and southeastern Louisiana (areas 3 and 6) and the Mississippi Alluvial Plain (area 4). Nearly half of the total discharge from the three areas (22.2 Mft^3/d) was discharged in the Mississippi Alluvial Plain area. Southeastern Texas (area 1) and southwestern Alabama (area 7) had relatively small rates of net recharge, 3.2 Mft^3/d and 0.6 Mft^3/d. In addition to recharge, the aquifer system received relatively small net inflows from the west (3.4 Mft^3/d to the southeastern Texas area), from the north (0.3 Mft^3/d to the Mississippi Alluvial Plain area from the Mississippi River valley alluvial aquifer), and from below (0.3 Mft^3/d as upward leakage through the Vicksburg-Jackson confining unit).

1987 Flow System

Ground-water pumpage has significantly altered the natural ground-water flow system. Comparison of simulated results for 1987 conditions (figs. 22-27, 30) with results for predevelopment conditions (figs. 16-21) indicates that major changes in water-level altitudes and flow rates have occurred. Changes from predevelopment water levels caused by pumpage through 1987 are shown in figures 22a-e. Figure 23 shows water-level profiles for 1987 along the same north-south and east-west lines shown for predevelopment conditions in figure 16. Comparisons show that, in general, lateral and vertical hydraulic gradients have steepened since predevelopment time in all permeable zones and that vertical hydraulic gradients have reversed in some areas.

Intensive pumpage has produced areally extensive cones of depression in the aquifer system (figs. 24a-f). Major pumping centers in southern Louisiana, in permeable zone A, and at Baton Rouge, La., in permeable zone C, have had the greatest effect on the aquifer system. Comparison with the predevelopment maps (figs. 17a-f) indicates that hydraulic gradients between the pumping centers and recharge areas have significantly increased while gradients toward discharge areas have been reduced or reversed. Flow in the northern part of the coastal lowlands aquifer system in 1987 remains primarily southerly and toward the major river valleys from the recharge areas in the upland terraces (fig. 25). Throughout most of the coastal plain of southern Louisiana, ground-water pumpage has altered or reversed flow directions and caused flow to converge toward the major pumping centers.

The rate of simulated recharge to the aquifer system under 1987 conditions is shown in figure 26. Comparison to the map of predevelopment flows (fig. 19) indicates that large parts of the Gulf Coastal Plain have been

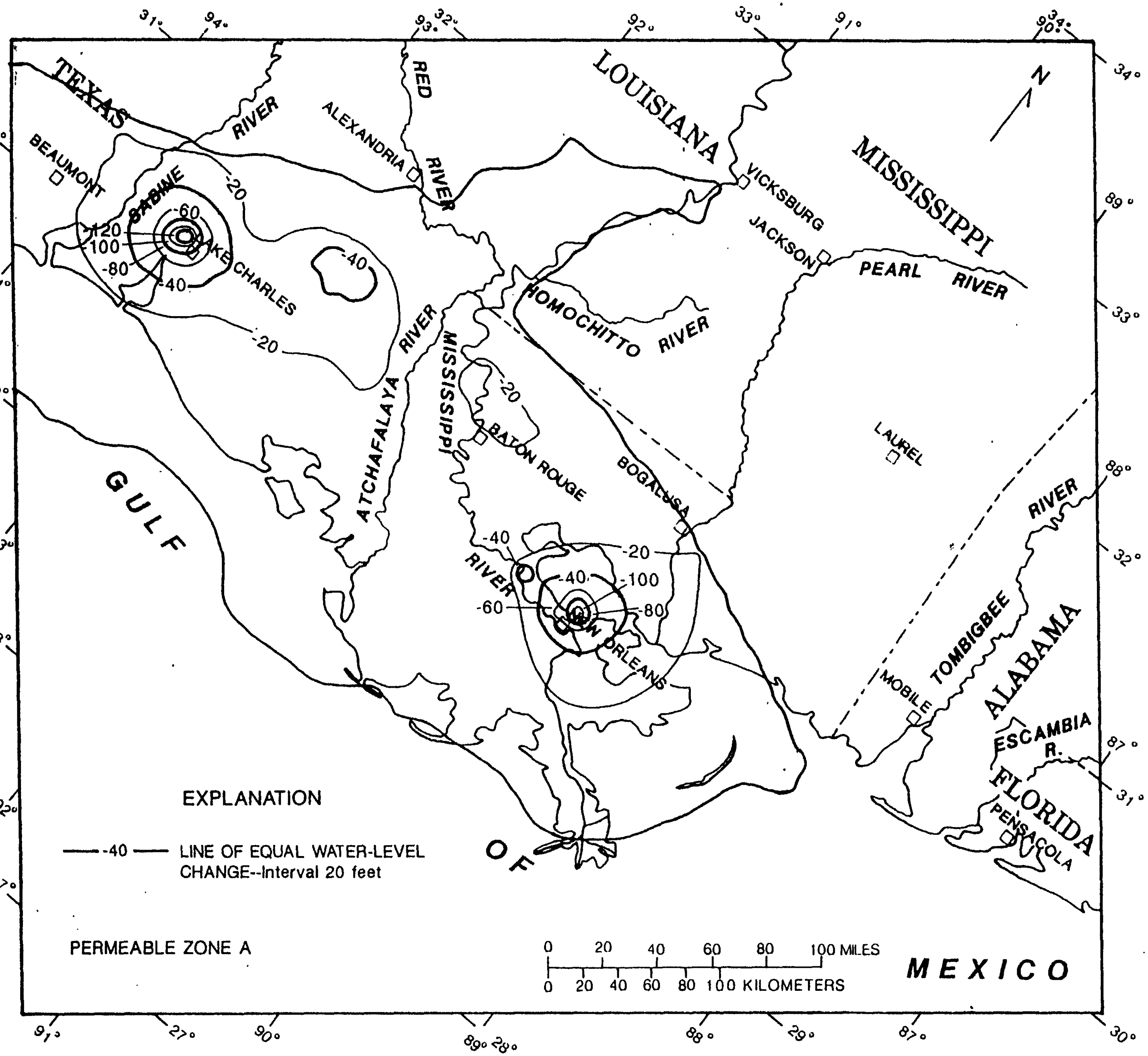


Figure 22a.--Changes from predevelopment water levels caused by pumpage through 1987, permeable zone A.

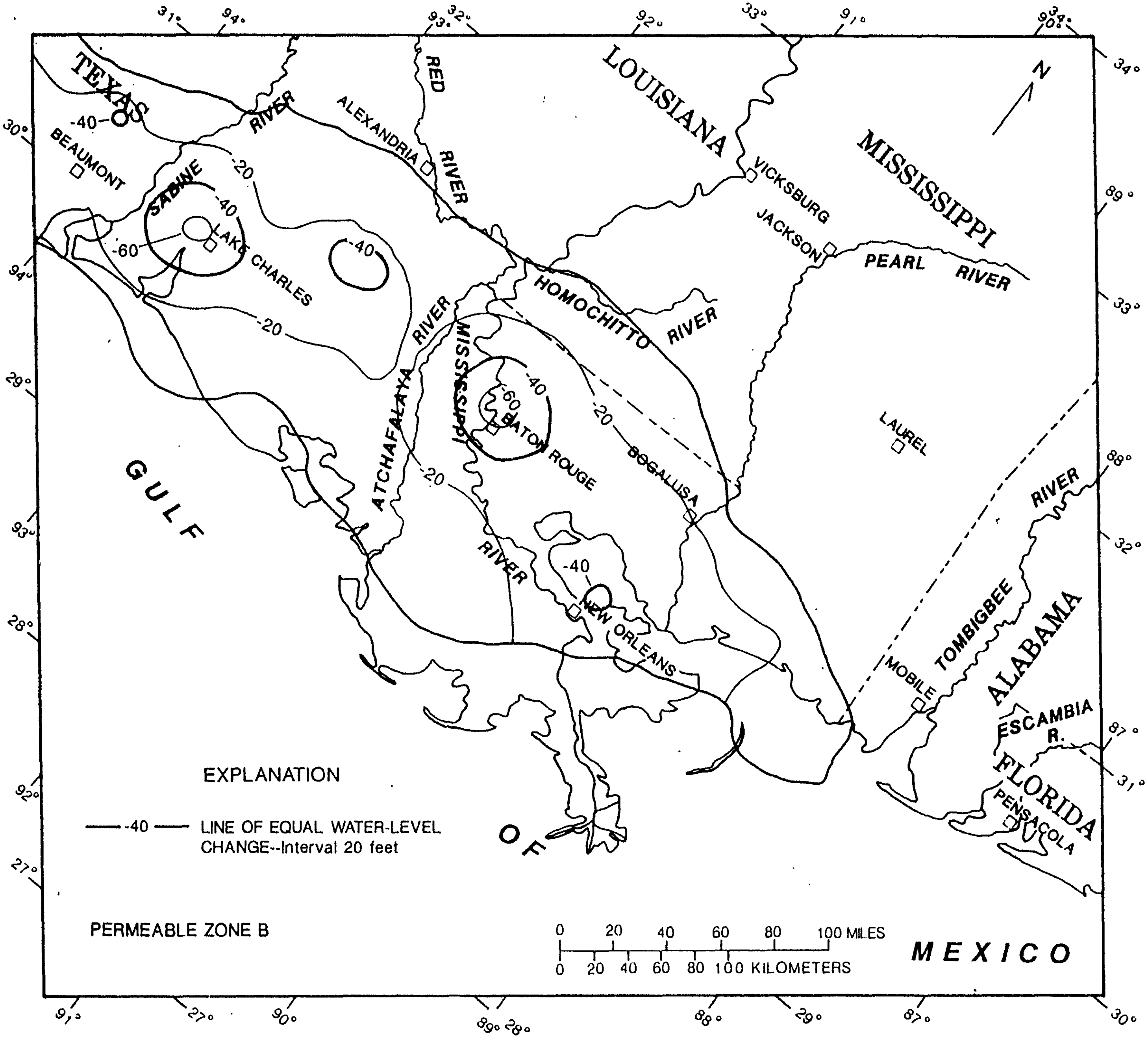


Figure 22b.--Changes from predevelopment water levels caused by pumpage through 1987, permeable zone B.

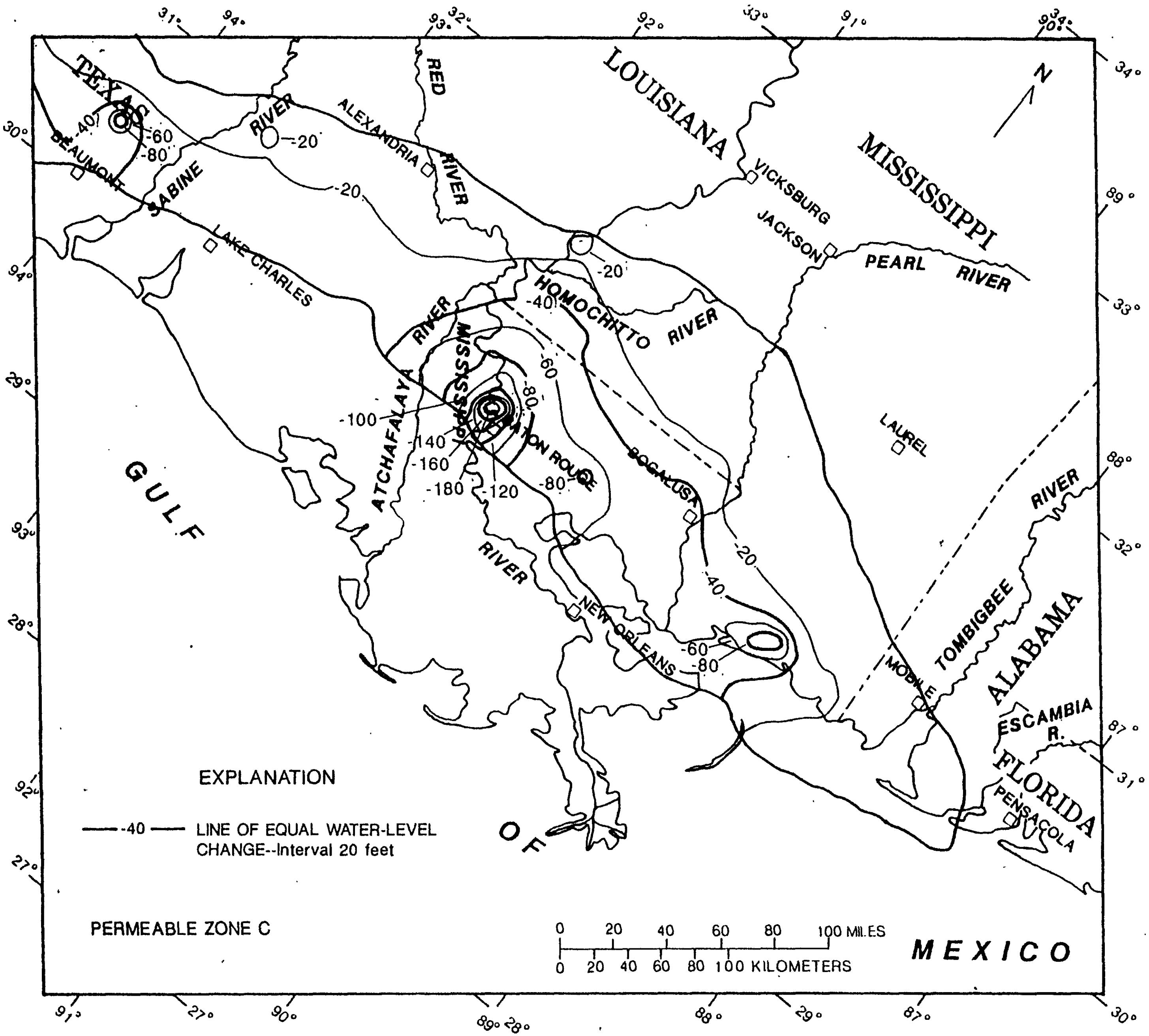


Figure 22c.--Changes from predevelopment water levels caused by pumpage through 1987, permeable zone C.

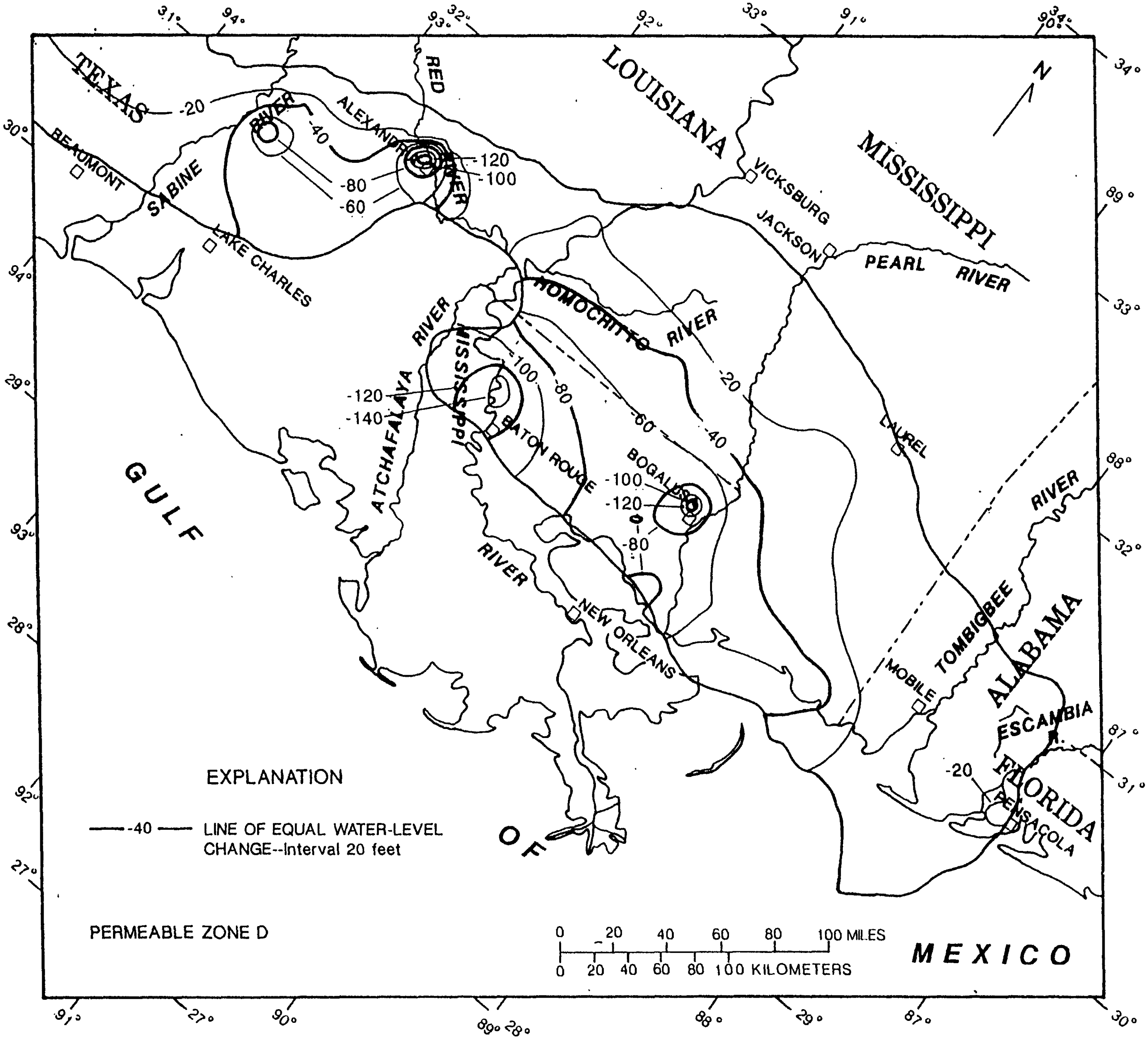


Figure 22d.--Changes from predevelopment water levels caused by pumpage through 1987, permeable zone D.

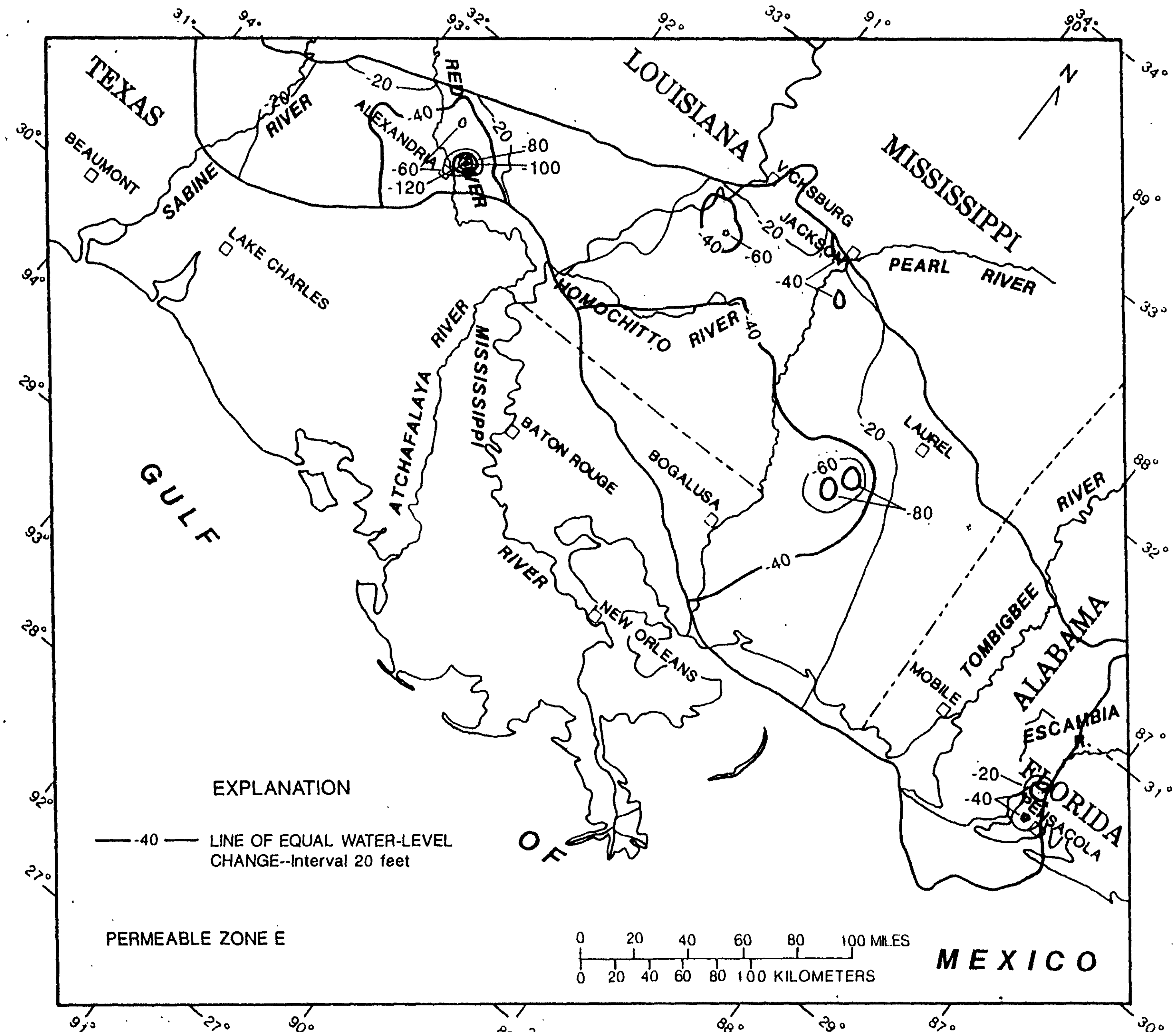


Figure 22e.--Changes from predevelopment water levels caused by pumpage through 1987, permeable zone E.

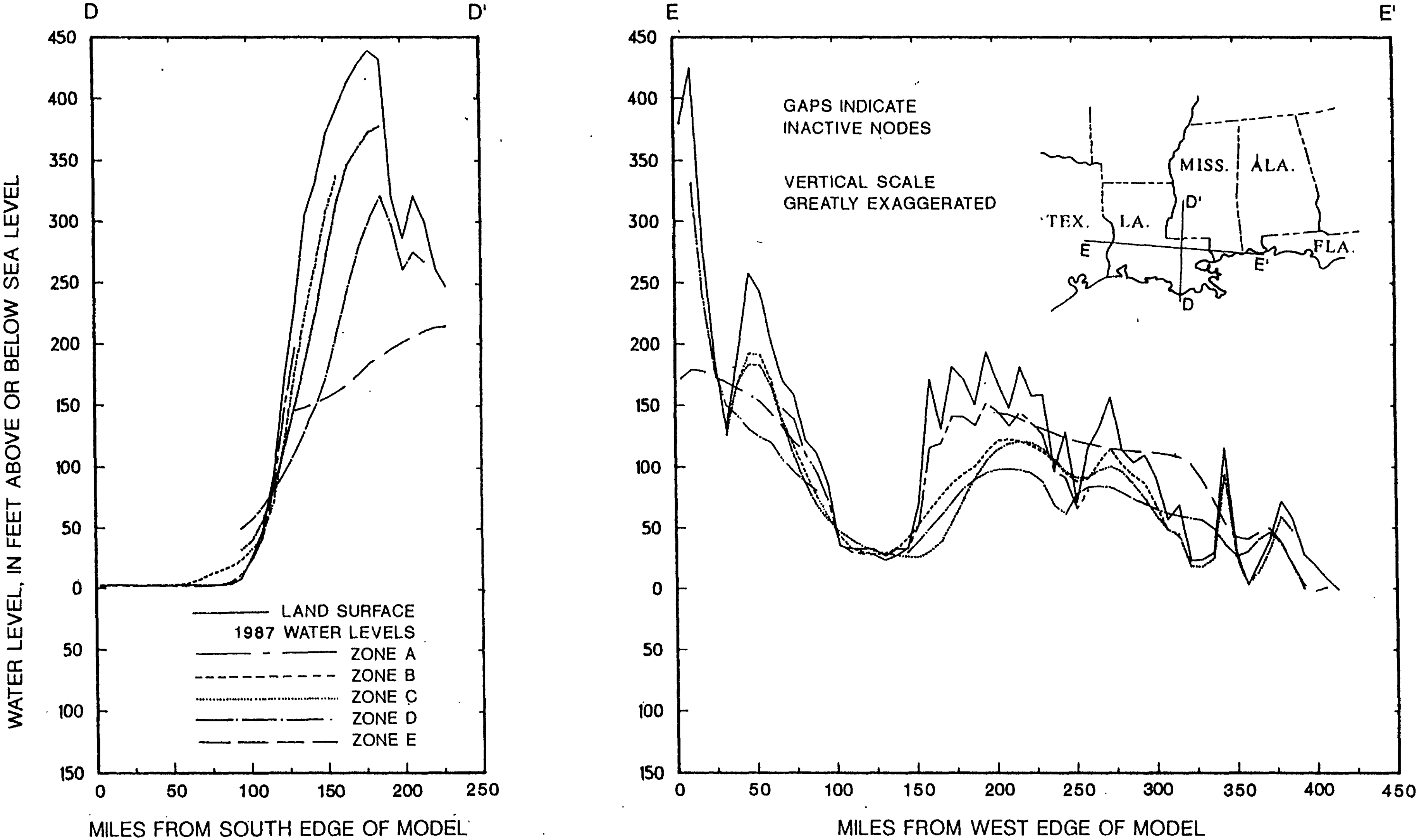


Figure 23.--Water levels in each permeable zone under 1987 conditions.

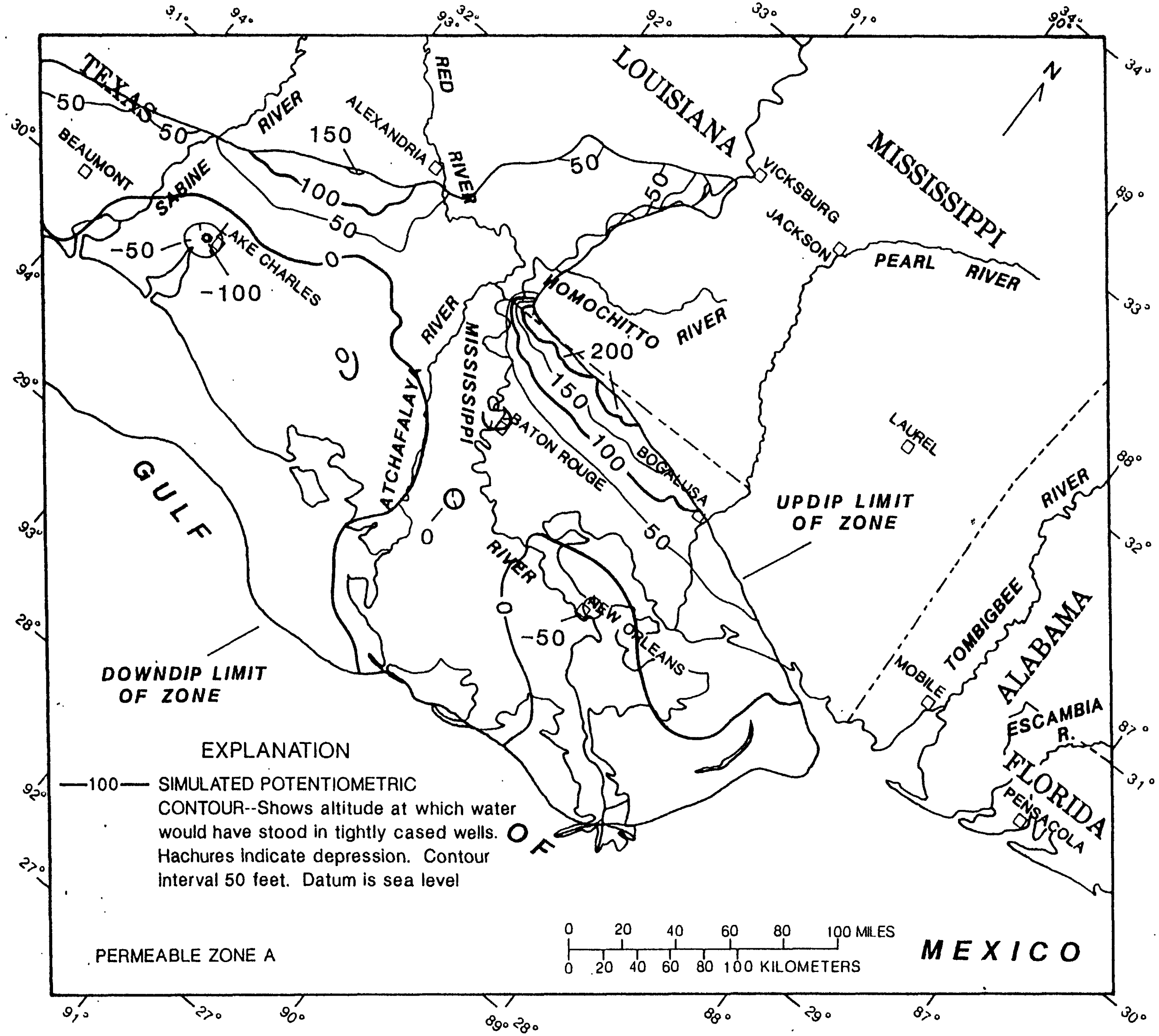


Figure 24a.--Simulated water levels under 1987 conditions, permeable zone A.

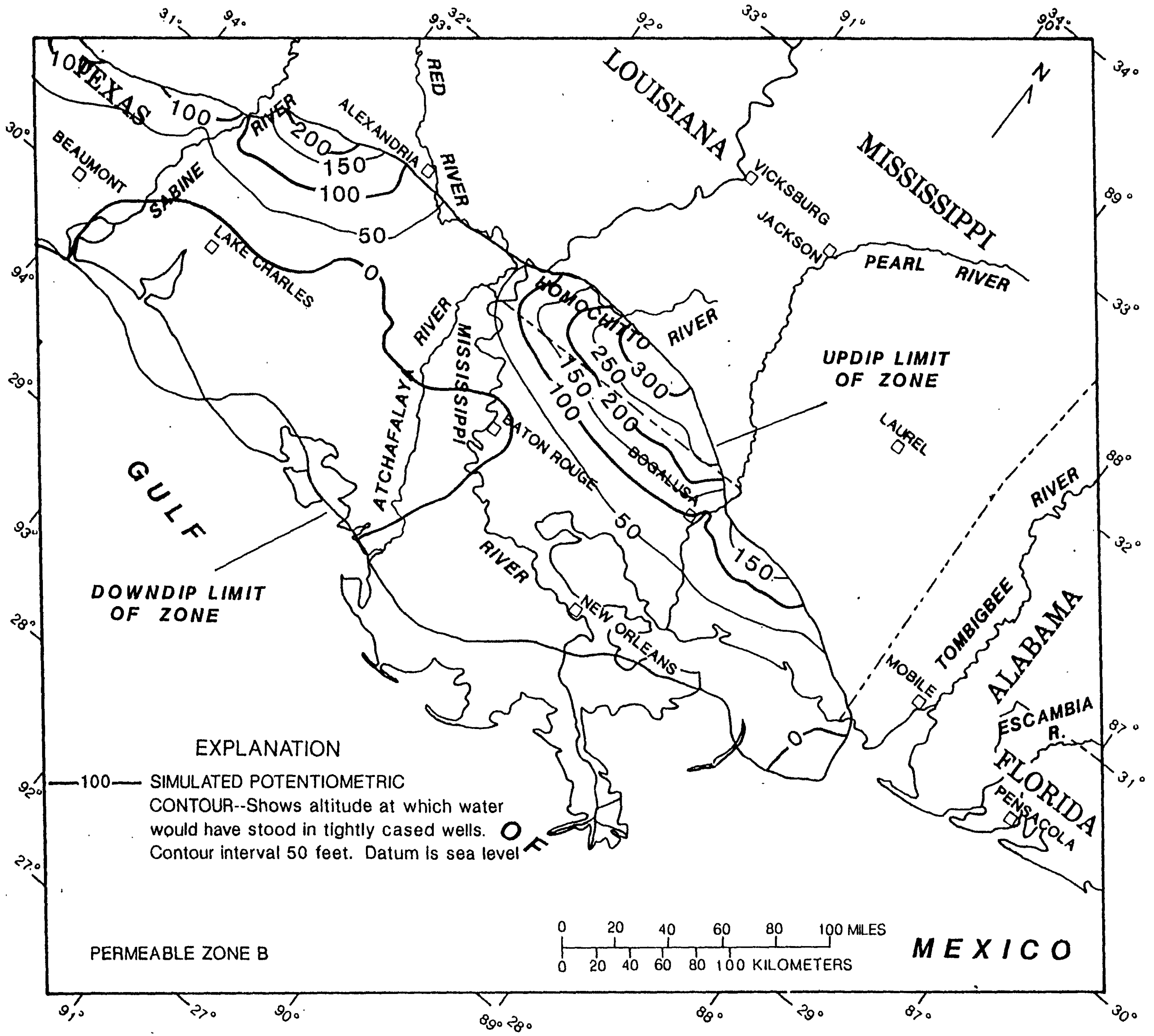


Figure 24b.--Simulated water levels under 1987 conditions, permeable zone B.

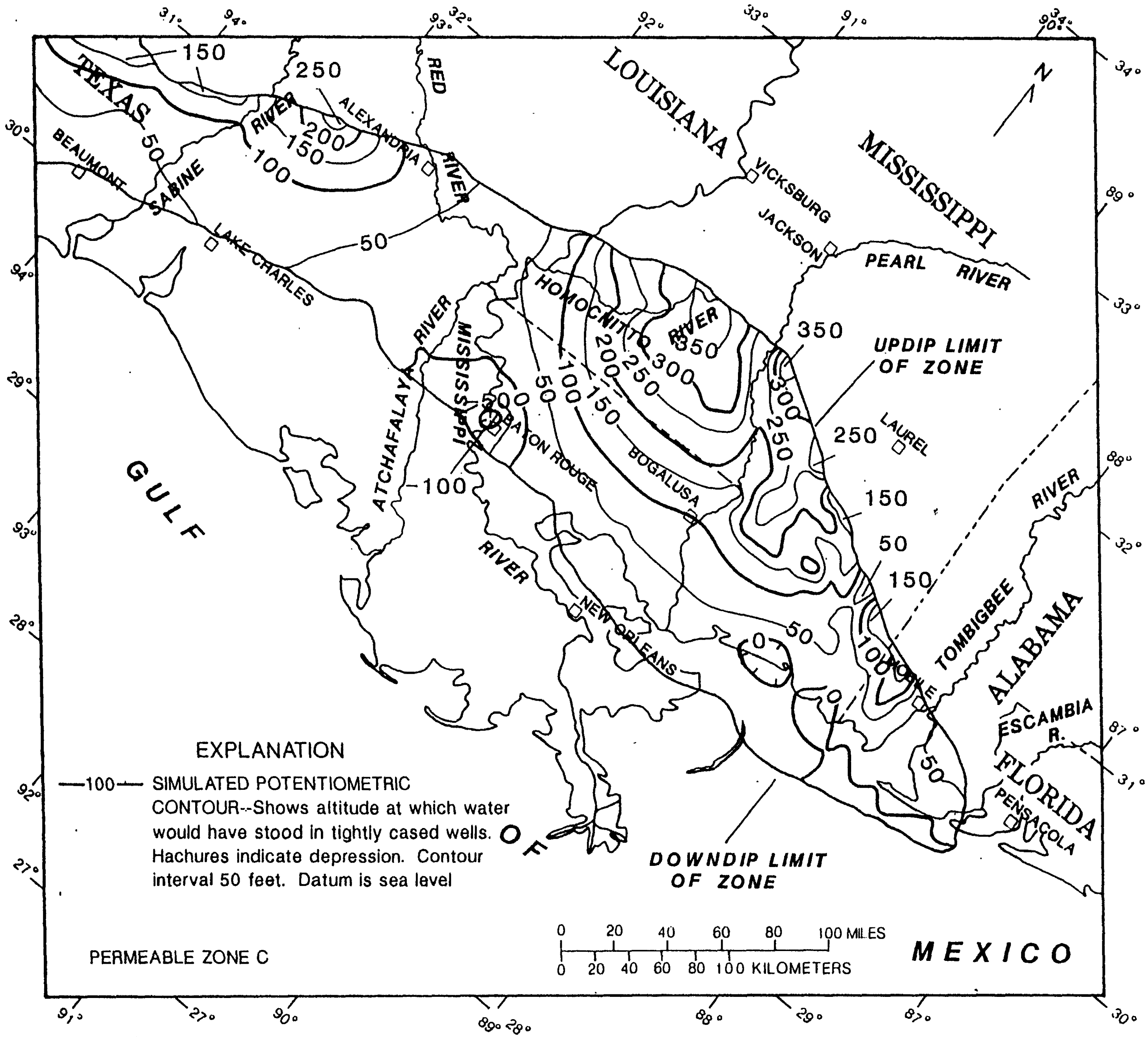


Figure 24c.--Simulated water levels under 1987 conditions, permeable zone C.

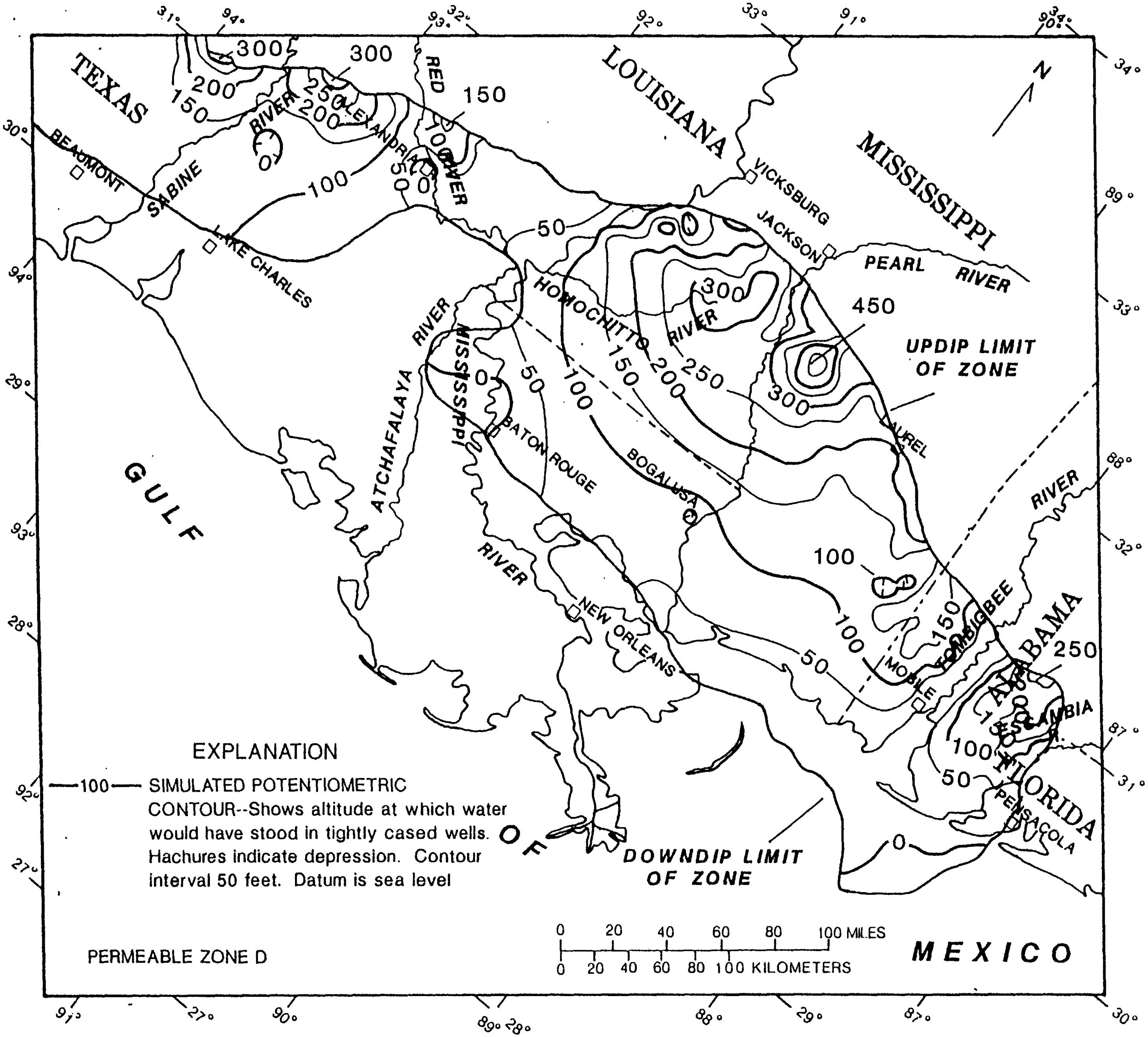


Figure 24d.--Simulated water levels under 1987 conditions, permeable zone D.

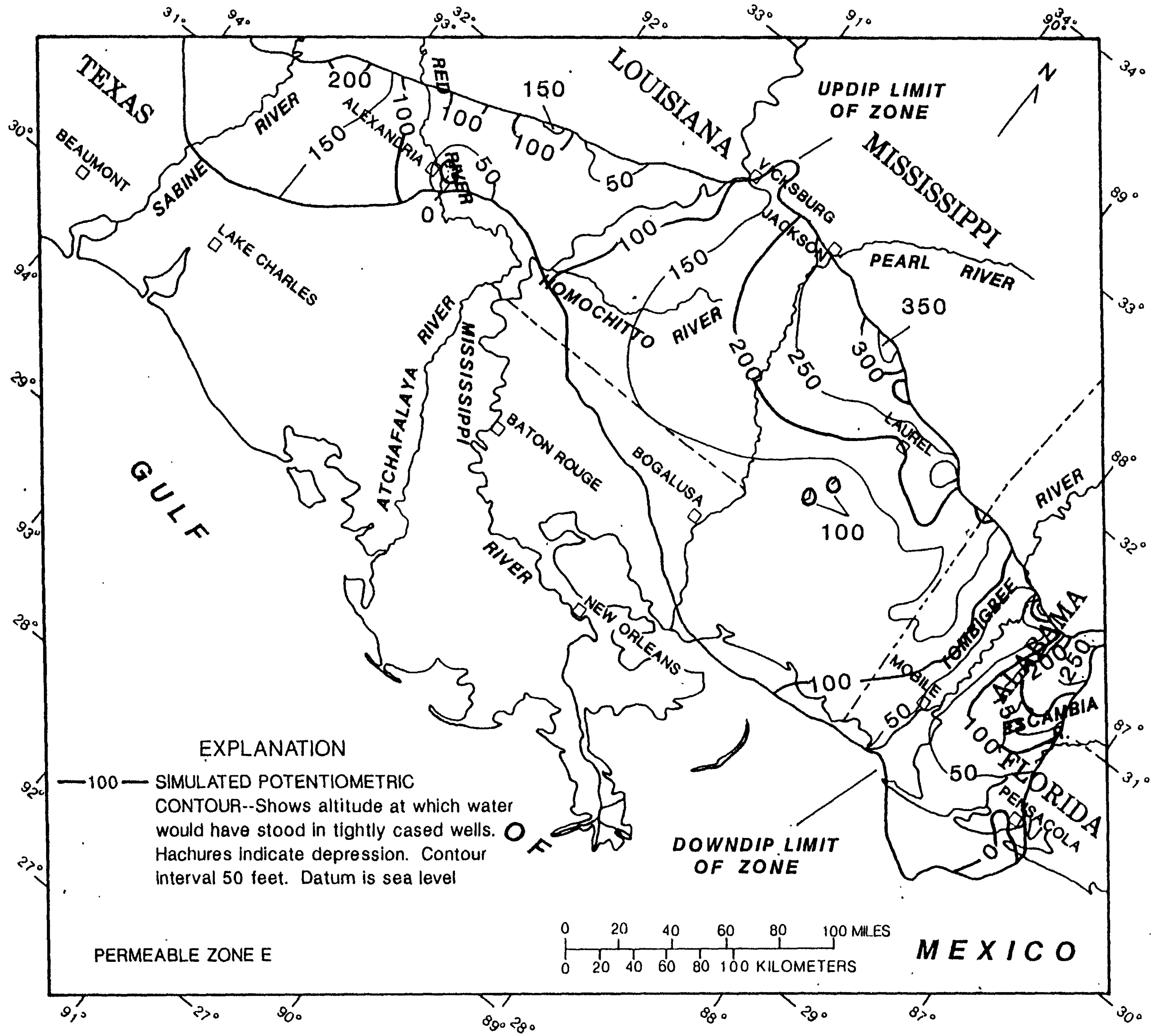


Figure 24e.--Simulated water levels under 1987 conditions, permeable zone E.

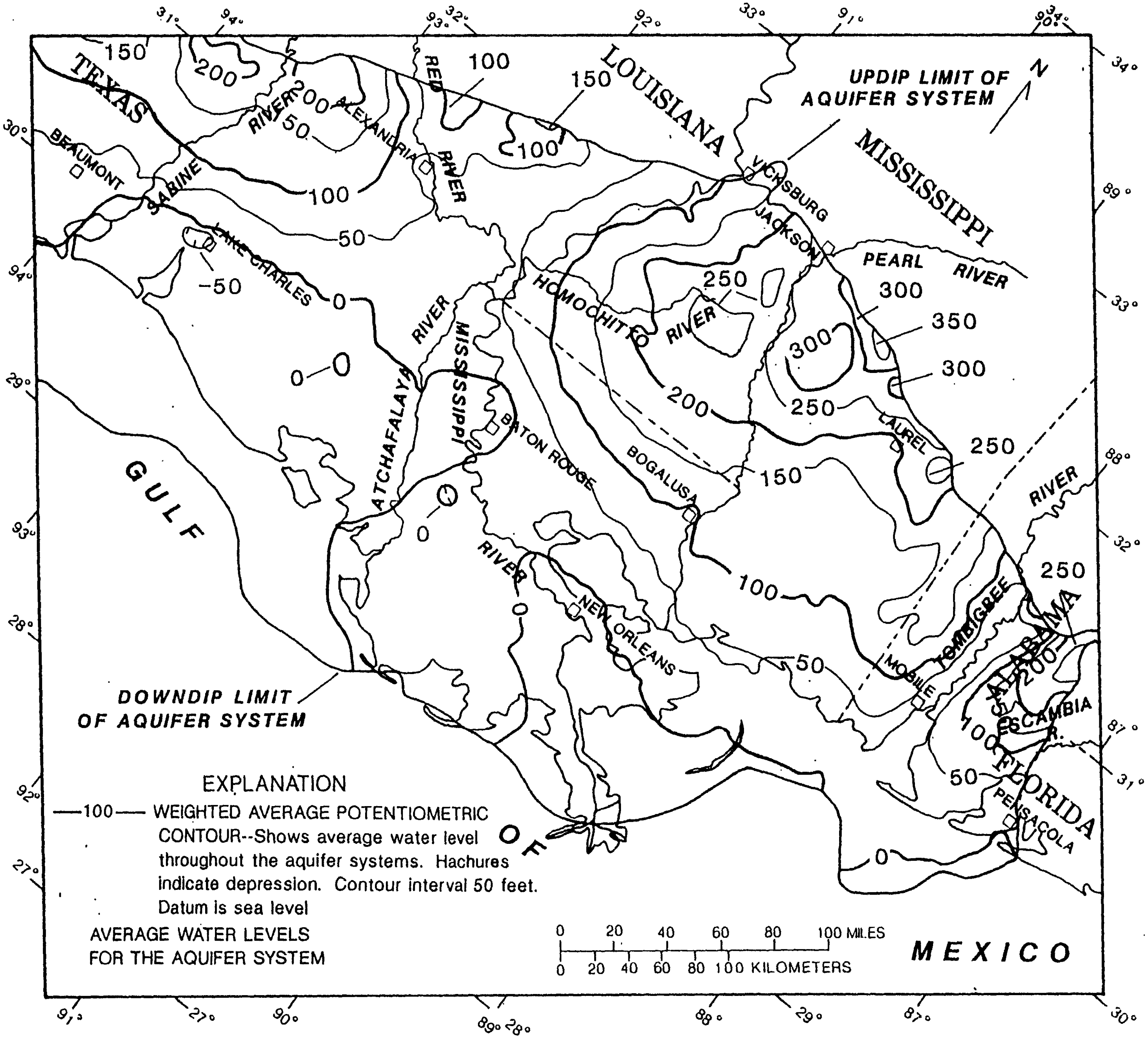


Figure 24f.--Simulated water levels under 1987 conditions, average water levels for the aquifer system.

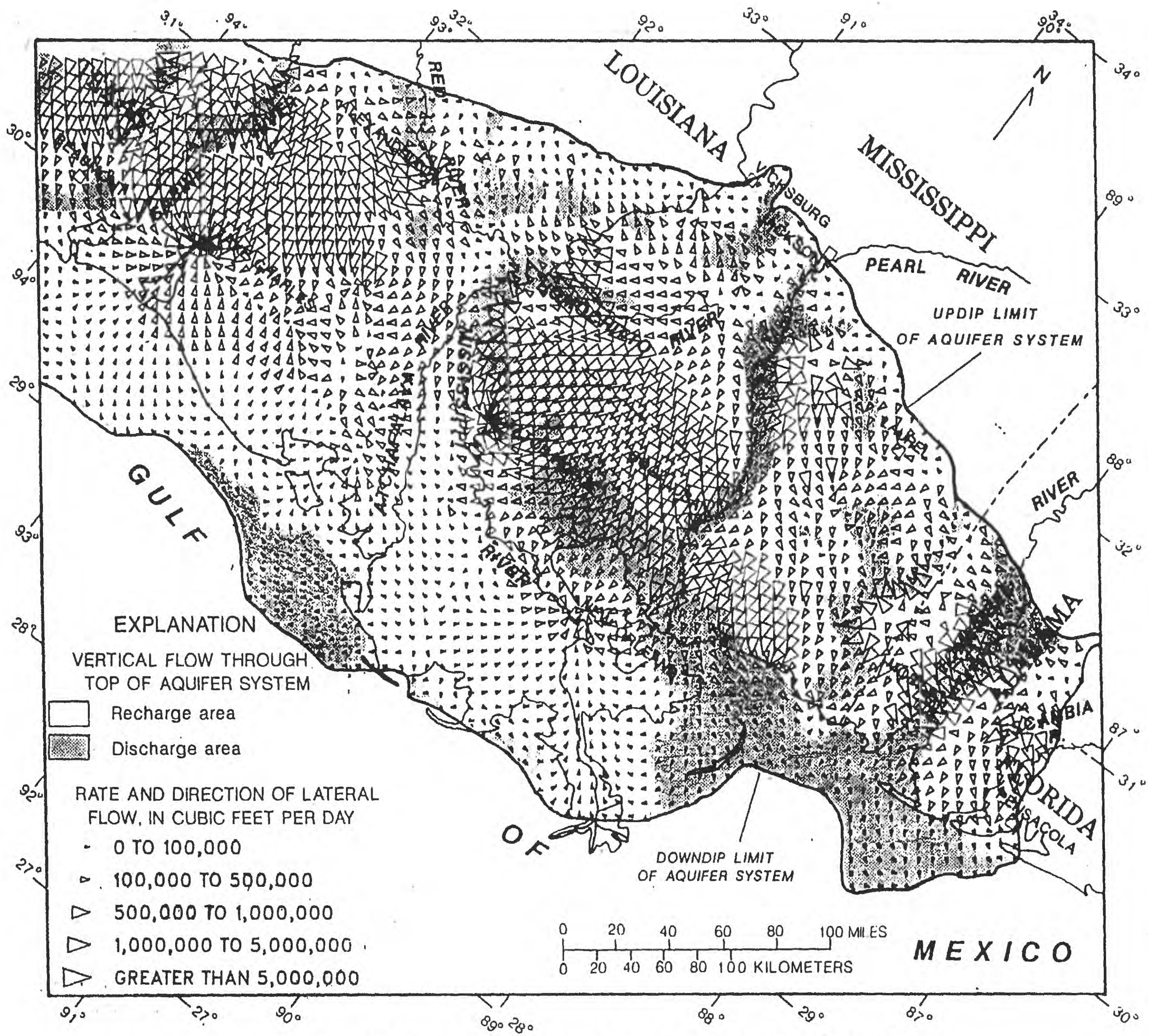


Figure 25.--Simulated ground-water flow in the aquifer system under 1987 conditions.

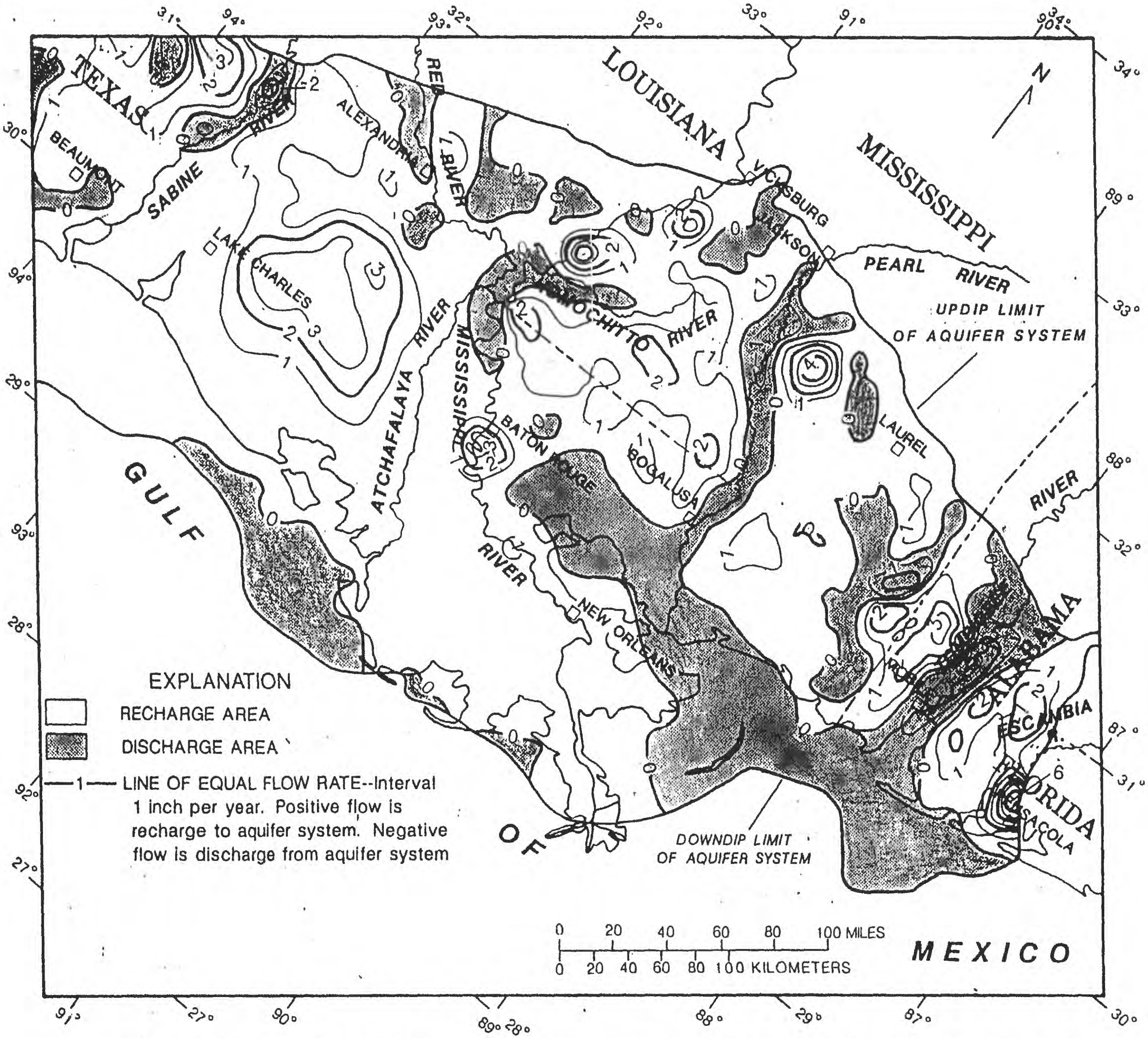
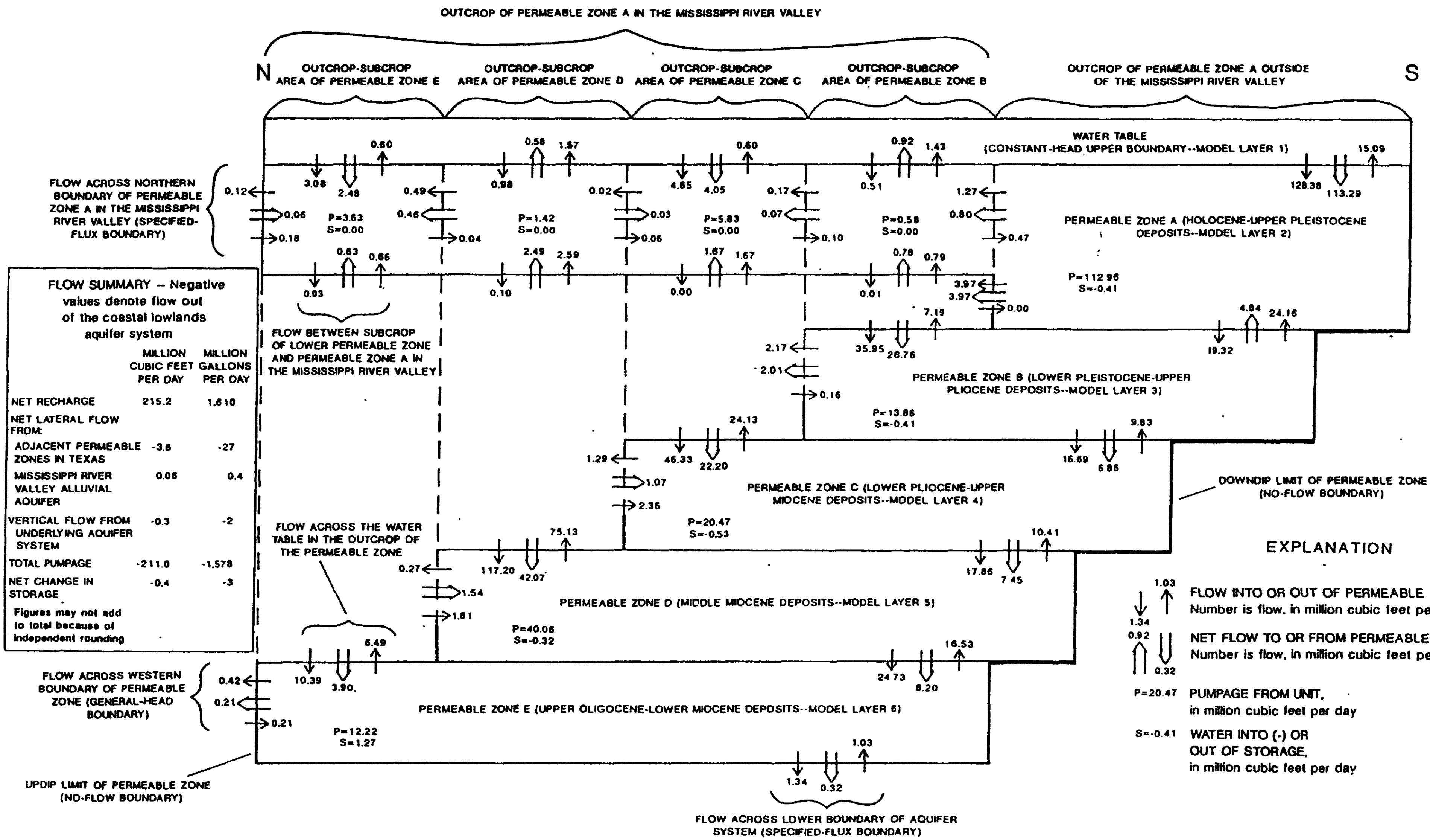


Figure 26.--Areal distribution of simulated recharge to and discharge from the aquifer system under 1987 conditions.

transformed from areas of natural discharge to areas of recharge. A large area in southwestern Louisiana that had been discharging up to 1 in/yr under predevelopment condition receives recharge up to 3 in/yr under 1987 conditions in response to pumpage from permeable zone A. Smaller areas near major pumping centers such as Baton Rouge, La., and Pensacola, Fla., show rates of induced recharge of 3 to 6 in/yr. The distribution of flow throughout the aquifer system in 1987 is shown in figure 27. The total flow entering the regional aquifer system under 1987 conditions was about 354 Mft^3/d (about 62 percent more than the predevelopment rate of 222 Mft^3/d) and natural discharge was reduced to 143 Mft^3/d (about 65 percent of the predevelopment rate). Pumpage of 211 Mft^3/d (1,578 Mgal/d) accounts for about 60 percent of the total discharge from the aquifer system. The pumpage from permeable zone A of 124 Mft^3/d (928 Mgal/d) amounts to about 35 percent of the total discharge. Pumpage of 86.6 Mft^3/d (647.8 Mgal/d) from permeable zones B through E makes up about 25 percent of the total discharge.

Less than one percent of the total flow into or out of the aquifer system under 1987 conditions is caused by water moving into or out of storage. Pumping rates decreased in permeable zones A through C after 1980 causing water levels to recover and the amount of water in storage to increase in these zones (fig. 27). Pumping rates increased in permeable zones D and E. Of the increased pumpage from permeable zone E, about 1.3 Mft^3/d is derived from storage.

The relation between cumulative pumpage since the beginning of development and the cumulative flows derived from recharge from the water table, lateral flow from adjacent aquifers, flow from the underlying Mississippi embayment aquifer system, and flow from storage within the aquifer system for the period 1958-87 is shown in figure 28. About 6 percent of the water pumped from the aquifer system prior to 1958 was derived from a decrease in storage, lateral flow from adjacent aquifers and permeable zones, and vertical flow from the underlying aquifer system. By 1987, the cumulative decrease in storage plus lateral and vertical flow from beyond the study area was less than 4 percent of the total amount of water pumped. Figure 29 shows separately the amounts of water derived from storage, lateral flow from adjacent aquifers, and vertical flow from the underlying aquifer system in the period 1958-87. The cumulative volume of water derived from storage increased through the first 8 pumping periods (1898-1982). In pumping period 9 (1983-87), water goes into storage as water levels rise due to a decrease in overall pumpage. The natural flow of water into the western parts of the model area in Texas had been reversed to a net outflow by pumping period 4 (1958-62). Increasing outflow from 1973 through 1987 (pumping periods 7 through 9) coincided with relatively large increases in pumpage outside of the study area in southeastern Texas and decreases in industrial pumpage within the study area at Lake Charles, La. The cumulative flow of water into the aquifer system from the north in the Mississippi River valley alluvial aquifer and upward through the underlying Vicksburg-Jackson confining unit reached a maximum in 1967. The cumulative total held relatively steady through 1977 and then declined from 1978 to 1987 as flow from the north decreased and inflow through the Vicksburg-Jackson confining unit reversed to a net outflow.



FLOW SUMMARY -- Negative values denote flow out of the coastal lowlands aquifer system

	MILLION CUBIC FEET PER DAY	MILLION GALLONS PER DAY
NET RECHARGE	215.2	1,610
NET LATERAL FLOW FROM:		
ADJACENT PERMEABLE ZONES IN TEXAS	-3.6	-27
MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER	0.06	0.4
VERTICAL FLOW FROM UNDERLYING AQUIFER SYSTEM	-0.3	-2
TOTAL PUMPAGE	-211.0	-1,578
NET CHANGE IN STORAGE	-0.4	-3

Figures may not add to total because of independent rounding

Figure 27.--Simulated flow between permeable zones and across boundaries of the coastal lowlands aquifer system under 1987 conditions.

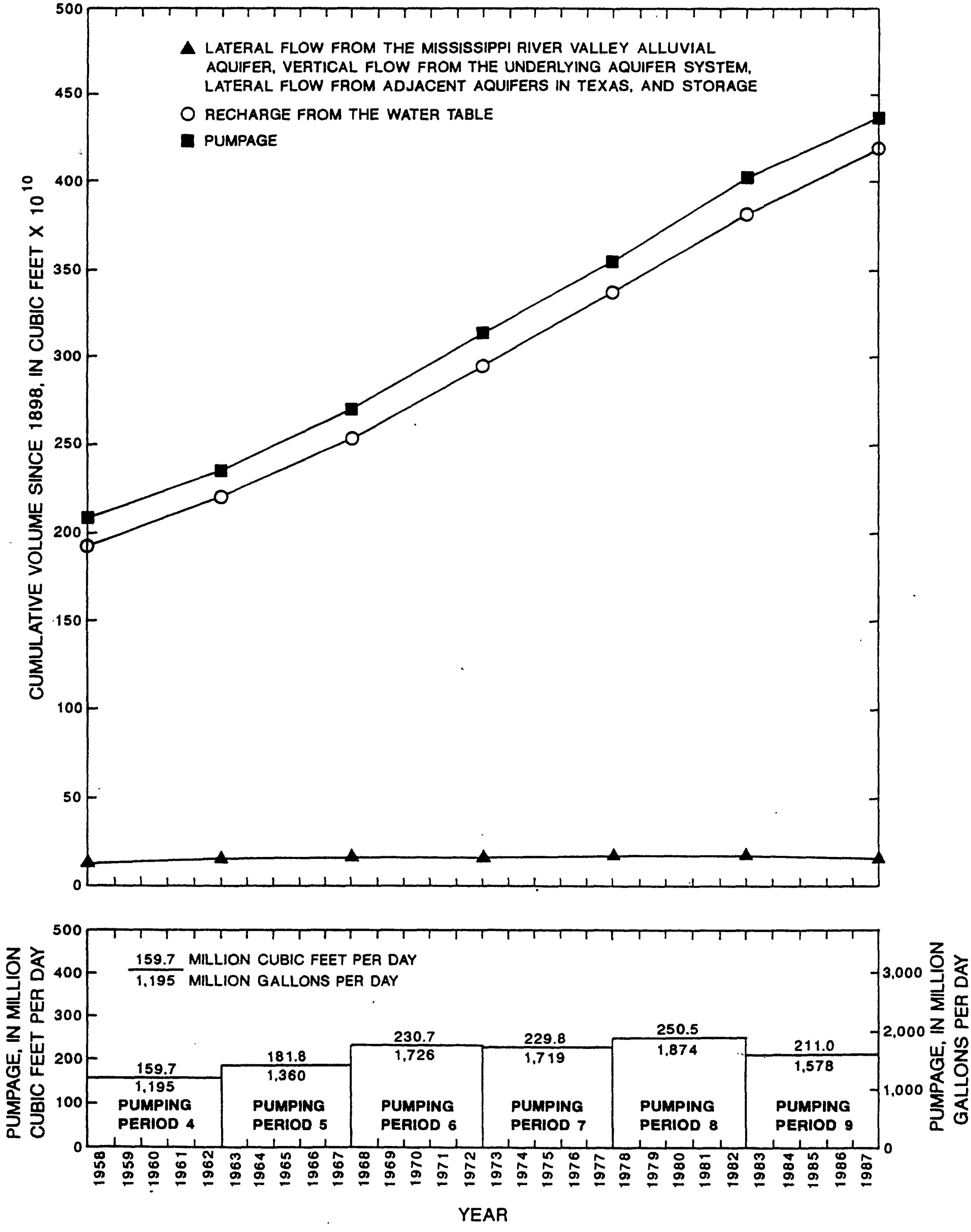


Figure 28.--Cumulative pumpage and the sources of water for the coastal lowlands aquifer system for the period 1958-87.

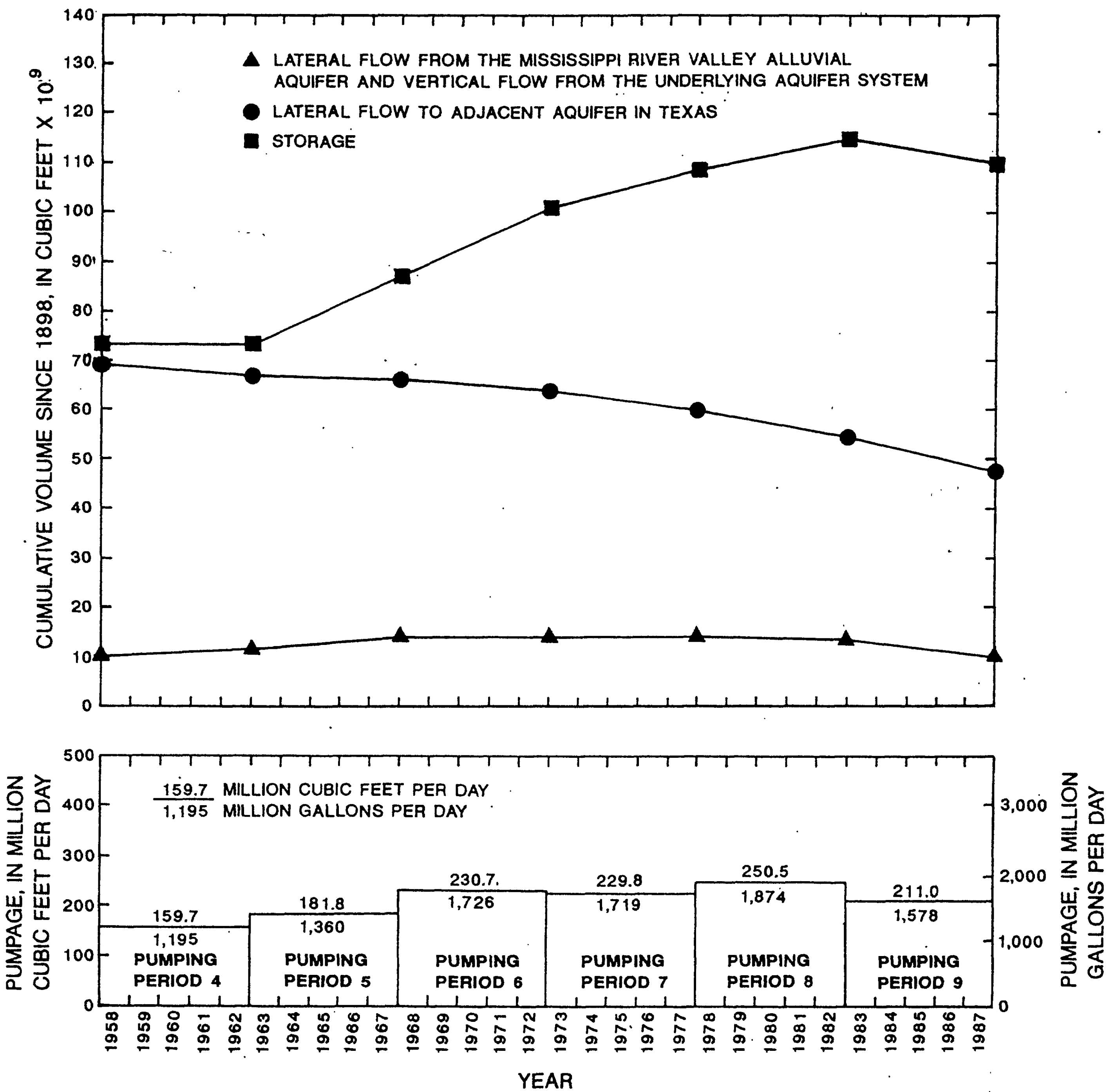


Figure 29.--Pumpage and the cumulative flow of water to or from storage and adjacent aquifers for the period 1958-87.

The distribution of flow under 1987 conditions between and within the seven areas is shown in figure 30. Comparison with the flow distribution under predevelopment conditions (fig. 21) indicates that recharge has increased into all areas. The greatest change occurred in southwestern Louisiana (area 3) where simulated recharge increased from 6.7 Mft^3/d under predevelopment conditions to 68.7 Mft^3/d in 1987 and a net discharge of 8.0 Mft^3/d to the water table under predevelopment conditions has been converted to a net recharge of 68.2 Mft^3/d from the water table in 1987. Net recharge in the Mississippi Alluvial Plain (area 4) and southeastern Louisiana (area 6) has replaced the net discharge that occurred under predevelopment conditions. Southward flows from the central Louisiana and southern Mississippi areas to the southwestern and southeastern Louisiana areas increased significantly. The Mississippi Alluvial Plain (area 4) continues to act as a drain for much of the central part of the study area, receiving net inflows from central Louisiana, southern Mississippi, and southeastern Louisiana. However, southwestern Louisiana (area 3) receives about 1.0 Mft^3/d net inflow from the Mississippi Alluvial Plain area instead of the predevelopment outflow of about 1.7 Mft^3/d. Pumpage in southwestern Louisiana (area 3) has altered gradients along the western side of the Mississippi Alluvial Plain (area 4) by capturing much of the flow that formerly drained to the Alluvial Plain and by inducing flow from the Alluvial Plain toward the pumping centers. East-west flows between other areas have not been greatly altered by pumpage.

Under 1987 conditions, a relatively small amount of water was derived from storage in southeastern Texas (area 1), central Louisiana (area 2), and southern Mississippi (area 5), indicating that water levels in parts of these areas were still declining slightly. Ground water in storage increased in southwestern Louisiana (area 3), the Mississippi Alluvial Plain (area 4), and southeastern Louisiana (area 6) as water levels generally rose slightly in response to reduced pumpage during the period 1983-87. There was no change in storage in southwestern Alabama (area 7) in 1987, indicating that the area as a whole was at steady state.

POTENTIAL OF THE AQUIFER SYSTEM FOR DEVELOPMENT

Four experiments were conducted utilizing the steady-state and transient models to evaluate the effects of possible future ground-water pumpage from the coastal lowlands aquifer system. The effects on water levels and flows of continuing the 1983-87 pumping rates and increasing or decreasing pumping rates were evaluated in three of the experiments. The fourth experiment was designed to determine which parts of the study area are hydrogeologically most favorable or least favorable for the development of large ground-water supplies without regard to the present pattern of development.

In the first model experiment, the 1983-87 pumping rate was extended for an additional 50 years (1988 to 2037). At the beginning of this experiment, water levels throughout most of the aquifer system were still changing in response to earlier changes in pumping rates and distribution. From 1980-85 pumpage decreased more than 25 percent in permeable zone A, 9 percent in permeable zone B, and 7 percent in permeable zone C; pumpage increased more than 11 percent in permeable zone D and 12 percent in permeable zone E. At

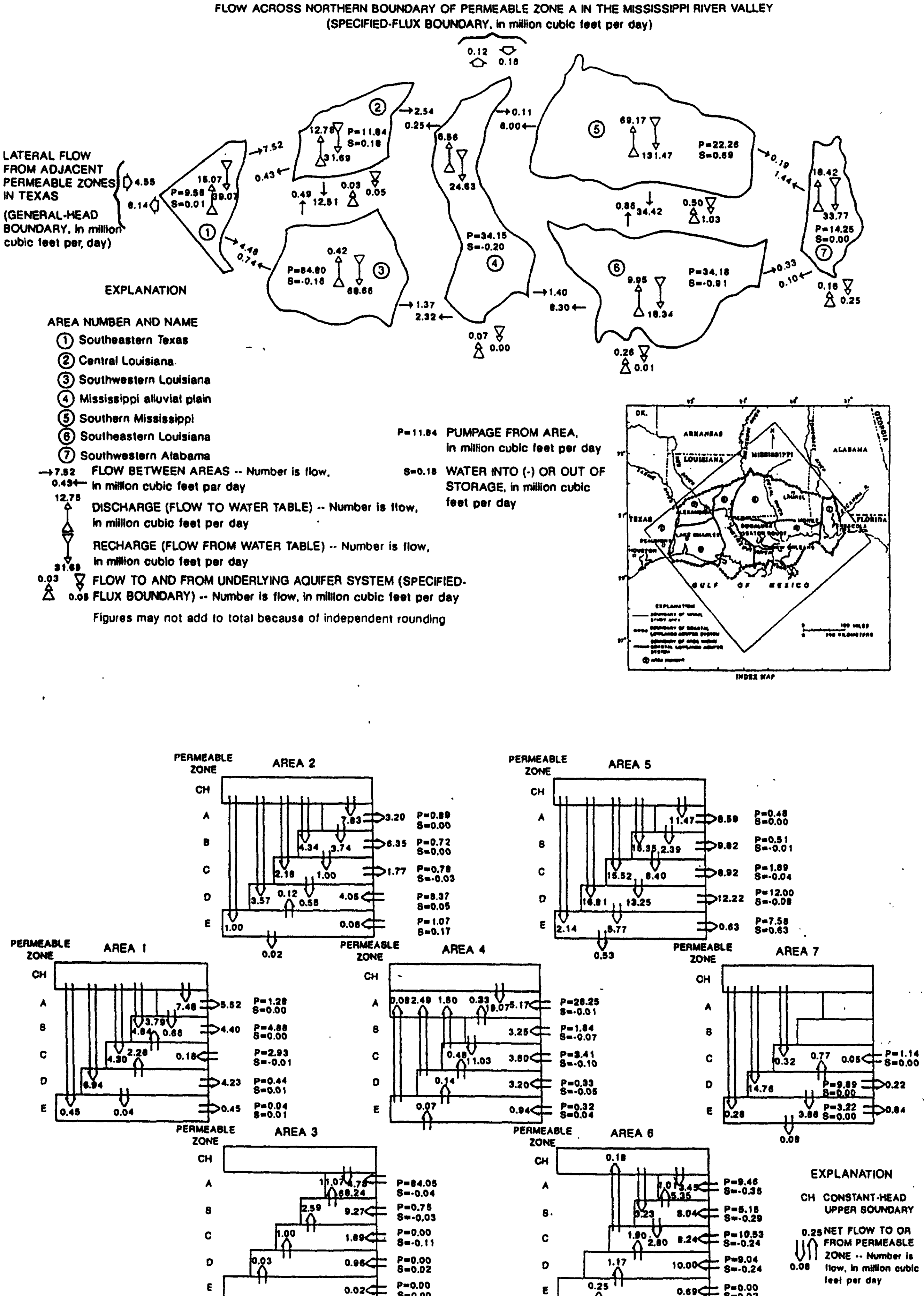


Figure 30.--Flow within and between areas and across boundaries of the coastal lowlands aquifer system under 1987 conditions.

the end of 1987, water levels were, on average, rising in permeable zones A through D, and falling in permeable zone E. By the end of the experiment in 2037, water levels were near steady state throughout the aquifer system with only permeable zones D and E showing slight declines, on average.

Simulated water-level changes, 1987-2037 with 1983-87 pumpage continued, for each permeable zone and the average change in the entire aquifer system are shown in figures 31a-f. Water levels would rise throughout permeable zones A and B and in most of permeable zone C with maximum rises of more than 2 ft in each zone. Water levels in permeable zone D would rise in southeastern Louisiana, ranging up to more than 3 ft near Baton Rouge, but would fall by less than 1 ft north of Lake Charles and by more than 1 ft in southern Mississippi. Water levels would decline throughout permeable zone E except in the outcrop area in Alabama and Florida. Maximum declines would exceed 6 ft in south-central Louisiana and 11 ft in southwestern Mississippi. The relatively large water-level declines in permeable zone E are largely the result of the low transmissivity of the zone, which slows its adjustment to changes in pumpage. At the beginning of this simulation, water levels had not yet adjusted throughout a large part of permeable zone E to the increase in pumpage that occurred between 1980-85.

Considering the entire aquifer system, average water levels would rise throughout the southern part of the study area, with rises of more than 2 ft near New Orleans and Baton Rouge, La. Average water levels would decline throughout the northern part of the study area, with maximum declines of more than 7 ft in southwestern Mississippi. Hydrographs in figure 32 show water-level changes resulting from this experiment at selected sites.

Because of the relatively small changes in water levels throughout the aquifer system, little difference would occur in the rate and direction of flow as a result of the additional 50 years of pumpage. The distribution of flow within the aquifer system at the end of the 50-year period is shown in figure 33. Comparison with 1987 conditions shows little difference in the total flow and the distribution of flow within the aquifer system. At the end of 1987, there was a net 0.4 Mft^3/d increase in aquifer system storage (fig. 27). The total gain in storage of 1.7 Mft^3/d in permeable zones A through D was greater than the loss in storage of 1.3 Mft^3/d in permeable zone E. By 2037 there would be a net inflow from storage of 0.05 Mft^3/d to permeable zones D and E (fig. 33). Net recharge to permeable zones C through E would increase slightly while net recharge to permeable zones A and B would decrease by 1.3 Mft^3/d. Net outflow across the western boundary would decrease by about 0.2 Mft^3/d.

In the second model experiment, the 1983-87 pumping rate was increased by 50 percent for a period of 50 years (1988 to 2037). Water-level changes for each permeable zone and the average change in the aquifer system resulting from this additional pumping period are shown in figures 34a-f. Because the rate of pumping was increased without changing the distribution of pumpage, water levels would be lower throughout the aquifer system, but the general patterns of water levels and flows in the aquifer system would be almost unchanged. Additional drawdown would range from less than 1 ft in parts of the outcrop areas to more than 80 ft in the Baton Rouge area in

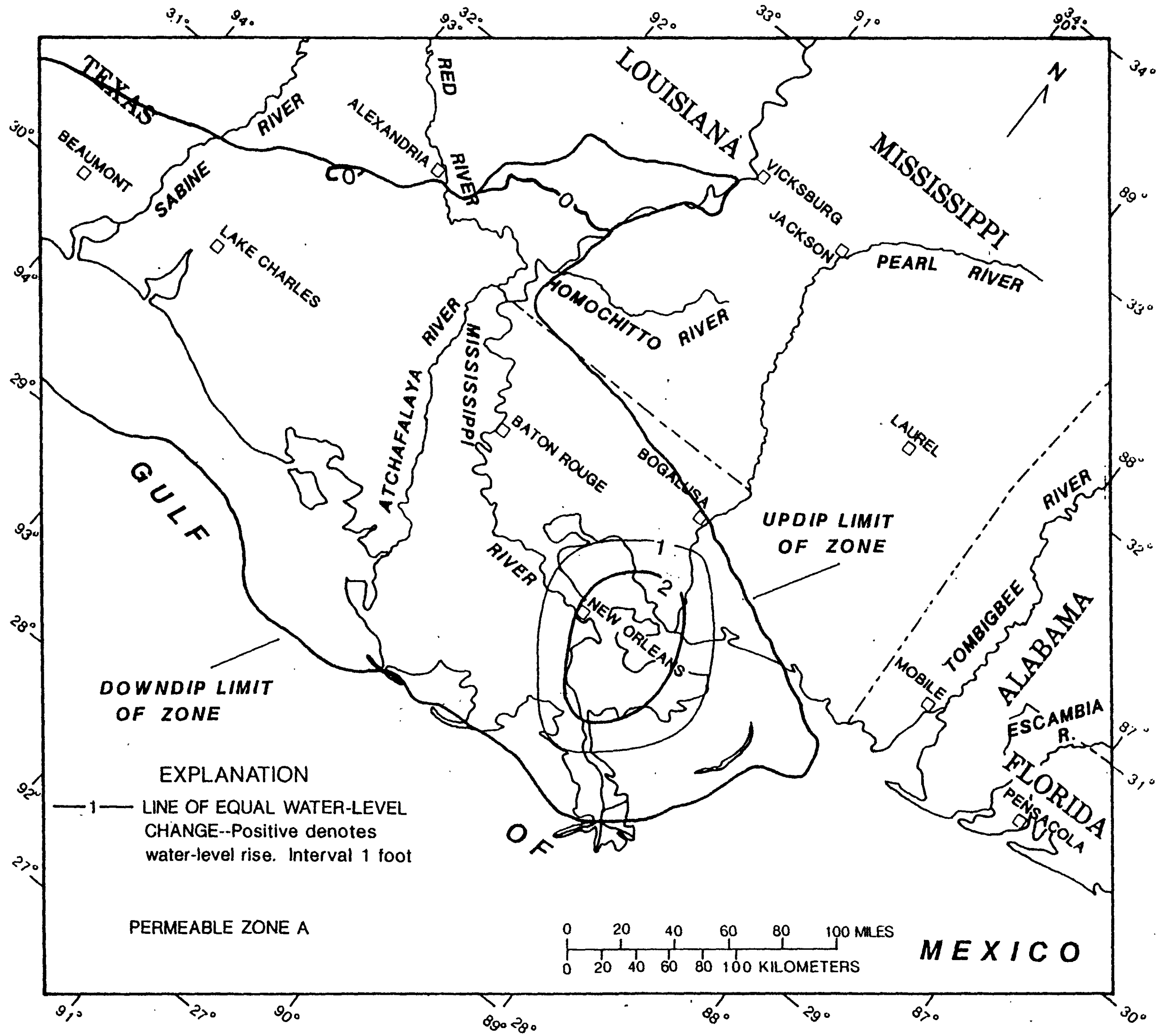


Figure 31a.--Changes from 1987 water levels resulting from an additional 50 years of pumpage at the 1983-87 rate, permeable zone A.

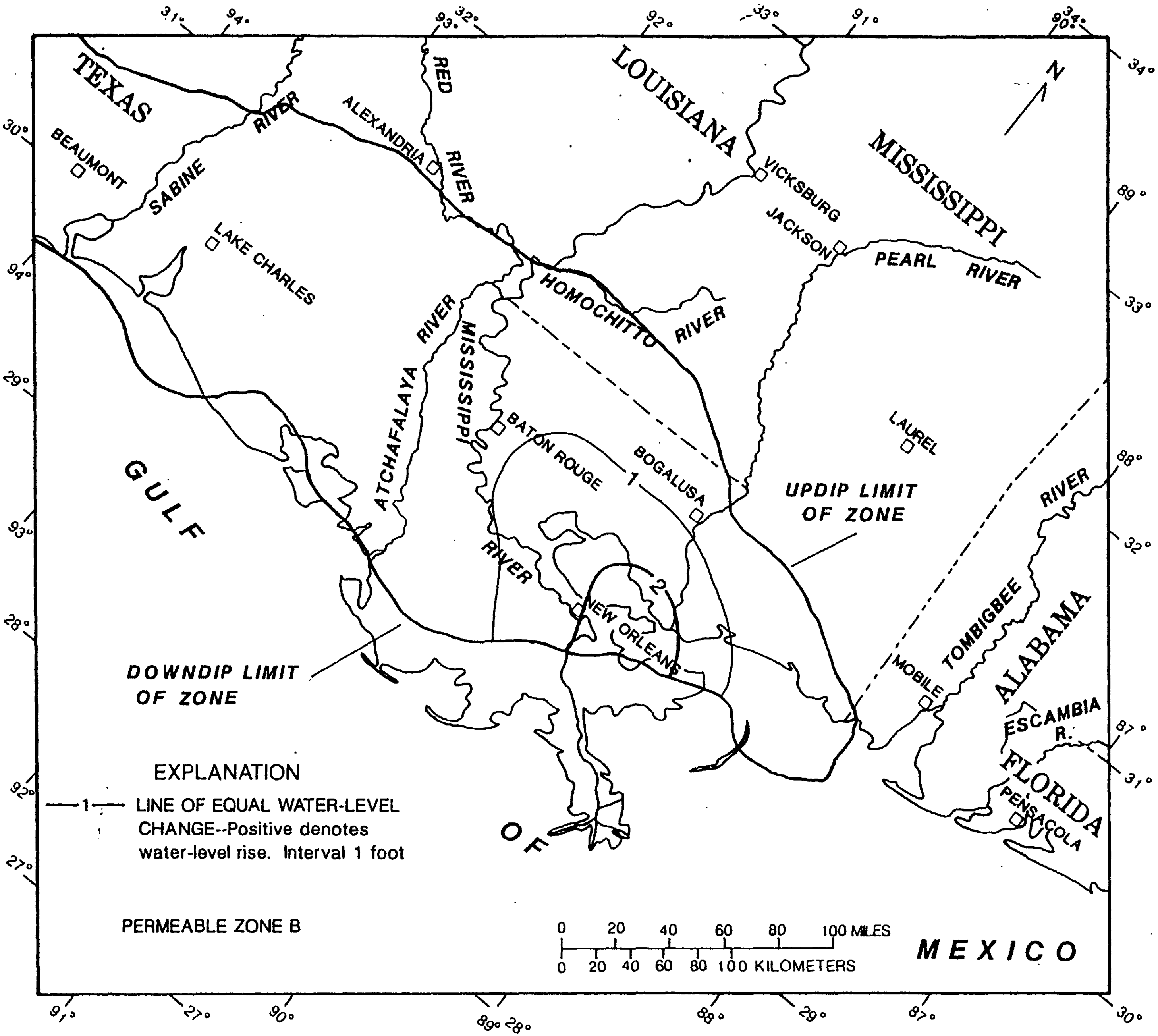


Figure 31b.--Changes from 1987 water levels resulting from an additional 50 years of pumpage at the 1983-87 rate, permeable zone B.

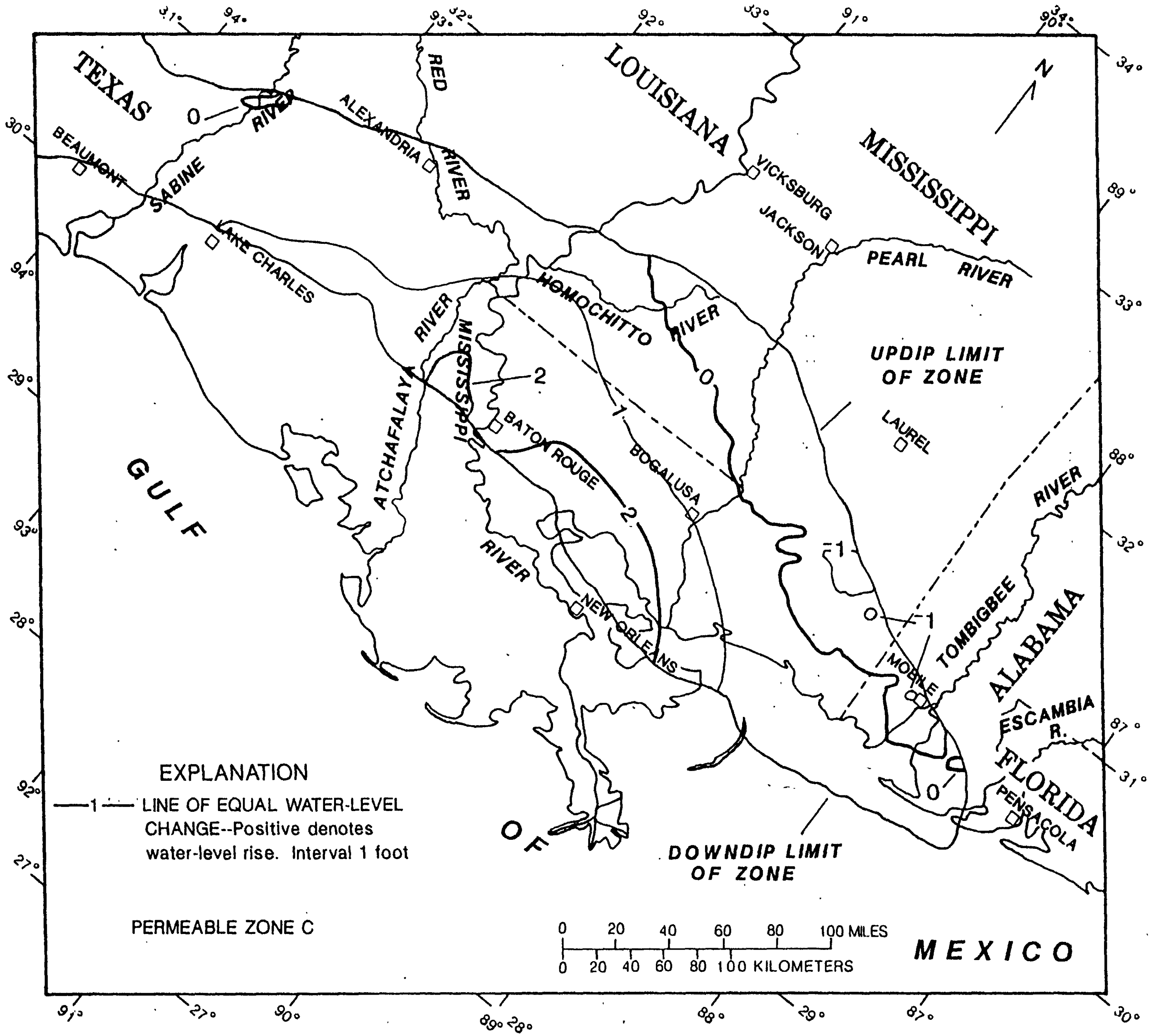


Figure 31c.--Changes from 1987 water levels resulting from an additional 50 years of pumpage at the 1983-87 rate, permeable zone C.

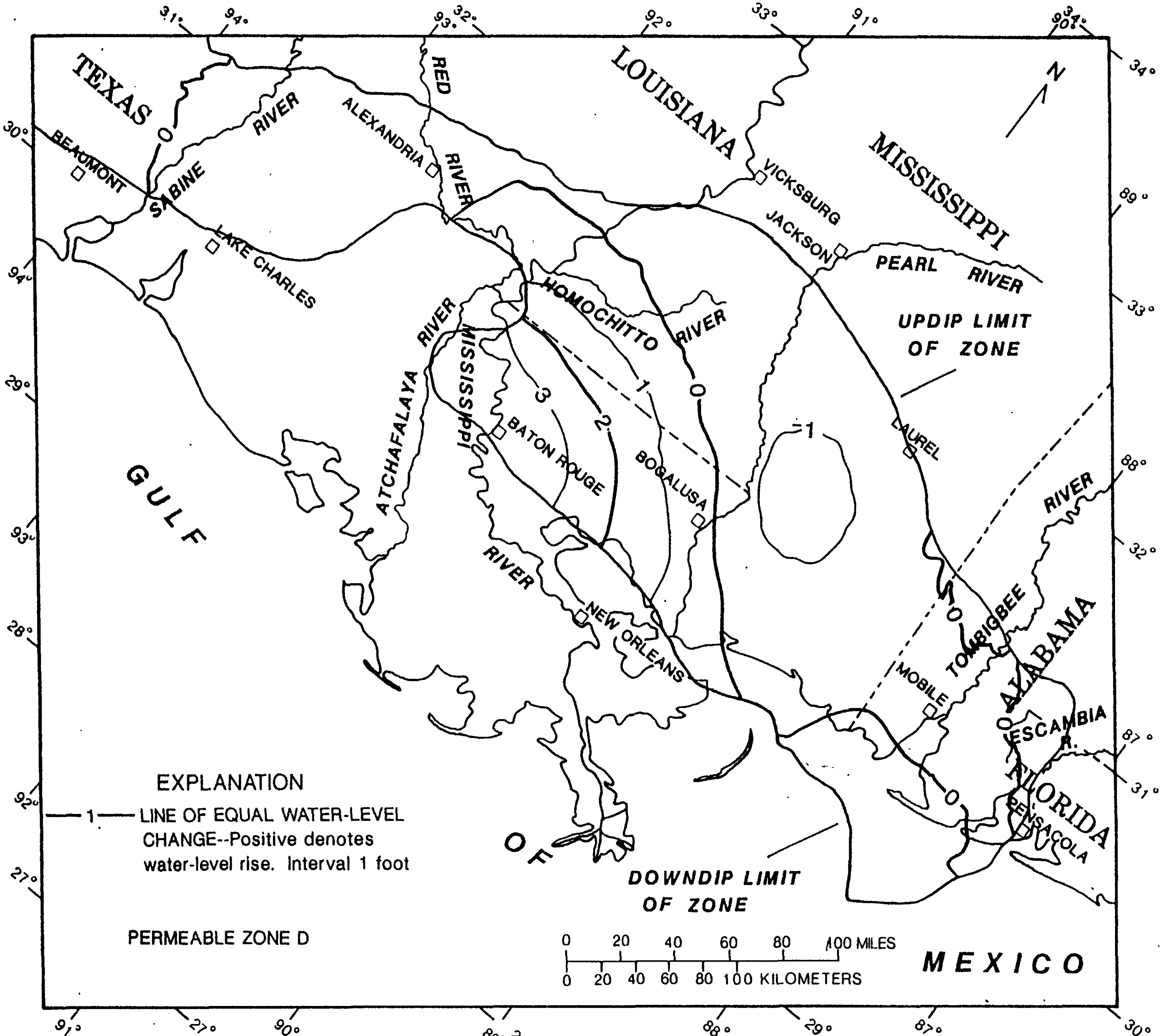


Figure 31d:--Changes from 1987 water levels resulting from an additional 50 years of pumpage at the 1983-87 rate, permeable zone D.

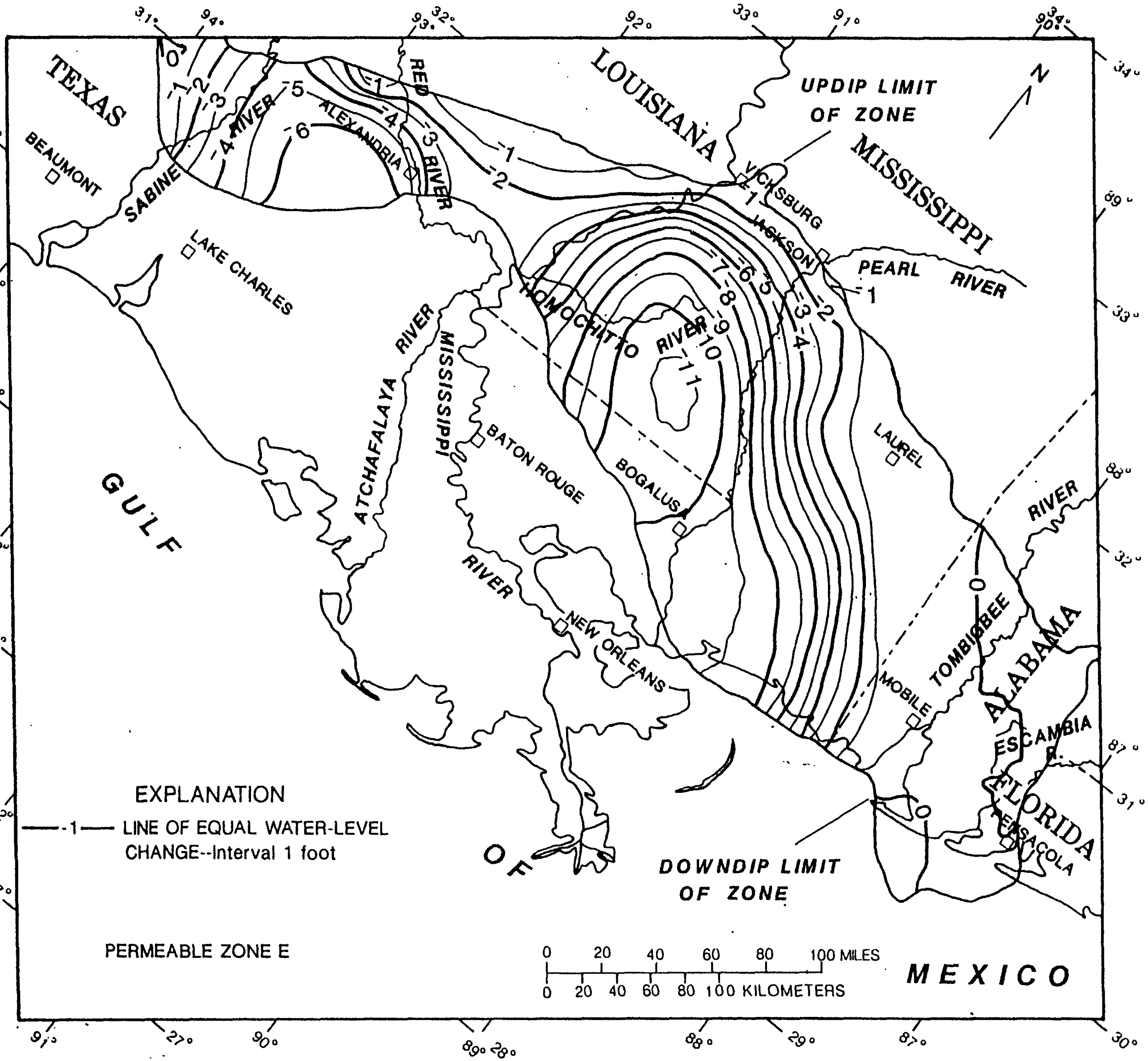


Figure 31e.--Changes from 1987 water levels resulting from an additional 50 years of pumpage at the 1983-87 rate, permeable zone E.

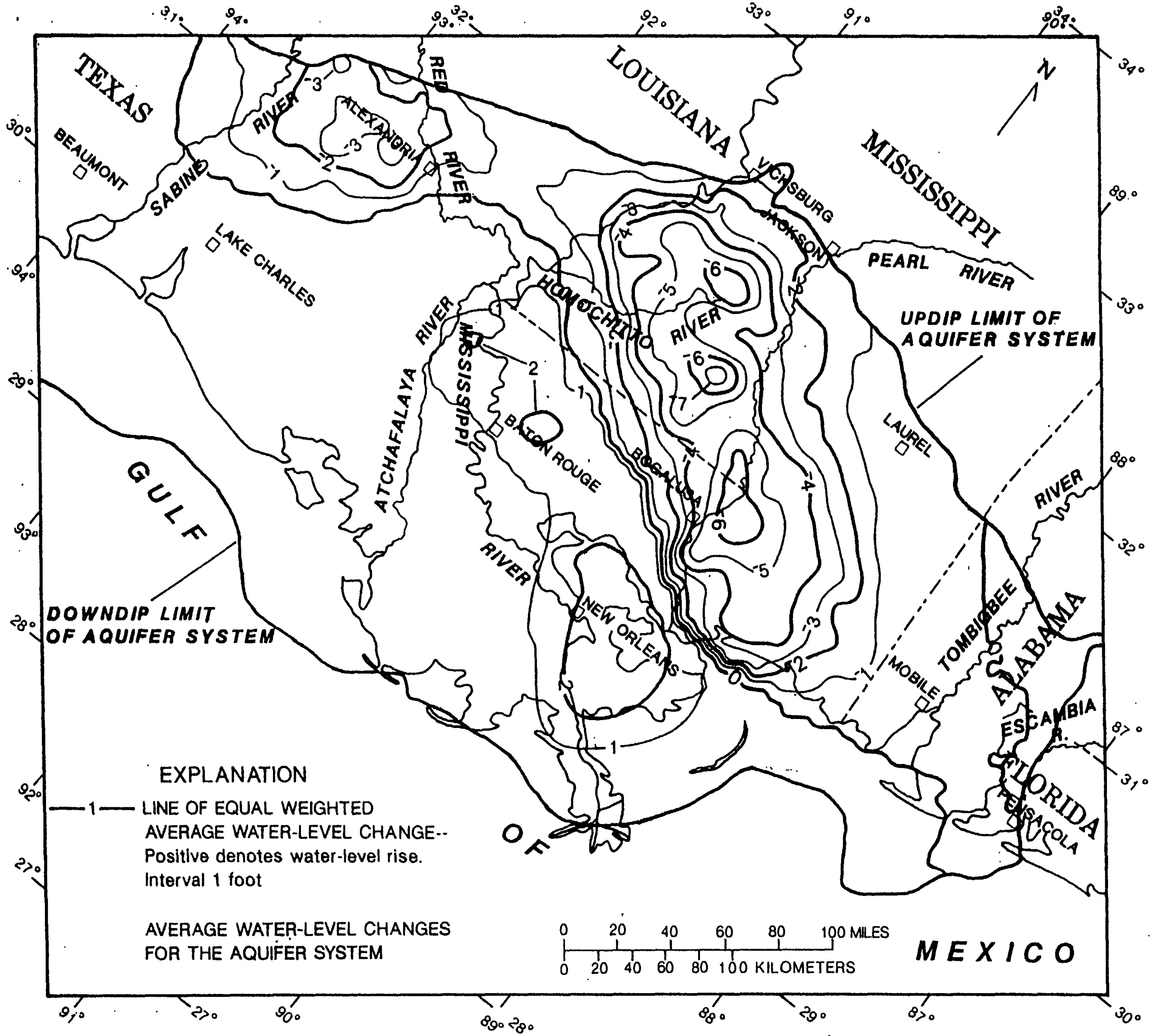


Figure 31f.--Changes from 1987 water levels resulting from an additional 50 years of pumpage at the 1983-87 rate, average water levels for the aquifer system.

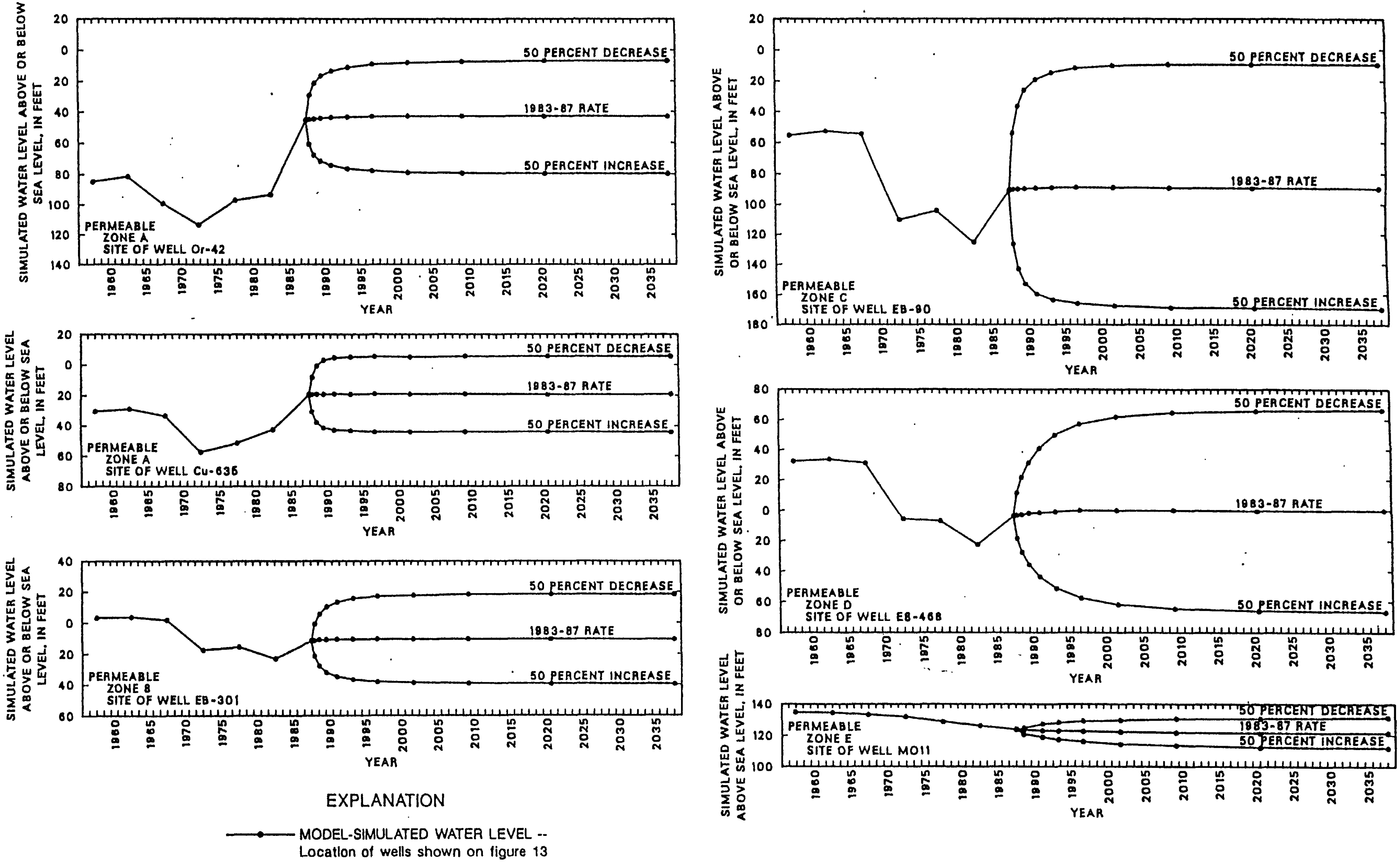
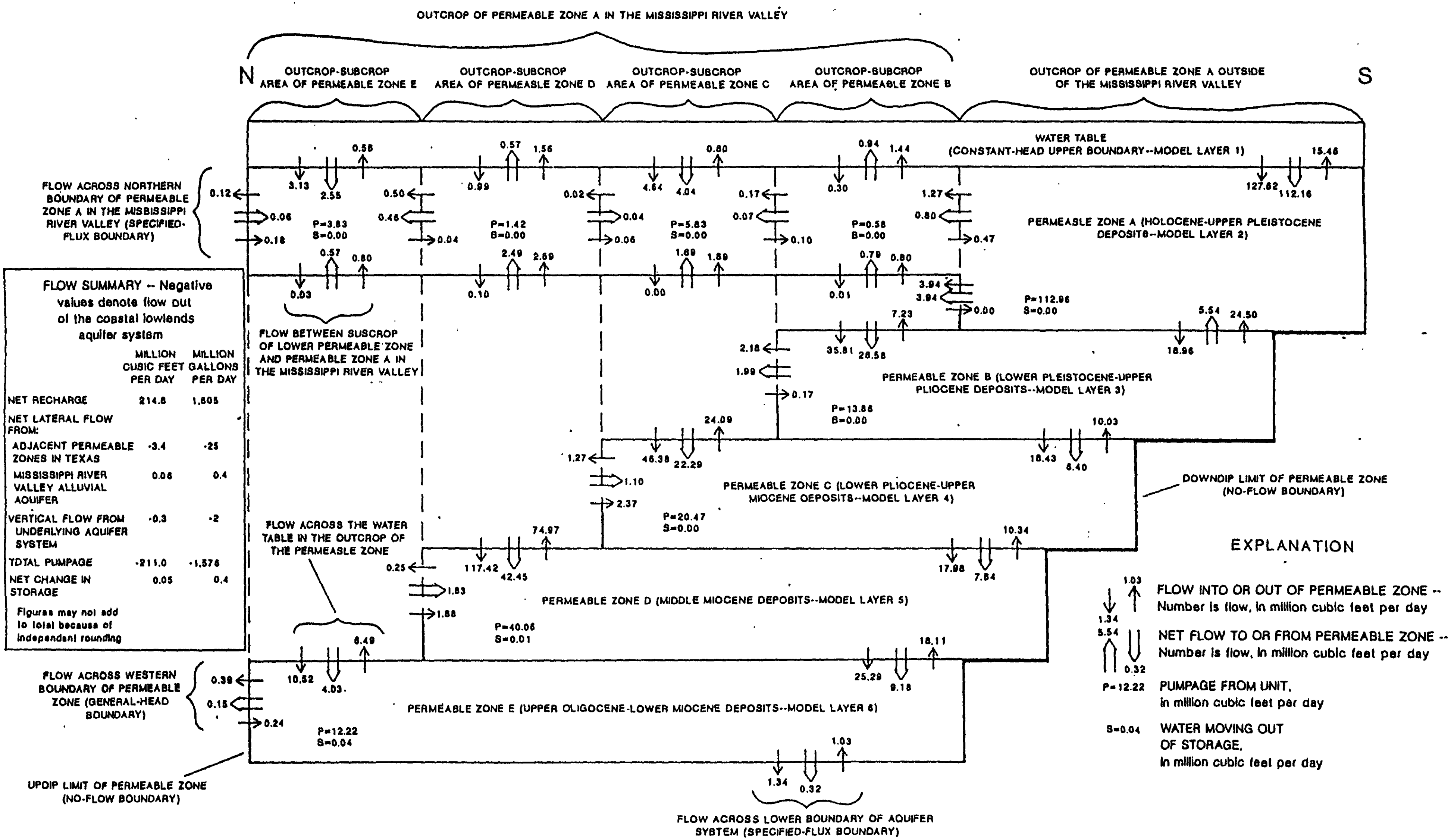


Figure 32.--The projected effects of an additional 50 years of pumpage at the 1983-87 rate and at increased and decreased rates.



FLOW SUMMARY -- Negative values denote flow out of the coastal lowlands aquifer system

	MILLION CUBIC FEET PER DAY	MILLION GALLONS PER DAY
NET RECHARGE	214.8	1,605
NET LATERAL FLOW FROM:		
ADJACENT PERMEABLE ZONES IN TEXAS	-3.4	-25
MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER	0.06	0.4
VERTICAL FLOW FROM UNDERLYING AQUIFER SYSTEM	-0.3	-2
TOTAL PUMPAGE	-211.0	-1,578
NET CHANGE IN STORAGE	0.05	0.4

Figures may not add to total because of independent rounding

Figure 33.--Simulated flow between permeable zones and across boundaries of the coastal lowlands aquifer system after an additional 50 years of pumpage at the 1983-87 rate.

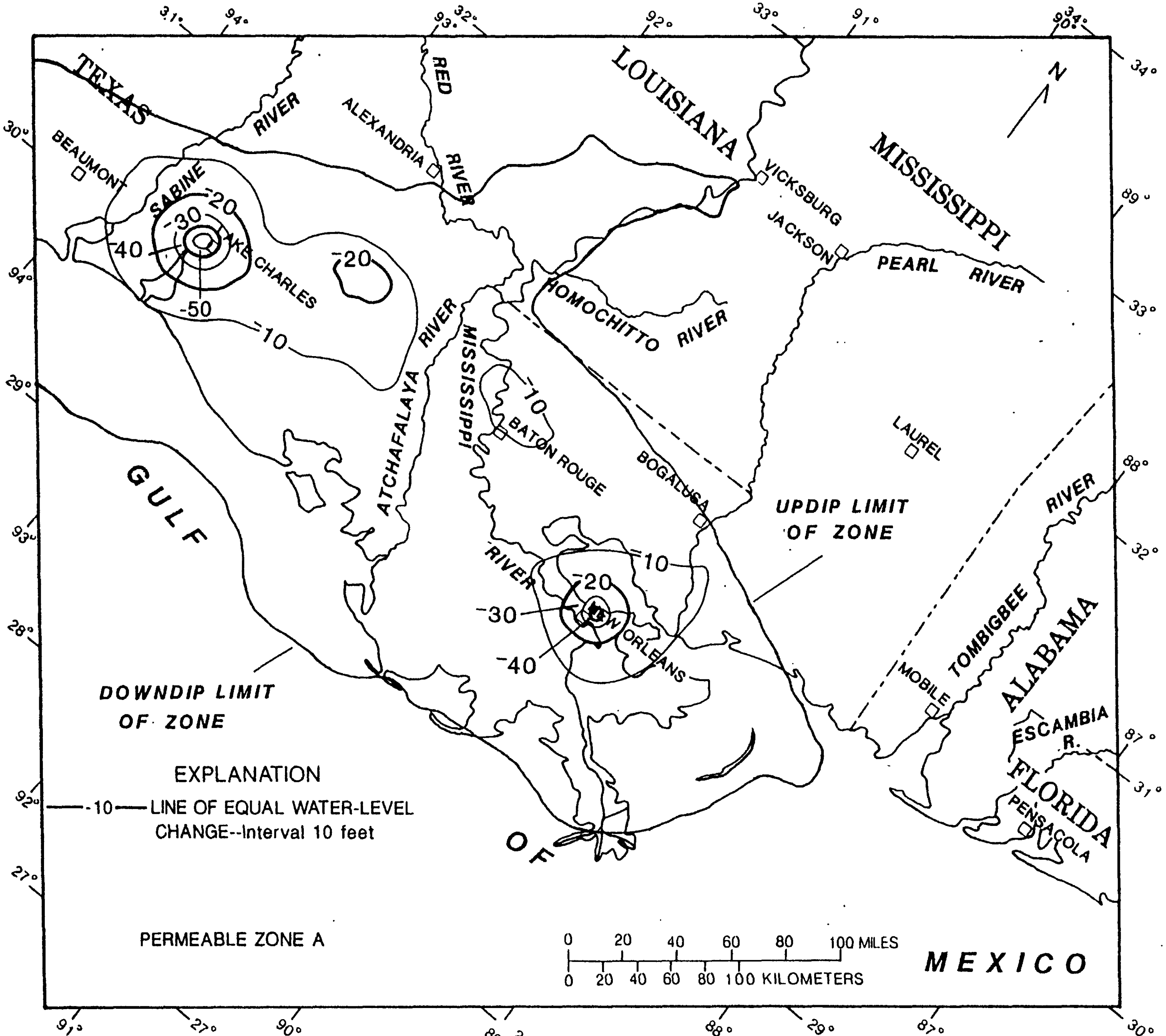


Figure 34a.--Projected changes from 1987 water levels resulting from an additional 50 years of pumpage at 150 percent of the 1983-87 rate, permeable zone A.

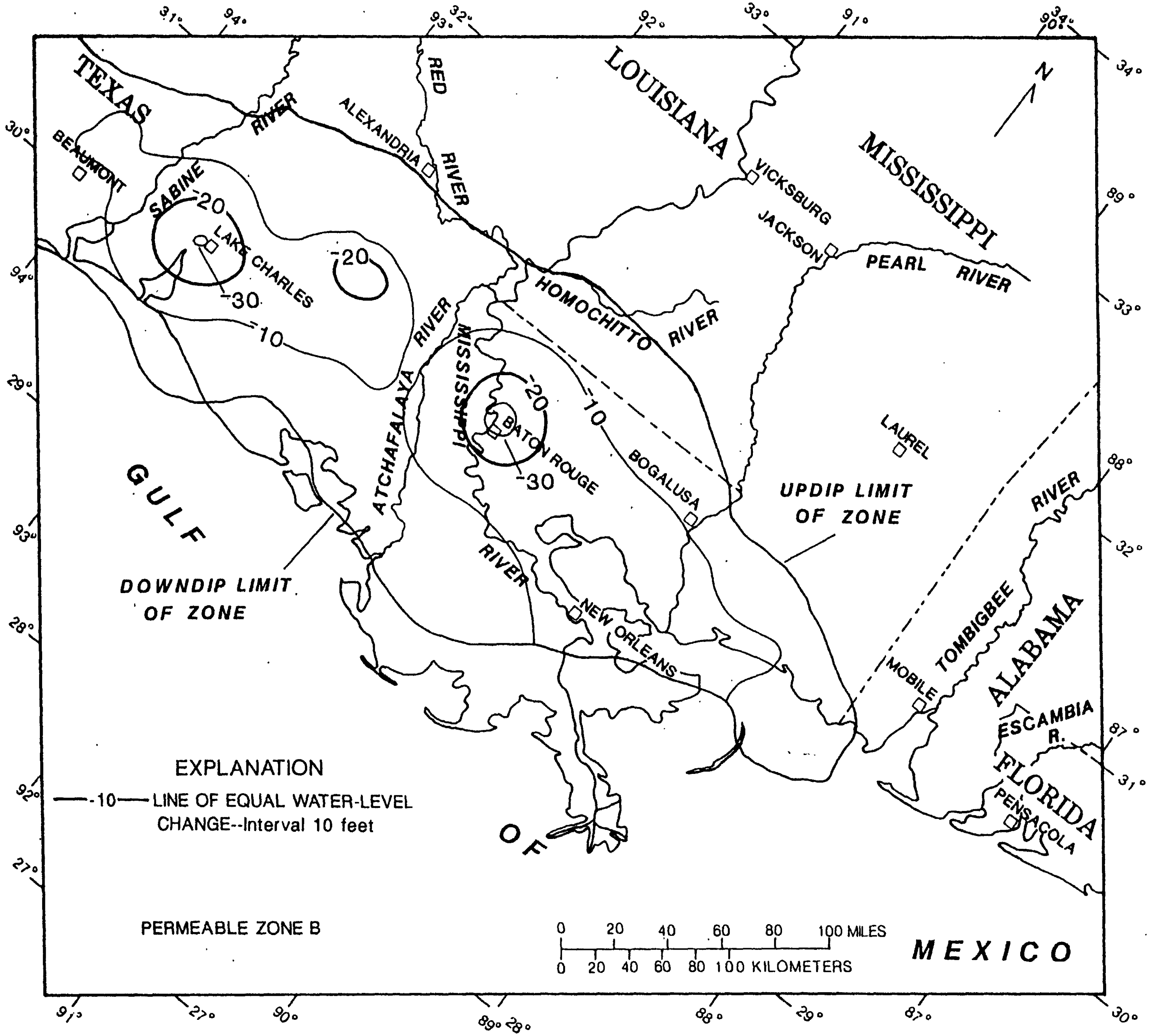


Figure 34b.--Projected changes from 1987 water levels resulting from an additional 50 years of pumpage at 150 percent of the 1983-87 rate, permeable zone B.

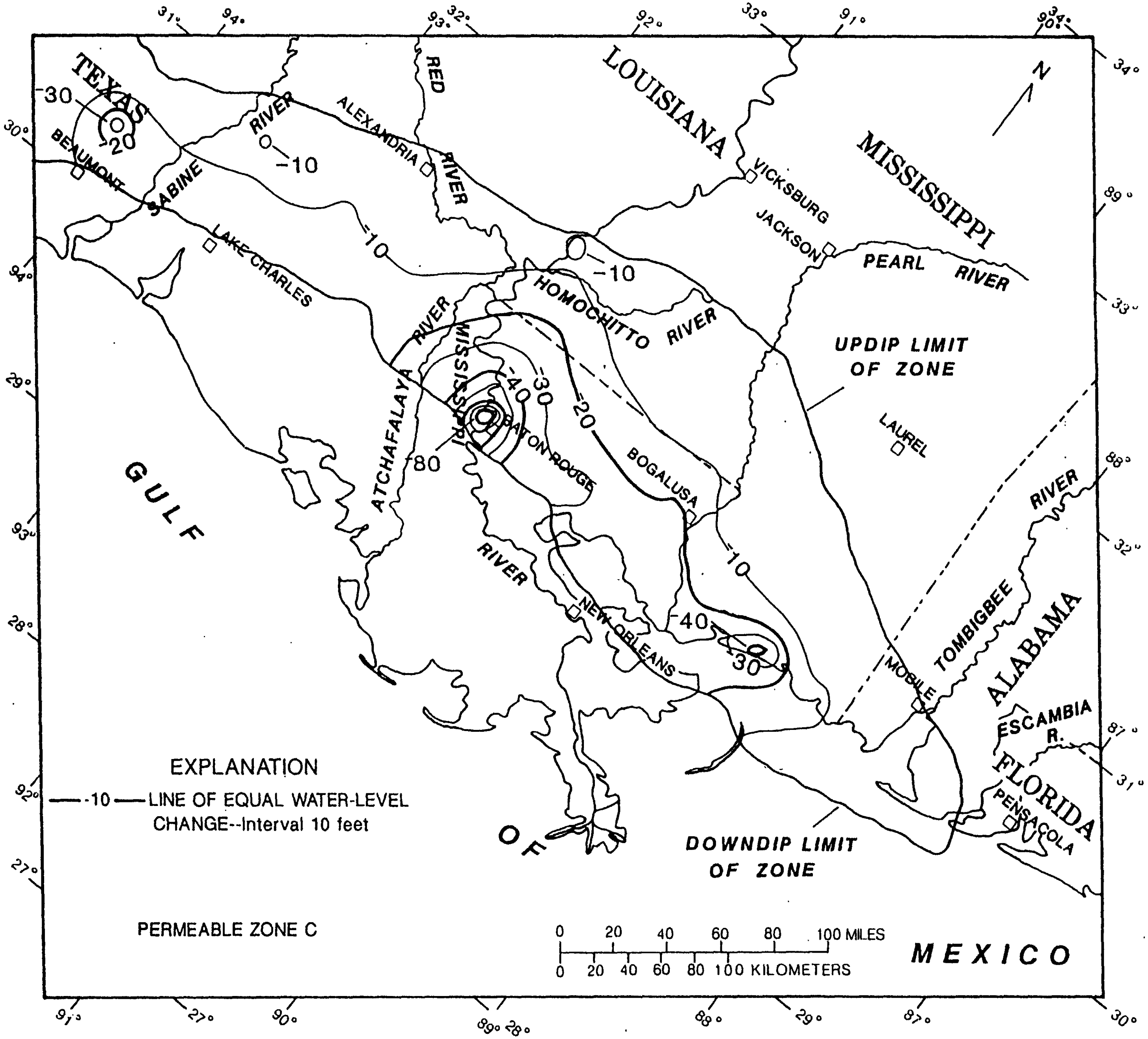


Figure 34c.--Projected changes from 1987 water levels resulting from an additional 50 years of pumpage at 150 percent of the 1983-87 rate, permeable zone C.

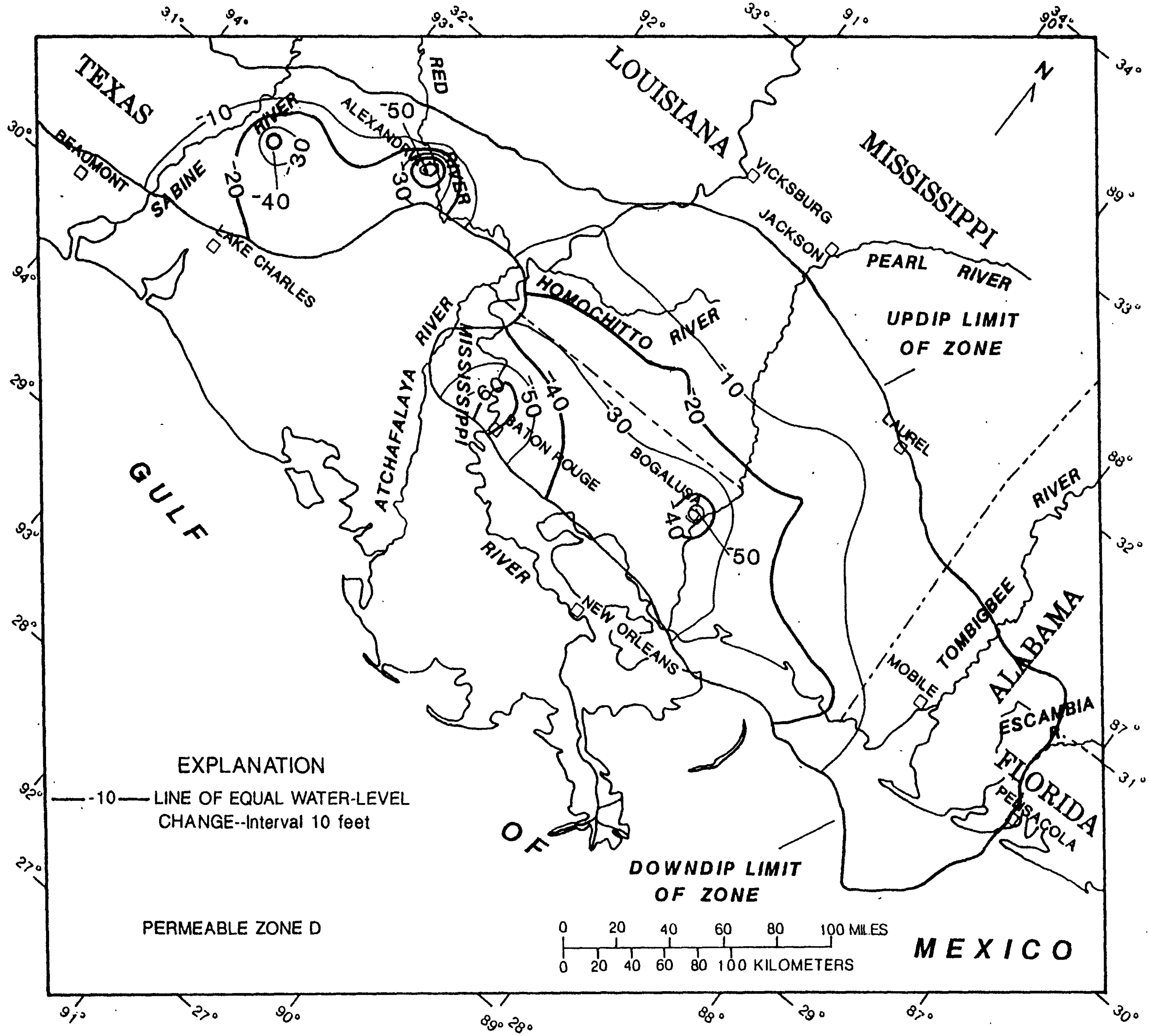


Figure 34d.--Projected changes from 1987 water levels resulting from an additional 50 years of pumpage at 150 percent of the 1983-87 rate, permeable zone D.

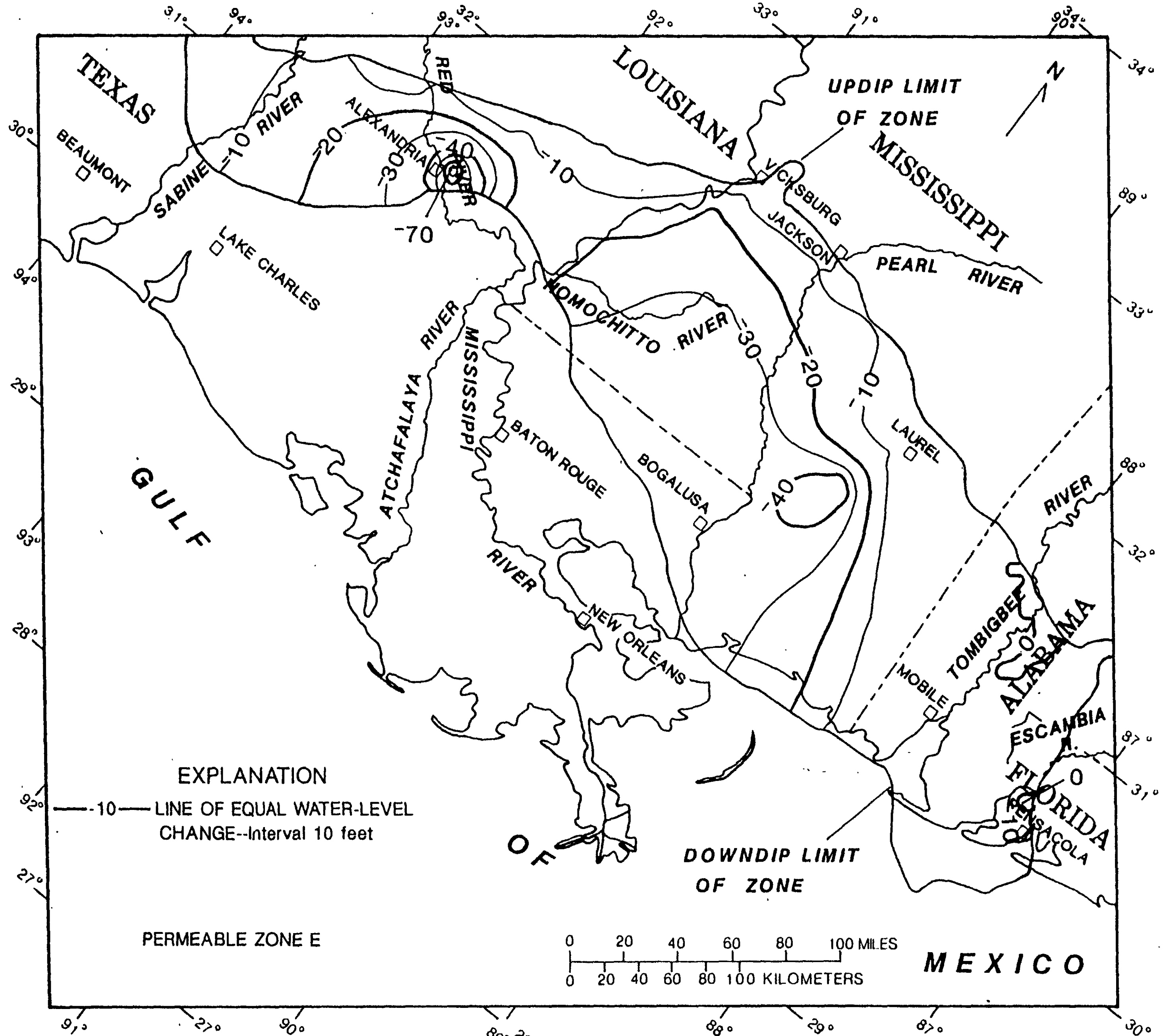


Figure 34e.--Projected changes from 1987 water levels resulting from an additional 50 years of pumpage at 150 percent of the 1983-87 rate, permeable zone E.

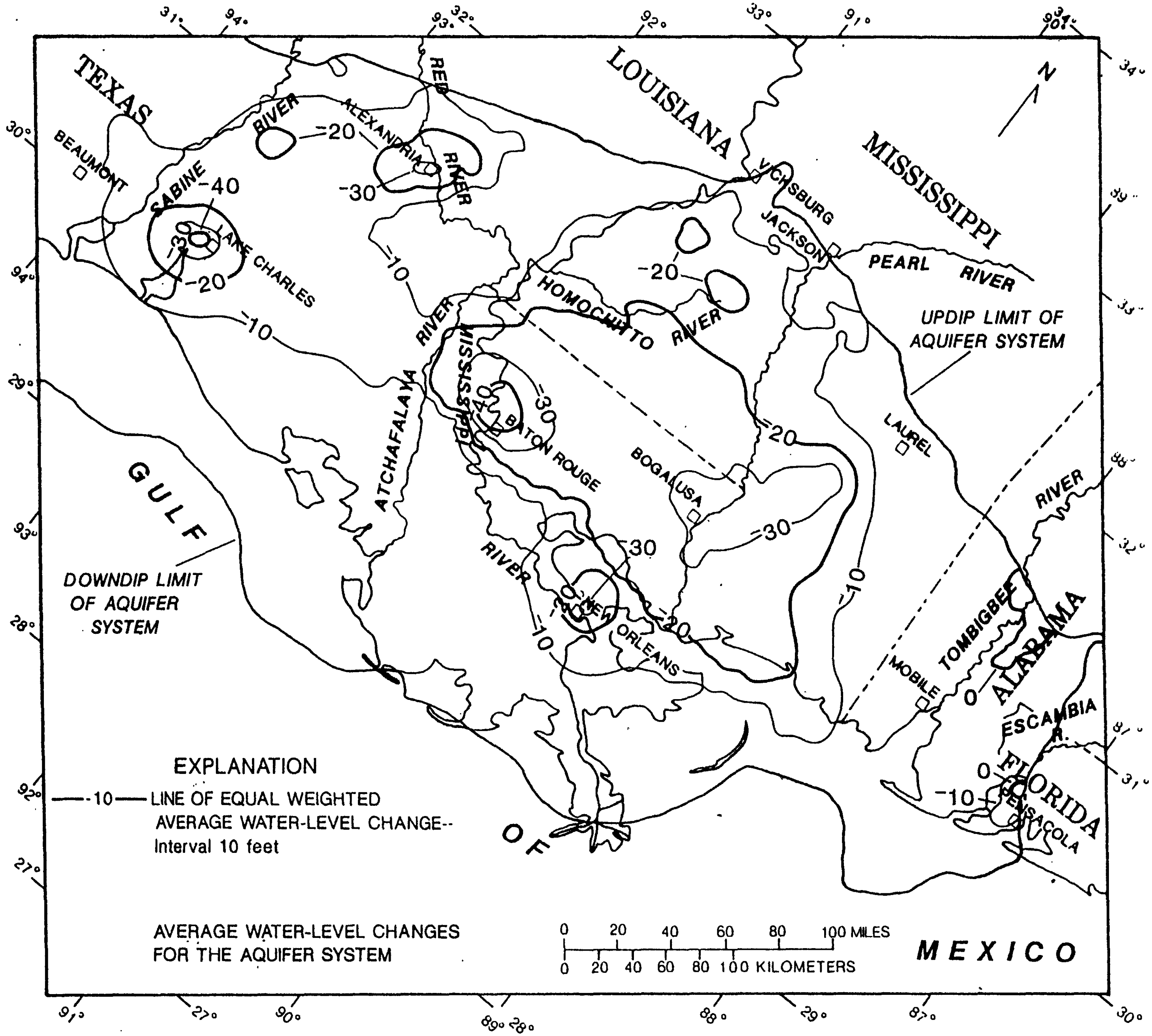


Figure 34f.--Projected changes from 1987 water levels resulting from an additional 50 years of pumpage at 150 percent of the 1983-87 rate, average water levels for the aquifer system.

permeable zone C. More than 50 ft of decline from 1987 levels would occur in the Lake Charles area and more than 40 ft in the New Orleans area of Louisiana in permeable zone A. Declines of more than 70 ft in permeable zone E and more than 50 ft in permeable zone D would occur in a small area near Alexandria, La. The average drawdown in the aquifer system would be more than 20 ft in a broad area of southeastern Louisiana and southwestern Mississippi. Average drawdown would exceed 30 ft in the Alexandria, New Orleans, and Bogalusa, La., areas, and 40 ft near Lake Charles and Baton Rouge, La. Water-level changes resulting from this experiment at selected well sites are shown in figure 32. Profiles along north-south and east-west lines (fig. 35) show that water-level gradients would increase throughout the aquifer system from 1987 conditions (fig. 23), with the largest gradient increases in the lower permeable zones where transmissivity is generally less than the transmissivity of the upper permeable zones.

The distribution of flow at the end of the 50-year period with a 50-percent increase in pumpage is shown in figure 36. The relation between pumpage, recharge, change in storage, and net flows from adjacent aquifers and the underlying aquifer system is shown in figures 37 and 38. More than 95 percent of the flow would be derived from recharge. Increasing the pumpage in permeable zone A by 50 percent, from about 124 to about 187 Mft^3/d (928 to about 1,399 Mgal/d), would increase the net recharge to permeable zone A by 61 percent, from 118 to 190 Mft^3/d (figs. 27 and 36). More than 93 percent of the additional water derived from storage would be withdrawn during the first 20 years of the period (fig. 38). Less than 0.3 Mft^3/d would be derived from storage at the end of the period, indicating that the aquifer system would be approaching steady state.

The simulated rate and direction of flow in the aquifer system at the end of the 50-year period are shown in figure 39. Comparison with flow vectors showing 1987 conditions (fig. 25) indicates that the increased pumpage would induce more lateral flow toward the major pumping centers. A larger area of the aquifer system would receive recharge (downward flow) at higher rates at the end of the period than in 1987. Simulation suggests that from 4 to 9 in/yr of recharge would occur near major pumping centers (fig. 40). This is about 1 to 3 in/yr more than under 1987 conditions (fig. 26).

Results from this experiment indicate that pumping at a rate 50 percent greater than the 1983-87 rate would be feasible based on the effects on water levels. Even though additional water-level declines of more than 80 ft would occur, this would not seriously affect the regional aquifer system because of the large available drawdowns and relatively high water levels in the aquifer system. Although recharge and lateral flow rates are high enough to maintain a 50 percent increase in pumpage from present pumping sites, there would be some adverse effects on water quality through increased saltwater encroachment or infiltration near the downdip limit of each permeable zone. Increased land-surface subsidence would accompany the greater water-level declines.

In the third model experiment, the 1983-87 pumping rate was decreased by 50 percent for a period of 50 years (1988 to 2037). The water-level changes for each permeable zone and the average change in all permeable zones are shown in figures 41a-f. As in the experiment with increased pumping rates,

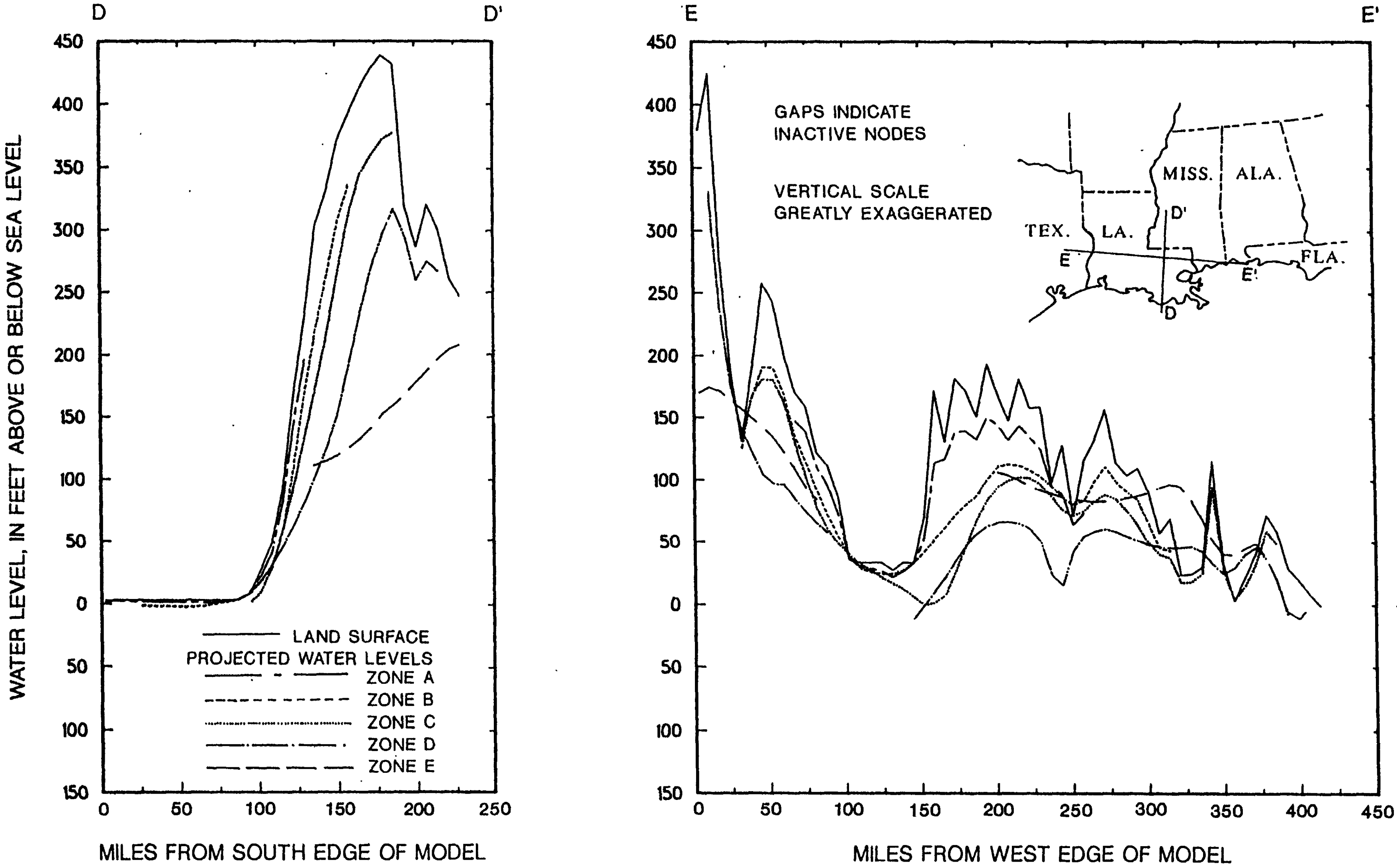


Figure 35.--Projected water levels in each permeable zone after an additional 50 years of pumpage at 150 percent of the 1983-87 rate.

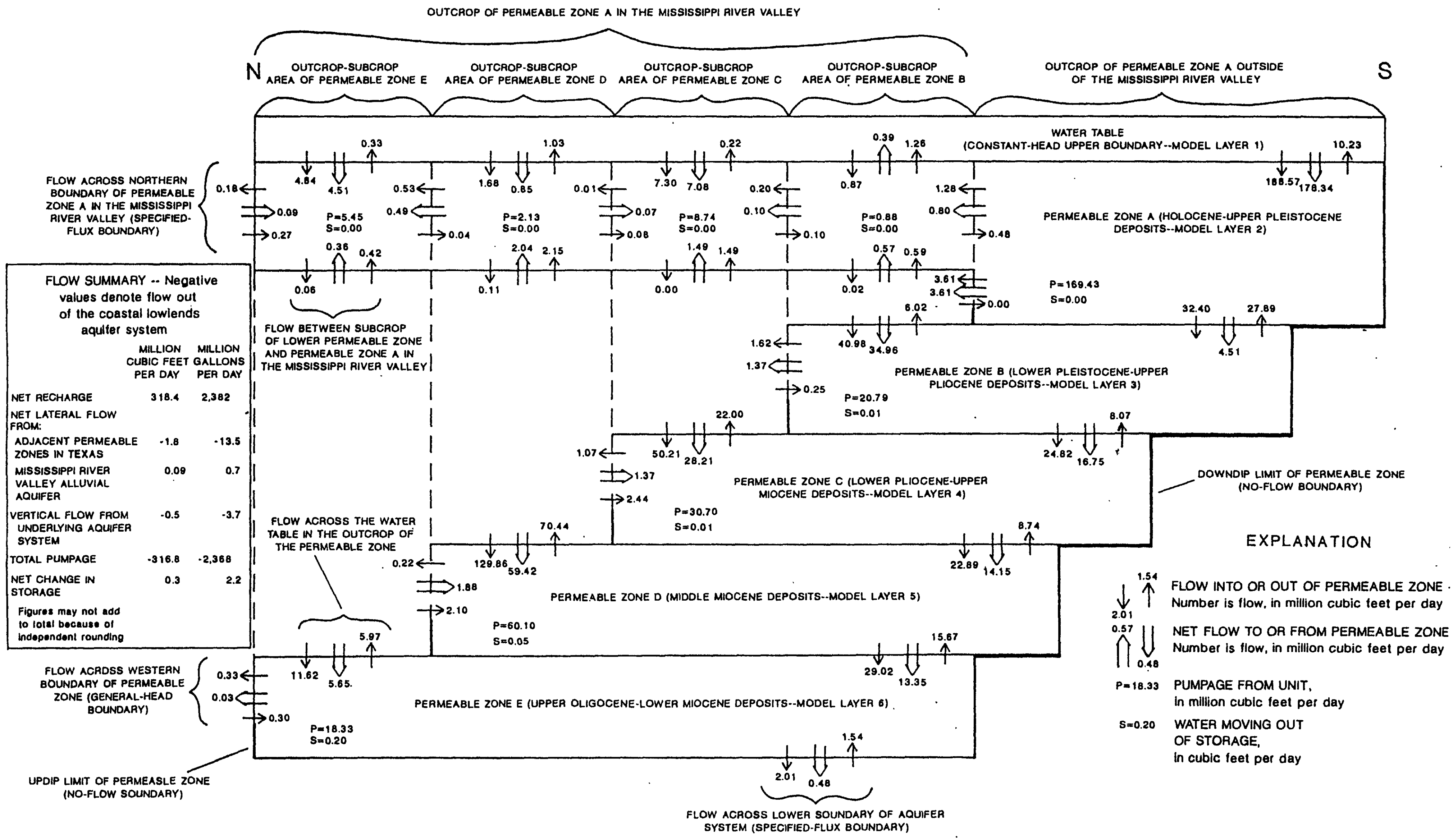


Figure 36.--Simulated flow between permeable zones and across boundaries of the coastal lowlands aquifer system after an additional 50 years of pumpage at 150 percent of the 1983-87 rate.

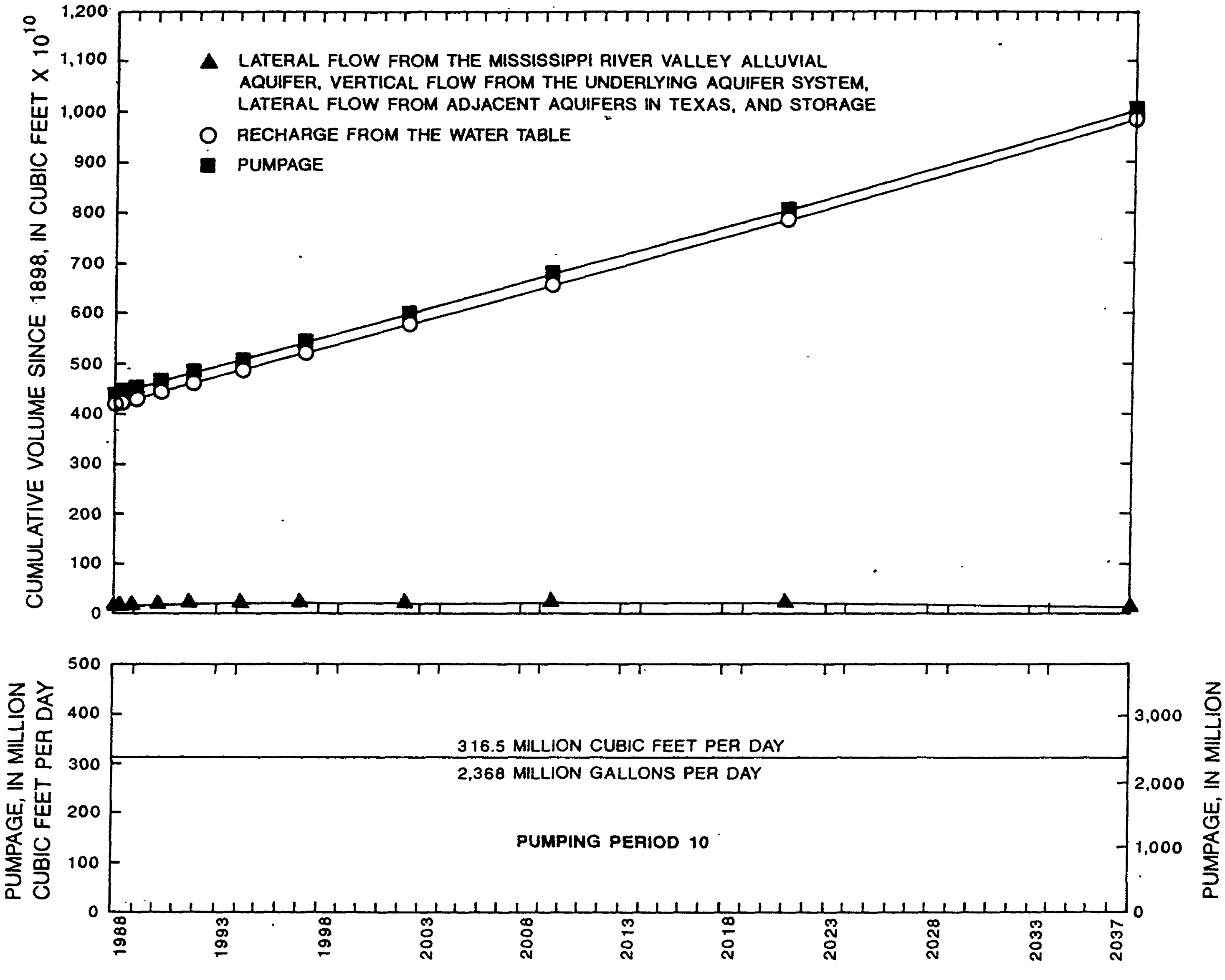


Figure 37.--Cumulative pumpage and the sources of water for the coastal lowlands aquifer system for an additional 50 years of pumpage at 150 percent of the 1983-87 rate.

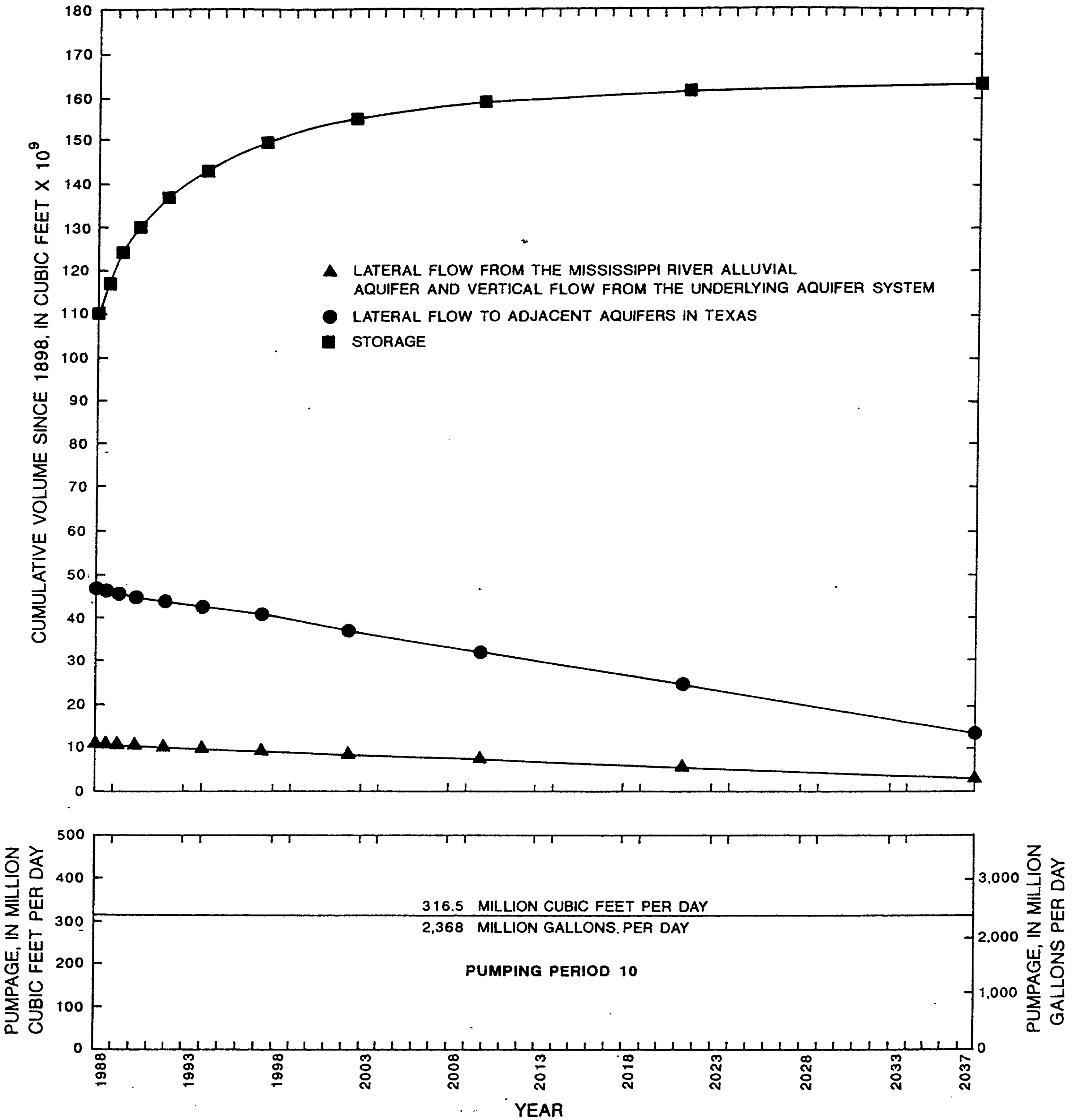


Figure 38.--Pumpage and the cumulative flow of water to or from storage and adjacent aquifers for an additional 50 years of pumpage at 150 percent of the 1983-87 rate.

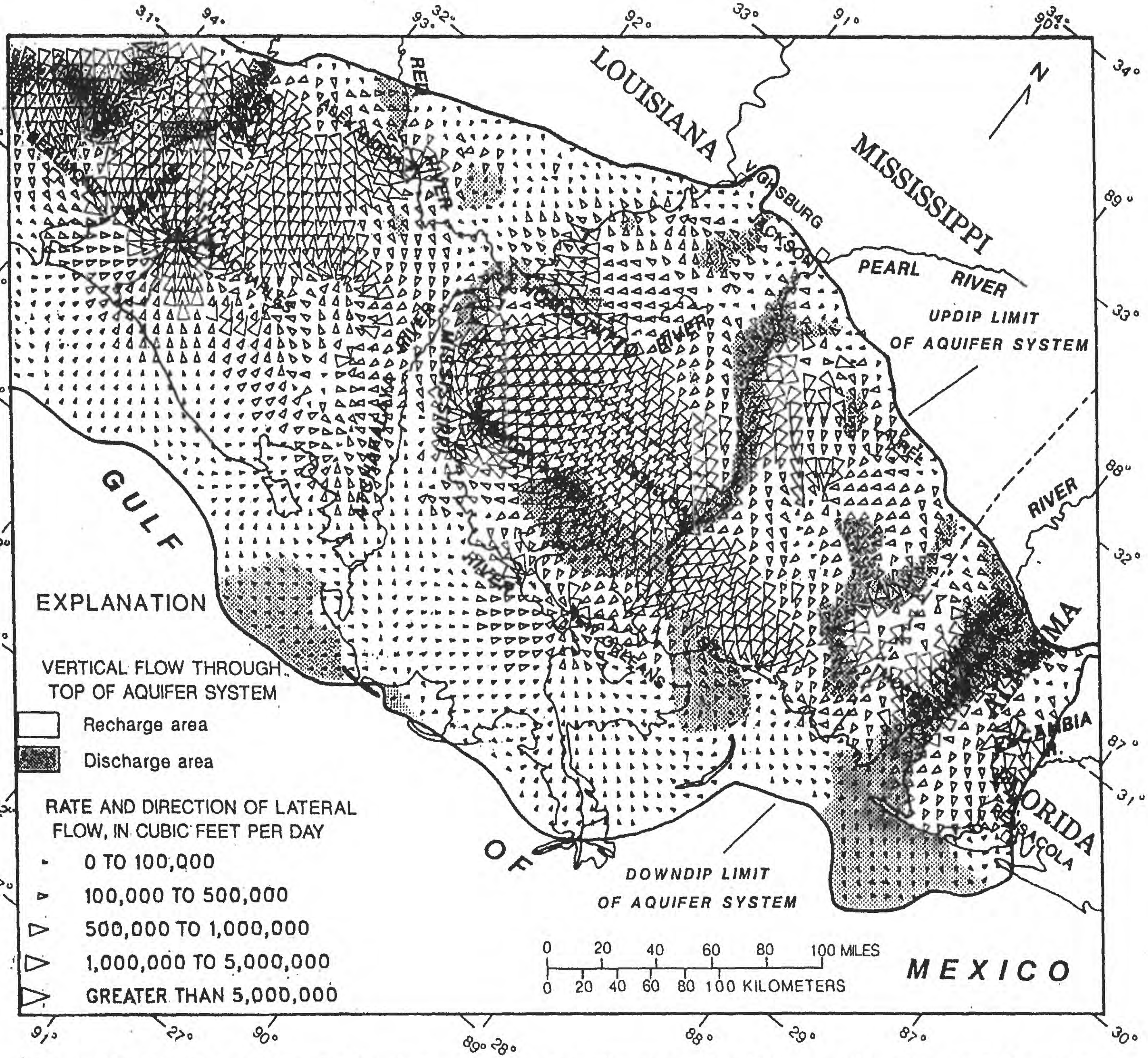


Figure 39.--Simulated ground-water flow in the aquifer system after an additional 50 years of pumpage at 150 percent of the 1983-87 rate.

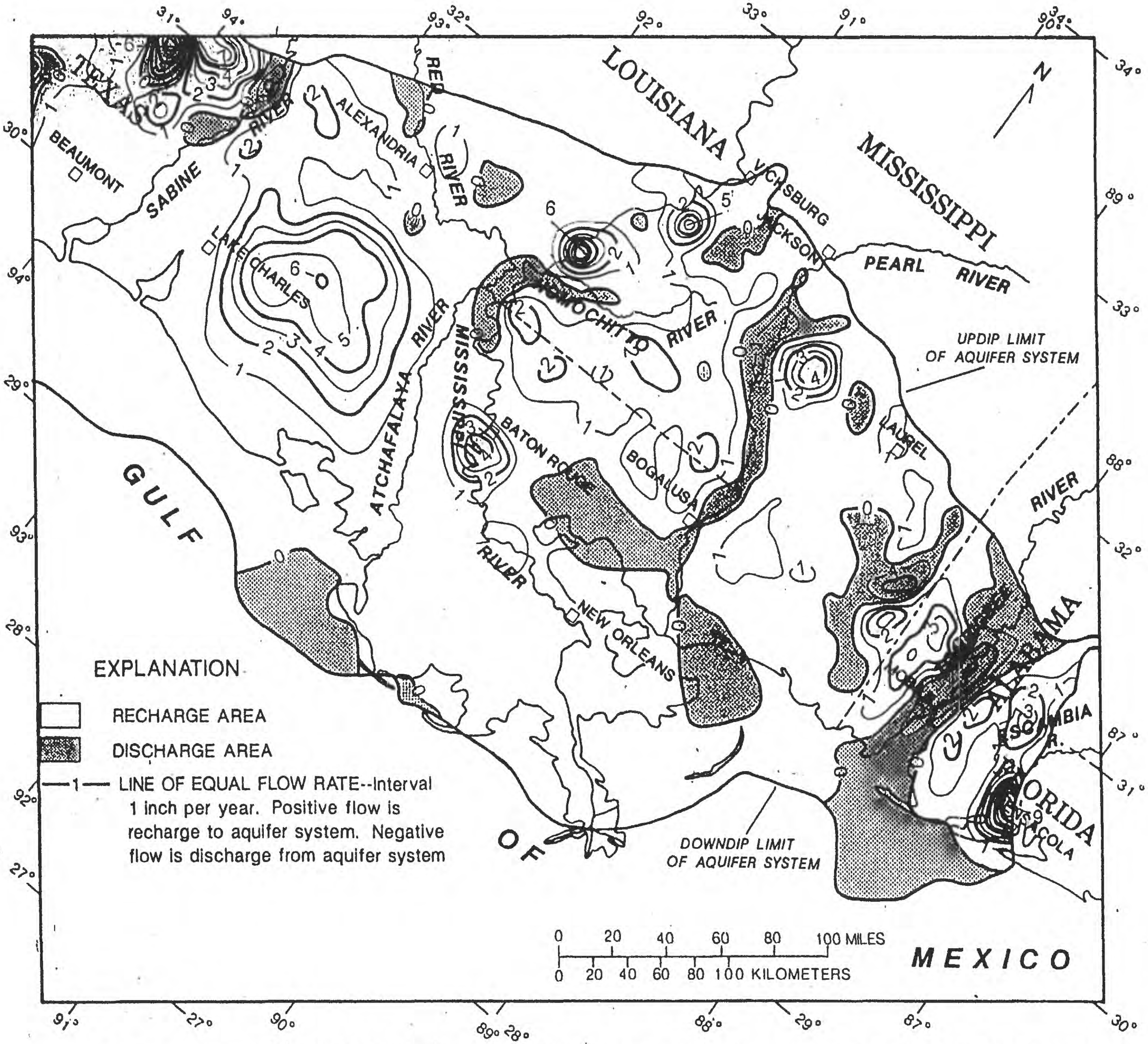


Figure 40.--Areal distribution of simulated rates of recharge to and discharge from the aquifer system after an additional 50 years of pumpage at 150 percent of the 1983-87 rate.

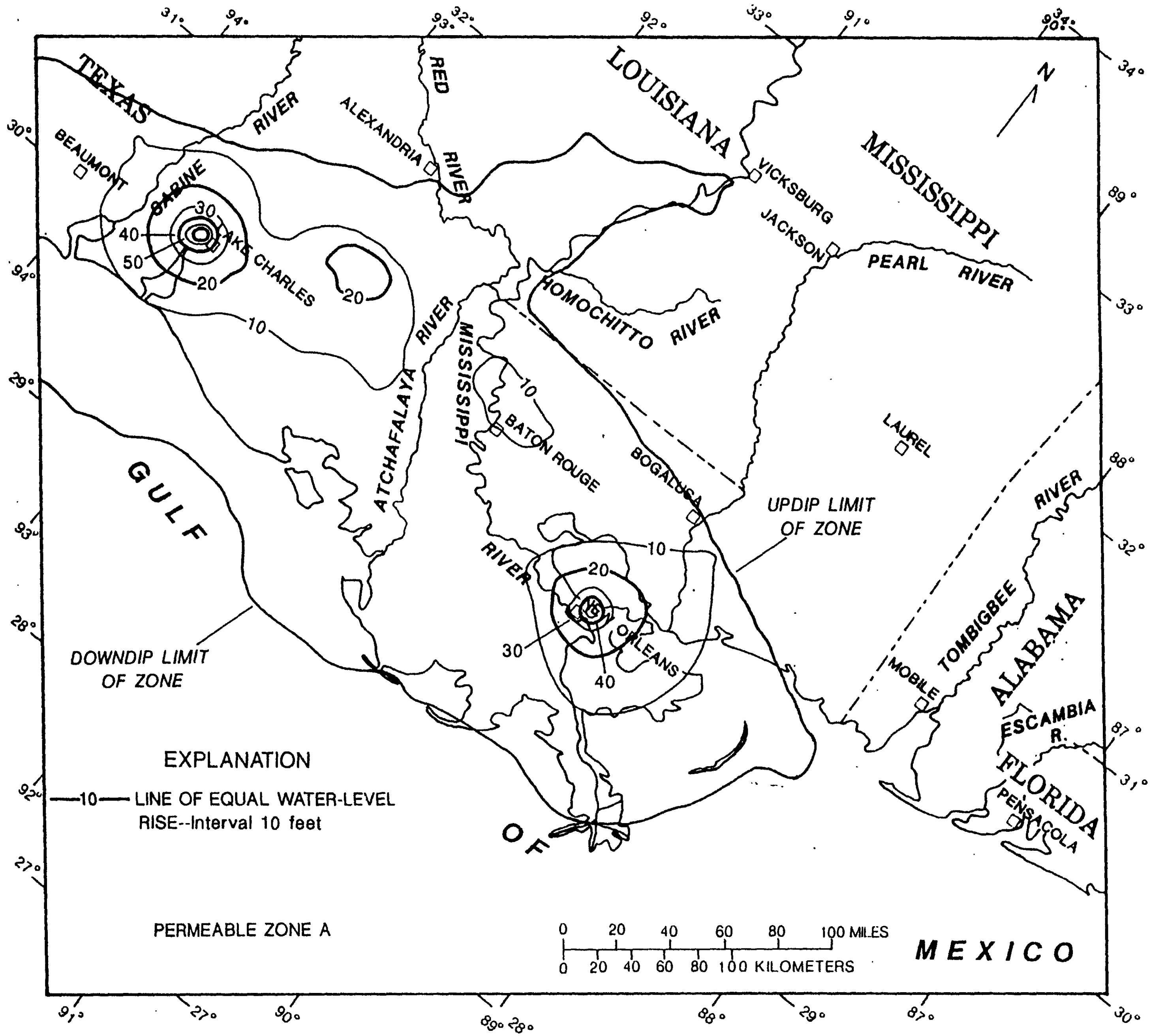


Figure 41a.--Recovery from 1987 water levels resulting from an additional 50 years of pumpage at 50 percent of the 1983-87 rate, permeable zone A.

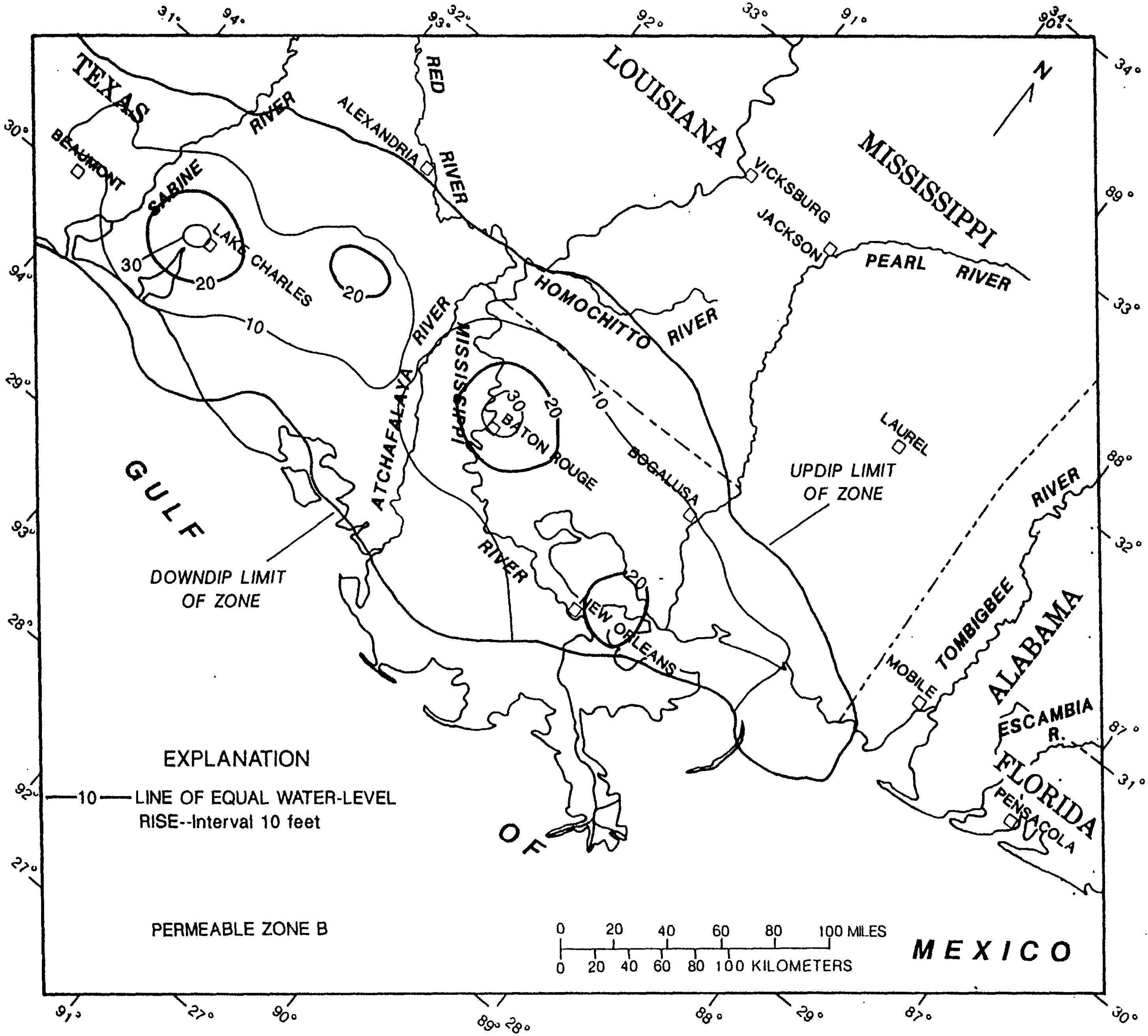


Figure 41b.--Recovery from 1987 water levels resulting from an additional 50 years of pumpage at 50 percent of the 1983-87 rate, permeable zone B.

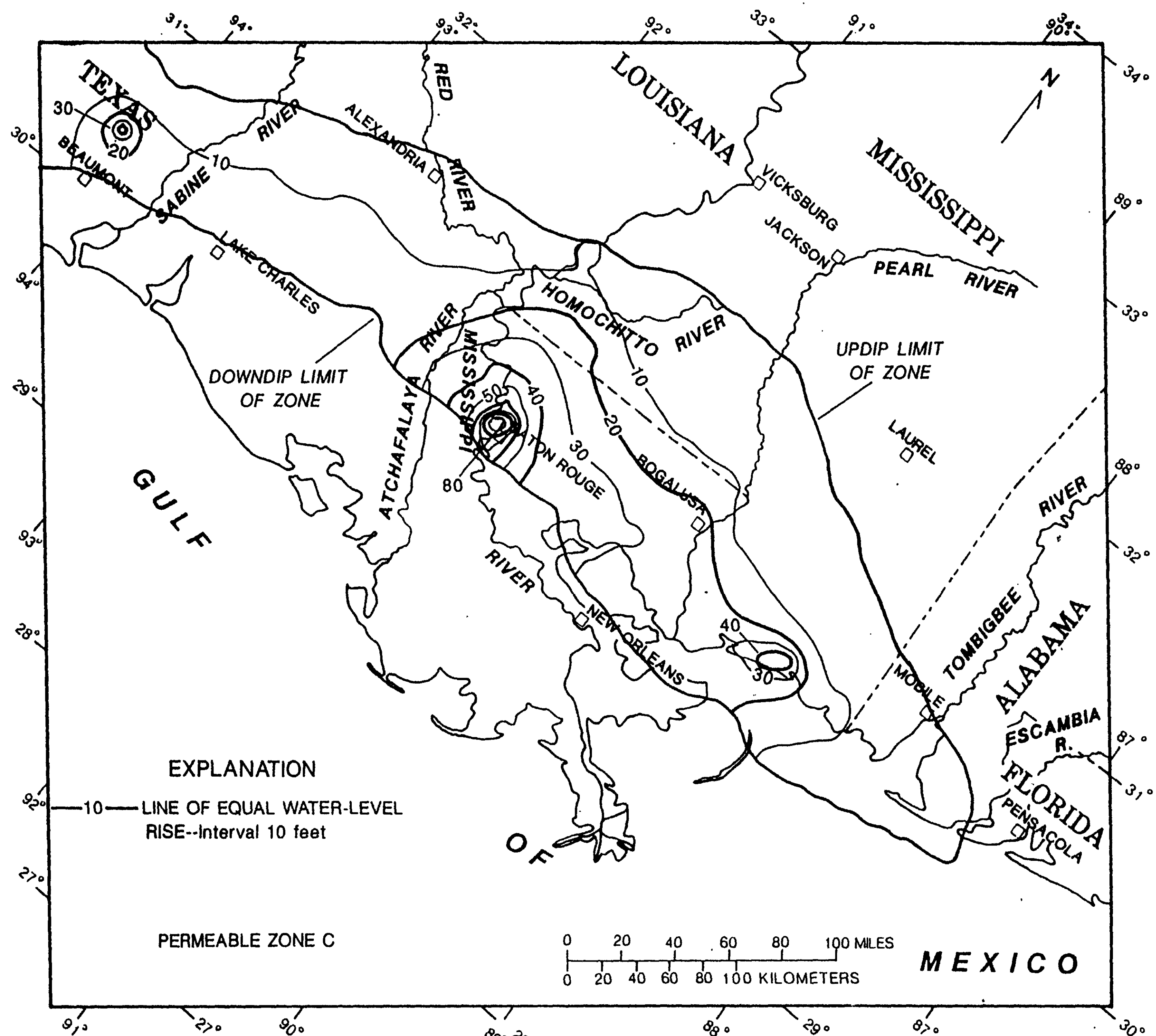


Figure 41c.--Recovery from 1987 water levels resulting from an additional 50 years of pumpage at 50 percent of the 1983-87 rate, permeable zone C.

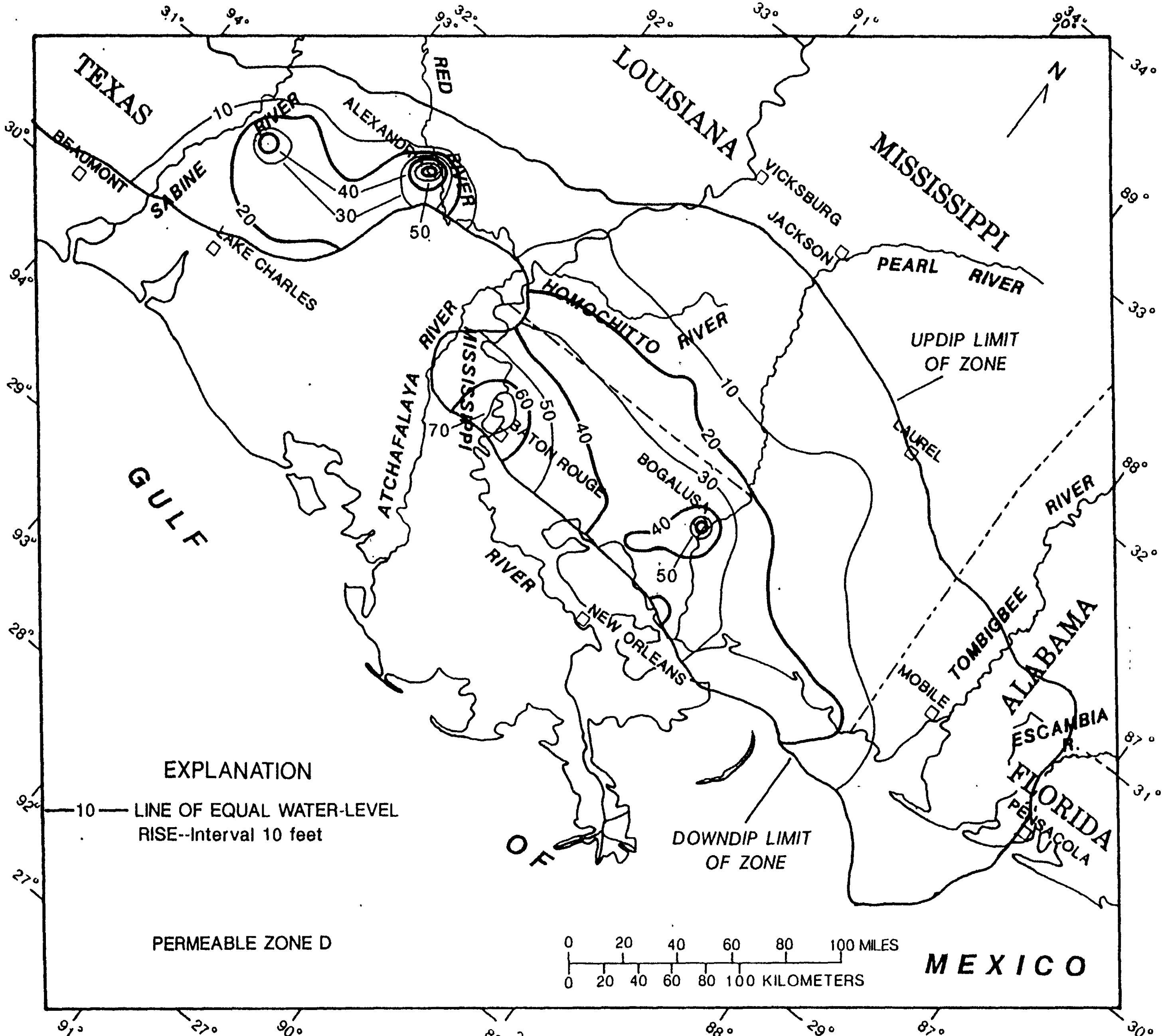


Figure 41d.--Recovery from 1987 water levels resulting from an additional 50 years of pumpage at 50 percent of the 1983-87 rate, permeable zone D.

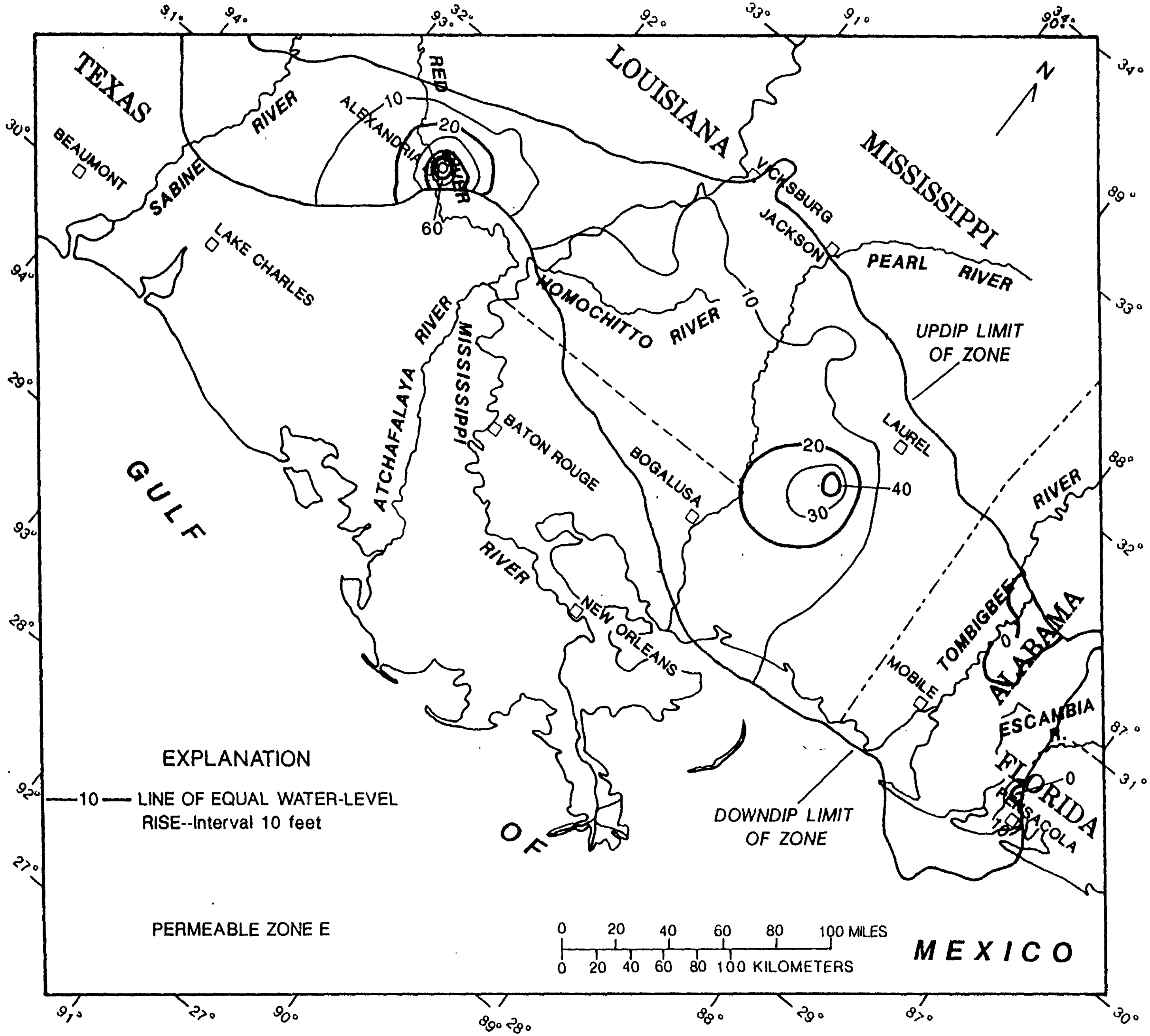


Figure 41e.--Recovery from 1987 water levels resulting from an additional 50 years of pumpage at 50 percent of the 1983-87 rate, permeable zone E.

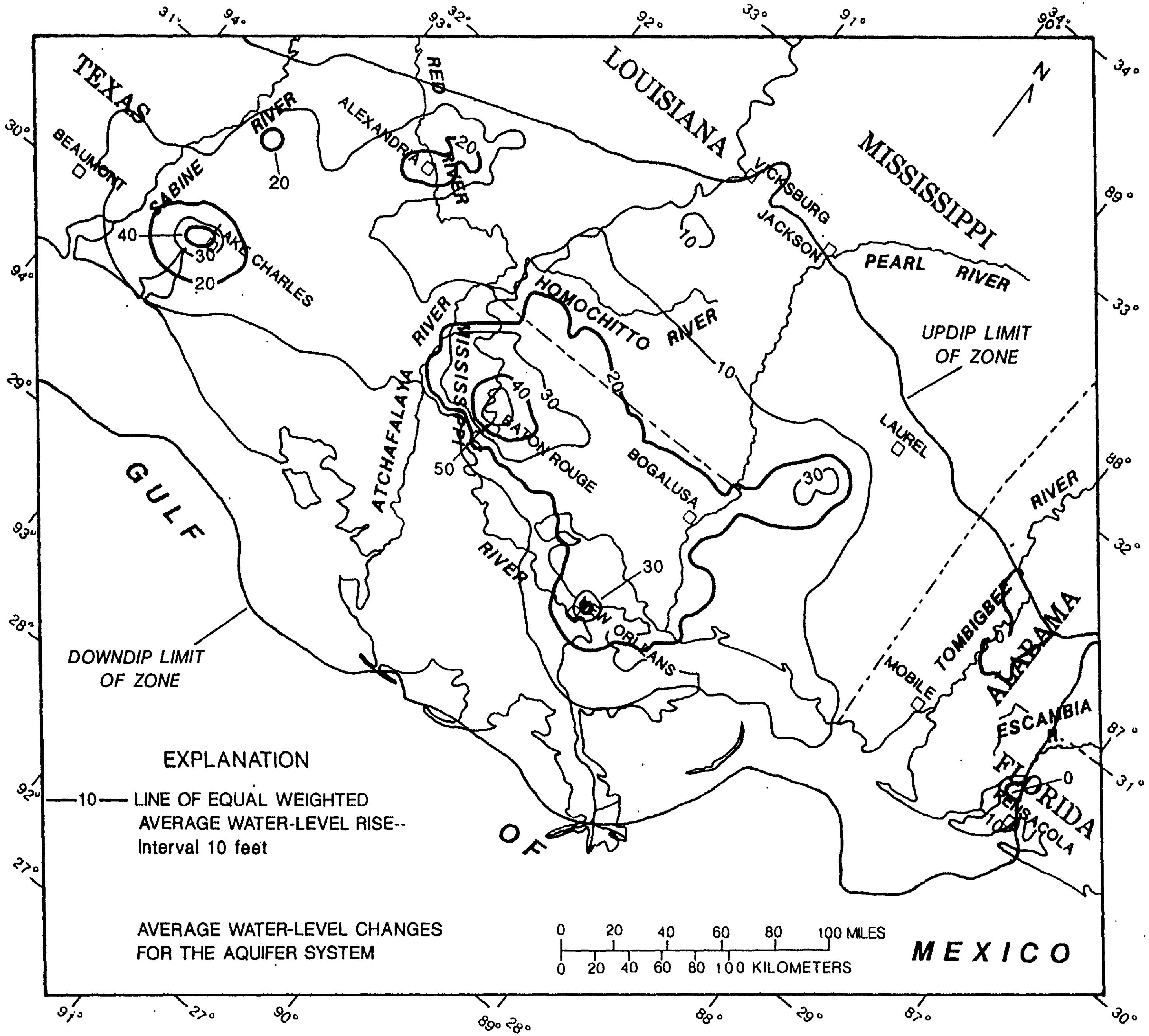


Figure 41f.--Recovery from 1987 water levels resulting from an additional 50 years of pumpage at 50 percent of the 1983-87 rate, average water levels for the aquifer system.

the areas of greatest change are in and near the major pumping centers. Average water levels would rise by more than 10 ft across much of the central part of the study area and by more than 20 ft throughout much of the northern part of southeast Louisiana extending a short distance into southwestern Mississippi. Recoveries of more than 50 ft would occur at Baton Rouge, La., more than 40 ft at Lake Charles, La., more than 30 ft at New Orleans, La., and more than 20 ft at Alexandria, La. Water-level profiles along north-south and east-west lines for each permeable zone in this experiment are shown in figure 42. Hydraulic gradients would decrease throughout the aquifer system, most notably between the outcrop of each permeable zone and the pumping centers downdip in that zone.

The maximum water-level recovery of more than 80 ft would occur at Baton Rouge, La., in permeable zone C. Permeable zone A would have more than 50 ft of recovery at Lake Charles and more than 40 ft at New Orleans, La. Recoveries of more than 30 ft would occur at Lake Charles and Baton Rouge, La., in permeable zone B. Small areas of southeastern Texas and coastal Mississippi would experience recoveries of more than 30 and 40 ft in permeable zone C. Water-level recovery in permeable zone D would be more than 70 ft near Baton Rouge, La., while small areas near Alexandria and Bogalusa, La., would recover more than 50 ft. More than 60 ft of recovery would occur at Alexandria, La., and more than 40 ft in southern Mississippi in permeable zone E. Water-level changes resulting from this experiment at selected sites are shown in figure 32.

The distribution of flow within the aquifer system and between the aquifer system and the water table and adjoining aquifer systems at the end of the 50-year recovery period with reduced pumpage is shown in figure 43. Decreasing the pumpage in permeable zone A from about 124 to 62.2 Mft^3/d (928 to 465 Mgal/d) would reduce the net recharge to permeable zone A by 62 percent, from 118 to 44.3 Mft^3/d. (See figs. 27 and 43.) The relation between pumpage, recharge, change in storage, and flows to and from adjacent aquifers and the underlying aquifer system is shown in figures 44 and 45. As in the second experiment where pumpage was increased by 50 percent, more than 95 percent of the flow would be derived from recharge. The cumulative amount of water derived from storage would decrease with the reduced pumpage as water would go into storage and water levels would rise (fig. 45). Most of the water going into storage would do so during the first 20 years after the pumpage reduction. A relatively small amount of water (0.2 Mft^3/d) would be going into storage at the end of the period, indicating that the aquifer system would be approaching steady state.

The rate and direction of flow in the aquifer system at the end of the 50-year period of reduced pumpage are shown in figure 46. Comparison with the map illustrating 1987 conditions (fig. 25) indicates that flow patterns generally would be similar but that flow rates around the major pumping centers would be less. Less water would move northward from coastal Louisiana toward pumping centers at Lake Charles, in the rice-growing area east of Lake Charles, and at New Orleans. Reducing the pumpage would decrease the amount of induced recharge from the surface. The reduction in pumpage would cause some areas that received recharge under 1987 conditions to become discharge areas by the end of the 50-year period. Recharge to and discharge from the

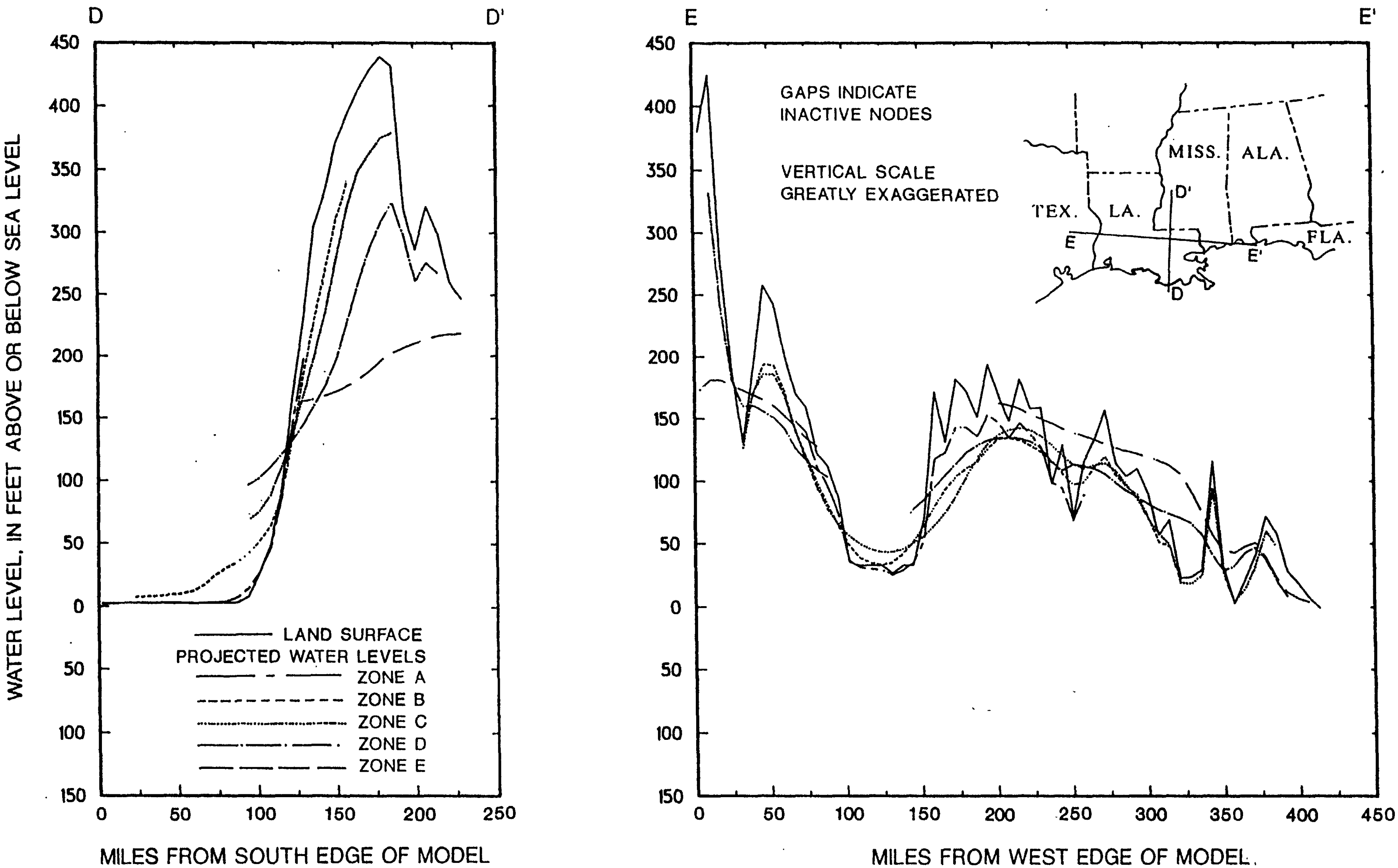


Figure 42.--Projected water levels in each permeable zone after an additional 50 years of pumpage at 50 percent of the 1983-87 rate.

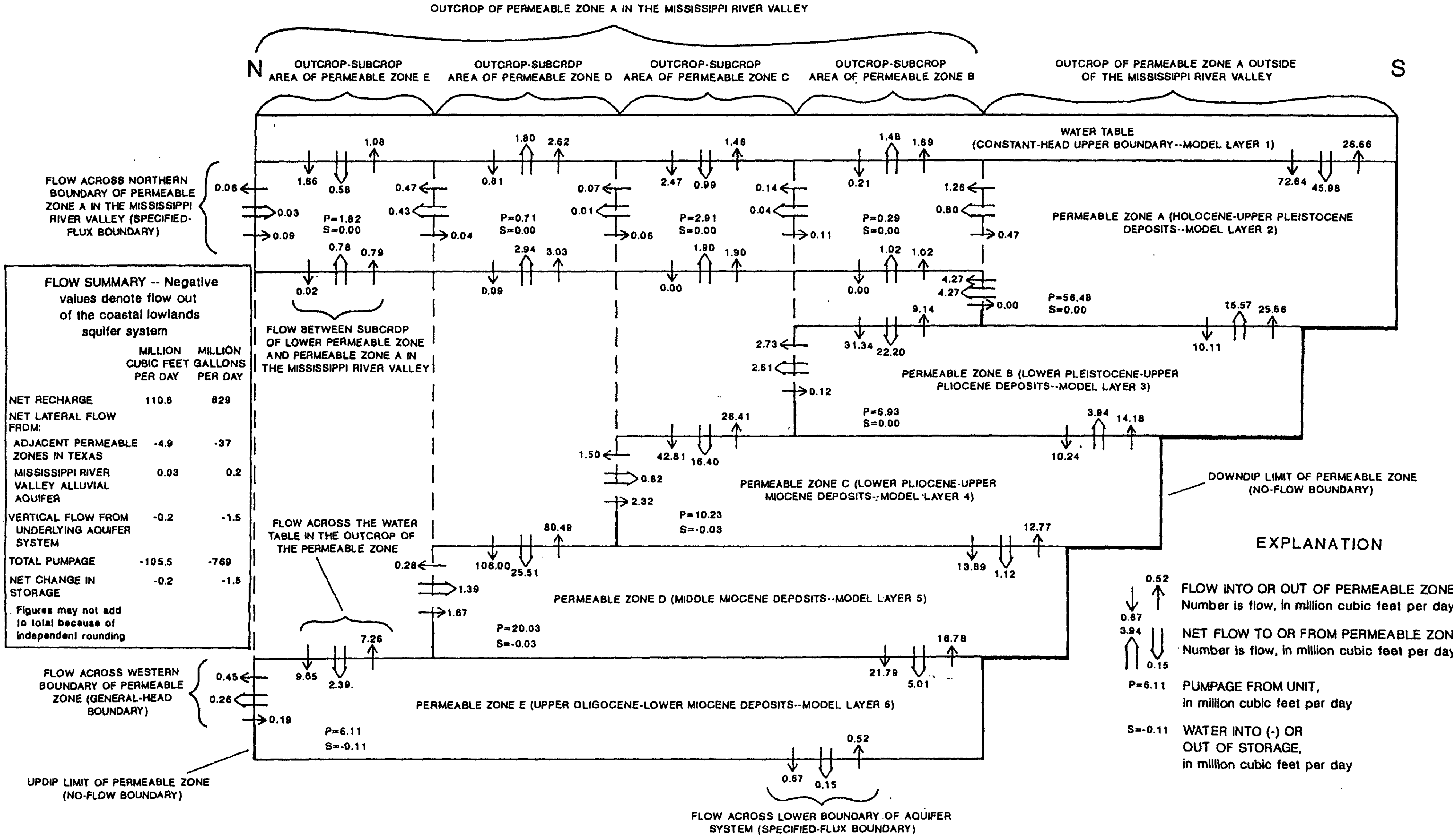


Figure 43.--Simulated flow between permeable zones and across boundaries of the coastal lowlands aquifer system after an additional 50 years of pumpage at 50 percent of the 1983-87 rate.

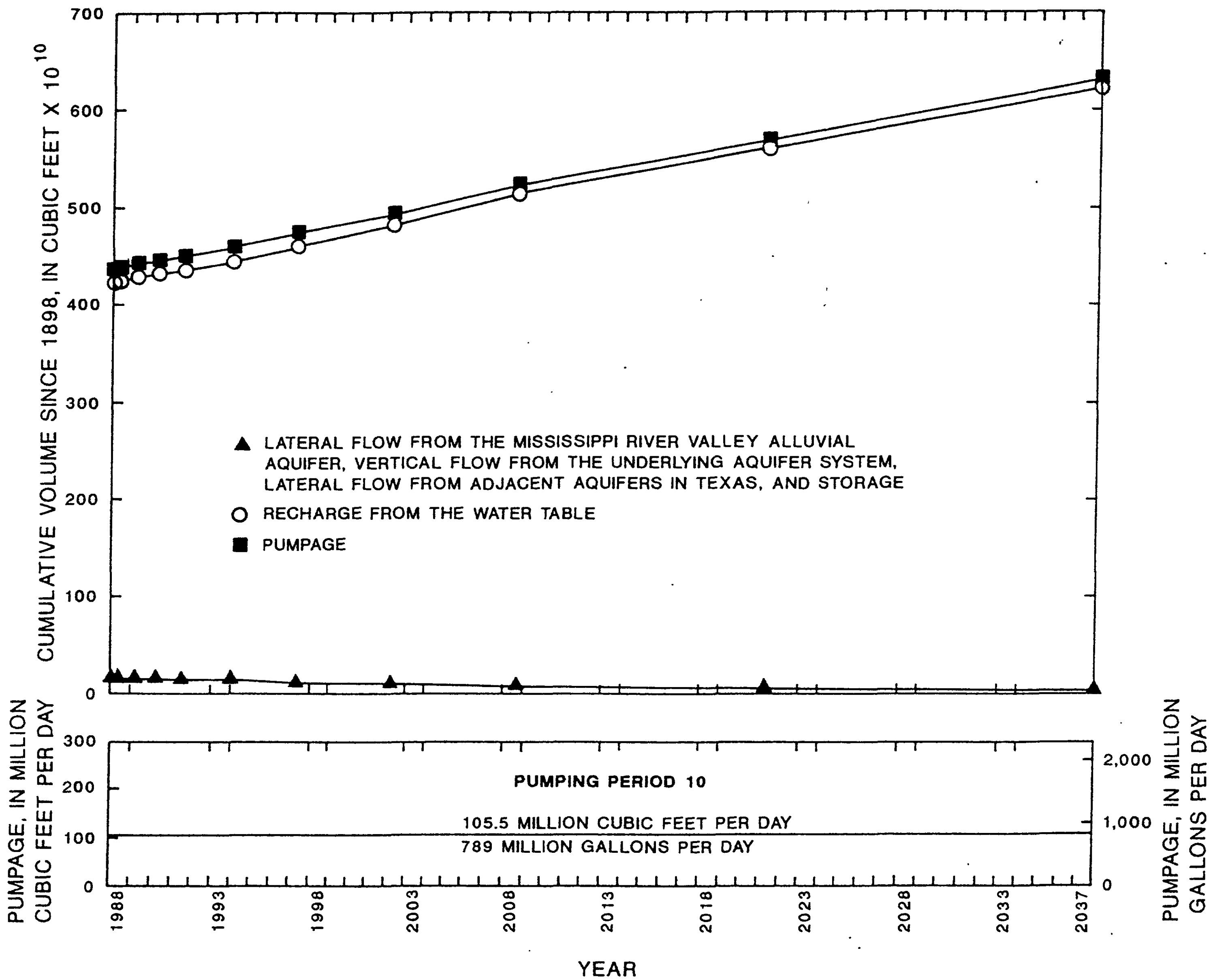


Figure 44.--Cumulative pumpage and the sources of water for the coastal lowlands aquifer system for an additional 50 years of pumpage at 50 percent of the 1983-87 rate.

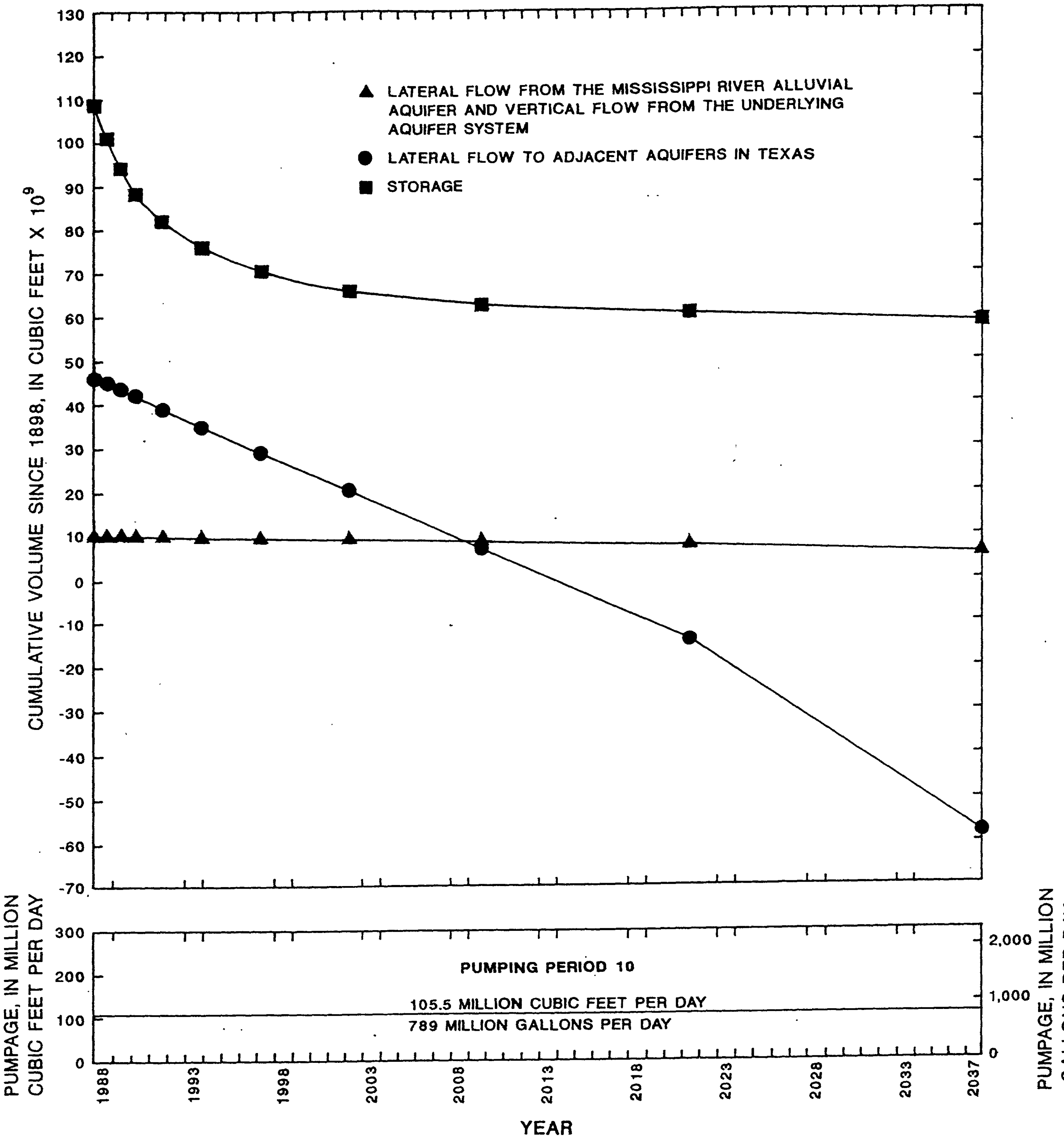


Figure 45.--Pumpage and the cumulative flow of water to or from storage and adjacent aquifers for an additional 50 years of pumpage at 50 percent of the 1983-87 rate.

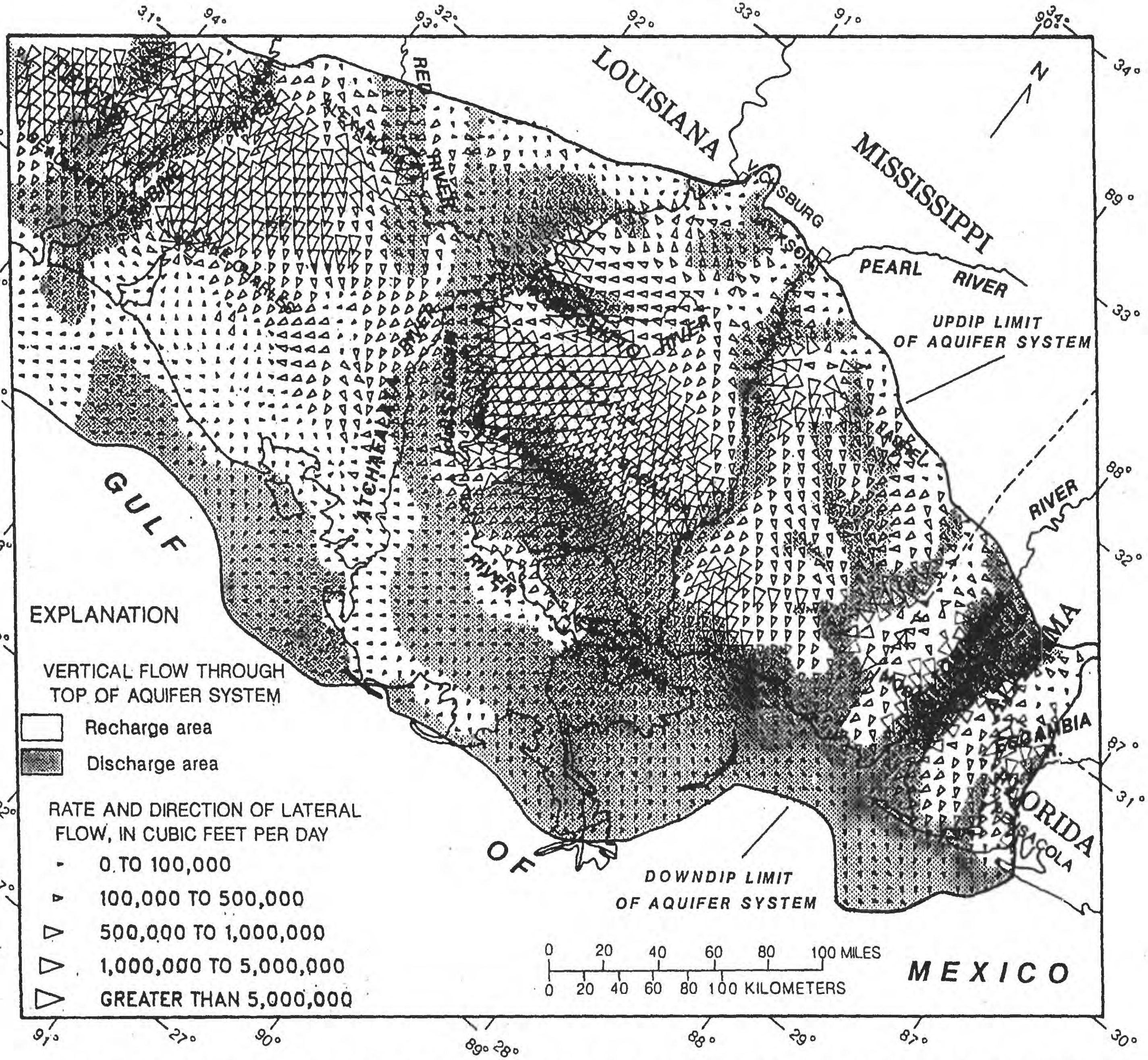


Figure 46.--Simulated ground-water flow in the aquifer system after an additional 50 years of pumpage at 50 percent of the 1983-87 rate.

aquifer system at the end of the period are shown in figure 47. Comparison with the map simulating 1987 conditions (fig. 26) shows that much of the Mississippi Alluvial Plain would revert to a discharge area as during predevelopment time (fig. 19) and that recharge rates in the central part of the rice-growing area would be decreased by 1 in/yr or more. No negative effects on the aquifer system would be expected due to a 50 percent decrease in pumpage.

In the fourth model experiment, designed to determine favorable and less favorable areas for development, 10,000 ft^3/d (75,000 gal/d) of pumpage was simulated from each square mile of the aquifer system in lieu of any other pumpage. The pumpage was distributed among the permeable zones beneath each grid block in proportion to the transmissivity of the zones. Total pumpage of 450 Mft^3/d (3,370 Mgal/d) was slightly more than double the 1985 pumpage. The steady-state model was used for this experiment to insure that the results would represent the full effects of the simulated pumpage. Drawdowns from predevelopment levels for each permeable zone are shown in figures 48a-e. These maps show that, in general, the most favorable conditions for development occur in the upper permeable zones. Using arbitrary criteria of a minimum thickness of 100 ft of sand and a maximum of 200 ft of projected drawdown in a zone, large parts of permeable zones A and B would be favorable for additional development. A small area near the Mississippi River southeast of New Orleans would be less favorable for development because relatively thick and nearly impermeable surficial clays impede recharge and more than 200 ft of drawdown occurs in each permeable zone. Some outcrop areas would be less favorable because the zones contain less than 100 ft of sand. Most of permeable zone C would be favorable except for part of the outcrop area in southern Mississippi and Alabama, where sand thickness is less than 100 ft, and a relatively small area north and east of New Orleans where more than 200 ft of drawdown occurs. Most of the outcrop area and shallow subsurface extent of permeable zone D would be favorable for development, but the deeper subsurface extent across southern Mississippi and in southeast Louisiana would be less favorable because of drawdown greater than 200 ft. Maximum drawdown in permeable zone D of more than 300 ft occurs near the downdip limit of the zone north of New Orleans. Permeable zone E would be favorable for development throughout most of its extent in western Florida, southern Alabama, and in the eastern part of southern Mississippi. Permeable zone E would be less favorable for development throughout most of southwestern Mississippi and central and southeastern Louisiana. Drawdowns of more than 400 ft were projected throughout most of southwestern Mississippi, all of southeastern Louisiana, and in central Louisiana in the Alexandria area.

Projected water-level profiles along north-south and east-west lines (fig. 49) show that water-level gradients are steeper and water levels are lower than under 1987 conditions throughout the area (fig. 23). Water-level declines are greatest in the downdip section of each permeable zone and become progressively greater in the lower zones.

The rate and direction of simulated ground-water flow in the aquifer system resulting from this experiment are shown in figure 50. Almost all natural discharge has been eliminated. The uniformly distributed pumpage across the area has created a pattern of ground-water flow in the northern

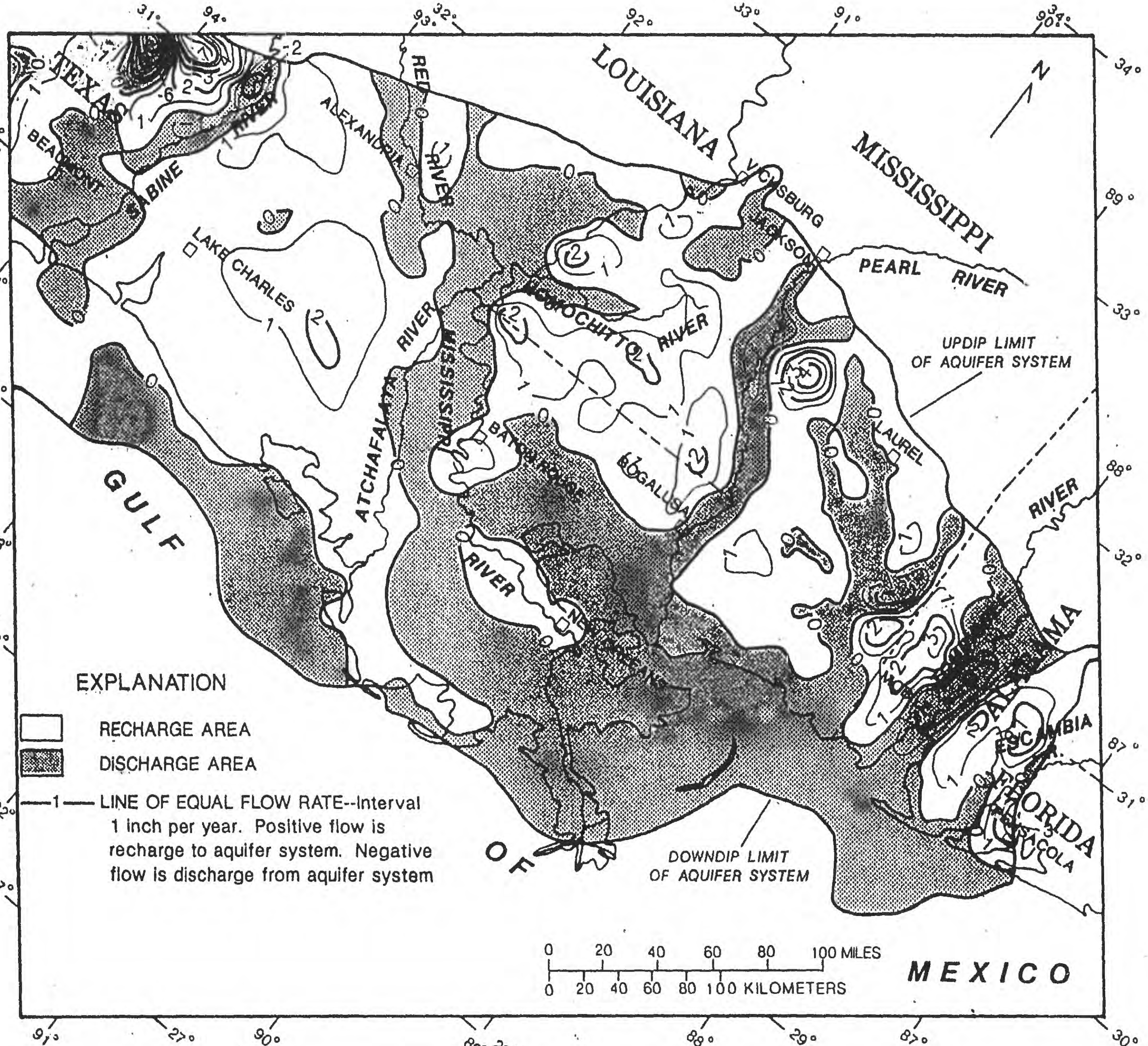


Figure 47.--Areal distribution of simulated rates of recharge to and discharge from the aquifer system after an additional 50 years of pumpage at 50 percent of the 1983-87 rate.

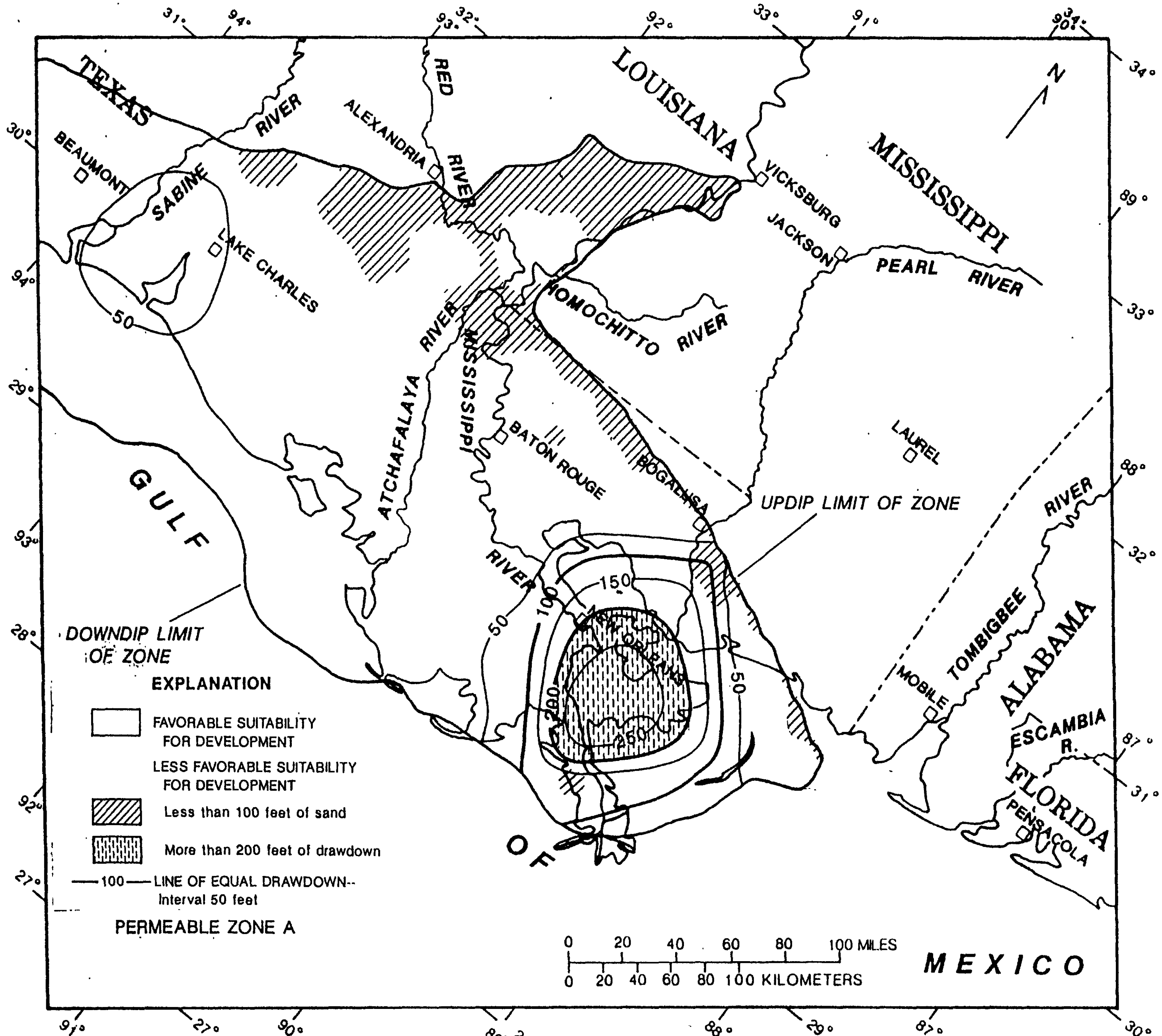


Figure 48a.--Suitability for future ground-water development based on sand thickness and projected drawdown in each permeable zone, permeable zone A.

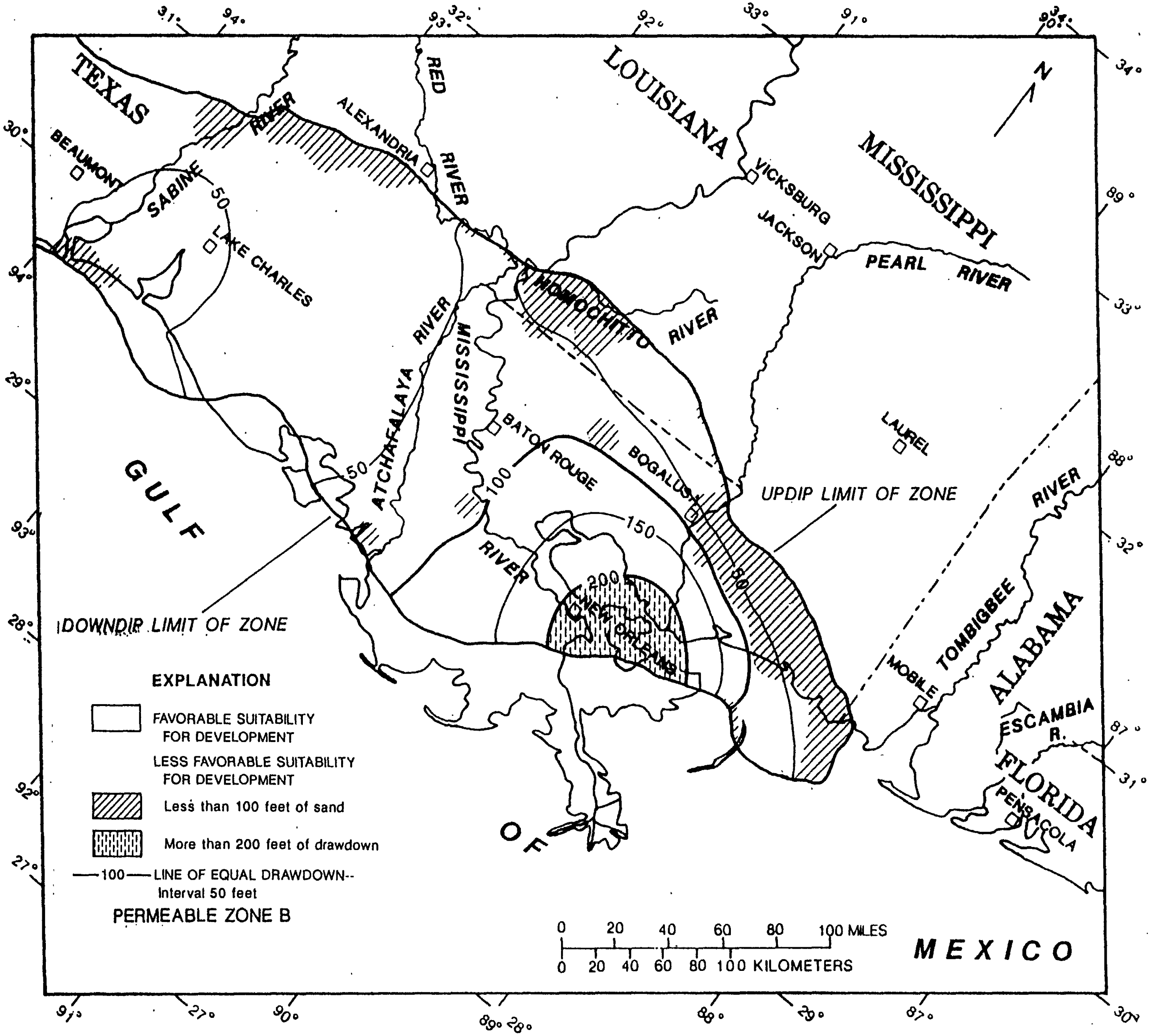


Figure 48b.--Suitability for future ground-water development based on sand thickness and projected drawdown in each permeable zone, permeable zone B.

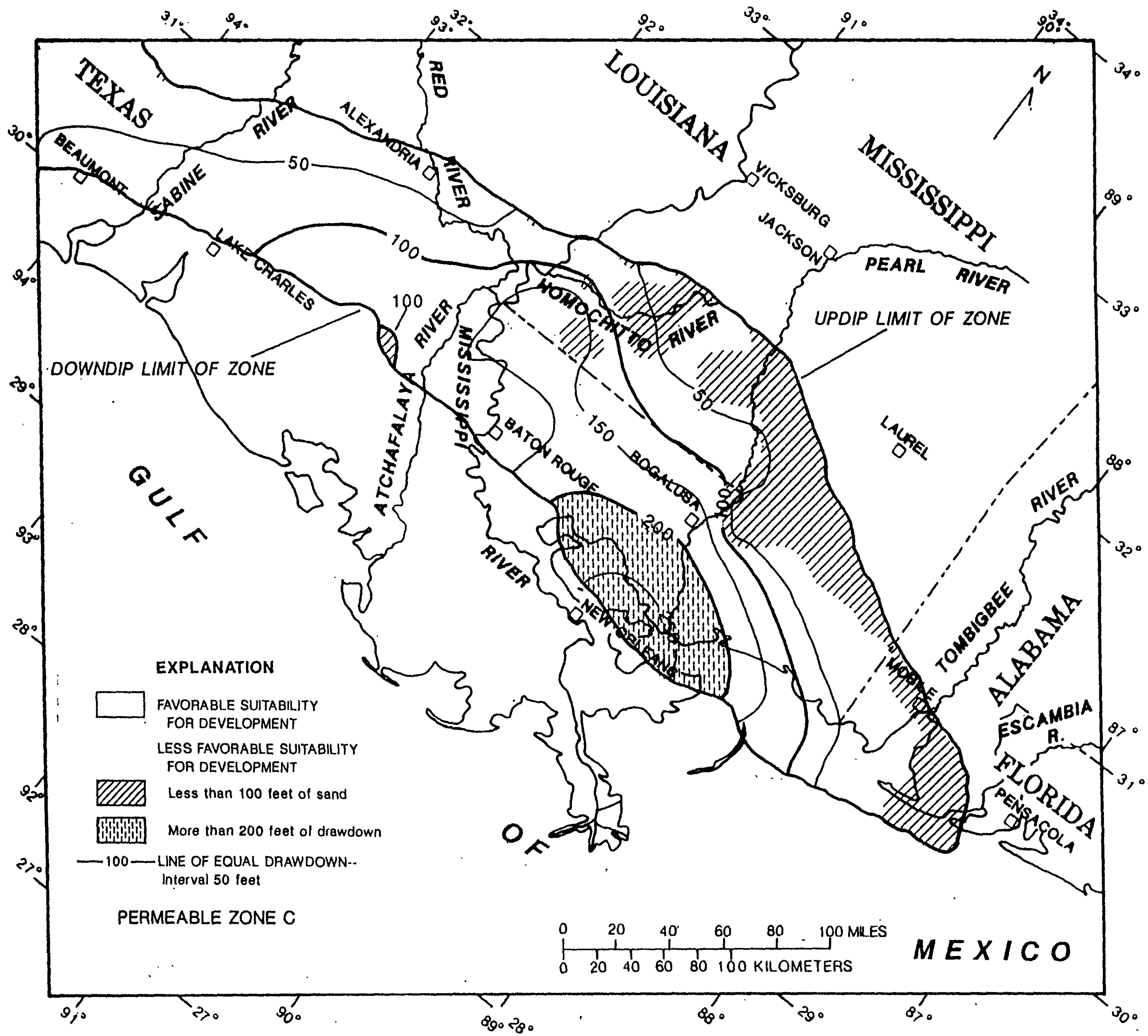


Figure 48c.--Suitability for future ground-water development based on sand thickness and projected drawdown in each permeable zone, permeable zone C.

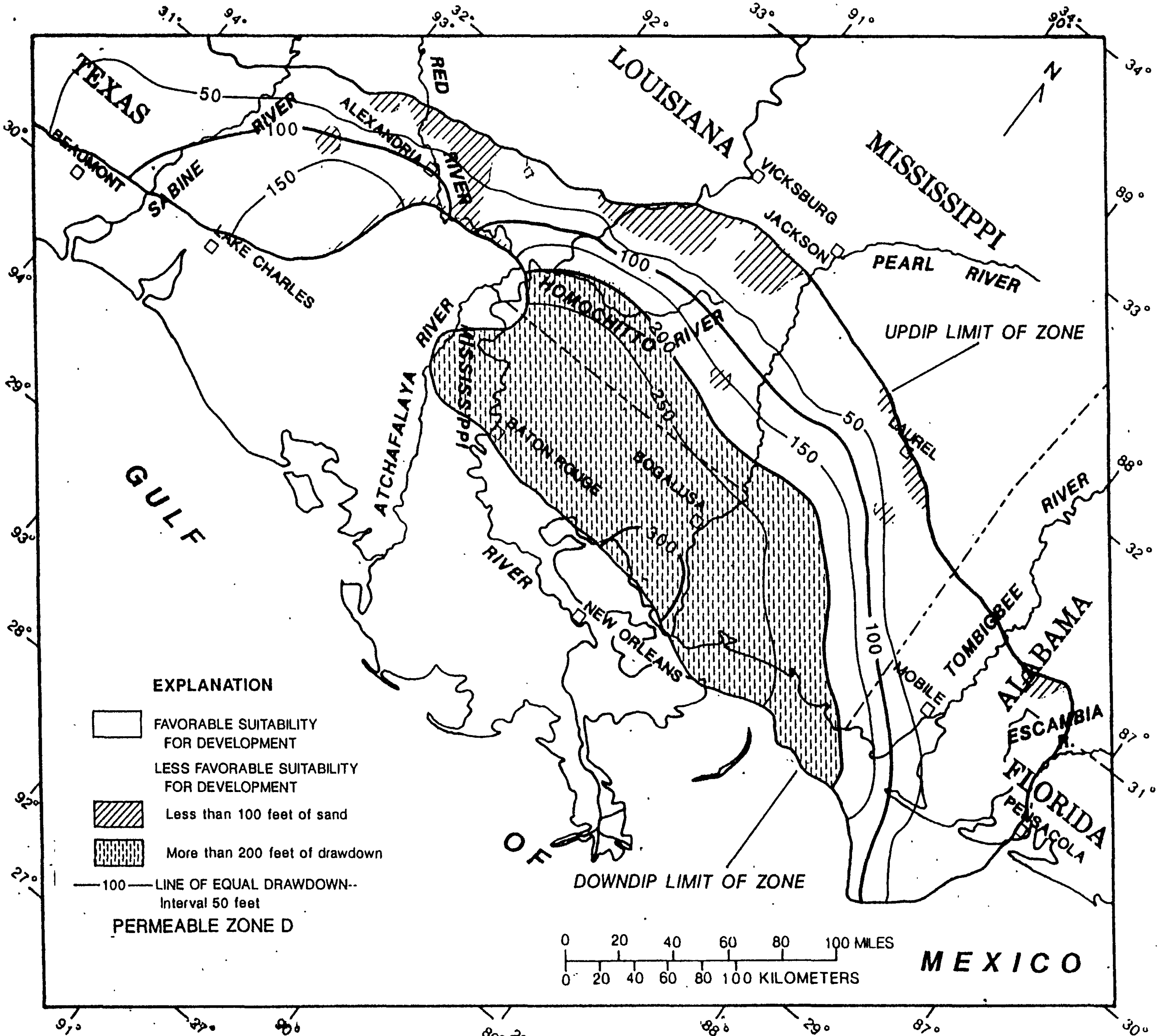


Figure 48d.--Suitability for future ground-water development based on sand thickness and projected drawdown in each permeable zone, permeable zone D.

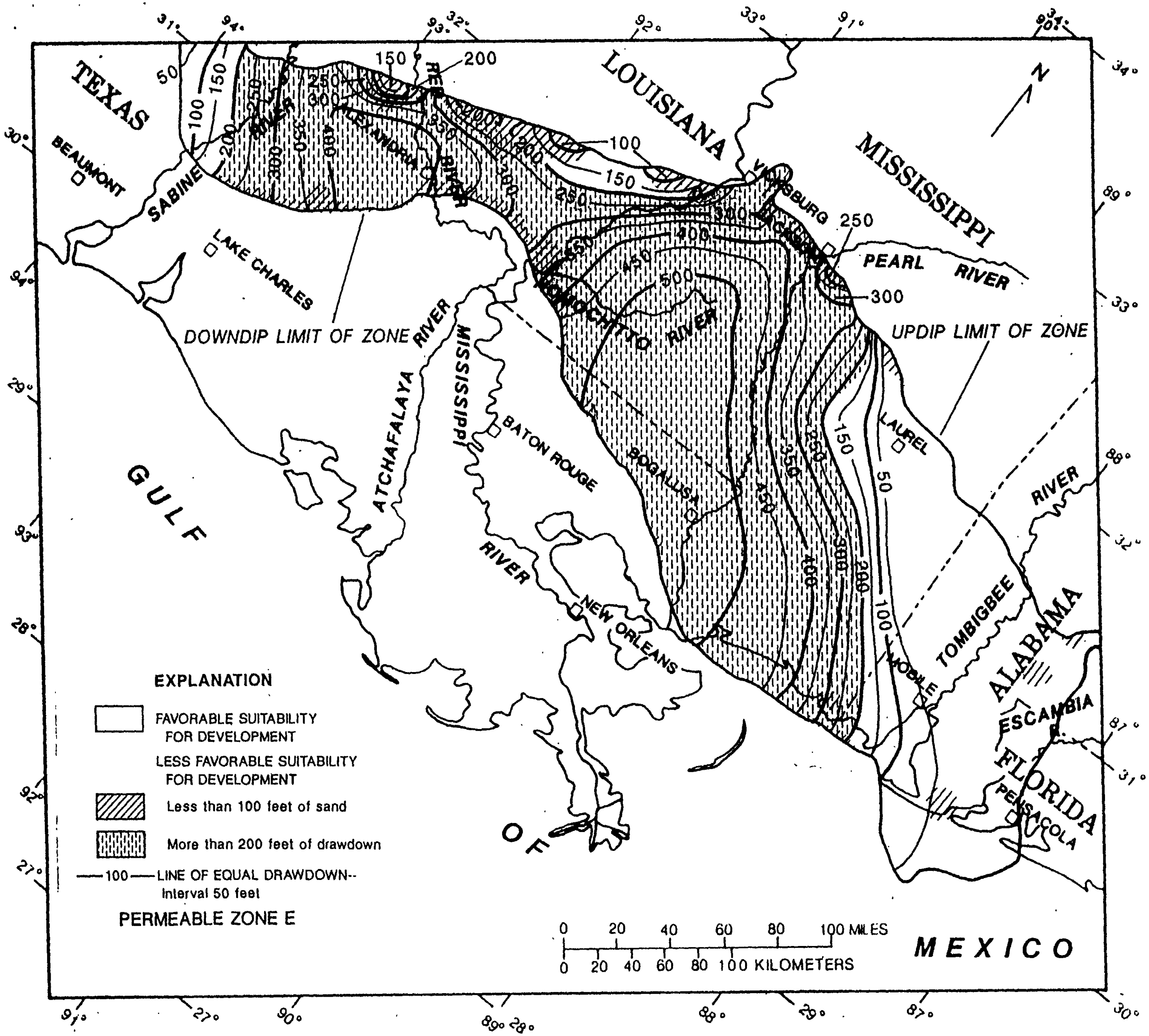


Figure 48e.--Suitability for future ground-water development based on sand thickness and projected drawdown in each permeable zone, permeable zone E.

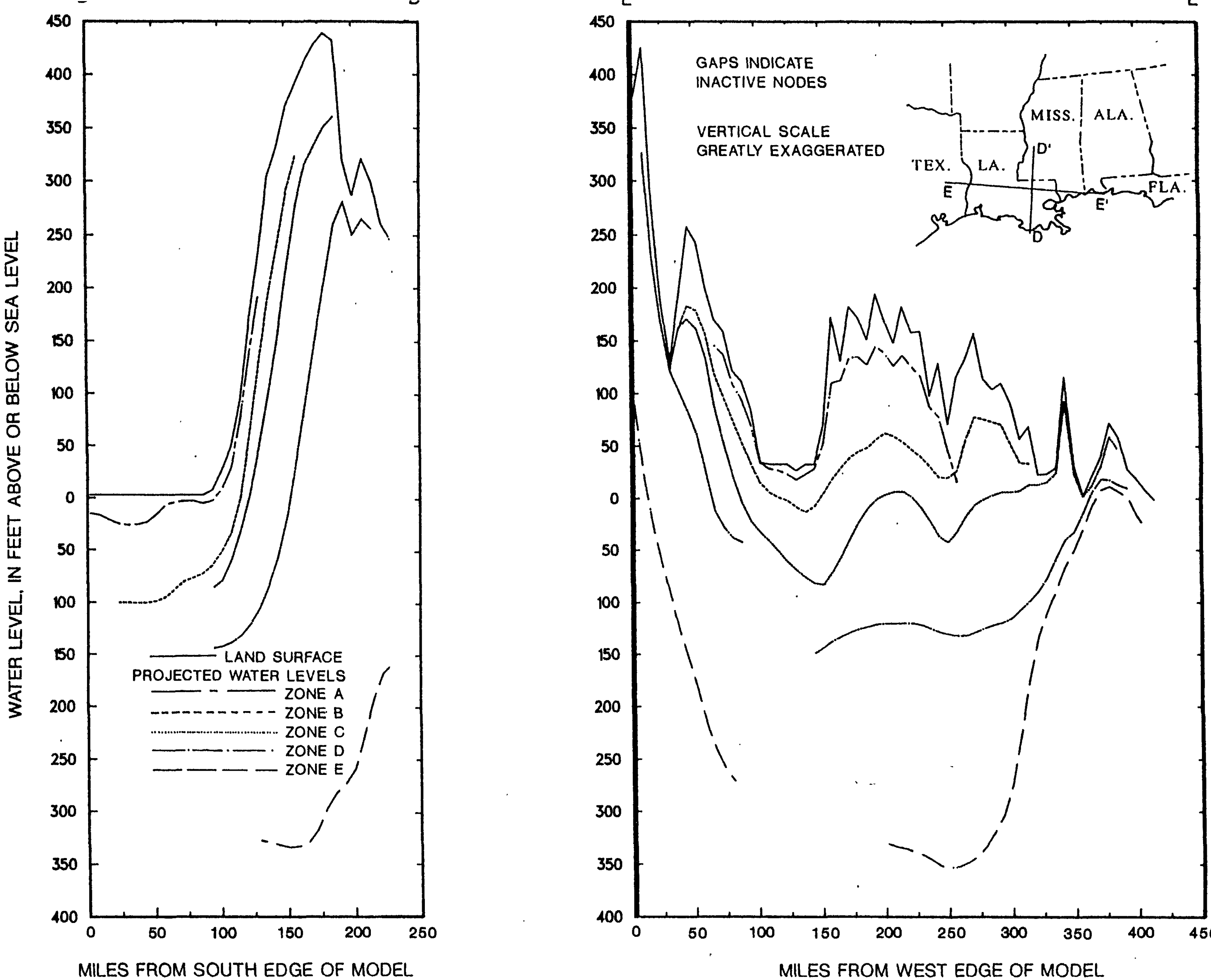


Figure 49.--Projected steady-state water levels in each permeable zone resulting from pumpage of 10,000 cubic feet per day (75,000 gallons per day) per square mile uniformly distributed across the extent of the aquifer system.

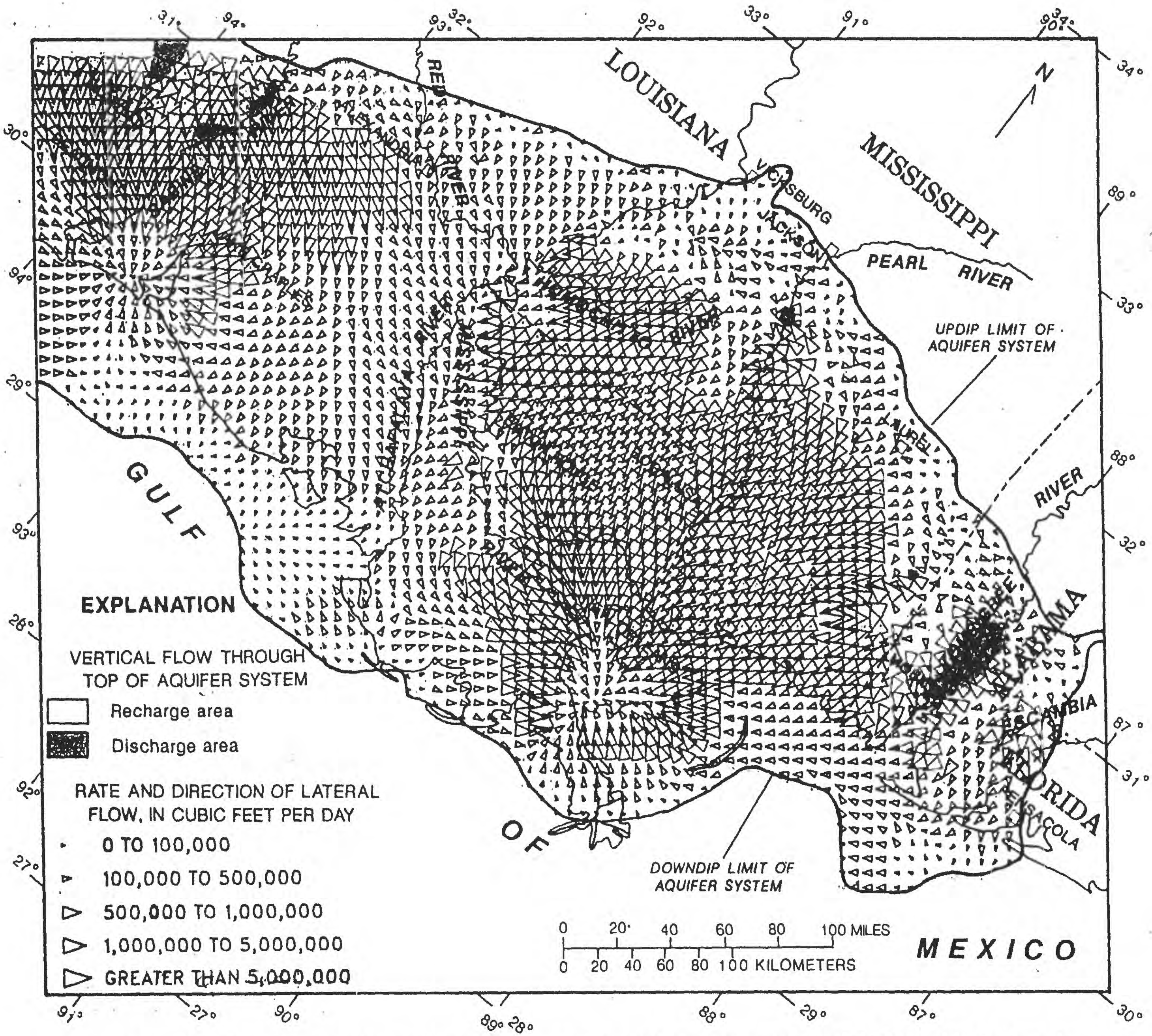


Figure 50.--Simulated ground-water flow in the aquifer system resulting from pumpage of 10,000 cubic feet per day (75,000 gallons per day) per square mile uniformly distributed across the extent of the aquifer system.

part of the area similar to the pattern under predevelopment conditions (fig. 18), though the rate of flow is greater with pumpage.

The pattern of ground-water flow in two areas of coastal Louisiana differs from the predevelopment pattern. The areas, one south of Lake Charles and the other southeast of New Orleans, both show converging radial flow. Both areas are characterized by thick surficial clays of minimal permeability that impede recharge from land surface. To meet the pumpage demand, water must flow laterally through the aquifer system from surrounding areas.

The preceding discussion of the fourth pumping experiment to determine favorable and less favorable areas for future development is based on minimum sand thicknesses and projected maximum drawdowns. Salty water is present downdip from and below the aquifer system as defined for this study. Development of a major pumping center near the downdip limit of freshwater (less than 10,000 mg/L dissolved solids) in a permeable zone would entail risk of saltwater encroachment. In addition, because water in the active area of the flow system may contain up to 10,000 mg/L dissolved solids, water in some areas shown as favorable for development on a quantitative basis may be too highly mineralized for public supply and many industrial and agricultural uses. There is a potential for significant land subsidence in areas where thick clay sections occur and projected drawdowns are greatest.

SUMMARY

The coastal lowlands aquifer system of Louisiana, Mississippi, Alabama, and Florida consists of alternating beds of sand, gravel, silt, and clay deposited under fluvial, deltaic, and marine conditions. The aquifer system comprises sediments of late Oligocene age and younger which thicken and dip toward the Gulf Coast. The sediments are highly heterogeneous with sand beds that are not traceable for more than a few miles.

This study was limited to the part of the aquifer system containing water with dissolved solids concentration of 10,000 mg/L or less. Thickness of that part of the aquifer system ranges from a feather edge along the northern edge of its outcrop area to more than 4,000 ft, with maximum sand thickness of over 2,000 ft in southeastern Louisiana and southern Mississippi. Sand content (including gravel) ranges from less than 10 percent to greater than 80 percent.

The coastal lowlands aquifer system was divided into five regional permeable zones to quantify the distribution of flow in the system. The permeable zones were defined on the basis of pumpage and water-level data from heavily pumped areas, and zone divisions were extrapolated into lesser-developed areas. The permeable zones represent deposits that from youngest to oldest are referred to as: Holocene-upper Pleistocene deposits (zone A), lower Pleistocene-upper Pliocene deposits (zone B), lower Pliocene-upper Miocene deposits (zone C), middle Miocene deposits (zone D), and the lower Miocene-upper Oligocene deposits (zone E).

Flow in the aquifer system prior to development was primarily from the upland terrace areas of southwestern Mississippi and south-central and southeastern Louisiana toward the Gulf Coast and major river valleys. Water-level altitudes decreased with depth in the recharge areas and increased with depth in the discharge areas. Freshwater moving from the recharge areas tends to flush saltwater occurring in the downdip parts of the aquifer system unless movement is blocked by pinchout of the sand beds or by faulting.

Lateral hydraulic conductivities of sand beds within the permeable zones were determined from aquifer-test results. Lateral hydraulic conductivity decreases from the upper to the lower permeable zones. On average, permeable zone A has the highest lateral hydraulic conductivity and zone E has the lowest.

Ground water is pumped for municipal, industrial, agricultural, and domestic use throughout most of the study area. Total pumpage increased during 1960-80 and peaked in 1980 at 251 Mft^3/d (1,874 Mgal/d). Pumpage then declined by more than 15 percent to 211 Mft^3/d (1,579 Mgal/d) in 1985. Pumpage from permeable zone A has ranged from 59 to 67 percent of the total pumpage from the aquifer system during the period 1960-85.

A six-layer, finite-difference ground-water flow model was used to investigate and quantify regional flow in the coastal lowlands aquifer system and to evaluate the effects of possible future ground-water pumpage. The model was calibrated to steady-state and transient conditions by adjusting transmissivities of the model layers that represent the five permeable zones, vertical leakances between layers, and storage coefficients of the permeable zones. Calibration was based on minimizing the RMSE of the residuals between simulated and measured water levels throughout the modeled area.

The model is generally most sensitive to changes in transmissivity and least sensitive to changes in storage coefficient. Generally, the model is more sensitive, in terms of water-level changes, to decreases than to increases in transmissivities and vertical leakances. The model is relatively insensitive to changes in storage coefficients.

The model was divided into seven areas to investigate in detail the flow patterns and distributions in the aquifer system. The areas were chosen based on factors affecting flow in the aquifer system, such as topography, the outcrop pattern of the zones, and drainage boundaries.

Simulation results indicate that pumping has significantly altered the natural ground-water flow system. Under 1987 conditions, about 60 percent of the water entering the regional flow system is discharged by pumping. The total flow circulating through the regional aquifer system in 1987 was about 354 Mft^3/d, which is about 62 percent greater than the predevelopment flow of 222 Mft^3/d. Less than one percent of the flow in the aquifer system under 1987 conditions is derived from water moving into or out of storage. Throughout most of the coastal plain of southern Louisiana, flow directions have been altered or reversed due to pumping so that flow now converges toward the major pumping centers. A large part of the Gulf Coastal Plain has been transformed from areas of natural discharge to areas of induced recharge. Major pumping centers in southern Louisiana, in permeable zone A, and at Baton Rouge, La., in permeable zone C, have had the greatest effect on the ground-water flow system.

Four model experiments were conducted to evaluate the effects of possible future ground-water pumpage from the aquifer system. Results of the first experiment show that relatively small changes in water levels occurred throughout the aquifer system when the 1983-87 pumping rate was continued for an additional 50 years (1988 to 2037). In the second experiment, results indicate that pumping from existing pumping centers at a rate 50 percent greater than the 1983-87 rate would be feasible based on the effects on water levels. Because of the large available drawdowns and relatively high water levels, there would be no serious impact on the regional aquifer system even though additional water-level declines of more than 80 ft would occur in places. There would be some adverse effects on water quality through increased saltwater encroachment or infiltration and on the rate of land-surface subsidence. Results of the third model experiment, involving a 50-percent pumpage reduction from the 1983-87 rate, show that water levels would recover rapidly throughout the aquifer system in response to the reduced pumpage. Results of the fourth experiment show that the most favorable conditions for development occur in the upper permeable zones. Favorable and less favorable areas are described in qualitative terms based on maximum drawdowns and minimum sand thicknesses within each permeable zone. Development of a major pumping center near the downdip limit of a permeable zone would entail risk of saltwater encroachment and the potential for land subsidence.

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