STATE OF LOUISIANA

DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

PUBLIC WORKS AND FLOOD CONTROL DIRECTORATE

WATER RESOURCES SECTION

WATER RESOURCES

TECHNICAL REPORT

NO. 54

ANALYSIS OF GROUND-WATER FLOW IN THE "1,200-FOOT" AQUIFER, BATON ROUGE AREA, LOUISIANA

Prepared by
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
In cooperation with
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
And
CAPITAL AREA GROUND WATER CONSERVATION COMMISSION

1994

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By

Keith J. Halford and John K. Lovelace

U.S. Geological Survey

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Multiply	By	To obtain
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per year (ft/yr)	0.3048	meter per year
foot squared (ft^2)	0.0929	meter squared
gallon (gal)	0.003785	cubic meter
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 meters per second
million gallons (Mgal)	3,785	cubic meters
million gallons per day (Mgal/d)	0.04381	cubic meters per second
million gallons per day per square mile [$(Mgal/d)/mi^2$]	1,460	cubic meters per day per square kilometer
square mile (mi^2)	2.590	square kilometer

Transmissivity: In this report, the mathematically reduced form for transmissivity, foot squared per day (ft^2/d), is used for convenience. The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)ft^2$]ft.

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:
°C = 5/9 X (°F-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 the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality unit used in report:

milligrams per liter (mg/L)

Analysis Of Ground-water Flow In The "1,200-foot" Aquifer, Baton Rouge Area, Louisiana

By Keith J. Halford and John K. Lovelace

Abstract

The "1,200-foot" aquifer is a major ground-water resource for industry and public supply throughout the Baton Rouge area in Louisiana. Pumpage from the aquifer in the Baton Rouge area was about 15 Mgal/d (million gallons per day) in 1987 and was divided evenly between industrial uses and public supply.

The hydrogeologic sequence in the study area is a complex series of alternating and lenticular beds of sand and layers of clay. Prior to extensive ground-water development in the Baton Rouge area, water flowed upward from deep aquifers to shallower ones southward from the outcrop area near the Mississippi-Louisiana State line. Increased pumping produced continuous water-level declines in the "1,200-foot" aquifer and adjacent aquifers from 1953 to 1980. Pumping decreased in the "1,200-foot" aquifer from 1980 to 1988, and water levels rose to reflect these changes.

A ground-water flow model was used to simulate flow in the "1,200-foot" aquifer and adjacent aquifers, and determine the effects of pumping changes. The calibrated model showed that from the time pumping began (predevelopment) to 1988 conditions: (1) flow patterns were altered in the "1,200-foot" aquifer, (2) water levels downgradient from the subcrop declined 40 feet, and (3) recharge to the "1,200-foot" aquifer increased about 0.5 inch per year. Most of the flow (62 Mgal/d) leaving the "1,200-foot" aquifer in 1988 was by pumpage (19 Mgal/d or 30 percent) and leakage (26 Mgal/d or 43 percent) to deeper aquifers. The "1,200-foot" aquifer responds quickly to changes in pumping north of the Baton Rouge fault.

The "1,200-foot" aquifer can sustain a pumping rate 50 percent greater than the 1985 pumping rate (18.6 Mgal/d) with drawdowns of 20 to 30 feet around the Baton Rouge industrial district. Pumping simulations produced maximum drawdowns of 50 to 60 feet per 10 Mgal/d of additional pumpage in southeast Baton Rouge north of the Baton Rouge fault.

INTRODUCTION

The "1,200-foot" aquifer, commonly called the "1,200-foot" sand (Meyer and Turcan, 1955), is a major ground-water resource for industry and public supply throughout the Baton Rouge area in Louisiana. Industries were the first users to extensively utilize the "1,200-foot" aquifer. Pumpage from the aquifer increased from 2.5 to 25 Mgal/d from 1953 to 1969 but decreased to 15 Mgal/d in 1987, even with increased pumping for public supply. The decrease was due to conservation measures practiced by industry since late 1974. Water use from the "1,200-foot" aquifer was divided evenly between industrial uses and public supply in 1987 (Capital Area Ground Water Conservation Commission, 1988). An adequate understanding of flow in the "1,200-foot" aquifer is needed for effective management of this water resource.

In 1975, the U.S. Geological Survey began a cooperative program with the Louisiana Department of Transportation and Development and the Capital Area Ground Water Conservation Commission to analyze ground-water flow in aquifers of the Baton Rouge area. The aquifers that have been studied since this program began include the "400-foot" and "600-foot," "1,500-foot" and "1,700-foot," and "2,000-foot" aquifers in the Baton Rouge area (Kuniansky, 1989; Huntzinger and others, 1985; Torak and Whiteman, 1982). This study of the "1,200-foot" aquifer is fourth in the series of studies.

Purpose and Scope

This report presents the results of a study to analyze ground-water flow in the "1,200-foot" aquifer and adjacent aquifers under 1988 conditions. The report also describes the effects of pumping changes (increases and decreases) on flow in the "1,200-foot" aquifer.

The study focused on potentiometric head changes in the aquifer in the five parishes of East Baton Rouge, West Baton Rouge, Pointe Coupee, East Feliciana, and West Feliciana (fig. 1). Estimates of changes in potentiometric head under various flow conditions and six pumping simulations were made using the McDonald and Harbaugh (1988) modular finite-difference model, a three-dimensional, digital ground-water flow model. All measured water-level data are on file at the U.S. Geological Survey office in Baton Rouge, Louisiana.

Physiography

Generalized regions denoted in the study area (fig. 2) for identification purposes in this report are the outcrop of the Southern Hills aquifer system, subcrop of the "1,200-foot" aquifer, Baton Rouge industrial district, and Baton Rouge area. The Mississippi River alluvial plain and the terraces of Pleistocene age are two distinct physiographic features within the study area. The terraces are slightly older alluvial deposits that were eroded by the Mississippi River (Kuniansky, 1989, p. 4). The present course of the Mississippi River approximately defines the eastern extent of the Mississippi River alluvial plain.

In East and West Feliciana Parishes, the terraces have been eroded to rolling hills that decrease in altitude above sea level, from 300 ft in the north to 100 ft in the south. In East Baton Rouge Parish, the terraces are less hilly and decrease to an altitude of 25 ft near the southern border of the parish (Kuniansky, 1989, p. 6). The terraces are drained by the Amite River, Thompson Creek, and other minor streams. The Mississippi River alluvial plain is essentially flat, poorly drained, and contains several large swamps. Land surface altitude is 50 ft at the

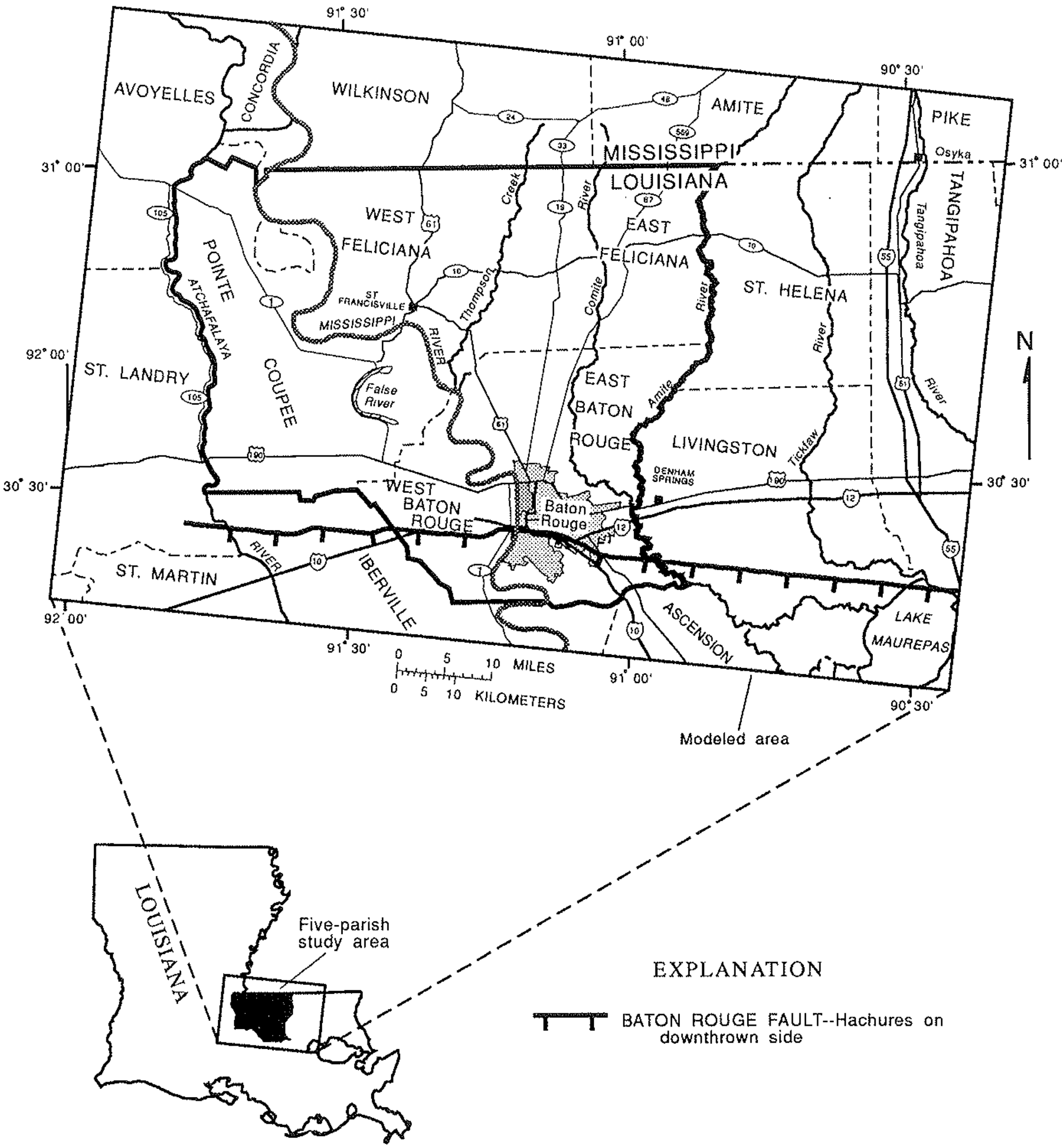


Figure 1. Five-parish study area, modeled area, and location of Baton Rouge fault.

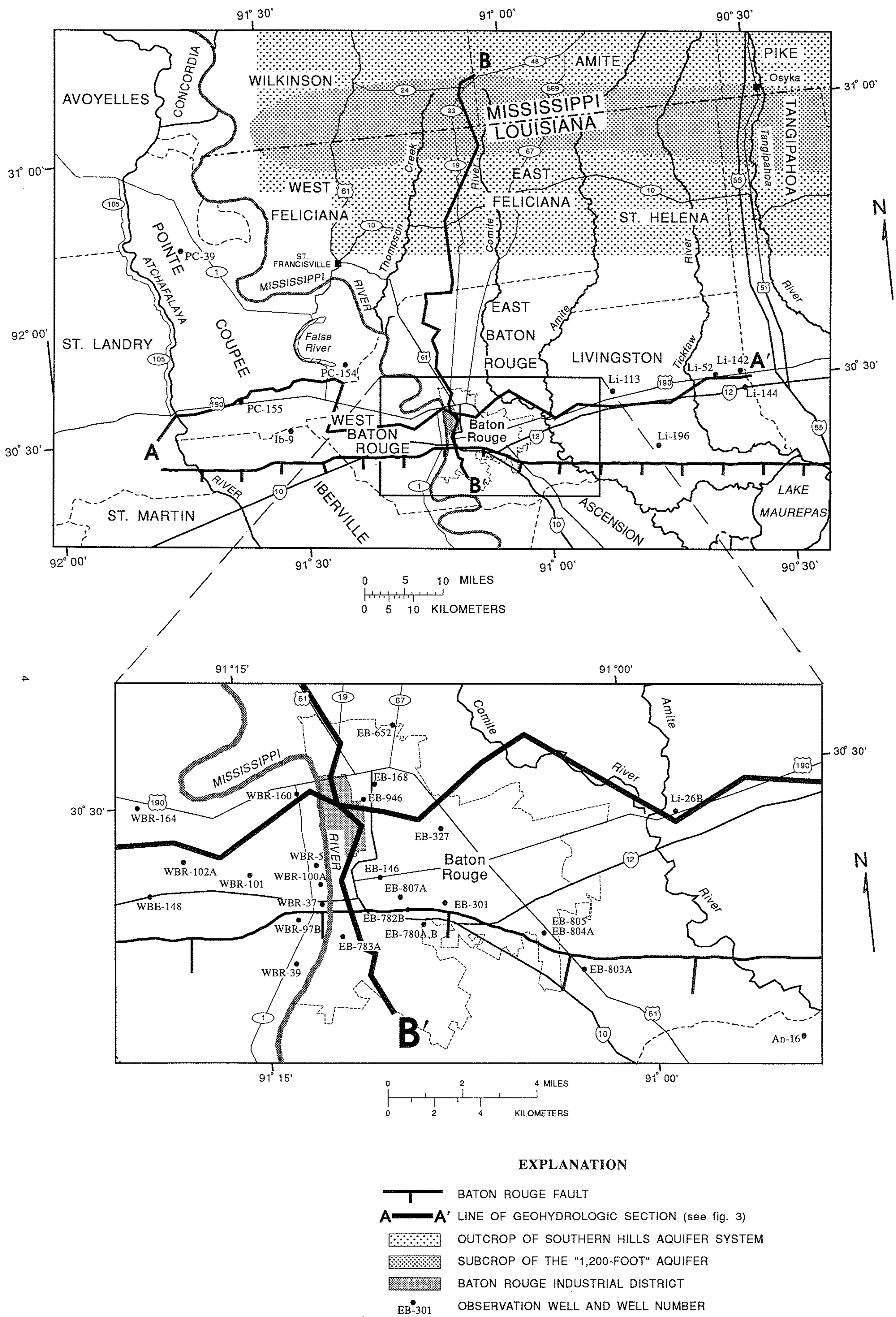


Figure 2. Subcrop of the "1,200-foot" aquifer and the locations of selected wells.

northern border of Pointe Coupee Parish and 25 ft in the southern part of West Baton Rouge Parish (Kuniansky, 1989, p. 6).

East of the Mississippi River most of the study area is rural land used for tree farming. The alluvial plain west of the Mississippi River is used for cultivated crops. Both sides of the Mississippi River are industrialized, from St. Francisville, Louisiana, to south of the study area. Baton Rouge, the only large city within the study area, has a large petrochemical industry and is a deep-water port.

Climate

Southern Louisiana has a humid, subtropical climate. Average precipitation over the study area ranges from 54 to 60 in/yr (National Oceanic and Atmospheric Administration, 1982). Rainfall is distributed evenly throughout the year except during drier, summer months. The average annual temperature is 68 oF. Summer temperatures range between 65 and 98 oF, whereas winter temperatures range between 20 and 65 oF.

Acknowledgments

The authors extend their appreciation to Mr. Zahir "Bo" Bolourchi, Chief, Water Resources Section, Louisiana Department of Transportation and Development for assistance provided during this study.

HYDROGEOLOGY

The hydrogeologic sequence in the study area is a complex series of alternating and lenticular beds of sand and layers of clay. The generalized sections through the study area (fig. 3) illustrate the complexity of this sequence. The sand beds and clay layers dip south to southeast (Morgan, 1963, p. 24), which places the outcrop of each successively deeper layer farther north. The dip of the sand and clay units (20 to 80 ft/mi) increases with depth at Baton Rouge and decreases updip from Baton Rouge. The aggregate of all aquifers in the study area, except for local shallow aquifers, form the Southern Hills aquifer system (Buono, 1983). The sand beds of the Southern Hills aquifer system are discontinuous in places and can be interrupted by or contain local clay layers. In other places, two sand beds can converge to form one.

The major sand units were identified as aquifers and named for their depth below land surface in the Baton Rouge industrial area by Meyer and Turcan (1955). Of these, the "400-foot," "600-foot," 800-foot," "1,000-foot," "1,200-foot," "1,500-foot," and "1,700-foot" aquifers are discussed in this report. Aquifer nomenclature varies from one locality to another within the study area (fig. 3a). In this report, nomenclature for aquifers in the Baton Rouge area by Meyer and Turcan (1955) will be used.

Because the major clay units between aquifers range from less than 1 foot to several hundred feet in thickness, some aquifers merge locally. Also, aquifers are hydraulically connected by leakage through the clay layers. No aquifer tests have been performed in the study area that allow calculation of the vertical conductance or the vertical hydraulic conductivity of the confining units. Bear (1979) reports the hydraulic conductivity of clay units range from

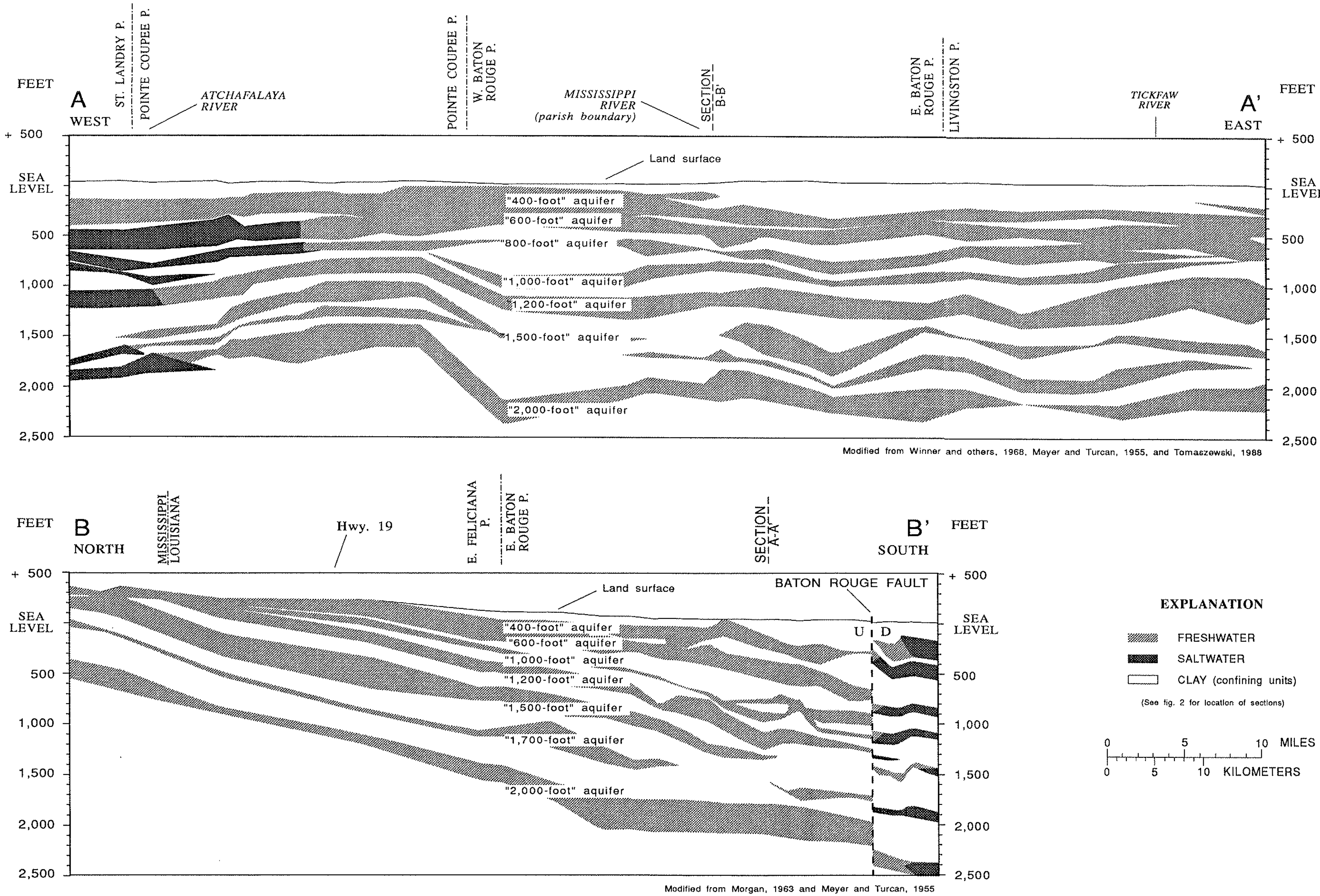


Figure 3. Generalized sections A-A' and B-B' through the study area.

System	Series	Southeastern Louisiana[1]	Baton Rouge area[2], Geismar-Gonzales area[3], Gramercy area[4]	East Feliciana Parish[5]	Livingston and St. Helena Parishes[6]		Tangipahoa Parish[7]	Model layer this report
		Aquifer unit						
Quaternary	Holocene and Pleistocene	Local shallow aquifers	Gonzales-New Orleans, and Gramercy and Norco aquifers		Shallow aquifer unit	Upper sand bed	Shallow aquifer / Gonzales-New Orleans aquifer	
		Southern Hills aquifer system	"400-foot"	Undifferentiated upland deposit		Lower sand bed	Upper Ponchatoula aquifer	1
			"600-foot"					
Tertiary	Pliocene		"800-foot"				Lower Ponchatoula aquifer	2
			"1,000-foot"	Zone 1	Aquifer unit 1	Upper sand bed / Lower sand bed		
			"1,200-foot"					3
			"1,500-foot"		Aquifer unit 2	Upper sand bed / Middle sand bed / Lower sand bed	Kentwood aquifer system: Abita aquifer, Covington aquifer	4
			"1,700-foot"	Zone 2				
	?		"2,000-foot"				Tchefuncta aquifer	Base of model
	Miocene		"2,400-foot"	Zone 3	Aquifer unit 3	Upper sand bed	Hammond aquifer / Amite aquifer / Ramsay aquifer / Franklinton aquifer	
			"2,800-foot"			Lower sand bed		

[1] Buono, 1983. [2] Morgan, 1961. [3] Long, 1965. [4] Dial and Kilburn, 1980. [5] Morgan, 1963 [6] Tomaszewski, 1988. [7] Nyman and Fayard, 1978.

Figure 3a. Hydrogeologic, aquifer, and model-layer correlations for the study area.

0.00000003 to 0.3 ft/d. Laboratory analyses of clay samples from the Baton Rouge industrial area yielded vertical hydraulic conductivity values of 0.000011 ft/d for samples taken from depths of 447 to 455 ft and 0.000016 ft/d for samples taken from depths of 2,113 to 2,116 ft (Whiteman, 1980, p. 18). Because the confining units in the study area contain considerable silt and sand, the overall vertical hydraulic conductivity is more likely to be about 0.0005 ft/d.

The "1,200-foot" aquifer is generally continuous throughout the study area. The aquifer has a maximum thickness of 260 ft in northern Tangipahoa Parish and a minimum thickness of 40 ft about 1 mi south of the Baton Rouge industrial district. The aquifer primarily is composed of fine- to medium-grained sand throughout the study area. Values of transmissivity, calculated from aquifer tests and geologic-log analyses, range from 3,000 to 16,000 ft^2/d (Morgan, 1961, p. 36). Storage coefficients for the "1,200-foot" aquifer range from 0.0001 to 0.0008 (Huntzinger and others, 1985, p. 6; Morgan, 1961, p. 36). Properties of the "1,200-foot" aquifer and other aquifers in the Baton Rouge area are listed in table 1.

Table 1. Thicknesses, transmissivities, and storage coefficients for aquifers in the Baton Rouge area

[Source: Huntzinger and others, 1985]

Aquifer	Lithologic description	Thick-ness (feet)	Transmissivity (foot squared per day)	Storage coefficient (dimension-less)
"400- and 600-foot"	Fine sand to pea gravel	75-400	1,700-26,000	0.0001-0.0025
"800-foot"	Fine to medium sand	50-150	3,400	.0001- .001
"1,000-foot"	Fine to coarse sand	40-90	9,500	.0001
"1,200-foot"	Fine to medium sand	40-100	10,000-16,000	.0002- .0008
"1,500- and 1,700-foot"	Fine to medium sand	20-300	4,300-12,000	.0001- .001
"2,000-foot"	Medium sand	100-300	22,000-39,000	.0006- .0008
"2,400-foot"	Fine to medium sand	50-250	13,000	.0001
"2,800-foot"	Fine to coarse sand	50-350	17,000	.0001

The Baton Rouge fault is an east-west trending normal fault (fig. 2) that restricts flow in all the aquifers. Three hundred feet or more of vertical displacement has occurred below a depth of 1,000 ft, causing the "1,200-foot" aquifer south of the fault to become hydraulically connected to the "1,500-foot" aquifer north of the fault. Using numerical methods, Torak and Whiteman (1982) indicated the hydraulic conductivity of the fault to be 0.00005 d^{-1}. The conductance was calculated by using a hydraulic conductivity of 0.03 ft/d over a 600-ft distance. The extent of the fault and its role in restricting ground-water movement is described in reports by Cardwell and others (1967), Rollo (1969), Smith (1979), Whiteman (1979), and Torak and Whiteman (1982).

GROUND-WATER FLOW SYSTEM

The primary recharge area for the "1,200-foot" aquifer is in the northern part of the study area where the aquifer subcrops unconfined, surficial deposits of Pleistocene age (fig. 2) along the Mississippi-Louisiana State line. Most recharge to the unconfined, surficial deposits of Pleistocene age is discharged locally to perennial streams or by evapotranspiration. Water that is not discharged locally enters the confined aquifer and moves downgradient toward Baton Rouge and toward an ancestral channel of the Mississippi River, which is beneath the present Atchafalaya River. Recharge rates are relatively high in the unconfined, surficial deposits of Pleistocene age because surface clay is thin or absent. The potential recharge available to the confined aquifers that subcrop the unconfined, surficial deposits of Pleistocene age in the Southern Hills outcrop area ranges from 0.3 to 5.3 in/yr (Kuniansky, 1989, p. 28) as determined by comparison of climatic water budget with streamflow measurements.

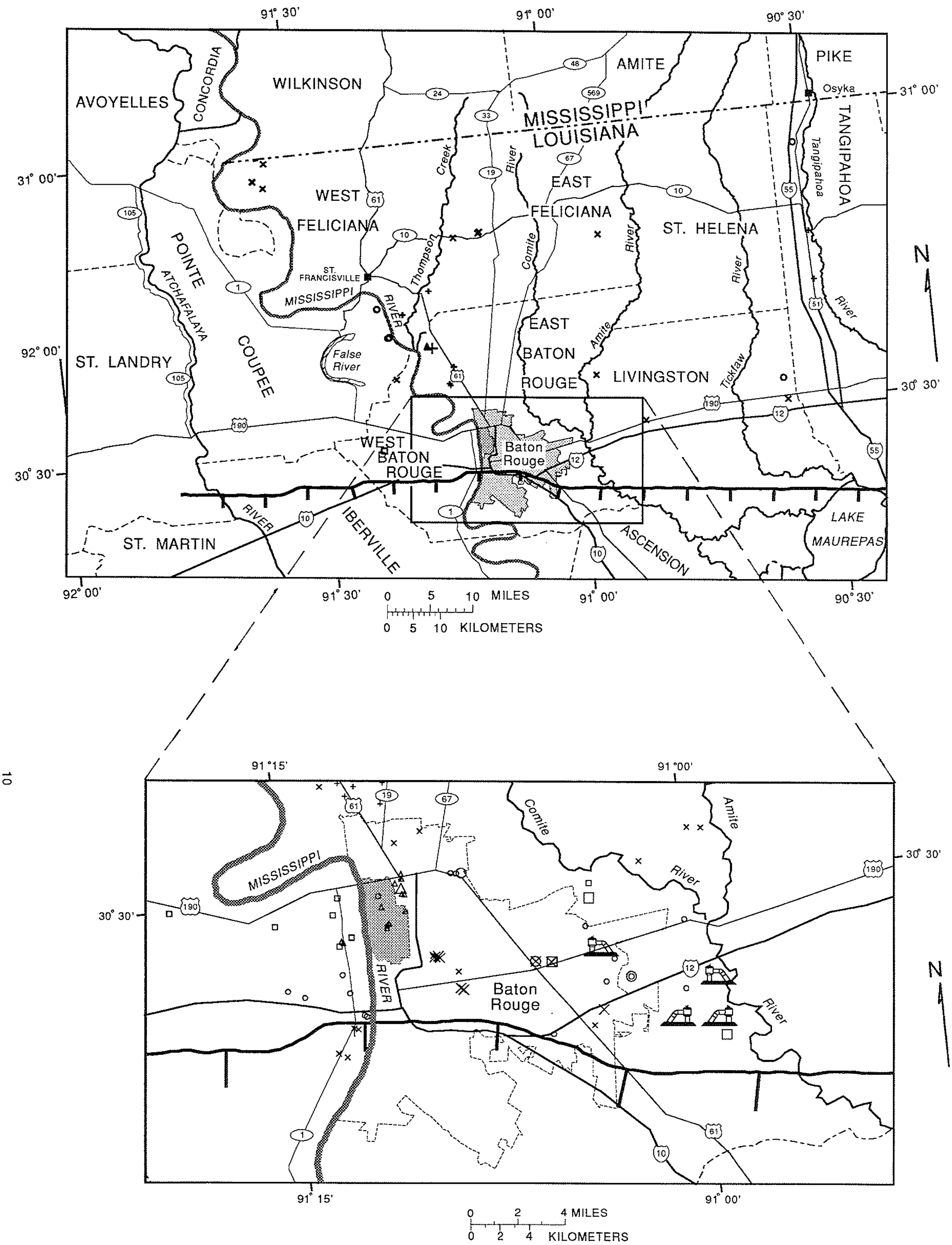
Prior to extensive pumping in the Baton Rouge area, natural discharge from confined aquifers flowed upward from the deep aquifers to shallower ones southward from the outcrop near the Mississippi-Louisiana State line. Head increased with depth because each successively deeper aquifer crops out at a higher altitude. Consequently, the "1,200-foot" aquifer received discharge from the "1,500-foot" and "1,700-foot" aquifers and discharged to the "800-foot" and "1,000-foot" aquifers to the south and west of the outcrop area. Upward flow was greatest through sandy interconnections where confining units between the aquifers are thin or missing.

The southern limit of freshwater in the "1,200-foot" aquifer and most of the other deep aquifers occurs just south of the Baton Rouge fault (fig. 3). Water containing less than 10,000 mg/L dissolved solids was considered freshwater in this study. Although water with dissolved-solids concentrations between 1,000 and 10,000 mg/L generally is considered salty, such water has hydraulic characteristics similar to those of freshwater for purposes of simulation.

PUMPAGE

Water withdrawal rates for the study area are from U.S. Geological Survey and Capital Area Ground Water Conservation Commission records. Detailed pumping information for the Baton Rouge area, where most of the pumping has been located (fig. 4), has been collected since 1960 as part of a cooperative program with the Louisiana Department of Transportation and Development. Pumpage from the "1,200-foot" aquifer between the 1946-52 period and 1958-62 period increased from 1.5 to 18 Mgal/d (fig. 5). From 1960 to 1988, the pumpage from the aquifer was at least 18 Mgal/d and as great as 25 Mgal/d. Prior to 1980, most pumpage from the aquifer had been for industrial purposes. In 1985, the 18.6 Mgal/d pumped from the "1,200-foot" aquifer was divided evenly between industrial and public-supply uses (Lurry, 1987) and remained so through 1987 (Capital Area Ground Water Conservation Commission, 1988).

Development of all aquifers from 1953 to 1980 produced continuous water-level declines in the "1,200-foot" aquifer and adjacent aquifers in the southern part of the study area (figs. 6 to 9). During this period, water levels declined at an average rate of 2 to 3 ft/yr near the industrial district (figs. 7 and 8). As water levels declined, the recharge potential from the unconfined, surficial deposits of Pleistocene age to the underlying, confined aquifers increased and flow increased southward toward the pumping centers. As pumping increased, movement of water through confining units reversed, and water flowed downward in the Baton Rouge area from the "1,200-foot" aquifer to the "1,500-foot" and "1,700-foot" and deeper aquifers. The reversal in



EXPLANATION

- BATON ROUGE FAULT
- BATON ROUGE INDUSTRIAL DISTRICT
- LOCATION 'A' FOR HYPOTHETICAL PUMPING SIMULATION
- LOCATION 'B' FOR HYPOTHETICAL PUMPING SIMULATION
- □ PUBLIC SUPPLY FROM THE "800-FOOT" AND "1,000-FOOT" AQUIFERS
- △ INDUSTRIAL FROM THE "1,200-FOOT" AQUIFER
- o PUBLIC SUPPLY FROM THE "1,200-FOOT" AQUIFER
- + INDUSTRIAL FROM THE "1,500-FOOT" AND "1,700-FOOT" AQUIFER
- × PUBLIC SUPPLY FROM THE "1,500-FOOT" AND "1,700-FOOT" AQUIFERS

Pumpage less than one millon gallons per day shown with the smaller symbol

Figure 4. Pumping locations and types of water use, by aquifer, within the study area.

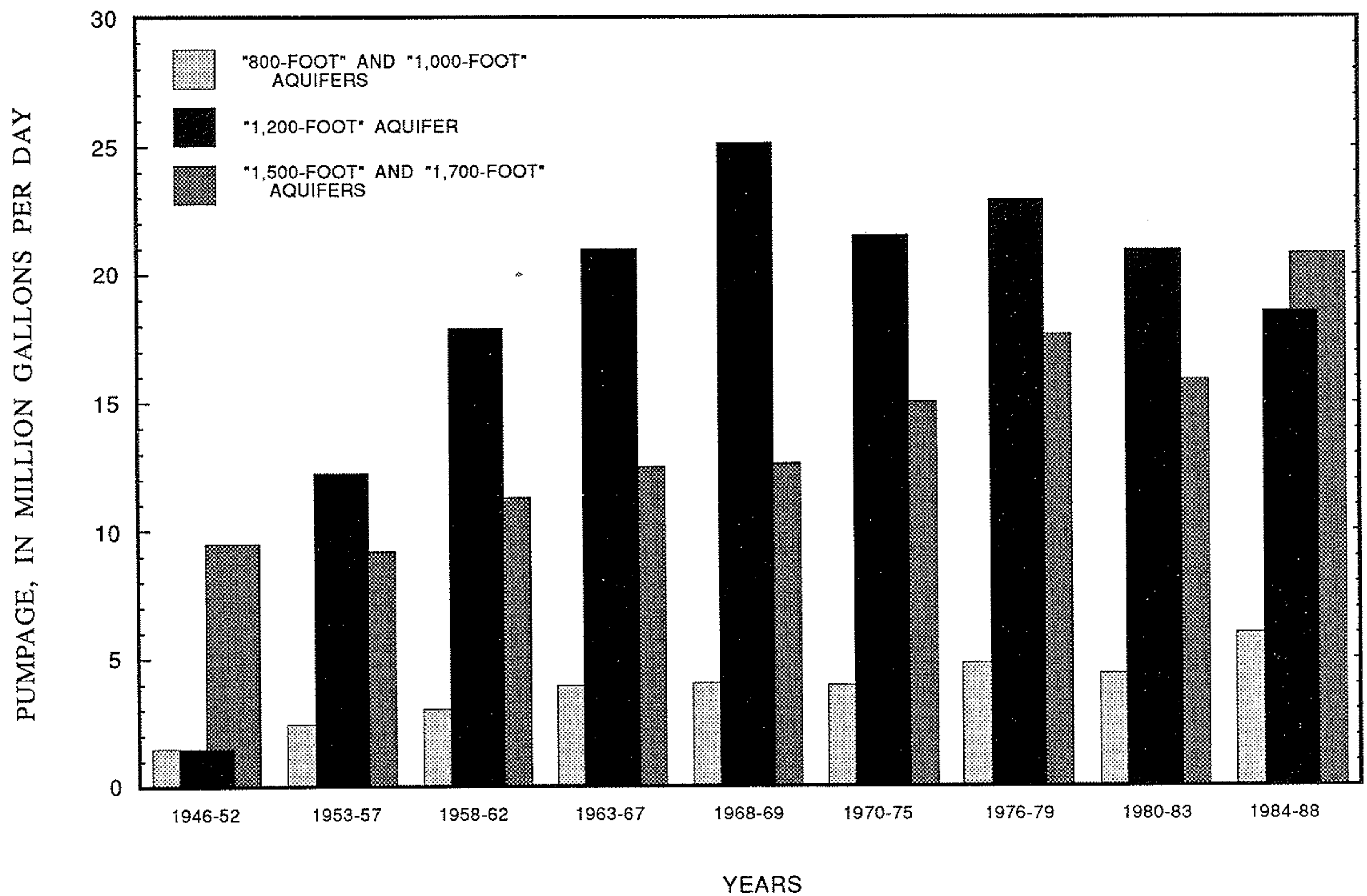


Figure 5. Pumpage by aquifer from 1946 through 1988.

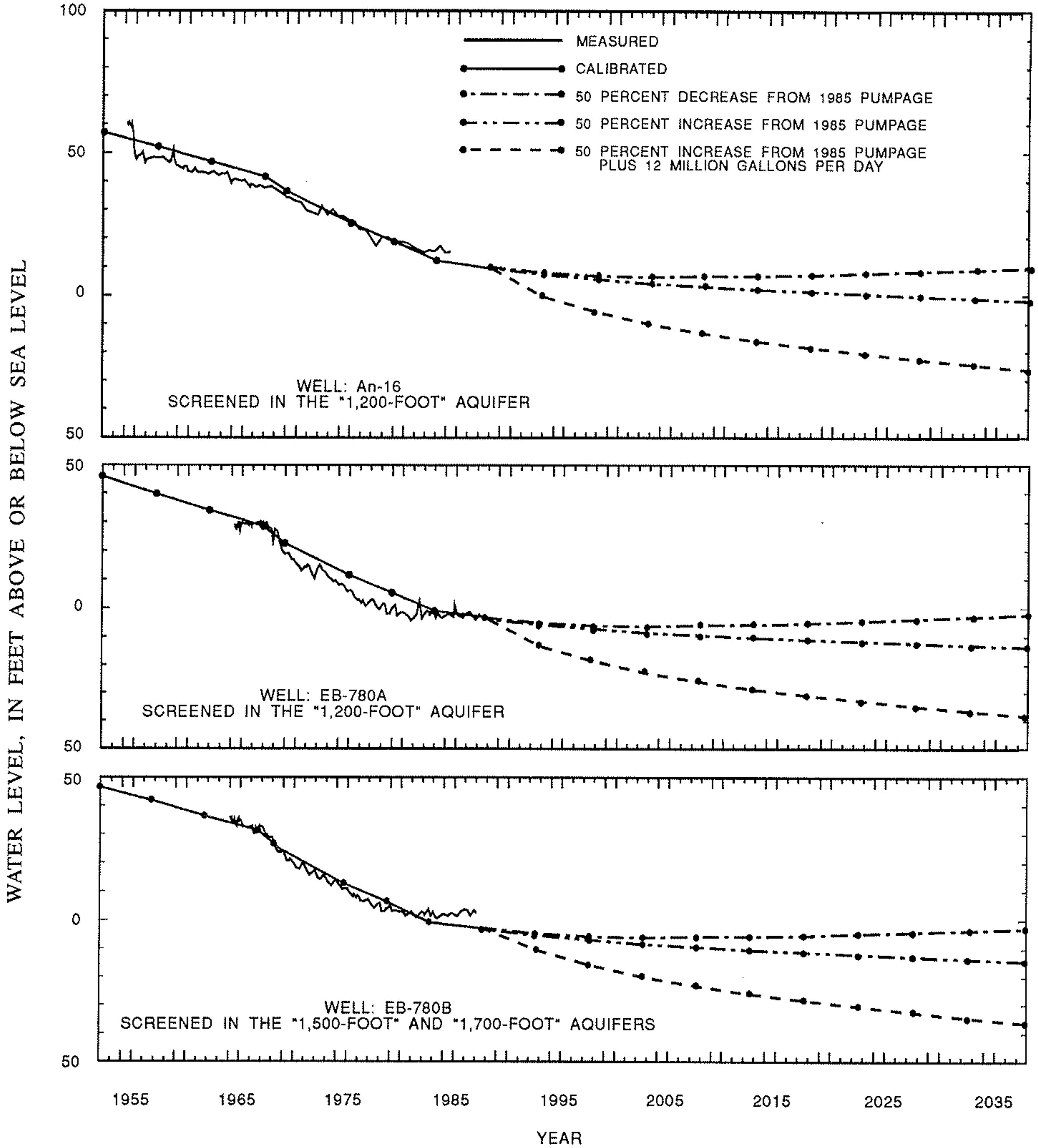


Figure 6. Simulated and measured water levels for wells An-16, EB-780A, and EB-780B south of the Baton Rouge fault. (See fig. 2 for well locations.)

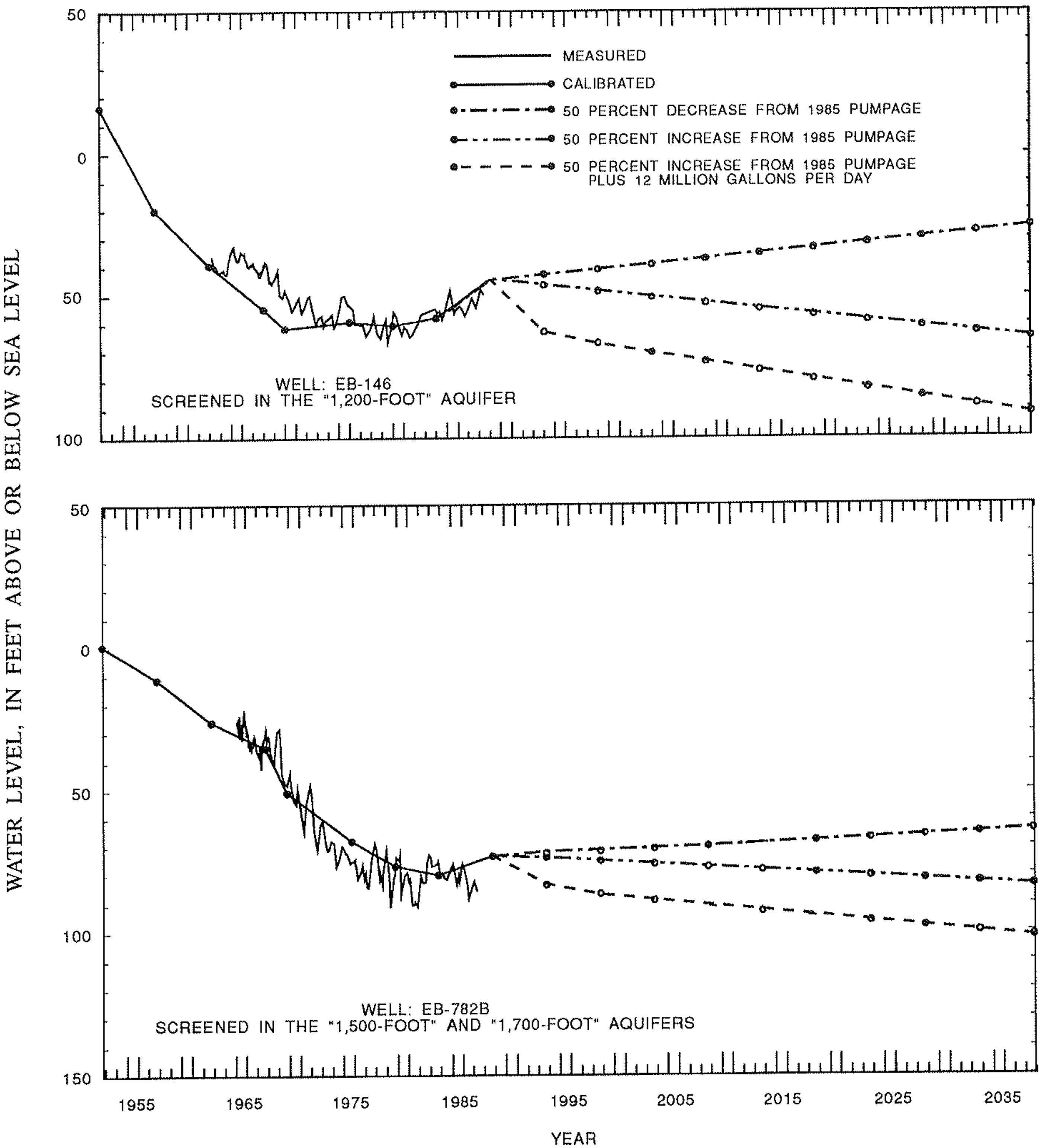


Figure 7. Simulated and measured water levels for wells EB-146 and EB-782B in Baton Rouge. (See fig. 2 for well locations.)

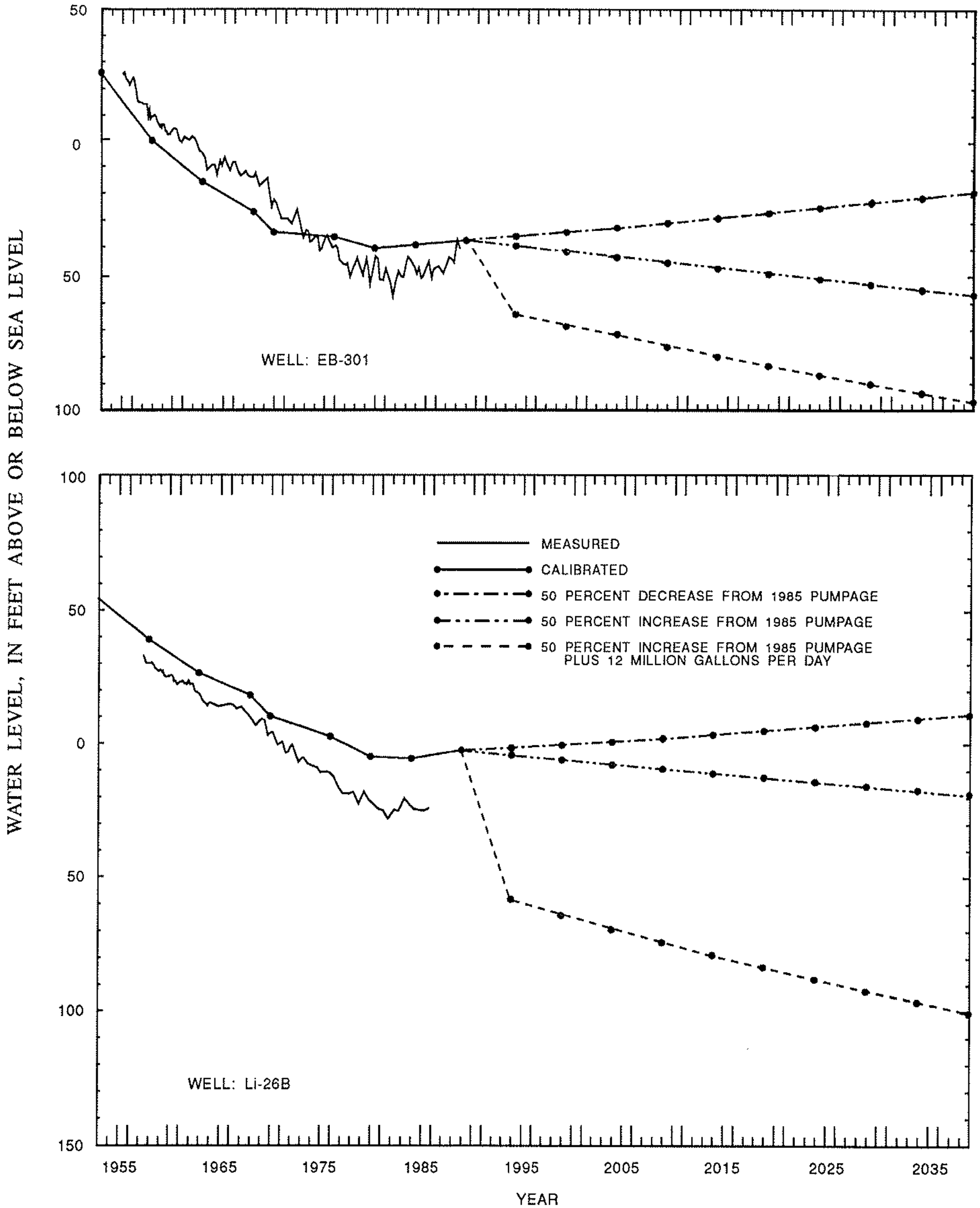


Figure 8. Simulated and measured water levels for wells EB-301 and Li-26B, which bracket an area of potential development in the "1,200-foot" aquifer. (See fig. 2 for well locations.)

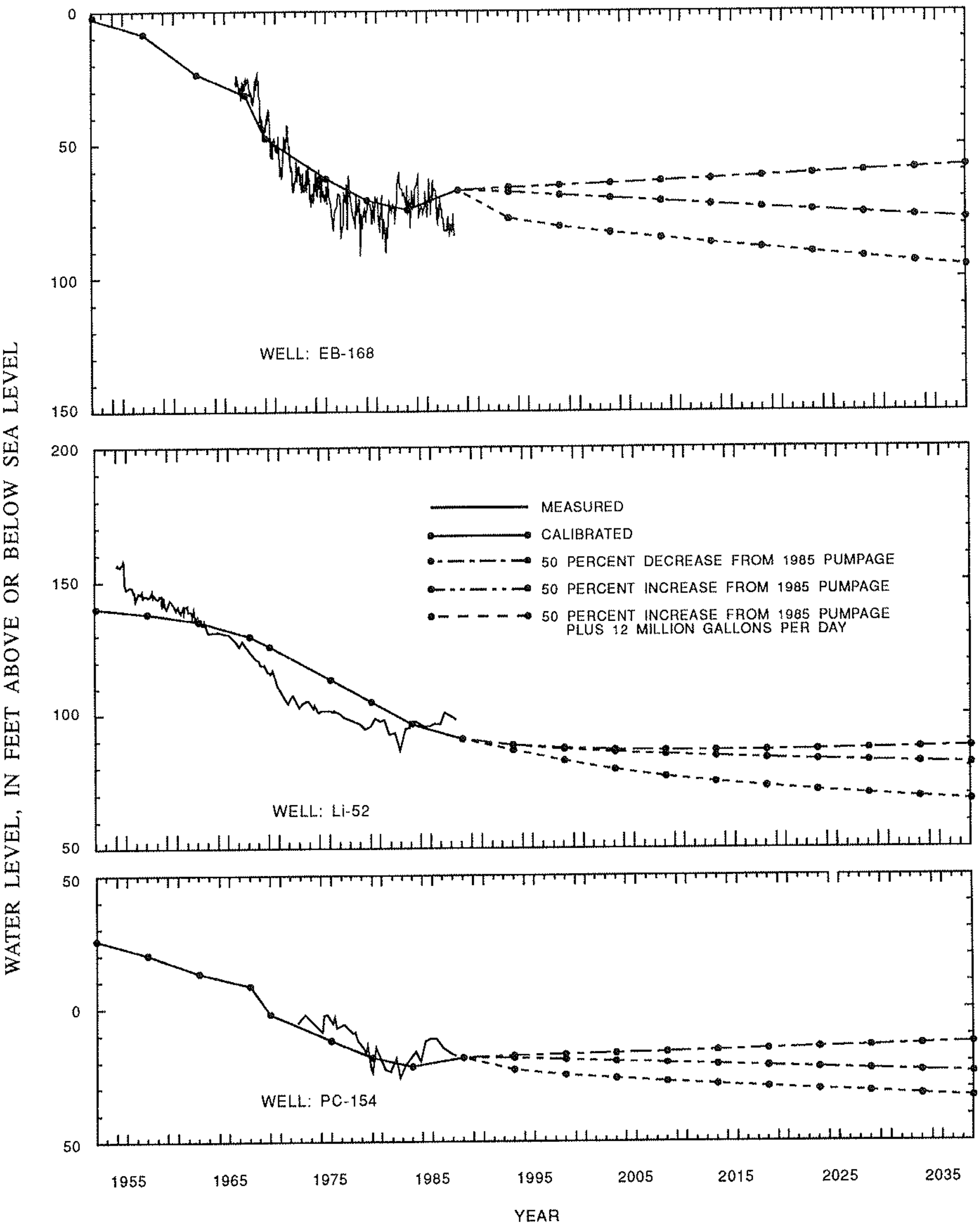


Figure 9. Simulated and measured water levels for wells EB-168, Li-52, and PC-154 completed in the "1,500-foot" and "1,700-foot" aquifers. (See fig. 2 for well locations.)

vertical flow was due to pumping from both the "1,500-foot" and "1,700-foot" aquifers and the "2,000-foot" aquifer (Torak and Whiteman, 1982).

Total pumping from the "1,200-foot" aquifer and adjacent aquifers decreased from the 1976-79 period to the 1980-83 period. From the 1980-83 period to the 1984-88 period, pumping from adjacent aquifers increased whereas pumping from the "1,200-foot" aquifer decreased (fig. 5). Water levels in wells in the "1,200-foot" aquifer near pumping centers (figs. 7 and 8) quickly reflected these changes, with recoveries of as much as 15 ft, whereas water levels in wells in the "1,200-foot" aquifer south of the Baton Rouge fault (fig. 6) responded slowly to pumping changes.

The progressive development of ground water (major pumping) has caused a local, shallow cone of subsidence to form around the Baton Rouge area. Local subsidence of at least 1.26 ft occurred during the period 1935-76 and averaged 0.035 ft/yr during 1964-76 (Whiteman, 1980, p. 1). An extensometer survey, 1975-79, indicated most of the permanent compaction was occurring below 1,700 ft (Whiteman, 1980) during a period of intense pumping and relatively stable water levels, while the sediments shallower than 833 ft responded quickly and elastically to water-level changes. Overall, local subsidence averaged less than 0.014 ft/yr during 1975-79 (Whiteman, 1980).

ANALYSIS OF FLOW IN THE "1,200-FOOT AQUIFER

Because of the complex multi-aquifer system, a four layer, three-dimensional model was used to quantitatively analyze the ground-water flow in the "1,200-foot" aquifer in the study area (Torak and Whiteman, 1982). The U.S. Geological Survey's modular finite-difference model McDonald and Harbaugh (1988) was used to simulate flow in the "1,200-foot" aquifer.

Digital Model Development

The three-dimensional movement of ground water of a constant density through porous media under confined conditions is described by the McDonald-Harbaugh model through the partial differential equation:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(T\frac{\partial h}{\partial z}\right) - Q = S_s\frac{\partial h}{\partial t}, \qquad (1)$$

where

T is the transmissivity ($L^2 t^{-1}$);

h is the potentiometric head (L);

Q is the volumetric flux per unit volume and represents sources or sinks of water (t^{-1});

Ss is the specific storage of the porous media (L^{-1}); and

t is the time (t)

(McDonald and Harbaugh, 1988).

The use of any finite-difference model requires the discretization of the aquifer system into blocks. This discretization is done in layers, rows, and columns. The sizes of these blocks were based on the distribution of pumpage in 1985 and the degree of resolution desired for simulation. The Baton Rouge area has been divided into small blocks (fig. 10), because of widely changing pumping rates and water levels in the area. The model grid covers an area greater than 6,000 mi and has been divided into 31 rows of 29 columns (fig. 10).

The grid is oriented parallel to the Baton Rouge fault throughout most of the model to better approximate the fault because it is a major hydrologic feature. Variably sized blocks were used to obtain more detail in highly stressed areas, such as the Baton Rouge industrial district. Some of the blocks are inactive because they are in areas where the aquifers do not exist (fig. 10). For these blocks, head is not computed and water does not enter or exit the block. The active blocks range in size from 0.25 to 132 mi^2. The largest blocks are in areas of little or no pumping and beyond the main areas of interest. Values of aquifer hydraulic properties are assigned to the center of each block, defined as a node, by averaging values within the block.

Four layers were used to simulate the "1,200-foot" aquifer and adjacent aquifers (fig. 11). Layer 1 is a specified-head upper boundary representing a composite of water levels in the "400-foot" and "600-foot" aquifers and the water table altitudes in the unconfined, surficial deposits of Pleistocene age in the Southern Hills outcrop area. Layers 2, 3, and 4 represent the "800-foot" and "1,000-foot" aquifers, the "1,200-foot" aquifer, and the "1,500-foot" and "1,700-foot" aquifers, respectively (figs. 3a and 11). All layers were modeled to represent confined aquifer conditions.

Vertical flow between aquifers is simulated by vertical leakance values assigned between each model layer. The vertical leakance is the vertical hydraulic conductivity of the confining unit divided by the thickness expressed as d^{-1}.

Clay compaction will not be considered as a water source for this model. Water levels in the "1,200-foot" aquifer were about 70 ft higher in 1988 than in 1969, when the lowest levels were recorded, in the Baton Rouge industrial district. The "1,200-foot" aquifer and adjacent confining units behaved elastically when water levels averaged 50 ft less than 1988 levels.

Boundary Conditions

Proper representation of model boundaries is one of the most important aspects in the simulation of flow in an aquifer system. Model boundaries must represent the true hydrologic boundaries as accurately as possible or be far enough away from any simulated stresses so that they will not be affected. An area larger than the study area (fig. 1) was modeled to satisfy boundary-condition requirements.

Water levels in the "400-foot" and "600-foot" aquifers (layer 1) are controlled by recharge from the unconfined, surficial deposits of Pleistocene age in the Southern Hills outcrop and by pumping in the Baton Rouge area. Layer 1, the uppermost layer in the model, acts as a source or sink for water entering or leaving the flow system (except for flow across the lower boundary and water removed by pumping) and was simulated as a specified-head boundary. The specified-head upper boundary used for the simulations is similar to the one shown in figure 12. Use of this boundary is acceptable because through 1987 there was no significant change in recharge to or pumping from the aquifers comprising layer 1.

Streams draining the recharge areas are characterized by high continuous base flows, indicating that storage requirements of surficial aquifers are generally satisified by rainfall infiltration and potential recharge is being rejected by the unconfined, surficial deposits of Pleistocene age in the Southern Hills outcrop area (Kuniansky, 1989).

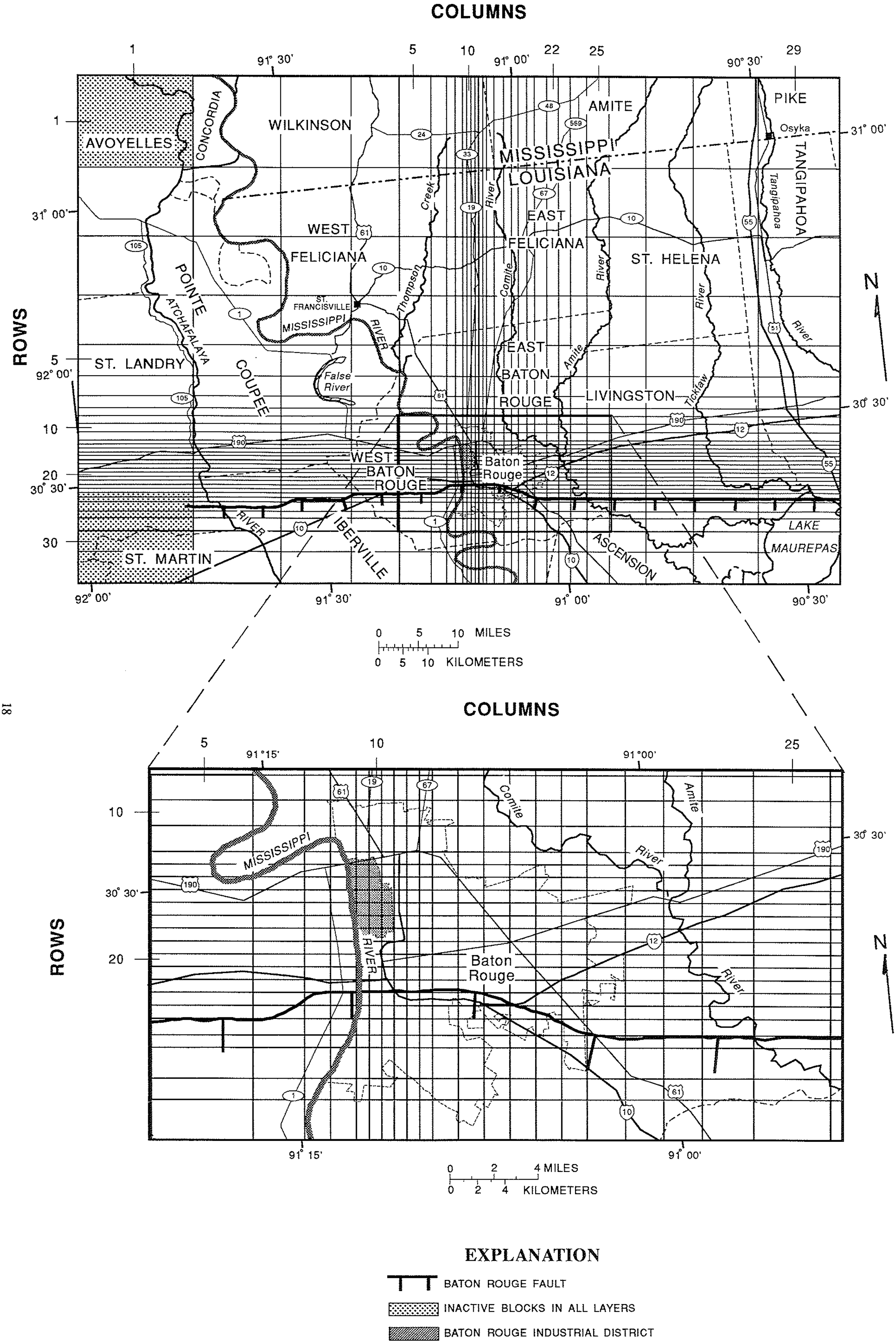


Figure 10. Model grid and extent.

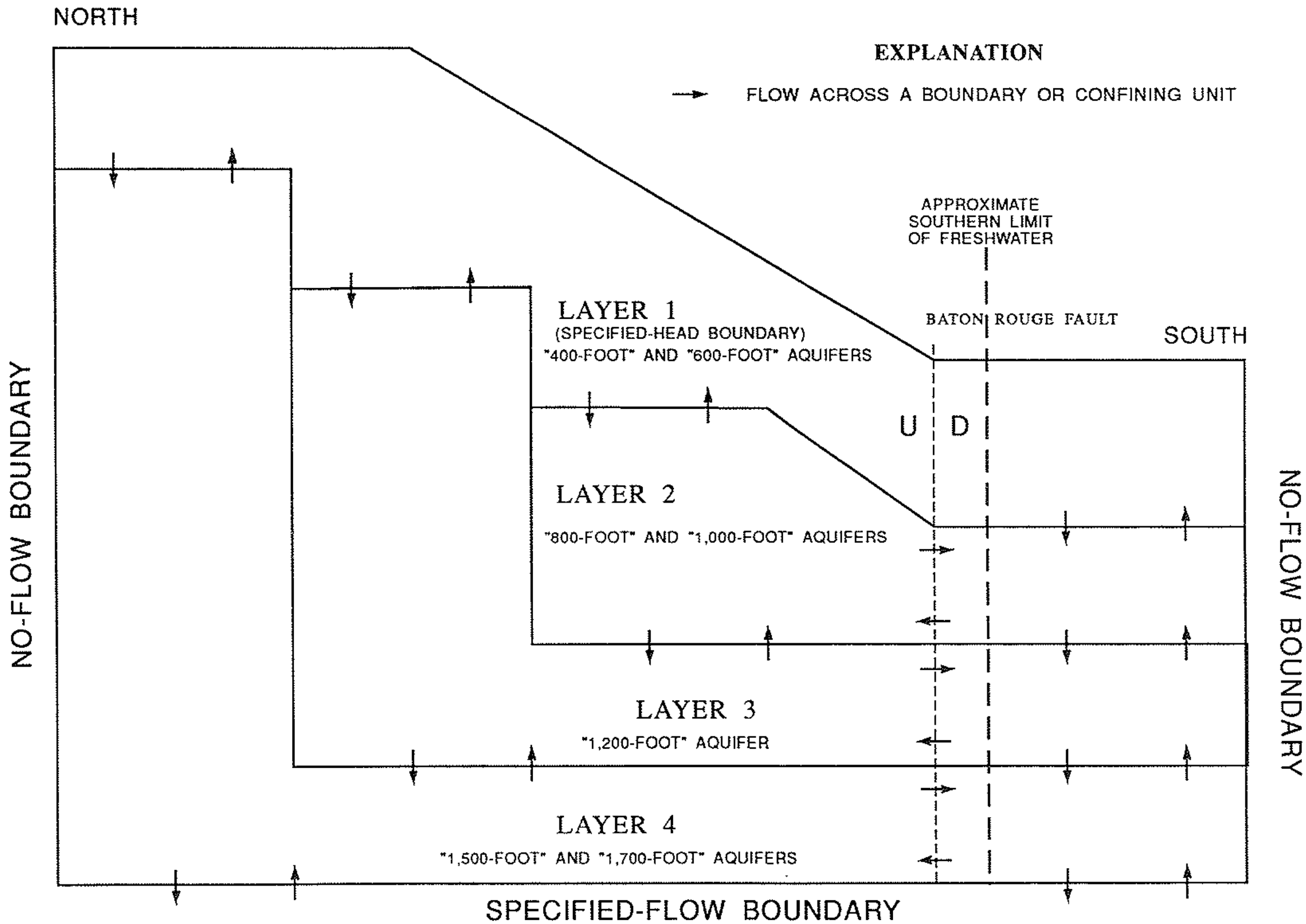


Figure 11. Conceptual model for the "1,200-foot" aquifer and adjacent aquifers.

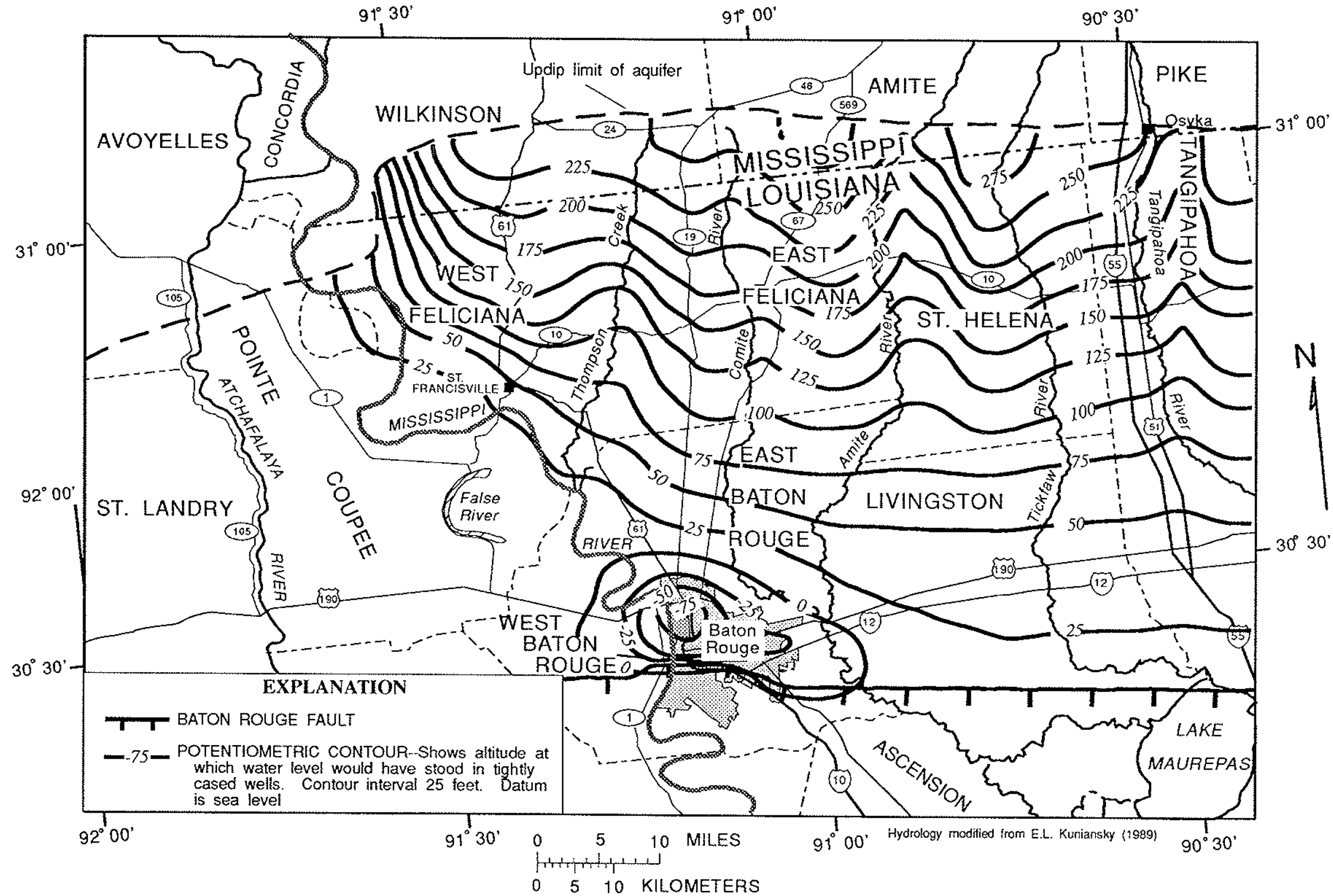


Figure 12. Simulated potentiometric surface of the "400-foot" and "600-foot" aquifers (layer 1) in 1984.

Pumping from the "400-foot" and "600-foot" aquifers primarily has been in the Baton Rouge industrial district. By the 1940's, a cone of depression had formed in the potentiometric surface of the "400-foot" and "600-foot" aquifers in this area. However, the influence of the Mississippi River, which is hydraulically connected to the "400-foot" and "600-foot" aquifers, and the proximity of the recharge area, confined the influence of the heavy pumping to the industrial area. Since pumping from the aquifers peaked in the 1950's, water levels in the Baton Rouge industrial district have undergone little change.

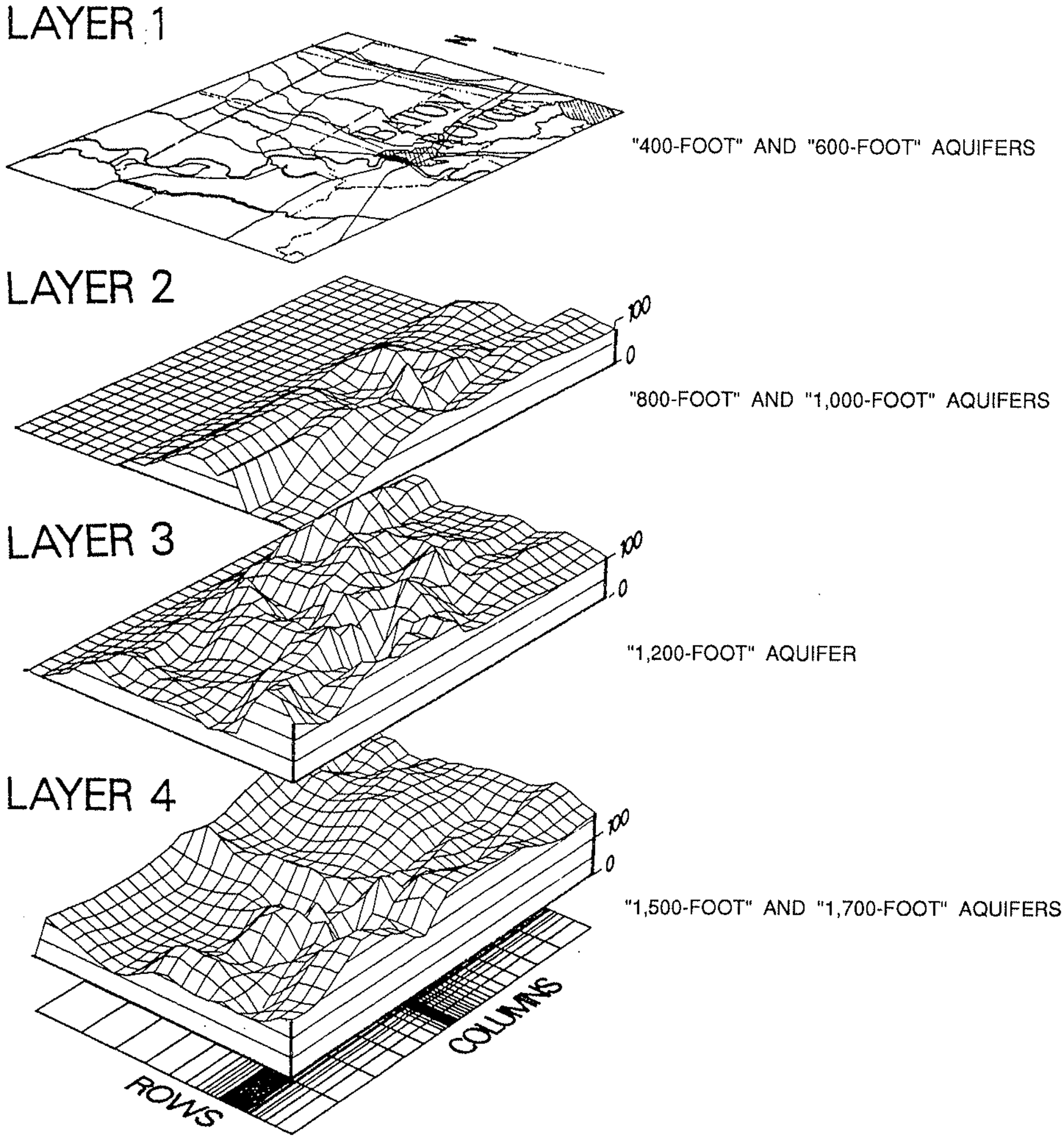
The lower model boundary is a set of specified-flow rates that approximate flow between the combined "1,500-foot" and "1,700-foot" aquifers (layer 4) and the "2,000-foot" aquifer (fig. 11). These flow rates were varied from 1946 to 1988 and were held constant at 1988 rates from 1988 onward for all simulations. The study by Torak and Whiteman (1982) showed there are appreciable flow rates between these two aquifers since the development of the "2,000-foot" aquifer. For this model, the flow rates between layer 4 and the "2,000-foot" aquifer were assumed to be negligible prior to pumping. The Gulf Coast Regional Aquifer-System Analysis (GCRASA) presents the most recent information for the specified fluxes between layer 4 and the "2,000-foot" aquifer (Martin and Whiteman, 1989).

All of the lateral model boundaries represent no-flow conditions (fig. 13). The northern edge of the model represents the pinchout of the "1,500-foot" and "1,700-foot" aquifers. Model layers 2 and 3 extend to the northern boundary although the aquifers modeled pinch out before the northern edge of the model. This representation provides continuity between layer 1, the upper specified-head boundary, and layers 3 and 4 where the "1,200-foot," "1,500-foot," and "1,700-foot" aquifers are present. The southern boundary in all layers of the model is treated as no-flow because the aquifers modeled have a dissolved-solids concentration of greater than or equal to 10,000 mg/L. This water is considered immobile relative to the time scale of the model and was not considered a part of the simulated flow system. The eastern boundary parallels a ground-water divide present in all layers (Martin and Whiteman, 1985). This divide constitutes a no-flow boundary because water will flow parallel to but not across the boundary. The western boundary lies along the present Atchafalaya River basin, which lies above an ancestral path of the Mississippi River, and serves as a no-flow boundary because the basin is a regional drain for all aquifers (Martin and Whiteman, 1985).

Model Input

Kriging was used to assign sand and clay thickness values to nodes and to fit water levels to the specified heads in layer 1. Kriging provides a less biased method of adapting irregularly spaced measurements to a regular grid (Skrivan and Karlinger, 1980). It is an interpolation technique that estimates spatially distributed properties at specific locations, using a set of weighting factors. The weighting factors are specifically determined by a semi-variogram that is based on the spatial variation of the data. For Kriging, the semi-variogram must be fitted with a functional form that is approximated by an appropriate theoretical distribution. Only the spherical and Gaussian distributions were used in this report.

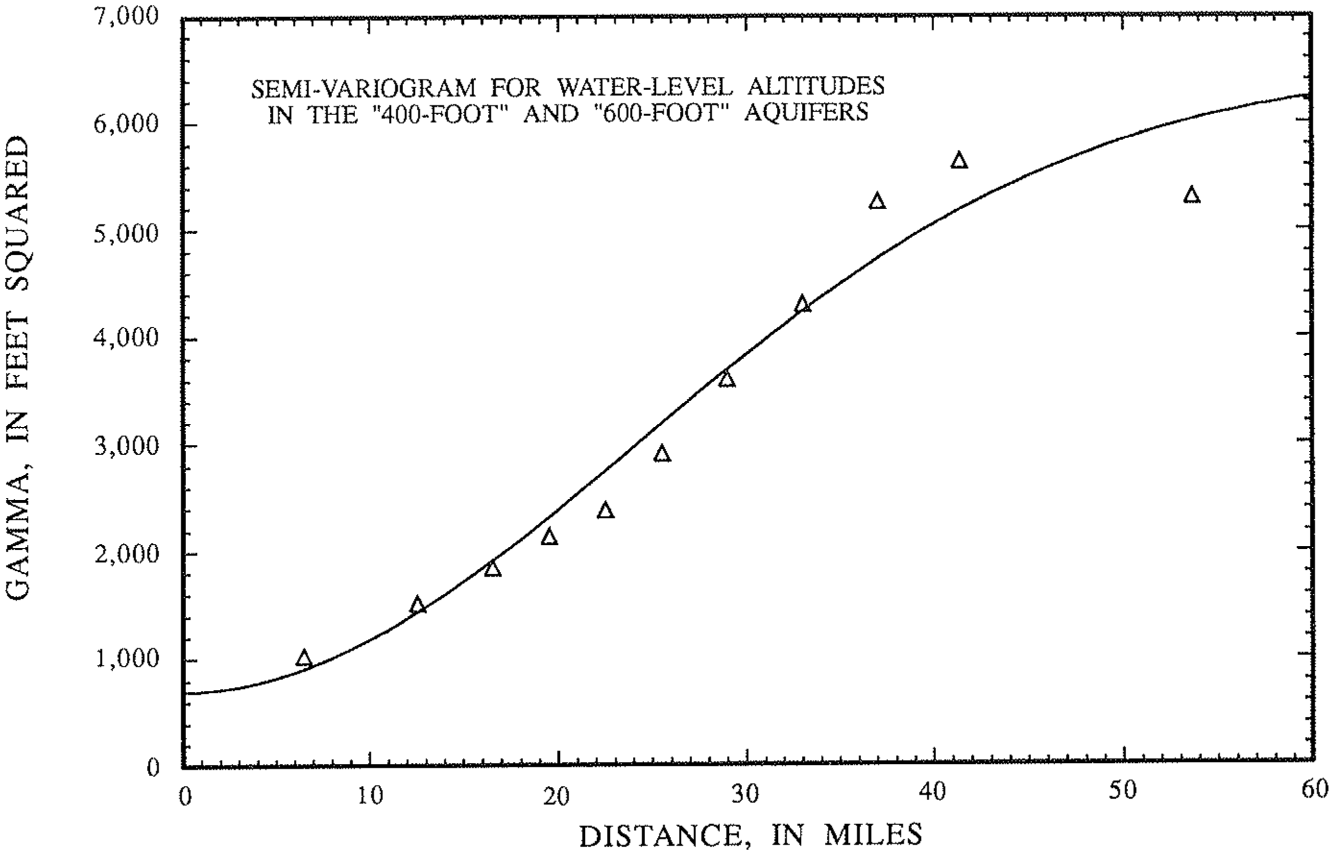
The semi-variogram shows the expected difference between values a specific distance apart. For example, the semi-variogram for sand thickness in figure 14 shows that a thickness value 4 mi away from an arbitrary point would be expected to differ by 46 ft (which is the square root of gamma and is similar to the standard deviation). The range of autocorrelation is the part of a semi-variogram for which a significant relation exists between the distance between data points and the difference between data values.



EXPLANATION

SAND THICKNESS--Interval 50 feet
ALL LATERAL BOUNDARIES ARE NO-FLOW

Figure 13. Sand thicknesses and lateral boundaries of the conceptual model for the "1,200-foot" aquifer.



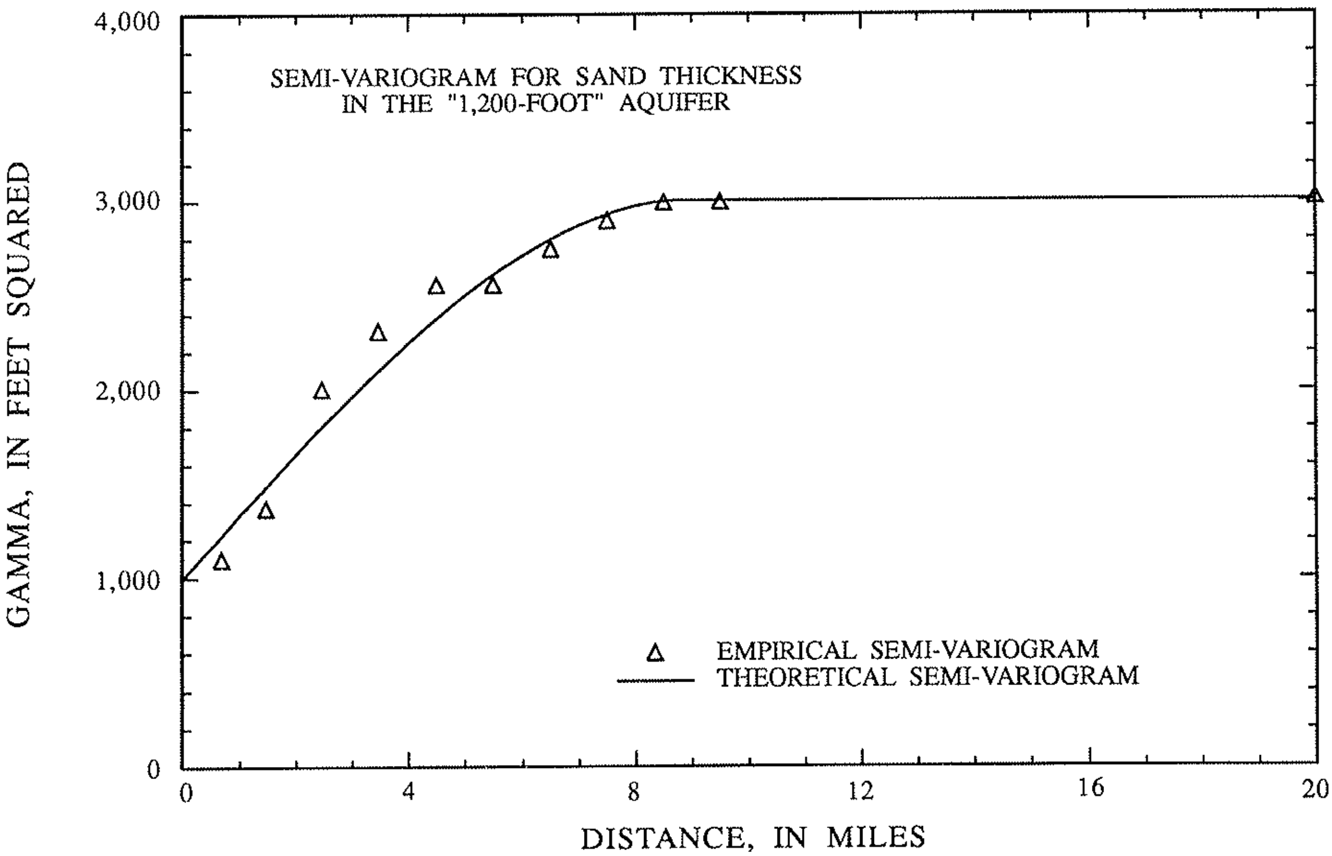


Figure 14. Semi-variograms for kriging water-level altitudes in the "400-foot" and "600-foot" aquifers and sand thickness in the "1,200-foot" aquifer.

Initial values of transmissivity for model layers 2, 3, and 4 were calculated from kriged sand thickness values and hydraulic conductivity values determined from aquifer tests. The sand (fig. 15) and clay thickness data are from previous studies (Huntzinger and others, 1985; Kuniansky and others, 1989) and electric logs of water and petroleum wells. The spherical semi-variogram best defined the distribution of sand thickness values. Autocorrelation in the "1,200-foot" aquifer was limited to a range of 9 mi (fig. 14). These relatively limited ranges of autocorrelation are "not surprising"considering the variability of thickness values (fig. 15).

The specified-head water levels (layer 1) are from the model of the "400-foot" and "600-foot" aquifers (Kuniansky, 1989) and supplemental water-level measurements. A Gaussian semi-variogram defined the distribution of water levels better than the spherical semi-variogram. Autocorrelation between water levels existed over a range of 40 mi (fig. 14). This greater range, when compared to the range for sand thicknesses, is understandable, considering that the effects of stresses that change water levels will be propagated throughout an aquifer (fig. 12).

Ground-water flow in the "1,200-foot" aquifer was simulated during the period 1946-88 to incorporate the major development that began in 1953. Prior to 1953, the "1,200-foot" aquifer was a minor water supply, providing less than 1.5 Mgal/d within the modeled area. Stress periods were selected so that the assumption of constant pumping rates within a period was valid. The pumpage from 1946 to 1988 was divided into nine stress periods: 1946-52, 1953-57, 1958-62, 1963-67, 1968-69, 1970-75, 1976-79, 1980-83, and 1984-88. Pumpage data for 1985 were used for the last stress period, 1984-88.

Initial conditions for layers 2, 3, and 4 of the model represent water levels that existed prior to aquifer development. Because little water-level data are available for this predevelopment period, initial water levels for model layers 2, 3, and 4 are the result of steady-state simulations without pumping stresses applied to the system. Maps of initial water levels for these model layers are shown in figures 16, 17, and 18.

MODEL CALIBRATION

Calibration is an attempt to reduce the discrepancy between measured data and model results by adjusting model input data. The difference between measured and simulated heads was the calibration criterion used for this model. Results from a deterministic ground-water model usually depart from reality by a considerable amount because it is impractical to obtain enough measurements to account for all of nature's variations.

A statistical optimization program was used to calibrate the model (H.T. Mitten and A.K. Williamson, U.S. Geological Survey, written commun., 1987). This program automatically makes many simulations, changing the value of a single parameter for each simulation. Changes can be made in a parameter for the entire model, for individual model layers, or for areas within a layer. After each simulation, the program statistically compares the results with the results of an initial base run and with measured water levels and computes a new value of the parameter that should improve the model. This iterative process is continued until model errors are reduced to a specified level or until a specified number of iterations have been made (Durbin, 1983).

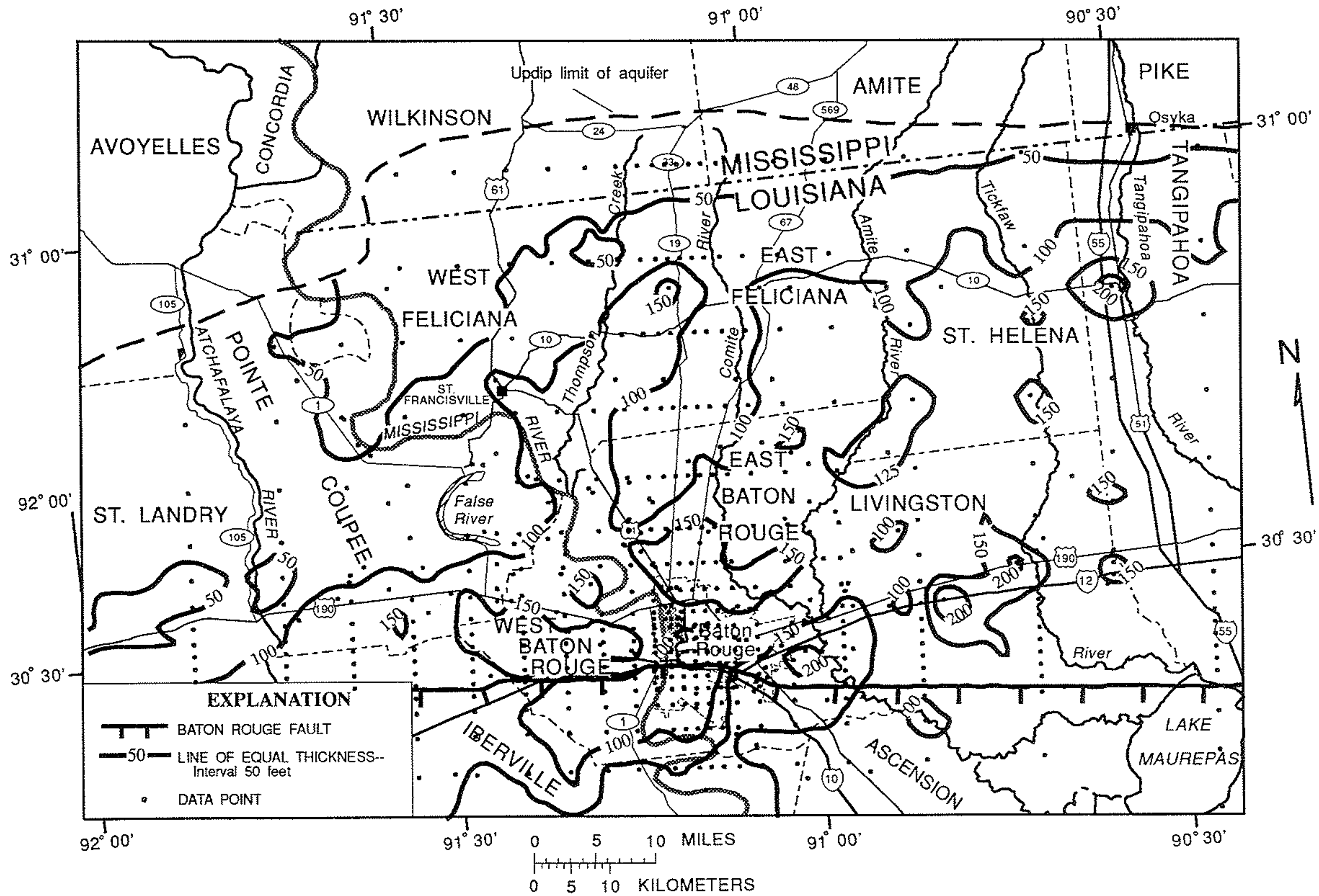


Figure 15. Sand thickness of the "1,200-foot" aquifer.

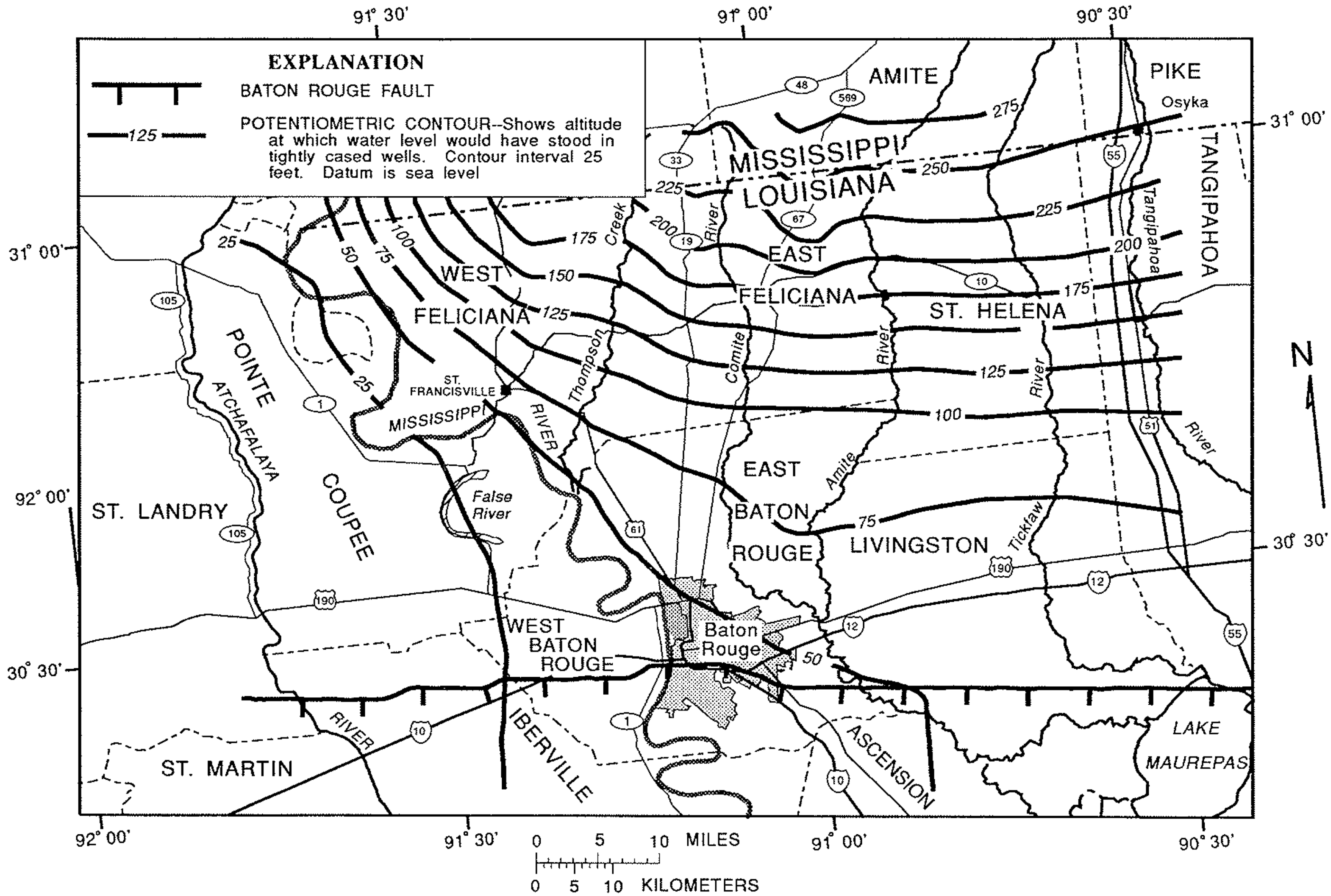


Figure 16. Simulated predevelopment potentiometric surface of the "800-foot" and "1,000-foot" aquifers (layer 2).

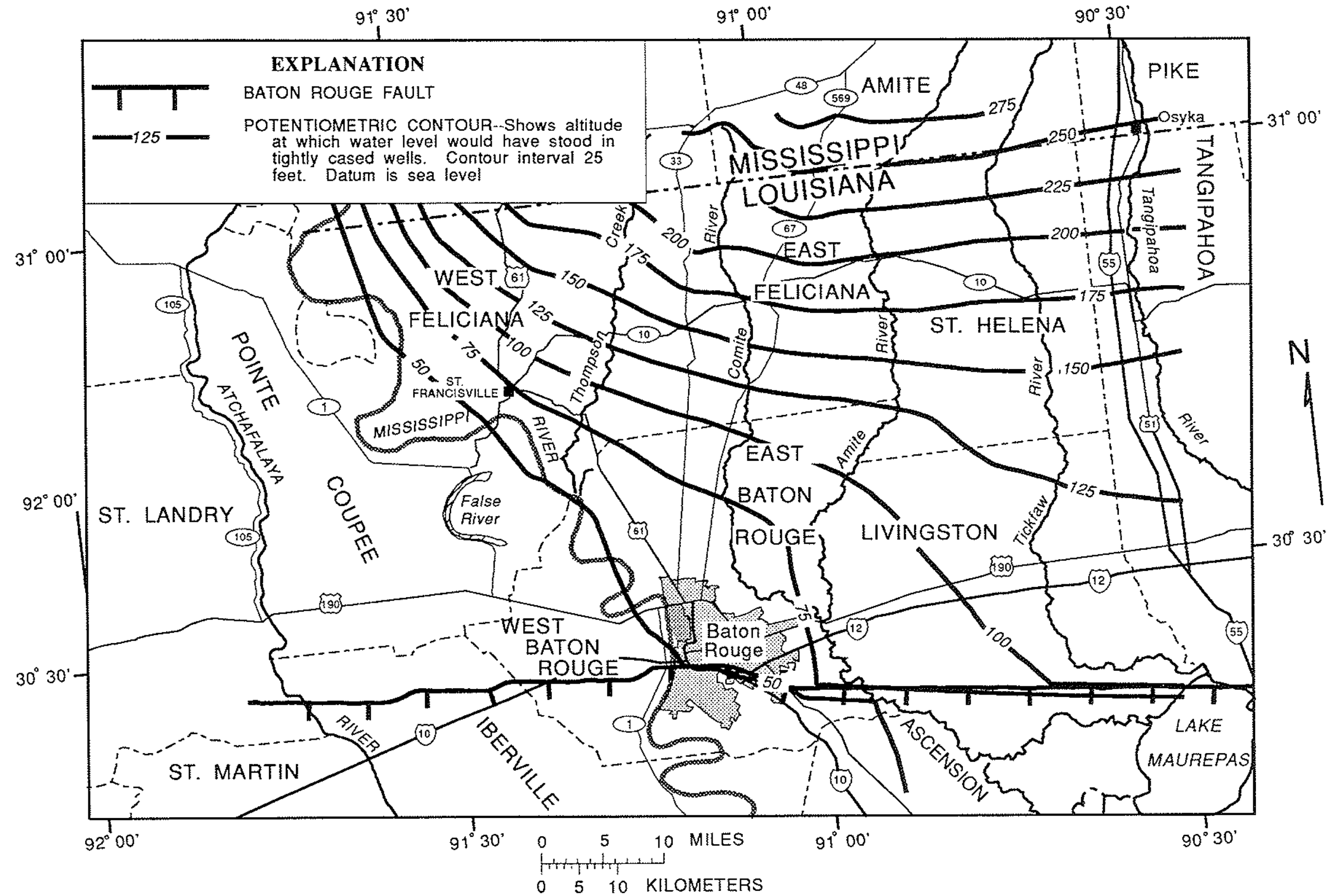


Figure 17. Simulated predevelopment potentiometric surface of the "1,200-foot" aquifer (layer 3).

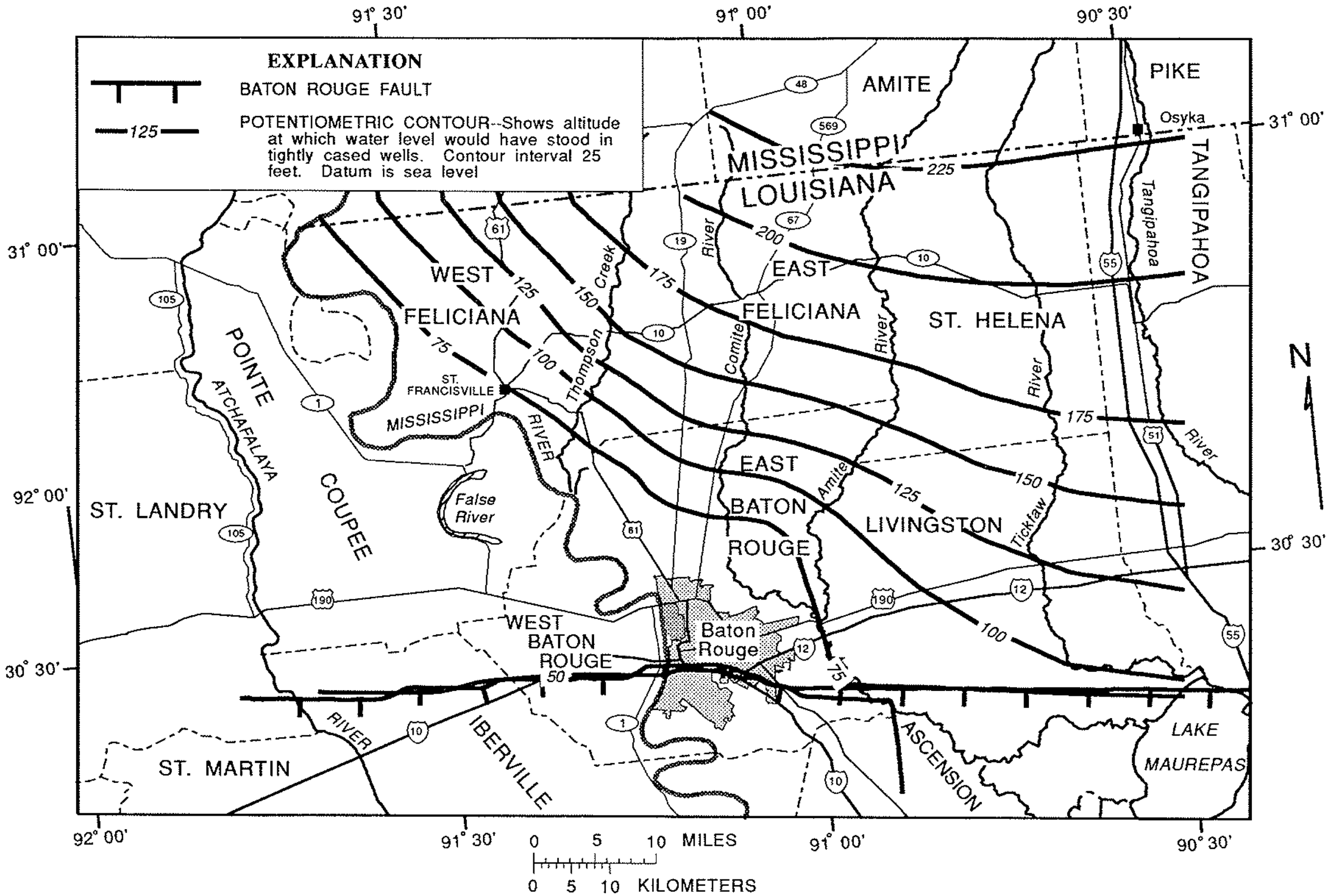


Figure 18. Simulated predevelopment potentiometric surface of the "1,500-foot" and "1,700-foot" aquifers (layer 4).

The model was calibrated by adjusting values for transmissivity, vertical leakance, and storage coefficient to minimize differences between measured and simulated water levels. The root-mean-square error (RMSE) between measured and simulated water levels provided a quantitative comparison between model simulations. The RMSE is defined by:

$$RMSE = \sqrt{\frac{\Sigma (h_m - h_s)^2}{NWLM}}, \quad (2)$$

where hm is the measured water level;
hs is the simulated water level; and
NWLM is the total number of water-level comparisons.

The difference between the measured and simulated water levels is defined as the water-level residual. The RMSE of the calibrated model was 12.15 ft overall and 11.18 ft for all stress periods in layer 3, the "1,200-foot" aquifer. This means, on average, there is about a 10-foot difference between measured heads and calculated heads in the "1,200-foot" aquifer within the modeled area for 1988. In the Baton Rouge area, there is a 3-foot difference between measured and calculated heads in the "1,200-foot" aquifer for 1988. The error statistics for the calibrated model are listed in table 2.

Measured water levels are from historical records and a water-level survey conducted in 1988. The greater number of water-level measurements available in 1988 biased the model calibration toward the last stress period (1984-88). The comparisons for the optimization program were averages of the hydrograph records during the last year in a stress period. Record periods of most of the hydrographs used were for only a part of the total simulation period. Simulated water levels compared favorably to water-level records, with most showing their best agreement from 1975 to 1985 (figs. 6 to 9).

The range of uncertainty differs for transmissivity, storage coefficient, and vertical leakance. Transmissivity and storage coefficient values are known with a higher degree of certainty because many aquifer tests are available to determine lateral hydraulic conductivity and storage coefficients and many well logs are available to determine aquifer thickness. Vertical leakance, being the least certain parameter, was varied the most. Maps of the values for calibrated transmissivity, vertical leakance, and storage coefficient are shown in figures 19 to 27.

Calibrated transmissivity values in the "1,200-foot" aquifer (model layer 3) were highest toward the eastern boundary of the modeled area and generally decreased from east to west (fig. 20). Values ranged from 16,000 ft^2/d in Livingston Parish to 600 ft^2/d in St. Landry Parish. [Because of space limitations, these data are not shown.] In the Baton Rouge area, calibrated transmissivities ranged from 2,000 to 10,000 ft^2/d.

Calibrated vertical leakance values for aquifers overlying and underlying the "1,200-foot" aquifer were lowest toward the eastern boundary of the modeled area and generally increased from east to west (figs. 21 and 22). Values ranged from 0.000001 d^{-1} in Livingston Parish to 0.00009 d^{-1} in Iberville Parish; values generally were lowest between layers 1 and 2 (fig. 22). In the Baton Rouge area, calibrated vertical leakance values for aquifers overlying and underlying the "1,200-foot" aquifer ranged from 0.00004 to 0.00007 d^{-1}.

Calibrated storage coefficient values in the "1,200-foot" aquifer were highest toward the eastern boundary of the modeled area and generally decreased from east to west (fig. 26). Values ranged from 0.001 in St. Landry Parish to 0.004 in Livingston Parish. In the Baton Rouge area, calibrated storage coefficients ranged from 0.001 to 0.002. Final calibrated transmissivity and storage coefficient values are greater than those calculated from aquifer tests because of variations in sand thicknesses and heterogeneities.

Table 2. Error statistics for the calibrated model

[--, Not determinable]

Stress period	Model layer	Number of residuals (feet)	Root-mean -square error (feet)	Mean of residuals (feet)	Maximum residuals (feet)	Minimum residual (feet)	Standard deviation (feet)
2	3	7	8.9	-0.9	15.9	-14.3	8.9
2	4	3	21.3	19.5	28.8	12.1	8.7
2	ALL	10	13.9	5.1	28.8	-14.3	12.9
3	2	1	7.7	-17.7	-17.7	-17.7	--
3	3	11	14.4	-3.6	20.5	-32.4	13.9
3	4	3	22.9	2.5	29.9	-25.9	22.7
3	ALL	15	16.7	-3.3	29.9	-32.4	16.3
4	2	4	11.8	-9.7	.2	-17.3	6.7
4	3	15	14.5	-4.0	20.6	-23.2	14.0
4	4	13	13.6	3.5	31.3	-16.0	13.2
4	ALL	32	13.9	-1.6	31.3	-23.2	13.8
5	2	4	11.1	-8.3	3.2	-17.1	7.3
5	3	16	13.9	.6	24.4	-17.7	13.8
5	4	14	14.1	7.6	27.9	-11.8	11.9
5	ALL	34	13.7	2.4	27.9	-17.7	13.4
6	2	4	3.7	-1.3	3.2	-6.5	3.5
6	3	20	9.8	-3.0	14.5	-17.4	9.3
6	4	18	8.7	-2.2	11.2	-27.0	8.5
6	ALL	42	8.9	-2.5	14.5	-27.0	8.6
7	2	5	10.7	8.9	17.9	-.1	6.0
7	3	17	13.1	-10.4	1.5	-30.4	8.0
7	4	17	9.5	-3.1	7.5	-25.2	9.0
7	ALL	39	11.4	-4.7	17.9	-30.4	10.3
8	2	6	15.3	4.0	30.2	-17.7	14.7
8	3	17	8.3	-1.5	18.1	-15.0	8.2
8	4	17	10.6	2.0	21.9	-25.6	10.4
8	ALL	40	10.6	.8	30.2	-25.6	10.6
9	2	22	10.1	.8	28.4	-15.1	10.0
9	3	60	9.9	.9	29.0	-21.8	9.8
9	4	36	15.6	-.7	40.8	-60.4	15.6
9	ALL	118	12.0	.4	40.8	-60.4	12.0
ALL	ALL	330	12.15	-0.4	40.0	-60.0	12.4

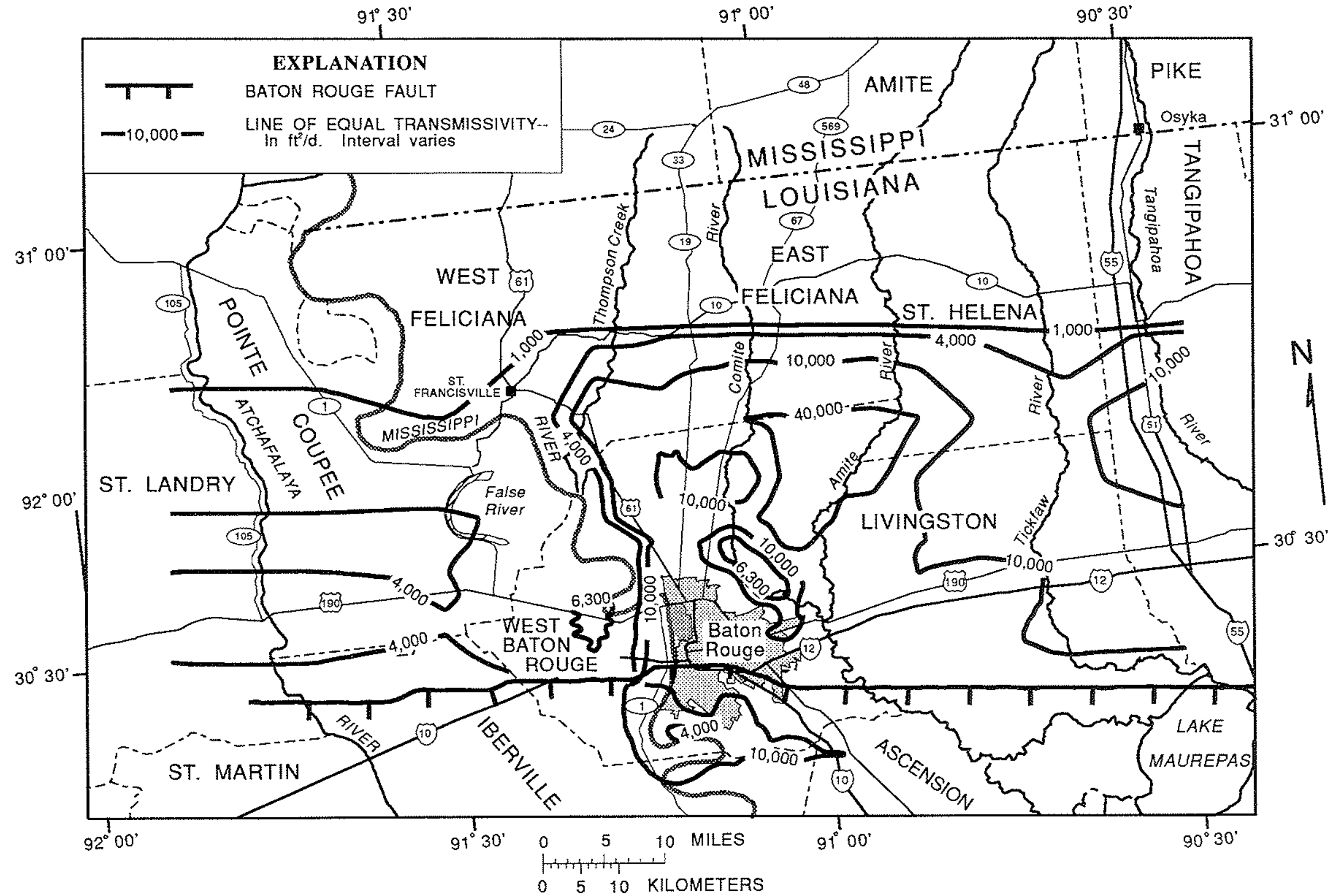


Figure 19. Calibrated transmissivity of the "800-foot" and "1,000-foot" aquifers (layer 2).

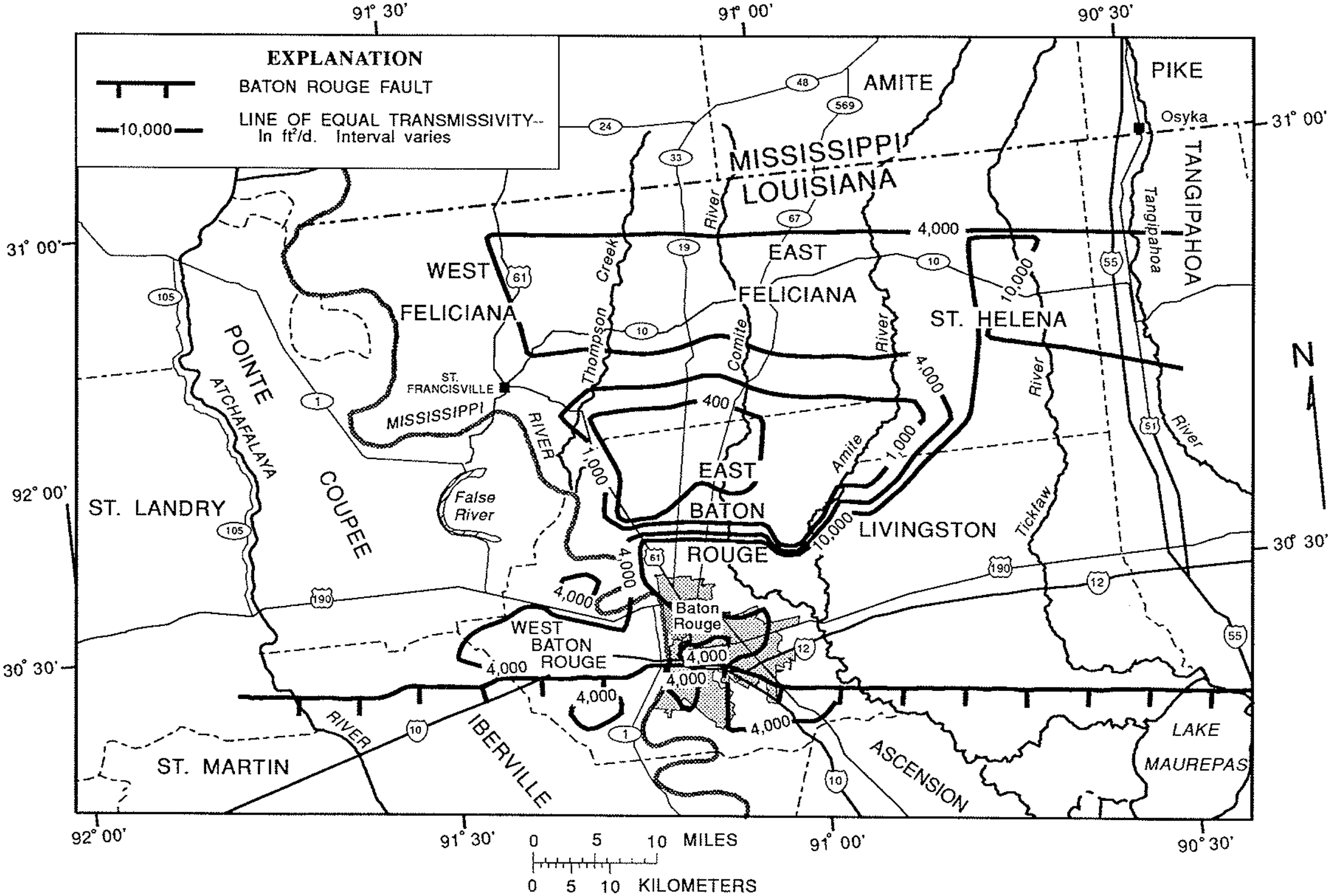


Figure 20. Calibrated transmissivity of the "1,200-foot" aquifer (layer 3).

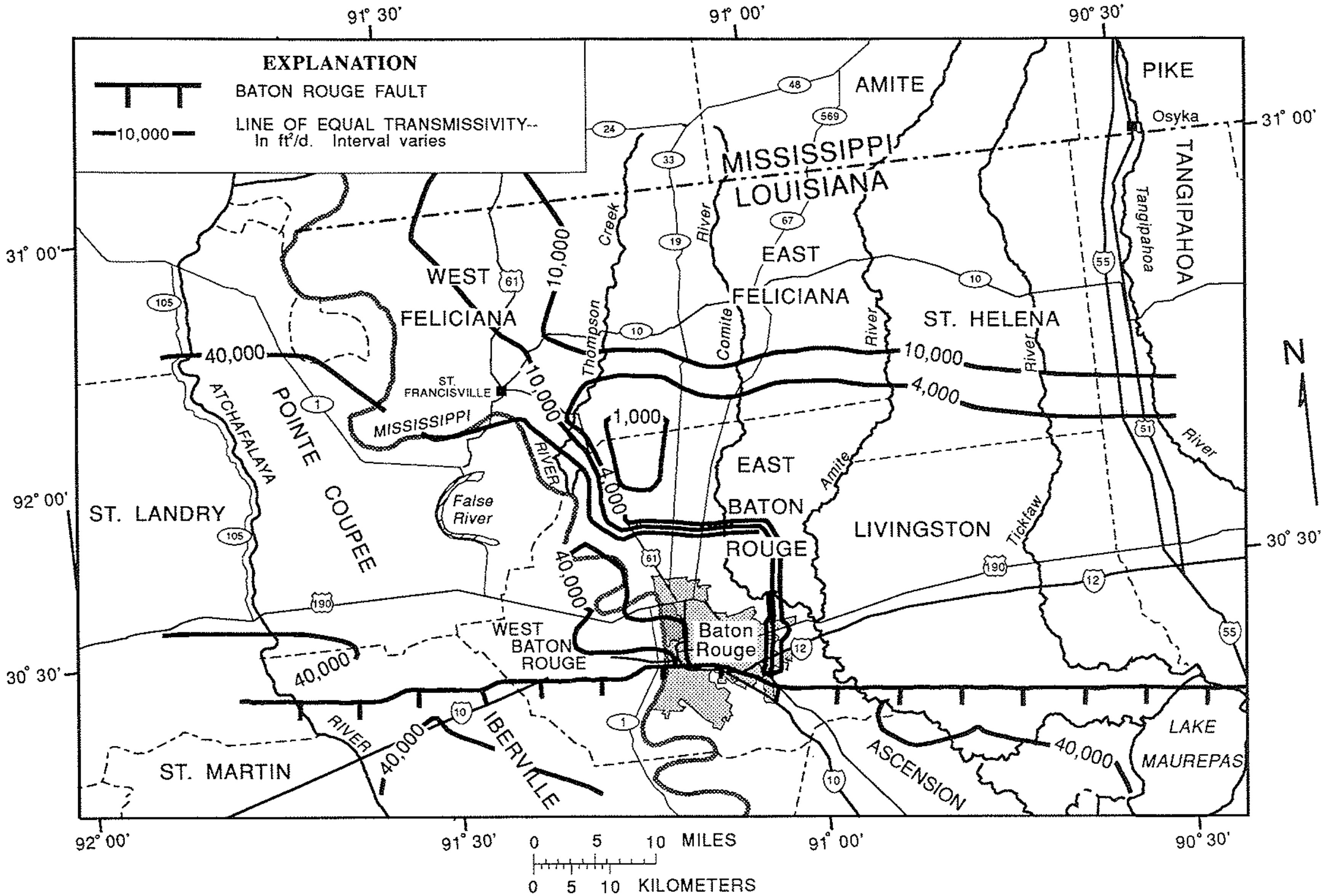


Figure 21. Calibrated transmissivity of the "1,500-foot" and "1,700-foot" aquifers (layer 4).

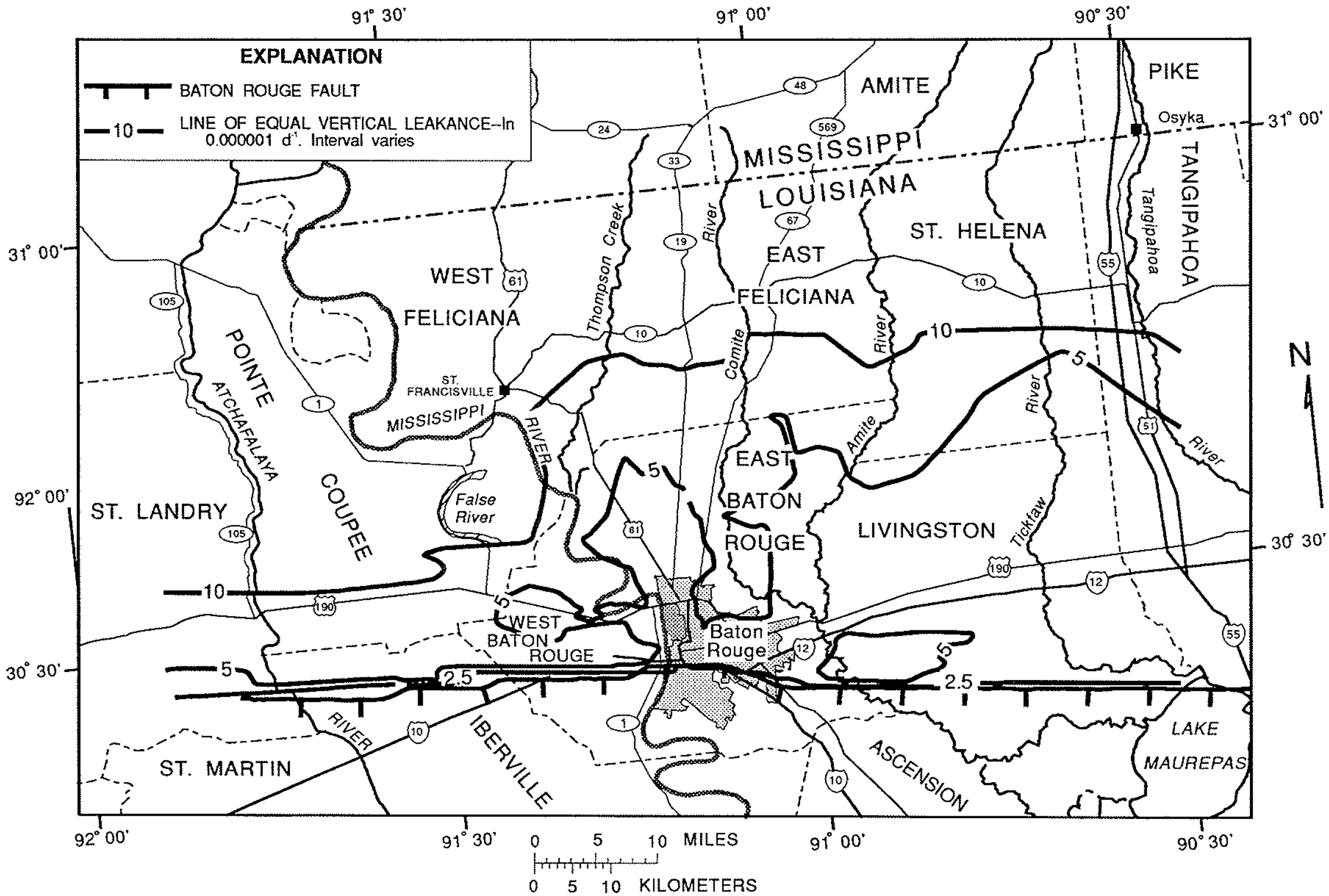


Figure 22. Calibrated vertical leakance between the "400-foot" and "600-foot" aquifers and the "800-foot" and "1,000-foot" aquifers (between layers 1 and 2).

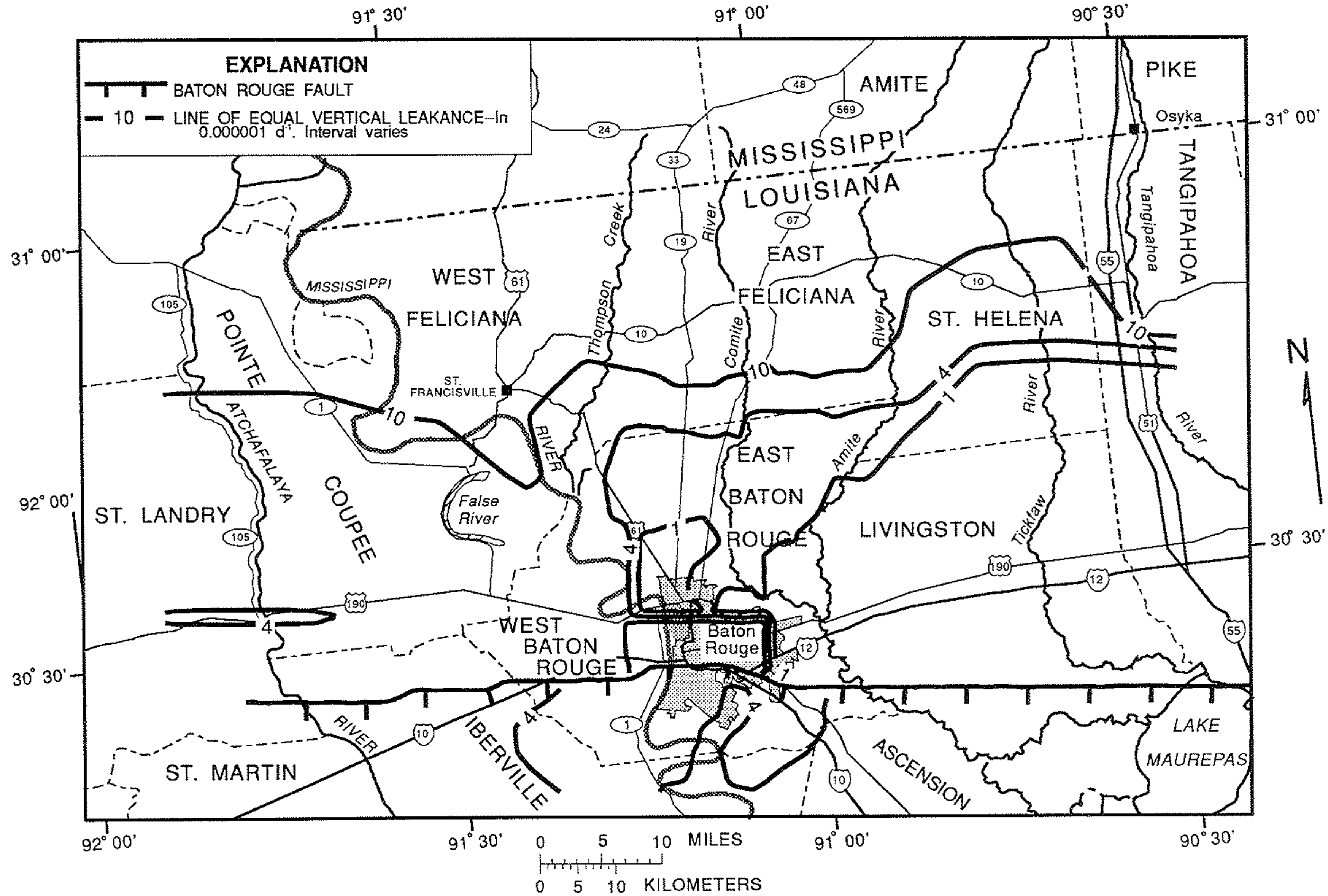


Figure 23. Calibrated vertical leakance between the "800-foot" and "1,000-foot" aquifers and the "1,200-foot" aquifer (between layers 2 and 3).

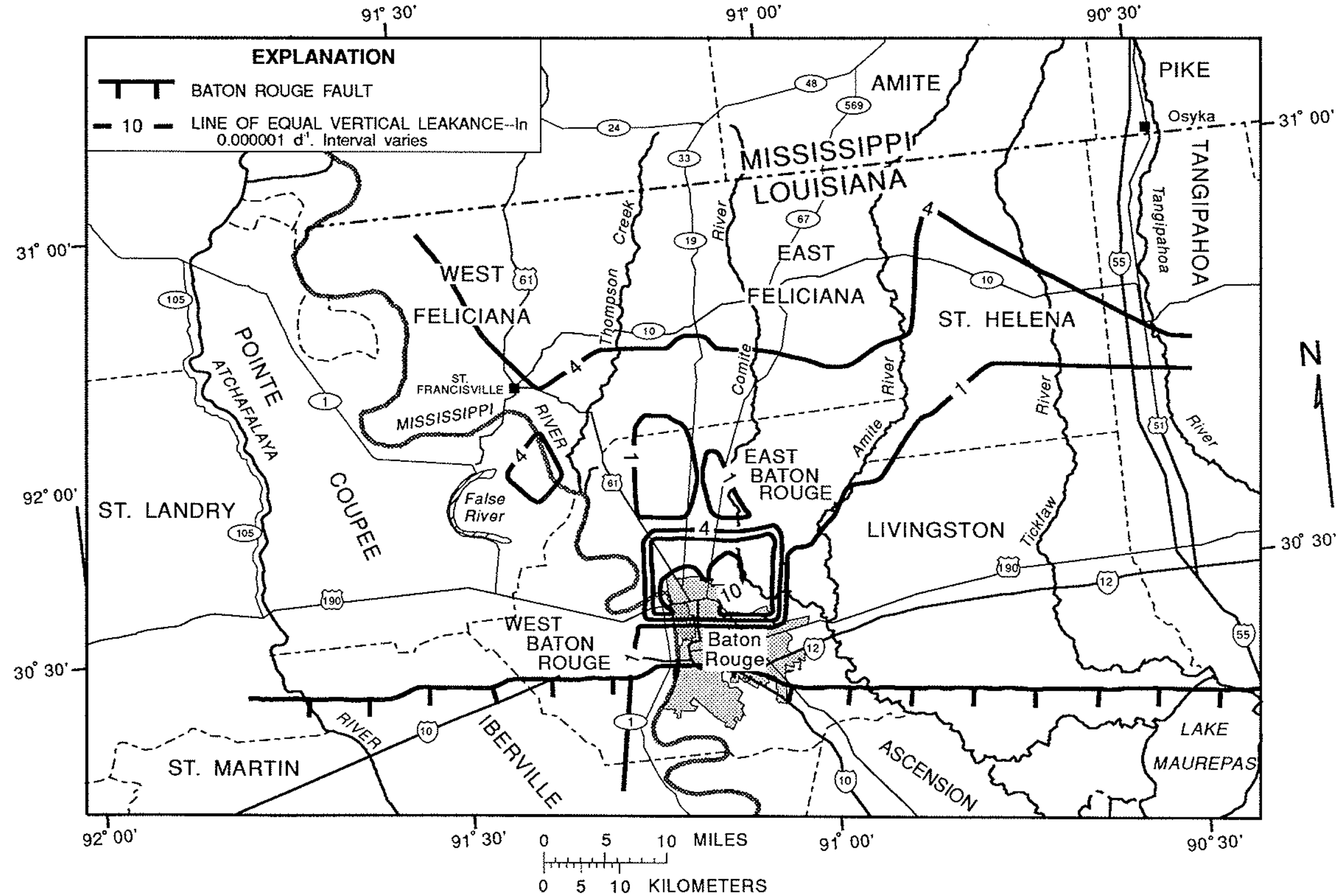


Figure 24. Calibrated vertical leakance between the "1,200-foot" aquifer and the "1,500-foot" and "1,700-foot" aquifers (between layers 3 and 4).

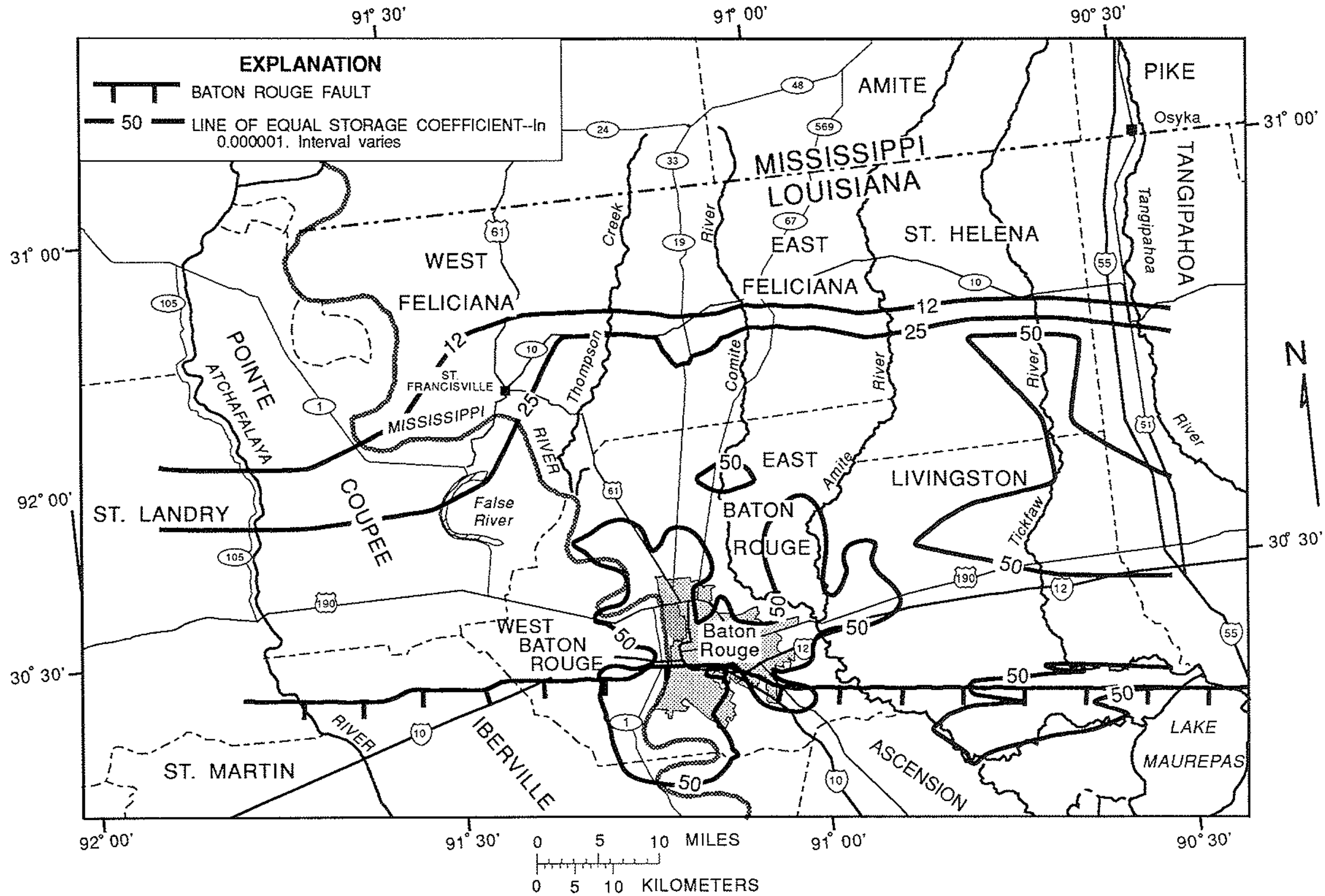


Figure 25. Calibrated storage coefficients of the "800-foot" and "1,000-foot" aquifers (layer 2).

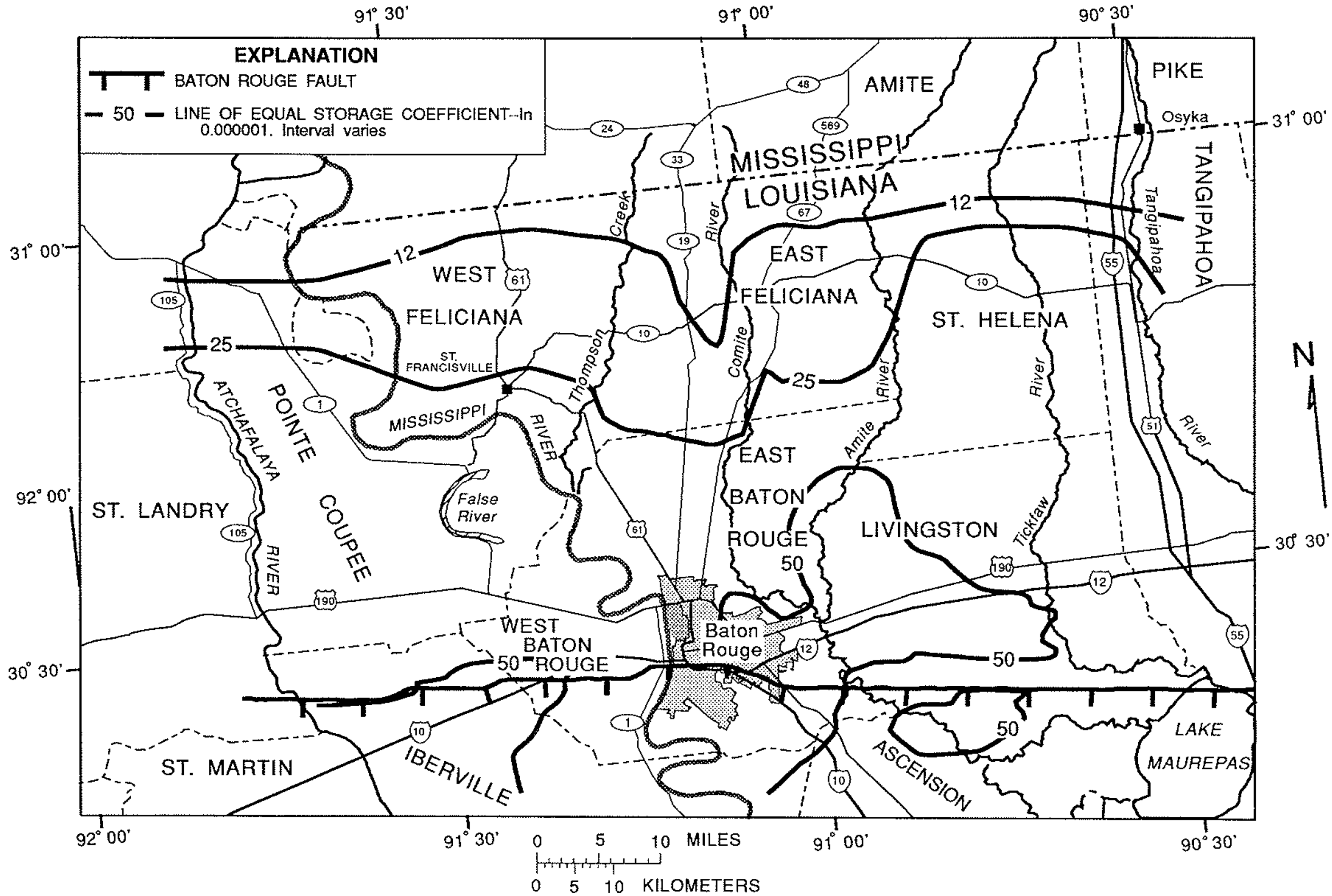


Figure 26. Calibrated storage coefficients of the "1,200-foot" aquifer (layer 3).

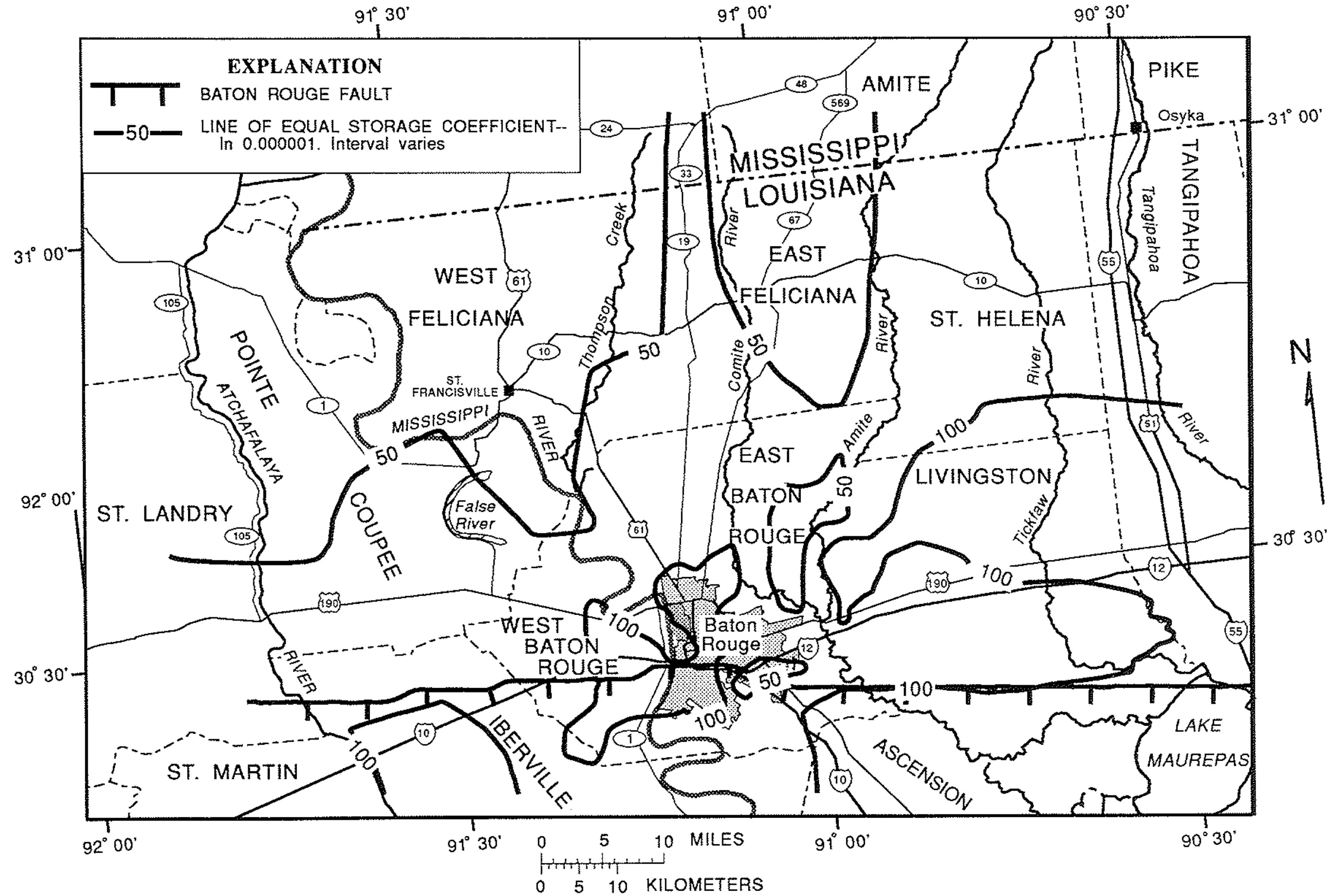


Figure 27. Calibrated storage coefficients of the "1,500-foot" and "1,700-foot" aquifers (layer 4).

Results from Calibration

After calibration, a steady-state simulation was made without pumping to represent prepumping conditions. Results of this simulation were compared with results for 1988 and showed that from predevelopment to 1988:

1. Flow patterns in the "1,200-foot" aquifer were altered downdip from the subcrop.
2. Discharge from the "1,200-foot" aquifer to shallower aquifers decreased and became areally less extensive.
3. Water levels in the "1,200-foot" aquifer declined 110 ft in the Baton Rouge industrial district.

Both the simulated potentiometric surface (fig. 17) and the flow-vector map (fig. 28) of the "1,200-foot" aquifer prior to pumping show flow was southwestward from the subcrop toward an ancestral path of the Mississippi River, which is located beneath the present Atchafalaya River basin. Water levels were near land surface in the Baton Rouge area and as much as 50 ft above land surface around the southern Livingston-Tangipahoa Parish boundary prior to pumping.

Under prepumping conditions, all recharge to the top of the "1,200-foot" aquifer took place within the subcrop area (figs. 2 and 29). Discharge rates from the aquifer averaged from 0.5 to 1 in/yr with higher rates occurring east of the Mississippi River.

Approximately 59 Mgal/d flowed through the "1,200-foot" aquifer (model layer 3) prior to extensive ground-water pumping. Thirty-eight percent (22 Mgal/d) of the total recharge entered in the subcrop "area" (fig. 30) while the remainder of inflow was from deeper aquifers. Ninety-four percent (56 Mgal/d) of the circulation through the "1,200-foot" aquifer occurred north of the Baton Rouge fault.

Flow patterns were altered from prepumping through 1988 conditions; flow in the "1,200-foot" aquifer converged from all directions toward pumping centers in Baton Rouge (figs. 31 and 32) in 1988. Water levels declined about 40 ft, on average, downgradient from the subcrop due to pumping (figs. 2 and 33) and declined a maximum of 120 ft in the Baton Rouge industrial district. Water levels in 1988 were down to 120 ft below land surface in the Baton Rouge area and up to 25 ft above land surface near the southern Livingston-Tangipahoa Parish boundary.

Pumping changed the area west of the Mississippi River from a discharge area (fig. 29) into a recharge area except for the area north of Old River (fig. 34). East of the Mississippi River, pumping extended the recharge area (fig. 34) to slightly south of the subcrop. Recharge to the "1,200-foot" aquifer throughout the area modeled increased by about 0.5 in/yr due to pumping.

Approximately 62 Mgal/d of water entered the "1,200-foot" aquifer under 1988 conditions (fig. 35). This is only 4 Mgal/d more flow than during predevelopment, but the flow directions are quite different. Fifty-eight percent (36 Mgal/d) of the flow entered the subcrop area under 1988 conditions (fig. 35). Most of the flow that left the "1,200-foot" aquifer was by pumpage (19 Mgal/d or 30 percent) and leakage (26 Mgal/d or 43 percent) to deeper aquifers. Only 0.2 Mgal/d of the flow in the "1,200-foot" aquifer came from storage under 1988 conditions. The remaining flow was discharged as leakage (17 Mgal/d or 27 percent) to shallower aquifers.

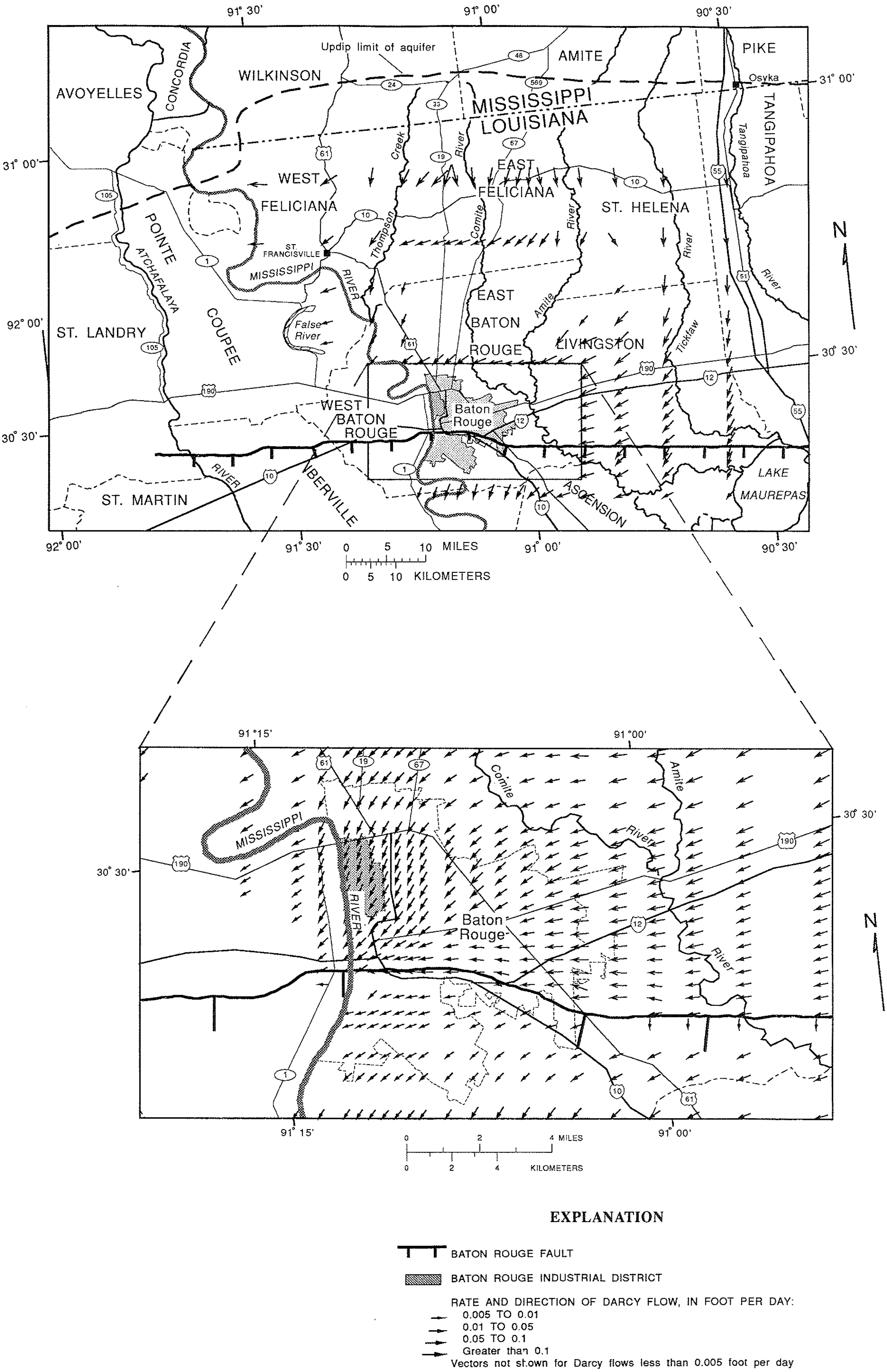


Figure 28. Simulated flow in the "1,200-foot" aquifer prior to pumping.

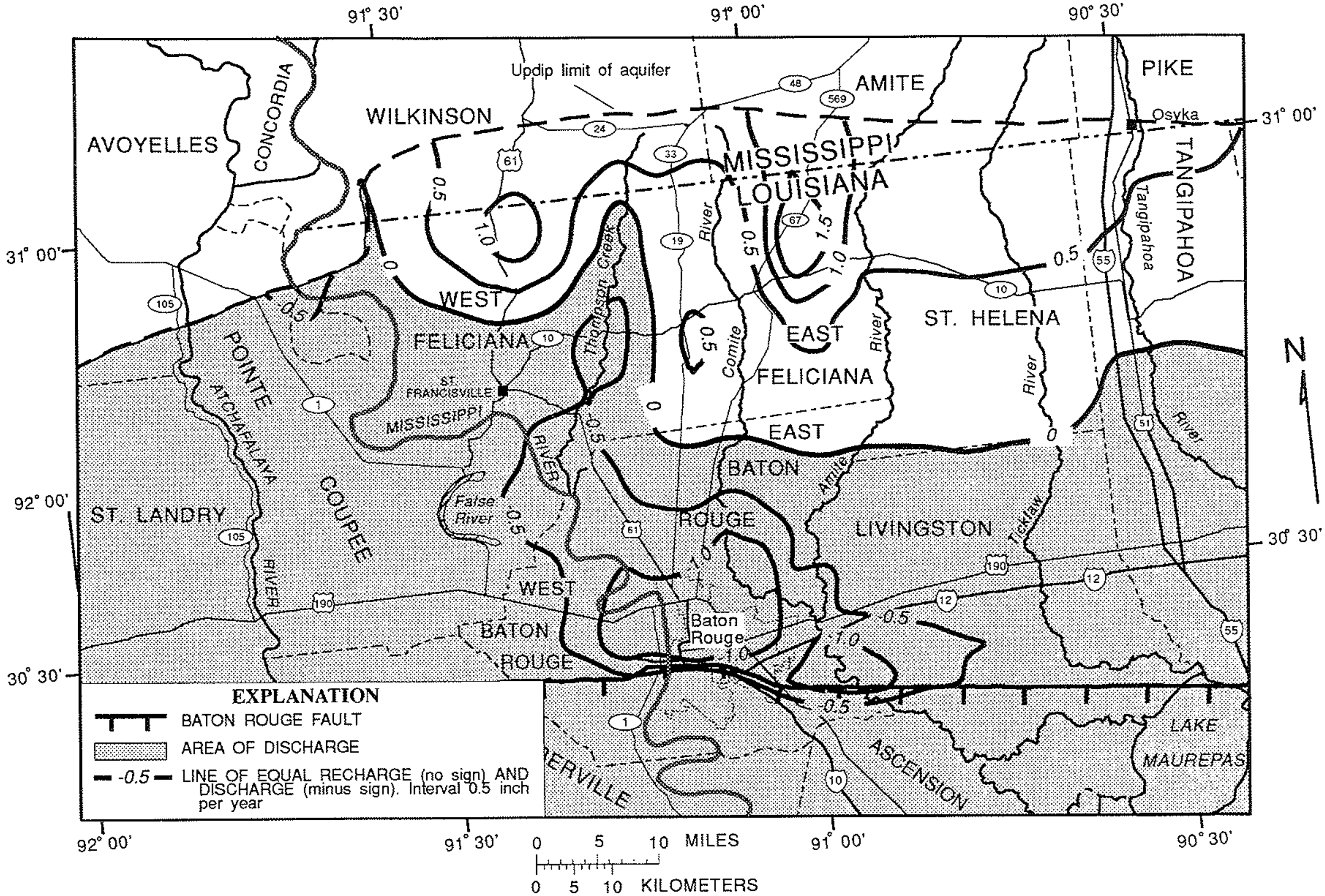


Figure 29. Simulated recharge and discharge across the top of the "1,200-foot" aquifer prior to pumping.

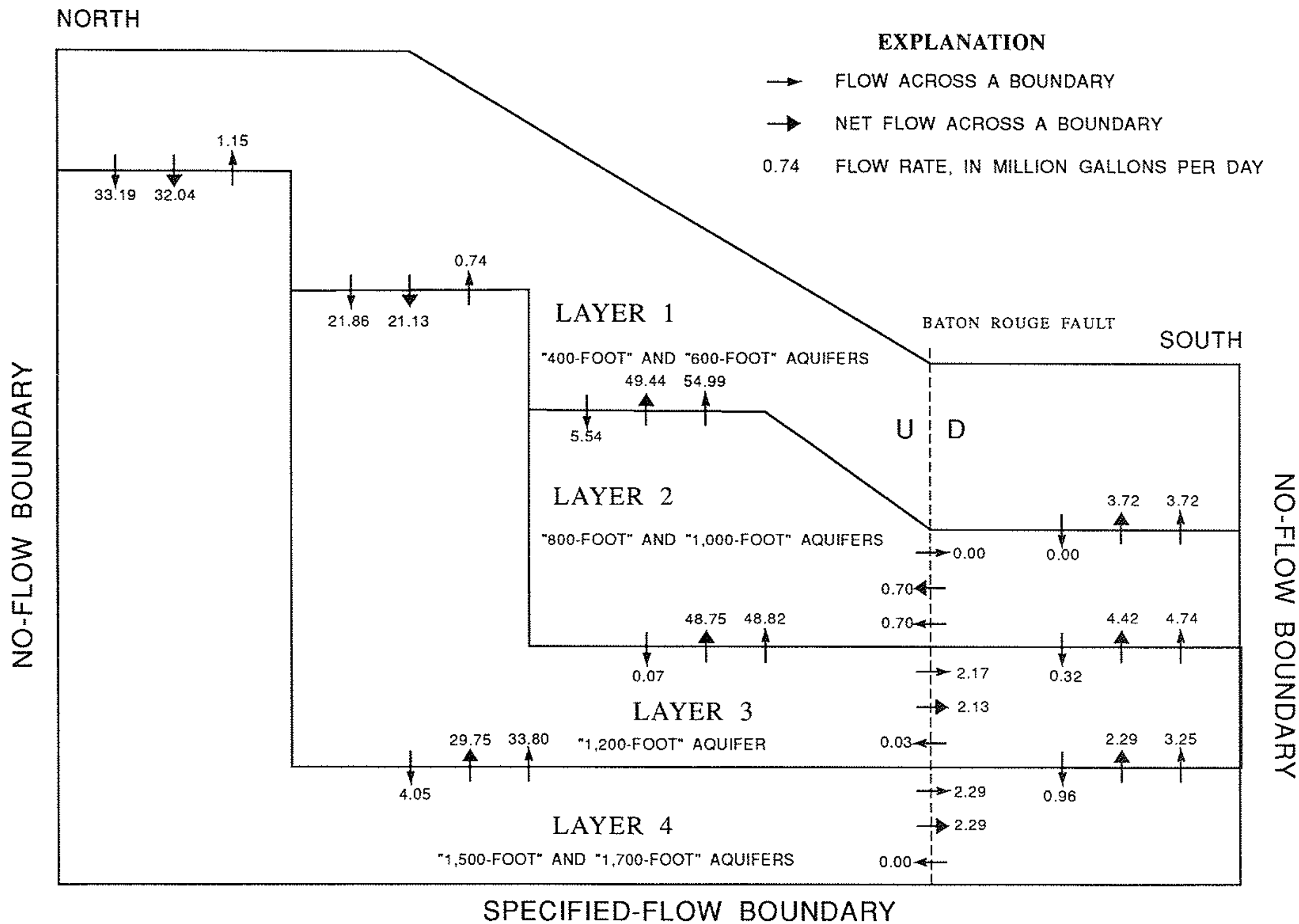


Figure 30. Simulated volumetric budget for the "1,200-foot" aquifer and adjacent aquifers prior to pumping.

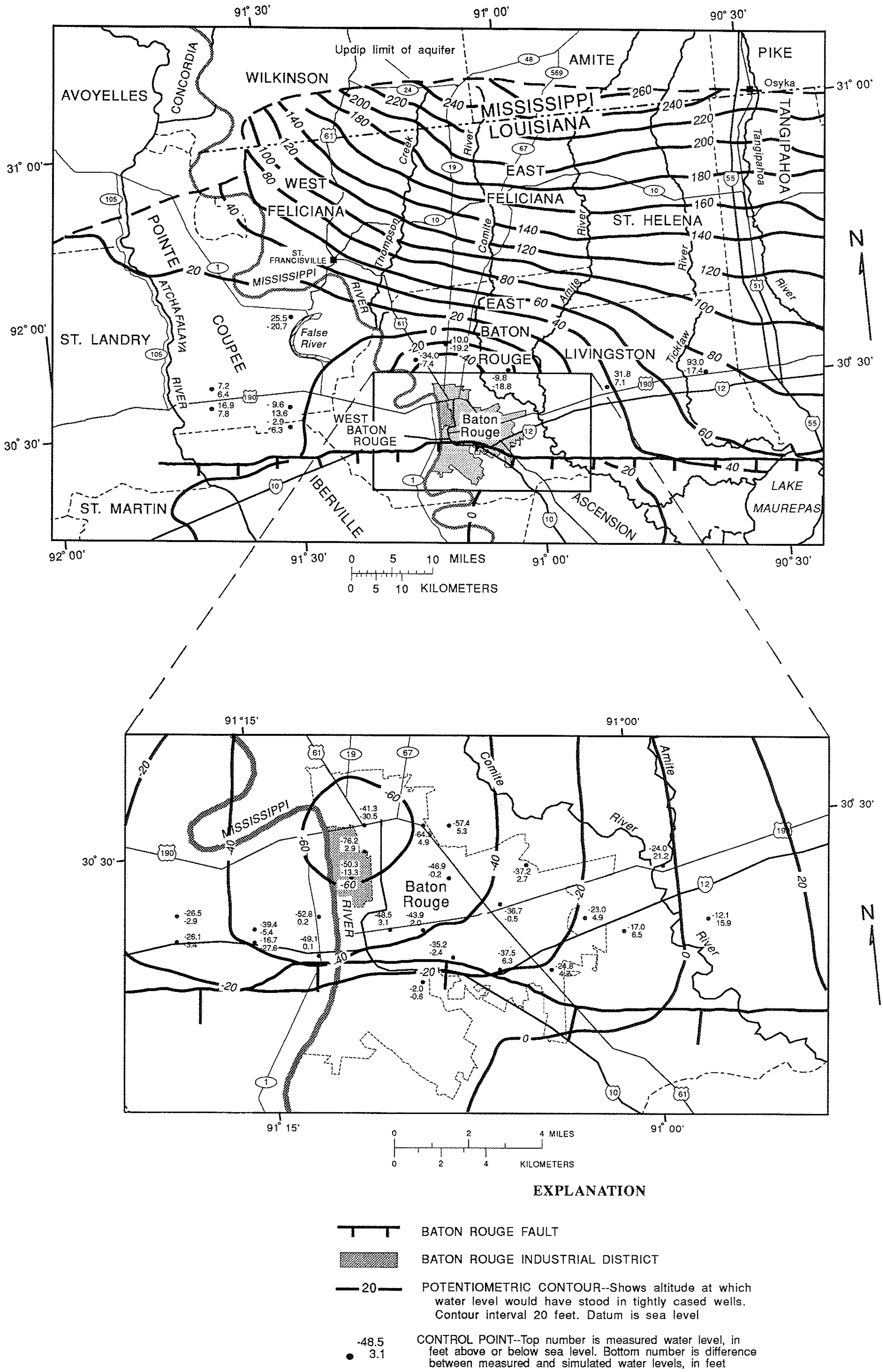


Figure 31. Simulated potentiometric surface of the "1,200-foot" aquifer in 1988.

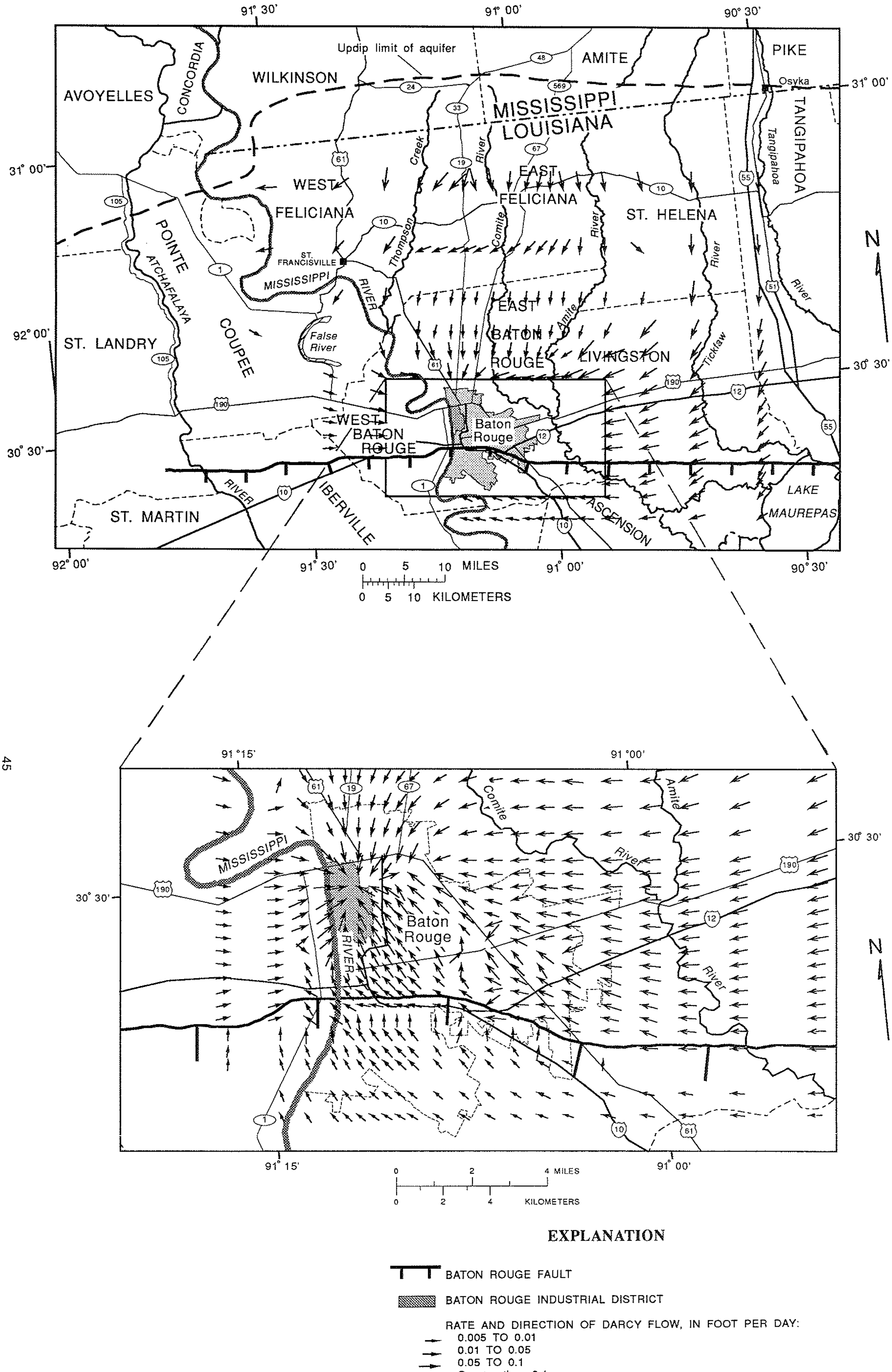


Figure 32. Simulated flow in the "1,200-foot" aquifer in 1988.

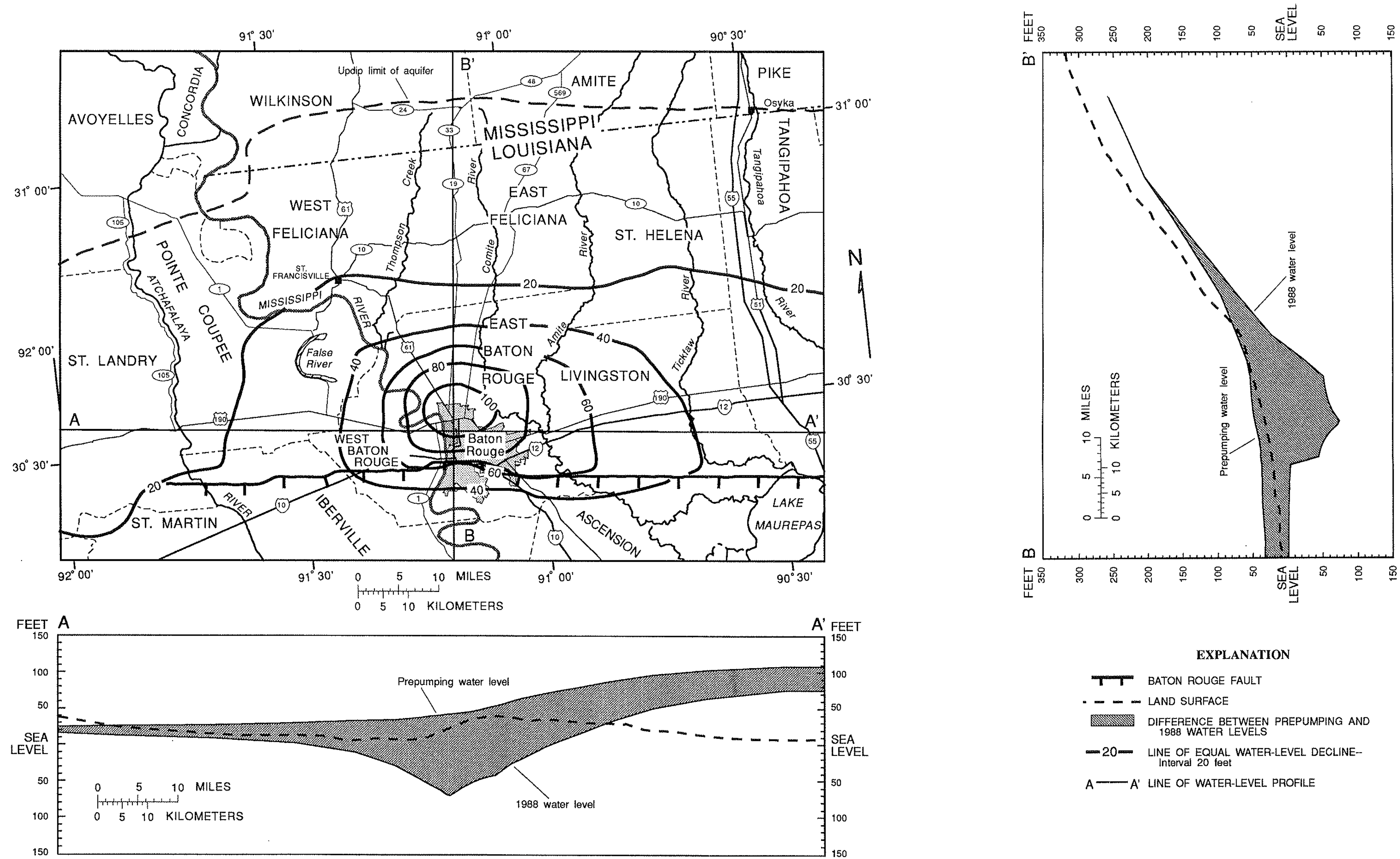


Figure 33. Drawdowns from prepumping water levels to 1988 water levels in the "1,200-foot" aquifer.

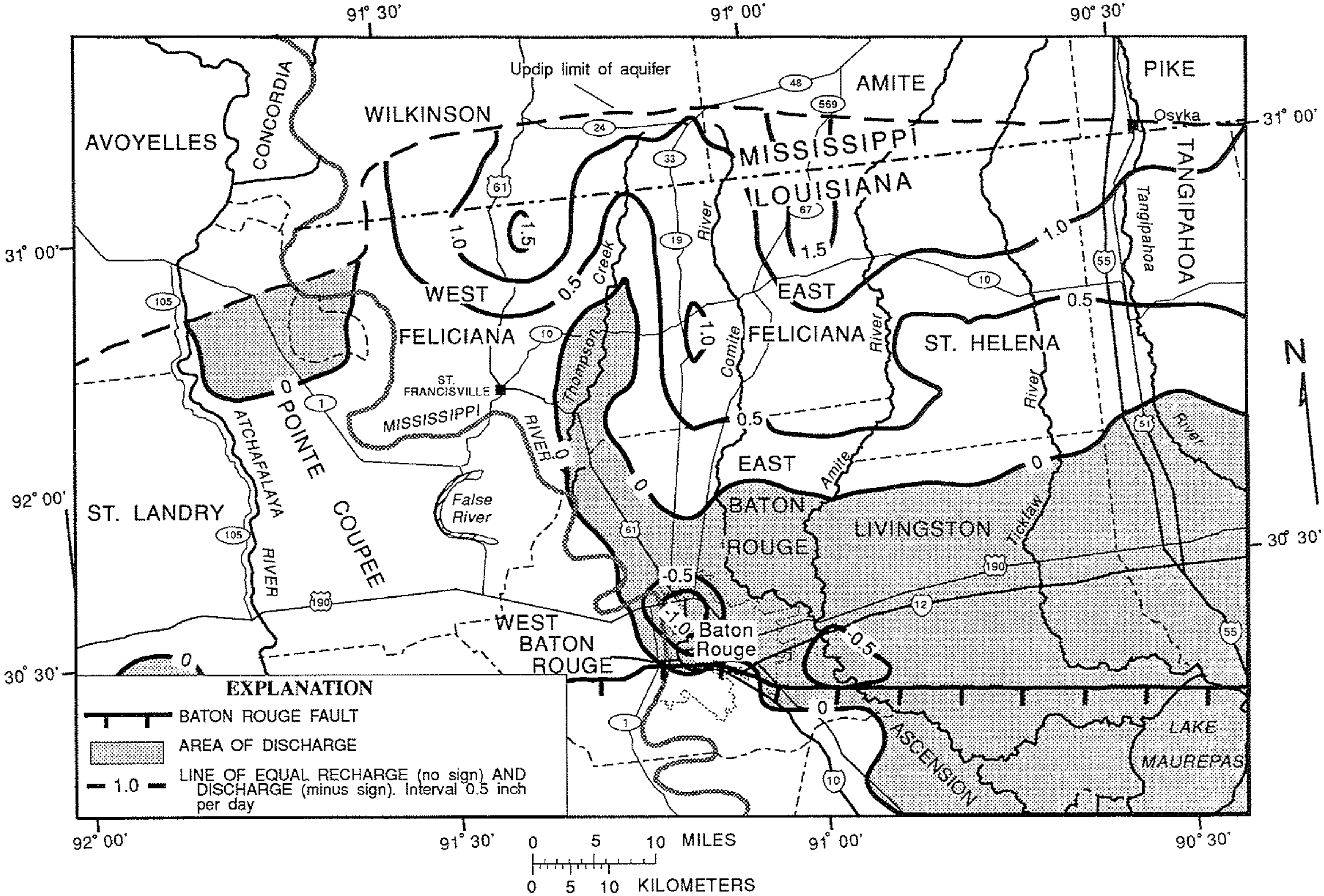


Figure 34. Simulated recharge and discharge across the top of the "1,200-foot" aquifer in 1988.

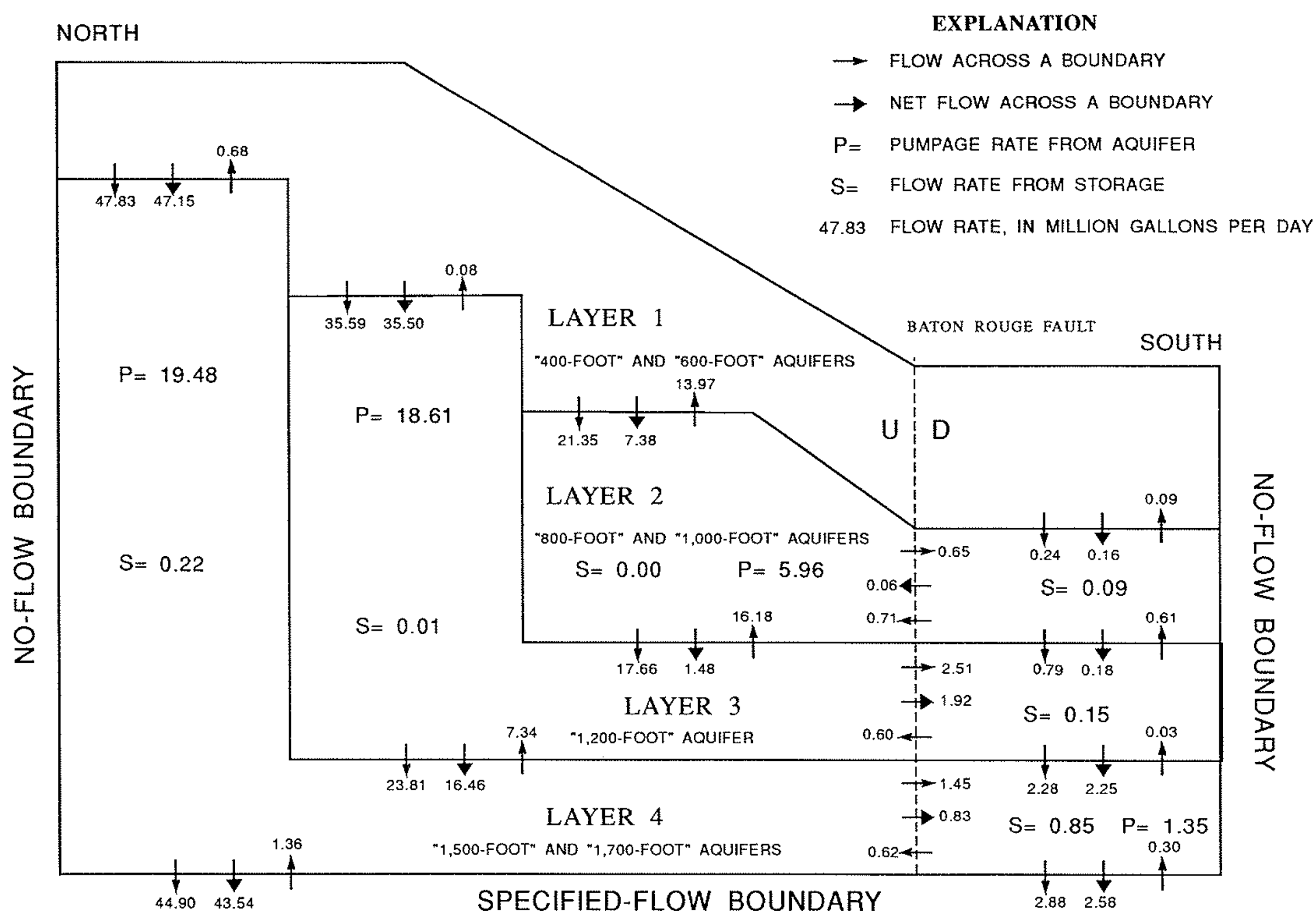


Figure 35. Simulated volumetric budget for the "1,200-foot" aquifer and adjacent aquifers in 1988.

Sensitivity Analysis

Transmissivity, vertical leakance, and storage coefficient were varied during model calibration because these parameters were known with the least degree of certainty. To determine how each of these parameters affected model simulation, each parameter was varied, singularly, over four orders of magnitude during sensitivity analysis simulations. This is a much greater range than the associated uncertainties but gives a better perspective on model sensitivity. Model sensitivity was described in terms of RMSE and water-level profiles with respect to 1984 observed water levels. Boundary conditions and pumping were not adjusted during calibration and were assumed to be correct, so a sensitivity analysis was not performed on them.

The model was most sensitive to changes in transmissivity (fig. 24) throughout the range examined because the Baton Rouge fault was modeled as a low transmissivity zone and large stresses are imposed at nearby pumping centers in Baton Rouge. The decreasing model sensitivity, as transmissivity values were increased to 10 times or greater than the calibrated values, was due to the lack of resistance to flow in the fault and near pumping centers (fig. 36). The effects of transmissivity changes are illustrated more clearly in the water-level profiles in figure 37.

The model was more sensitive to vertical leakance decreases than to increases (figs. 36 and 37). The profile produced by the tenfold vertical leakance decrease is 50 ft lower, on average, than the profile from the calibrated model. The profile produced with a tenfold vertical leakance increase practically coincides with the profile from the calibrated model. This asymmetrical model sensitivity to vertical leakance changes exists for transmissivity values other than the calibrated values (fig. 38).

Overall, the model was least sensitive to changes in storage coefficient (fig. 36) (than to transmissivity or leakance), but showed a greater sensitivity to storage coefficient increases than to decreases. This is indicated by the water-level profiles in figure 37. The profile produced by a tenfold storage coefficient increase is 15 ft higher, on average, than the profile from the calibrated model. The profile produced with a tenfold storage coefficient decrease practically coincides with the profile from the calibrated model.

Areally, the model is more sensitive to parameter changes between the subcrop area and the Baton Rouge fault (fig. 37). More pronounced effects occurred near the Baton Rouge area where major pumping centers are located. The effects of the major pumping centers are accentuated on both water-level profiles in figure 37 for transmissivity values divided by 10.

SIMULATED AQUIFER RESPONSE TO ALTERNATE PUMPING PLANS

Two sets of three simulations were completed with the calibrated model to estimate the response of the "1,200-foot" aquifer to pumping changes in the aquifer. The first set simulated the effects for 1 year after adding pumping centers (fig. 4) to 1985 pumpage, where:

1. 3 Mgal/d per node was added to the two "A" locations in figure 4 for a total of 6 Mgal/d more than 1985 pumpage.
2. 3 Mgal/d per node was added to the two "B" locations in figure 4 for a total of 6 Mgal/d more than 1985 pumpage.
3. 3 Mgal/d per node was added to the "A" and "B" locations in figure 4 for a total of 12 Mgal/d more than 1985 pumpage.

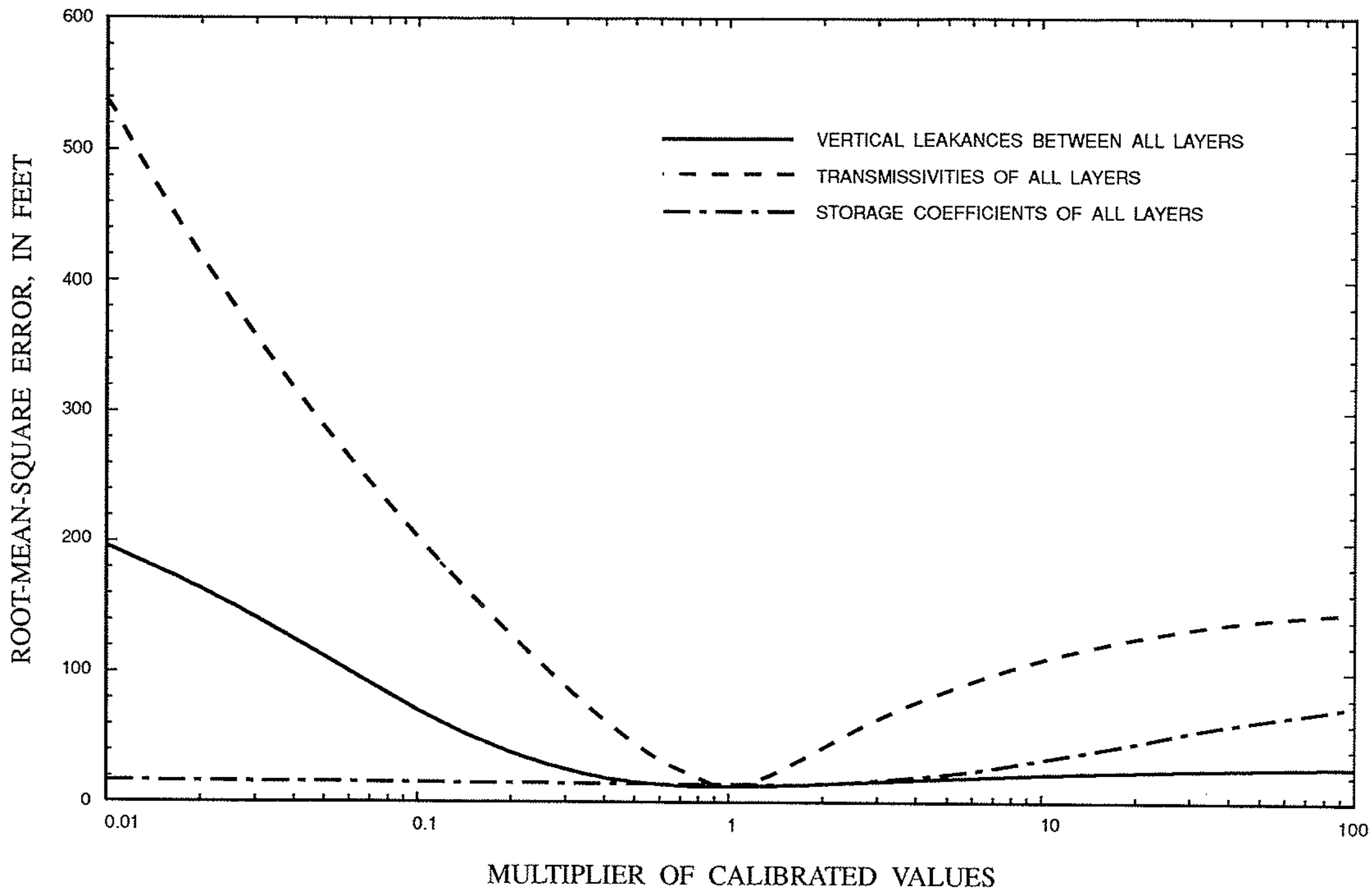


Figure 36. Model sensitivity to changes in transmissivity, vertical leakance, and storage coefficient.

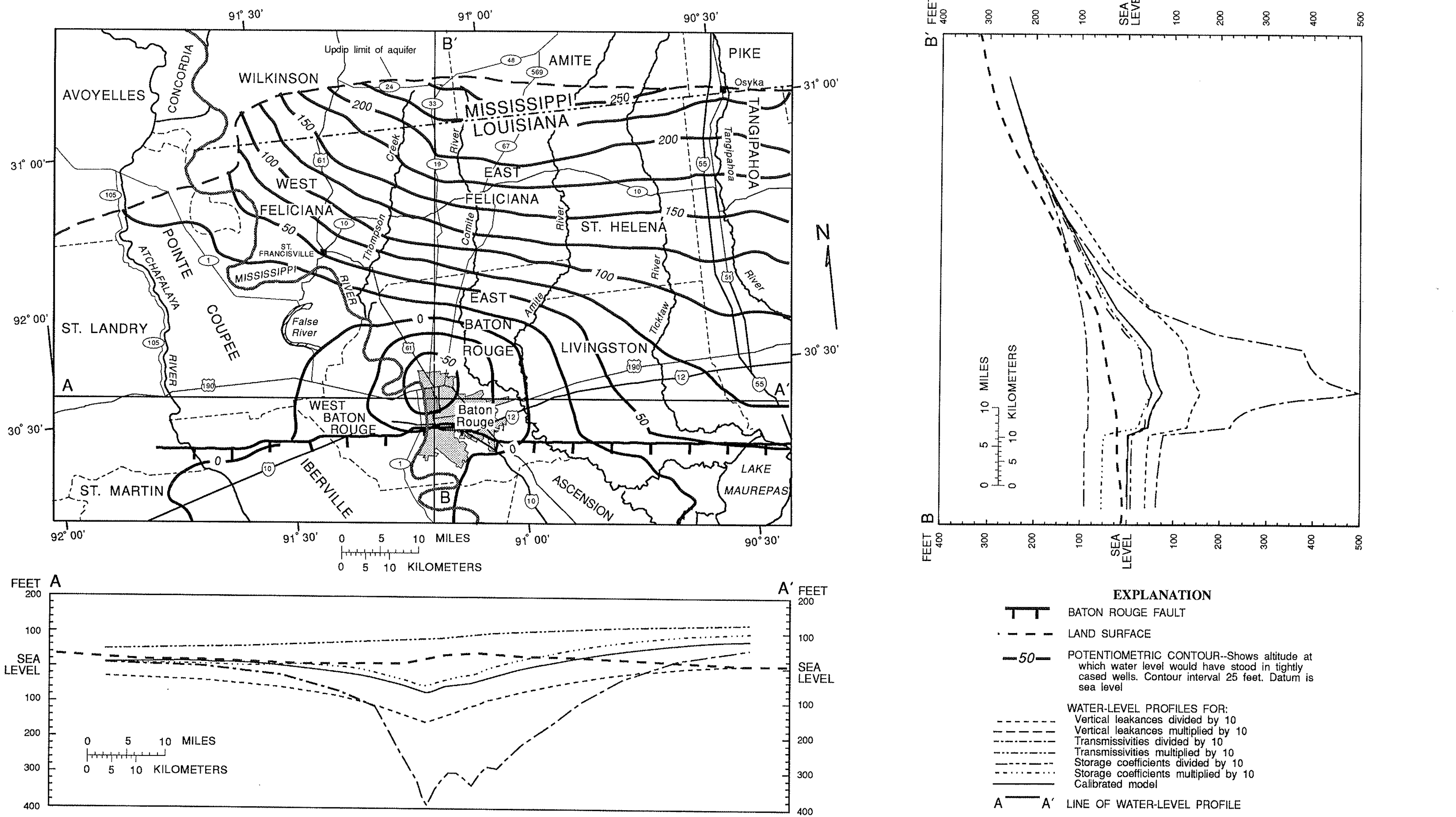
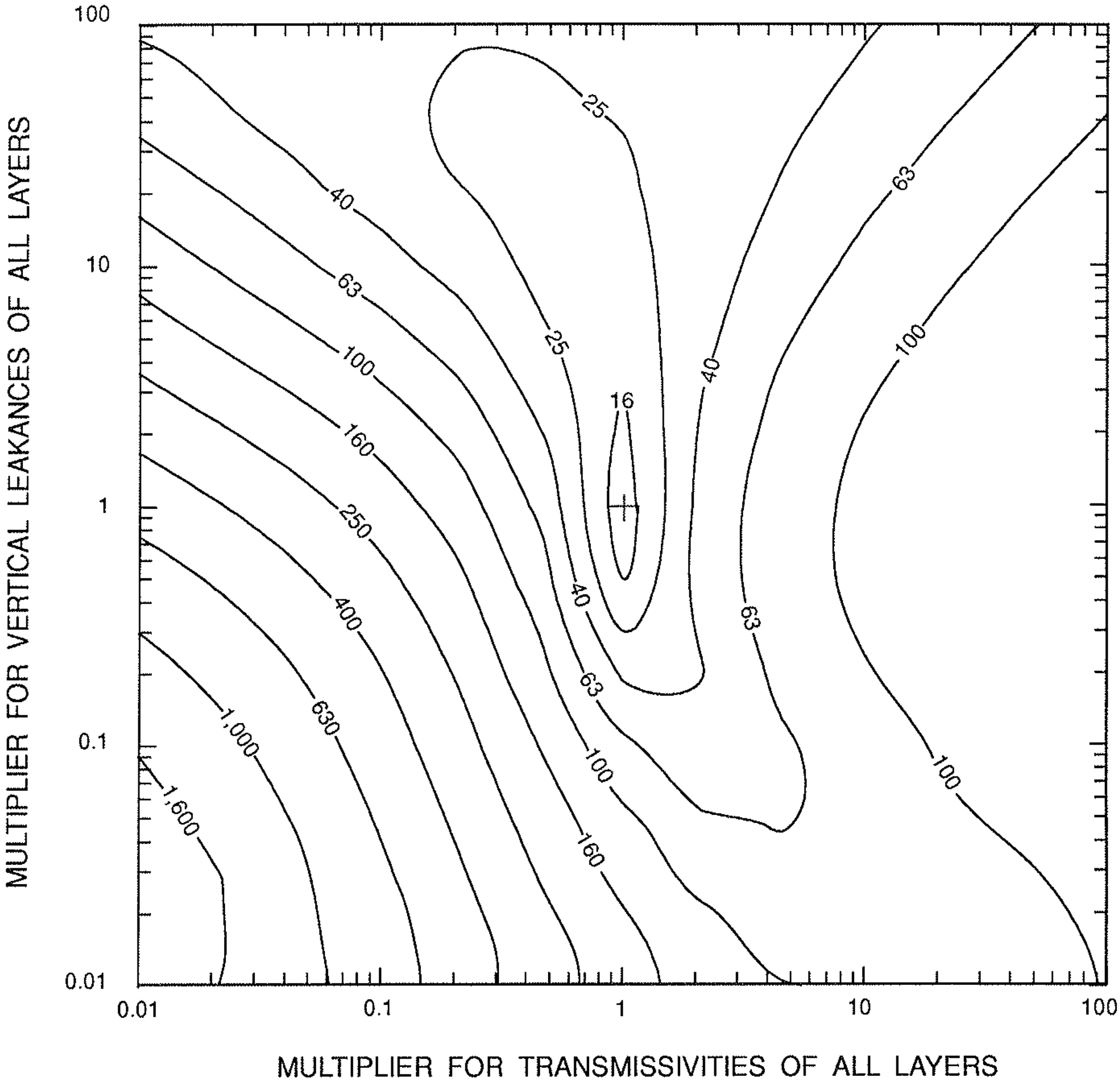


Figure 37. Simulated potentiometric surface of the "1,200-foot" aquifer in 1988 and model sensitivity to effects of selected parameter changes on water levels in the aquifer.



EXPLANATION

—63— LINE OF EQUAL ERROR--Interval varies, in feet

+ ERROR OF CALIBRATED MODEL, 12.15

Figure 38. Model sensitivity to changes in transmissivity and vertical leakance.

The locations of the hypothetical new pumping centers were chosen in areas where additional demands for water for public supplies from the "1,200-foot" aquifer have been projected.

The second set simulated aquifer responses for three conditions over 50 years where:

4. The 1985 pumpage in the "1,200-foot" aquifer was decreased by 1 percent per year from 1989 to 2038 for a net decrease of 50 percent.
5. The 1985 pumpage in the "1,200-foot" aquifer was increased by 1 percent per year from 1989 to 2038 for a net increase of 50 percent.
6. The pumpage from simulation 3 was increased by 1 percent per year from 1989 to 2038 for a net increase of 50 percent.

The 1 percent per year increases and decreases in pumping from the "1,200-foot" aquifer hypothesized in this set of simulations are consistent with the magnitude of increases and decreases that have occurred over shorter periods in the past.

The additional pumping in simulation 1 lowered water levels in the "1,200-foot" aquifer 25 ft from 1988 levels near the new "A" pumping centers. The greatest drawdowns were east of the new pumping centers, extending through Livingston Parish (fig. 39), whereas the lowest water levels still occurred near the Baton Rouge industrial district. Drawdowns of more than 10 ft would extend 20 mi east and 5 mi west of the new pumping centers. Because of the flow restriction caused by the Baton Rouge fault, the drawdowns caused the closed water-level decline lines on figure 39 to form an oval shape trending east-west.

Water levels in the "1,200-foot" aquifer were lowered 35 ft from 1988 levels near the new "B" pumping centers in simulation 2 (fig. 40). The greater drawdowns resulted because the new pumping centers in simulation 2 were closer together than those in simulation 1 (fig. 4). Away from the new pumping centers, the drawdowns were similar to those in simulation 1 because the additional pumping for each simulation was the same.

Simulation 3 was a composite of simulations 1 and 2, thus the drawdowns resulting from simulation 3 were equal to the sum of those from simulations 1 and 2 (fig. 41). Drawdowns greater than 10 ft extended 35 mi east and 10 mi west of the new pumping centers. Water levels were lowered 60 ft from 1988 levels near the new pumping centers in simulation 3 (fig. 41).

The drawdowns were great enough to lower water levels near the new pumping centers to the levels in the Baton Rouge industrial district (figs. 41 and 42). Water levels were down to 135 ft below land surface in the Baton Rouge area and lowered to 10 ft above land surface around the southern Livingston-Tangipahoa Parish boundary in simulation 3. The flow distribution throughout most of the area modeled was similar to the 1988 distribution, except around the Baton Rouge area (fig. 43). Flows were reversed east of U.S. 61 and converged at the new pumping centers.

The additional pumping reduced the discharge area of the "1,200-foot" aquifer south of the subcrop but not west of the Mississippi River and north of Old River. Recharge to the aquifer (fig. 44) changed very little from 1988 conditions (fig.22) in the subcrop area and increased areally south of the subcrop area.

Approximately 69 Mgal/d of water entered the "1,200-foot" aquifer in simulation 3 (fig. 45). This was only 8 Mgal/d more circulation within the "1,200-foot" aquifer than under 1988 conditions. Most of the flow left the "1,200-foot" aquifer by pumpage (31 Mgal/d or 44 percent) and leakage to deeper aquifers (23 Mgal/d or 33 percent). About 52 percent (36 Mgal/d) of the flow entered around the subcrop area. This was less than 1 Mgal/d more than the flow that

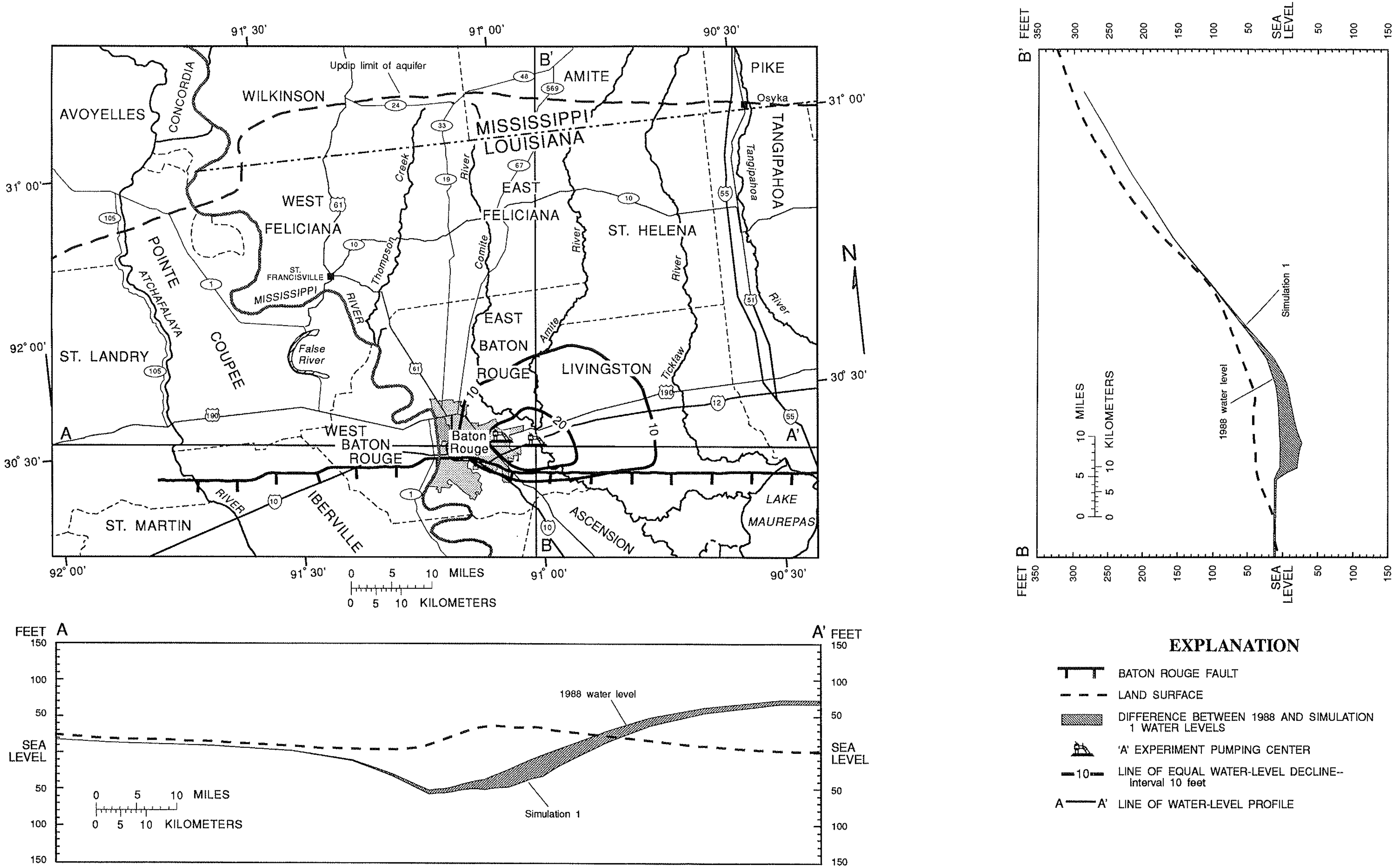
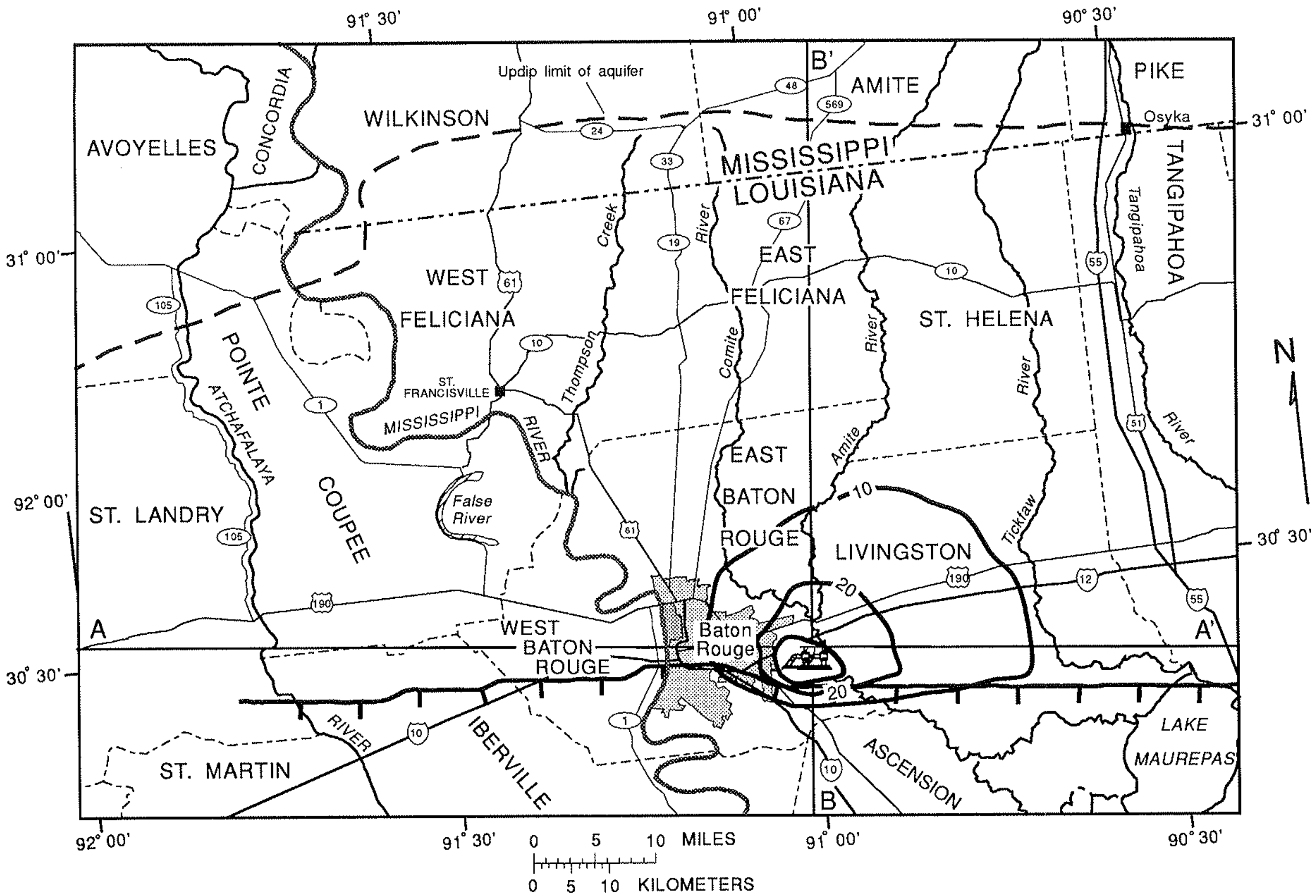
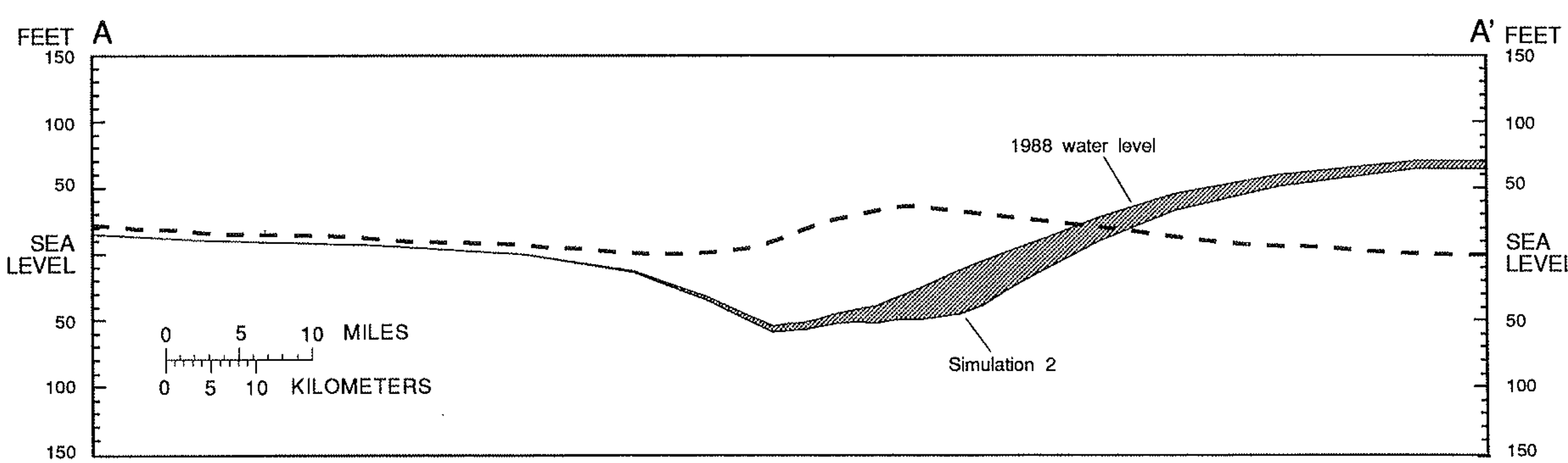
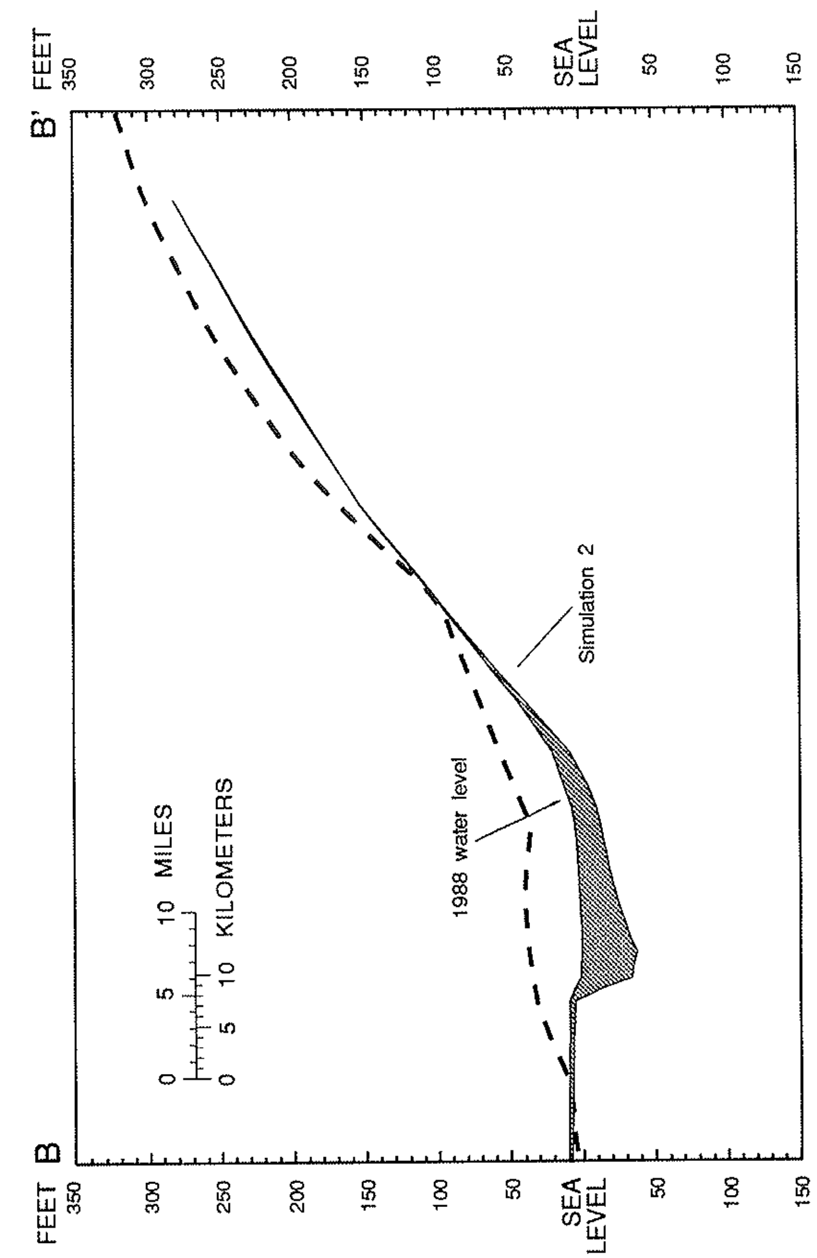


Figure 39. Drawdowns from 1988 water levels to water levels calculated at the end of simulation 1 in the "1,200-foot" aquifer.







EXPLANATION

- BATON ROUGE FAULT
- LAND SURFACE
- DIFFERENCE BETWEEN 1988 AND SIMULATION 2 WATER LEVELS
- 'B' EXPERIMENT PUMPING CENTER
- 10 — LINE OF EQUAL WATER-LEVEL DECLINE-- Interval 10 feet
- A——A' LINE OF WATER-LEVEL PROFILE

Figure 40. Drawdowns from 1988 water levels to water levels calculated at the end of simulation 2 in the "1,200-foot" aquifer.

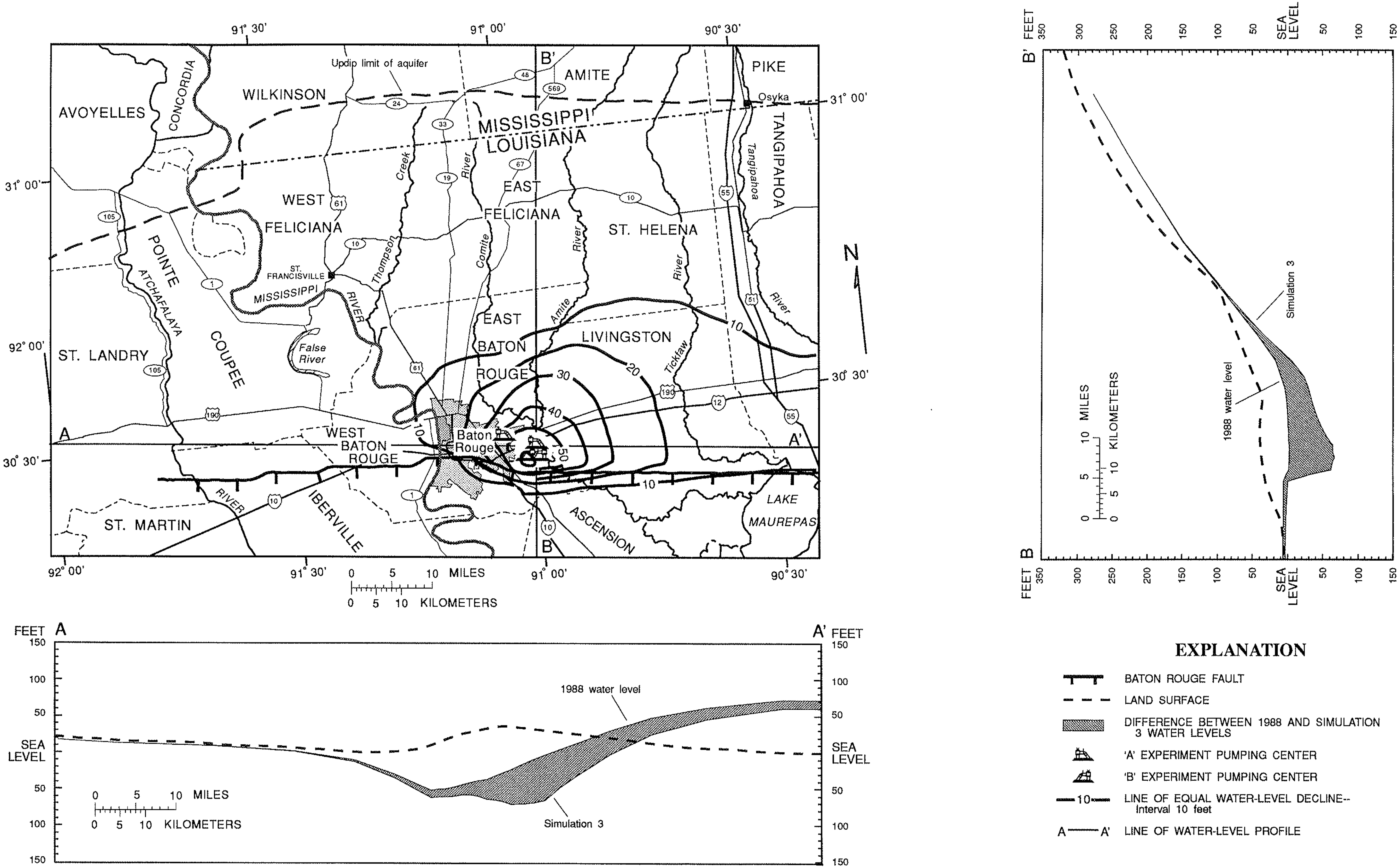


Figure 41. Drawdowns from 1988 water levels to water levels calculated at the end of simulation 3 in the "1,200-foot" aquifer.

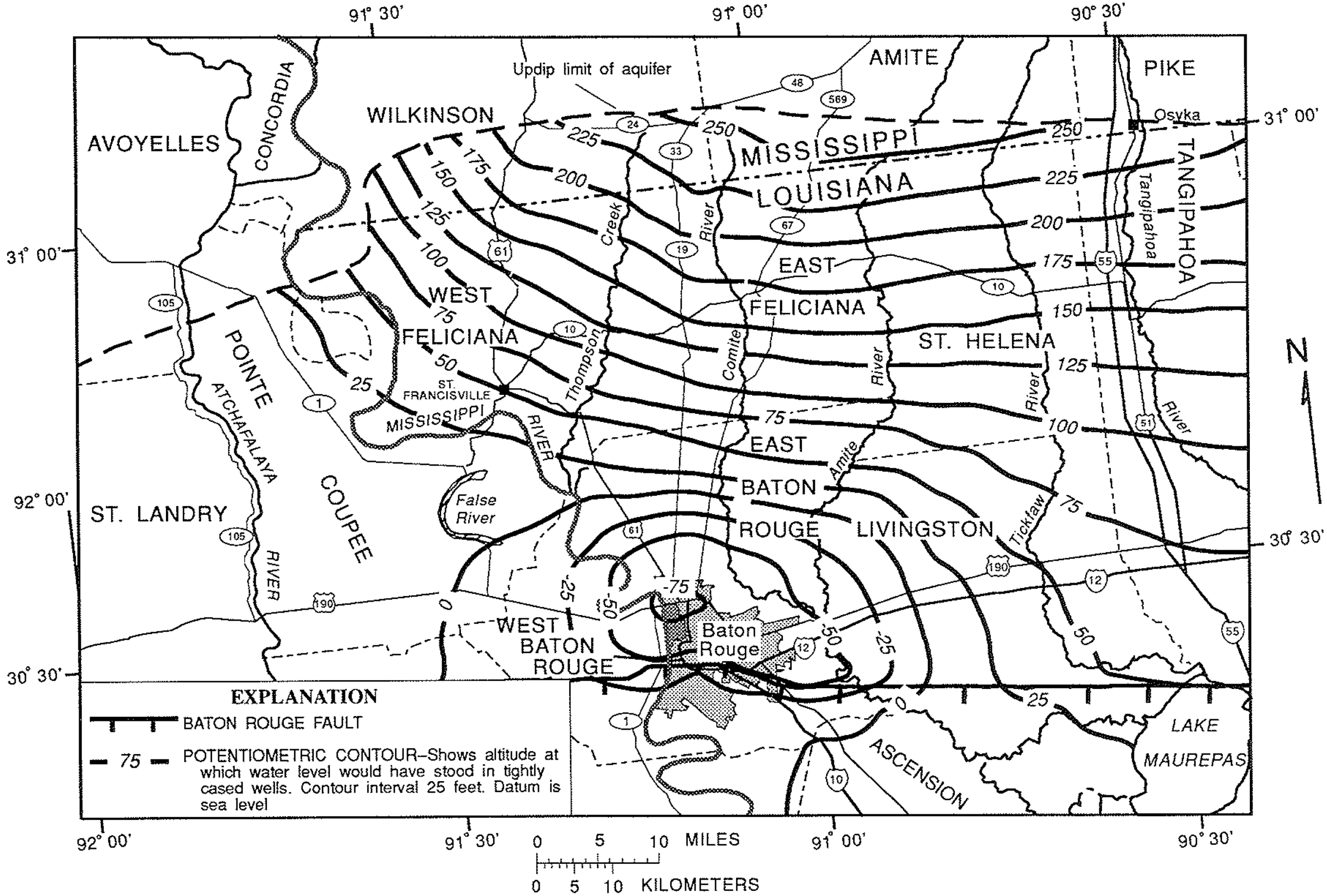


Figure 42. Potentiometric surface of the "1,200-foot" aquifer at the end of simulation 3.

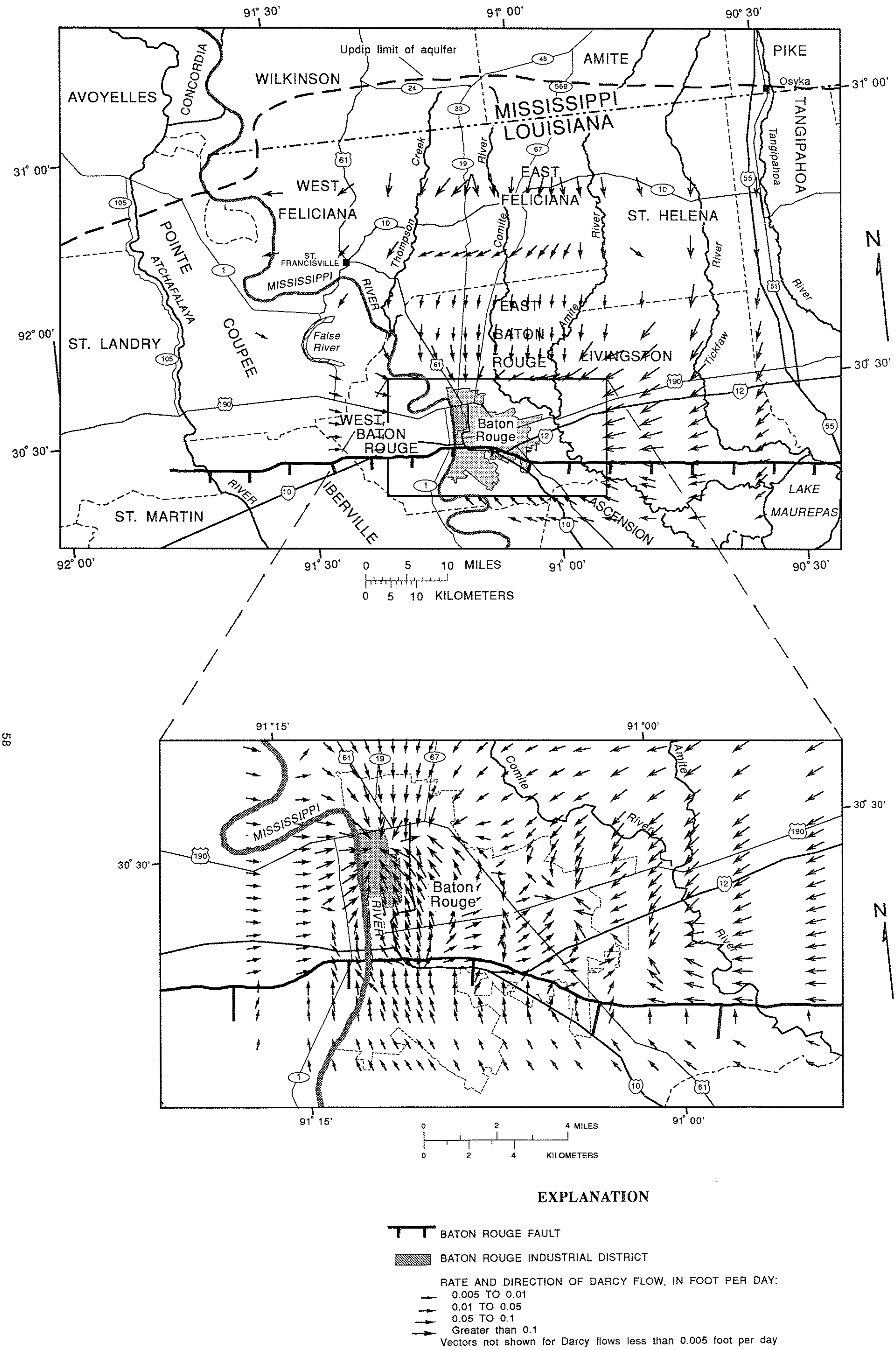


Figure 43. Flow in the "1,200-foot" aquifer at the end of simulation 3.

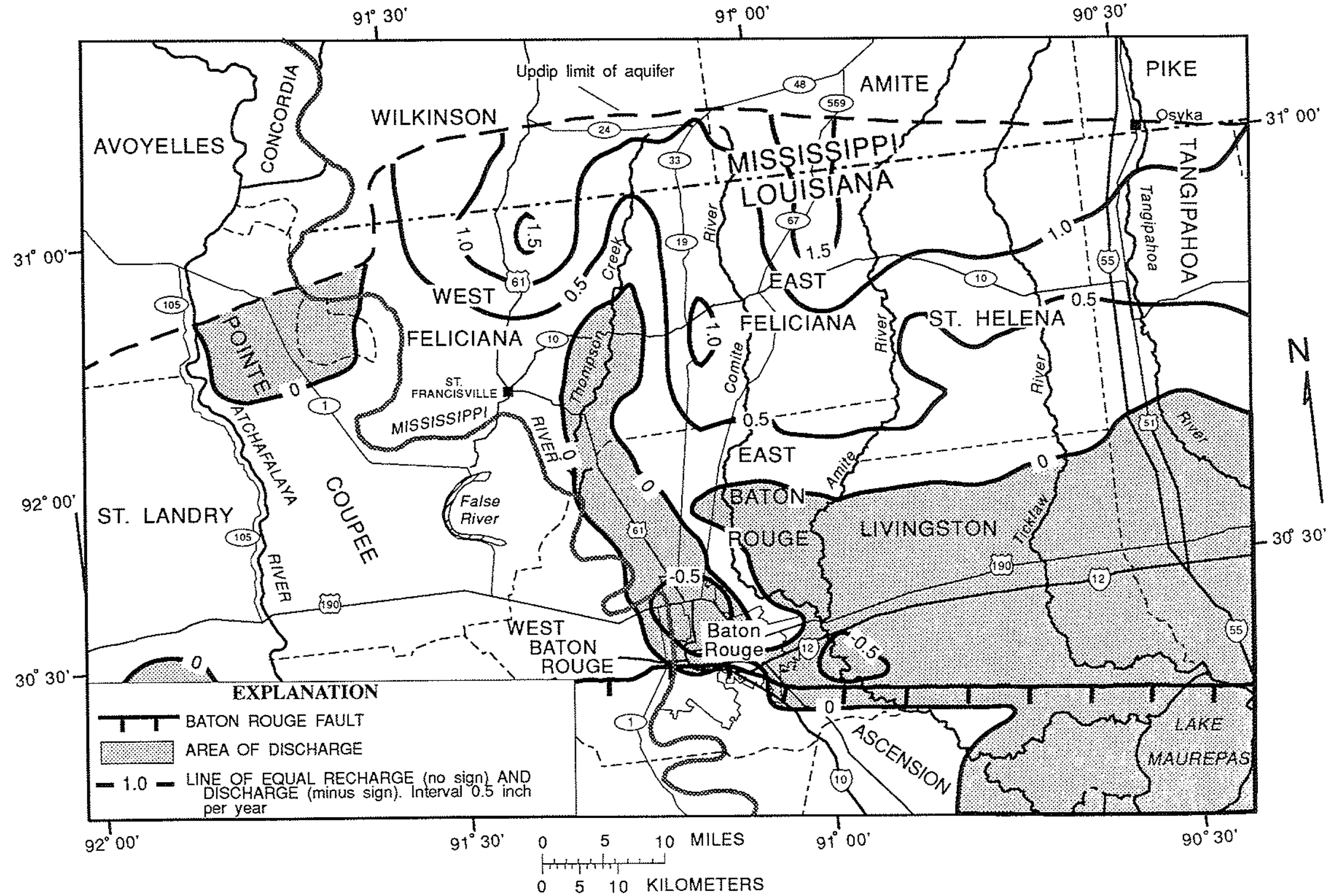


Figure 44. Recharge and discharge across the top of the "1,200-foot" aquifer at the end of simulation 3.

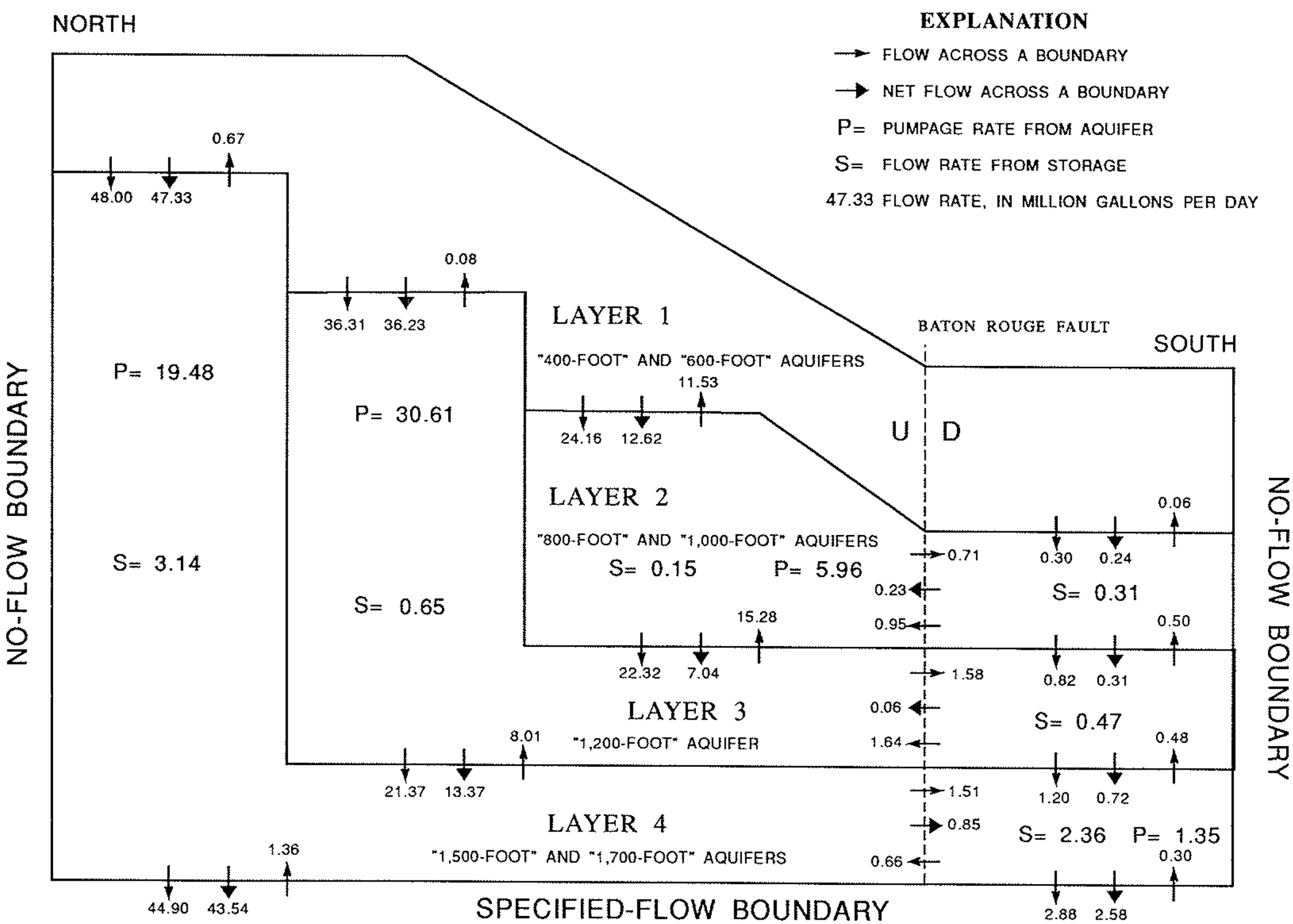


Figure 45. Volumetric budget for the "1,200-foot" aquifer and adjacent aquifers at the end of simulation 3.

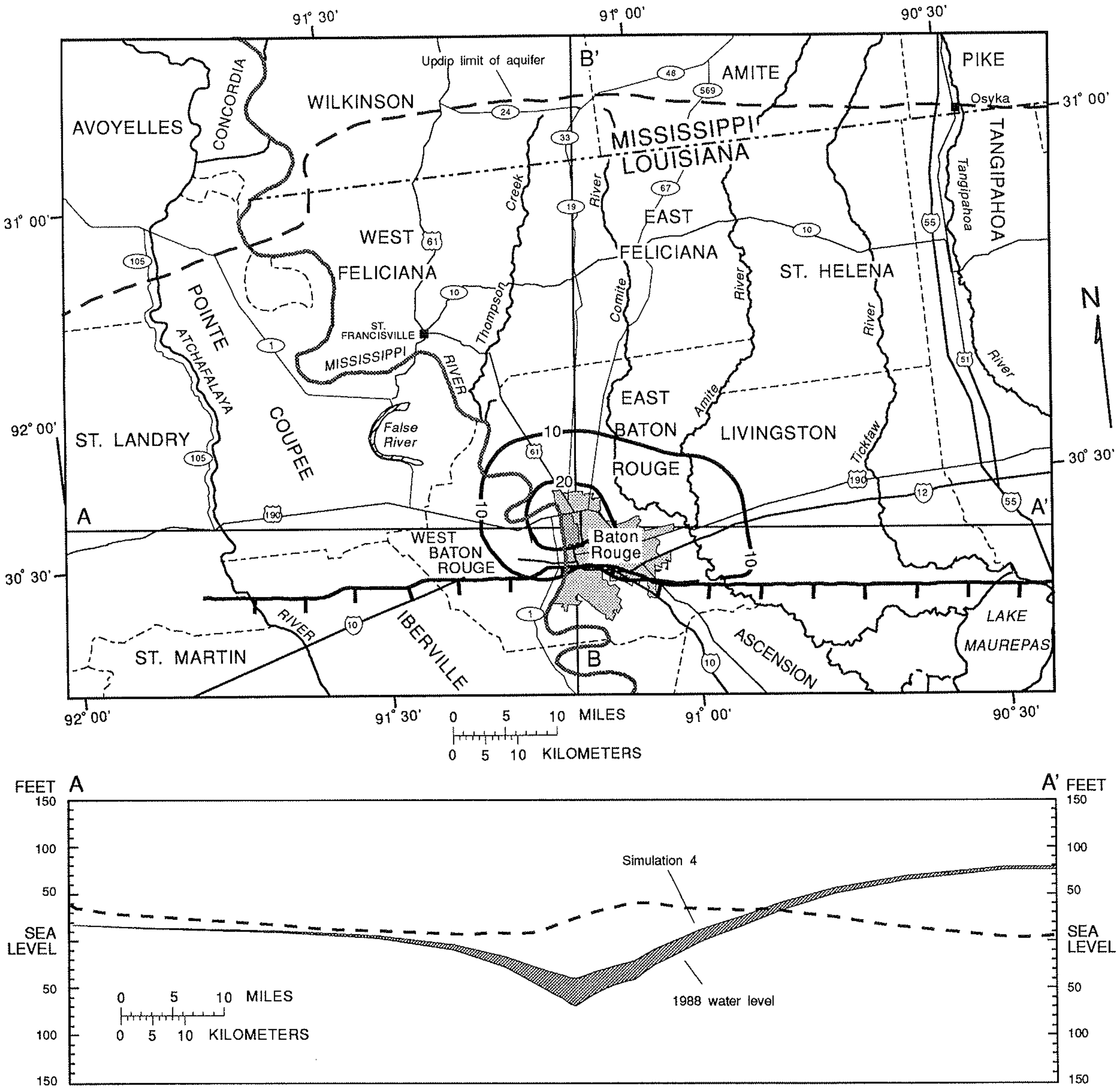
entered around the subcrop area under 1988 conditions, though 1988 pumpage conditions accounted for only 6 percent of the additional water demand in simulation 3. Forty-eight percent (about 6 Mgal/d) of the additional water demand was supplied by increased vertical leakage from adjacent aquifers. The remaining demand came from reduced leakage to adjacent aquifers (4 Mgal/d or 38 percent) and from storage (1 Mgal/d or 8 percent).

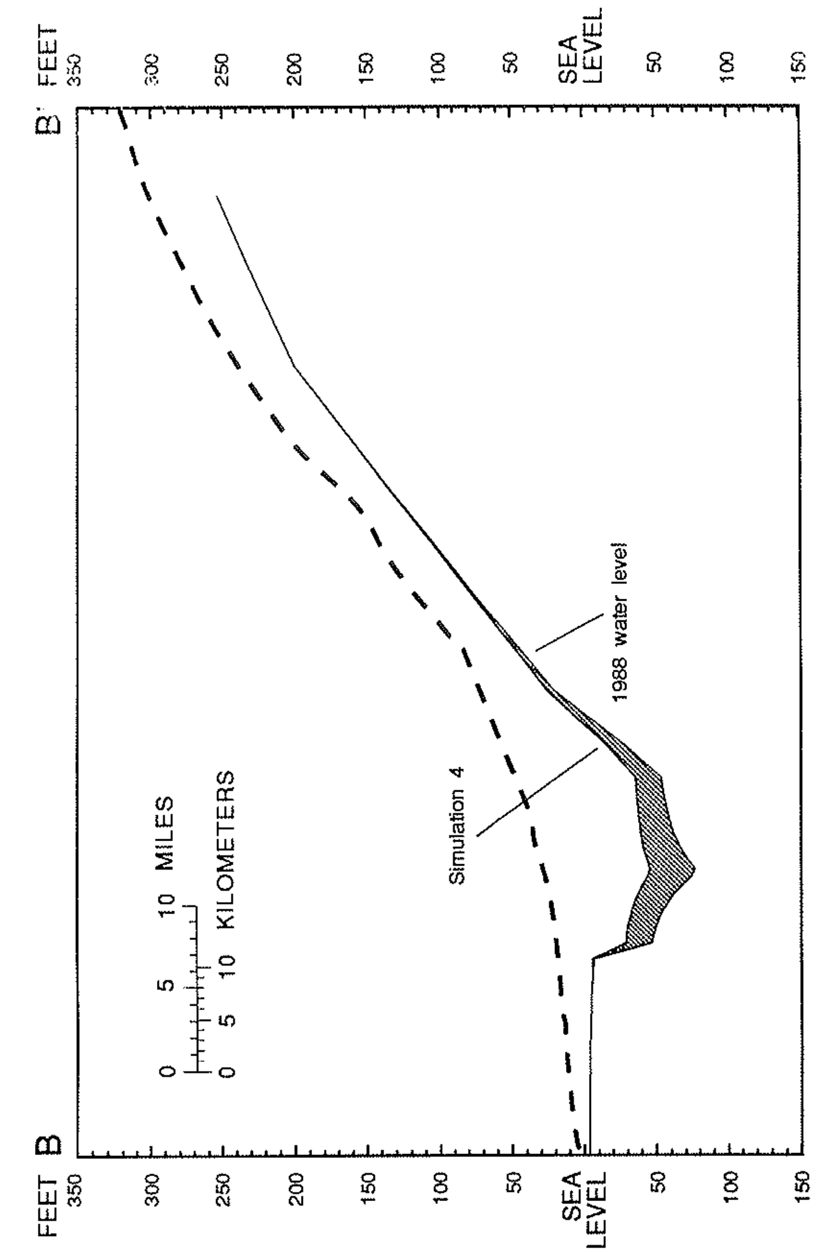
Simulation 4, a decrease in pumping of 1 percent per year over a 50-year period, caused a recovery of almost 30 ft (fig. 46) at the center of the Baton Rouge industrial district. Hydrographs for wells EB-146 (fig. 7) and EB-301 (fig. 8) showed water-level recoveries of 20 ft about 5 mi from the center of the Baton Rouge industrial district. The apparent lack of water-level changes south of the Baton Rouge fault at the end of simulation 4, as shown in the north-south water-level profile in figure 34, was due to the long delay between pumping changes and water-level responses in this area. Hydrographs for wells south of the Baton Rouge fault (fig. 6) in both the "1,200-foot" aquifer and the "1,500-foot" and "1,700-foot" aquifers showed a continuing water-level decline for 20 years after pumping had been reduced, before water levels increased.

The largest water-level declines from an increase in pumping of 1 percent per year over 50 years (simulation 5) were almost 30 ft (fig. 47), and the declines occurred in the center of the Baton Rouge industrial district. Hydrographs for wells EB-146 (fig. 7) and EB-301 (fig. 8) showed water-level declines of 20 ft about 5 mi from the center of the Baton Rouge industrial district. The exaggerated water-level changes south of the Baton Rouge fault (fig. 47) at the end of simulation 5, as opposed to the apparent lack of water-level changes in simulation 4 (fig. 46), were due to the long delay between pumping increases and water-level declines in this area. Hydrographs for water levels in wells south of the Baton Rouge fault (fig. 6) in both the "1,200-foot" aquifer and the "1,500-foot" and "1,700-foot" aquifers showed the effects of pumping changes prior to 1988 as late as 2010.

An increase in pumping of 1 percent per year over 50 years with the new pumping centers included, simulation 6, produced the largest and most rapid water-level changes from 1988 water levels in all hydrographs (figs. 6 to 9) throughout the modeled area. The largest water-level declines in simulation 6 were almost 120 ft (fig. 48), and the declines occurred at a new pumping center between Baton Rouge and Denham Springs, Louisiana. Hydrographs for wells EB-301 and Li-26B (fig. 8) completed in the "1,200-foot" aquifer showed water-level declines east and west, respectively, of the new pumping center. The exaggerated water-level changes south of the Baton Rouge fault (fig. 48) at the end of simulation 6, as opposed to the apparent lack of changes in simulation 4 (fig. 46), were due to the long delay between pumping increases and water-level declines in this area. Hydrographs for water levels in wells south of the Baton Rouge fault (fig. 6) in both the "1,200-foot" aquifer and the "1,500-foot" and "1,700-foot" aquifers showed the effects of pumping changes prior to 1988 as late as 2020.

All of the pumping simulations with new pumping centers near the southern East Baton Rouge-Livingston Parish boundary showed water-level declines near the new pumping centers of 50 to 60 ft per 10 Mgal/d of additional pumpage. Water-level hydrographs for wells north of the Baton Rouge fault responded rapidly to pumping changes whereas those south of the fault lagged 20 to 30 years behind in all pumping simulations.





EXPLANATION

BATON ROUGE FAULT

LAND SURFACE

DIFFERENCE BETWEEN 1988 AND SIMULATION 4 WATER LEVELS

LINE OF EQUAL WATER-LEVEL RECOVERY--Interval 10 feet

A——A' LINE OF WATER-LEVEL PROFILE

Figure 46. Recoveries from 1988 water levels to water levels calculated at the end of simulation 4 in the "1,200-foot" aquifer.

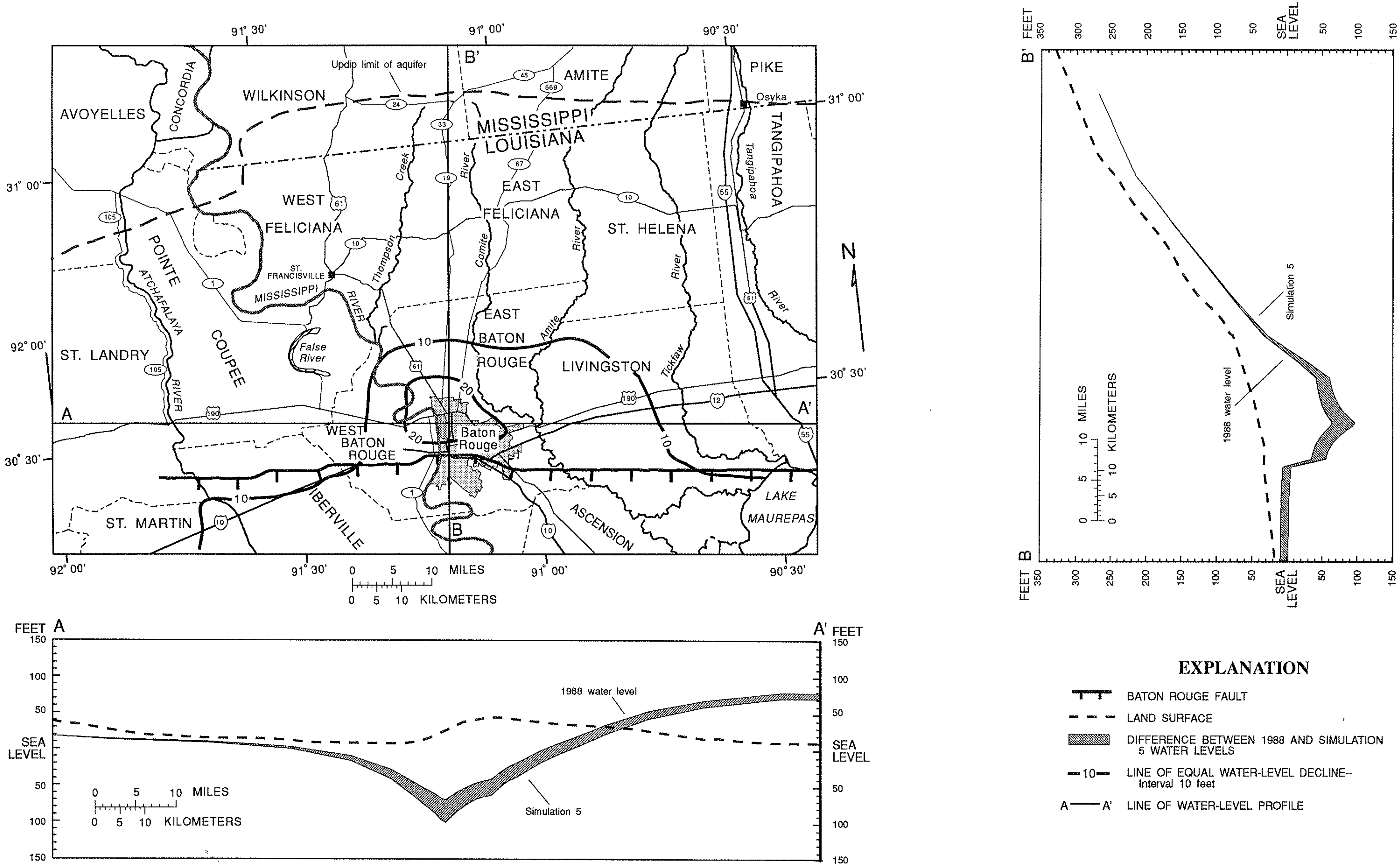


Figure 47. Drawdowns from 1988 water levels to water levels calculated at the end of simulation 5 in the "1,200-foot" aquifer.

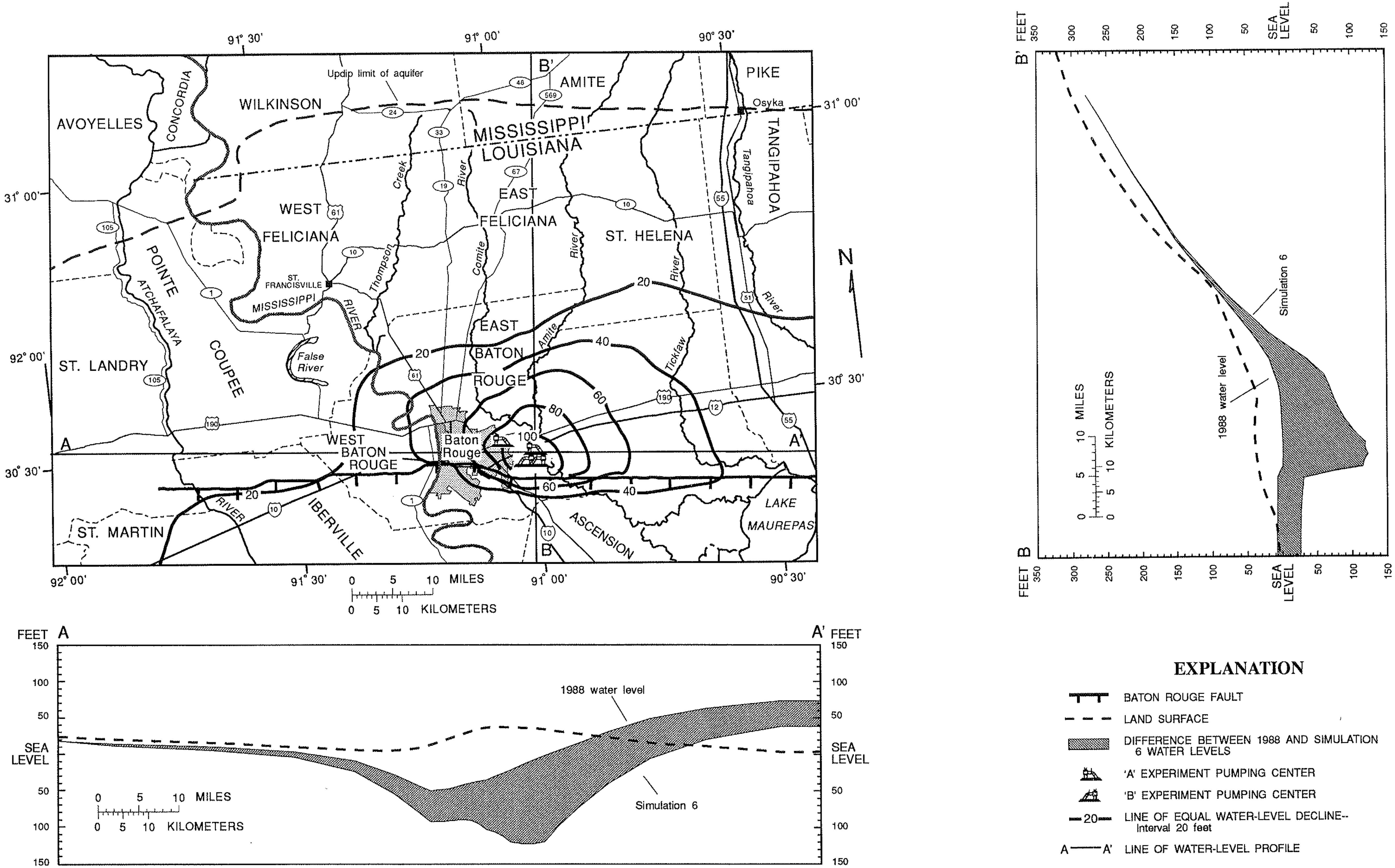


Figure 48. Drawdowns from 1988 water levels to water levels calculated at the end of simulation 6 in the "1,200-foot" aquifer.

SUMMARY

The "1,200-foot" aquifer is a major ground-water resource for industry and public supply throughout the Baton Rouge area in Louisiana. Industries were the first to extensively utilize the "1,200-foot" aquifer. Pumpage from the aquifer increased from 2.5 to 25 Mgal/d from 1953 to 1969 but decreased to 15 Mgal/d in 1987, even with increased pumping for public supply.

The hydrogeologic sequence in the study area is a complex series of alternating and lenticular beds of sand and layers of clay. The major clay units between aquifers range from less than 1 foot to several hundred feet in thickness, and some aquifers merge locally. Also, aquifers are hydraulically connected by leakage through the clay layers. The "1,200-foot" aquifer has a maximum thickness of 260 ft and a minimum of 40 ft. The aquifer primarily is composed of fine- to medium-grained sand. For the "1,200-foot" aquifer, transmissivity values range from 3,000 to 16,000 ft^2/d, and storage coefficient values range from 0.0001 to 0.0008. The Baton Rouge fault is an east-west trending normal fault that restricts flow through the "1,200-foot" aquifer due to the 300 ft or more of vertical displacement below a depth of 1,000 ft.

Most of the recharge for the "1,200-foot" aquifer occurs along the Mississippi-Louisiana State line. Water moves downgradient from the unconfined, surficial deposits of Pleistocene age in the Southern Hills outcrop toward Baton Rouge and toward an ancestral channel of the Mississippi River, which is beneath the present Atchafalaya River. Prior to extensive pumping in the Baton Rouge area, natural discharge from confined aquifers flowed upward from the deep aquifers to shallower ones.

Development of the "1,200-foot" and adjacent aquifers as major water supplies produced continuous water-level declines in those aquifers in the southern part of the study area from 1953 to 1980. However, pumping decreased in the "1,200-foot" aquifer from 1980 to 1988, and water levels recovered by as much as 15 ft in response to these changes.

A four-layer, finite-difference model was used to simulate flow in the "1,200-foot" aquifer and adjacent aquifers, and determine the effects of pumping changes. Kriging was used to fit irregularly spaced sand and clay thickness values and water-level measurements for input into the model. The calibration period was 1946-88. A statistical optimization program was used to calibrate the model by minimizing the differences between simulated and measured water levels. Simulated water levels compared favorably to water-level records, with most showing their best agreement from 1975 to 1985.

Flow patterns were altered from prepumping to 1988 conditions; in 1988 flow in the "1,200-foot" aquifer converged from all directions toward pumping centers in Baton Rouge. Pumping lowered water levels 40 ft, on average, downgradient from the subcrop, and a maximum of 120 ft in the Baton Rouge industrial district. Prolonged pumping changed the area west of the Mississippi River from a discharge area into a recharge area. Recharge to the aquifer throughout the area modeled increased by 0.5 in/yr due to pumping effects. Fifty-eight percent (36 Mgal/d) of the flow entered in the subcrop area under 1988 conditions. Most of the flow (62 Mgal/d) that left the "1,200-foot" aquifer in 1988 was by pumpage (19 Mgal/d or 30 percent) and leakage (26 Mgal/d or 43 percent) to deeper aquifers. Only 0.2 Mgal/d of the flow in the "1,200-foot" aquifer was from storage under 1988 conditions. The remaining flow was discharged as leakage (17 Mgal/d or 27 percent) to shallower aquifers.

The model was most sensitive to changes in transmissivity. The model was more sensitive to vertical leakance decreases than increases. Overall, the model was least sensitive to changes in storage coefficient values, but showed a greater sensitivity to increases in storage coefficient

values than to decreases. Areally, the model is more sensitive to transmissivity and vertical leakance changes north of the Baton Rouge fault, where the aquifer is stressed by pumping.

Six simulations were completed with the calibrated model to estimate the response of the "1,200-foot" aquifer to pumping changes. Three simulations simulated the effects for 1 year after adding between 6 and 12 Mgal/d of pumpage to the 1985 pumping rate (18.6 Mgal/d) near the East Baton Rouge-Livingston Parish boundary. Maximum drawdowns between 25 and 60 ft resulted from these pumping changes. The simulation that added 12 Mgal/d of pumpage resulted in increased vertical leakage from adjacent aquifers by 6 Mgal/d and reduced leakage to adjacent aquifers by 4 Mgal/d.

The other three simulations simulated the response of the "1,200- foot" aquifer to a 50-percent decrease in 1985 pumpage, a 50- percent increase in 1985 pumpage, and a 50-percent increase in 1985 pumpage plus 12 Mgal/d of pumpage over a 50-year period. Water levels recovered about 20 to 30 ft around the Baton Rouge industrial district from a 50-percent decrease in 1985 pumpage. Water levels declined about 20 to 30 ft around the Baton Rouge industrial district from a 50-percent increase in 1985 pumpage. The last simulation produced water-level declines of almost 120 ft at new pumping center locations.

All of the pumping simulations in the "1,200-foot" aquifer produced maximum drawdowns of 50 to 60 ft per 10 Mgal/d of additional pumpage in southeast Baton Rouge north of the Baton Rouge fault. Water levels north of the Baton Rouge fault responded rapidly, but water levels south of the fault lagged 20 to 30 years between pumping changes and water-level responses.

SELECTED REFERENCES

Bear, Jacob, 1979, Hydraulics of Groundwater: New York, McGraw-Hill, Inc., 567 p.

Buono, Anthony, 1983, The Southern Hills regional aquifer system of southeastern Louisiana and southwestern Mississippi: U.S. Geological Survey Water-Resources Investigations Report 83- 4189, 38 p.

Capital Area Ground Water Conservation Commission, 1988, Newsletter: Baton Rouge, La., vol. 14, no. 1, 9 p.

Cardwell, G.T., Forbes, M.J., Jr., and Gaydos, M.W., 1967, Water resources of the Lake Pontchartrain area, Louisiana: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources Bulletin no. 12, 105 p.

Davis, S.N., and De Wiest, R.J.M., 1966, Hydrogeology: New York, John Wiley and Sons, Inc., 463 p.

Dial, D.C., and Kilburn, Chabot, 1980, Ground-water resources of the Gramercy area, Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report no. 24, 39 p.

Durbin, T.J., 1983, Application of Gauss algorithm and Monte Carlo simulation to the identification of aquifer parameters: U.S. Geological Survey Open-File Report 81-0688, 28 p.

Huntzinger, T.L., Whiteman, C.D., Jr., and Knochenmus, D.D., 1985 [1986], Simulation of ground-water movement in the "1,500- and 1,700-foot" aquifers of the Baton Rouge area, Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report no. 34, 52 p.

Jones, P.H., Turcan, A.N., Jr., and Skibitzke, H.E., 1954, Geology and ground-water resources of southwestern Louisiana: Louisiana Department of Conservation Geological Bulletin 30, 285 p.

Kuniansky, E.L., 1989, Geohydrology and simulation of ground-water flow in the "400-foot," "600-foot," and adjacent aquifers, Baton Rouge area, Louisiana: Louisiana Department of Transportation and Development, Water Resources Technical Report no. 49, 90 p.

Kuniansky, E.L., Dial, D.C., and Trudeau, D.A., 1989, Maps of the "400-foot," "600-foot," and adjacent aquifers and confining beds, Baton Rouge area, Louisiana: Louisiana Department of Transportation and Development, Water Resources Technical Report no. 48, 16 p.

Long, R.A., 1965, Feasibility of a scavenger-well system as a solution to the problem of vertical saltwater encroachment: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources Pamphlet no. 15, 27 p.

Lurry, D.L., 1987, Pumpage of water in Louisiana, 1985: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Special Report no. 4, 14 p.

Martin, Angel, Jr., and Whiteman, C.D., Jr., 1985, Map showing generalized potentiometric surface of the Evangeline and equivalent aquifers in Louisiana, 1980: U.S. Geological Survey Water-Resources Investigations Report 84-4359, map (1 sheet).

----- 1989, Geohydrology and regional ground-water flow of the coastal lowlands aquifer system in parts of Louisiana, Mississippi, Alabama, and Florida--A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 88-4100, 88 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 576 p.

Meyer, R.R., and Turcan, A.N., Jr., 1955, Geology and ground-water resources of the Baton Rouge area, Louisiana: U.S. Geological Survey Water-Supply Paper 1296, 138 p.

Morgan, C.O., 1961, Ground-water conditions in the Baton Rouge area, 1954-59, with special reference to increased pumpage: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources Bulletin no. 2, 78 p.

----- 1963, Ground-water resources of East Feliciana and West Feliciana Parishes, Louisiana: Louisiana Department of Public Works, 58 p.

Morgan, C.O., and Winner, M.D., Jr., 1964, Saltwater encroachment in aquifers of the Baton Rouge area--Preliminary report and proposal: Louisiana Department of Public Works, 37 p.

National Oceanic and Atmospheric Administration, 1982, Climatological data, annual summary, Louisiana 1982: U.S. Department of Commerce, NOAA, v. 87, no. 13, 25 p.

Nyman, D.J., and Fayard, L.D., 1978, Ground-water resources of Tangipahoa and St. Tammany Parishes, southeastern Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report no. 15, 76 p.

Rollo, J.R., 1969, Saltwater encroachment in aquifers of the Baton Rouge area, Louisiana: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources Bulletin no. 13, 45 p.

Skrivan, J.A., and Karlinger, M.R., 1980, Computer program documentation users manual, semi-variogram estimation and universal kriging program: U.S. Geological Survey, Water Resources Division, 98 p.

Smith, C.G., 1979, A geohydrologic survey of the "1,200-foot" aquifer in the Capital Area Ground Water Conservation District: Capital Area Ground Water Conservation Commission Bulletin 3, 19 p.

Tomaszewski, D.J., 1988, Ground-water hydrology of Livingston, St. Helena, and parts of Ascension and Tangipahoa Parishes, southeastern Louisiana: Louisiana Department of Transportation and Development Water Resources Technical Report no. 43, 54 p.

Torak, L.J., and Whiteman, C.D., Jr., 1982, Applications of digital modeling for evaluating the ground-water resources of the "2,000-foot" sand of the Baton Rouge area, Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report no. 27, 87 p.

Whiteman, C.D., Jr., 1979, Saltwater encroachment in the "600-foot" and "1,500-foot" sands of the Baton Rouge area, Louisiana, 1966-78, including a discussion of saltwater in other sands: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report no. 19, 49 p.

----- 1980, Measuring local subsidence with extensometers in the Baton Rouge area, Louisiana, 1975-79: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report no. 20, 18 p.

Winner, M.D., Jr., 1963, The Florida Parishes--an area of large, undeveloped ground-water potential in southeastern Louisiana: Louisiana Department of Public Works, 50 p.

Winner, M.D., Jr., Forbes, M.J., Jr., and Broussard, W.L., 1968, Water resources of Pointe Coupee Parish, Louisiana: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources Bulletin no. 11, 110 p.