Analysis of Ground-Water Flow in the Catahoula Aquifer System in the Vicinity of Laurel and Hattiesburg, Mississippi

By Keith J. Halford and Nancy L. Barber

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Abstract

The upper, middle, and lower Catahoula aquifers in the vicinity of the cities of Laurel and Hattiesburg in southern Mississippi are made up of irregular, discontinuous sand zones in the Catahoula Formation of Miocene age. Withdrawal from the Catahoula aquifer system increased from 28 to 41 million gallons per day from 1970 to 1985, and decreased to 38 million gallons per day during 1990. Most withdrawal in the Laurel area is from the lower and middle Catahoula, and most withdrawal in the Hattiesburg area is from the middle and upper Catahoula aquifers. In the Laurel area, water levels in the lower Catahoula aquifer declined at rates ranging from about 1 to 3.6 feet per year from 1964 until the late 1980's in response to the increase in pumping.

A three-dimensional model was developed to represent ground-water flow in the Catahoula aquifer system. Simulated water levels in the lower Catahoula aquifer, the layer most affected by pumping, were lowered from predevelopment levels as much as 130 feet in the Laurel area and 100 feet in the Hattiesburg area, according to the model analysis of 1992 conditions. Three scenarios of increased pumpage for the period 1992-2020 were simulated. Under the low-growth scenario, water-level declines would be 20 feet or less below 1992 water levels in the middle and upper Catahoula aquifer in the Hattiesburg area, and about 60 feet in the lower Catahoula aquifer in the Laurel area. Under the moderate-growth scenario, water-level declines would be 40 feet or less below 1992 water levels in the middle Catahoula aquifer in the Hattiesburg area. Water-level decline would be about 110 feet in the lower Catahoula aquifer in the Laurel area, and water levels would be near the top of the aquifer. Under the high-growth scenario, water-level decline would be 40 feet or less in the upper Catahoula aquifer and about 80 feet in the middle Catahoula, with the largest decline occurring in the Hattiesburg area. Water levels would decline about 130 feet and would be drawn down below the top of the lower Catahoula aquifer in the Laurel area under the high-growth scenario.

INTRODUCTION

The Catahoula aquifer system, the lowermost aquifers of the Miocene-age series in Mississippi, is a major source of water for industry and public supply throughout the Laurel and Hattiesburg areas in southern Mississippi. In the Laurel area, most public and industrial water supplies are obtained from the lower and middle Catahoula aquifers. Supplies for the city of Laurel are obtained from the lower Catahoula exclusively. In the Hattiesburg area, most pumpage is from the middle and upper Catahoula aquifers, although the lower Catahoula also is used. Withdrawal from the aquifers in the Laurel and Hattiesburg areas increased from about 17 Mgal/d during 1960 to 41 Mgal/d during 1985, and decreased to 38 Mgal/d during 1990. Water levels near pumping centers in Laurel and Hattiesburg declined at rates ranging from about 1 to 3.6 ft/yr between 1955 and 1985. However, the rates of decline have decreased from 1985 to 1993, and in some areas, primarily in Laurel, water levels have recovered in response to decreases in ground-water pumpage and to changes in the pumping distribution. If ground-water use increases in response to population growth or industrial development, water levels may decline below the contemporary (1992) or historical low levels. The ability to estimate the potential of the Catahoula aquifer system would facilitate the management and plans for additional development of ground-water resources in the Laurel and Hattiesburg areas.

A study of the Catahoula aquifer system in the Laurel and Hattiesburg areas was performed as part of a larger study by the U.S. Geological Survey designed to improve understanding of ground-water flow for the Miocene-age aquifers in selected areas of southern Mississippi. This report was prepared in cooperation with the Pat Harrison Waterway District and with the Mississippi Department of Environmental Quality, Office of Land and Water Resources (OLWR).

Purpose and Scope

This report describes the ground-water flow system in the Catahoula aquifer system near two areas of ground-water development: the cities of Laurel, in Jones County, and Hattiesburg, in Forrest County. The report is based on a study that included the collection of water-level and water-use data, and the analysis of electric-resistivity well logs to help define the hydrogeologic framework.

Although the cities of Laurel and Hattiesburg and adjacent areas are of specific interest to this study, ground-water flow model investigations encompassed a much larger area that covered much of southeastern Mississippi and parts of Louisiana and Alabama (fig. 1). The model was used to estimate the changes in water levels in the upper, middle, and lower Catahoula aquifers under three scenarios of simulated pumpage.

Physiography and Climate

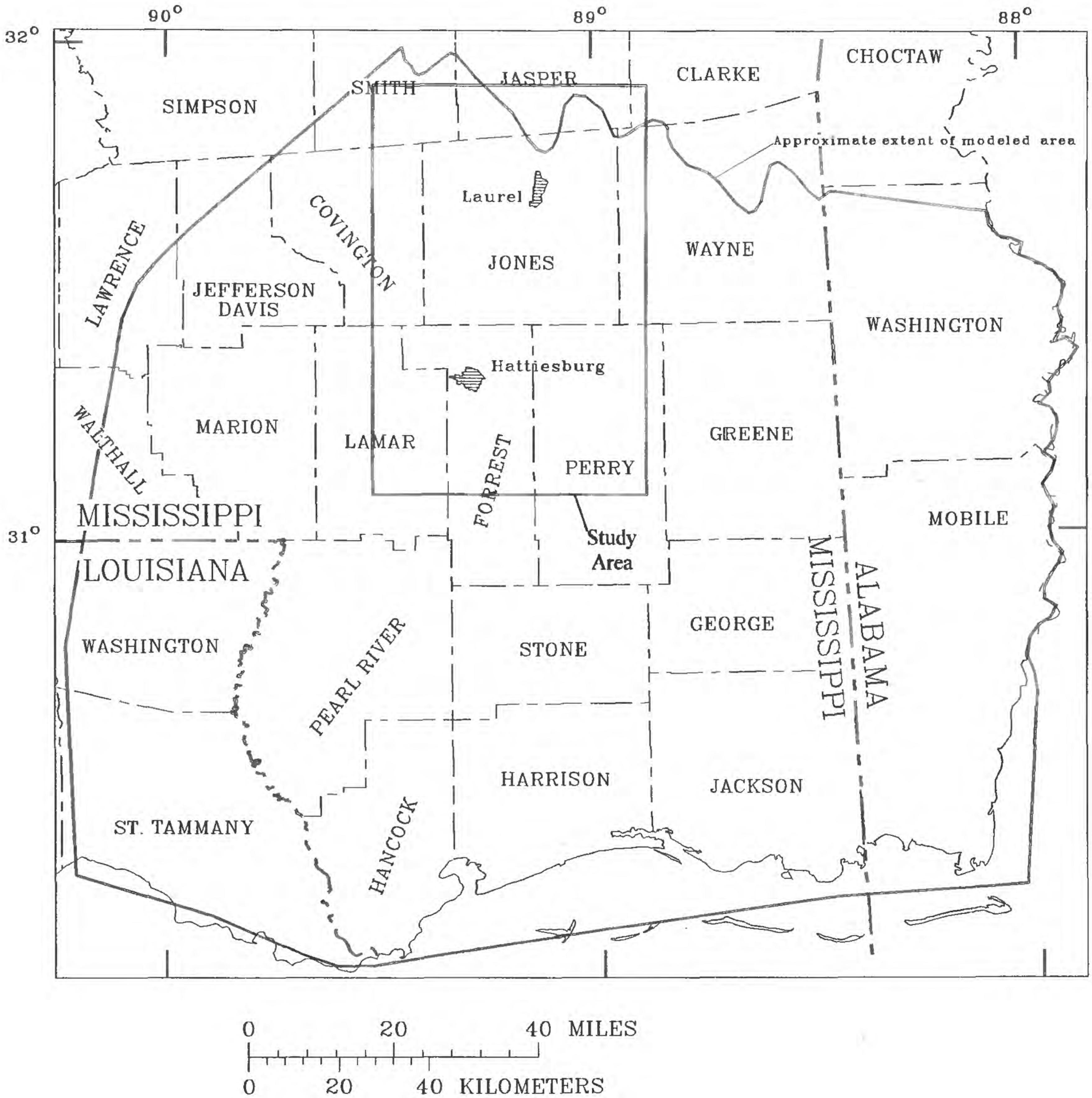
Most of the area included in the ground-water flow model is located in the Long-Leaf Pine Hills physiographic district (Stephenson and others, 1928), an area of rolling to moderately rugged hills ranging from 100 to 500 ft above sea level. The southern part of the area is located in the Coastal Pine Meadows, a narrow physiographic district near the gulf coast that is relatively flat and contains extensive areas of swamp and marsh.

Southern Mississippi is characterized by a humid, subtropical climate. Average precipitation over the study area ranges from 54 to 60 in/yr (National Oceanic and Atmospheric Administration, 1985). Rainfall is distributed evenly throughout the year except during drier summer months. The average yearly temperature is 68 °F. Summer temperatures range from 65 to 98 °F, and winter temperatures range from 20 to 65 °F.

The major population centers in the study area are Hattiesburg, with a 1990 population of 41,882, and Laurel, with a 1990 population of 19,730 (U.S. Bureau of the Census, 1991). Larger cities are located on the gulf coast, but these are not within the area of development of the Catahoula aquifer system because of the availability of shallower aquifers in the coastal area.

Previous Investigations

The water-yielding properties of the Catahoula Formation in Mississippi were first



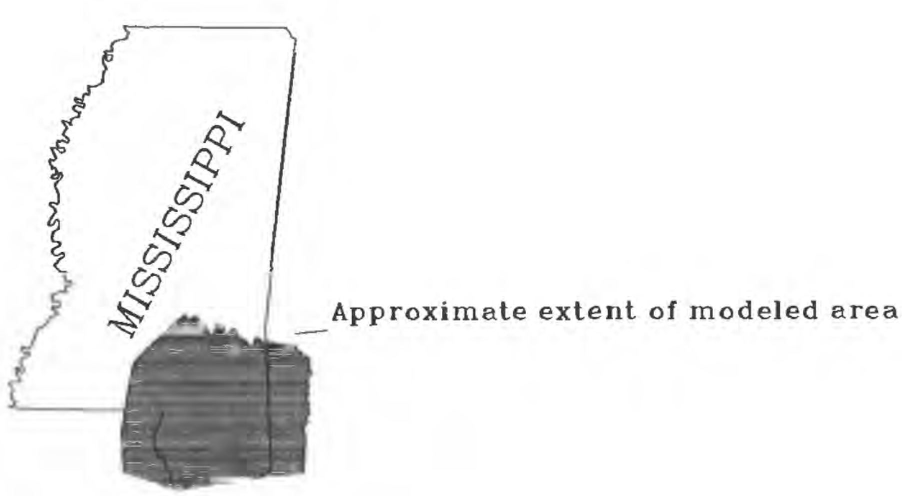


Figure 1. Location of study area.

described by Stephenson and others (1928). Shows and others (1966), Boswell and others (1970), and Brahana and Dalsin (1977) discussed the water sources, quantity, and quality for groups of counties in the study area in a series of reports that describe water availability for industrial development. The ground-water resources of Jones County are described by Boswell and others (1987). Withdrawal data for public and industrial water supplies in southern Mississippi were compiled for 1970 (Callahan, 1971) and for 1974 (Callahan, 1975). Newcome (1975) first discussed the hydrogeology of the Miocene aquifer system (which encompasses the Catahoula aquifer system) and Sumner and others (1989) investigated and simulated ground-water flow in the Miocene aquifer system in the coastal region of Mississippi. Martin and Whiteman (1989) performed a regional analysis of the coastal lowland ground-water flow system, including the Miocene aquifer system.

GEOHYDROLOGY OF THE CATAHOULA AQUIFER SYSTEM NEAR LAUREL AND HATTIESBURG

This section of the report describes the geohydrology of the Catahoula aquifer system near Laurel and Hattiesburg, Mississippi. The section includes descriptions of the geology, hydrogeology, water use, and the effects of pumping.

Geology

Geologic units at land surface in the study area are sediments of Miocene age consisting of a complex series of alternating and lenticular beds of sand and clay, and other sediments of Pliocene and younger age. The beds of Miocene age dip to the southwest 30 to 100 ft/mi, and the steepest dips are nearest the coast (Newcome, 1975). The gentle dip of the Miocene beds is modified in some places by salt domes which have uplifted the younger sediments. However, none of the salt domes in the study area penetrate the Miocene sediments, and their effect is limited to displacing other Miocene units to shallower depths near the domes (Spiers and Gandl, 1980).

Rocks of the Catahoula Formation of Miocene age crop out along the northeastern boundary of the modeled area (fig. 2) and are the oldest surface or near-surface rocks in the study area (table 1). The Catahoula Formation consists of beds of medium to coarse sand containing many small to large clay lenses (Stephenson and others, 1928, p. 55). The formation thickness ranges from 100 ft or less in areas of outcrop to more than 500 ft downdip. Miocene-age rocks of the Hattiesburg and Pascagoula Formations overlie the Catahoula and are also composed of interbedded, lenticular sands and clays. The Hattiesburg and Pascagoula Formations contain a higher percentage of clay than the Catahoula Formation, but the three formations are so similar that they cannot be separated in the subsurface based on lithologic or geophysical characteristics (Newcome, 1975). Identification of these formations in the subsurface usually is inferred from their relative position in the stratigraphic sequence.

In much of the modeled area, the Miocene sediments are unconformably overlain by the Citronelle Formation, a discontinuous deposit of sand, clay, and gravel of Pliocene and Pleistocene age, or by terrace or alluvial deposits of Holocene age. These overlying deposits are thicker and more continuous near the coast, but generally are less than 100 ft thick throughout the area (Gandl, 1982). The Miocene sediments are underlain by several hundred feet of clay and limestone of Oligocene age: the Paynes Hammock Formation, the Chickasawhay Limestone, and the Vicksburg Group (Sumner and others, 1989, p. 3).

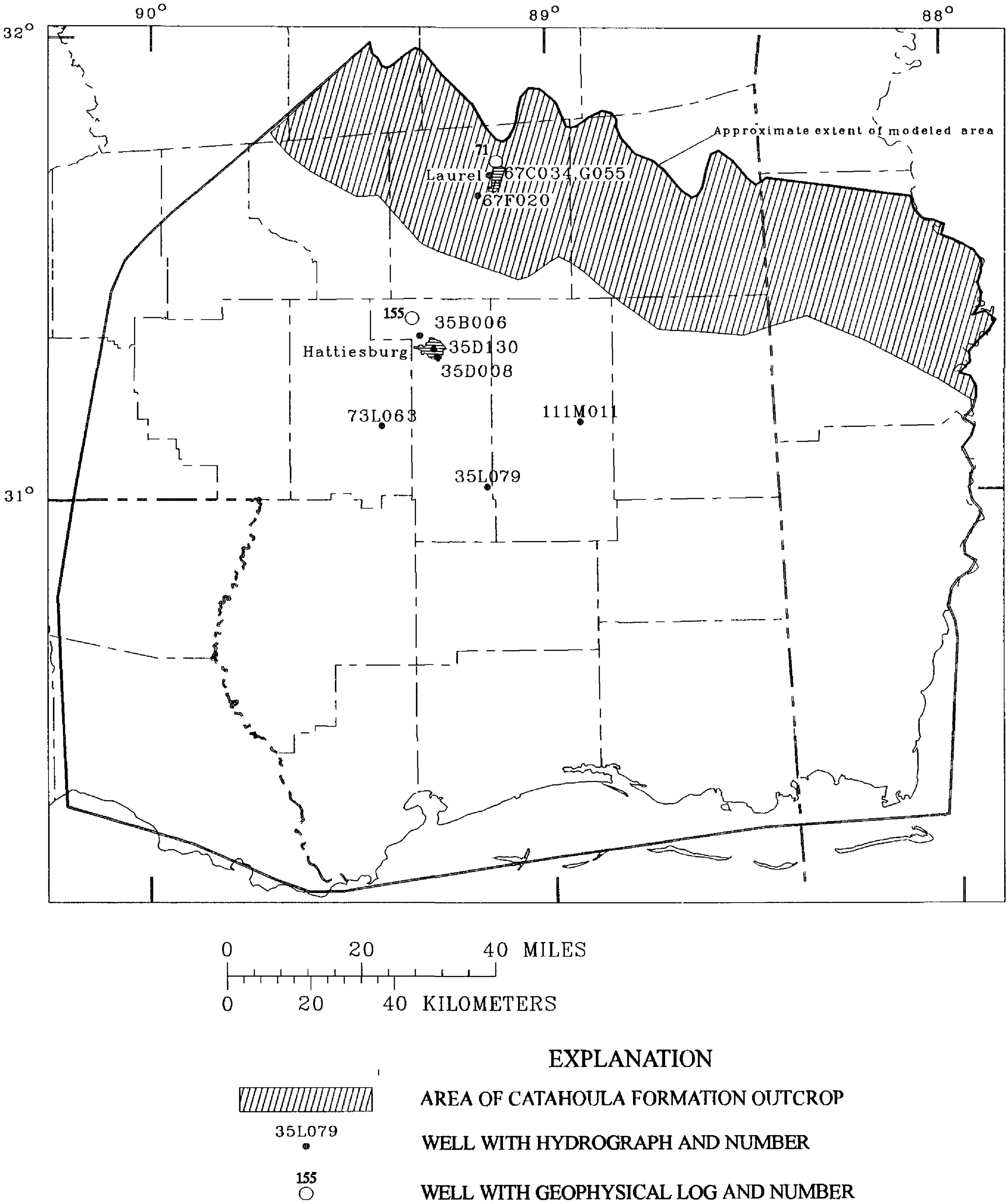


Figure 2. Outcrop of the Catahoula Formation in the modeled area and the location of selected wells.

Table 1. Geologic units underlying southeastern Mississippi (Modified from Dockery, 1981)

System	Series	Group	Geologic unit
Quaternary	Holocene		Undifferentiated alluvium and terrace deposits
	Pleistocene		Citronelle Formation
Tertiary	Pliocene		Graham Ferry Formation
	Miocene		Pascagoula Formation Hattiesburg Formation Catahoula Formation
	Oligocene		Paynes Hammock Formation Chickasawhay Limestone
		Vicksburg	Bucatunna Formation Byram Formation Glendon Limestone Marianna Limestone Mint Spring Formation
	Eocene	Claiborne	Cockfield Formation

Hydrogeology

The principal sources of ground water in the Laurel and Hattiesburg areas are sands within the Catahoula Formation which compose the Catahoula aquifer system. Generally the Catahoula Formation contains a thick water-bearing sand near the base of the formation and two other sands higher in the sequence; however the sands generally cannot be correlated regionally. Between and within the sands are units of clay that vary in thickness and areal extent. Following Boswell and others (1987, p. 18), the sands in this report are referred to as the lower, middle, and upper Catahoula aquifers. The base of the lower Catahoula aquifer system in the study area was identified using borehole geophysical logs and the Glendon Formation, a highly resistive limestone unit within the Vicksburg Group, as the primary marker bed. Typical electric-resistivity log patterns for the Catahoula Formation in the Laurel and Hattiesburg areas (fig. 3) illustrate the alternating sand and clay zones.

The configuration of the base of the lower Catahoula aquifer is irregular (fig. 4) but generally dips to the south and west; the dip of the middle and upper Catahoula aquifers is similar. Generalized hydrogeologic sections through the modeled area (fig. 5) illustrate the irregular thickness and dip of the Catahoula aquifer system and the intervening confining units. Within the Jones-Forrest County area, the three aquifers can be correlated in an area approximately 10 to 15 mi east-west and 30 to 40 mi north-south. Outside of this area, the correlation of aquifers and confining units between borehole locations is less certain.

The sand thicknesses of the upper, middle, and lower Catahoula aquifers and related confining units also were measured using borehole geophysical logs (figs. 6-8). The aquifers are irregular in thickness, are discontinuous in

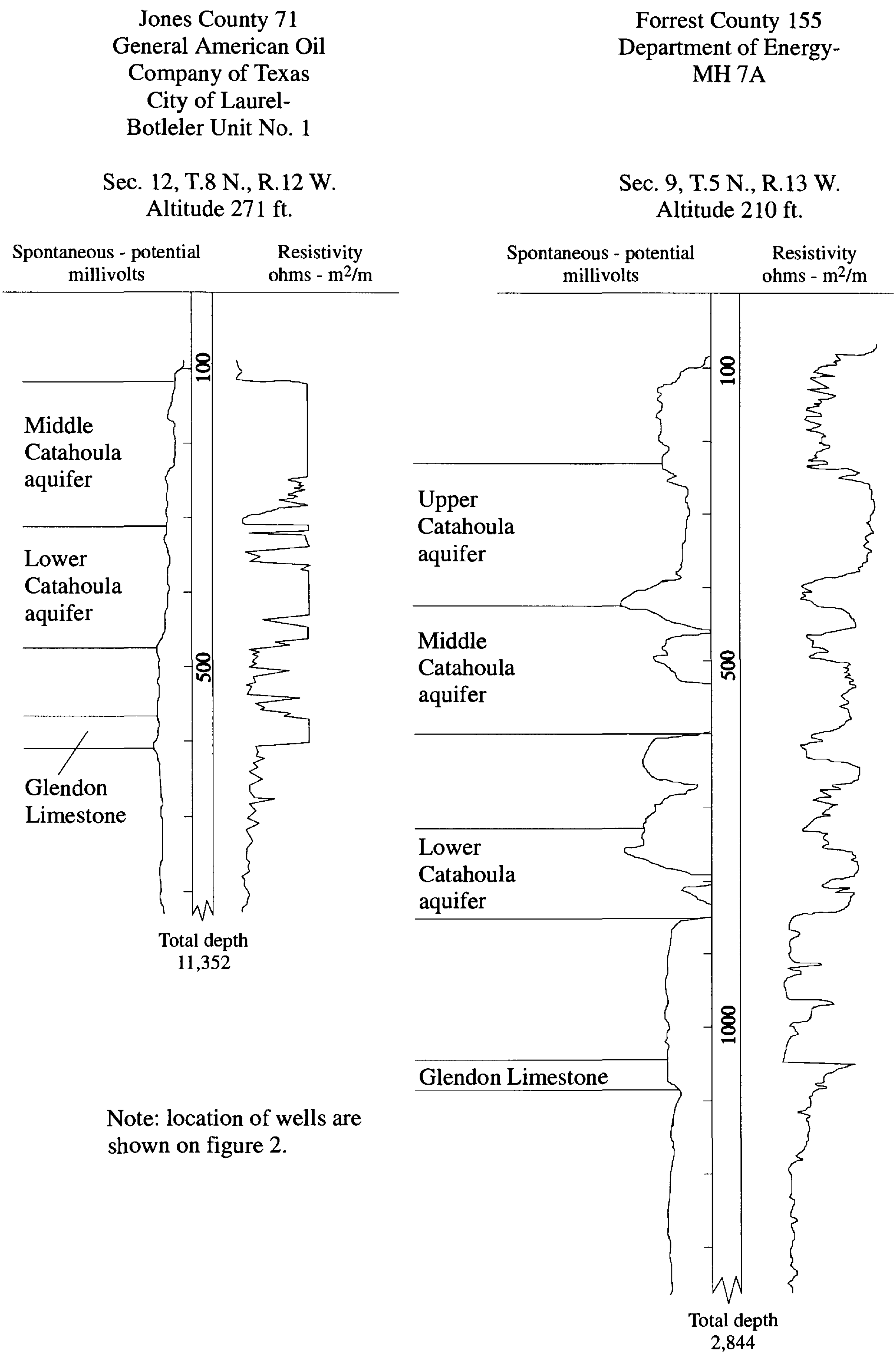
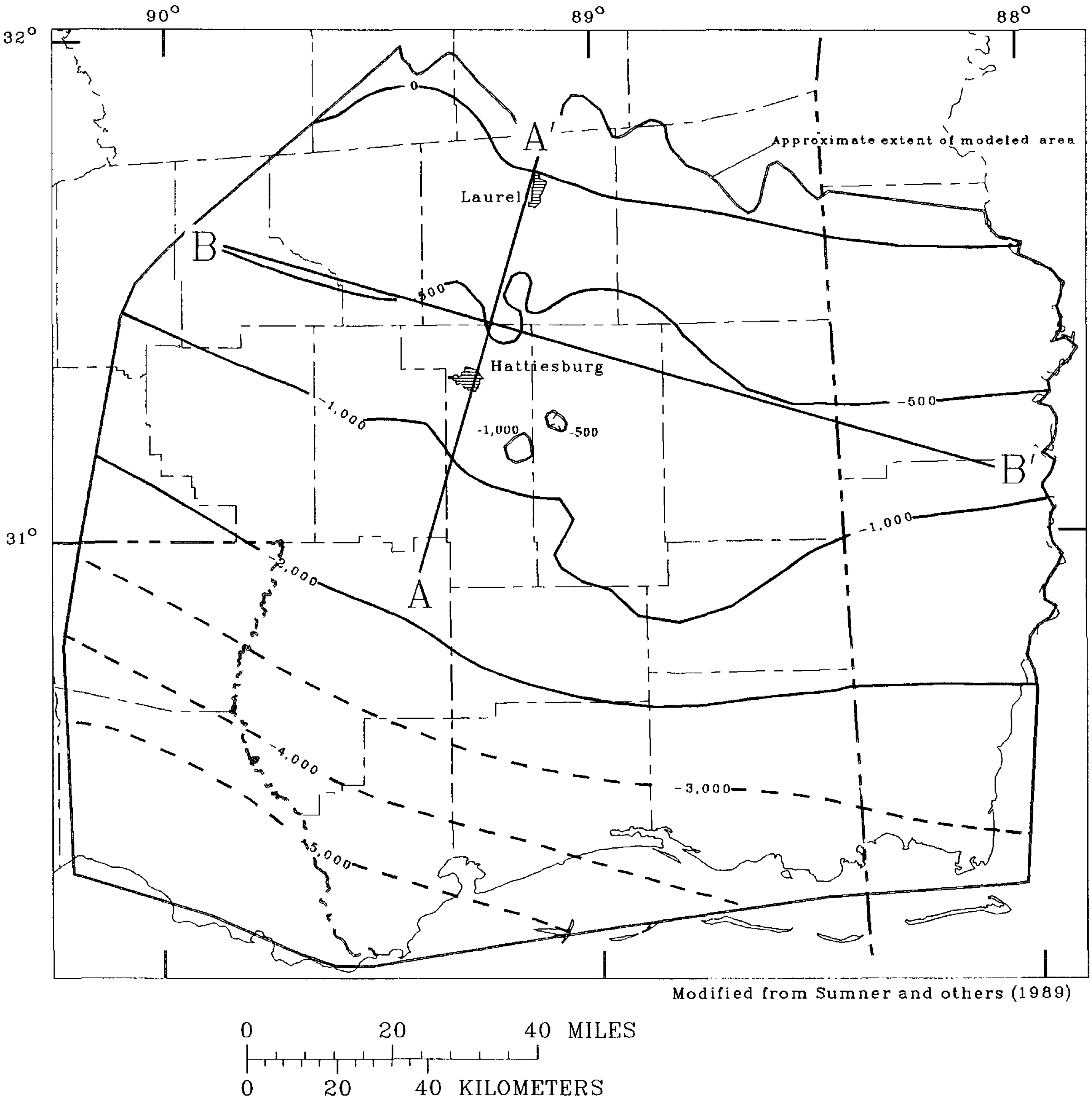


Figure 3. Geophysical logs and aquifers in the Laurel and Hattiesburg, Mississippi areas.



EXPLANATION

—-2,000— SUBSURFACE CONTOUR--Shows altitude of base of lower Catahoula aquifer. Dashed where approximately located. Contour interval variable, in feet. Datum is sea level

A ——— A′ TRACE OF CROSS SECTION (See fig. 5)

Figure 4. Altitude of base of the lower Catahoula aquifer in the modeled area.

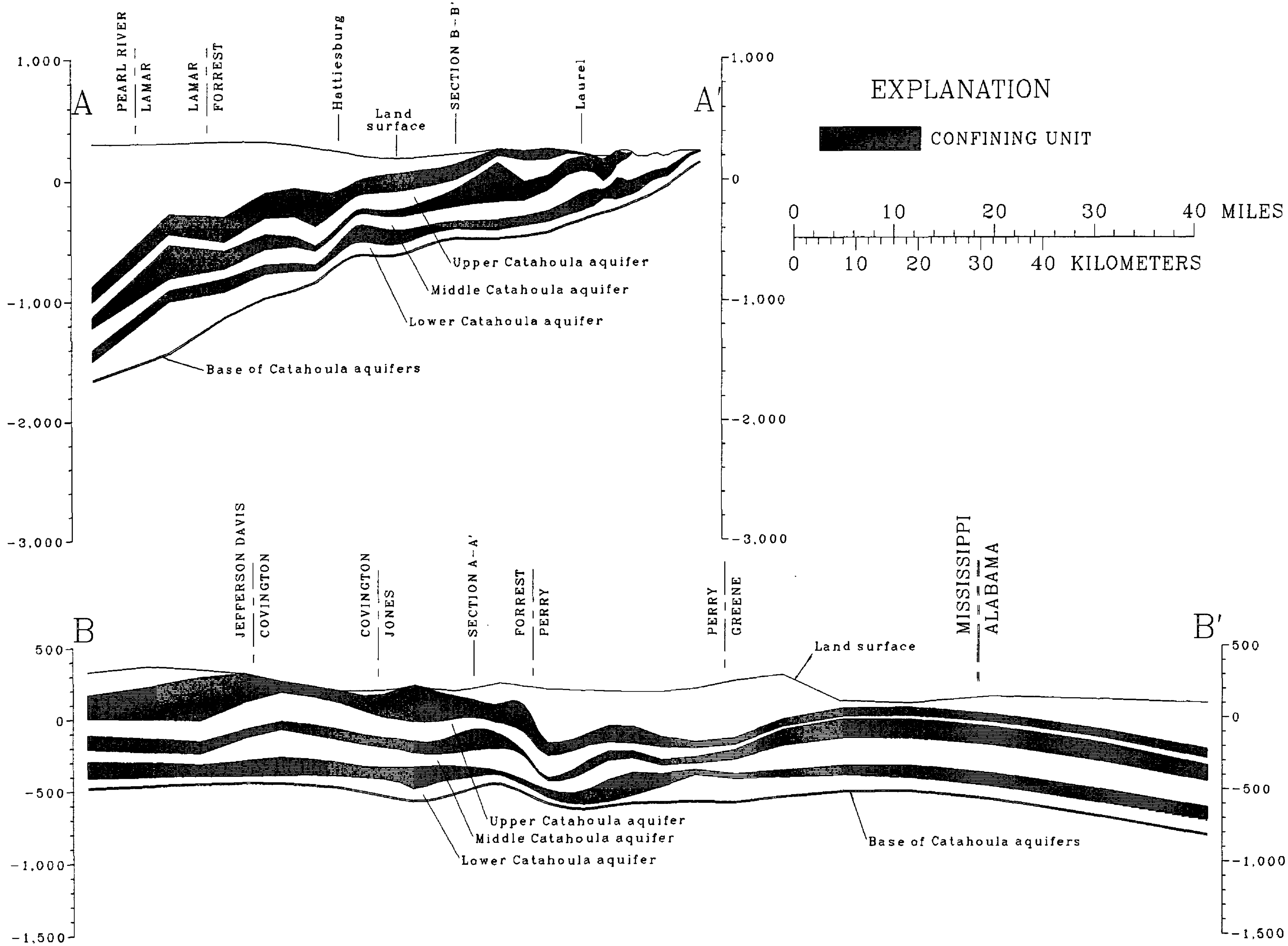


Figure 5. Diagrammatic sections A - A' and B - B' in the modeled area.

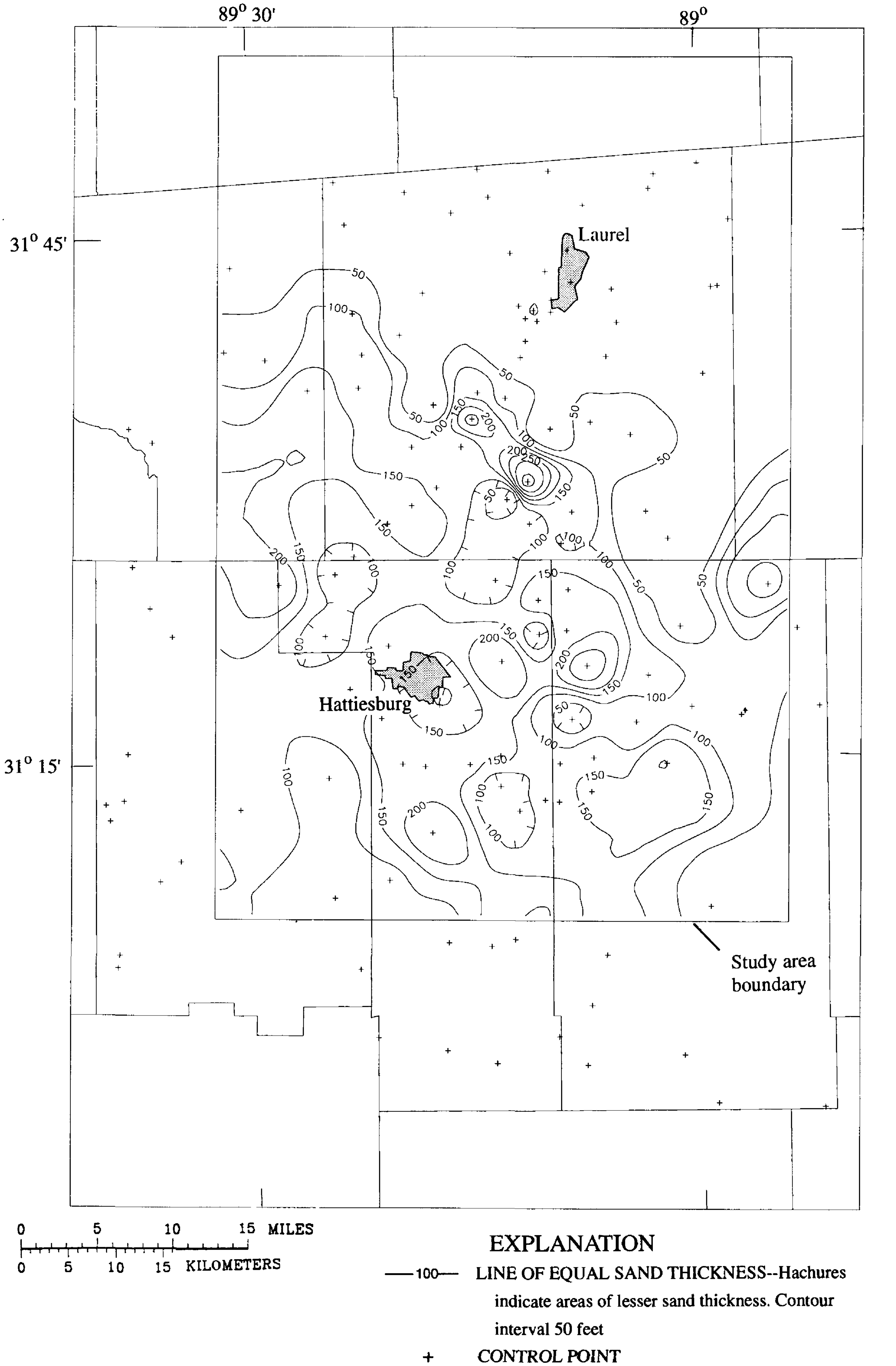
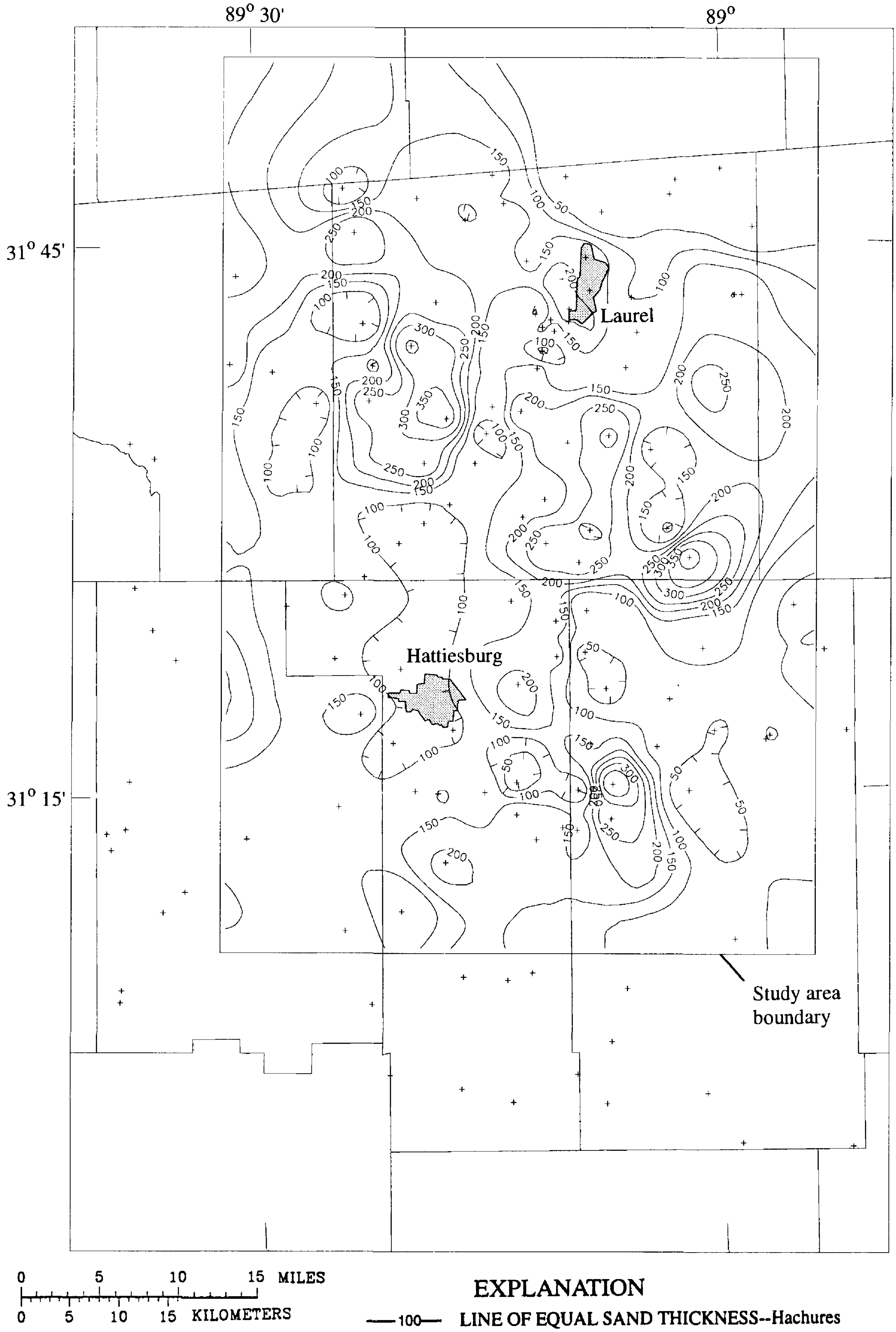


Figure 6. Sand thickness of the upper Catahoula aquifer in the study area.

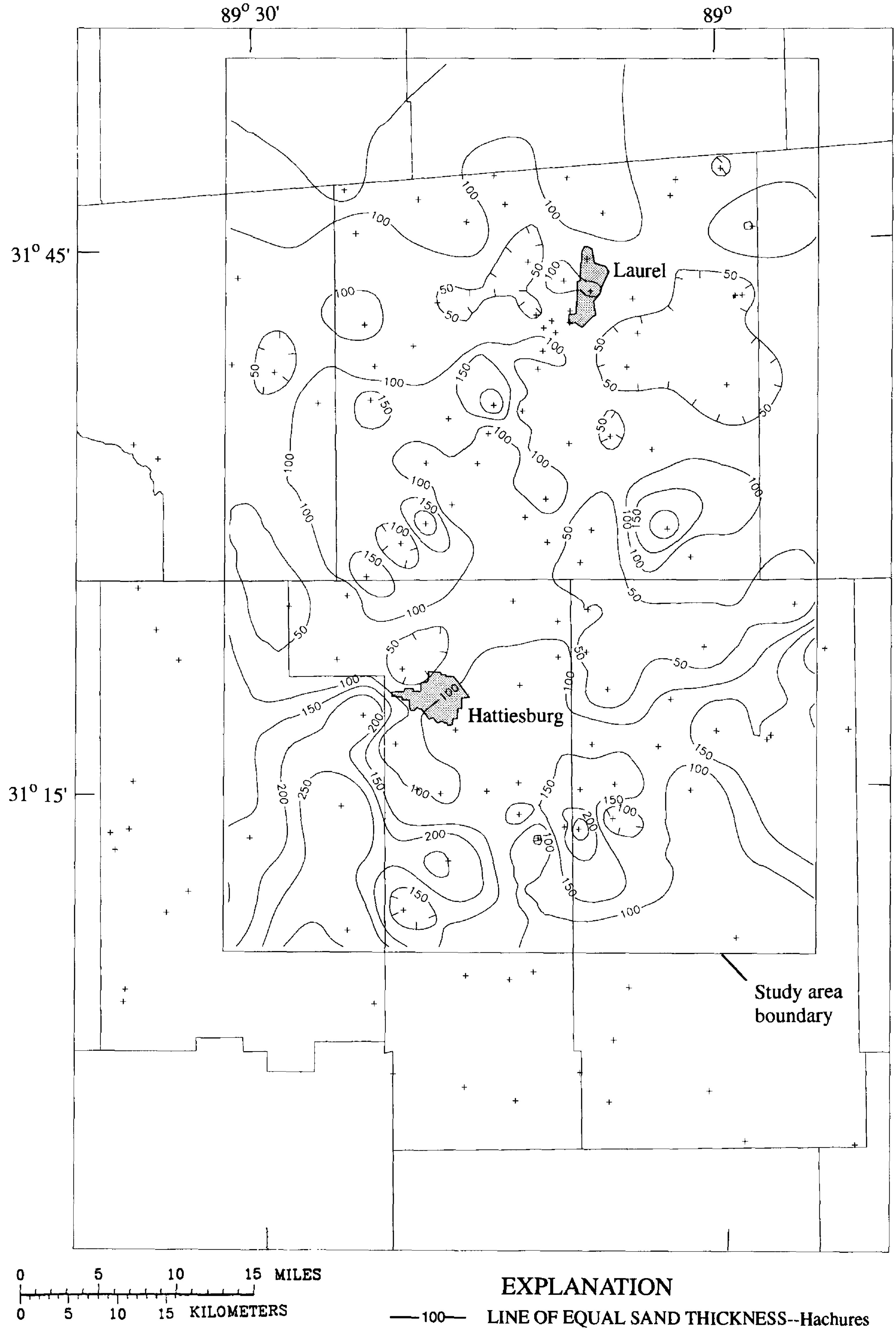


EXPLANATION

—100— LINE OF EQUAL SAND THICKNESS--Hachures indicate areas of lesser sand thickness. Contour interval 50 feet

+ CONTROL POINT

Figure 7. Sand thickness of the middle Catahoula aquifer in the study area.



EXPLANATION

—100— LINE OF EQUAL SAND THICKNESS--Hachures indicate areas of lesser sand thickness. Contour interval 50 feet

\+ CONTROL POINT

Figure 8. Sand thickness of the lower Catahoula aquifer in the study area.

places, and may contain discontinuous lenses of clay. Between clay lenses, two aquifers coalesce to form one aquifer. Accordingly, the three Catahoula aquifers form a complex system (which will be referred to as the Catahoula aquifer system in this report), in which the individual aquifers may be hydraulically well connected because of missing or thin confining units. In the Hattiesburg area, where the upper and middle Catahoula aquifers are the primary water sources, the sand thickness of the upper Catahoula is about 200 ft, and the sand thickness of the middle Catahoula generally is less than 100 ft. In the Laurel area, the sand thickness of the lower Catahoula aquifer (the water source for the city of Laurel) generally is less than 100 ft. However, the irregular thickness and extent of the aquifers can cause variations in sand thickness of 50 ft between wells that are 100 ft apart.

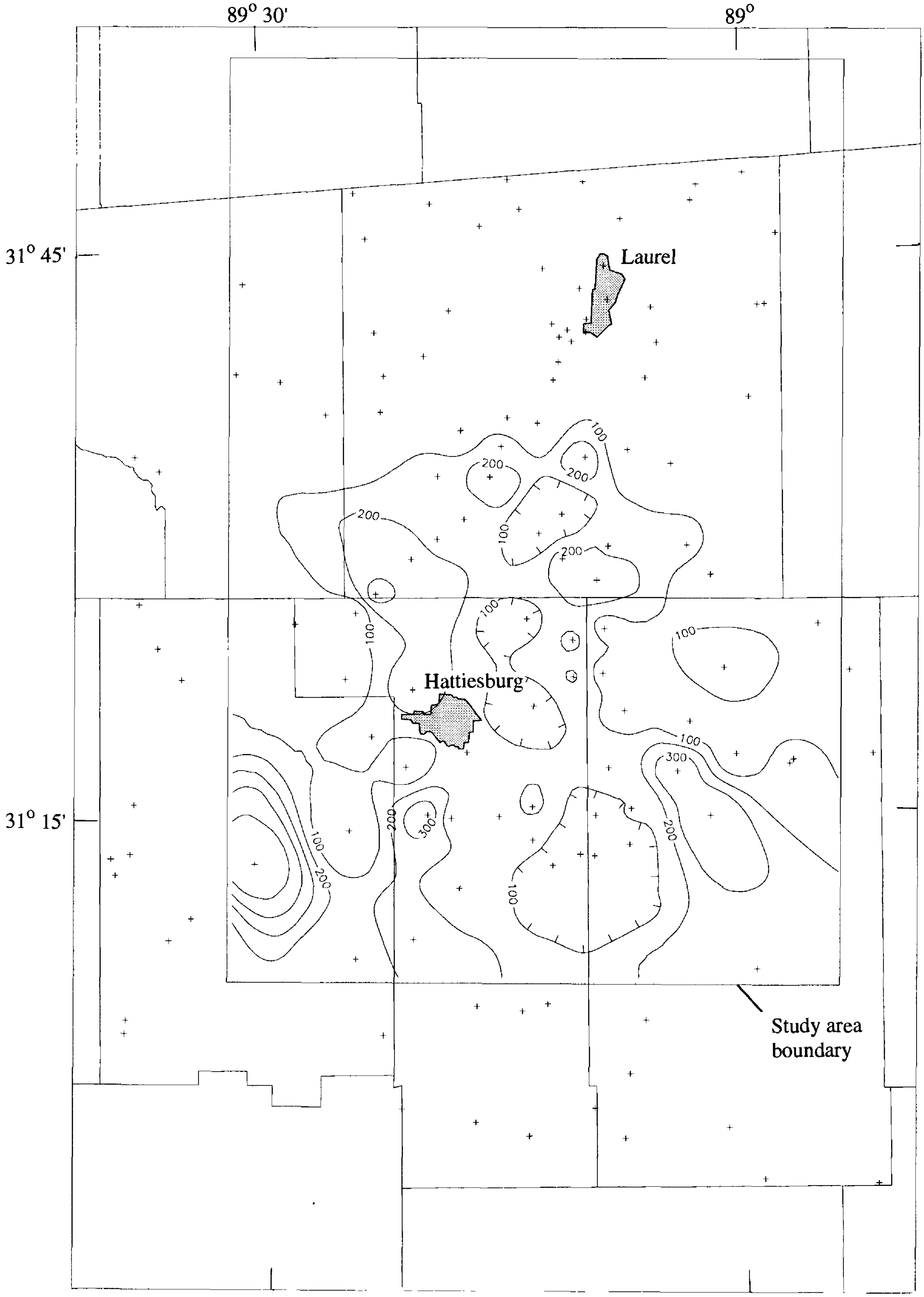
The confining units overlying the upper, middle, and lower Catahoula aquifers are primarily clays within the Catahoula, Pascagoula, and Hattiesburg Formations. These clays vary in thickness from nearly zero to several hundred feet (figs. 9-11). The thick clays of the Paynes Hammock Formation, the Chickasawhay Limestone, and the Vicksburg Group underlie and are the base of the Catahoula aquifer system in various parts of the study area.

Beyond the boundaries of the study area, aquifer and confining unit maps were highly generalized by extending thickness values determined near the study area to the periphery of the modeled area. This generalization effectively extends the hydrogeologic framework identified within the study area to realistic hydrologic boundaries useful for ground-water-flow model calibration. Pumping is small within this area of generalization compared to withdrawals at Laurel and Hattiesburg, and no long-term water-level changes are known to have occurred.

The primary recharge area for the Catahoula aquifer system is in the northern part of the modeled area where the aquifers crop out in Clarke, Covington, Greene, Jasper, Jones, Smith, and Wayne Counties, Mississippi and in Washington County, Alabama (figs. 1-2). The recharge areas for the individual Catahoula aquifers have not been mapped, but generally the upper Catahoula aquifer crops out along the southern edge of the outcrop area shown in figure 2, the middle Catahoula crops out parallel to the upper Catahoula and farther to the north and east, and the lower Catahoula aquifer crops out along the northern edge of the modeled area. The upper Catahoula aquifer (fig. 6) is not present in the Laurel area.

The principal source of water for the Catahoula aquifer system is the infiltration of rainfall in the outcrop areas. Most of the water available for recharge either runs off directly to streams or is discharged locally as base flow to perennial streams. The water that does infiltrate the outcropping sands of the Catahoula aquifer system moves within a regional ground-water flow system downgradient toward the Gulf of Mexico and toward the Tombigbee River (Martin and Whiteman 1989, fig. 33). The regional ground-water flow from outcrop areas toward the gulf coast is distorted locally in the Laurel and Hattiesburg areas by cones of depression caused by pumping. In addition to the lateral, downgradient movement of water within the aquifers, water also moves vertically through overlying and underlying confining units. The vertical movement is much slower than the lateral movement because the clays of the confining units do not transmit water as readily as the sands of the aquifers.

The southern limit of freshwater (water having less than 10,000 mg/L dissolved-solids concentration) in the Catahoula aquifer system is near the gulf coast. Water with a dissolved-solids concentration between 1,000 and 10,000 mg/L generally is not considered freshwater; however, for simulation purposes the density of such waters is sufficiently similar to that of



0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

—100— LINE OF EQUAL CONFINING UNIT THICKNESS-- Hachures indicate areas of lesser confining unit thickness. Contour interval 100 feet

+ CONTROL POINT

Figure 9. Thickness of confining units overlying the upper Catahoula aquifer in the study area.

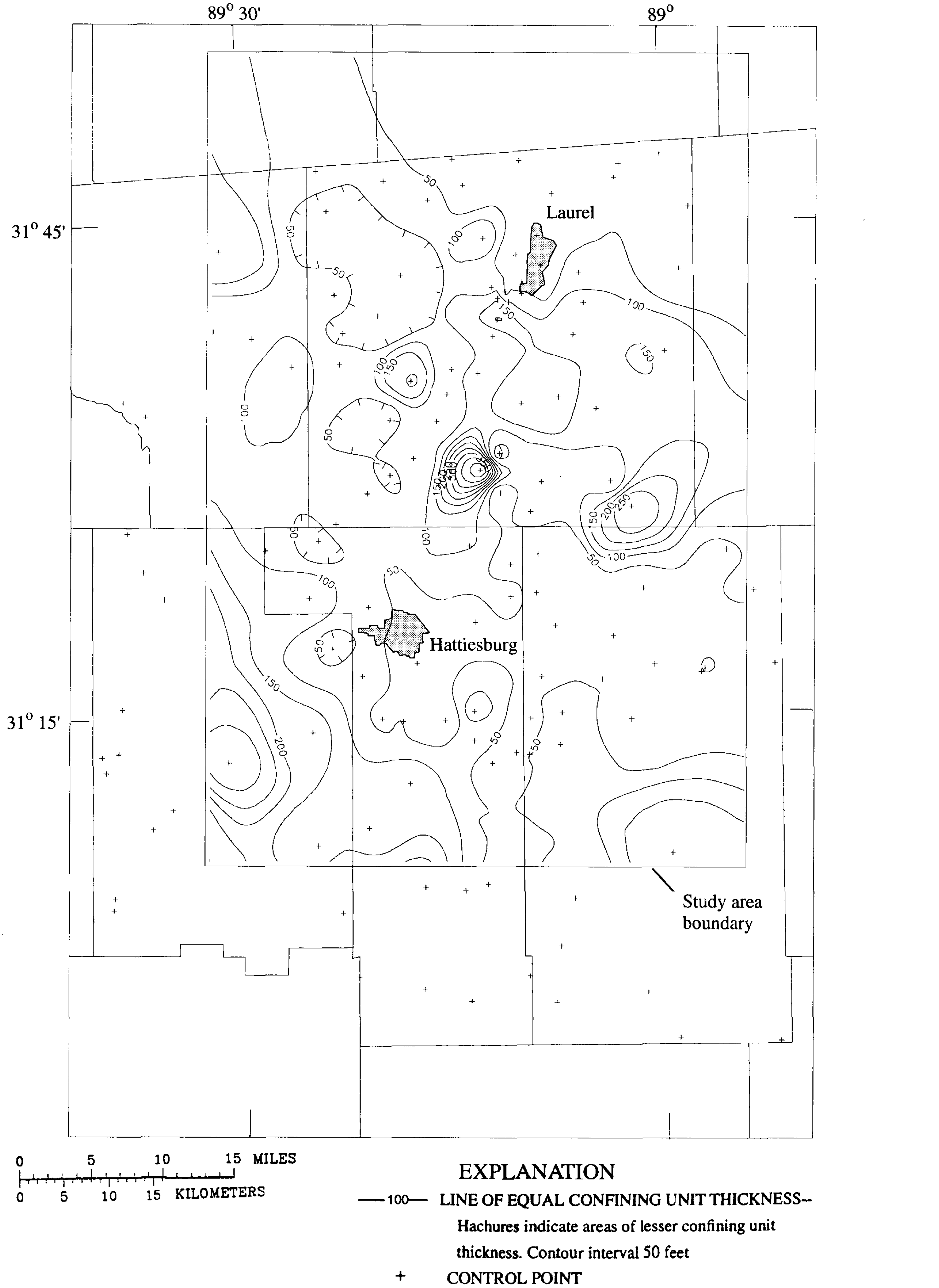
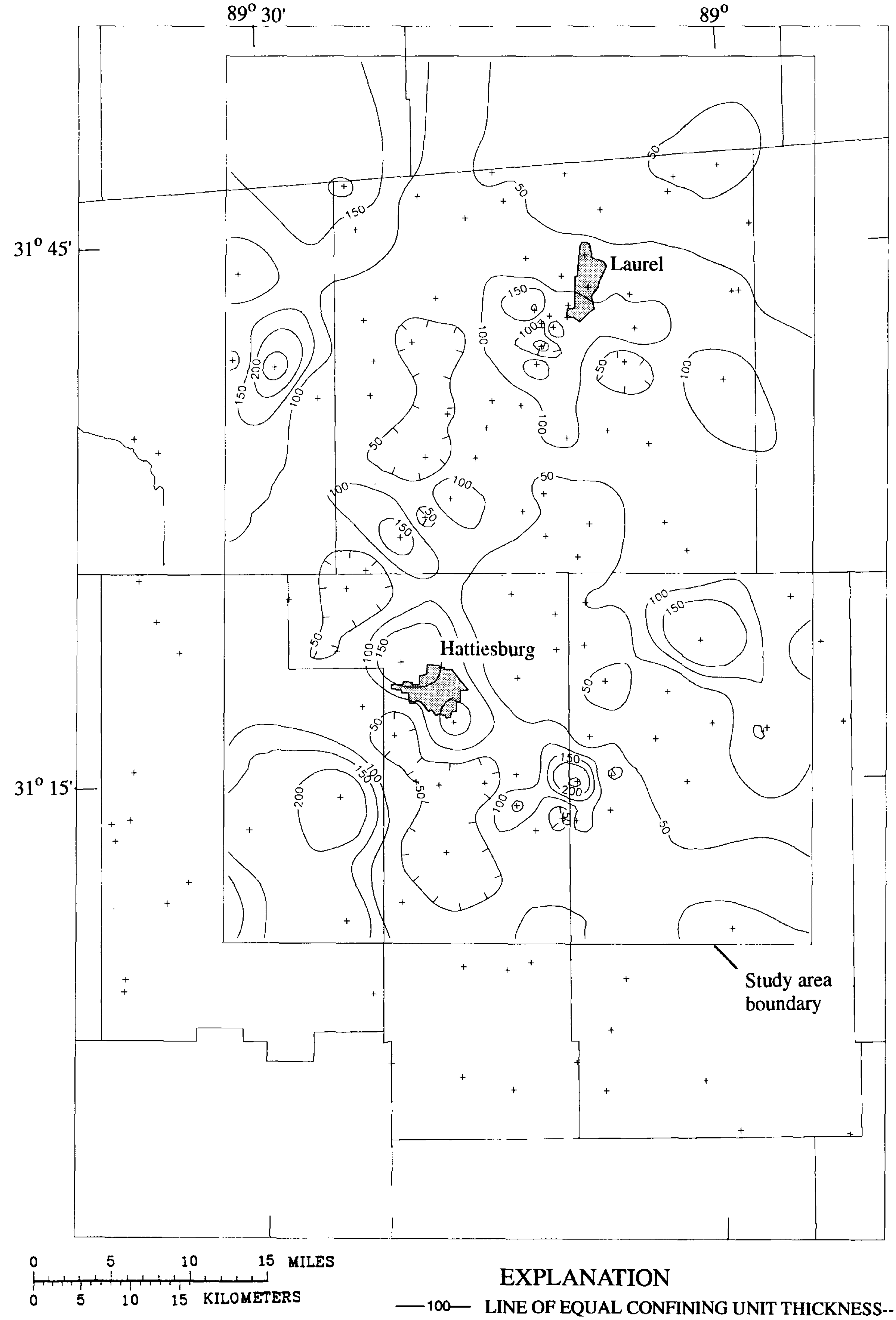


Figure 10. Thickness of confining units overlying the middle Catahoula aquifer in the study area.



EXPLANATION

—100— LINE OF EQUAL CONFINING UNIT THICKNESS--
Hachures indicate areas of lesser confining unit thickness. Contour interval 50 feet

\+ CONTROL POINT

Figure 11. Thickness of confining units overlying the lower Catahoula aquifer in the study area.

freshwater to consider these waters a continuum of freshwater.

Water Use

Water-use data for areas of heavy pumping in and near Laurel and Hattiesburg (fig. 12) have been collected since 1972 at 5-year intervals as part of a cooperative program with the Mississippi Office of Land and Water Resources (OLWR). Additional data for the period before 1972 for some water users are available from U.S. Geological Survey files and published reports. Much of the reported water use is based on telephone interviews, with supplemental information from OLWR permit files and Mississippi State Department of Health records. For this study, water-use data were compiled for the years 1960, 1965, 1970, 1975, 1980, 1985, and 1990.

Water-use data are of varying reliability. Many water users do not meter their withdrawals, and water use must be estimated from other information such as the population served or the yield of the well. Larger public suppliers and industries generally meter their withdrawals and can provide more accurate water-use data than the estimated amounts. Well locations for larger water users generally have been field-verified. Well locations for smaller users may be field-verified or may be based on a reported location.

Withdrawals from the Catahoula aquifer system in the modeled area are concentrated in the Laurel and Hattiesburg areas (fig. 12). In the Laurel area, most public-supply and industrial withdrawal is from the lower and middle Catahoula aquifers, and some additional pumpage is from the deeper Cockfield Formation of Eocene age. The city of Laurel withdraws water from the lower Catahoula exclusively. In the Hattiesburg area, most withdrawal is from the middle and upper Catahoula aquifers, although some withdrawal also is from the lower Catahoula aquifer. South of Hattiesburg, water is available from sand zones in the overlying Hattiesburg and Pascagoula Formations, and the Catahoula aquifers are not widely pumped.

From 1970 to 1985 the total estimated pumpage from the Catahoula aquifer system in the modeled area increased from 28 Mgal/d to 41 Mgal/d; during 1990 pumpage decreased to 38 Mgal/d (fig. 13). The decline in total pumpage from 1985 to 1990 primarily resulted from declines in withdrawals for thermoelectric power generation and for industrial purposes. Industrial withdrawals declined steadily from 1970 to 1990. Public-supply withdrawals increased more than 120 percent from 1970 to 1990, reflecting population growth, increasing numbers of public water-supply systems, and increased water use per person.

Effects of pumping

Withdrawal from the Catahoula aquifer system has affected water levels in the aquifers. In the Laurel area, the water level in the lower Catahoula aquifer declined until the late 1980's in response to increases in the amount of water pumped from the aquifer. The water level in well 67G055 (fig. 14), located in a Laurel well field west of the center of the city (fig. 2), declined about 83 ft between 1964 and 1987, an average rate of 3.6 ft/yr. However, between 1987 and 1993 the water level rose 27 ft. (All hydrographs in figs 14-16 are shown for the period 1970-92 for ease of comparison. Several water-level measurements were made prior to 1970 and were used to calculate long-term rates of water-level decline.) The water level in well 67F020, located in the Laurel airport well field, and well 67C034, located in the same well field as well 67G055, declined at average rates between 1 and 2 ft/yr before 1988; water levels at these wells increased from 1988 to 1993. The average rate of water-level decline for wells 67F020 and 67C034 prior to 1988 is less than the rate of decline

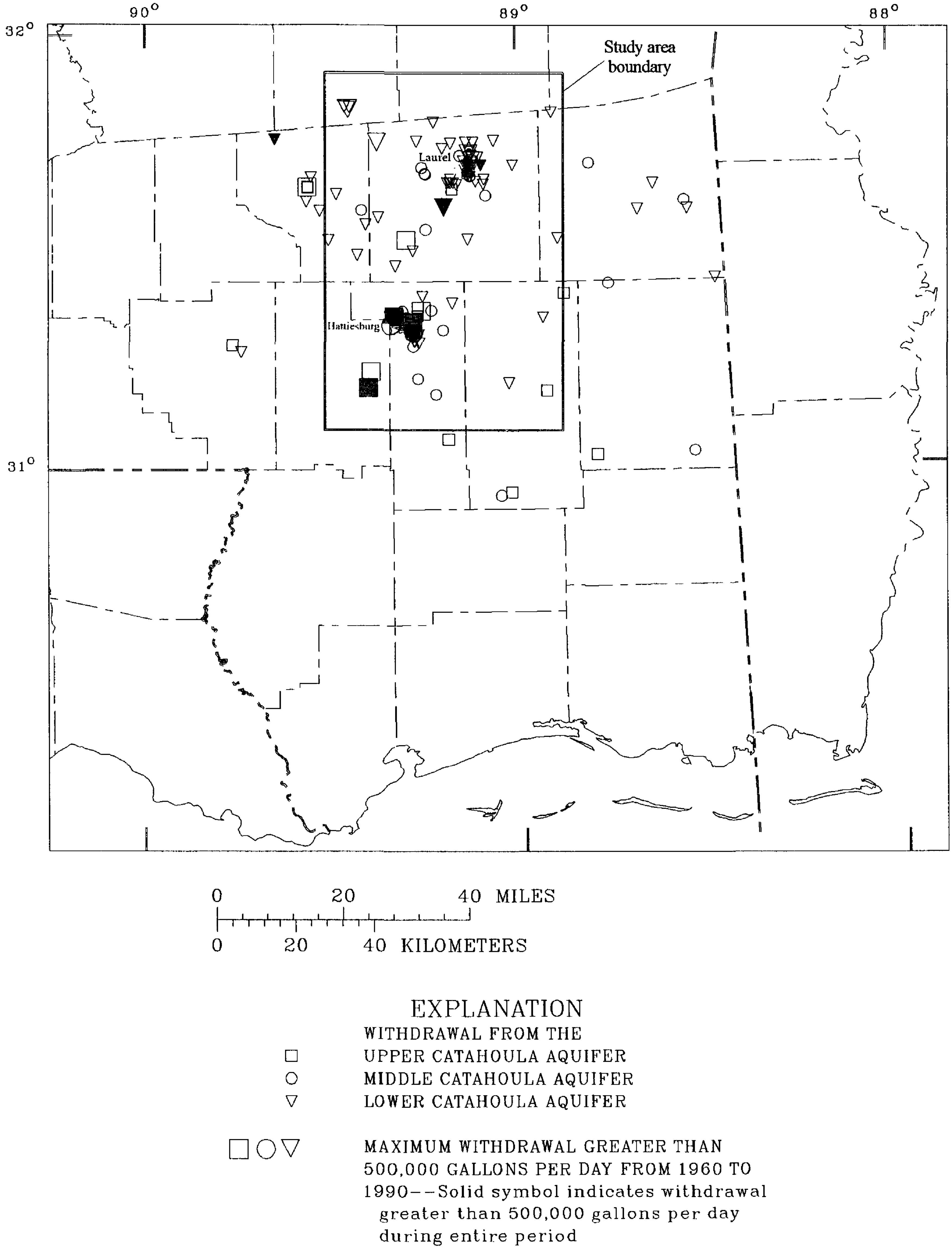


Figure 12a. Pumping centers in the modeled area.

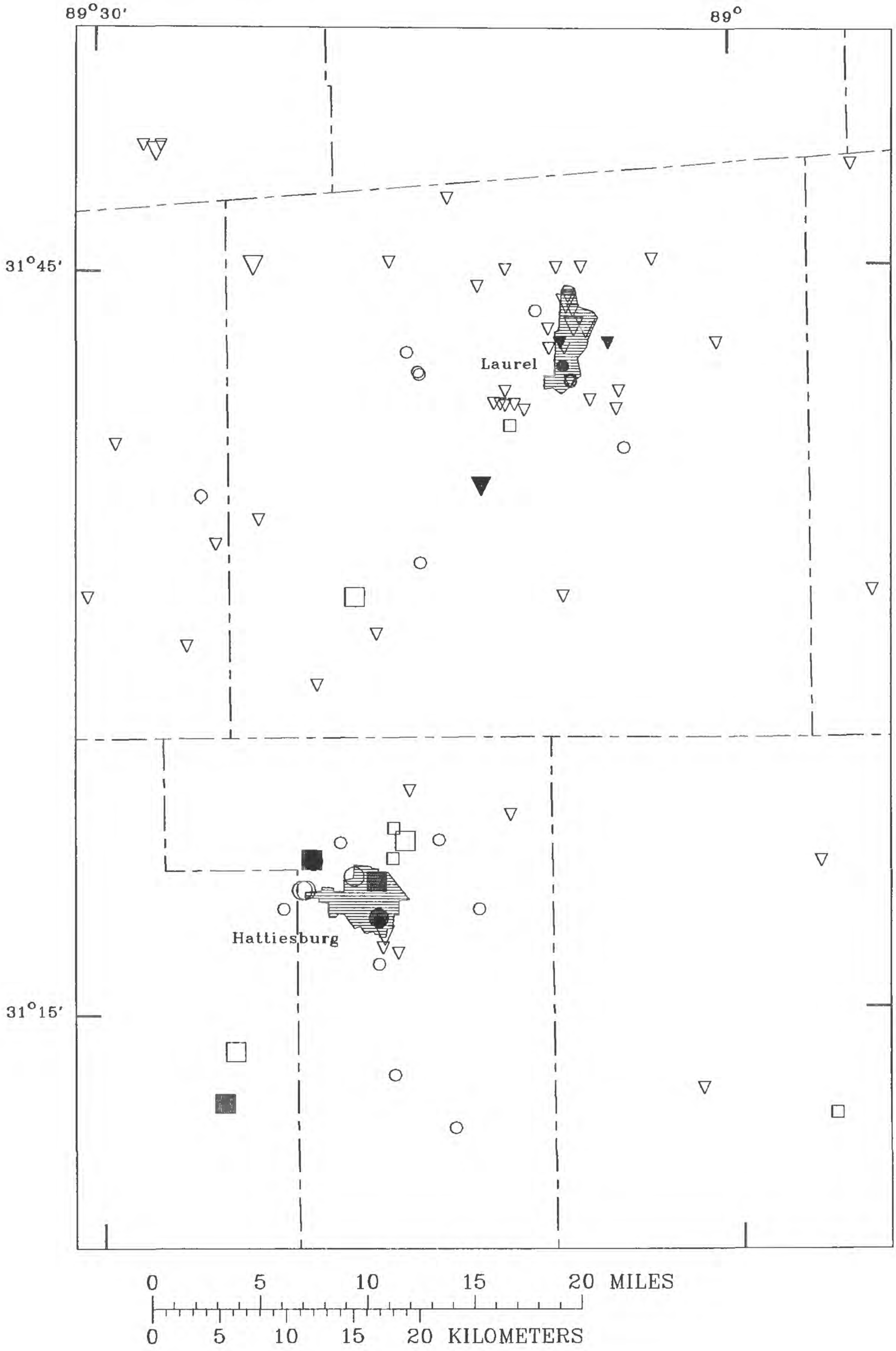


Figure 12b. Pumping centers in the study area.

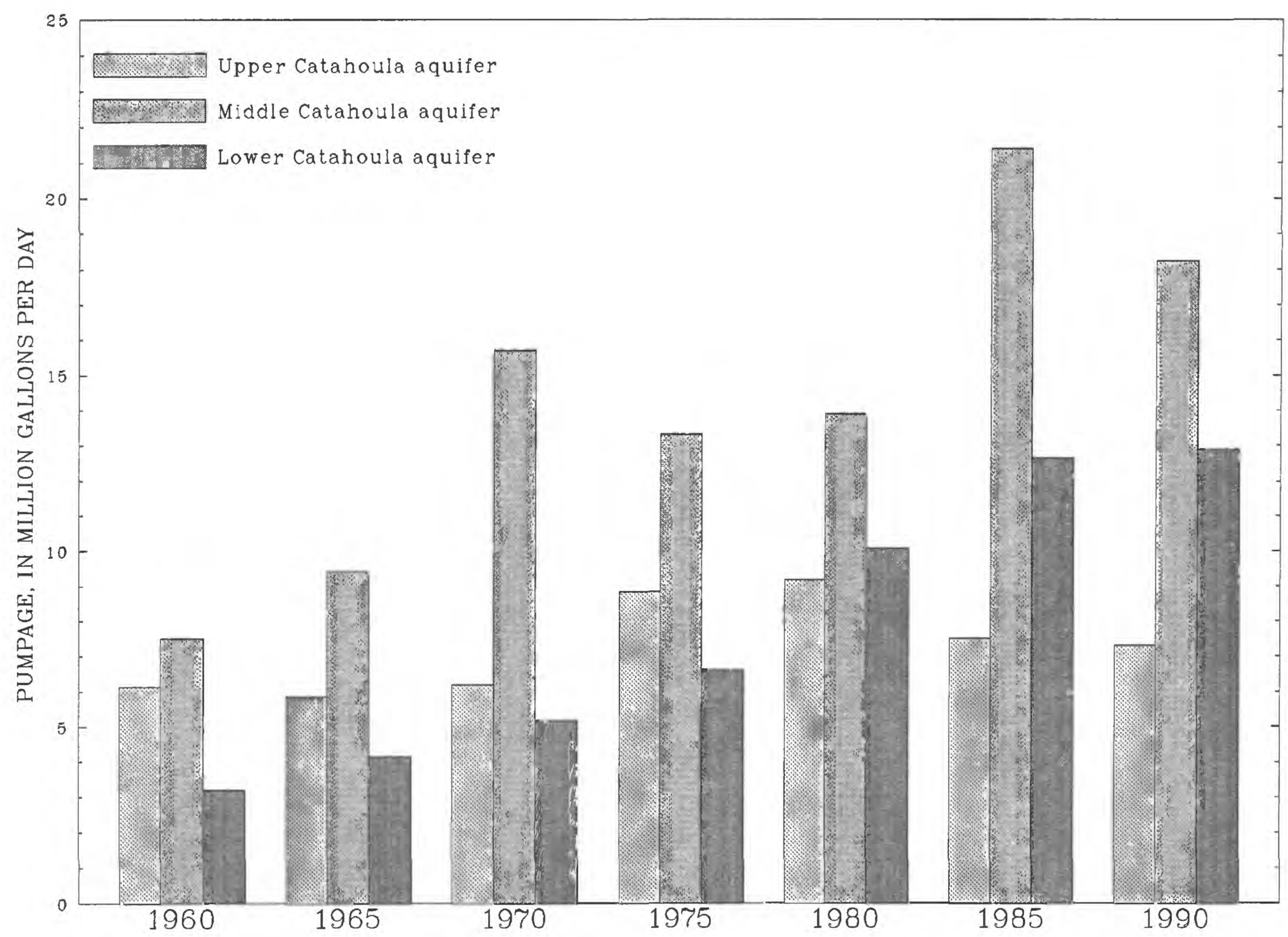


Figure 13. Pumpage from the upper, middle, and lower Catahoula aquifers in the Laurel-Hattiesburg area, Mississippi, 1960-90.

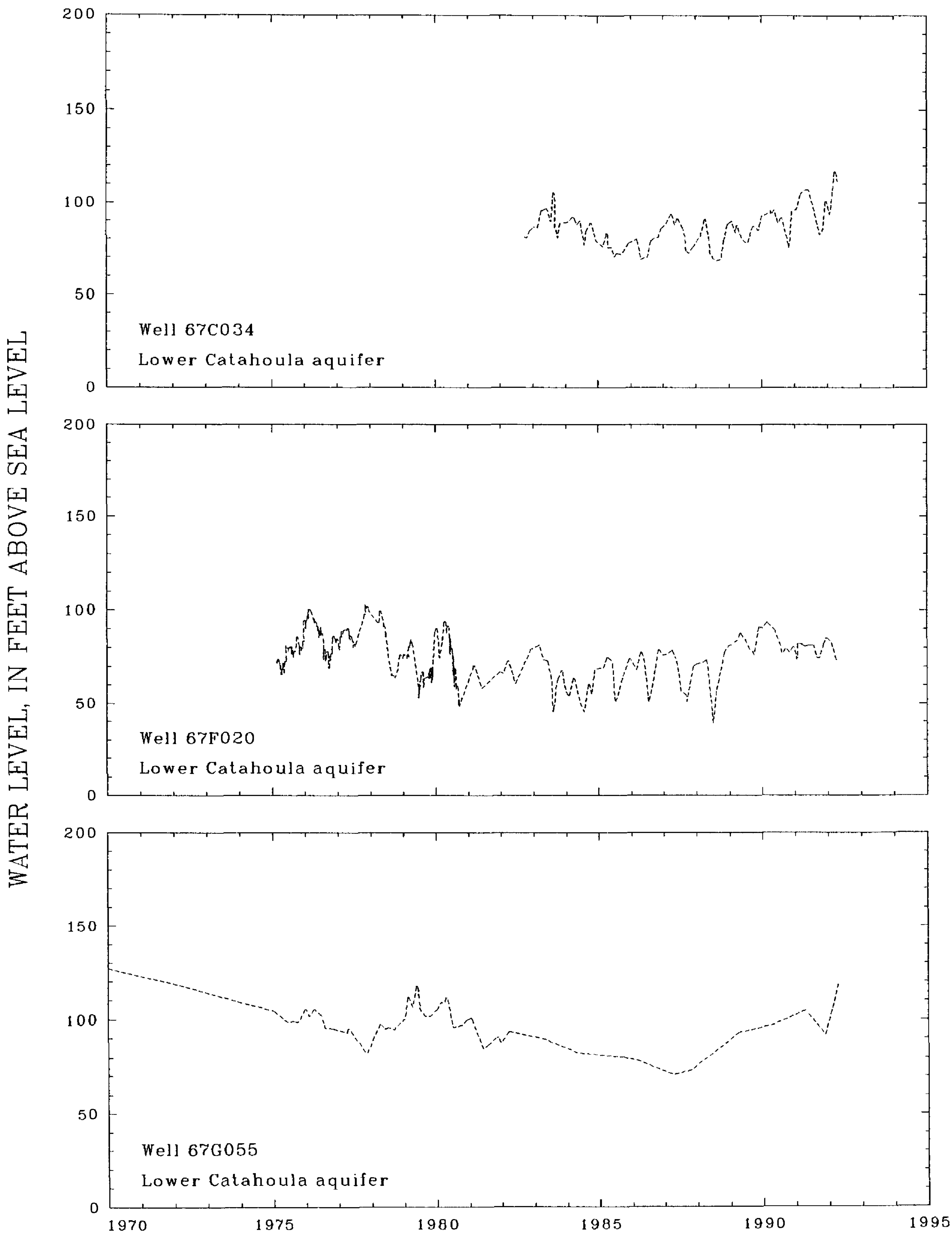


Figure 14. Water levels for wells 67C034, 67F020, and 67G055 near Laurel, Mississippi.

computed for well 67G055 because of a shorter and more recent period of record. Water levels in these wells were not measured during the 1960's and 1970's, when the water levels in the lower Catahoula declined more rapidly. The recovery of water levels in the lower Catahoula during the late 1980's and early 1990's resulted as the city of Laurel began actively managing pumpage, using water-level changes to decide the distribution of withdrawal between the two well fields.

Long-term water-level declines also occurred in the Hattiesburg area as ground-water withdrawals increased (fig. 15). The water level in well 35D008 in Hattiesburg, screened in the middle Catahoula aquifer, declined at an average rate of about 2 ft/yr from 1964 to 1992. The water level in well 35B006, screened in the upper Catahoula aquifer, declined at a rate of less than 1 ft/yr from 1955 to 1992. The average water-level decline in well 35D130 in Hattiesburg, also screened in the upper Catahoula aquifer, was about 1 ft/yr from 1946 to 1981.

Water levels in areas outside of the major pumping centers near Laurel and Hattiesburg also have declined but at smaller rates (fig. 16) than water levels near the pumping centers. At well 35L079 in southern Forrest County and screened in the upper Catahoula aquifer, the water level declined at an average rate of 0.7 ft/yr between 1970 and 1992. Water levels in well 73L063, located in Lamar County and screened in the middle Catahoula aquifer, declined at a rate of 1.2 ft/yr between 1975 and 1992, although most of this decline took place before 1980. In well 111M011, located in Perry County and also screened in the middle Catahoula aquifer, water levels declined 0.6 ft/yr between 1979 and 1993.

ANALYSIS OF THE GROUND-WATER FLOW SYSTEM

A three-dimensional model was used to quantitatively analyze the ground-water flow in the Catahoula aquifer system in the study area. The McDonald and Harbaugh (1988) modular finite-difference model (MODFLOW) was used to simulate flow in the Catahoula aquifer system and solve the governing equation:

$$-\nabla (K \nabla h) + Q = S_s \frac{\partial h}{\partial t},$$

where
- ∇ is del, the vector differential operator
- K is hydraulic conductivity,
- Q is the source/sink term,
- h is hydraulic head,
- S_s is specific storage, and
- t is time.

Description of Model

The use of a finite-difference model requires the discretization of the aquifer system into cells. Each cell is specified by layer, row, and column. The size of these cells in the model for this study was based on the distribution of estimated pumpage during 1960-90 and on the distribution of water-level and budget data used to calibrate the model. The active cells ranged in size from 0.25 to 114 mi^2. Variably spaced, small cells were used in the Laurel and Hattiesburg areas (fig. 17), where water-level data are relatively numerous and pumping rates have changed greatly over time. The largest cells were in areas of little or no pumping and outside of the study area. The model grid covered an area greater than 13,500 mi^2 and was divided into 56 rows of 48 columns.

The grid was oriented parallel to the outcrop area throughout most of the model because the outcrop area was better defined than the other lateral boundaries. No measurements of anisotropy were available and a lateral anisotropy ratio of 1 to 1 was used for simulation. Values of aquifer and confining unit hydraulic properties were assigned to the center of each cell, defined as a node, by

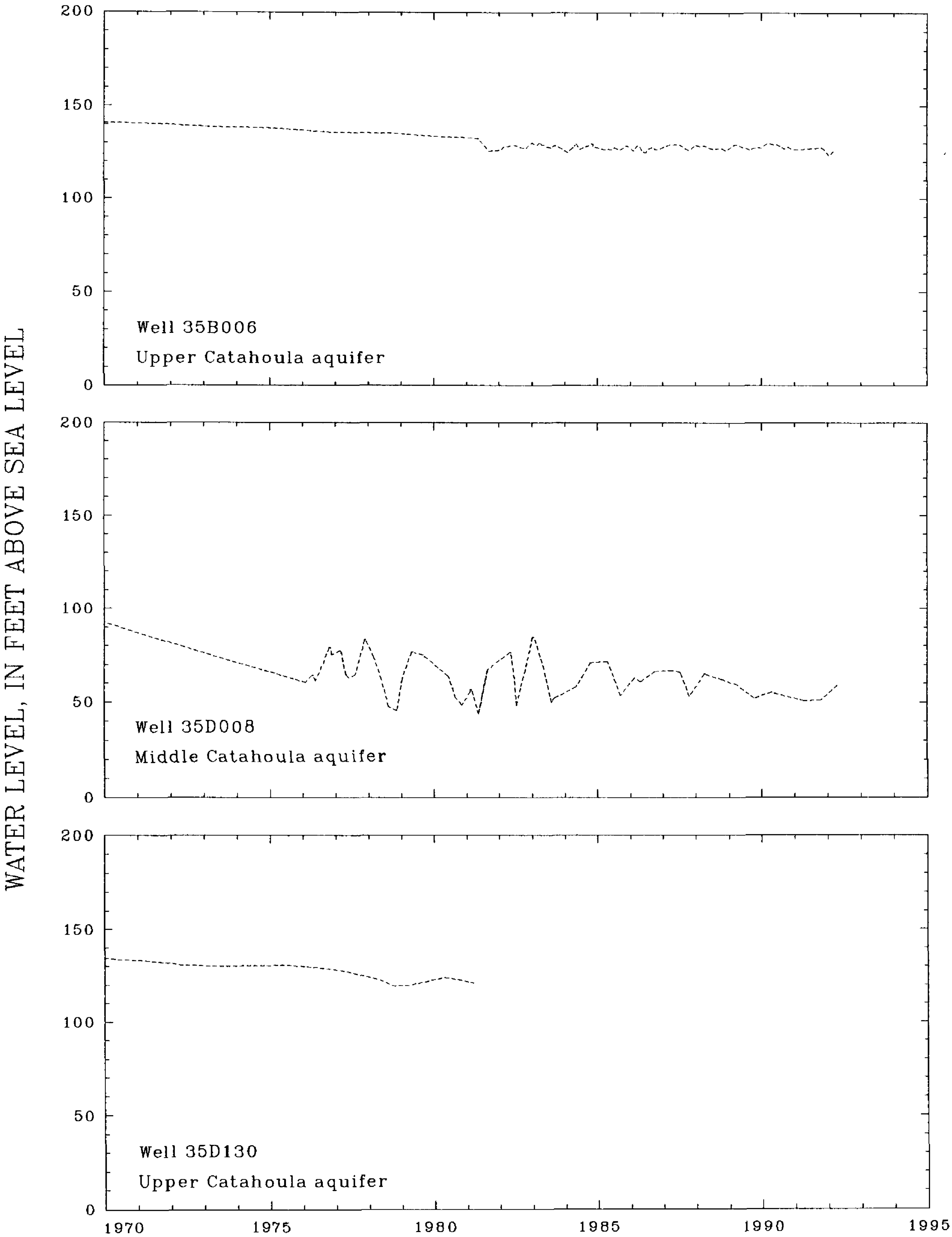


Figure 15. Water levels for wells 35B006, 35D008, and 35D130 near Hattiesburg, Mississippi.

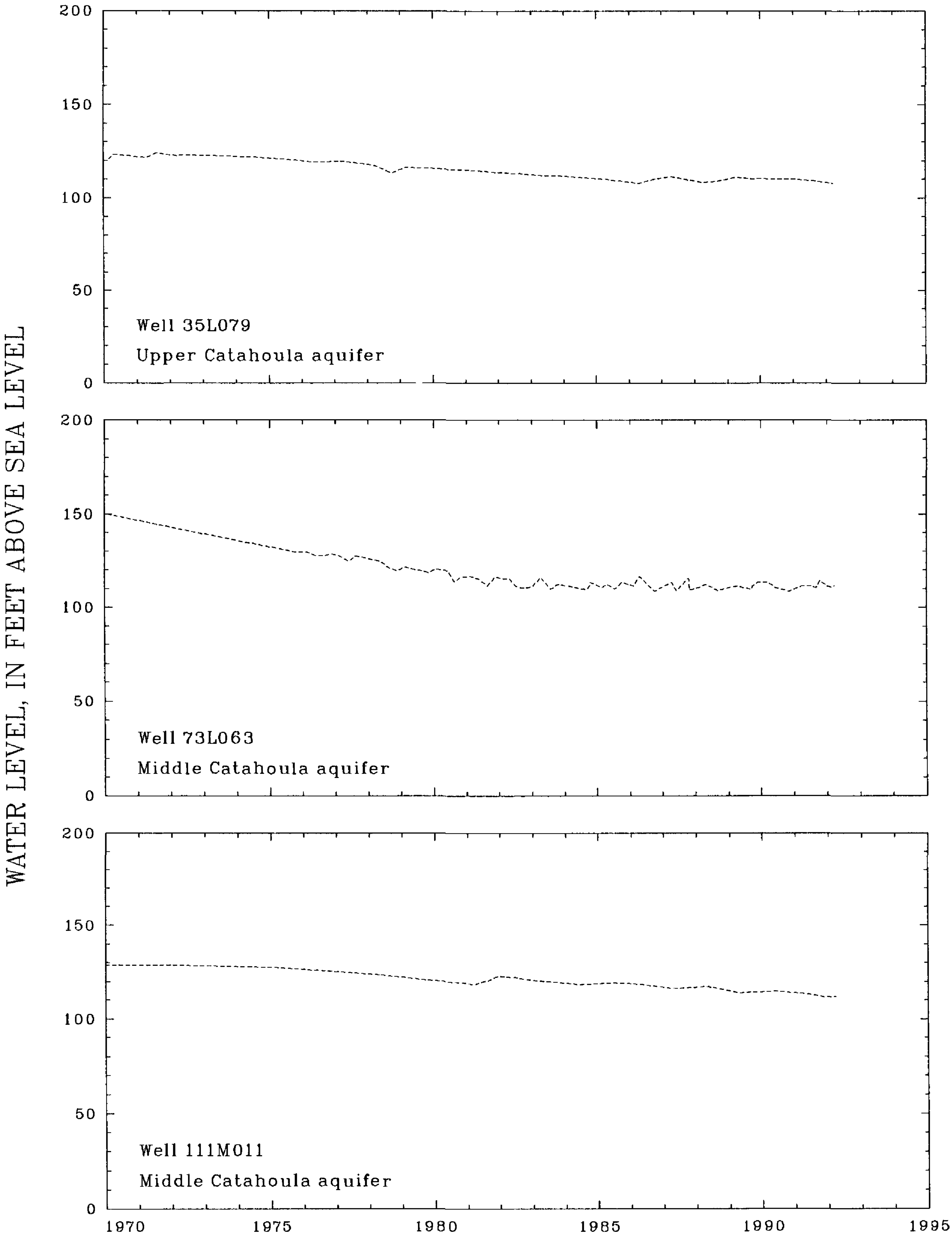


Figure 16. Water levels for wells 35L079, 73L063, and 111M011, generally unaffected by major pumping centers in the modeled area.

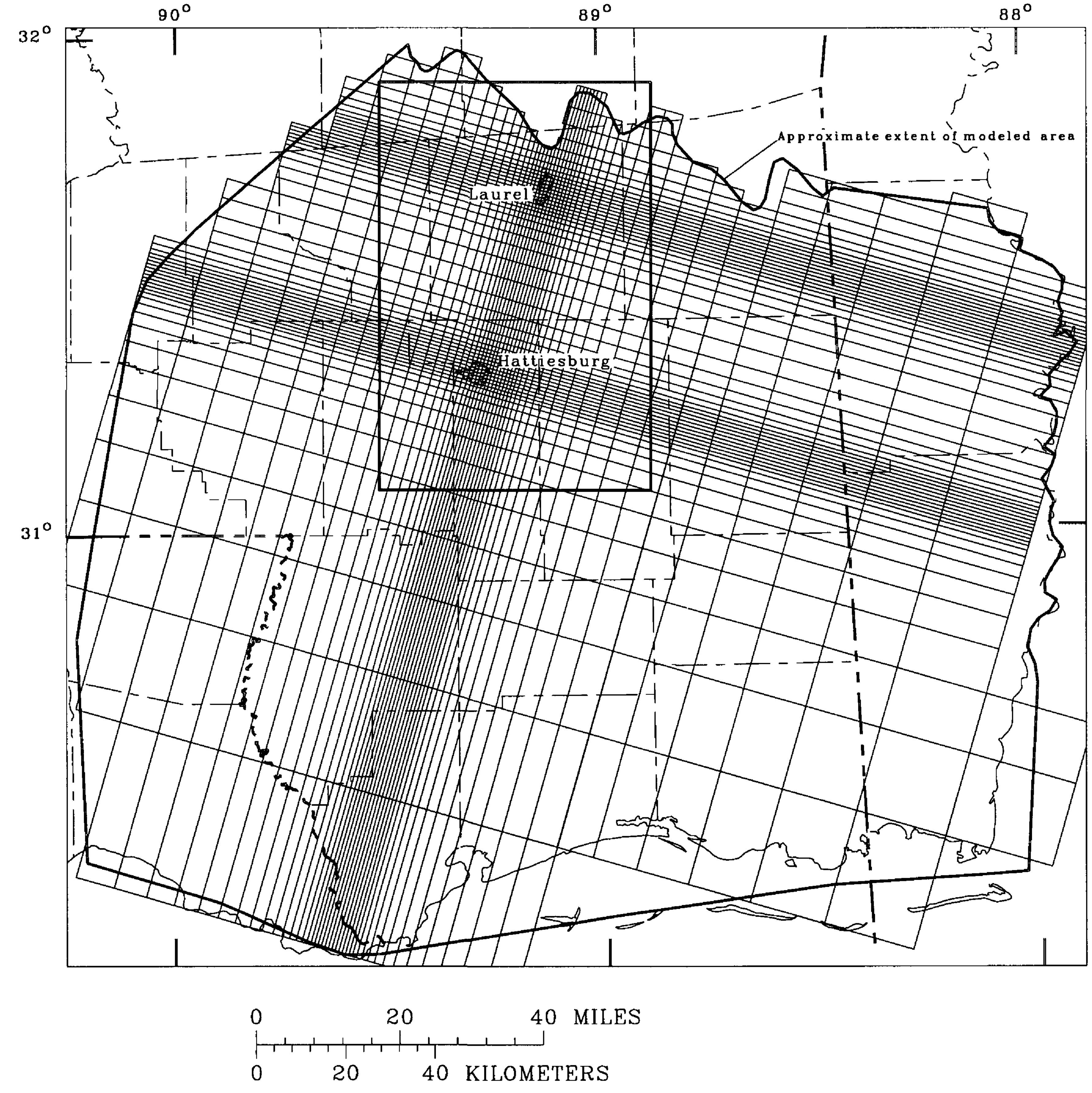


Figure 17a. Model grid and extent.

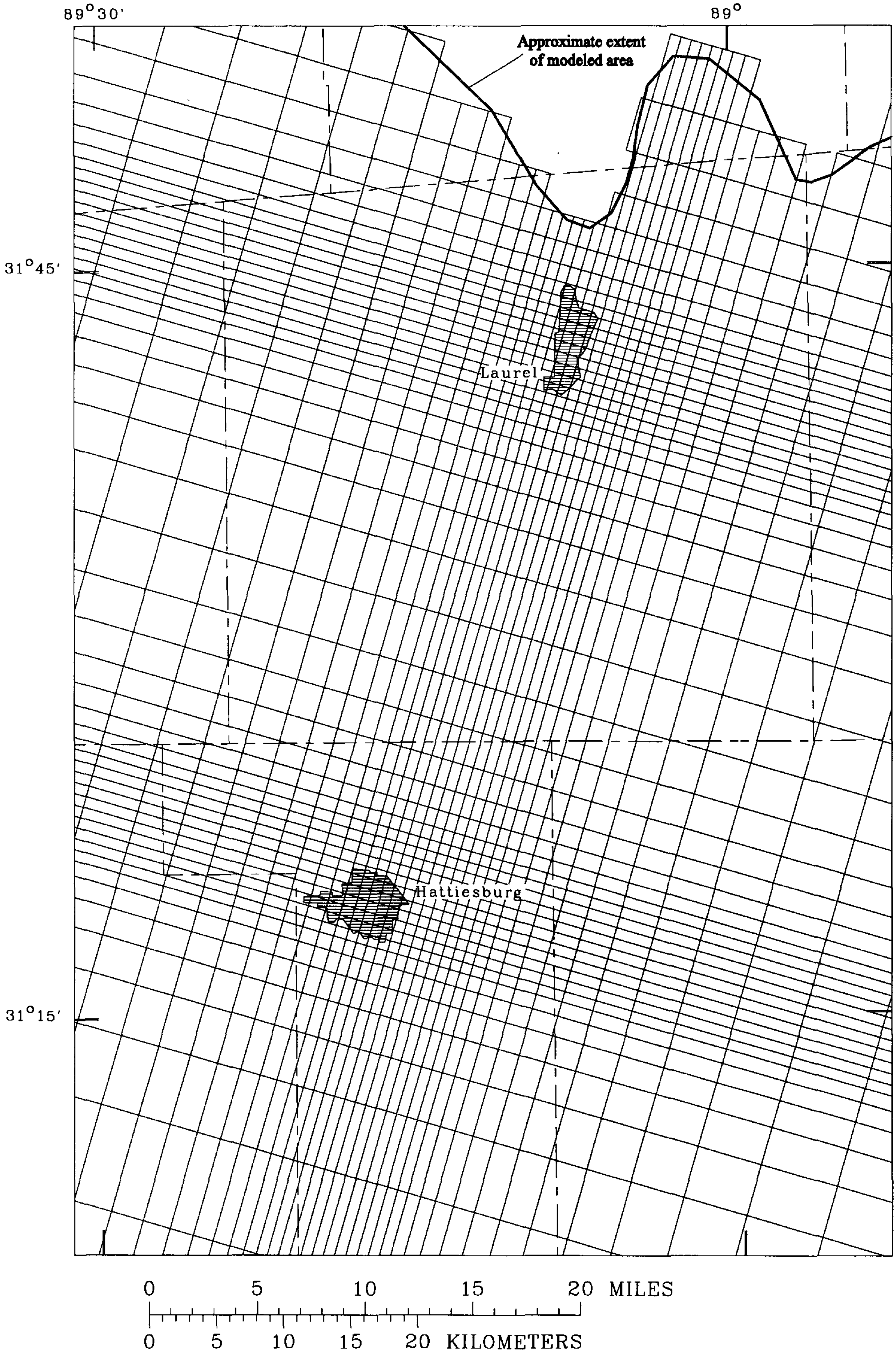


Figure 17b. Model grid in study area.

averaging observed or estimated point values within the cell.

The simulation approach was based on the assumptions that (1) flow is primarily lateral within the aquifers, (2) flow through the confining units is primarily vertical, and (3) the amount of water released from storage from the confining units is negligible compared to the total lateral flow within the aquifers. The assumptions of flow directions in the aquifers and confining units are reasonable because the hydraulic conductivity of sand composing the aquifers is much greater than that of clay composing the confining units. The model was vertically discretized into four layers, three of which were used to simulate the Catahoula aquifer system. Layer 1 represented the surficial aquifer and was the specified-head upper boundary for the model (fig. 18). Layers 2, 3, and 4 represented the upper, middle, and lower Catahoula aquifers, respectively.

Vertical flow between aquifers was simulated with leakance values assigned at each cell between model layers. The leakance is the vertical hydraulic conductivity of the confining unit divided by its thickness in units of feet per day per foot. Throughout most of the model area the leakances used represent the resistance to flow across individual confining units. The zone parallel to the outcrop from Hattiesburg to the south and between layers 1 and 2 is an exception. The leakances in this zone represent the combined vertical resistance to flow across all confining units and aquifers between the surficial aquifer and the upper Catahoula aquifer.

Boundary Conditions

Proper representation of model boundary conditions is one of the most important aspects in the simulation of an aquifer system. Model boundaries are assigned to represent the actual hydrologic boundaries as accurately as possible. Where model boundaries are necessarily highly generalized, they are placed far enough away from the influence of hydrologic stresses in the model area to minimize their effects on simulation results.

The upper boundary model, layer 1, is a source or sink for the Catahoula aquifer system. A specified-head was used to define the upper boundary and represents the long-term, average water-table altitude throughout the model area. There has been no significant long-term decline or rise in the water table in the outcrop area for the Catahoula aquifer system or elsewhere in the model area (W.T. Oakley, U.S. Geological Survey, oral commun., 1993).

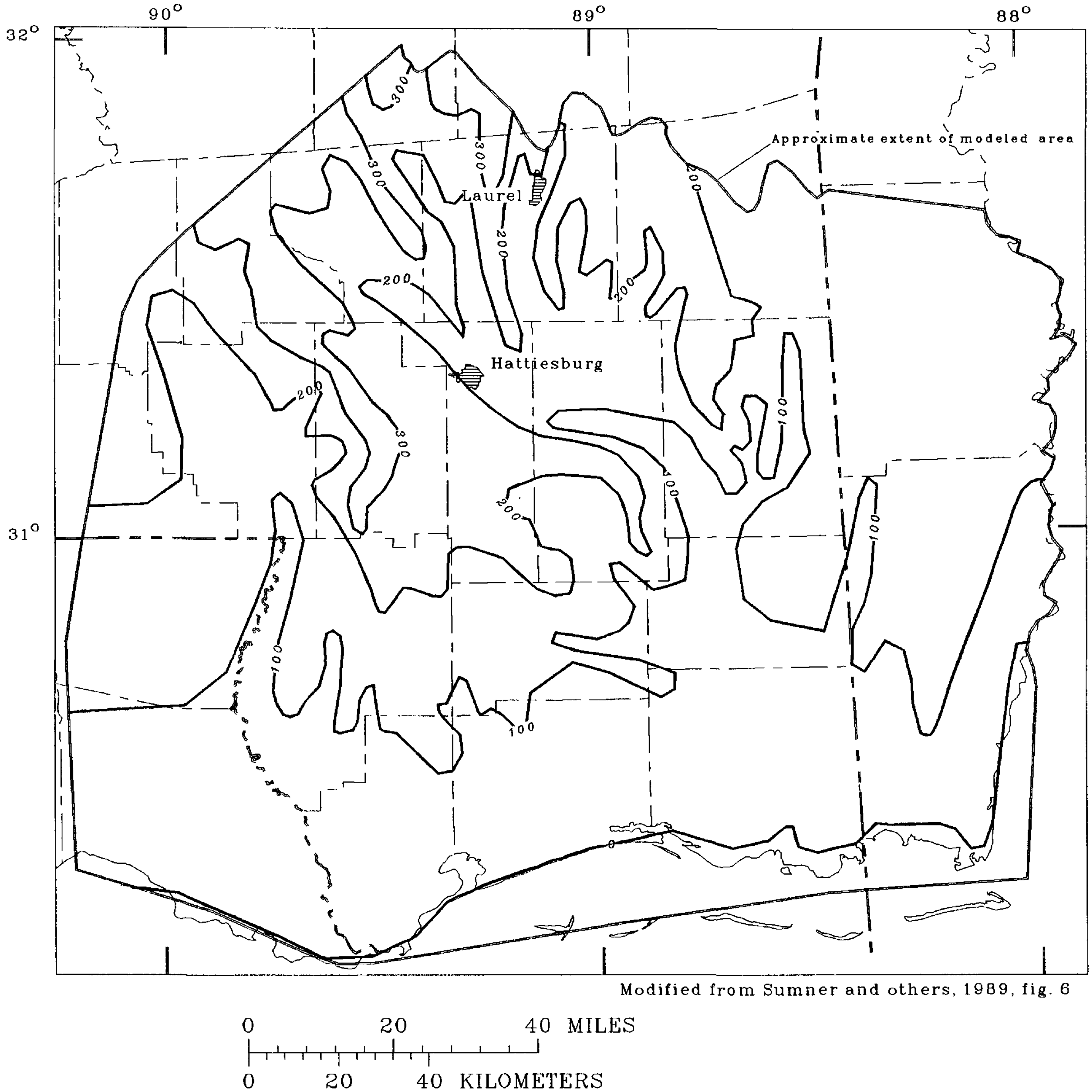
Estimates of potential recharge to the Catahoula aquifer system were determined from a climatic budget. Assuming that the spatial variation in evapotranspiration corresponds with the spatial variation in rainfall, a contour map of rainfall available for recharge was derived by adjusting contoured values of average annual rainfall (not shown, Lamonds and Boswell, 1986, p. 297) by:

$$\text{Fraction of rainfall remaining} = \frac{\text{Total rainfall - Total evapotranspiration}}{\text{Total rainfall}}$$

For southern Mississippi, with an average rainfall of 56 in/yr and evapotranspiration of about 35 in/yr (Callahan and Barber, 1990, p. 321), the fraction of rainfall remaining after evapotranspiration is:

$$\frac{56\ \text{in/yr} - 35\ \text{in/yr}}{56\ \text{in/yr}} = 0.38.$$

The maximum potential recharge map (fig. 19) was made by subtracting spatially-distributed values of surface-water runoff (Lamonds and Boswell, 1986, p. 297) from the spatially corresponding values of available rainfall. Thus, the potential recharge available



EXPLANATION

——200—— WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval 100 feet. Datum is sea level

Figure 18. Altitude of water table (layer 1) in the modeled area.

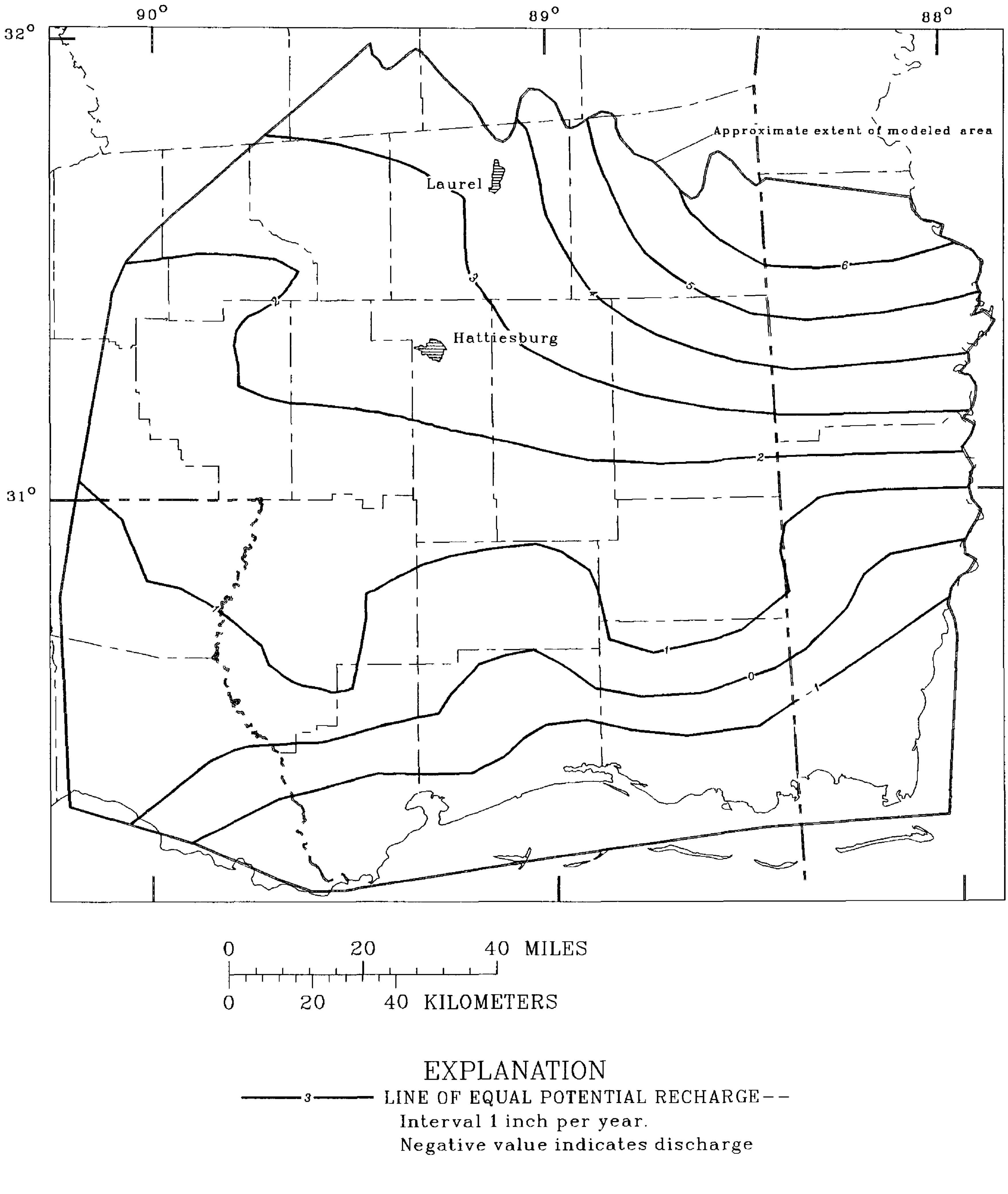


Figure 19. Maximum potential recharge available in the modeled area.

to the Catahoula aquifer system within the outcrop area ranges from 3 to 6 in/yr. The potential recharge available in the outcrop area (3,300 mi^2) is approximately 700 Mgal/d, which is considerably greater than the maximum historical ground-water withdrawal of 41 Mgal/d from the Catahoula aquifer system.

The lower model boundary was considered a no-flow boundary and corresponds to the top of clays previously assigned to the Paynes Hammock Formation, the Chickasawhay Limestone, and the Vicksburg Group. Results of the Gulf Coast Regional Aquifer-System Analysis (GC RASA) indicated negligible flow across the confining layer which underlies the lower Catahoula aquifer (Martin and Whiteman, 1989).

The model area is much larger than the study area to satisfy boundary-condition requirements. All the lateral model boundaries in each layer are no-flow boundaries (fig. 20). The northern edge of the model was the updip extent of the lower Catahoula aquifer (layer 4). Layer 2 extends to the northern boundary although the upper Catahoula aquifer pinches out south of the northern edge of the model. Extending layer 2 provides continuity between layer 1, the upper specified-head boundary, and lower layers. The southern boundary approximated the downdip limit of the freshwater system (Sumner and others, 1989, p. 42). Lateral movement of water across this boundary was considered negligible. The location of the freshwater/saltwater interface also was considered to be stable over time. The eastern no-flow boundary is along the valley of the Tombigbee River, which lies above a deep graben feature. The Tombigbee River is a ground-water divide because the river is a regional drain for all the Catahoula aquifer system (Martin and Whiteman, 1989). Water moves upward from deeper to shallower aquifers along this boundary and is discharged to the specified head boundary (layer 1) which incorporates the river stage. The western boundary corresponds to a wide zone of parallel flow in all layers (Martin and Whiteman, 1989, fig. 33). This divide constitutes a no-flow boundary because water flows parallel to but not across the boundary. Previous development has not affected ground-water flow in the vicinity of this divide and the effects of further development are expected to be negligible.

Hydraulic Properties

Initial estimates of values for lateral hydraulic conductivity and storage coefficient were obtained from aquifer tests performed between 1942 and 1984 (Slack and Darden, 1991). The largest number of tests (table 2) were performed in the lower Catahoula aquifer

Table 2. Ranges of reported lateral hydraulic conductivity and storage coefficient for the Catahoula aquifer system in southeastern Mississippi

	Lateral hydraulic conductivity, in feet per day			Storage coefficient
	Upper Catahoula aquifer	Middle Catahoula aquifer	Lower Catahoula aquifer	Lower Catahoula aquifer
Minimum	4	18	12	1×10^{-4}
Average	94	52	76	3×10^{-4}
Maximum	180	80	190	5×10^{-4}
Standard deviation	54	20	44	1×10^{-4}
Number of tests	12	6	53	18

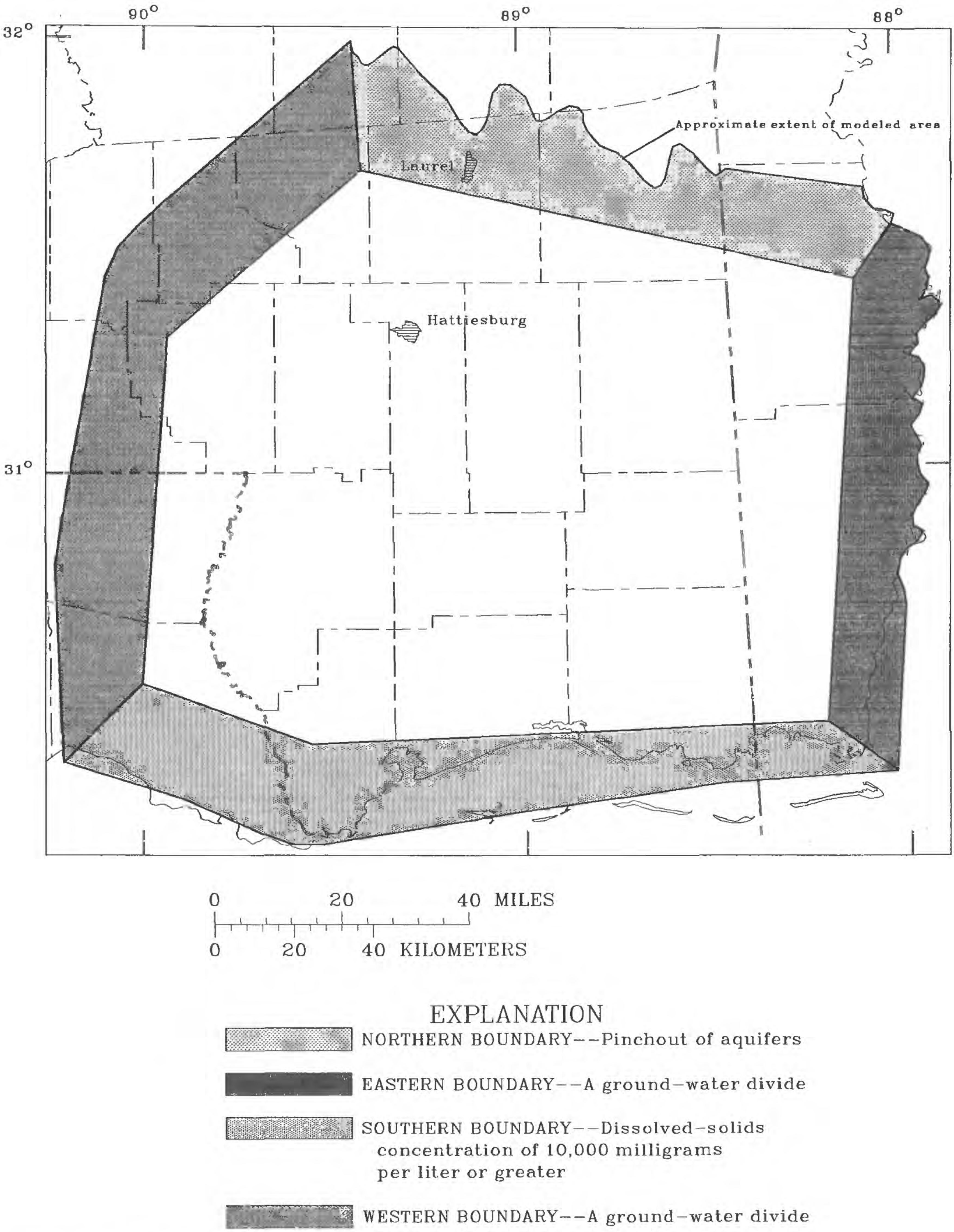


Figure 20. Conceptual model for the Catahoula aquifer system.

near Laurel and Hattiesburg. Only a few tests were performed in the upper and middle Catahoula aquifers near Hattiesburg. The initial transmissivity arrays input to the model were calculated by multiplying the average lateral hydraulic conductivity for each layer by the corresponding sand thickness for that layer.

No aquifer tests have been performed in the study area that permit calculation of the vertical conductance or the vertical hydraulic conductivity of the confining units. Bear (1979, p. 68) reports that the hydraulic conductivity of clay ranges from $3x10^{-8}$ to $3x10^{-1}$ ft/d. Vertical hydraulic conductivity of clay samples from similar confining units in southeastern Louisiana are about $1x10^{-5}$ ft/d (Whiteman, 1980, p. 18). Because the confining units in the study area contain considerable silt and sand, the average vertical hydraulic conductivity was considered to be about $1x10^{-4}$ ft/d. The initial leakance arrays input to the model were calculated dividing the average vertical hydraulic conductivity by the confining unit thickness between each layer.

Model Calibration

Calibration is the attempt to reduce the difference between model results and measured data by adjusting model input. Calibration is generally accomplished by adjusting input values of transmissivity and leakance until an acceptable calibration criterion is achieved. The difference between simulated and measured water levels was the acceptable match for this model. Calculated water levels from a calibrated, deterministic ground-water model usually depart from measured water levels by a considerable amount, even after diligent effort has been made to have model input closely approximate field observations. The discrepancy between simulation results and measured water levels (model error) usually is caused by grid scale and the difficulty of obtaining sufficient measurements to account for all of the spatial variation in hydraulic properties throughout the model area.

The initial arrays of transmissivity and leakance input to the model were adjusted to calibrate the model. Six parameters were used as global multipliers, three for each confining unit leakance array between each aquifer and three for each transmissivity array of the Catahoula aquifers (layers 2, 3, and 4). Global multipliers change the value of either leakance or transmissivity by a fixed amount throughout the model. Two additional parameters used during calibration were weight-matrix multipliers, which change an array value by varying amounts throughout the model. The weight matrices were based on the lateral hydraulic conductivity distributions from aquifer tests within the upper and lower Catahoula aquifers (layers 2 and 4) respectively. No weight matrix was generated for layer 3 because the available data for the middle Catahoula aquifer were from wells located exclusively in Hattiesburg. The weight matrices define hydraulic conductivity variations over the model area within individual aquifers. Weight-matrix multipliers are used to modify the matrices because the best estimates of the difference in hydraulic conductivity from one location to another are not the same as the initial estimate of the hydraulic conductivity distribution. The combined effect of the global and weight matrix multipliers is shown in figure 21. Additional information on the use of weight-matrix multipliers may be found in Halford (1992). A uniform storage coefficient of $3x10^{-4}$ (the average value from available aquifer tests of the lower Catahoula) was assigned to each layer and not adjusted to calibrate the model. The use of a uniform storage coefficient was based on the insensitivity of models with source/sink upper boundaries to changes in storage coefficient and not on the certainty with which this value was known.

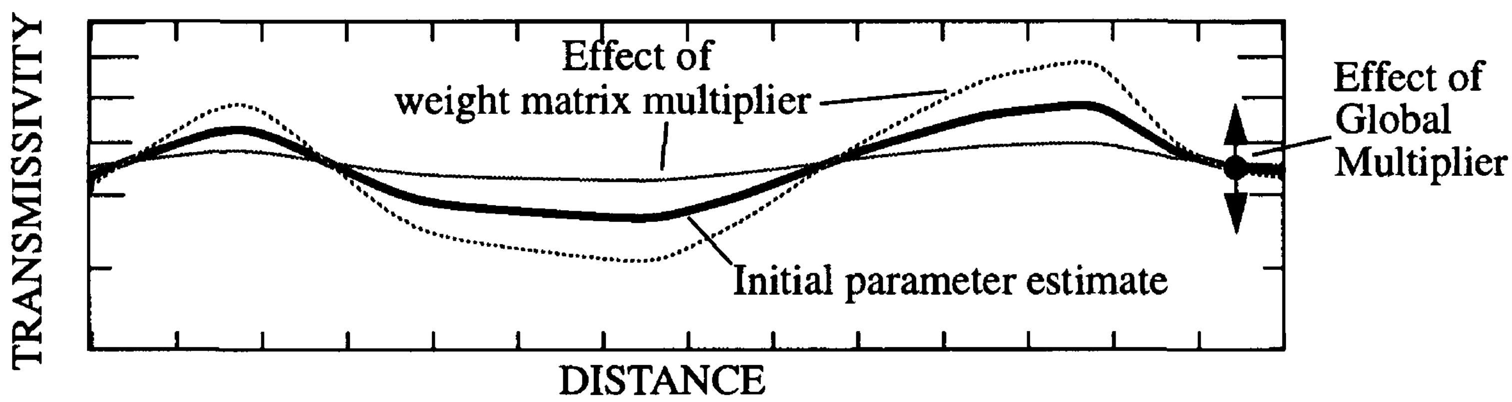


Figure 21. Effect of parameter modifiers as applied to a hypothetical section of lateral hydraulic conductivity.

Calibration improvement was determined by decreases in root-mean-square error (RMSE) which is defined by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (h_s - h_m)^2}{N}} ,$$

where

h_s is the simulated water level in feet,

h_m is the measured water level in feet, and

N is the total number of water-level comparisons.

As measured water levels rarely coincide with node locations, simulated water levels were interpolated laterally to points of measurement from surrounding nodes. Simulated water levels were interpolated because they were assumed to be part of a continuous distribution representing the aquifer. Vertical interpolation usually is inappropriate because model layers correspond to confined aquifers and the water levels are considered discontinuous across layers.

Model calibration also was facilitated by a parameter estimation program (Halford, 1992). The parameter estimation process began by using the model to establish the initial differences between simulated and measured water levels. These differences, or residuals, were minimized by the parameter estimation program. The sensitivity coefficients, the derivatives of simulated water-level change with respect to parameter change, were calculated by the influence coefficient method (Yeh, 1986) using the initial model results. This method required changing each parameter a small amount and using MODFLOW to compute new water levels. A quasi-Newton procedure (Gill and others, 1981, p. 137) was used to compute new values of the parameters that should improve the model. The model was updated to reflect the latest parameter estimates and a new set of residuals was calculated. The entire process of changing a parameter in the model, calculating new residuals, and computing a new value for the parameter, was continued iteratively until model error or model-error change was reduced to a specified level or until a specified number of iterations were made.

Steady-State Simulation

A steady-state version of the model was used for preliminary parameter estimation. Because only one set of water levels described the steady-state flow system and the model solved for them, the initial water levels in layers 2, 3, and 4 did not need to be representative of the water levels being simulated. The period from 1980 to 1981 was used for steady-state calibration because a comprehensive water-level survey was completed in 1981 and the system was close to equilibrium conditions. Hydrographs indicate that during this period water levels, on average, were neither rising or declining (figs. 14-16). Pumpage data for the steady-state simulation were based on water-use data collected for 1980.

After calibration, pumpage was removed from the steady-state model to simulate predevelopment conditions. The resulting potentiometric surfaces for the upper, middle, and lower Catahoula aquifers (fig. 22) indicate ground water flows from the outcrop areas toward the gulf coast. In the Laurel and Hattiesburg areas, the simulated predevelopment surfaces agree with the ground-water flow pattern from the gulf coast regional aquifer-system analysis by Martin and Whiteman (1989, fig. 49). The simulated potentiometric surfaces provided the initial water levels for the transient-state simulations.

The volumetric flow budget for the Catahoula aquifer system prior to development is shown schematically in figure 23. The left side of the diagram represents the part of the aquifer system in the outcrop area of the Catahoula aquifer system, and the right side represents the downdip area of the aquifer system. The arrows drawn between the various layers show the flow across the boundary between those layers, and the arrows drawn between the outcrop area and the downdip area show the amount of water moving through each layer. The amounts of water that move in and out of a layer within the outcrop or downdip area represent the shallow flow system, whereas the water in the three deeper flow systems can be inferred from the net flow amounts.

The predevelopment flow rate through the Catahoula aquifer system was about 29 Mgal/d, of which about 12 Mgal/d entered the middle Catahoula and nearly 8 Mgal/d entered the upper Catahoula aquifer in the outcrop area (fig. 23). The remaining 9 Mgal/d entered the aquifer system in the downdip area. The inflow of 20 Mgal/d translates into an effective recharge rate of 0.13 in/yr over a 3,300 mi^2 area, compared to the potential recharge of 3 to 6 in/yr in the outcrop area. The large differences are the result of a substantial and relatively immediate discharge of infiltrated rainfall to nearby streams in the outcrop area that is not simulated by this model. The net flow rate downgradient from the outcrop area was about 10 Mgal/d.

Transient Simulation

The response of the Catahoula aquifer system to ground-water pumping was simulated from 1941 to 1992 using eight stress periods: 1941-57, 1958-62, 1963-67, 1967-72, 1973-77, 1978-82, 1983-87, and 1988-92. Five-year stress periods were used from 1958 to 1992 because the most complete pumpage data were collected for the years 1960, 1965, 1970, 1975, 1980, 1985, and 1990. Pumpage during the first stress period, 1941-57, was approximated as half the 1960 rates. Pumpage was distributed spatially by assigning the locations shown in figure 11 to whatever model cell surrounded it.

Simulated water levels also were interpolated to the time a water level was measured. To avoid undue bias toward wells with a large number of water-level measurements, only one average measured water level from each of the simulation periods of 1941-57, 1958-62, 1963-67, 1968-72, 1973-77, 1978-82,

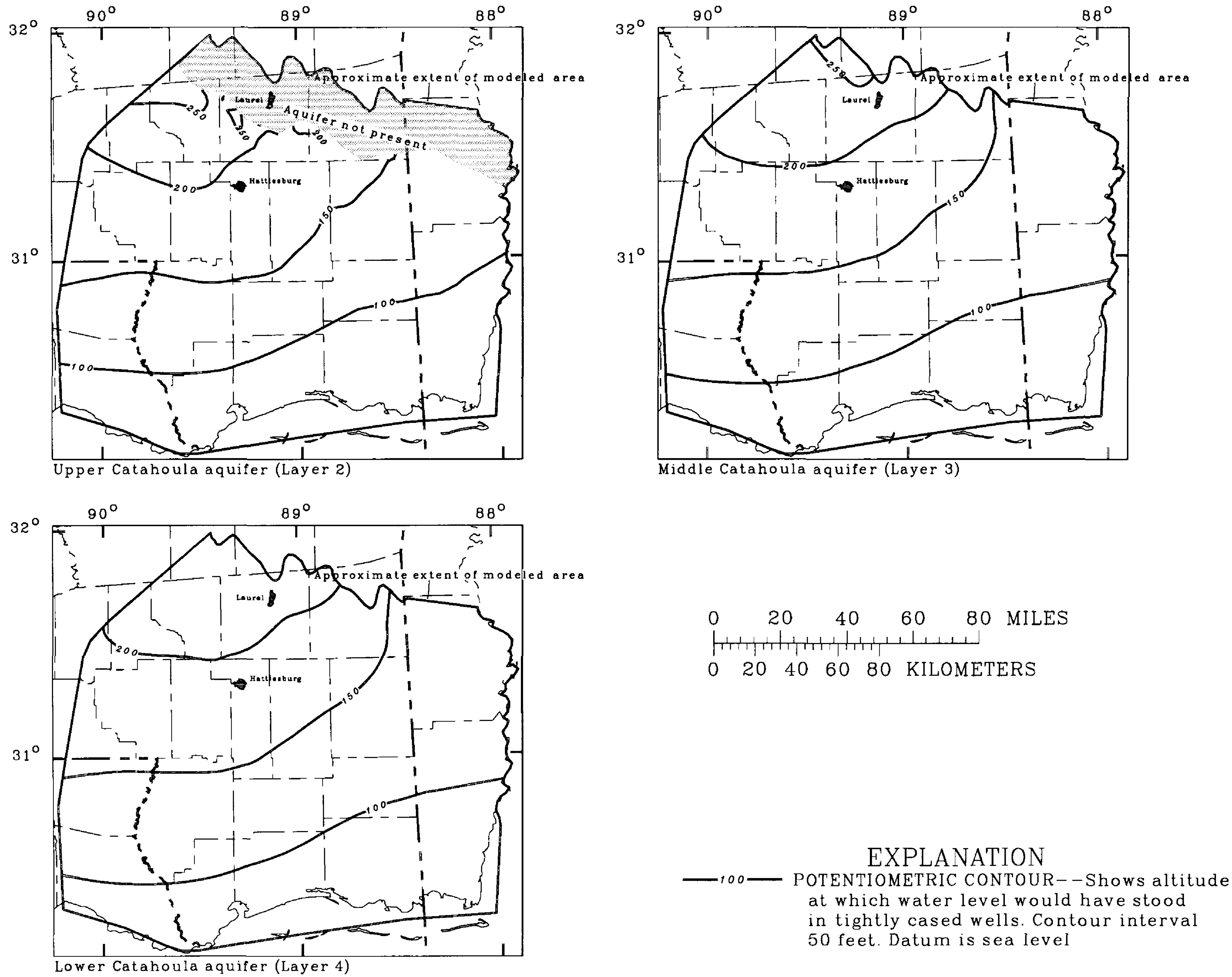


Figure 22. Simulated predevelopment potentiometric surfaces of the upper, middle, and lower Catahoula aquifers in the modeled area.

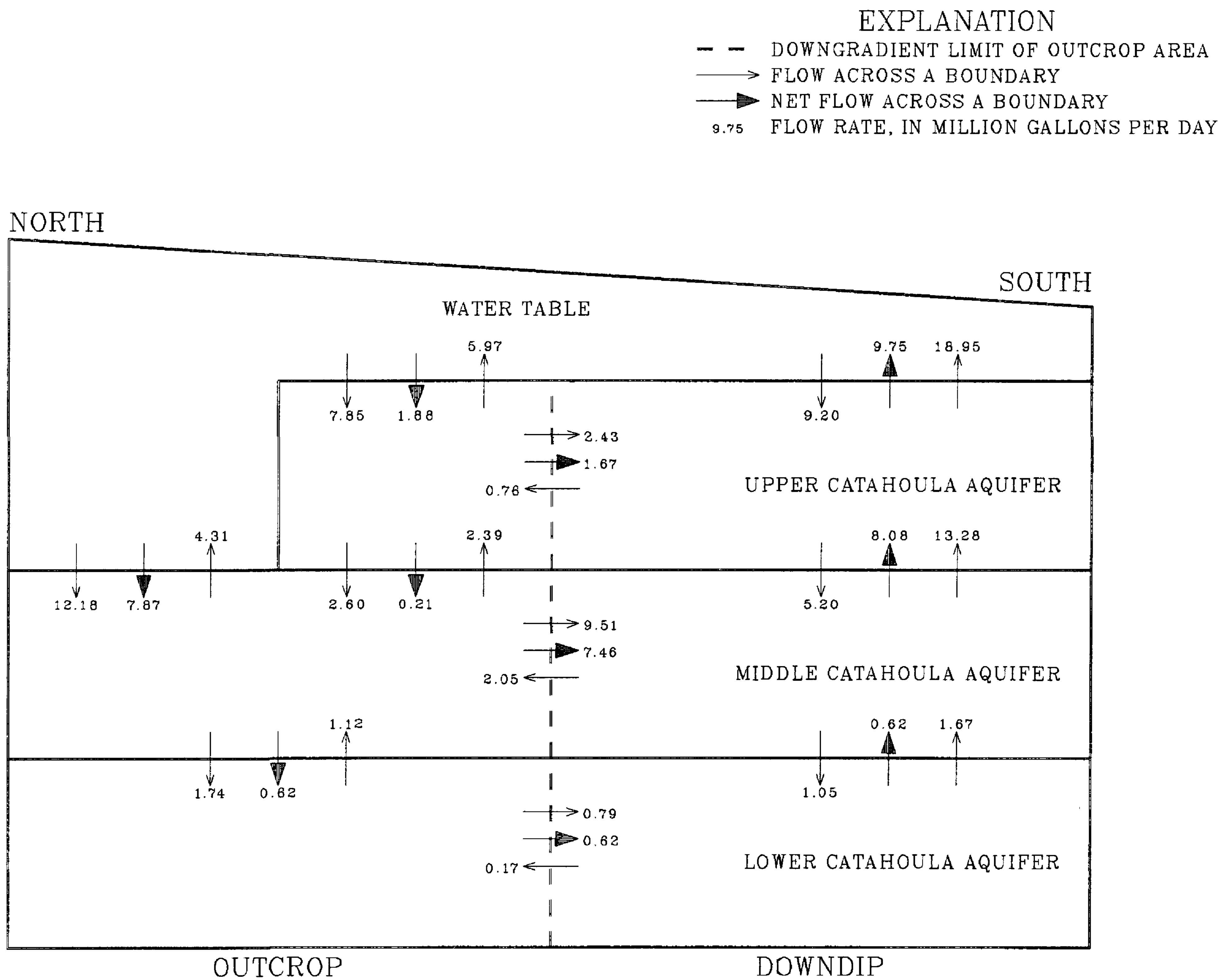


Figure 23. Simulated predevelopment volumetric flow budget for the Catahoula aquifer system in the modeled area.

1983-87, and 1988-92 was used for comparison. For example, for a well having 200 water-level measurements made uniformly across four periods, only four comparisons between simulated and measured water levels were made. Each measured water level used for comparison was an average of 50 measurements from each period.

The error statistics for the calibrated model over all stress periods are:

RMSE	16.92 ft
Average	1.84 ft
Maximum	38.57 ft
Minimum	-35.43 ft
Standard deviation	16.92 ft.

Measured water levels were obtained from historical records and from water-level surveys conducted during 1981 and 1991. The greater number of water-level measurements available after 1980 biased model calibration toward the last three stress periods (1978-92). The simulated potentiometric surfaces of the Catahoula aquifer system for 1992 agreed reasonably well with measured water levels (fig. 24). The cones of depression in the upper and middle Catahoula aquifers near Hattiesburg, and the cones in the lower Catahoula near Laurel and near Hattiesburg, are reflected in the simulated potentiometric surfaces. Residuals from the last stress period (1988-92) generally show the smallest differences between simulated and measured values in the Laurel and Hattiesburg areas. Simulated and measured water levels from the calibrated model are listed in table 3.

The period of record for the hydrographs used to compare measured and simulated water levels was less than the total simulation period. Simulated water levels agreed well with hydrograph records (figs. 25-27) but generally tended to be higher. The average model error was 2 ft based on 85 observations. Agreement between simulated and measured water levels was best for wells 67F020 (fig. 25) and 35D130 (fig. 26). The worst match between simulated and measured water levels occurred at well 35L079 (fig. 27), where the simulated water levels were consistently higher than the measured water levels. However, even for this well the trend in simulated water levels was in close agreement with the trend in measured water levels.

Simulated budget results at the end of stress period 8 (1988-92) are shown in figure 28. Approximately 55 Mgal/d of water entered the Catahoula aquifer system during this period, and about 1.9 Mgal/d was released from storage. This rate of inflow was about 25 Mgal/d more than during predevelopment and some predevelopment-flow directions were altered. About 37 Mgal/d, or 67 percent of all inflow to the aquifers, occurred as recharge in the outcrop area under 1992 conditions. Most of the flow leaving the Catahoula aquifer was by pumpage (38 Mgal/d or 69 percent). The remaining discharge (17 Mgal/d or 31 percent) occurred as leakage to overlying aquifers. The rate of leakage to overlying aquifers during 1992 was 42 percent less than the corresponding predevelopment rate. Net flow in the downdip area, which had been upward to overlying model layers, was reversed under 1992 conditions.

Lateral flow directions also were altered from predevelopment to 1992 conditions. Flow in the Catahoula aquifer system converged from all directions toward pumping centers in Laurel and Hattiesburg (fig. 24) during 1992. Water levels in the lower Catahoula aquifer, the most heavily pumped aquifer, were as much as 130 ft lower in Laurel and 100 ft lower in Hattiesburg (fig. 29) than predevelopment levels. Water-level declines were less than 30 ft in all aquifers south of Forrest County and east of Jones County.

Calibrated leakance values for all confining unit arrays between and above the Catahoula aquifer system were highest toward the outcrop of the modeled area and generally decreased from north to south (figs. 30-32). Leakance values ranged from greater than

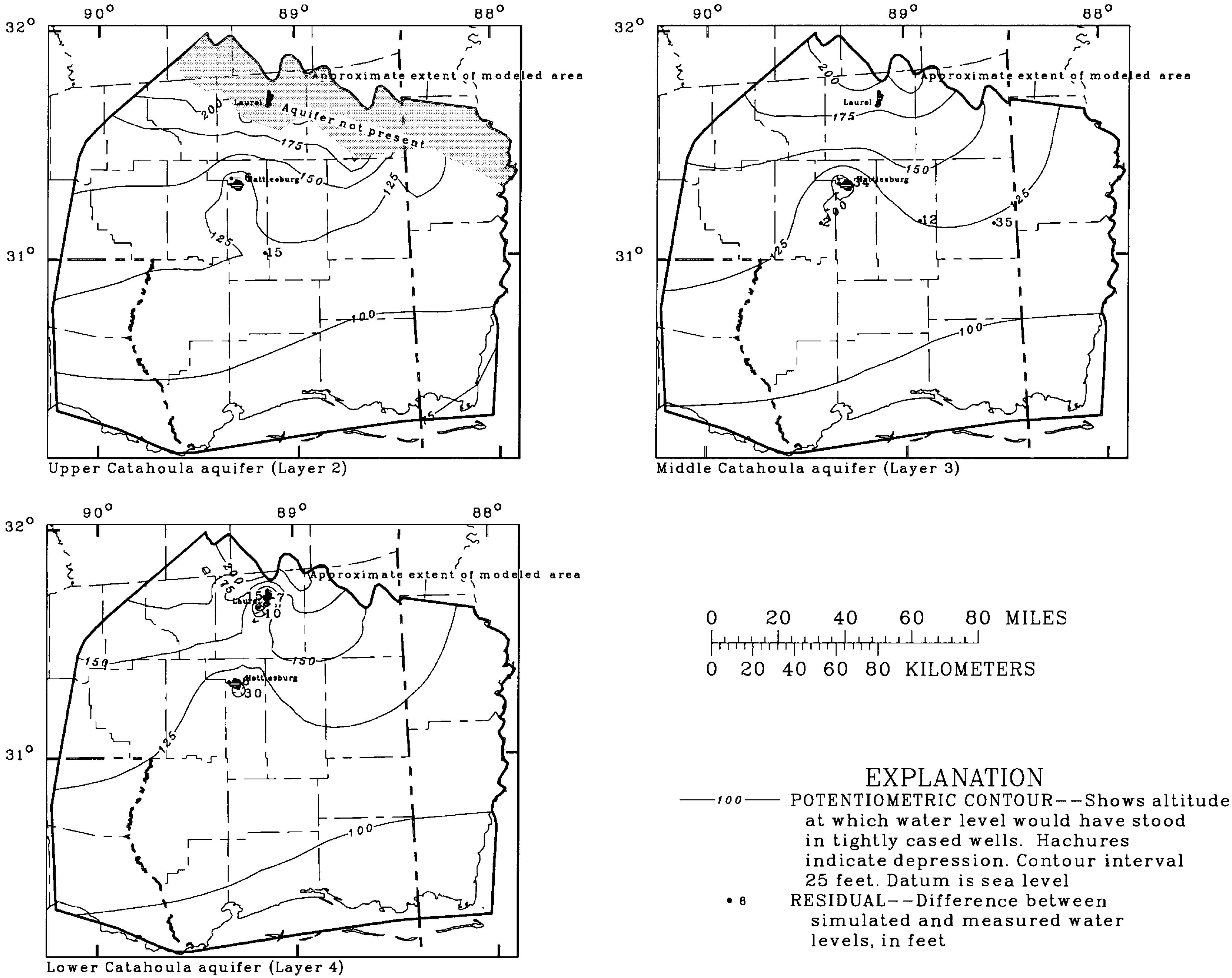


Figure 24. Simulated potentiometric surfaces of the upper, middle, and lower Catahoula aquifers in the modeled area in 1992.

Table 3. Simulated and measured water levels used to calibrate the transient model

Layer	Well	Simulated	Measured	Residual
	Stress period 1 (1941-57)			
2	35D130	163.69	156.60	7.09
2	35D130	160.87	157.32	3.55
2	35D130	160.70	152.76	7.94
4	67C034	166.79	149.00	17.79
4	67G104	160.89	149.00	11.89
	Stress period 2 (1958-62)			
2	35D130	142.04	146.23	-4.19
4	67G104	107.33	128.01	-20.68
	Stress period 3 (1963-67)			
4	153N001	175.09	157.85	17.24
4	67G104	105.72	122.18	-16.46
	Stress period 4 (1968-72)			
2	35L079	138.30	122.29	16.01
4	67G004	89.30	92.32	-3.03
4	67G004	87.17	76.72	10.45
	Stress period 5 (1973-77)			
2	91G006	159.30	155.00	4.30
2	67J037	161.22	167.70	-6.48
2	35L079	135.38	119.24	16.14
3	41D001	138.33	159.54	-21.21
3	73L063	132.44	127.00	5.44
3	111M011	136.32	125.90	10.42
4	67D072	183.13	187.04	-3.91
4	67G004	68.81	88.35	-19.54
4	67F020	69.59	80.65	-11.06
4	67G055	113.11	99.16	13.95
	Stress period 6 (1978-82)			
2	35L079	131.99	114.49	17.50
2	35B115	142.55	138.58	3.97
3	41A021	154.84	165.50	-10.66
3	41U025	120.68	96.00	24.68
3	73L063	128.58	118.37	10.21
3	35B002	77.04	84.40	-7.37
3	111M011	131.51	119.95	11.56
3	111Q024	121.64	98.33	23.31
4	35D008	86.63	67.85	18.78
4	67J061	157.85	166.30	-8.45
4	67N012	156.43	169.50	-13.08
4	111H009	136.46	115.20	21.26
4	67F020	63.86	74.26	-10.40
4	35B119	142.11	160.88	-18.77
4	35D008	80.53	62.03	18.50
4	67G055	110.27	99.25	11.02
4	67L051	148.72	135.40	13.32
4	111C040	139.08	142.08	-3.00
	Stress period 7 (1983-87)			
2	35B006	115.29	126.36	-11.08
2	35B006	111.37	127.23	-15.86
3	35E214	119.63	116.72	2.91
3	41L019	133.61	117.00	16.61
3	111R002	118.58	81.30	37.28
3	73L063	107.63	111.00	-3.37
3	41P039	124.13	94.15	29.98
3	111M011	125.95	117.67	8.28
4	35B071	128.90	154.75	-25.85
4	35B102	136.33	155.65	-19.32
4	35C064	123.00	145.81	-22.81
4	67G001	113.89	119.00	-5.12
4	67B079	163.14	156.94	6.20
4	67A003	194.37	218.10	-23.73
4	67H035	171.02	197.43	-26.41
4	67J050	158.56	172.00	-13.44
4	35D008	86.00	63.17	22.83
4	67C031	90.55	81.85	8.70
4	67C034	90.11	82.95	7.16
4	67C067	127.04	88.47	38.57
4	67C096	99.74	86.02	13.72
4	67C153	71.05	83.75	-12.70
4	67F020	58.72	64.16	-5.44
4	67F044	39.81	74.38	-34.57
4	67F059	68.03	76.76	-8.73
4	67F060	81.16	61.25	19.91
4	67F061	48.49	57.99	-9.50
4	67F062	70.24	73.99	-3.75
4	67F063	79.69	60.10	19.59
4	35D107	108.59	121.00	-12.41
4	67G055	86.18	77.52	8.66
	Stress period 8 (1988-92)			
2	35L079	124.88	109.22	15.66
2	35B006	115.25	127.00	-11.75
2	35L079	124.70	109.64	15.06
3	35D108	86.41	121.84	-35.43
3	35D108	86.64	120.42	-33.78
3	41P039	123.26	88.60	34.66
3	73L063	111.84	110.18	1.66
3	111M011	125.75	113.50	12.25
4	73E214	111.51	119.25	-7.74
4	35D008	87.55	57.71	29.84
4	67C034	93.61	78.85	14.76
4	67F020	81.28	71.54	9.74
4	67G055	86.09	92.69	-6.60
4	73E214	112.12	118.25	-6.13

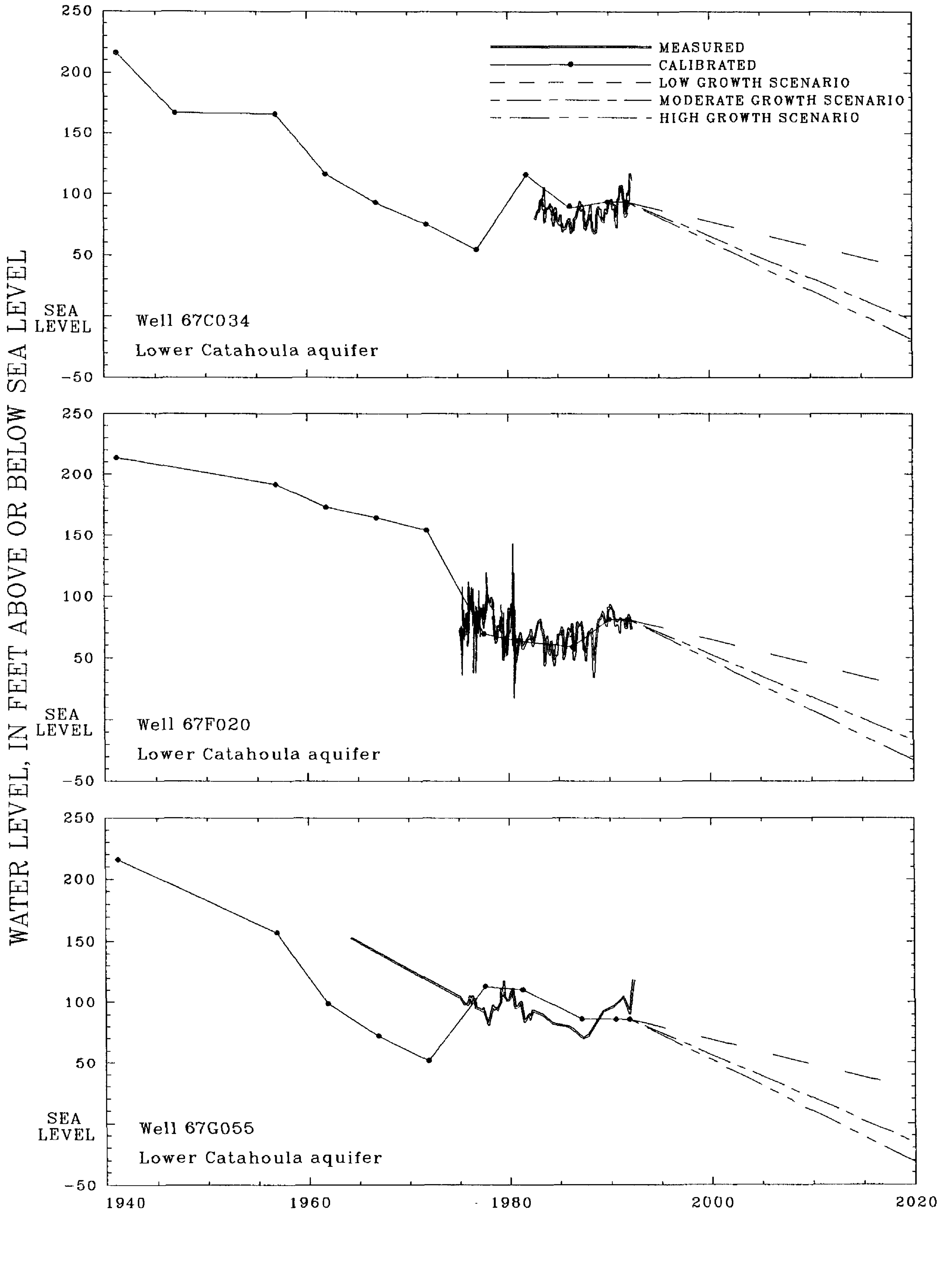


Figure 25. Measured and simulated water levels for wells 67C034, 67F020, and 67G055 near Laurel, Mississippi.

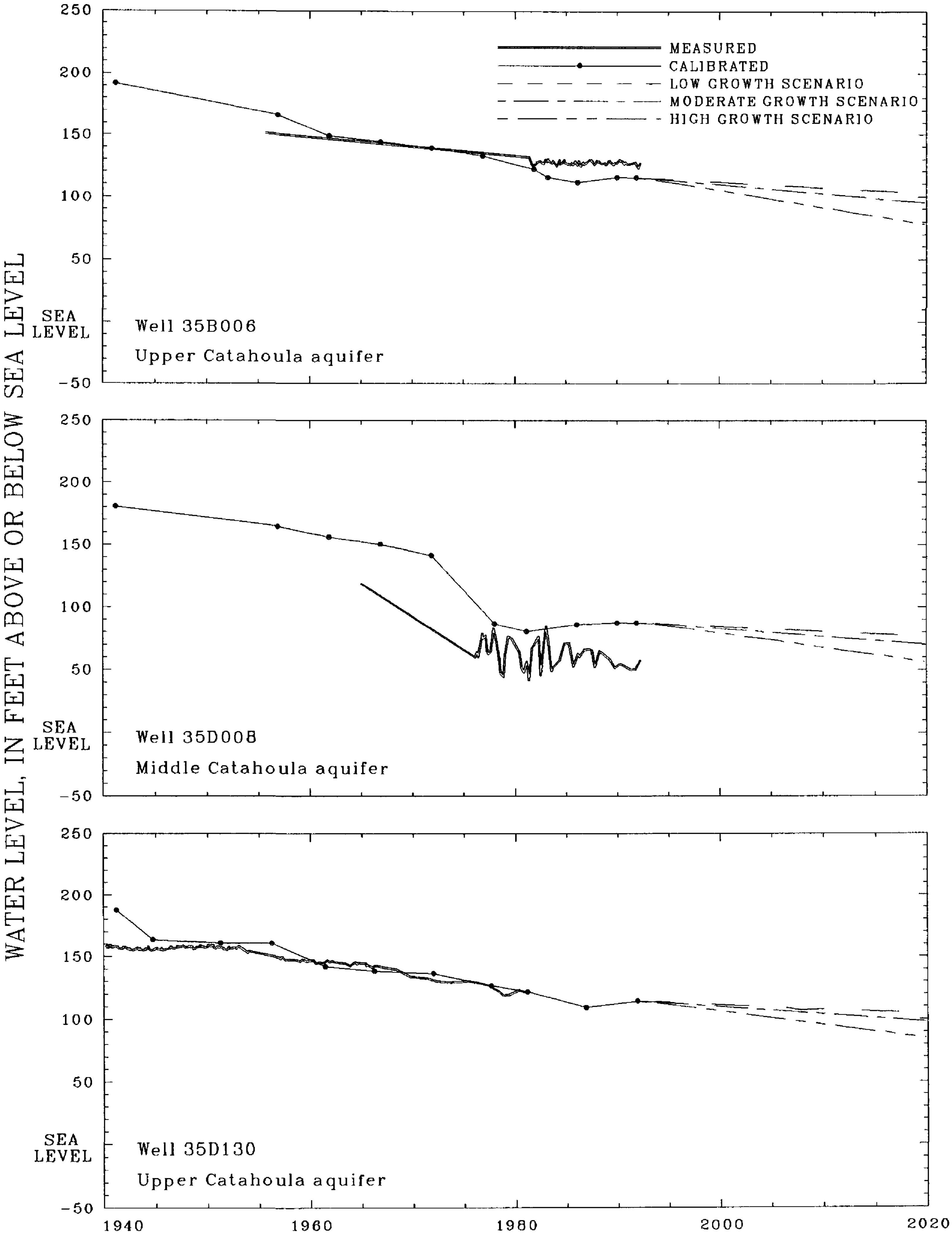


Figure 26. Measured and simulated water levels for wells 35B006, 35D008, and 35D130 near Hattiesburg, Mississippi.

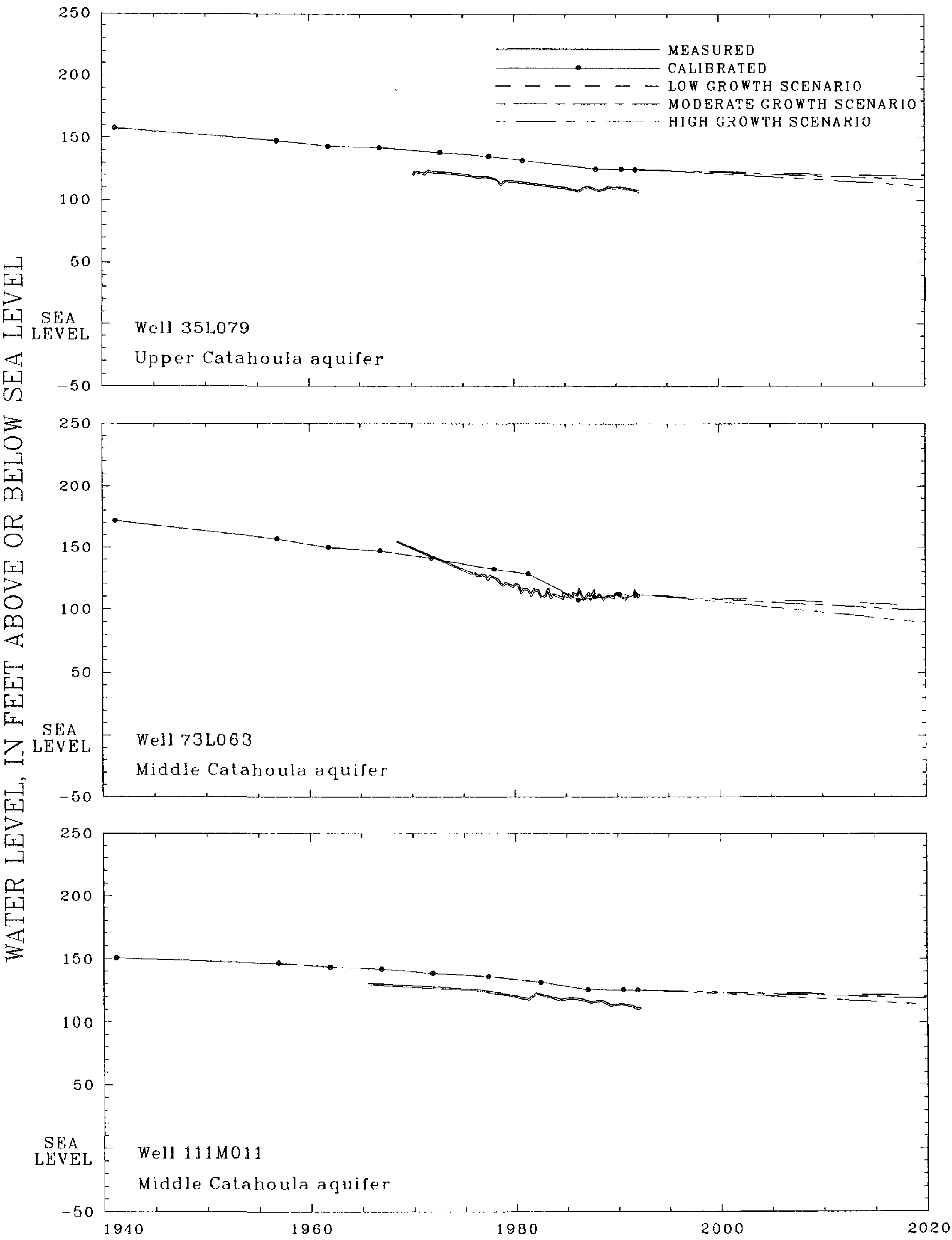


Figure 27. Measured and simulated water levels for wells 35L079, 73L063, and 111M011 generally unaffected by major pumping in the modeled area.

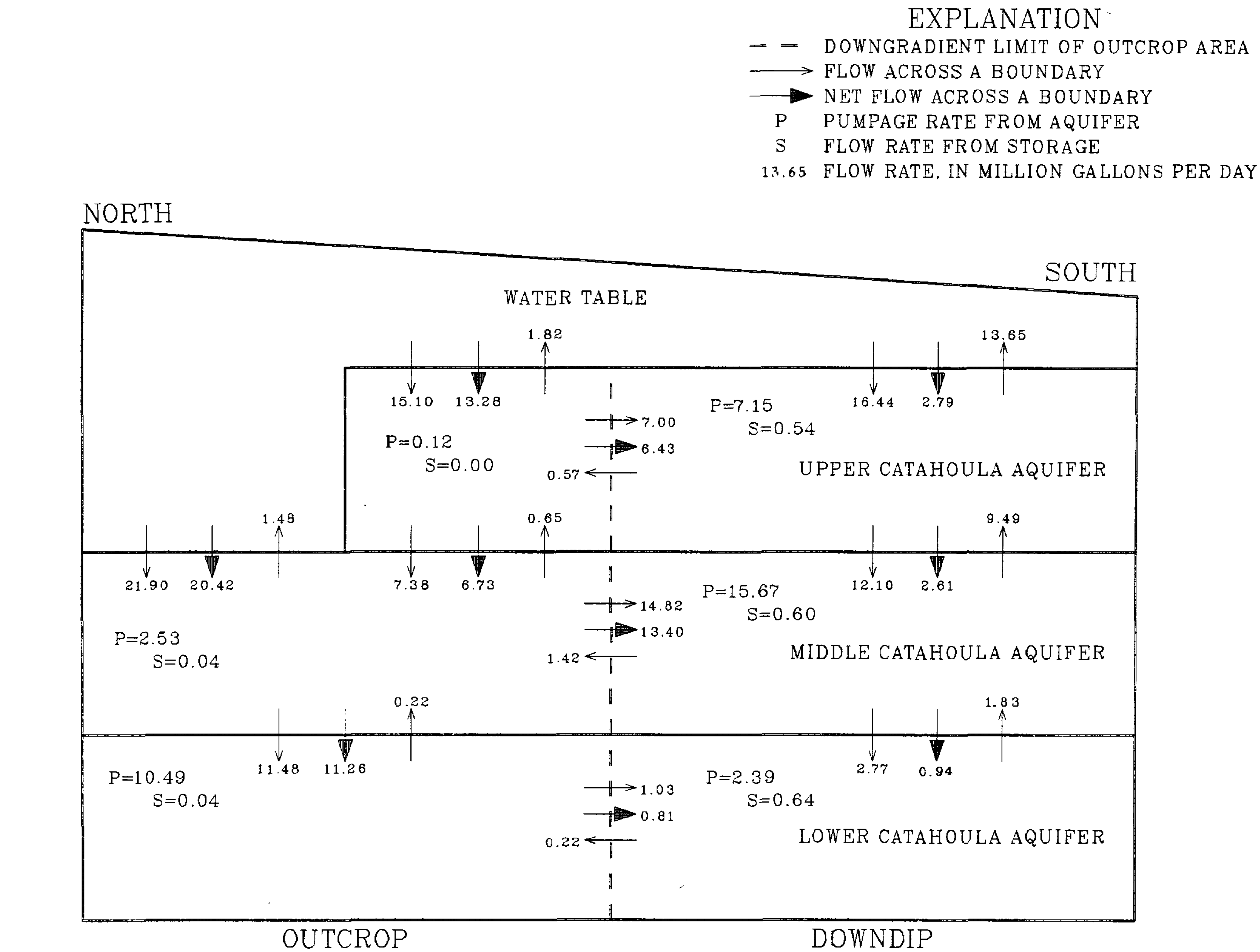


Figure 28. Simulated volumetric flow budget for the Catahoula aquifer system in the modeled area in 1992.

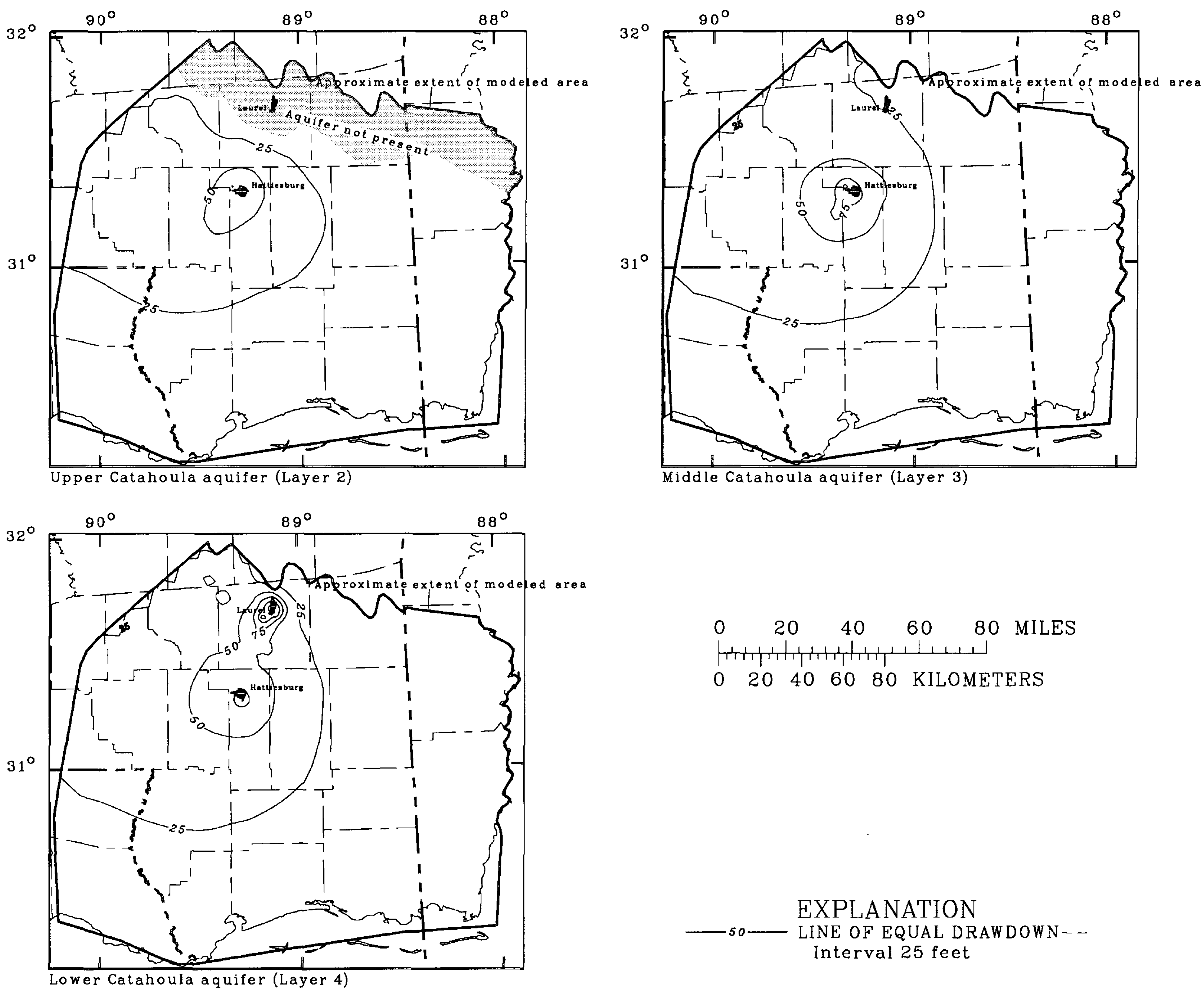
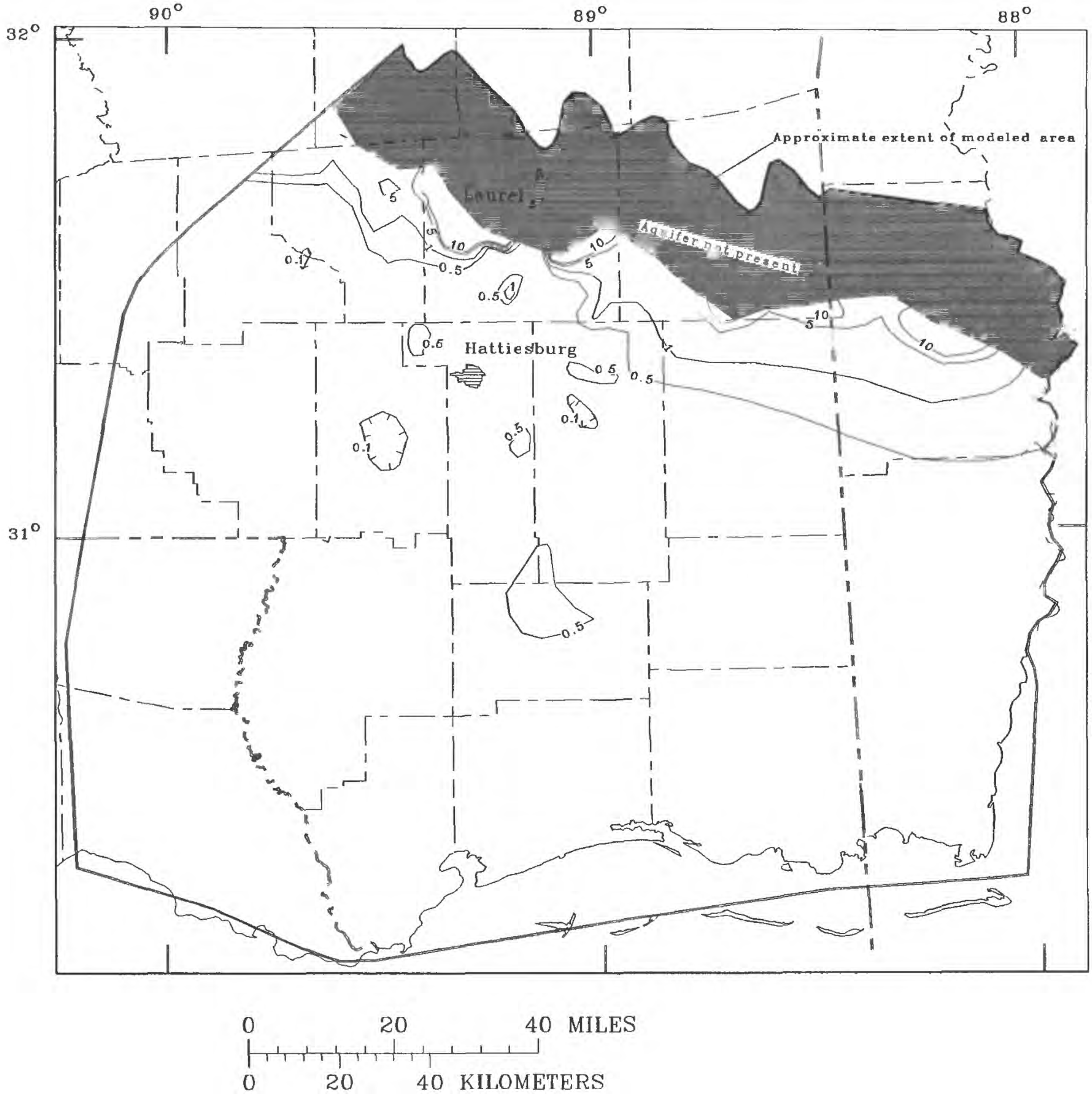


Figure 29. Simulated water-level declines from predevelopment to 1992 in the upper, middle, and lower Catahoulamaquifersmin the modeled area.



EXPLANATION

——10—— LINE OF EQUAL LEAKANCE--
Vertical hydraulic conductivity/confining unit thickness. Hachures indicate lesser leakance. Interval, in feet per day per foot $x10^{-6}$, is variable

Figure 30. Calibrated leakance of confining units above the upper Catahoula aquifer in the modeled area.

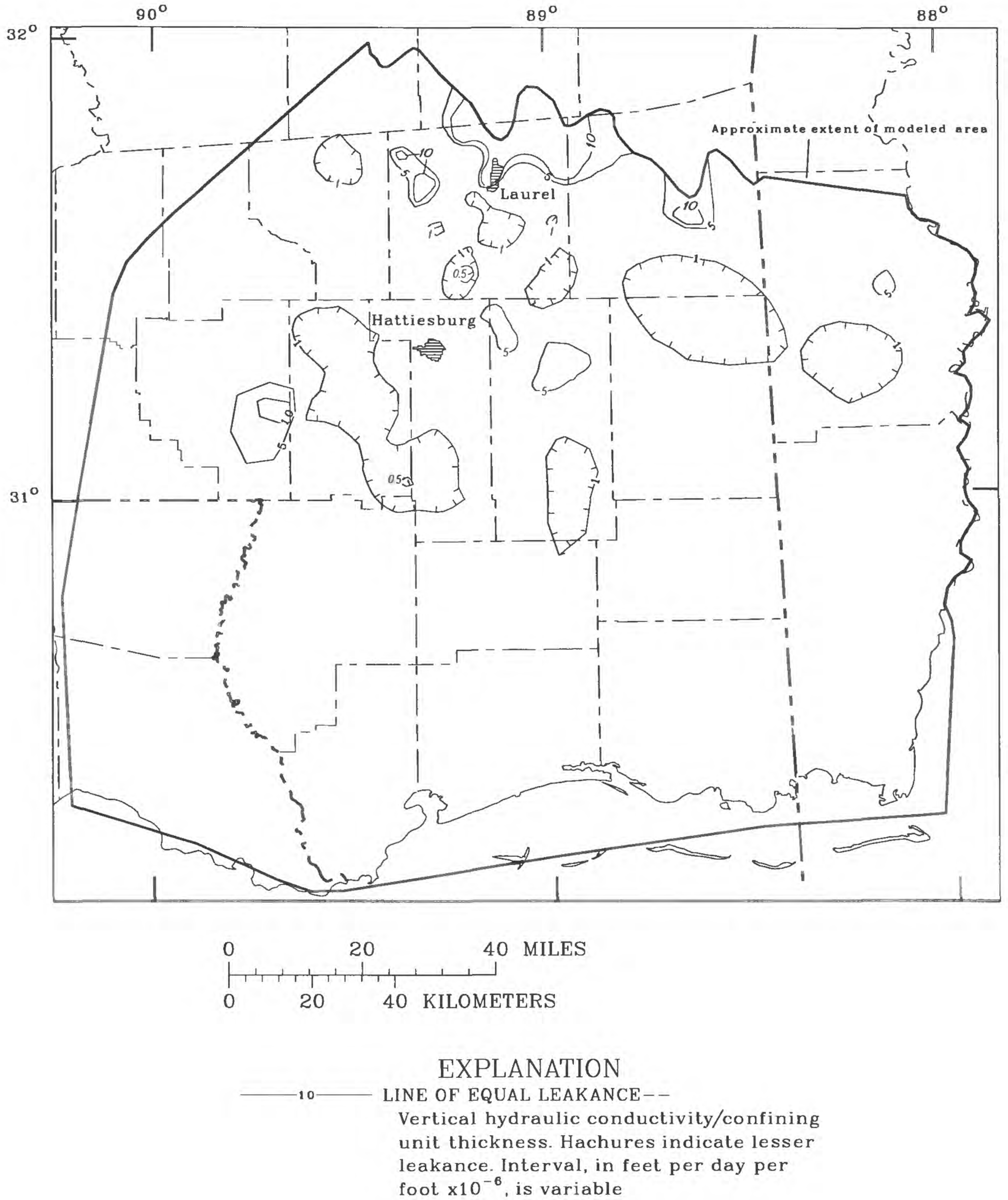


Figure 31. Calibrated leakance of confining uints above the middle Catahoula aquifer in the modeled area.

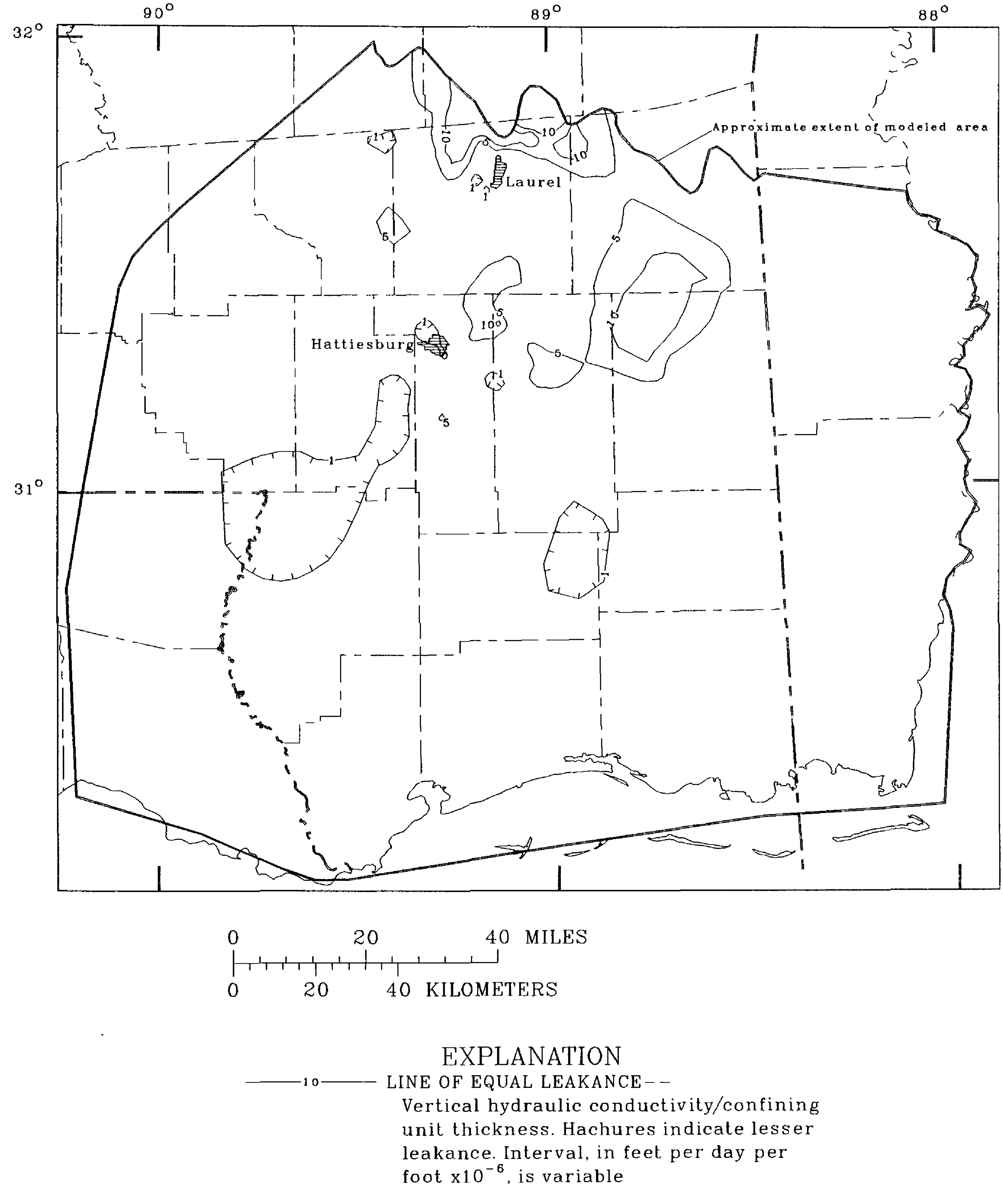


Figure 32. Calibrated leakance of confining units above the lower Catahoula aquifer in the modeled area.

$1x10^{-5}$ 1/d in Jones County to less than $5x10^{-7}$ 1/d in southeast Forrest County.

Transmissivity estimates in the Catahoula aquifer system generally were lower than transmissivities determined from aquifer tests (figs. 33-35). The effective transmissivity represented by the calibrated model arrays generally is less than the average determined from aquifer tests because individual wells in the study area are characteristically screened in the most permeable sands. These sands generally are lensoidal and discontinuous and probably are not representative of the entire volume of clastic sediments within the area corresponding to the model cell, which characteristically include sands as well as clayey-sands and clays. Spatial variation in model-estimated and measured transmissivity values was similar. Transmissivity estimates from the calibrated model ranged from 300 ft^2/d in the lower Catahoula aquifer (fig. 35) to 20,000 ft^2/d in the middle Catahoula aquifer (fig. 34) in Jones County.

Sensitivity Analysis

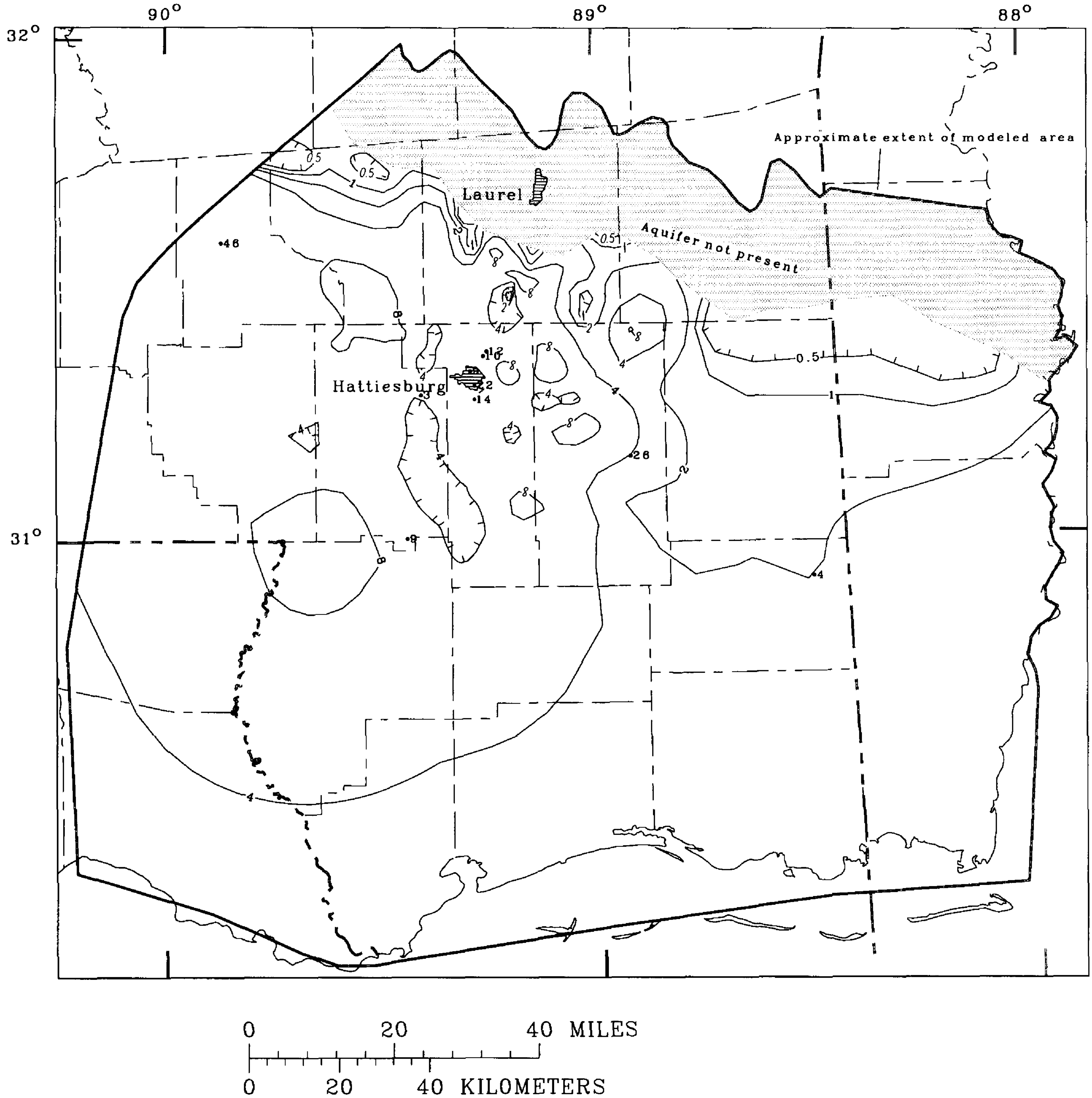
To determine how transmissivity, leakance, and storage coefficient affected simulation results, each parameter was varied, independently, over a range of four orders of magnitude. This range was greater than the uncertainties associated with these parameters but gave a more complete perspective on model sensitivity. Model sensitivity was described in terms of RMSE. The model was determined to be more sensitive to changes in transmissivity than to changes in leakance (fig. 36), and more sensitive to decreases in transmissivity and leakance than to increases. Figure 36 shows the sensitivity of the model to changing one parameter while all others are held at their calibrated values. Like other models simulating confined aquifer systems with a specified-head source/sink boundary, this model was quite insensitive to changes in storage coefficient. Boundary conditions and pumpage were not adjusted during calibration and sensitivity analysis was not performed for these parameters.

Two parameters, transmissivity and leakance, were varied simultaneously, and the sensitivity of the model to these changes is shown as a RMSE map in figure 37. The sensitivity of the model to changes in transmissivity and leakance shown in figure 36 are cross sections through the RMSE map. The model was more sensitive to decreases in transmissivity than to increases in transmissivity even when leakance values were something other than the calibrated value. This same sensitivity pattern existed for leakance even when transmissivity values were something other than the calibrated values (fig. 37). In all cases the lowest RMSE was associated with the calibrated model.

Limitations of model application

The model was developed using regional characteristics of the aquifers to determine the effects of increased pumpage on the ground-water conditions of the Laurel and Hattiesburg areas. The water level calculated by the model is an approximation of the average water level for the area included in the model grid cell, but may not be a reliable approximation of the water level in a well or a wellfield.

Most pumping from the Catahoula aquifer system is from the confined aquifer system, therefore the model was developed primarily to simulate ground-water flow and evaluate the effects of withdrawals on water levels within the confined Catahoula aquifer system. The model does not provide an analysis of flow in the parts of the Catahoula aquifers which are under unconfined conditions. Although the model can be used to identify conditions and areas where water levels might be lowered to the top of one of the aquifers, the model was not designed to simulate the change from



EXPLANATION

——2—— LINE OF EQUAL TRANSMISSIVITY--Hachures indicate lesser transmissivity. Interval variable, in 1,000 feet squared per day

•5 TRANSMISSIVITY VALUE DETERMINED FROM AQUIFER TEST--In 1,000 feet squared per day

Figure 33. Calibrated transmissivity of upper Catahoula aquifer in the modeled area.

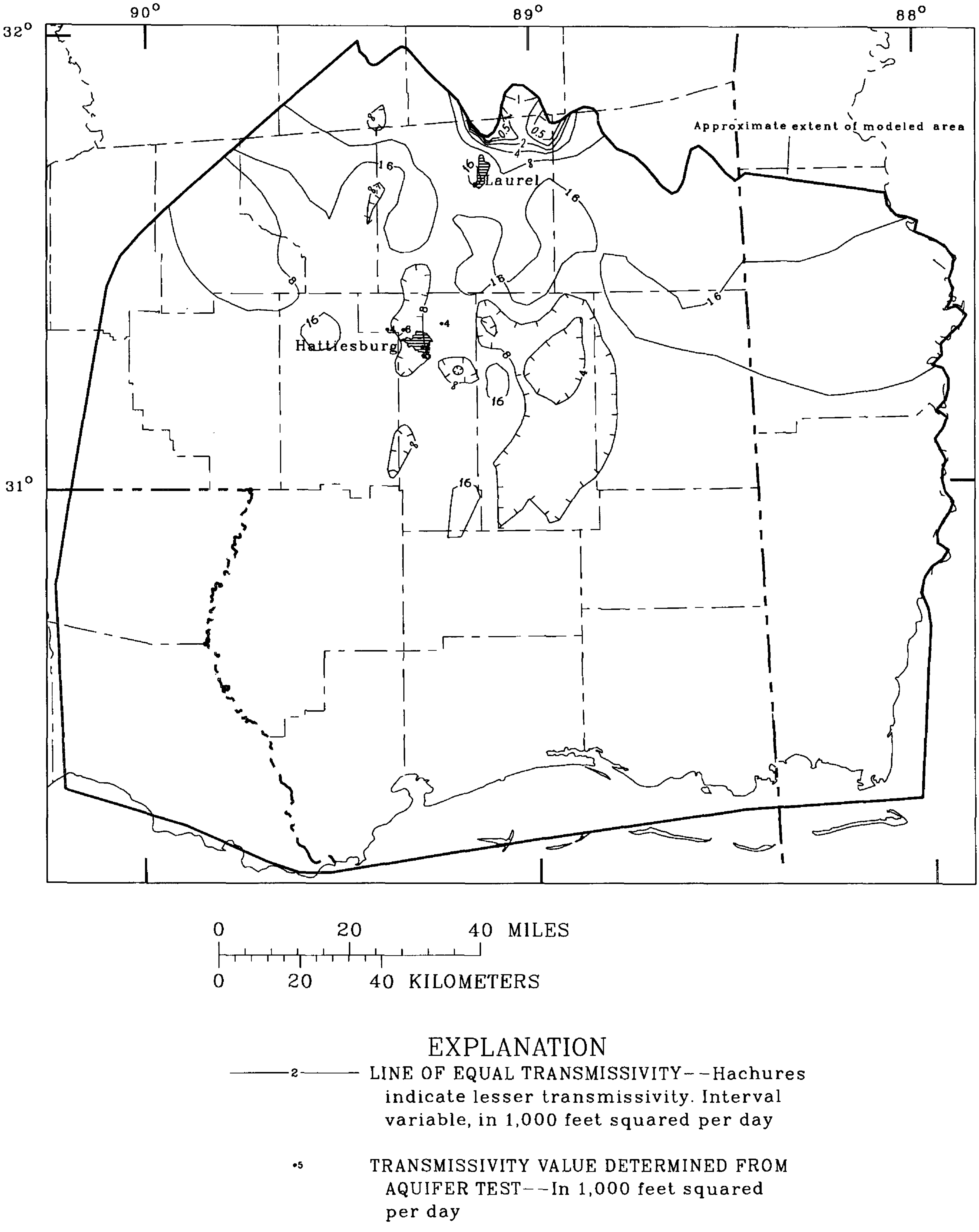
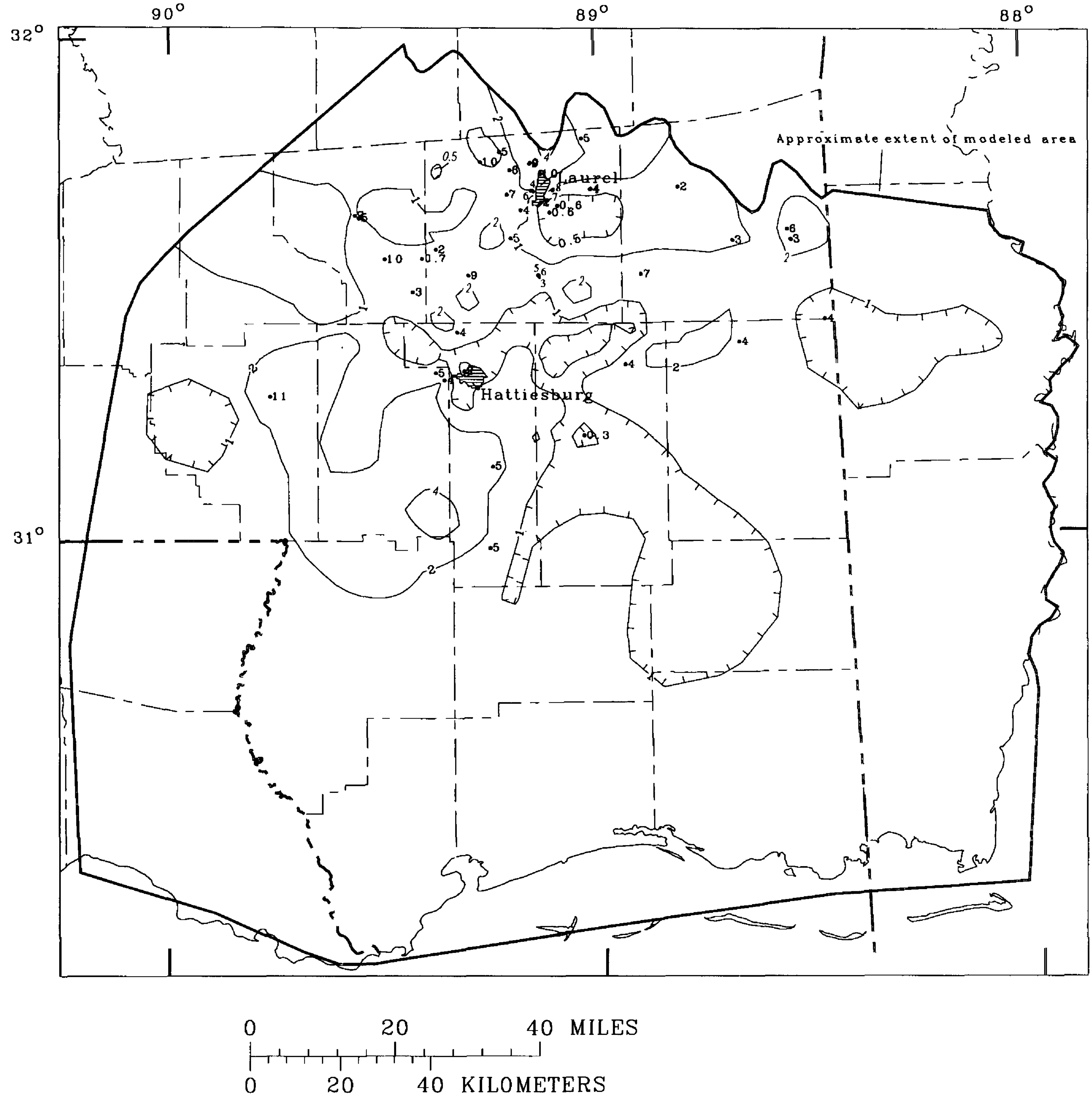


Figure 34. Calibrated transmissivity of middle Catahoula aquifer in the modeled area.



EXPLANATION

——2—— LINE OF EQUAL TRANSMISSIVITY--Hachures indicate lesser transmissivity. Interval variable, in 1,000 feet squared per day

•5 TRANSMISSIVITY VALUE DETERMINED FROM AQUIFER TEST--In 1,000 feet squared per day

Figure 35. Calibrated transmissivity of lower Catahoula aquifer in the modeled area.

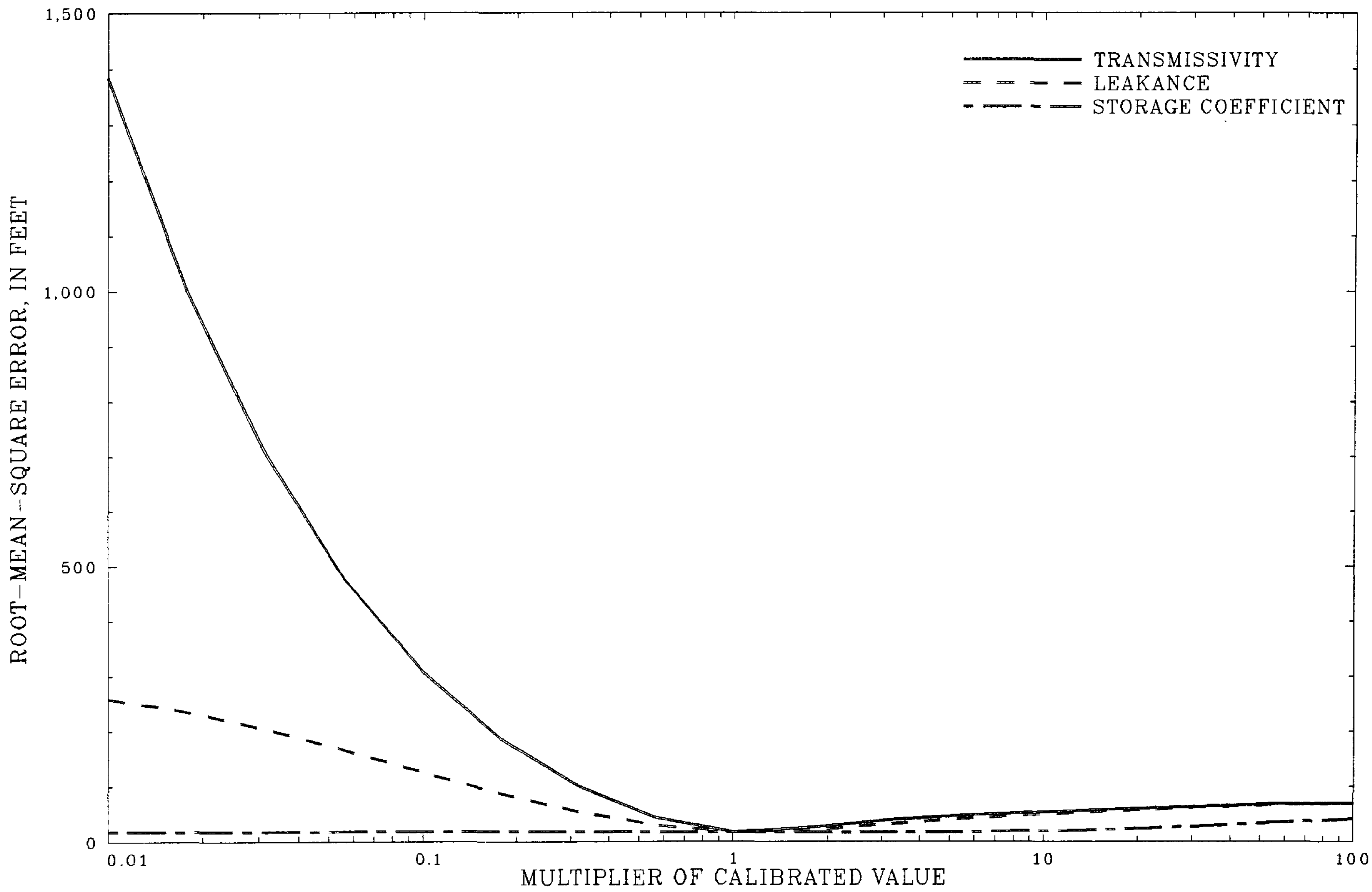
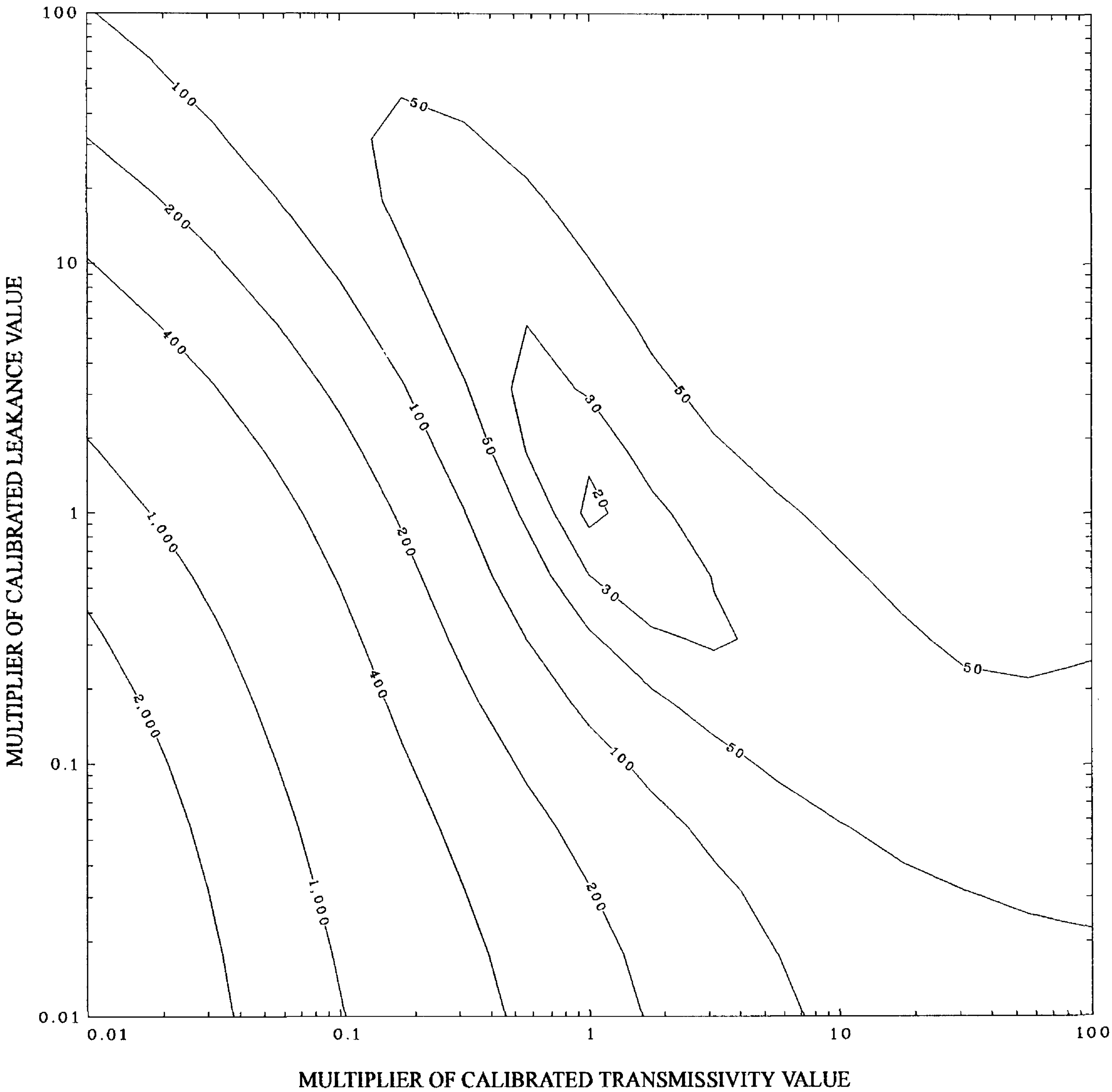


Figure 36. Model sensitivity to independent changes in transmissivity, leakance, and storage coefficient.



———500——— LINE OF EQUAL ERROR--Shows root-mean-squared error of model. Interval variable, in feet

Figure 37. Model sensitivity to simultaneous changes in transmissivity and leakance.

confined to unconfined conditions. If future pumping increased to the extent that the water level did drop below the top of an aquifer, the model would require modification to simulate the new conditions.

The western and eastern boundaries of the model are ground-water divides and were assumed to be no-flow boundaries. However, extensive pumping close to one of these boundaries could shift the location of the divide and would require modification of the model to simulate the new boundary. No such development of the Catahoula aquifers or their lithostratigraphic equivalents is anticipated.

SIMULATED AQUIFER RESPONSE TO PUMPING SCENARIOS

Three scenarios were simulated to estimate the response of the Catahoula aquifer system to pumping changes near Laurel and Hattiesburg (table 4). The scenarios were:

1. The 1992 pumpage in Laurel was increased 2 percent per year and 1992 pumpage in Hattiesburg was increased 1.2 percent per year from 1992 to 2020, for a net increase of 6.40 Mgal/d (low-growth scenario).
2. The 1992 pumpage in Laurel was increased 3.5 percent per year and 1992 pumpage in Hattiesburg was increased 2 percent per year from 1992 to 2020, for a net increase of 10.95 Mgal/d (moderate-growth scenario).
3. The 1992 pumpage in Laurel was increased 4 percent per year and 1992 pumpage in Hattiesburg was increased 4 percent per year from 1992 to 2020, for a net increase of 17.07 Mgal/d (high-growth scenario).

Under the low-growth scenario, approximately 5 Mgal/d of additional water would enter the Catahoula aquifer system compared to 1992 conditions, with about 1.0 Mgal/d of this total released from storage (fig. 38). This quantity represents a 9 percent increase in volumetric flow over 1992 conditions. Net flow directions would be little changed compared to 1992. About 41 Mgal/d, or 69 percent of all inflow to the system, would enter in the out-

Table 4. Summary of alternate pumping scenarios with total pumpage in 2020
[Mgal/d, million gallons per day; --, not applicable]

	Laurel area		Hattiesburg area		Study area total	
	Percent growth	Pumpage (Mgal/d)	Percent growth	Pumpage (Mgal/d)	Percent growth	Pumpage (Mgal/d)
Base conditions (1992)	--	5.74	--	9.50	--	34.56
Low-growth scenario	2.0	8.95	1.2	12.69	0.7	40.97
Moderate-growth scenario	3.5	11.37	2.0	14.82	1.1	45.51
High-growth scenario	4.0	12.17	4.0	20.14	1.8	51.63

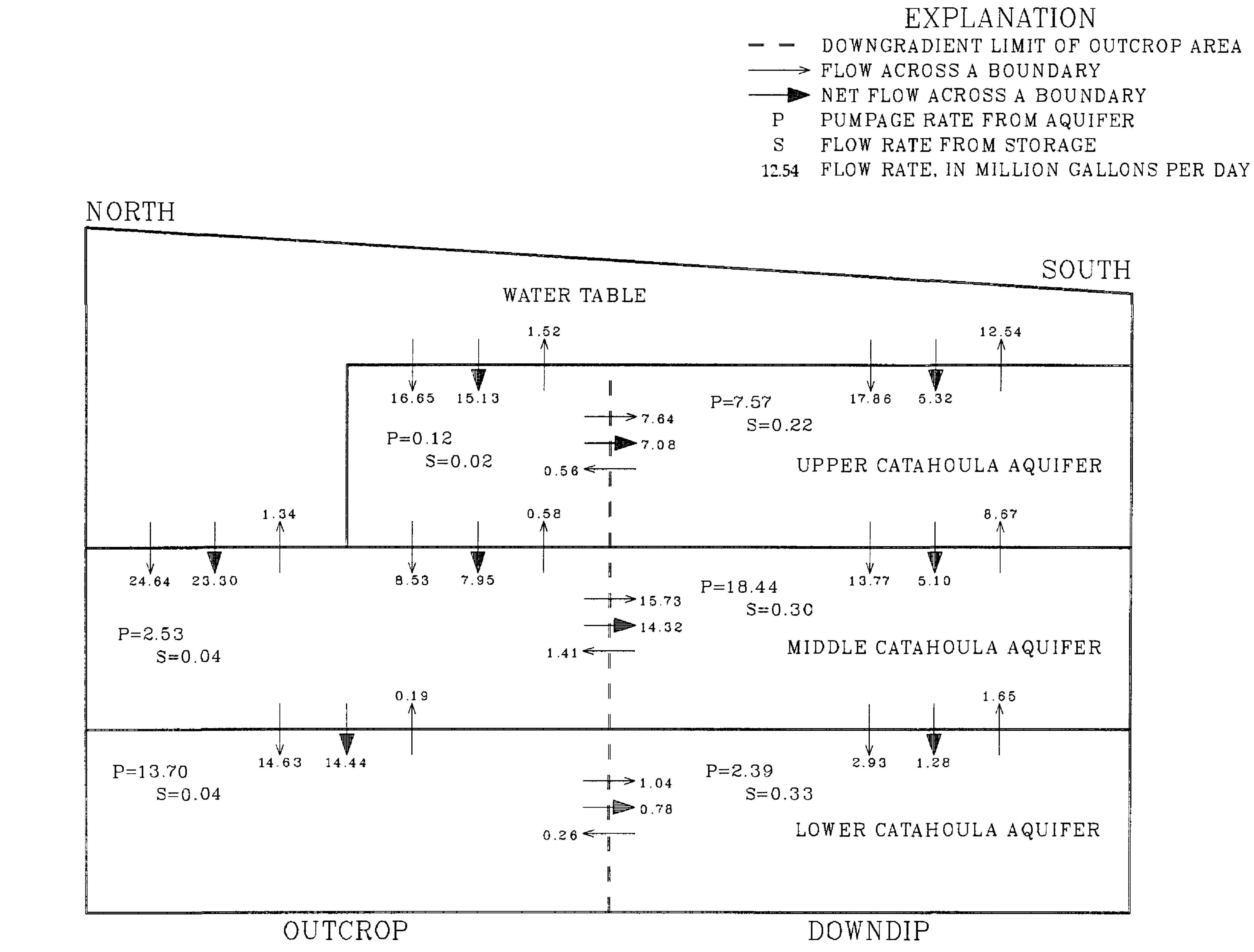


Figure 38. Simulated volumetric flow budget for the Catahoula aquifer system in 2020 at the end of the low-growth scenario.

crop area under this scenario. Most of the flow leaving the Catahoula aquifer system would be pumpage (45 Mgal/d or 74 percent). Vertical leakage to overlying aquifers would be 15 Mgal/d, which represents a small decrease compared to 1992 conditions.

Simulated changes in water levels from 1992 to 2020 for the low-growth scenario are presented in figure 39. Water-level declines would be 20 ft or less in the Hattiesburg area for the middle and upper Catahoula aquifers. Water-level declines in the lower Catahoula aquifer in the Laurel area would be about 60 ft under this scenario. Water-level declines in all other parts of the study area would be less than 10 ft.

About 64 Mgal/d of inflow to the Catahoula aquifer system would occur under the moderate-growth scenario, in which withdrawal would increase 3.5 percent each year in Laurel and 2 percent each year in Hattiesburg. About 1.6 Mgal/d of this total would be released from storage (fig. 40). This quantity represents a 16 percent increase compared to 1992 conditions. Net flow directions would be little changed compared to 1992 conditions and the low-growth scenario. About 44 Mgal/d, or 69 percent of all inflow, would enter the aquifer system in the outcrop area under this scenario. Most of the flow leaving the Catahoula aquifer system would be pumpage (49 Mgal/d or 77 percent). The remaining 15 Mgal/d of outflow would be leakage to overlying aquifers.

The simulated average water-level decline in the upper Catahoula aquifer would be 20 ft or less (fig. 41) under the moderate-growth scenario, with the largest decline occurring in the Hattiesburg area. Simulated declines in the middle Catahoula would be 40 ft or less, also with the largest declines occurring in the Hattiesburg area.The water-level decline in the lower Catahoula would be about 110 ft, which places the water level at or near the top of the aquifer. A decline in the water level below the top of an aquifer results in a change from confined to unconfined conditions within the aquifer. This change could cause dewatering of the aquifer and possible compaction of the aquifer material. The model was not developed to simulate such conditions.

Under the high-growth scenario, in which withdrawal would increase 4 percent each year in both the Laurel and Hattiesburg areas, approximately 70 Mgal/d of water would enter the Catahoula aquifer system. This quantity represents a 26 percent increase over 1992 conditions: about 2.8 Mgal/d of this total was released from storage (fig. 42). Net flow directions were little changed from 1992 conditions. About 47 Mgal/d, or 68 percent of all inflow to the system, would enter in the outcrop area under this scenario. Most of the discharge from the Catahoula aquifer system would be pumpage (55 Mgal/d or 80 percent). The remaining 14 Mgal/d of outflow would be leakage to overlying aquifers.

Under the high-growth scenario, simulated water-level declines in the upper Catahoula aquifer would be 40 ft or less, with the largest declines occurring in the Hattiesburg area (fig. 43). Water-level declines in the middle Catahoula would be about 80 ft, also with the largest declines occurring in the Hattiesburg area. The water-level decline would reach a maximum of 38 ft below the top of the lower Catahoula aquifer in the Laurel area under the high-growth scenario, about 130 ft below 1992 levels. However, with the drop in water level below the top of the aquifer, the aquifer would have changed from confined to unconfined conditions and the model was not designed to simulate this change. The magnitude of the decline in water level below the top of the aquifer would probably be less than 38 ft, as the effective storage coefficient of an unconfined aquifer is higher than a confined aquifer, yielding more water to wells and slowing the decline in water levels. Further analysis of ground-water conditions under the high-growth scenario would require modification of the model.

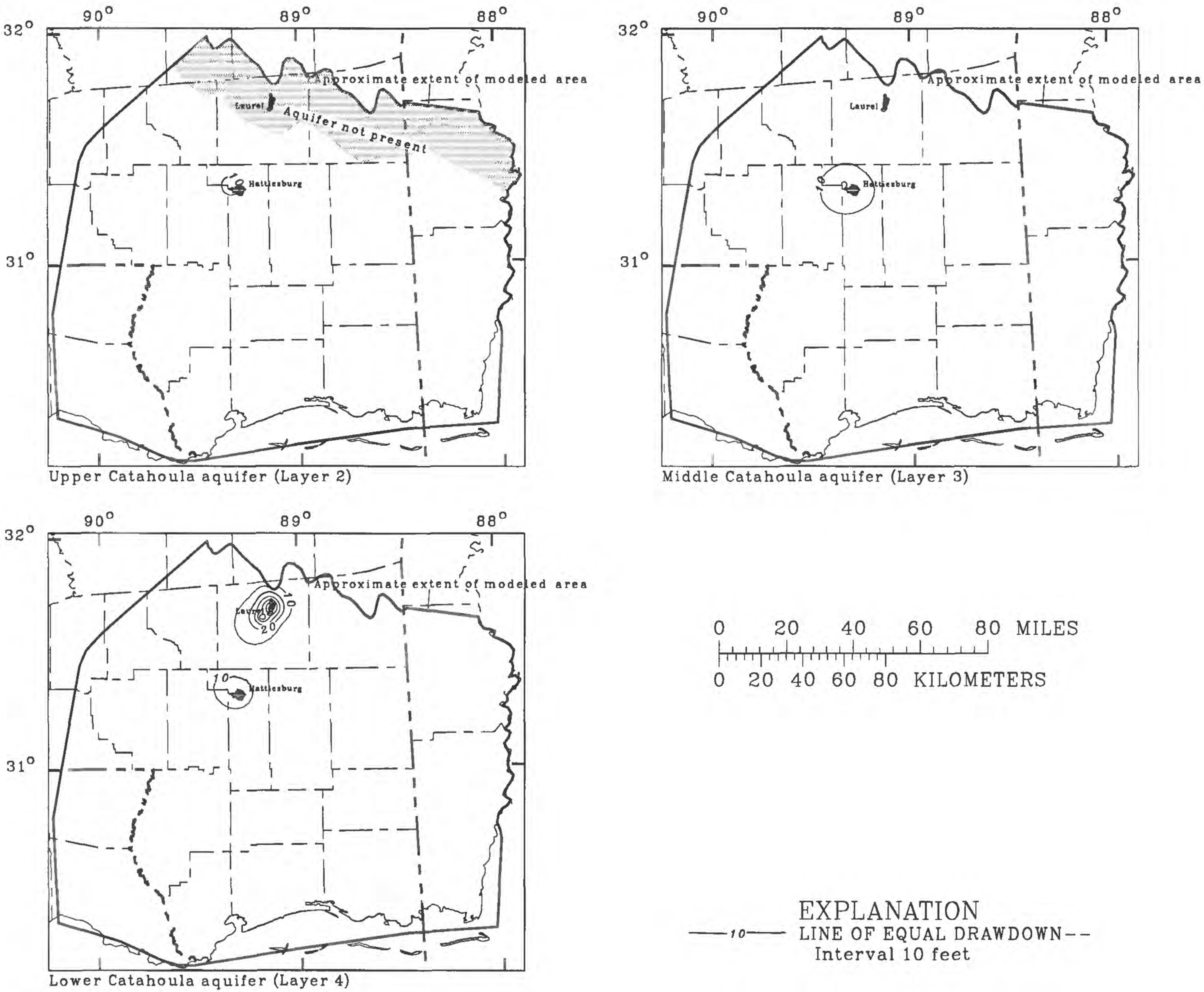


Figure 39a. Simulated water-level declines from 1992 to 2020 in the upper, middle, and lower Catahoula aquifers in the modeled area at the end of the low-growth scenario.

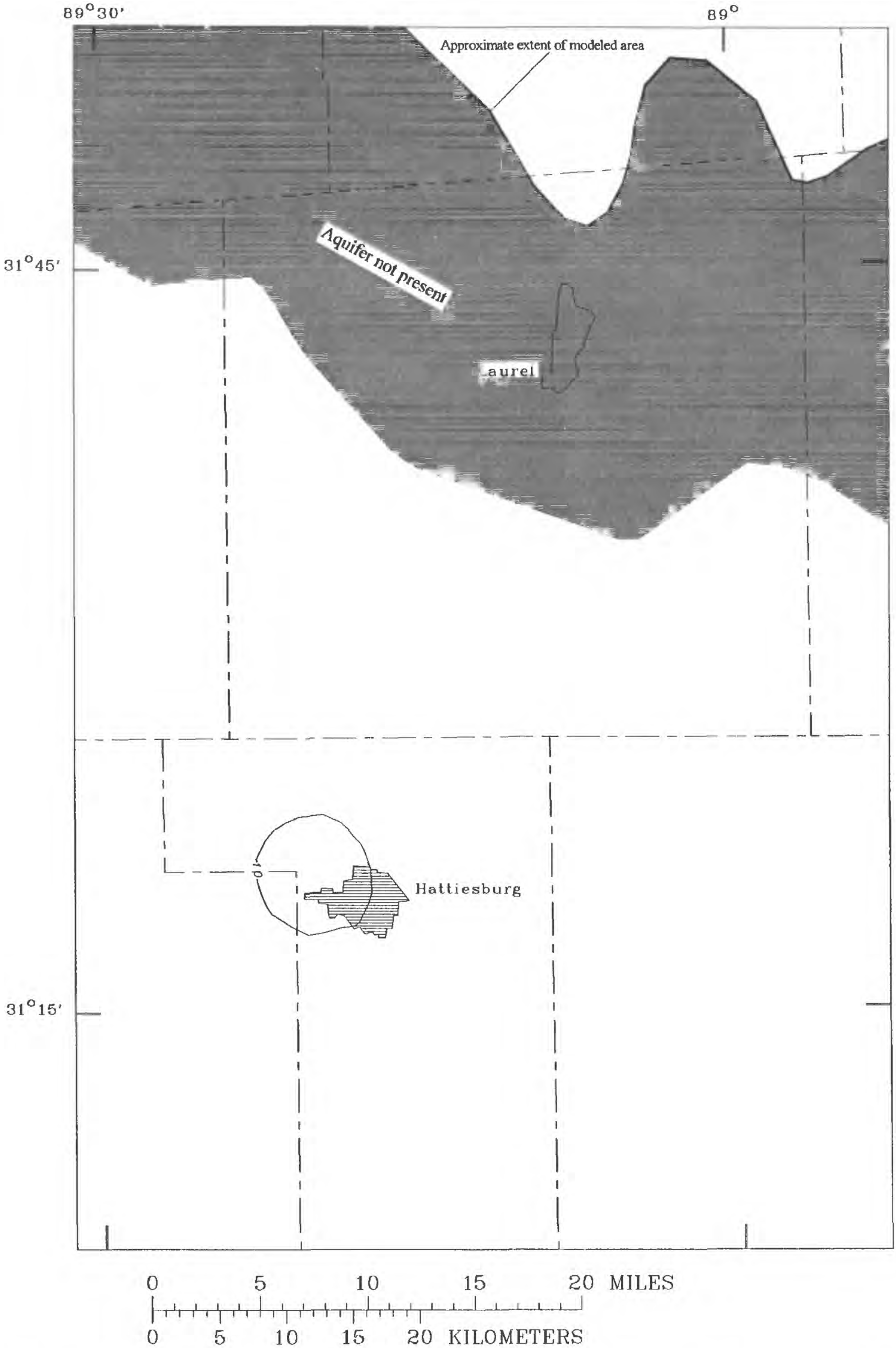


Figure 39b. Simulated water-level declines from 1992 to 2020 in the upper Catahoula aquifer in the study area at the end of the low-growth scenario.

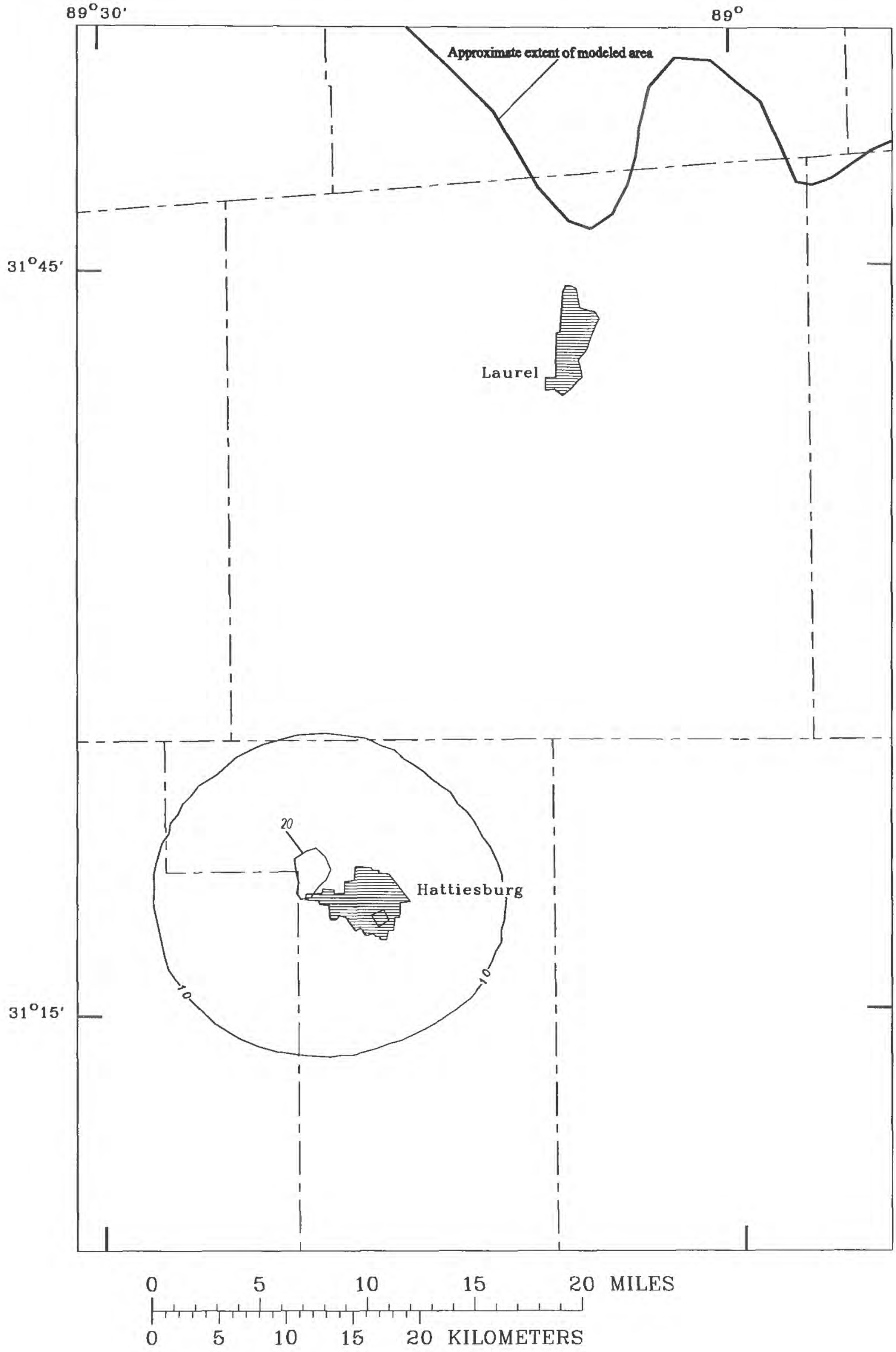


Figure 39c. Simulated water-level declines from 1992 to 2020 in the middle Catahoula aquifer in the study area at the end of the low-growth scenario.

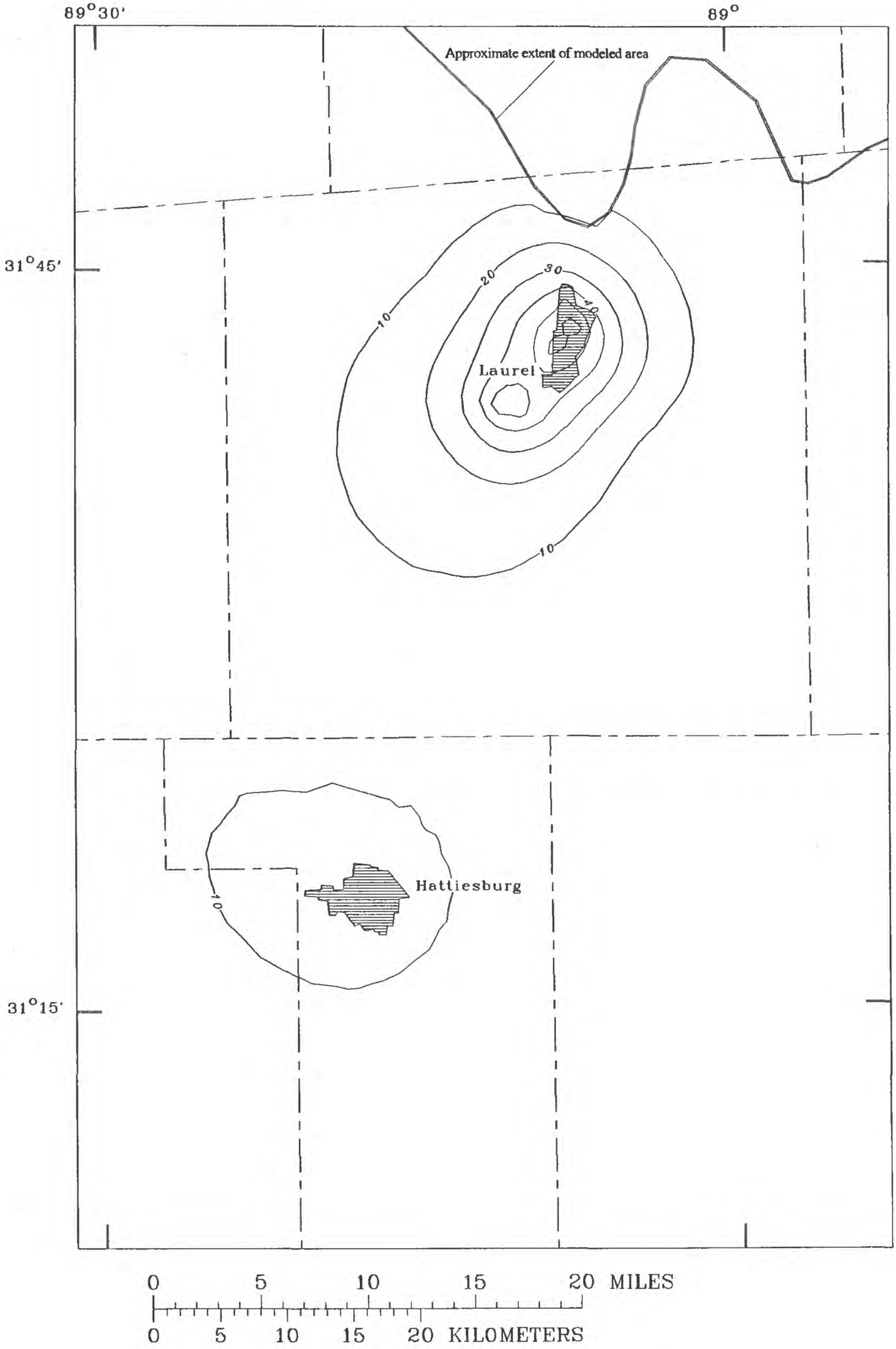


Figure 39d. Simulated water-level declines from 1992 to 2020 in the lower Catahoula aquifer in the study area at the end of the low-growth scenario.

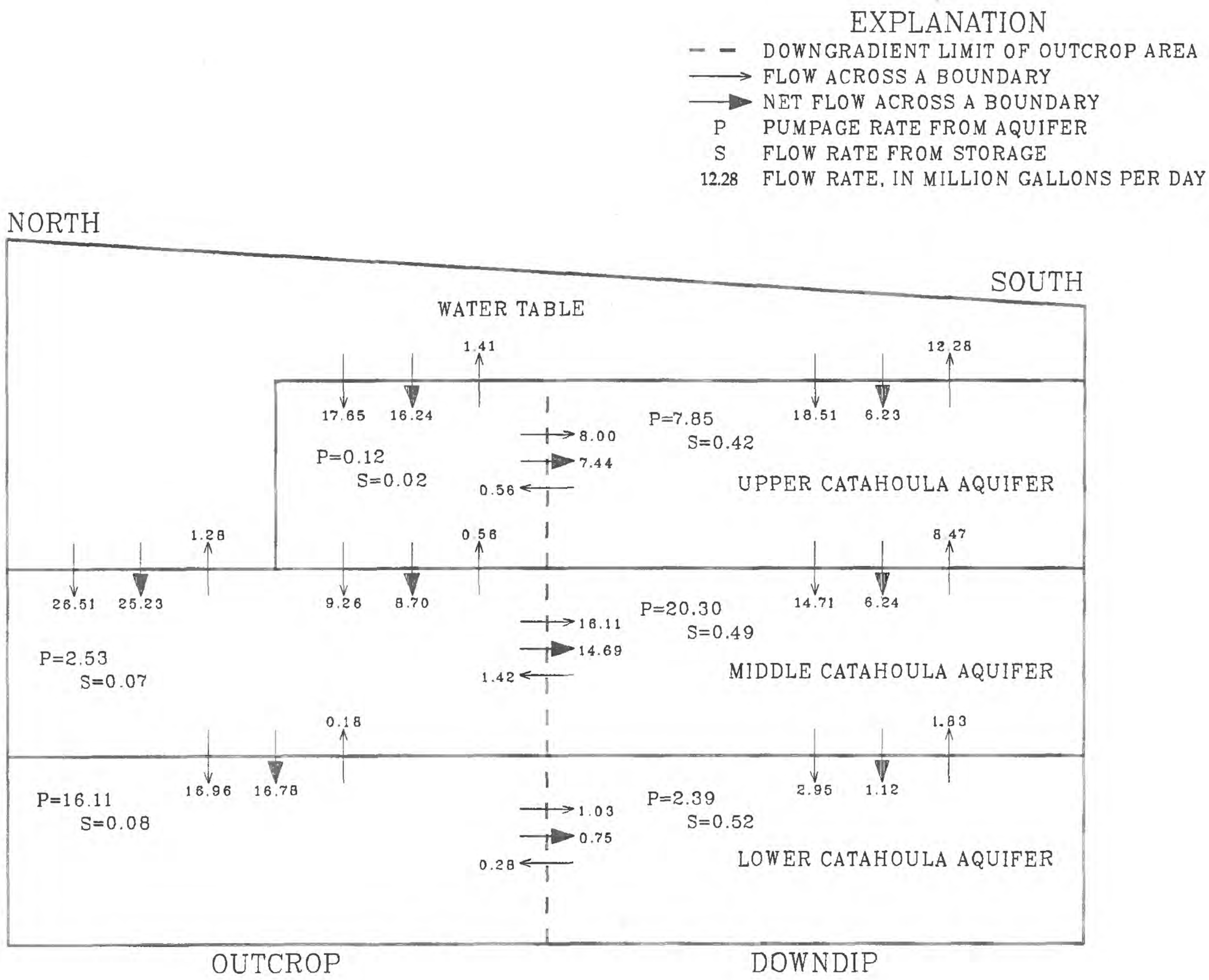


Figure 40. Simulated volumetric flow budget for the Catahoula aquifer system in 2020 at the end of the moderate-growth scenario.

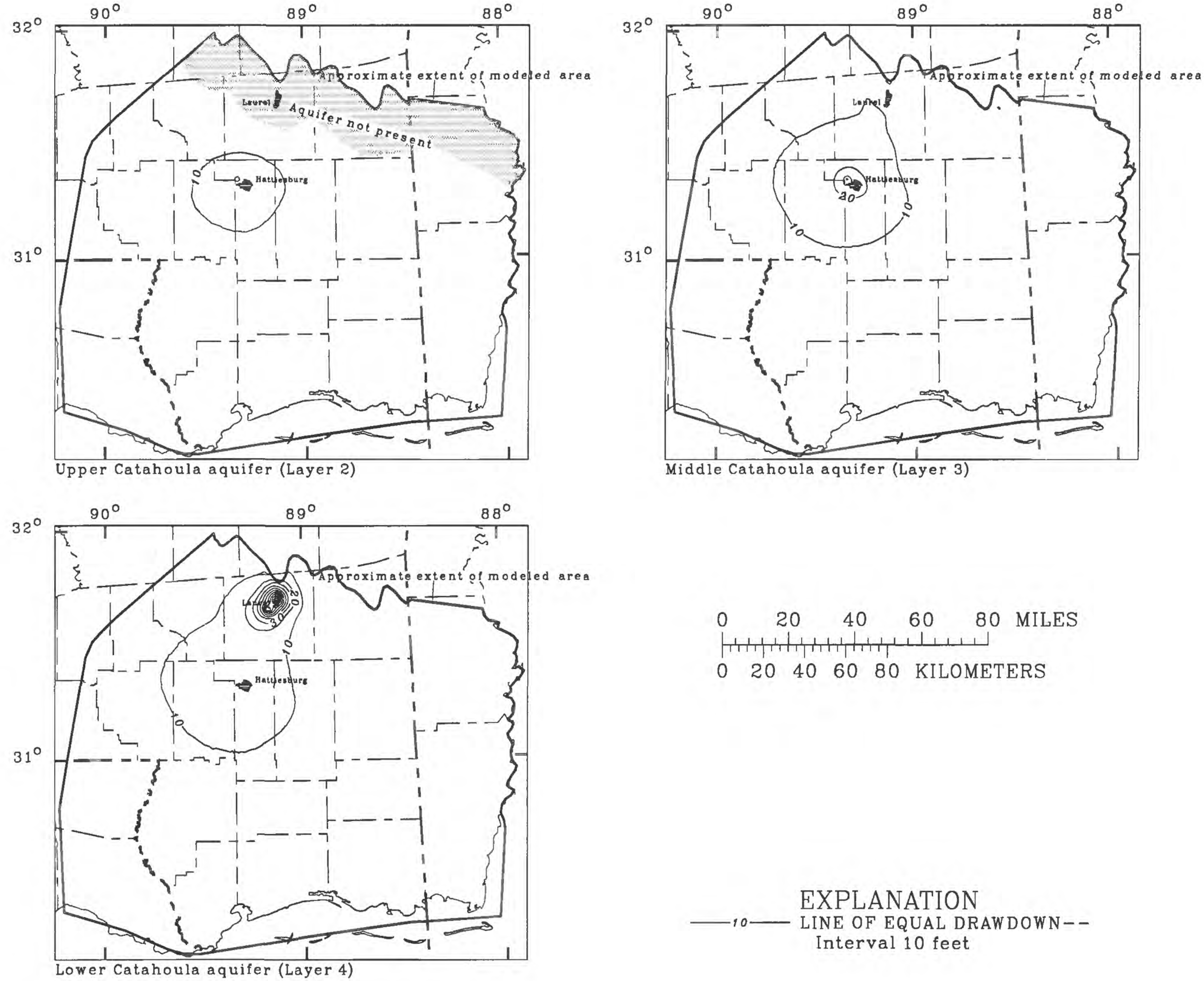


Figure 41a. Simulated water-level declines from 1992 to 2020 in the upper, middle, and lower Catahoula aquifers in the modeled area at the end of the moderate-growth scenario.

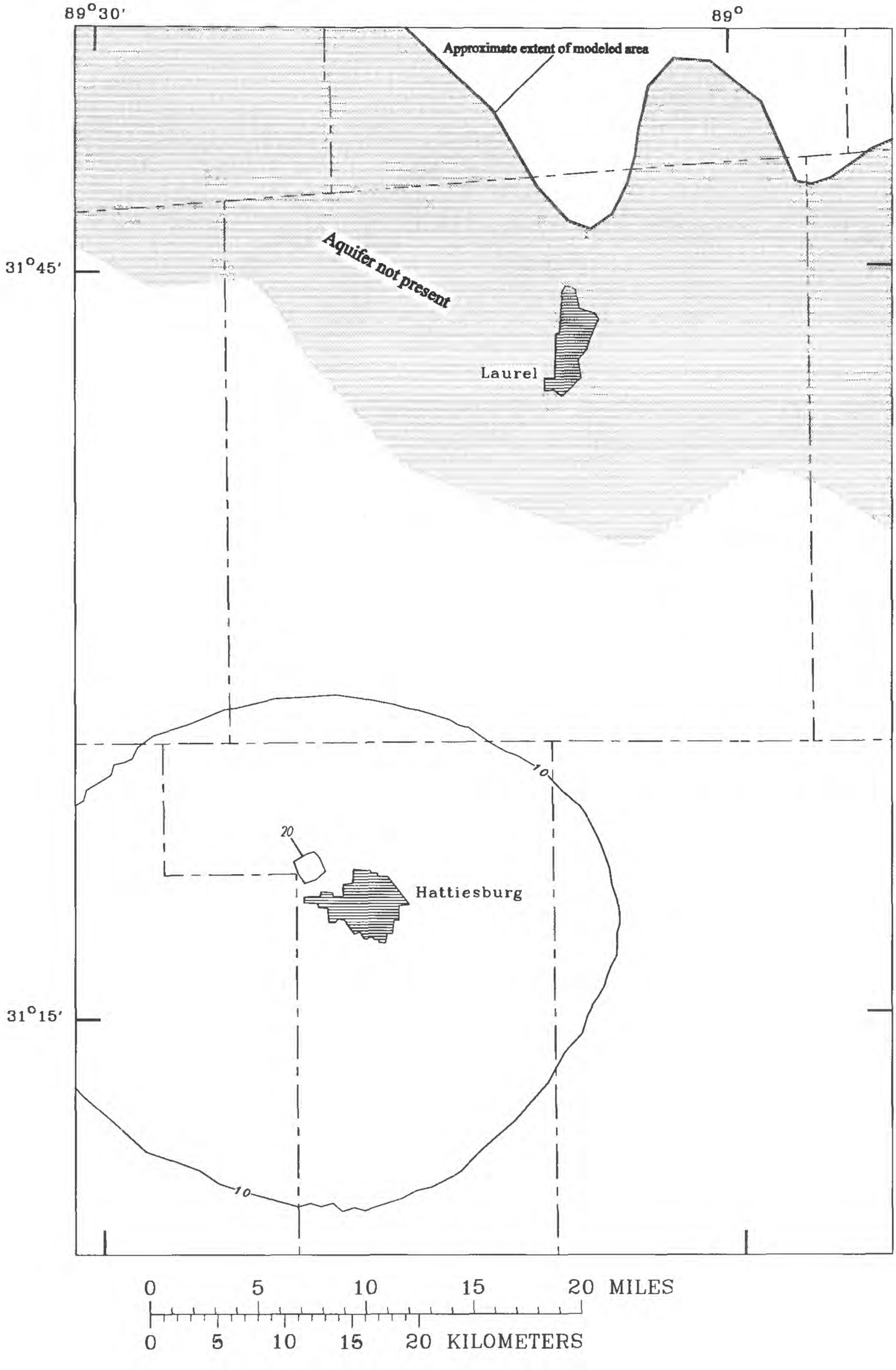


Figure 41b. Simulated water-level declines from 1992 to 2020 in the upper Catahoula aquifer in the study area at the end of the moderate-growth scenario.

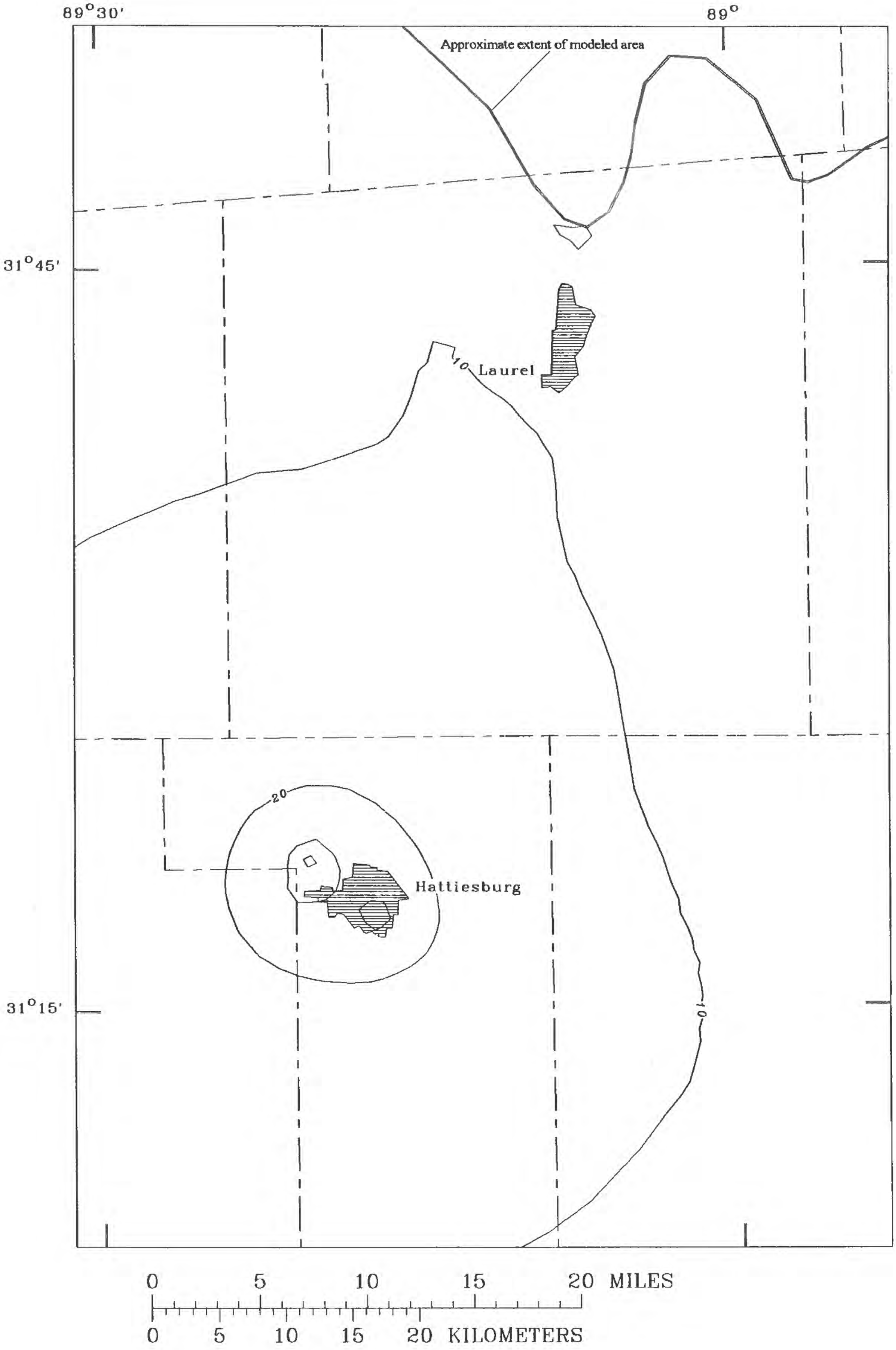


Figure 41c. Simulated water-level declines from 1992 to 2020 in the middle Catahoula aquifer in the study area at the end of the moderate-growth scenario.

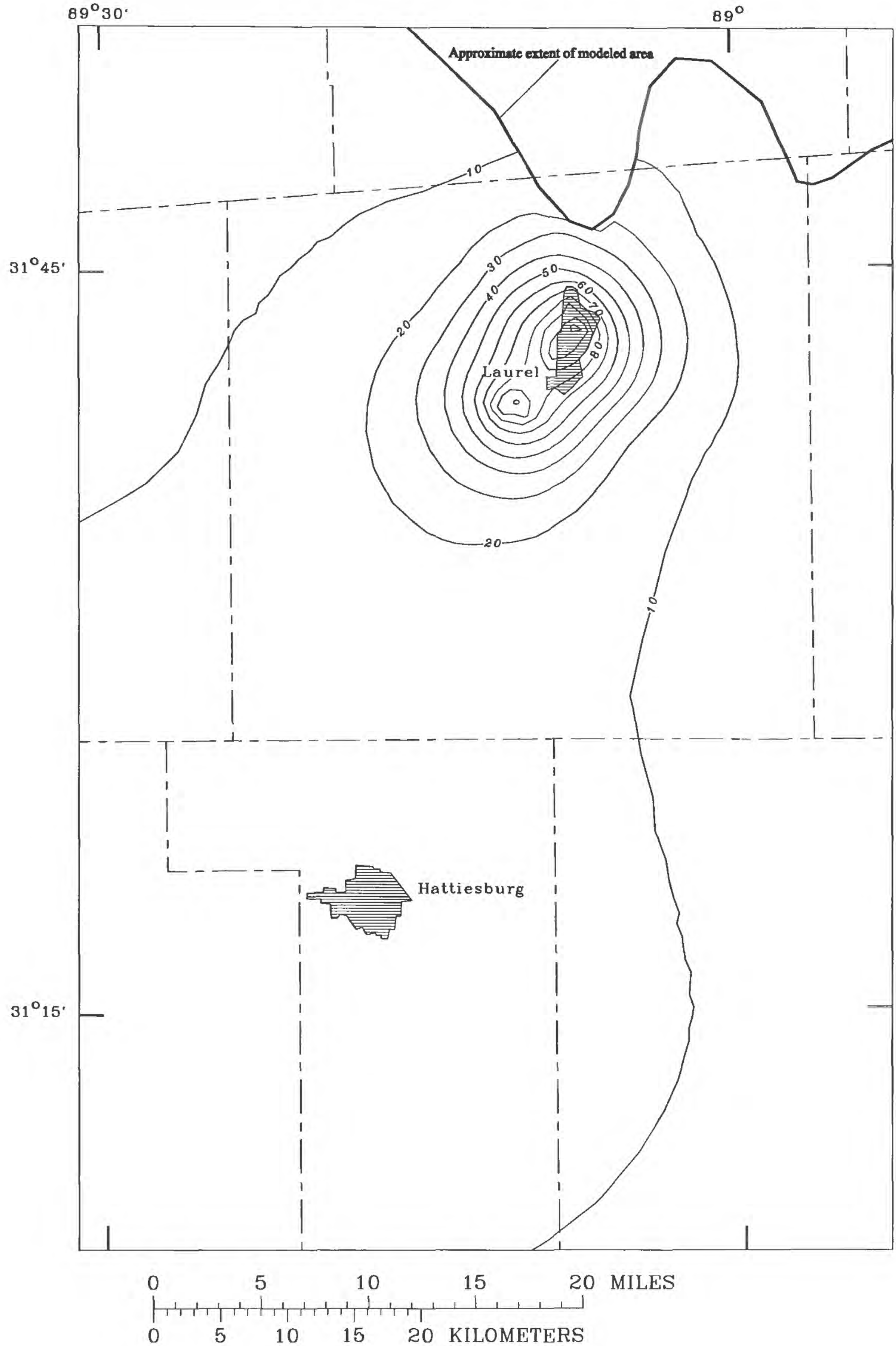


Figure 41d. Simulated water-level declines from 1992 to 2020 in the lower Catahoula aquifer in the study area at the end of the moderate-growth scenario.

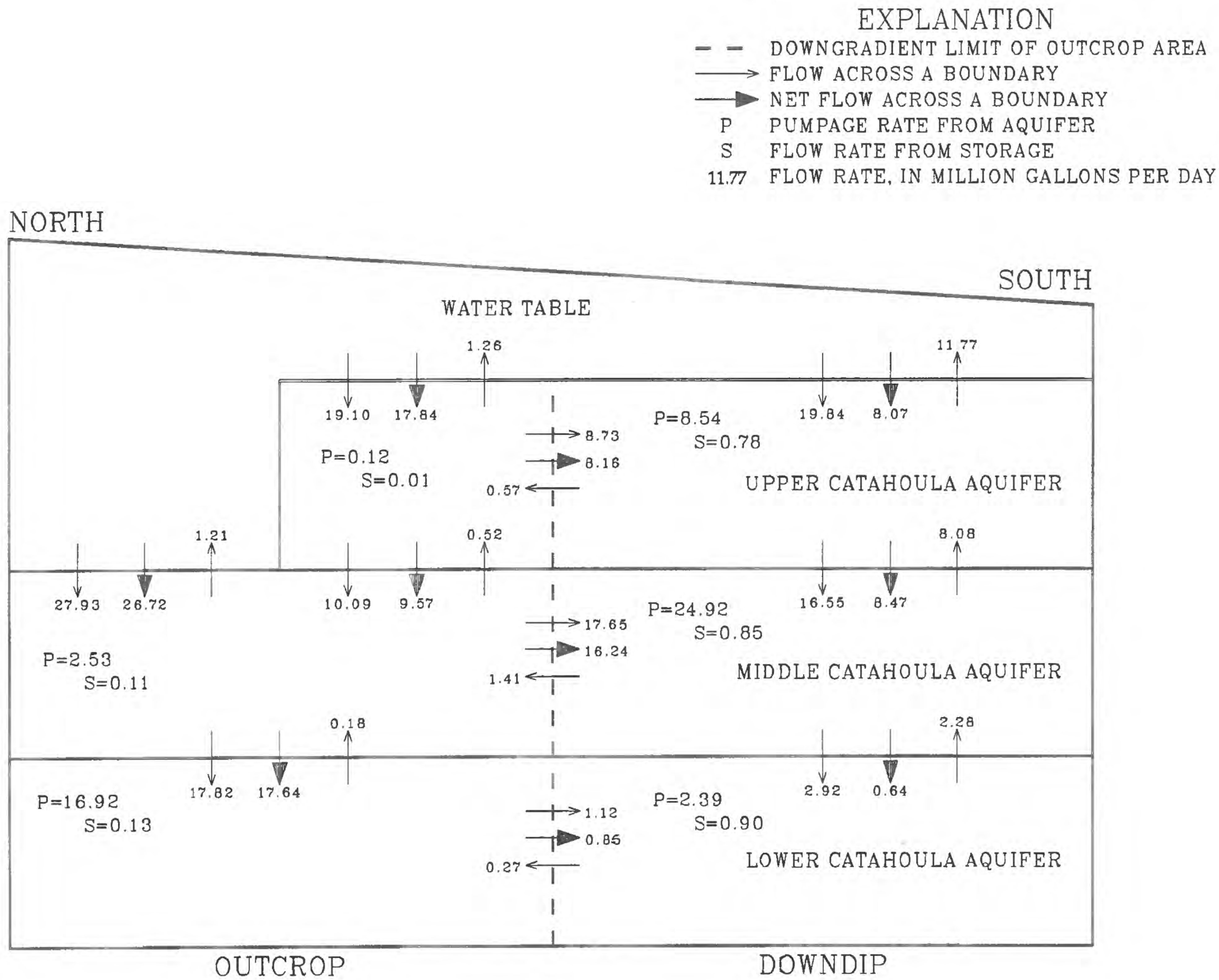


Figure 42. Simulated volumetric flow budget for the Catahoula aquifer system in 2020 at the end of the high-growth sceanrio.

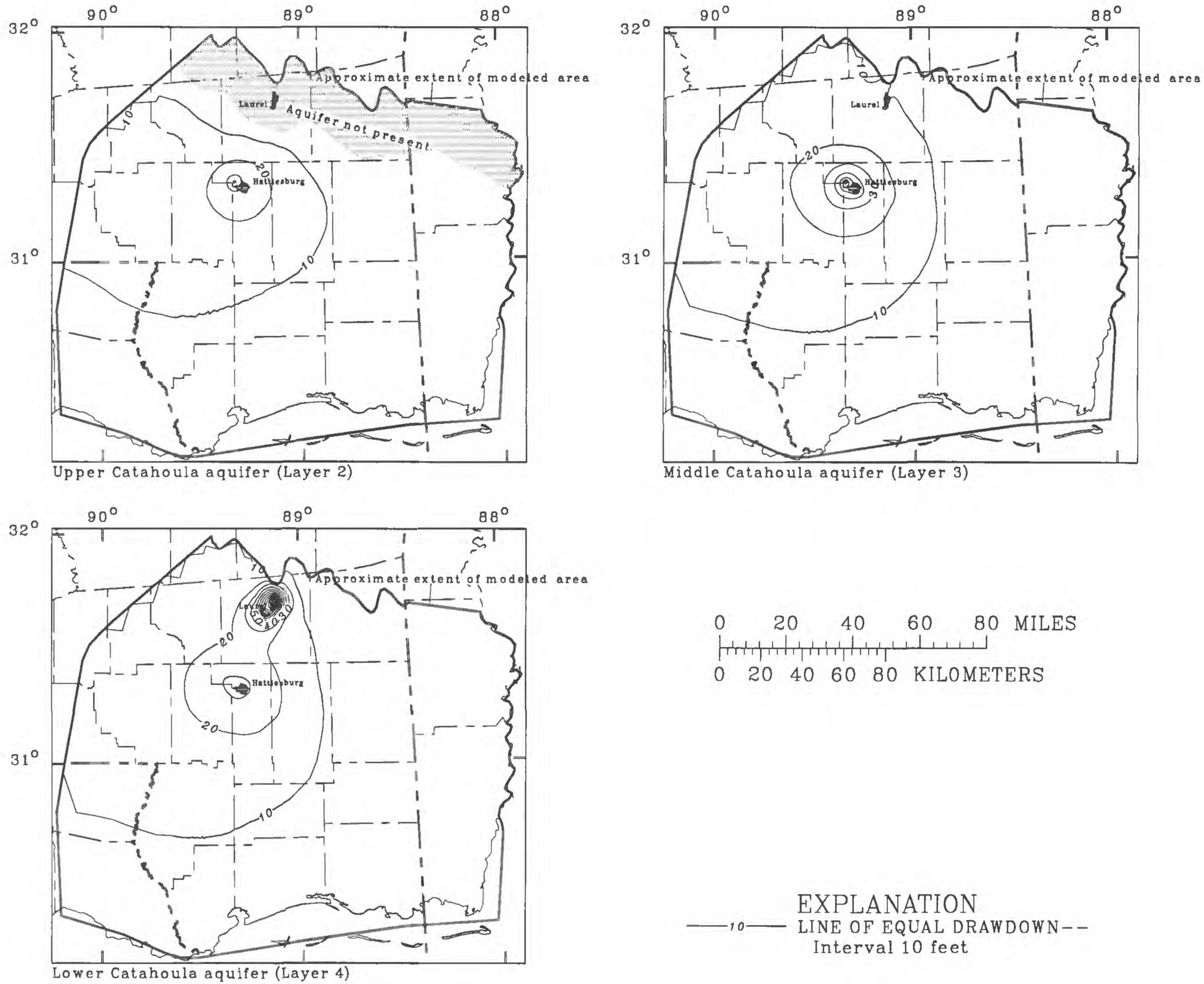


Figure 43a. Simulated water-level declines from 1992 to 2020 in the upper, middle, and lower Catahoula aquifers in the modeled area at the end of the high-growth scenario.

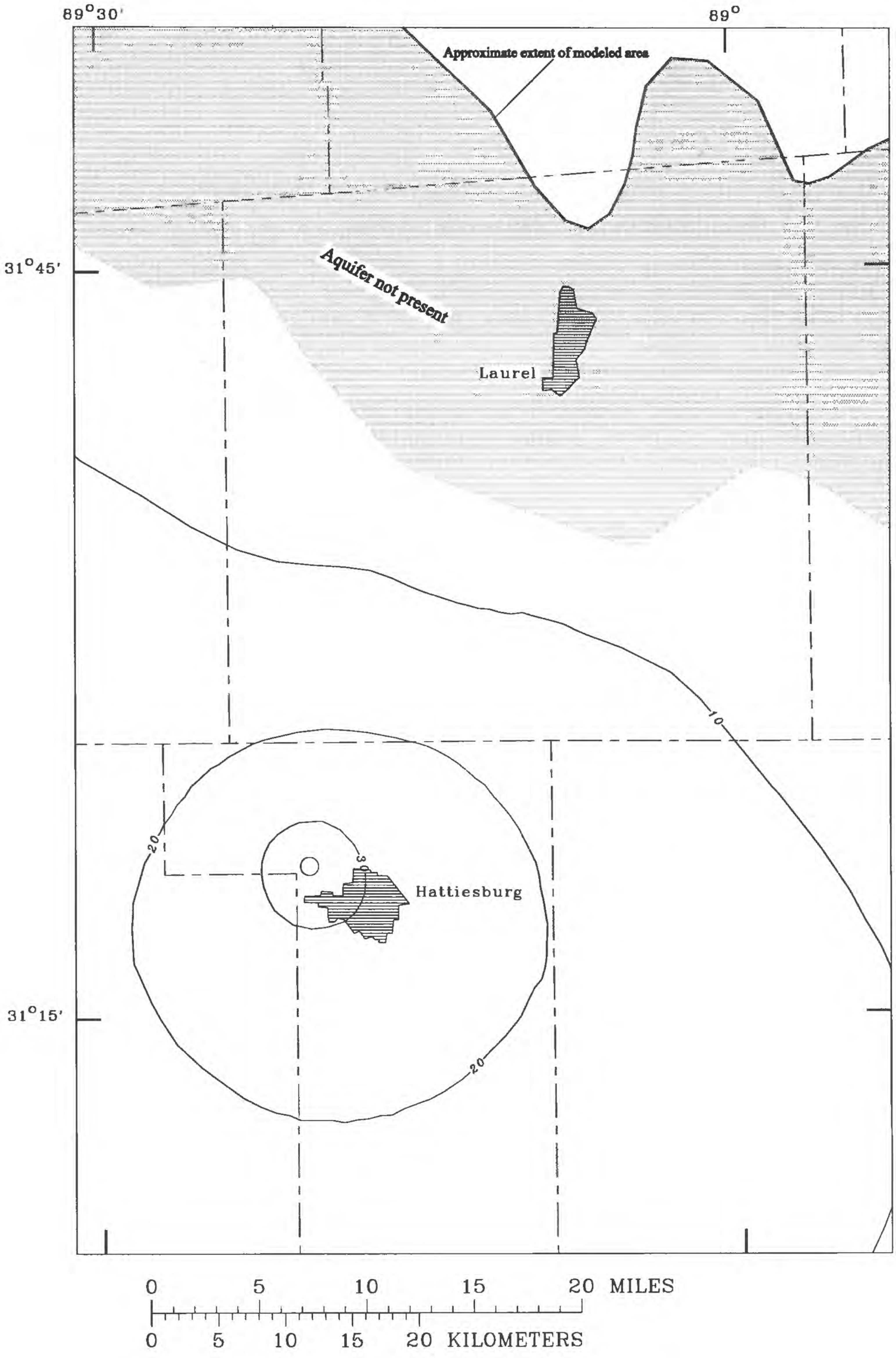


Figure 43b. Simulated water-level declines from 1992 to 2020 in the upper Catahoula aquifer in the study area at the end of the high-growth scenario.

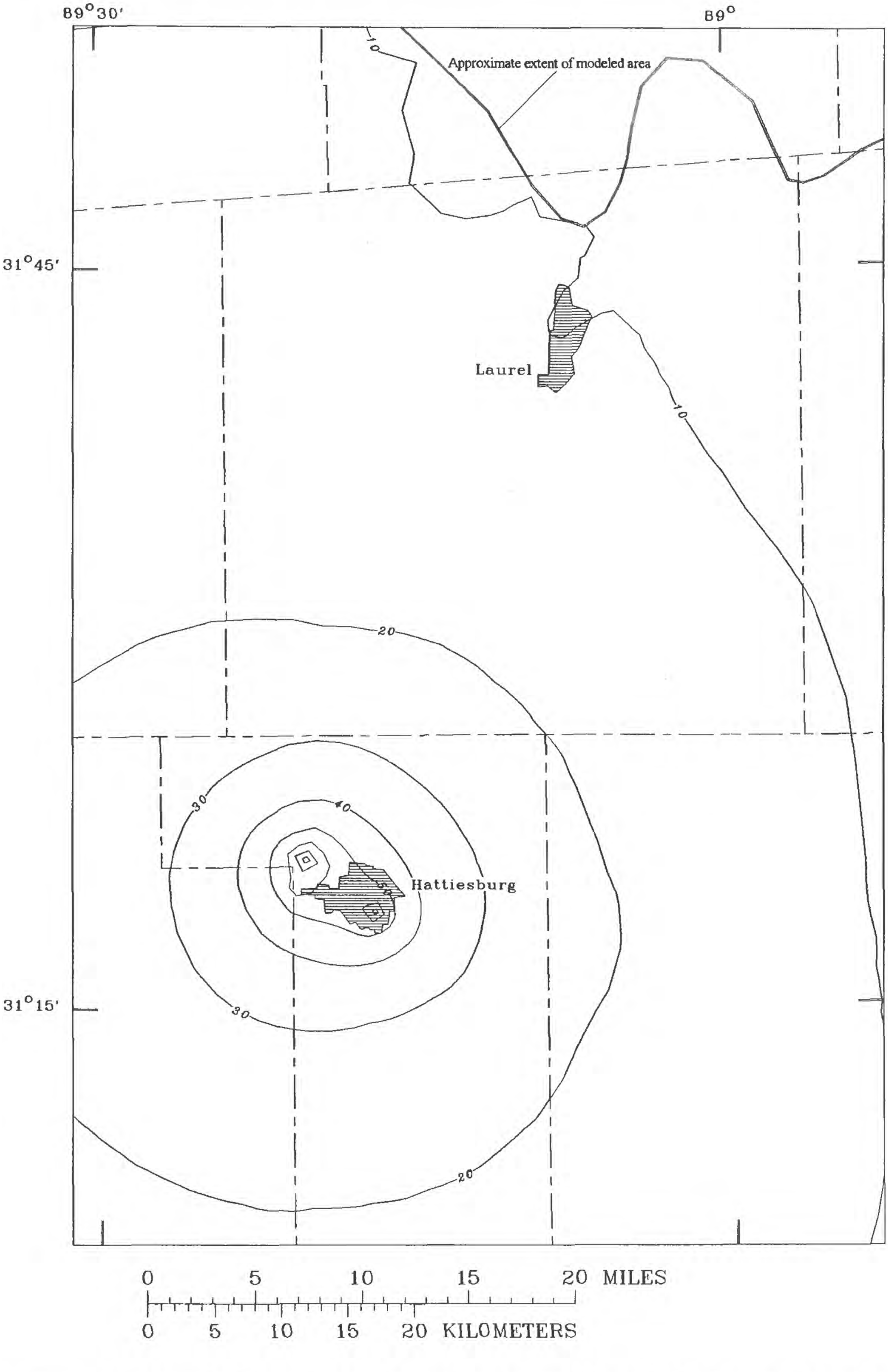


Figure 43c. Simulated water-level declines from 1992 to 2020 in the middle Catahoula aquifer in the study area at the end of the high-growth scenario.

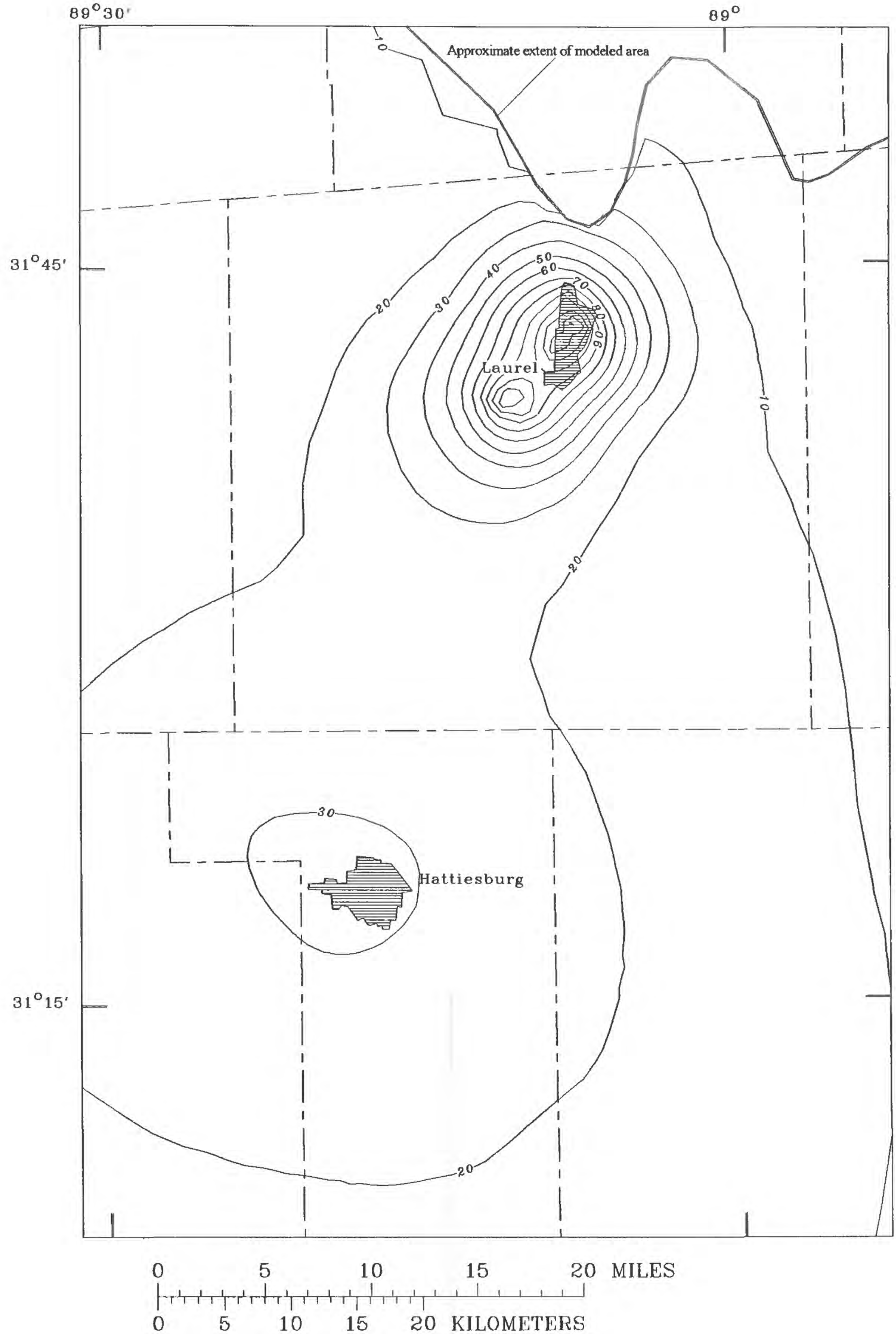


Figure 43d. Simulated water-level declines from 1992 to 2020 in the lower Catahoula aquifer in the study area at the end of the high-growth scenario.

SUMMARY

The flow of ground-water in the Catahoula aquifer system in the vicinity of the cities of Laurel and Hattiesburg, in southern Mississippi, is described in this report. The Catahoula aquifer system is made up of irregular, discontinuous sand zones in the Catahoula Formation of Miocene age. The Catahoula Formation generally contains a sand zone near the base of the formation and two other sand zones higher in the sequence. These three sand zones are referred to as the lower, middle, and upper Catahoula aquifers. The three aquifers form a complex system in which specific aquifers may be hydraulically connected because of a missing or incomplete confining unit between them. Primary recharge for the Catahoula aquifer system is rainfall in the outcrop area in the northern part of the modeled area. Rain that infiltrates the aquifers moves downgradient toward the gulf coast and toward the Tombigbee River, on the eastern edge of the study area. The regional flow pattern is distorted by cones of depression, caused by pumping, in the Laurel and Hattiesburg areas.

Pumpage from the Catahoula aquifer system increased from 28 to 41 Mgal/d from 1970 to 1985, and decreased to 38 Mgal/d for 1990. In the Laurel area, water levels in the lower Catahoula aquifer declined at rates ranging from about 1 to 3.6 ft/yr from 1964 until the late 1980's in response to the increase in pumping. Since the late 1980's, redistribution of withdrawals from the aquifer by the city of Laurel has resulted in increases in the water levels in the city well fields. In the Hattiesburg area, water levels have declined at rates from less than 1 to 2 ft/yr in both the lower and upper Catahoula aquifers, and in undeveloped areas water levels in the middle and upper Catahoula aquifers generally have declined less than 1 ft/yr.

A digital model was developed for the Catahoula aquifer system in the Laurel and Hattiesburg areas to further analyze the flow system and to examine the effects of three scenarios of increased pumping on water levels in the aquifers. A specified-head upper boundary was used because the water table in the area has shown no significant decline or rise, and because the potential recharge for the system is much greater than the amount of withdrawal from the aquifers. The lower, no-flow boundary of the digital model represented the Vicksburg Group and underlying units. All lateral boundaries were also no flow, representing the outcrop area to the north, the regional drain for all the Catahoula aquifers of the Tombigbee River to the east, the freshwater/saltwater interface to the south, and a stable ground-water divide to the west. The properties of lateral hydraulic conductivity and leakance were adjusted to calibrate the model using a parameter-estimation technique. A steady-state model was calibrated using 1980 pumpage information and 1981 measured water levels. Pumpage was then removed from the calibrated model to simulate predevelopment conditions and to provide initial water levels for the transient-state model. Total predevelopment flow through the Catahoula aquifer system was about 29 Mgal/d, with about 20 Mgal/d of this amount entering the aquifers in the outcrop area. The inflow from the outcrop area translates into a recharge rate of 0.13 in/yr.

The transient-state model was used to simulate the Catahoula aquifer system for the period from 1941 to 1992 using eight stress periods. Simulated water levels agreed well with available hydrograph records, and simulated potentiometric surfaces reflected the cones of depression in the upper and middle Catahoula near Hattiesburg, and the cones in the lower Catahoula near Laurel and near Hattiesburg. Residuals from the last stress period (1988-92) generally show the smallest differences between simulated and calibrated values in the Laurel and Hattiesburg areas, the main areas of interest for the study. The RMSE of the calibrated model was 17 ft. About

55 Mgal/d of water flowed through the Catahoula aquifer system under 1992 conditions, with about 1.9 Mgal/d of this total released from storage. Under 1992 conditions, flow, which had been upward to overlying layers under predevelopment conditions, was downward, and lateral flow was primarily toward the pumping centers in Laurel and Hattiesburg. Water levels in the lower Catahoula aquifer, the layer most affected by pumping, were lowered from predevelopment levels as much as 130 ft in the Laurel area and 100 ft in the Hattiesburg area. Sensitivity analysis showed that the model was most sensitive to changes in transmissivity but was also sensitive to leakance changes. The simulated aquifer system was insensitive to changes in storage coefficient. The model was developed primarily to simulate ground-water flow within confined aquifers, and would require modification in order to simulate conditions where the aquifer system changed from confined to unconfined conditions as the water level dropped below the top of an aquifer.

Three scenarios of increased pumpage were simulated with the calibrated model. Pumpage was increased 2, 3.5, and 4 percent per year from 1992 rates to the year 2020 for the Laurel area, and 1.2, 2, and 4 percent for the Hattiesburg area for the low-, moderate-, and high-growth scenarios respectively. Under the low-growth scenario, the additional water-level decline over the 1992 levels would be 20 ft or less in the upper and middle Catahoula aquifers in the Hattiesburg area, and about 60 ft in the lower Catahoula aquifer in the Laurel area. Water-level declines in all other parts of the study area would be less than 10 ft.

Under the moderate-growth scenario, the water-level decline would be 20 ft or less in the upper Catahoula aquifer, but 40 ft or less in the middle Catahoula aquifer in the Hattiesburg area. The water-level decline in the lower Catahoula would be about 110 ft in the Laurel area, and the water level would be near the top of the aquifer.

Under the high-growth scenario, the water-level decline would be 40 ft or less in the upper Catahoula, and the water-level decline would be about 80 ft or less in the middle Catahoula, with the largest decline in the Hattiesburg area. The water level would decline below the top of the lower Catahoula aquifer in the Laurel area under the high-growth scenario. With the decline in water level below the top of the aquifer, the aquifer would have changed from confined to unconfined conditions. The model was not designed to simulate this change.

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