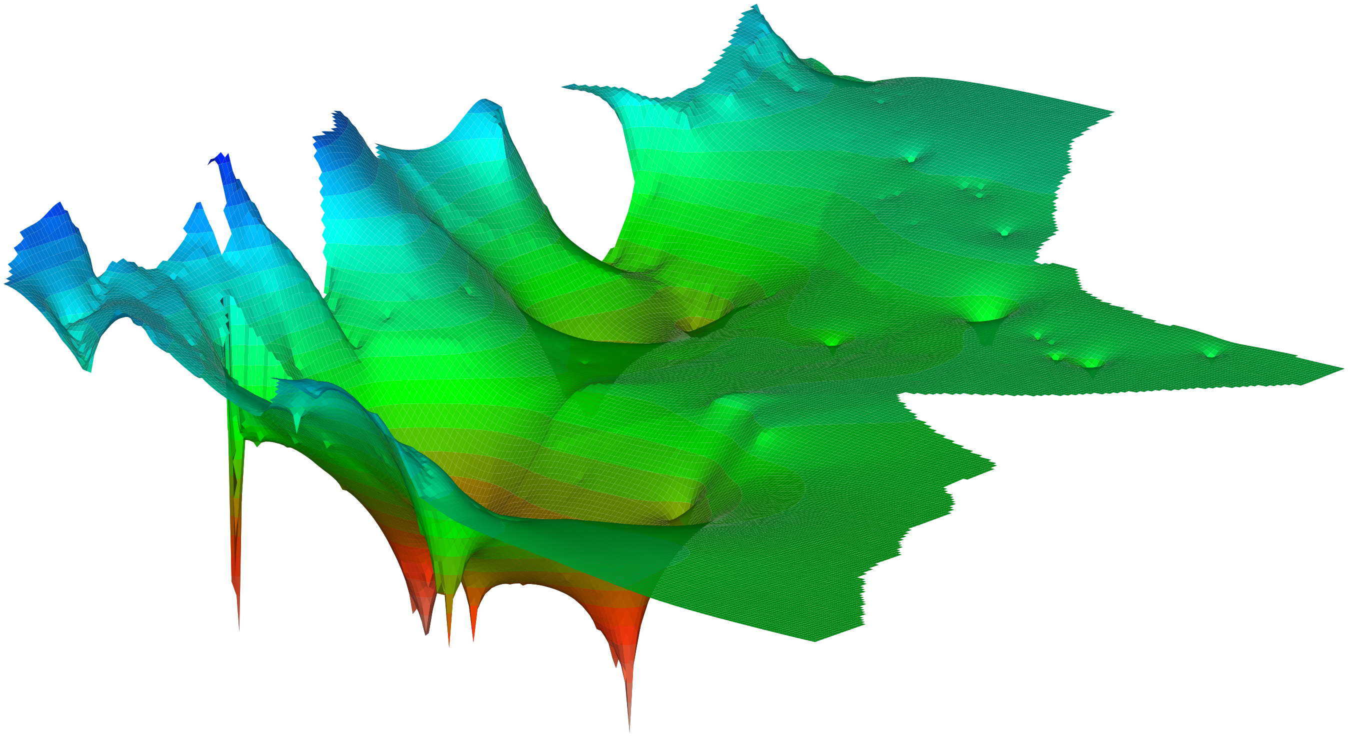
Prepared in cooperation with the

U.S. Army Corps of Engineers, Memphis District and the

Arkansas Soil and Water Conservation Commission

DEVELOPMENT AND CALIBRATION OF A GROUND-WATER FLOW MODEL FOR THE SPARTA AQUIFER OF SOUTHEASTERN ARKANSAS AND NORTH-CENTRAL LOUISIANA AND SIMULATED RESPONSE TO WITHDRAWALS, 1998-2027

Water-Resources Investigations Report 03-4132



U.S. Department of the Interior
U.S. Geological Survey

Cover: Oblique view of 1997 simulated hydraulic heads of the Sparta aquifer, also shown in animations included on the compact disk in the back of the report.

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U.S. GEOLOGICAL SURVEY
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Little Rock, Arkansas
2003

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Denver Federal Center
Denver, Colorado 80225

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
	Rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
million cubic feet per day (Mft^3/d)	7.481	million gallons per day (Mgal/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	square meter per day (m^2/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

In this report, vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). Horizontal coordinate information is referenced to North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above or below NGVD of 1929.

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

DEVELOPMENT AND CALIBRATION OF A GROUND-WATER FLOW MODEL FOR THE SPARTA AQUIFER OF SOUTHEASTERN ARKANSAS AND NORTH-CENTRAL LOUISIANA AND SIMULATED RESPONSE TO WITHDRAWALS, 1998-2027

By Paul W. McKee and Brian R. Clark

ABSTRACT

The Sparta aquifer, which consists of the Sparta Sand, in southeastern Arkansas and north-central Louisiana is a major water resource and provides water for municipal, industrial, and agricultural uses. In recent years, the demand in some areas has resulted in withdrawals from the Sparta aquifer that substantially exceed replenishment of the aquifer. Considerable drawdown has occurred in the potentiometric surface forming regional cones of depression as water is removed from storage by withdrawals. These cones of depression are centered beneath the Grand Prairie area and the cities of Pine Bluff and El Dorado in Arkansas, and Monroe in Louisiana. The rate of decline for hydraulic heads in the aquifer has been greater than 1 foot per year for more than a decade in much of southern Arkansas and northern Louisiana where hydraulic heads are now below the top of the Sparta Sand. Continued hydraulic-head declines have caused water users and managers alike to question the ability of the aquifer to supply water for the long term. Concern over protecting the Sparta aquifer as a sustainable resource has resulted in a continued, cooperative effort by the Arkansas Soil and Water Conservation Commission, U.S. Army Corps of Engineers, and the U.S. Geological Survey to develop, maintain, and utilize numerical ground-water flow models to manage and further analyze the ground-water system. The work presented in this report describes the development and calibration of a ground-water flow model representing the Sparta aquifer to simulate observed hydraulic heads, documents major differences in the current Sparta model compared to the previous Sparta model calibrated in the mid-1980's, and presents the results of three hypothetical future withdrawal scenarios.

The current Sparta model—a regional scale, three-dimensional numerical ground-water flow model—was constructed and calibrated using available hydrogeologic, hydraulic, and water-use data from 1898 to 1997. Significant changes from the previous model include grid rediscretization of the aquifer, extension of the active model area northward beyond the Cane River Formation facies change, and representation of model boundaries. The current model was calibrated with the aid of parameter estimation, a nonlinear regression technique, combined with trial and error parameter adjustment using a total of 795 observations from 316 wells over 4 different years—1970, 1985, 1990, and 1997. The calibration data set provides broad spatial and temporal coverage of aquifer conditions. Analysis of the residual statistics, spatial distribution of residuals, simulated compared to observed hydrographs, and simulated compared to observed potentiometric surfaces were used to analyze the ability of the calibrated model to simulate aquifer conditions within acceptable error. The calibrated model has a root mean square error of 18 feet for all observations, an improvement of more than 12 feet from the previous model.

The current Sparta model was used to predict the effects of three hypothetical withdrawal scenarios on hydraulic heads over the period 1998-2027 with one of those extended indefinitely until equilibrium conditions were attained, or steady state. In scenario 1a, withdrawals representing the time period from 1990 to 1997 was held constant for 30 years from 1998 to 2027. Hydraulic heads in the middle of the cone of depression centered on El Dorado decreased by 10 feet from the 1997 simulation to 222 feet below NGVD of 1929 in 2027. Hydraulic heads in the Pine Bluff cone of depression showed a greater decline from 61 feet below NGVD of 1929 to 78 feet below NGVD of 1929 in the center of the cone. With these same withdrawals extended to steady state (scenario 1b), hydraulic heads in the Pine Bluff cone of depression center declined an

additional 26 feet to 104 feet below NGVD of 1929, while the hydraulic-head decline in the El Dorado cone of depression center was only an additional 7 feet.

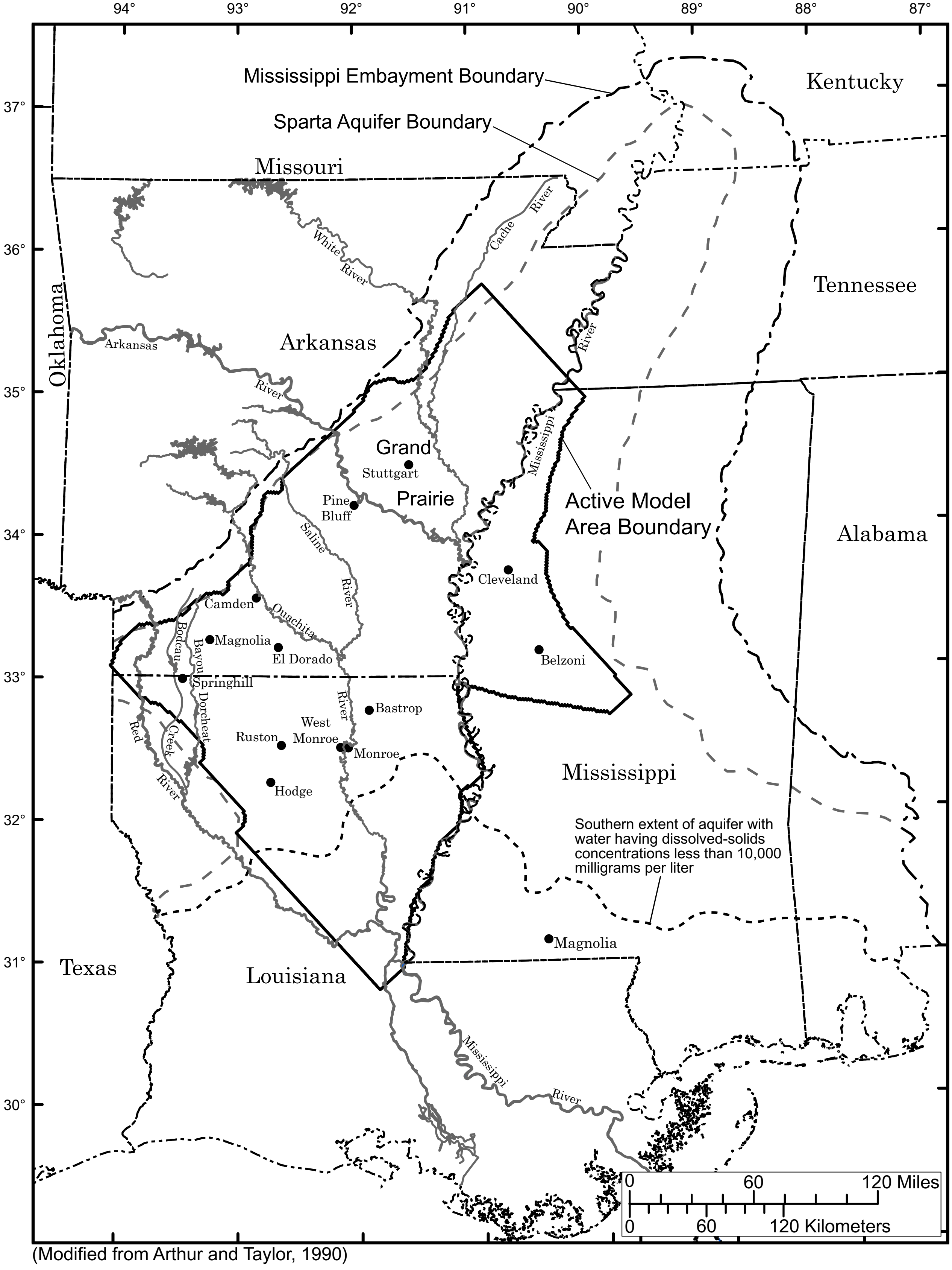
In scenario 2, withdrawals were extended as in scenario 1a while reducing withdrawals in industrial areas in Pine Bluff and El Dorado, Arkansas. Selected pumpage was removed to simulate effects of industry changing to alternate sources of water. Removal of selected withdrawal points in both the Pine Bluff and El Dorado areas results in shallower, less expansive cones of depression compared to scenario 1a. In the cone of depression centers, hydraulic heads recovered more than 120 and 165 feet, respectively, in the Pine Bluff and El Dorado areas. With this recovery, the area of Union County where hydraulic heads are below the top of the Sparta Sand decreased from 51.9 percent in 1997 to 7.3 percent by 2027.

In scenario 3, withdrawals gradually were increased 25 percent over 30 years while withdrawals were reduced in industrial areas of Jefferson and Union Counties. The results are similar to scenario 2, however, magnitudes of recovery are less because of continued increases in withdrawals elsewhere in the aquifer. In the cone of depression centers for Pine Bluff and El Dorado, hydraulic heads recovered more than 100 and 124 feet, respectively. Even though substantial hydraulic-head recovery occurred in both scenarios 2 and 3, hydraulic heads continued to decline in the Grand Prairie area and in much of north-central Louisiana as withdrawals increased through 2027.

INTRODUCTION

The Sparta aquifer is a confined aquifer of regional importance within the Mississippi Embayment aquifer system. It consists of varying amounts of unconsolidated sand, interstratified with silt and clay lenses within the Sparta Sand of the Claiborne Group. It extends through eastern and southeastern regions of Arkansas, northern Louisiana, and portions of Texas, Mississippi, and Tennessee (fig. 1). The Sparta aquifer of southeastern Arkansas and north-central Louisiana is a major source of water for municipal, industrial, and agricultural uses. Approximately 333 million gallons per day (Mgal/d) was pumped from the aquifer in Arkansas and Louisiana in 2000 (T.W. Holland, U.S. Geological Survey, oral commun., 2002). Historically, the Sparta aquifer has provided abundant water of high quality. In recent years, however, the demand for water in some areas has resulted in withdrawals from the Sparta aquifer that substantially exceed recharge to the aquifer. Considerable drawdown has occurred in the potentiometric surface, and water users and managers question the ability of the aquifer to supply water for the long term. As is typical in confined systems, large withdrawals have resulted in the development of large cones of depression that are centered beneath the Grand Prairie area (irrigated farm land between the Arkansas and White Rivers) and the cities of Pine Bluff and El Dorado in Arkansas, and Monroe in Louisiana (Joseph, 1998b). Hydraulic heads (often used interchangeably with water-level altitude or potentiometric surface) in the areas of these cones have declined at rates greater than 1 foot per year (ft/yr) for more than a decade in much of southern Arkansas and northern Louisiana and are currently below the top of the Sparta Sand (though not necessarily below the tops of the producing sand units) in parts of Union and Columbia Counties, Arkansas, and in several parishes of Louisiana. The cones of depression centered beneath El Dorado and Monroe have coalesced across 60 miles (mi) to form a single, large, elongated depression. A smaller cone of depression centered beneath Magnolia, Arkansas, has diminished substantially after the impoundment of nearby Lake Columbia and installation of a surface-water supply system in March 1993 that resulted in decreased withdrawals from the Sparta aquifer. Continued, heavy withdrawals in the Sparta aquifer, where alternative water sources are not considered or available, will result in continued expansion of the cones of depression as well as increased drilling and pumping costs, decreased aquifer yield, and reduced water quality.

To address these concerns, in 1985, the U.S. Geological Survey (USGS), in cooperation with the Arkansas Soil and Water Conservation Commission (ASWCC) and the Louisiana Department of Transportation and Development (DOTD), began a project to study the hydrogeologic characteristics of the Sparta aquifer and evaluate the regional effects of increased pumpage on hydraulic heads in the aquifer. The primary product of the project was a computer model of ground-water flow in the Sparta aquifer (Fitzpatrick and others, 1990; McWreath and others, 1991) calibrated and verified using 1970 and 1985 observation data, respectively, hereafter, referred to as the “previous Sparta model.” In 1991, this model was updated and verified (Kilpatrick, 1992) through 1989 by the USGS in cooperation with the ASWCC and selected scenarios of future ground-water withdrawals in



(Modified from Arthur and Taylor, 1990)

Figure 1. Location of study and model area.

Union County, Arkansas, were simulated. In 1997, the USGS, in cooperation with the ASWCC and DOTD, again updated and reverified the same model with pumping stresses through 1997, and five potential pumping scenarios were evaluated (Hays and others, 1998). In 2000-2002, the USGS worked cooperatively with both the Memphis District of the Corps of Engineers (MCOE) and the ASWCC to modify and recalibrate the previous Sparta model for the purpose of evaluating potential pumping scenarios and optimizing withdrawal rates to determine sustainable yield for the Sparta aquifer.

Purpose and Scope

The purpose of this report is to document the modification, reconstruction, and recalibration of the previous Sparta model to improve the ability of the model to simulate aquifer behavior, and describe the results of model simulations of hypothetical future water withdrawals. The model will be used as a management tool to simulate future hydraulic heads given various projected water-use demands. In addition, the model will be used in future cooperative studies to develop a conjunctive-use optimization model for determining sustainable yield for the Sparta aquifer.

Modifications to the previous Sparta model include rediscretizing the model grid, extending the model area northward, revising the surfaces representing the top and bottom of the Sparta Sand, and changing to the most recent version of MODFLOW, from MODFLOWARC to MODFLOW-2000. Reconstruction of the Sparta model includes changing representation of model layers and various boundaries. The calibration methodology and procedure are discussed along with results from three hypothetical withdrawal rate scenarios.

Previous Studies

The previous Sparta model, constructed by Fitzpatrick and others (1990) and McWreath and others (1991) to simulate hydraulic heads from 1889-1985, was calibrated and verified using 1970 and 1985 hydraulic-head observations and applied to the period 1985-2005. The model code used was the modular finite-difference ground-water flow model (MODFLOW 88) developed by McDonald and Harbaugh (1988). MODFLOW simulates flow in three dimensions using a block-centered, finite-difference approach to the solution of the partial-differential equation for flow. These Sparta model reports define the initial goals of the model and describe model testing and simulation results for the pumping scenarios posed. Detailed discussion of the history of Sparta aquifer water use, study area hydrogeologic setting, and a description of the aquifer system also are included in the two reports and are not repeated in detail here.

Original development of the previous Sparta model was based on information available on the hydrogeology of the region provided through the U.S. Geological Survey's Gulf Coast Regional Aquifer System Analysis (RASA). The Gulf Coast RASA included a large-scale hydrogeologic analysis of the region that includes the Sparta aquifer. Hydrogeologic framework characterization and initial parameter estimates for construction of the previous Sparta model largely were based upon Gulf Coast RASA results (Williamson and others, 1990; Arthur and Taylor, 1990; 1998). Additional data were obtained from reports by Broom and others (1984), Hosman (1982), Payne (1968), Trudeau and Buono (1985), and Petersen and others (1985). These reports present information on the distribution of hydrogeologic characteristics and ground-water conditions, and provide additional hydrogeologic information for the Sparta aquifer including boundaries, faults, transmissivity, storage coefficients, specific yield, recharge, and hydraulic heads.

Kilpatrick (1992) updated pumping data in the model for 1985-1989 and performed a verification. The model was used to predict the effects of six hypothetical pumping scenarios (1990-2019) on hydraulic heads in the area of El Dorado, Arkansas.

Hays and others (1998) converted the model to run in MODFLOWARC, a version of MODFLOW that allows interface with a geographical information system (Orzol and McGrath, 1992). The model conversion was successfully validated to ensure that functionality and output were unchanged from originally reported results. Hays and others (1998) then updated pumping data in the model for 1990-1997 and performed a reverification. This model was used to predict the effects of five hypothetical pumping scenarios (1998-2027) on hydraulic heads in southeastern Arkansas and north-central Louisiana.

Although not used directly in the calibration of the current Sparta model described in this report, the 1999 (Joseph, 2000) and 2001 (Schrader, 2003) potentiometric maps of the Sparta aquifer and additional hydrogeologic information by Brantly and others (2002) were useful in analyzing model results for withdrawal scenarios after the 1997 calibration.

General Description of the Previous Sparta Model

The previous Sparta model consists of two layers discretized on a variably spaced grid of 113 rows and 95 columns, which represents a 267-mile by 218-mile area. Active model cells constitute 8,996 of 10,735 grid cells. Cell dimensions range from 1 mile by 1 mile to 10 miles by 23 miles. Hydraulic heads are simulated only in layer 2, which represents the Sparta aquifer. Layer 1, which represents the overlying Mississippi River Valley alluvial and Cockfield aquifers, is modeled as a constant-head layer; heads remain unchanged throughout the simulation and are a constant source of water to the simulation. Flow from layer 1 to layer 2, through the Cook Mountain confining unit, is controlled by the vertical hydraulic conductance assigned to layer 1. Because the Sparta aquifer is underlain by the relatively impervious Cane River confining unit, the base of layer 2 is modeled as a no-flow boundary. Lateral boundary conditions are a combination of no-flow and specified-head boundaries. The specified-head boundaries are at the north, east, and south boundaries of the model; specified heads change at designated intervals throughout the simulation period to account for long-term Sparta aquifer hydraulic-head declines since predevelopment. Hydraulic conductivities used for computation of transmissivity of the Sparta aquifer ranged from 1 to 35 feet per day (ft/d). Vertical hydraulic conductivities used for computation of conductances of the Cook Mountain confining unit ranged from $9x10^{-6}$ to $3x10^{-4}$ ft/d. The calibrated storage coefficient for the Sparta aquifer was $1x10^{-4}$ (Kilpatrick, 1992). More comprehensive discussions of model construction and calibration are included in the Fitzpatrick and others (1990) and McWreath and others (1991). The period for model simulation is from 1898 (predevelopment) to 1997. During initial model construction and calibration, the period 1898 to 1985 was divided into 4 simulation periods (intervals for adjusting specified heads) and 25 stress periods (intervals for changing ground-water withdrawals). Kilpatrick (1992) represented the period 1986-1989 with an additional simulation period and stress period. Hays and others (1998) represented the period 1990-1997 by 1 additional simulation period and stress period for a total of 6 simulation and 27 stress periods.

Model Area Description

The model area includes southern and east-central Arkansas, northern Louisiana, and northwestern Mississippi (fig. 1). This area lies within the Mississippi Alluvial Plain and West Gulf Coastal Plain sections of the Coastal Plain physiographic province (Fenneman, 1938). Land-surface altitudes range from more than 500 ft along the western boundary and outcrop recharge zones to less than 100 ft along the Mississippi River. The principal rivers draining the study area are the Mississippi, Arkansas, Saline, Ouachita, and Red Rivers, Bayou Dorcheat, and Bodcau Creek. Mean annual precipitation is approximately 50 inches (Freiwald, 1985). Water withdrawn from the Sparta aquifer in the study area is used for municipal supply, agriculture, aquaculture, and manufacturing of forest products, chemicals, and other industrial products.

HYDROGEOLOGY OF THE SPARTA AQUIFER

Detailed description of the hydrogeology of the Sparta aquifer is discussed in numerous reports including Payne (1968), Hosman and others (1968), Petersen and others (1985), and Fitzpatrick (1990). Therefore, the following is only a brief summary of the hydrogeology of the Sparta aquifer.

Hydrogeologic Units and Geologic Setting

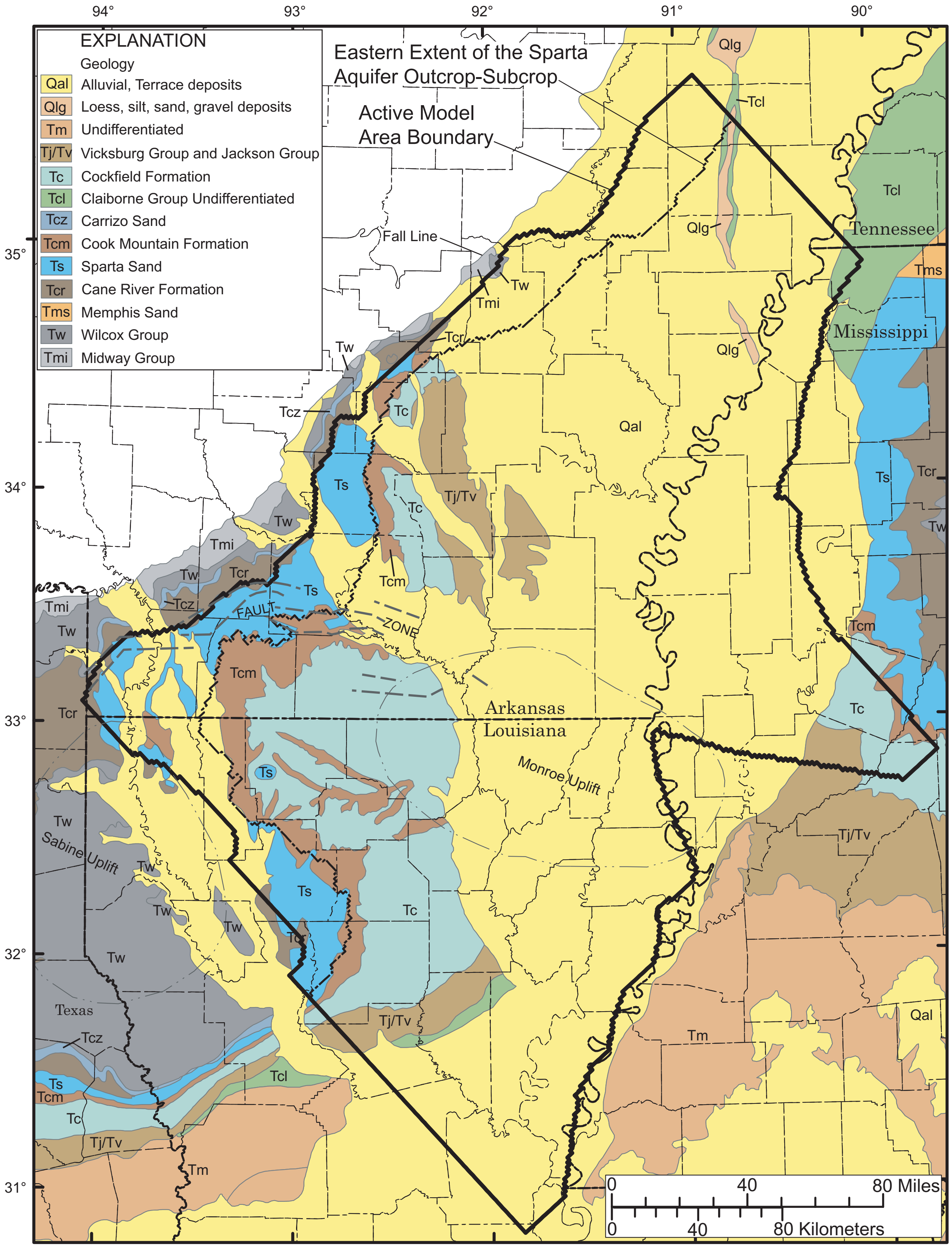
The Sparta aquifer is an aquifer of regional importance within the Mississippi Embayment aquifer system, and comprises a sequence of unconsolidated sand, silt, and clay units within the Sparta Sand of Claiborne Group. The Mississippi Embayment (fig. 1) is a structural basin with an axis trending northward roughly following the Mississippi River (Petersen and others, 1985). The Sparta Sand extends through eastern and southeastern regions of Arkansas, northern Louisiana, western Mississippi, and portions of Texas and Tennessee (fig. 2). The western extent in Arkansas parallels the “Fall Line” separating the embayment from the mountainous highlands. Surface materials in a large part of the area are Quaternary-age alluvial and terrace deposits. The Sparta Sand, ranging in total thickness from 100-1,000 feet, is stratigraphically positioned between the overlying Cook Mountain Formation and underlying Cane River Formation, both Tertiary-age units of the Claiborne Group (table 1). These units generally dip and thicken from the east and west outcrop areas toward the axis of the embayment where they are deeply buried in the subsurface (fig. 3). The Cook Mountain and Cane River Formations are predominantly clay units with thickness ranges of 100-150 ft and 300-800 ft, respectively. North of 35 degrees latitude, the Sparta Sand becomes part of the Memphis Sand as the Cane River Formation undergoes a facies change from marine clays to sand (Hosman and others, 1968).

Aquifer System Description

The Sparta aquifer outcrops and is unconfined on both the west and east sides of the Mississippi Embayment, and then becomes confined as it dips toward the axis of the embayment and southward toward the Gulf of Mexico. It is confined above by the Cook Mountain confining unit and below by the Cane River confining unit (fig. 3). Sand within the aquifer generally ranges in thickness from 200 to 600 ft. Sources of flow to the Sparta aquifer are direct recharge from precipitation on the outcrop, recharge from rivers in the outcrop, downward flow from the alluvial aquifer where the Sparta subcrops (intersects the overlying alluvium), and leakage from confining units where the vertical hydraulic gradient is towards the Sparta Sand. Discharge from the Sparta aquifer occurs by withdrawal from wells and by natural discharge. Natural discharge is primarily leakage through the overlying and underlying confining beds to adjacent units with lower hydraulic heads and to rivers in the outcrop. Ground-water flow in the Sparta aquifer generally coincides with structural dip and is from the outcrop areas to the axis of the embayment and southward toward the gulf coast (fig. 3). This flow pattern dominated the regional movement of water in the Sparta aquifer prior to aquifer development (Reed, 1972). However, continued, large withdrawals caused cones of depression in the potentiometric surface since development that have altered the natural flow paths toward the centers of these depressions. An additional factor affecting ground-water flow is the presence of faults in southwest Arkansas. Individual faults are not well defined, so a fault zone is identified on figure 2.

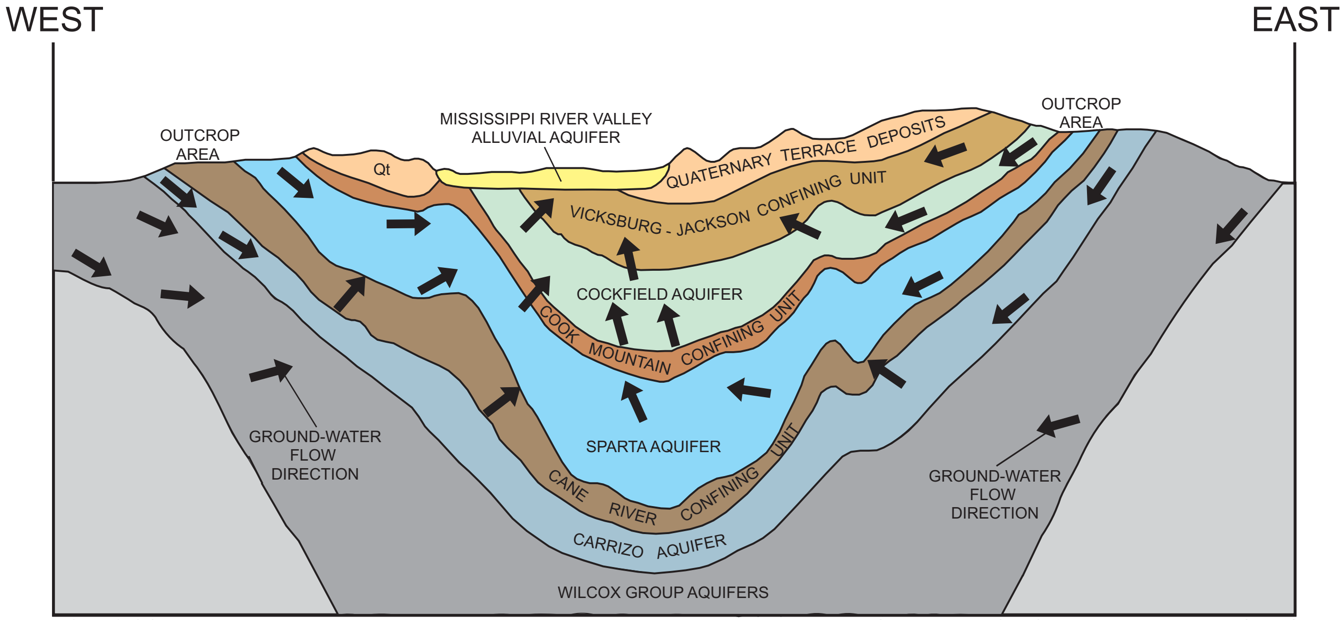
Table 1. Description of geologic units and correlation to hydrogeologic units in the Mississippi Embayment aquifer system (modified from Petersen and others, 1985)

Group	Geologic Unit		Maximum thickness (feet)	Lithology	Hydrogeologic unit		
	Alluvium and terrace deposits		200	Base - gravel Surface - sand, silt, clay	Mississippi River Valley alluvial aquifer		
Jackson	Undifferentiated		300	Clay; some fine sand	Vicksburg-Jackson confining unit		
Claiborne	Cockfield Formation		<300	Lignitic sand, carbonaceous clay	Cockfield aquifer		
	Cook Mountain Formation		150	Carbonaceous clay, some lignitic sand	Cook Mountain confining unit		
	Memphis Sand	Sparta Sand	1,000	Sand; some clay interbeds	Sparta aquifer	Greensand aquifer Middle confining unit El Dorado aquifer	Memphis aquifer
		Cane River Formation	800	Clay, sand	Cane River confining unit		
		Carrizo Sand	400	Fine to medium sand	Carrizo aquifer		
Wilcox	Undifferentiated		1,100	Interbedded sand and clay, lignitic	Wilcox Group aquifers		



Geology modified from Hosman (1988)

Figure 2. Surficial geology and selected structural features of the study area.



Geology modified from Arthur and Taylor (1990)

Figure 3. Hydrogeologic units within generalized cross section of the Mississippi Embayment aquifer system.

Sparta Aquifer Development and Associated Effects

Rates of flow into and discharge from the Sparta aquifer are controlled by hydraulic gradients, which are affected by ground-water withdrawal from the aquifer. The term “predevelopment” used in this report indicates aquifer conditions before 1898 or before the aquifer was stressed by appreciable ground-water withdrawal. The term “post-development” in this report indicates aquifer conditions after development of the aquifer began.

The earliest known withdrawals from the Sparta aquifer in the study area began in 1898 for industrial use in Pine Bluff, Arkansas. About 1920 substantial withdrawals totaling an estimated 10 million gallons per day (Mgal/d) or 1.3 million cubic feet per day (Mft^3/d) began in the aquifer for rice irrigation in the Grand Prairie area. Since that time, the aquifer has been used heavily for industrial and municipal supply, providing water of excellent quality. Ground-water withdrawal from wells altered the predevelopment potentiometric-surface gradients and changed the naturally occurring flowpaths in the aquifer system. Continued ground-water withdrawal through time has caused the potentiometric surface to decline in the aquifer (Joseph, 1998b; Schrader, 2003). Wells completed in the Sparta aquifer generally produce 100-500 gallons per minute (gal/min), with less common rates up to 1,200 gal/min. Withdrawals from the aquifer in Arkansas and Louisiana totaled 355 Mgal/d or 47.5 Mft^3/d in 1995 (Joseph, 1998b) and decreased to 333 Mgal/d or 44.6 Mft^3/d in 2000 (Terry Holland, U.S. Geological Survey, written commun., 2002). The principal areas of ground-water withdrawal in the study area are in El Dorado and Pine Bluff, Arkansas, the Grand Prairie area, Monroe and West Monroe, Louisiana, and Cleveland, Mississippi.

GROUND-WATER FLOW MODEL

The transient, three-dimensional, numerical model of ground-water flow in the Sparta aquifer described in this report is a modified and reconstructed version of the previous flow model described in Fitzpatrick and others (1990), McWreath and others (1991), Kilpatrick (1992), and Hays and others (1998).

Although the last verification of the previous Sparta model indicated that it was simulating conditions in the aquifer within acceptable error for study goals at that time, analysis of reverification results identified specific areas where recalibration could improve the ability of the model to simulate behavior in areas with steep hydraulic gradients and increasing withdrawals (Hays and others, 1998). Because the Sparta model is being maintained as a tool to improve understanding of the aquifer and help with management issues, it was necessary to develop, construct, and calibrate the current Sparta model. Modifications from the previous Sparta model incorporated more hydrologic and geophysical data since the 1985 calibration and were designed to meet the current needs of Federal, State, and local water managers and planners. Modifications to the previous Sparta flow model include rediscretizing the model grid, extending the model area northward, revising the surfaces representing the top and bottom of the Sparta Sand, and changing the model to MODFLOW-2000, the most recent version of the model code from the USGS. Reconstruction of the previous Sparta model included changing representation of model layers and various boundaries. The reconstructed model, referred hereafter as the current model, was calibrated using both trial and error and parameter-estimation techniques to simulate hydraulic heads from predevelopment (1898) to 1997.

Numerical Method

Transient, three-dimensional ground-water flow in a confined, anisotropic, heterogeneous aquifer is described by the following partial differential equation where the partial derivatives represent hydraulic conductivity in three dimensions:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W = S_s\frac{\partial h}{\partial t} \quad (1)$$

where x, y are cartesian coordinates in the horizontal direction (L);

z is cartesian coordinate in the vertical direction (L);

Kxx, Kyy, Kzz is hydraulic conductivity in the x, y, and z directions (LT^{-1});

h is hydraulic head (L);

W is volumetric flux per unit volume (T^{-1});

S_s is specific storage (L^{-1}); and

t is time.

For this report, the modular three-dimensional (3D) finite-difference code, USGS MODFLOW-2000 (Harbaugh and others, 2000), was used to approximate the differential equation, and the preconditioned conjugate gradient solver (Hill, 1990) was used for the numerical solution technique. The aquifer is subdivided into a set of discrete blocks in space and time. The blocks represent cells of porous material within which the hydraulic properties are the same. Each cell then has a finite-difference equation describing the flow through it. These equations can be solved for either steady state to simulate equilibrium conditions, or transient to simulate changes in stresses over fixed periods of time. The model simulates 100 years of system response to stress by dividing the model into stress periods with each stress period representing a period of time for which ground-water withdrawal rates (water use) are relatively unchanged. MODFLOW-2000 provides a parameter estimation feature (Hill and others, 2000) that uses a nonlinear least-squares regression method to aid in estimating hydrologic properties and to further evaluate the model. The aquifer is subdivided into a set of discrete blocks in space and time. The blocks represent cells of porous material within which the hydraulic properties are the same. Each cell then has a finite-difference equation describing the flow through it.

Model Assumptions

A model is a simplification of a process or a system. The objective of the current model is to maintain a balance between simplicity and adequate representation of the complex aquifer system. Simplifications and assumptions used in the development of this flow model include: (1) two layers are adequate to represent the Sparta aquifer; (2) hydraulic properties are homogeneous within a model cell of the finite-difference grid; (3) the system is horizontally isotropic; (4) pumpage in a model cell may represent multiple wells, but is simulated as a single withdrawal from the cell center; (5) pumpage throughout a stress period is constant and represents an average pumping rate throughout that time period; and (6) recharge from precipitation is constant throughout the entire model simulation.

Model Development

The following is a description of how the physical system was represented and integrated into the current numerical model. In addition, major differences from the previous Sparta model are discussed, however, the interested reader should refer to Fitzpatrick and others (1990) for complete details of the previous Sparta model to better understand differences between these models.

Spatial Discretization

The current model area is discretized into a finite-difference grid of 267 rows by 218 columns of uniform 1-square mile (mi^2) cells covering 58, 206 mi^2. The grid is aligned roughly with the Fall Line with the y-coordinate axis at an azimuth of approximately N.45° E. In the previous Sparta model developed by Fitzpatrick and others (1990), the grid was variably spaced ranging in rectangular size from 10 by 23 mi to 1 mi^2 with identical grid orientation. The uniform grid spacing of 1 mi^2 in the current model improves numerical accuracy in areas where hydraulic gradients are large and continue to steepen or where new cones of depression have formed since the previous Sparta model was developed in 1985.The active model area covers 38,220 mi^2 with 38,220 active model cells representing the Sparta aquifer (fig. 4). The active model area was extended northward from the north boundary of the previous Sparta model. This extension goes northward beyond the facies change where the Sparta Sand, Cane River Formation, and Carrizo Sand become the single hydrogeologic unit of the Memphis aquifer. The extension of the active model area northward was necessary to adequately cover additional counties of Arkansas where aquifer withdrawals are causing substantial hydraulic-head declines. Northward beyond the facies change of the Cane River Formation, properties and geometry of the Memphis aquifer are used in the model. Clays of the Wilcox Group are assumed to provide adequate confining conditions to justify the bottom of the model as a no-flow boundary in that area.

The Sparta Sand thickness varies spatially. The current model is a two-layer representation of the upper and lower water-bearing zones in the Sparta aquifer separated by a quasi-3D confining bed representing a semiconfining unit of clay that exists, but is not well defined, in southern Arkansas and north-central Louisiana (Baker and others, 1948; Broom and others, 1984). This differs from the previous two-layer Sparta model in which only one layer, the lower one, was used to simulate hydraulic heads in the Sparta aquifer and the overlying layer represented the Cockfield aquifer as a constant-head boundary. These layers in the previous Sparta model were separated with a quasi-3D confining unit to simulate vertical flow through the clay confining unit of the Cook Mountain Formation. The influence of overlying aquifers on the Sparta aquifer are represented in the current model by a head-dependent boundary discussed in a later section.

Surfaces representing the Sparta Sand top and total thickness were modified from the previous Sparta model. The altitude of top of the Sparta Sand (layer 1) is based on a composite map created by digitizing separate, but similar maps of the top of the Sparta Sand and selectively combining them. Petersen and others (1985) cover Arkansas, and Brantley and others (2002) cover Louisiana in detail. Pugh and others (2000) provide additional detail in selected areas of Arkansas. The Gulf Coast RASA publication series provided regional coverage to substitute any missing information from the more detailed maps to cover the model area (Grubb, 1998; Hosman, 1996; Hosman and Weiss, 1991). The composite map provided a detailed representation of the top of the Sparta Sand based on all available information for use in the current model.

The Sparta Sand comprises layers of sand interbedded with clay lenses and discrete clay units. Based on data from the Gulf Coastal RASA study (A.K. Williamson, U.S. Geological Survey, written commun., 2001; Hosman and Weiss, 1991) and geophysical logs from Union County and surrounding areas, the thickness of the Sparta aquifer was calculated by summing the thickness of the discrete sand beds. From the total sand thickness, 60 percent was assigned to the lower water-bearing zone (layer 2) and the remaining 40 percent was assigned to the upper water-bearing zone (layer 1). The remaining thickness of the total formation is assumed to be clay and is represented in the model as a quasi-3D confining bed. Therefore, the thickness associated with the quasi-3D confining bed is the total formation thickness based on data from the Gulf Coastal RASA study minus the total sand thickness. The continuous confining unit averaged approximately 100 ft thick. The extension of this confining unit outside the Union County area also is variable, either representing an assumed discrete clay unit of defined thickness or a combination of interbedded clay lenses which combine to effectively restrict vertical flow. The bottom of the Sparta Sand was computed as the top of the Sparta Sand minus the total formation thickness.

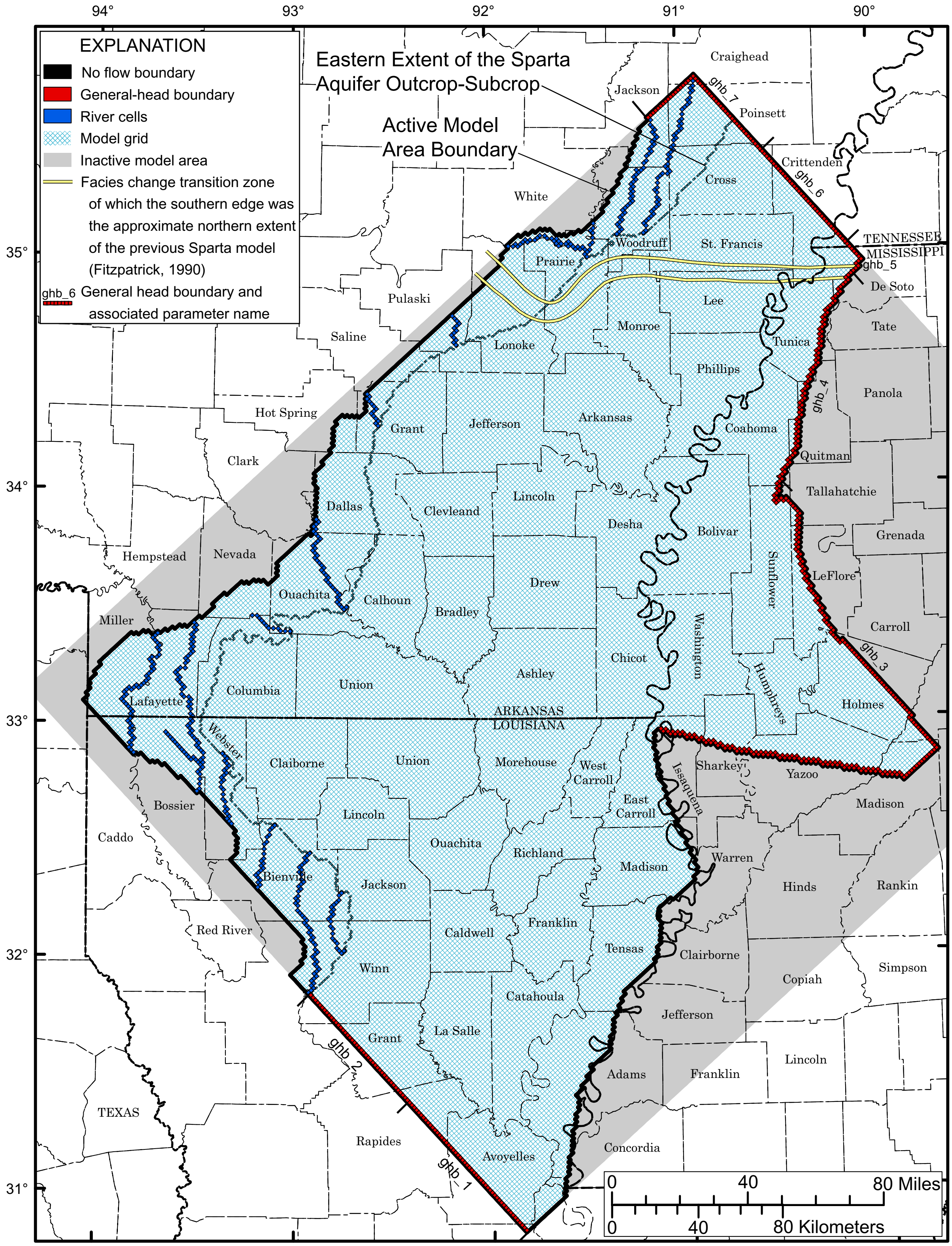


Figure 4. Model grid of active cells with boundary conditions and river nodes.

Time Discretization

Ground-water flow in the Sparta aquifer in the current model is simulated from 1898 through 1997. Steady-state conditions are simulated prior to 1898 and represent predevelopment aquifer conditions. This was done to obtain a head distribution that would not vary with time and would be in equilibrium with model boundary conditions. MODFLOW 2000 allows the user to define steady-state and transient stress periods in the same simulation. Therefore, stress period 1 in the model represents steady-state conditions of predevelopment. The transient simulation from 1898 to 1997 is divided into 27 stress periods for a total of 28 stress periods in the model (table 2). Stress period lengths were selected on the basis of intervals of relatively constant ground-water withdrawals; pumping stresses in the model are constant for the duration of a stress period. The length of each stress period ranges from 1 to 20 years. Because withdrawal amounts generally are reported as annual totals, the minimum stress period is 1 year and pumpage rates are averaged over the entire year. With this temporal discretization, seasonal effects, such as irrigation wells, are not simulated. However, because the Sparta aquifer is predominantly used for industry and public supply, error because of seasonal fluctuations in water use is minimal. In addition, the objective is to simulate effects of stress over long periods of time; therefore, seasonal variations are not examined in this model.

Boundary Conditions

Model boundaries determine the locations and quantities of simulated flow into and out of the model; therefore, the selection of appropriate boundaries for the model is a major concern in any modeling effort. The selection of model boundaries for the aquifers in the current model is based on a conceptual interpretation of the flow system developed using information reported by Payne (1968), Hosman and others (1968), Petersen and others (1985), and that of the previous Sparta model (Fitzpatrick and others, 1990). Boundaries require the definition of model input variables, also called parameters.

Head-Dependent Boundaries

Head-dependent boundaries represent a potentially infinite supply of water, whereby rate of flow from or to the boundary is affected by changes in hydraulic head within the aquifer and the resultant hydraulic gradient. Appropriate uses of this boundary type to represent hydrologic conditions include rivers, lakes, and adjacent geologic units. Flows into and out of the aquifer can change over time with changes in aquifer hydraulic head because of system stresses, such as ground-water withdrawals.

Table 2. Model stress periods and corresponding time periods represented

Stress period	Start of year	End of year	Total years
1	Steady state with no pumping		
2	1898	1899	2
3	1900	1919	20
4	1920	1924	5
5	1925	1929	5
6	1930	1930	1
7	1931	1934	4
8	1935	1937	3
9	1938	1942	5
10	1943	1943	1
11	1944	1947	4
12	1948	1949	2
13	1950	1951	2
14	1952	1954	3
15	1955	1956	2
16	1957	1957	1
17	1958	1962	5
18	1963	1964	2
19	1965	1967	3
20	1968	1969	2
21	1970	1970	1
22	1971	1972	2
23	1973	1977	5
24	1978	1980	3
25	1981	1982	2
26	1983	1985	3
27	1986	1989	4
28	1990	1997	8

General-Head Boundaries

Head-dependent boundaries used to represent lateral inflows to and outflows from the Sparta aquifer are represented in the current model using the MODFLOW general-head boundary package. The conductance term of the general-head boundary was the parameter considered for inclusion in the set of parameters to be adjusted during the parameter estimation process. These boundaries are shown in figure 4.

The general-head boundaries in the model on the north and south do not represent natural boundaries based on structural features; however, they are artificially placed far enough from primary areas of concern and interest that boundary effects are minimal. The southern boundary in Louisiana is beyond the radius of influence of any significant pumping center and thus boundary effects are minimal. The southern boundary in Mississippi and the northern boundary in Arkansas, while not totally beyond the radius of influence of pumping outside the boundary, are located such that the effects on hydraulic heads in major areas of interest of the model in southeastern Arkansas and north-central Louisiana are negligible. General-head boundaries in the current model differ from the previous Sparta model, which used constant-head boundaries varied over defined simulation periods to represent lateral flows into and out of the aquifer system.

Rivers

Head-dependent flow representing rivers is simulated using the river package of MODFLOW-2000 (Harbaugh and others, 2000). In the river package, flow between a stream and the underlying cell of the ground-water flow model is a function of the altitude or stage of the stream; the simulated hydraulic head in the cell; the length (L) and width (W) of the stream in the cell; and the altitude, vertical hydraulic conductivity (K), and thickness (M) of the streambed. For rivers simulated in this model, the streambed conductance (KLW/M) was the parameter considered for inclusion in the set of parameters to be adjusted during the parameter-estimation process.

Stream segments from 15 rivers and streams in Arkansas and Louisiana were simulated in the model in the Sparta outcrop area (fig. 5). The simulated streams include the Bayou Deview, Cache River, White River, Cypress Bayou, Arkansas River, Saline River, Ouachita River, Smackover Creek, Bodcau Creek, Caney Creek, Bayou Dorcheat, Black Lake Bayou, Saline Bayou, and Dugdemona River. Streams were initially selected based on mean annual flows greater than 1,000 cubic feet per second (ft^3/s) then smaller streams were included to better define the ground-water/surface-water interaction in the outcrop area. Streamflows and equivalent stream stages (fig. 6) were prorated upstream and downstream using mean annual flow data for the period of record from nearby USGS streamflow gaging stations located within the reaches being modeled based on discharge/drainage area relations (Elton Porter, U.S. Geological Survey, written commun., 2001).

Simulation of Overlying Geologic Units

Leakage from overlying geologic units was simulated in the current 2-layer model using the MODFLOW-2000 river package described previously. The specified stage represents water levels of the Cockfield aquifer (fig. 6). Where the Cockfield aquifer is absent, the stage represents hydraulic heads in Quaternary-age aquifers or in the Cook Mountain Formation where they are hydraulically connected to the Cockfield aquifer. The length and width of the “streambed” are the cell dimensions. The altitude of the “streambed” represents the top of the Sparta Sand and the “streambed thickness” represents the Cook Mountain Formation thickness. Using this boundary condition, the vertical hydraulic conductivity of the “streambed,” which represents the vertical hydraulic conductivity of the Cook Mountain Formation (fig. 5), is the parameter considered for inclusion in the set of parameters to be adjusted during the parameter-estimation process.

Construction and explanation of the contoured potentiometric surface of the overlying aquifers (Cockfield and Quaternary-age aquifers) are discussed in detail in Fitzpatrick and others (1990). These were modified to provide additional input data in the extended area north of the Cane River Formation facies change. Changes in hydraulic head in the Cockfield aquifer through time relative to those in the Sparta aquifer were small and resulted in negligible effects on system response in the Sparta aquifer (Ackerman, 1987; Brantley and Seanor, 1996; Joseph, 1998a; Trudeau and Buono, 1985).

Specified Flow Boundaries

No-Flow Boundaries

The Cane River confining unit, which underlies the Sparta aquifer, is considered relatively impervious (Petersen and others, 1985) and is represented in the

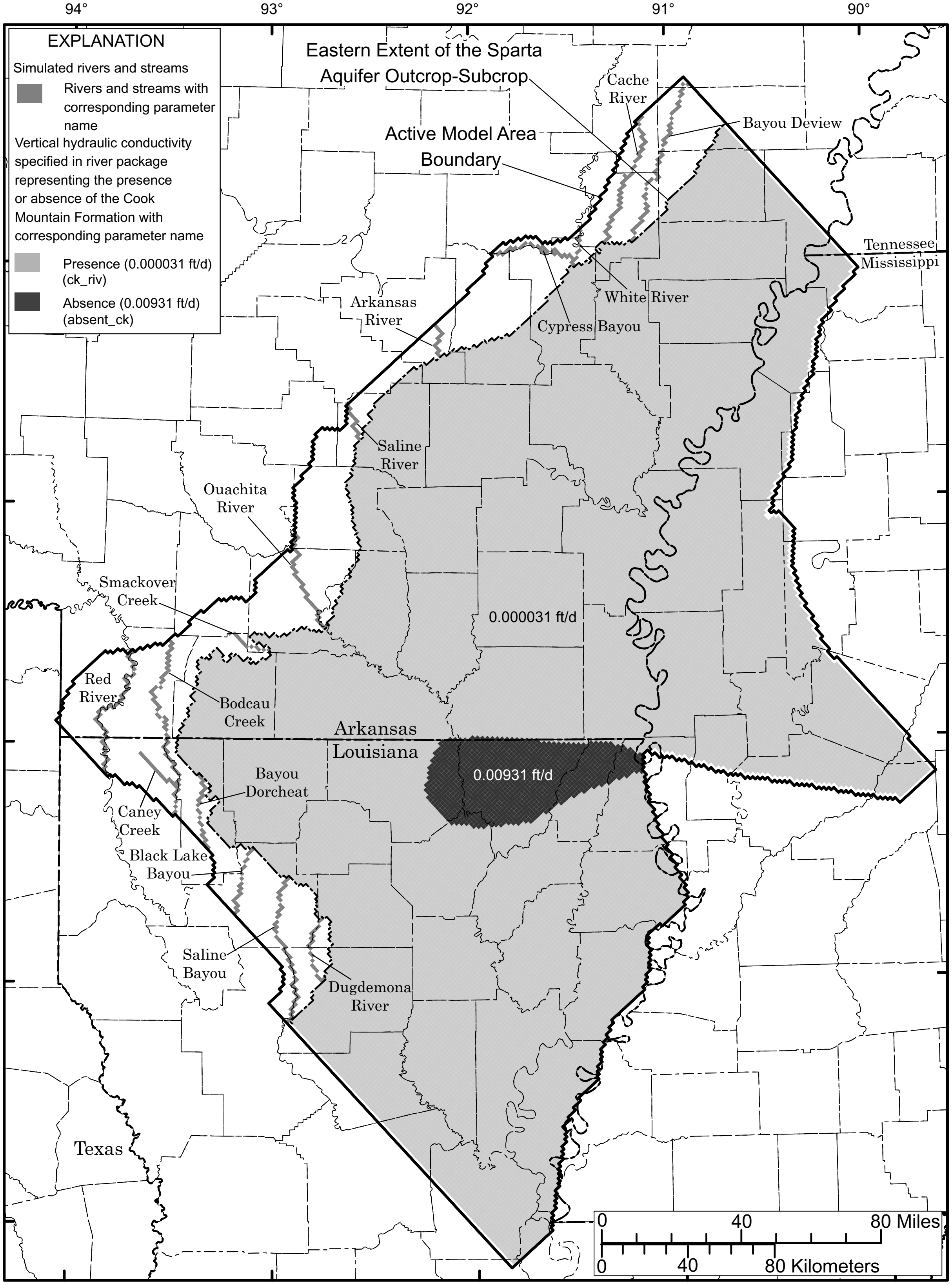


Figure 5. Hydraulic parameter names and zonations representing rivers and vertical hydraulic conductivity of the Cook Mountain Formation.

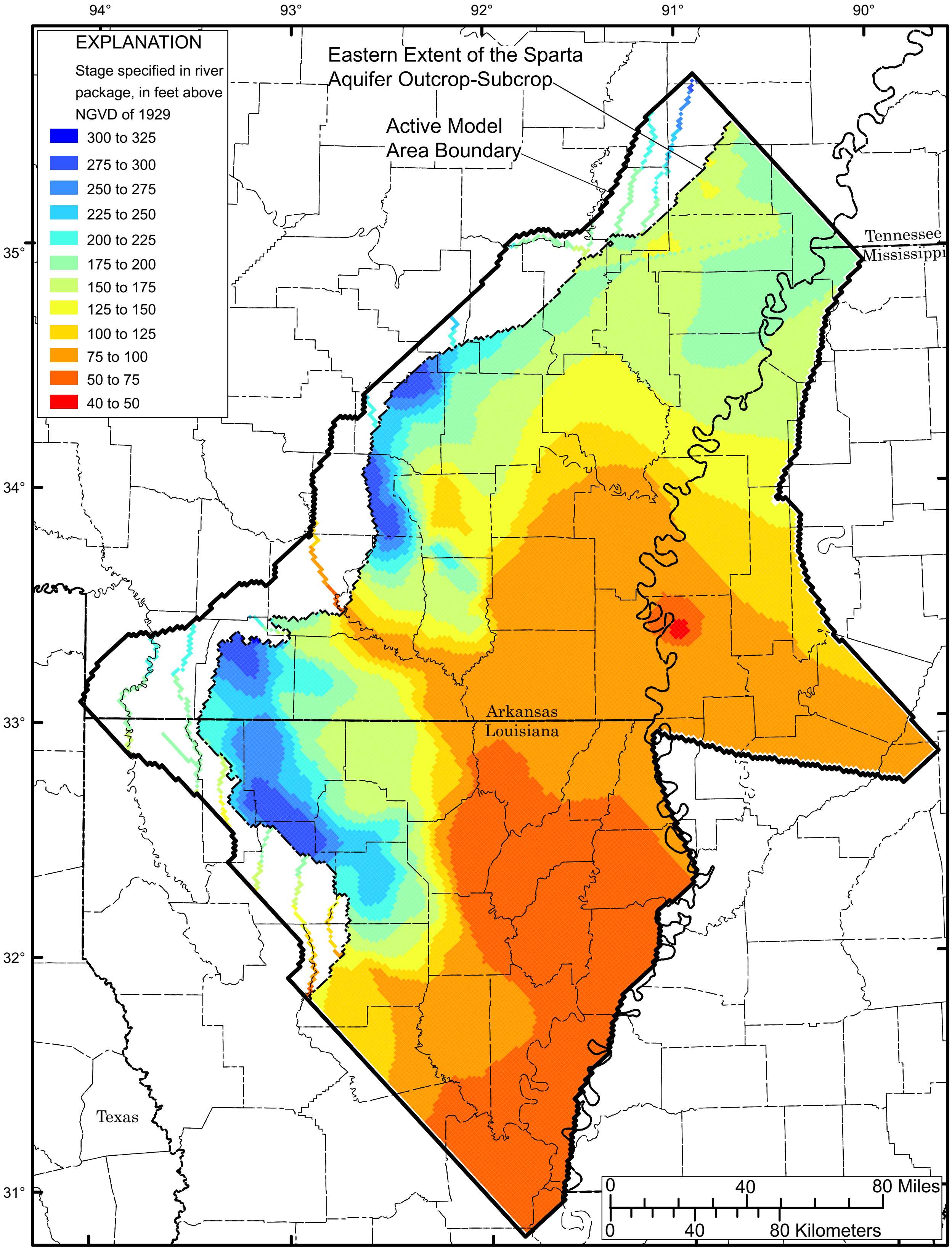


Figure 6. River package stage values representing mean annual water levels in rivers in the Sparta outcrop/subcrop and a combined potentiometric surface of aquifers overlying the Sparta Sand.

model as a no-flow boundary throughout the entire study area at the bottom of layer 2 (Fitzpatrick and others, 1990). In the active model area extended northward beyond the Cane River Formation facies change, clays of the Wilcox Group are assumed to provide sufficient confining conditions to justify a no-flow boundary at the bottom of layer 2. The western and southwestern updip limits of the Sparta outcrop are simulated as no-flow boundaries. This corresponds to the Fall Line and Sabine uplift, respectively. The Fall Line and the Mississippi River, where aligned with the model boundary, represent no-flow boundaries because vertical flow is assumed along these boundaries.

Areal Recharge in Outcrop

An average of about 50 inches per year (in/yr) (Freiwald, 1985) of precipitation falls on the aquifer outcrop area. Only a small fraction of the precipitation enters the confined ground-water-flow system as recharge. To account for this recharge, remaining outcrop area not covered by rivers and streams was represented as a specified-flux boundary. The outcrop area was initially subdivided into zones distinguishing subcrop and outcrop areas, each representing a specific rate of recharge. These zones were subsequently further divided during the calibration process to improve model fit (fig. 7). The recharge rate of each zone is the parameter to be adjusted during the parameter-estimation process.

Ground-Water Withdrawal

The model simulates 100 years of system response to stress by dividing the model into stress periods with each stress period representing a period of time for which ground-water withdrawal rates (water use) are relatively unchanged. Stress periods with associated ground-water withdrawal rates are shown in figure 8. The spatial distribution of model cells representing ground-water withdrawal for stress period 28 (1990-1997) is shown in figure 9. All ground-water withdrawals are taken from layer 2 because the majority of wells are completed and screened in the lower, more productive zone of the aquifer.

The water-use data and stress periods used in the current model are the same as compiled for the previous Sparta model (Fitzpatrick and others, 1990) through 1985. The northern extension of the model area required water-use data to be compiled and analyzed in nine Arkansas counties (or parts of) including Crittenden, Cross, Lee, Lonoke, Monroe, Poinsett, Prairie, St. Francis, and Woodruff Counties north of the Cane River Formation facies change (approximately 35 ° latitude) (fig. 4). Water use for these counties prior to 1965 was compiled (Terry Holland, U.S. Geological Survey, written commun. 2001) using similar methods and procedures described in Fitzpatrick and others (1990). From 1965 through 1985, a database of ground-water withdrawals reported every 5 years was used to estimate county totals for corresponding stress periods. The county water-use totals were distributed equally between pumping wells known to exist during that time period. This method assumes that monitored wells represent a similar distribution of wells used for water supply and was preferred to the other alternative of dividing the pumpage equally over all cells. Withdrawal amounts used in the previous Sparta model through 1985 (through stress period 26) were adapted to the current model grid by distributing the same pumpage over an equivalent area in cases where the previous and current model cells were not the same. For the period 1986 to 1997 (stress periods 27 and 28), water-use data were recompiled for the entire model from withdrawal and well location information available from Arkansas, Louisiana, and Mississippi water-use data bases for 1985, 1989, 1990, 1995, 1996, and 1997 (Terry Holland, U.S. Geological Survey, written commun., 2001; Sargent, 2000; David Burt, U.S. Geological Survey, written commun., 2001). The withdrawal amounts used in the current model are slightly different from those in the models of Fitzpatrick and others (1990), Kilpatrick (1992), and Hays and others (1998) because pumpage data were adjusted based on improved water-use compilation and estimation procedures. This adjustment is supported by the need for withdrawal rates within any one stress period to adequately represent the entire stress period and not just one specific year. Adjusted rates were compared to data published for 1990 and 1995 as part of the 5-year national water-use compilation to assure that the rates were within acceptable ranges (Terry Holland, U.S.Geological Survey, oral commun., 2002). Differences in the amount of withdrawals reported and published in a specific year and the amount of withdrawals used in a corresponding model stress period could be caused by several factors including: (1) withdrawals in a stress period represent multiple years compared to reported water use for an individual year; (2) exclusion of water-use data for wells with unknown completion zones; and (4) exclusion of some gross livestock and irrigation estimates.

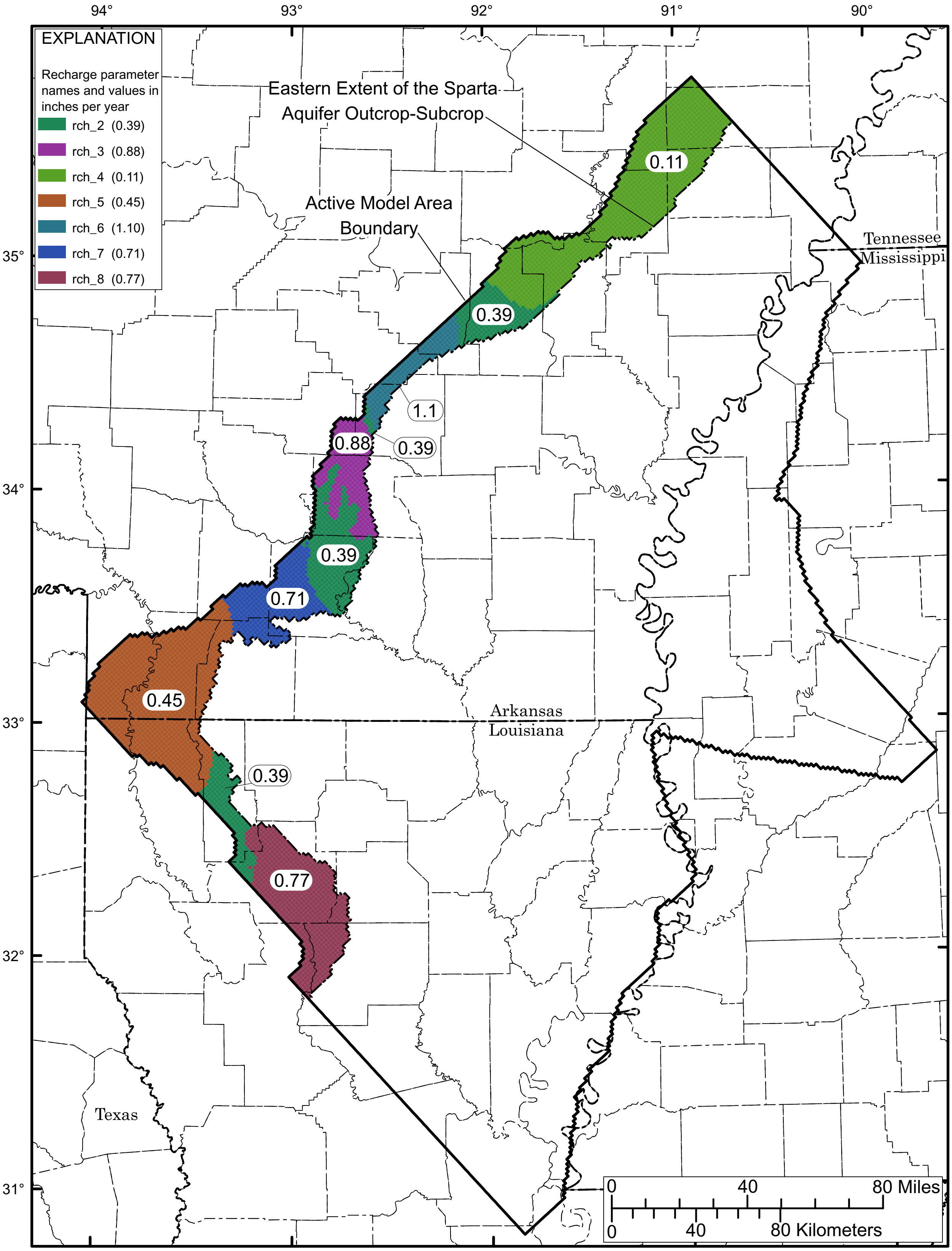


Figure 7. Hydraulic parameter names and zonations representing recharge rates in the outcrop and subcrop areas of the Sparta aquifer.

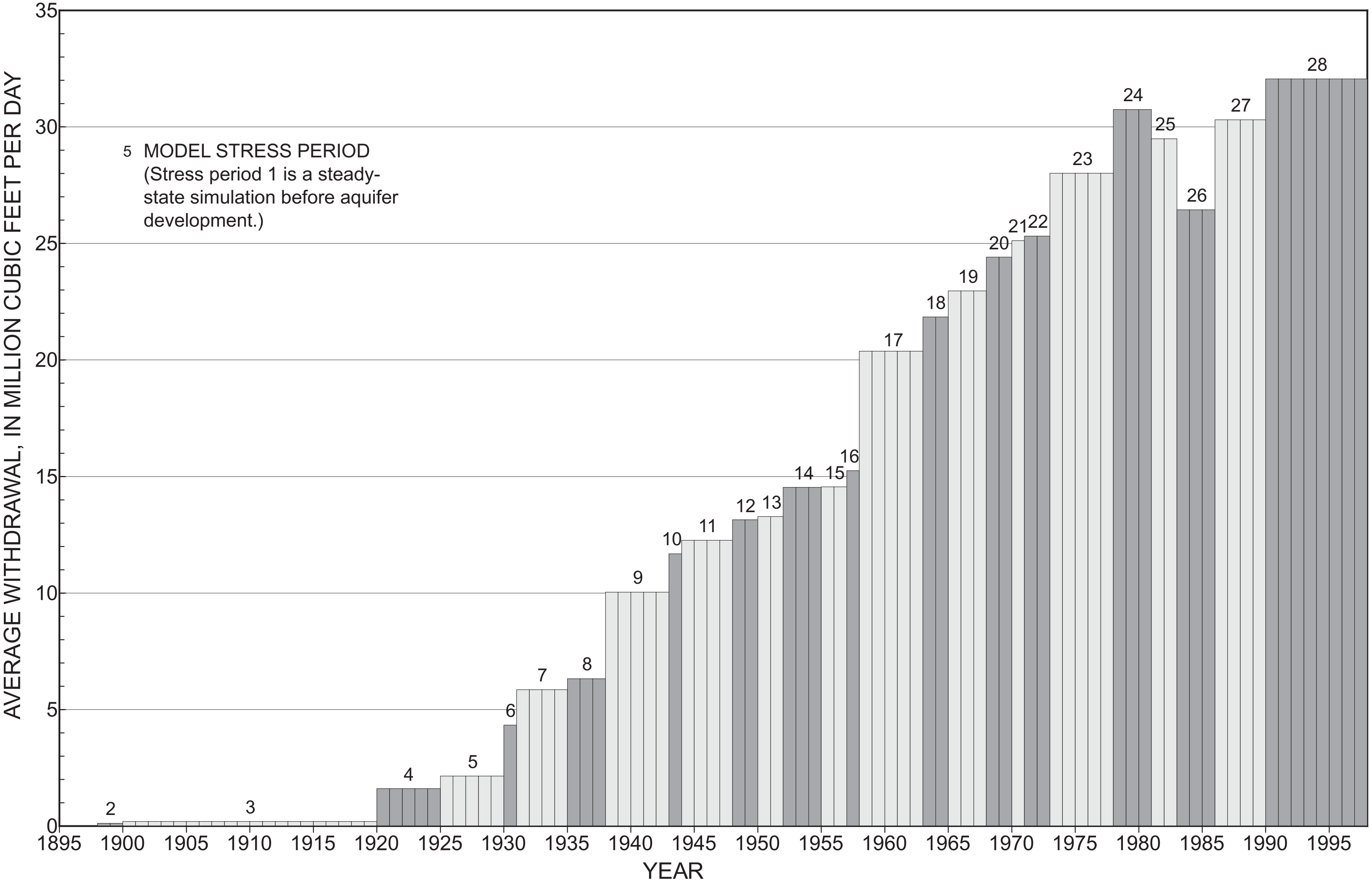


Figure 8. Total ground-water withdrawal from the Sparta aquifer and associated stress periods for the model area, 1898-1997.

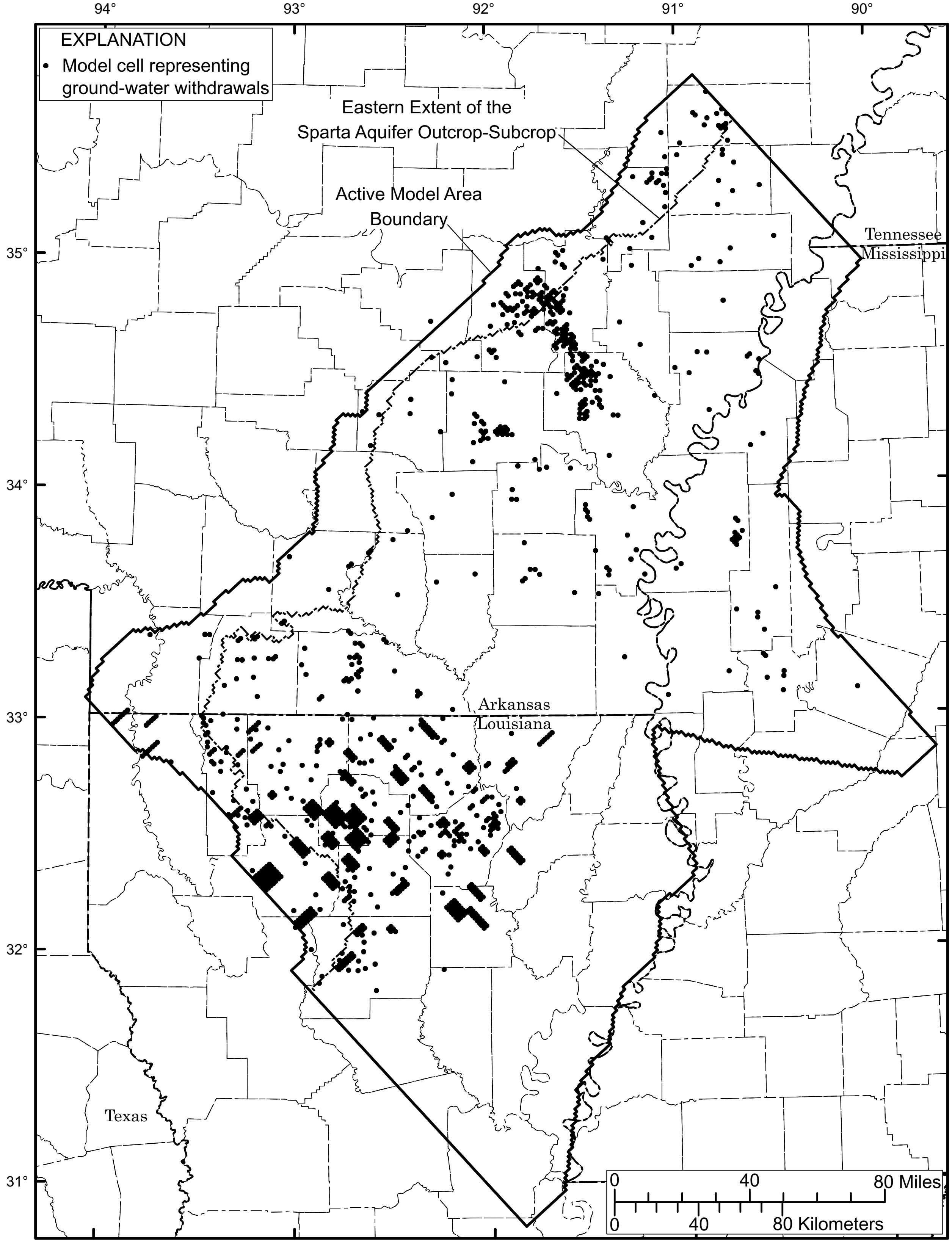


Figure 9. Spatial distribution for ground-water withdrawals represented in stress period 28, 1990-1997.

Hydraulic Property Zones

Hydraulic properties of the Sparta aquifer vary spatially in the model. These properties include hydraulic conductivity, storage, and vertical leakance. In addition, there are areas that have been faulted and the properties associated with faults were specified.

Hydraulic Conductivity

Horizontal hydraulic-conductivity parameter values and zones initially were assigned and defined from all available hydraulic data throughout the model area. Identical hydraulic-conductivity parameter zones are used for layers 1 and 2. Three hydraulic-conductivity parameter zones were defined (fig. 10) in each layer (six total). The initial values were adjusted during the calibration process. A single zone for vertical hydraulic conductivity was assigned in each layer and was defined by one parameter. The hydraulic conductivities of these zones are parameters considered for inclusion in the set to be adjusted during the parameter-estimation process.

Faults

The existence of faults in and around Columbia and Union Counties are supported by previous studies (Hosman, 1988; Tait and others, 1953; Baker and others, 1948; Broom and others, 1984), geophysical logs, and analysis of historical hydraulic heads and potentiometric maps (Joseph, 1998b, 2000; Schrader, 2003). The previous Sparta model documented the need to improve simulation of heads in these two counties where faults are known to exist, but not well defined (Hays and others, 1998). Faults were simulated in the current model using the Horizontal Flow Barrier (HFB) package that allows a reduction in horizontal hydraulic conductivity between adjacent cells to represent faults. Six faults were represented in the model, each with a separate parameter considered for inclusion in the set to be adjusted during the parameter-estimation process (fig. 10). For simplication, the width of the horizontal flow barrier is assumed to be 1.0 ft. The vertical hydraulic conductivity of cells containing faults is unaffected by the presence of the fault in the model.

Storage

Two specific-storage parameter zones and values for each layer were adjusted during calibration (fig. 11). Zones representing specific storage were the same for both layer 1 and 2 and were defined based on all available hydraulic data in the model area and known storage values of similar materials. One parameter for each layer (two total) represents specific yield where the aquifer is unconfined. These two parameters were fixed during the parameter-estimation process.

Vertical Hydraulic Conductivity of Layers and Confining Bed

Six parameter zones and values representing vertical hydraulic conductivity of the quasi-3D confining bed between layers 1 and 2 were adjusted based on limited analysis of geophysical logs and parameter estimation. Zonation of the quasi-3D confining bed is shown in figure 12. Only one parameter represents the vertical hydraulic conductivity of both layers and was adjusted during the parameter-estimation process. The initial value was based on one-tenth of the horizontal hydraulic conductivity.

MODEL CALIBRATION PROCEDURE

Calibration is the process of adjusting the model input variables, also called parameters, to produce the best match between simulated and observed aquifer heads. During calibration, parameters representing aquifer hydraulic properties were adjusted both manually and using automatic parameter-estimation techniques to match observed hydraulic heads from observation wells. MODFLOW-2000 provides a parameter-estimation feature (Hill and others, 2000) that uses a nonlinear least-squares regression method to aid in estimating hydrologic properties and to further evaluate the model. The parameters estimated in the calibration process represent the hydrologic properties distributed as constant values over broad parameter zones or over extended linear features such as rivers and, therefore, are not intended to represent specific values of field tests at individual points within that zone.

Non-Linear Least-Squares Regression Method

Non-linear least-squares regression is an automated parameter-estimation technique that is more efficient and objective compared to trial-and-error calibration because parameter values are adjusted automatically to obtain the best possible fit between simulated and observed values. The numerical difference between observed minus simulated values is

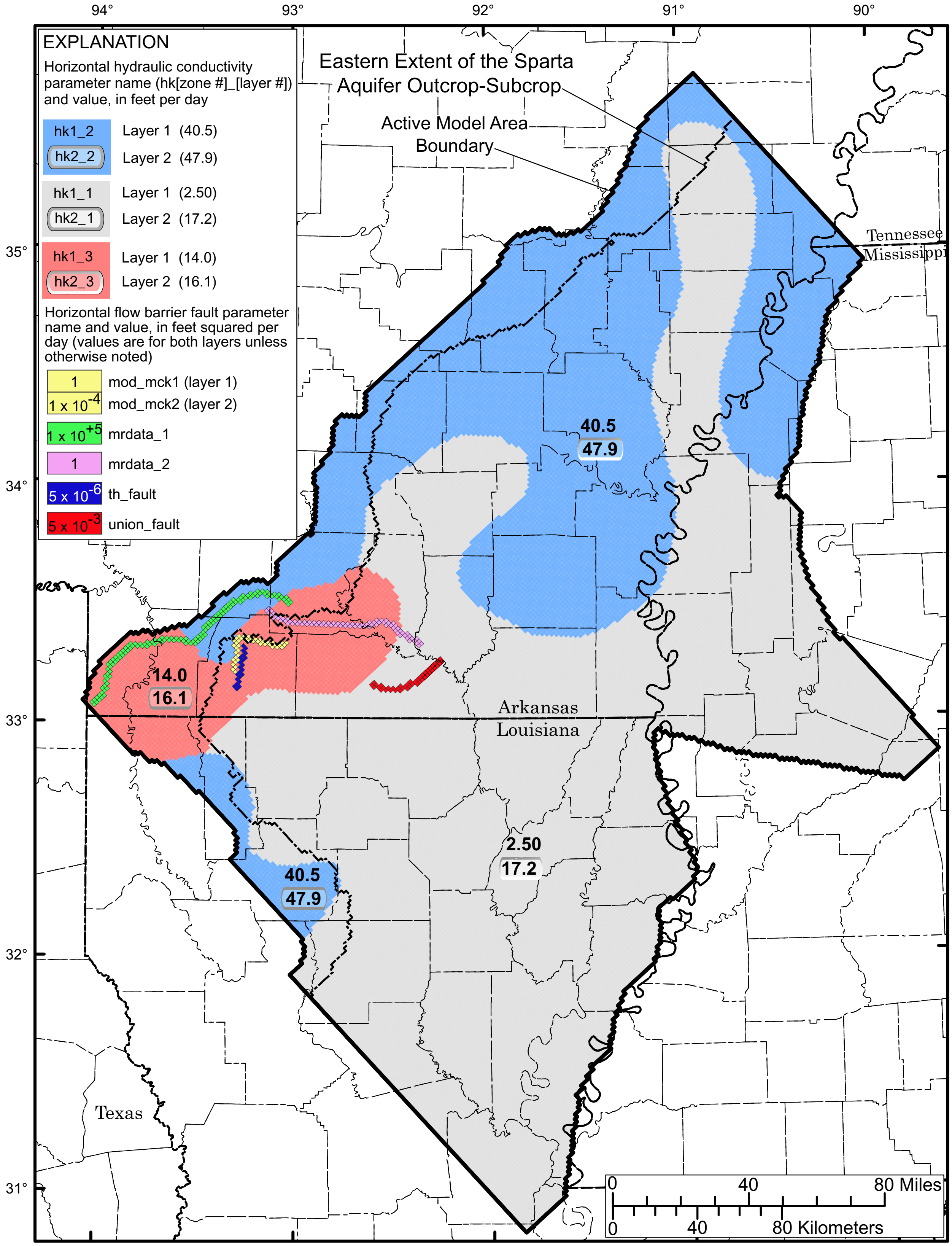


Figure 10. Hydraulic parameter names and zonations representing horizontal hydraulic conductivity and faults.

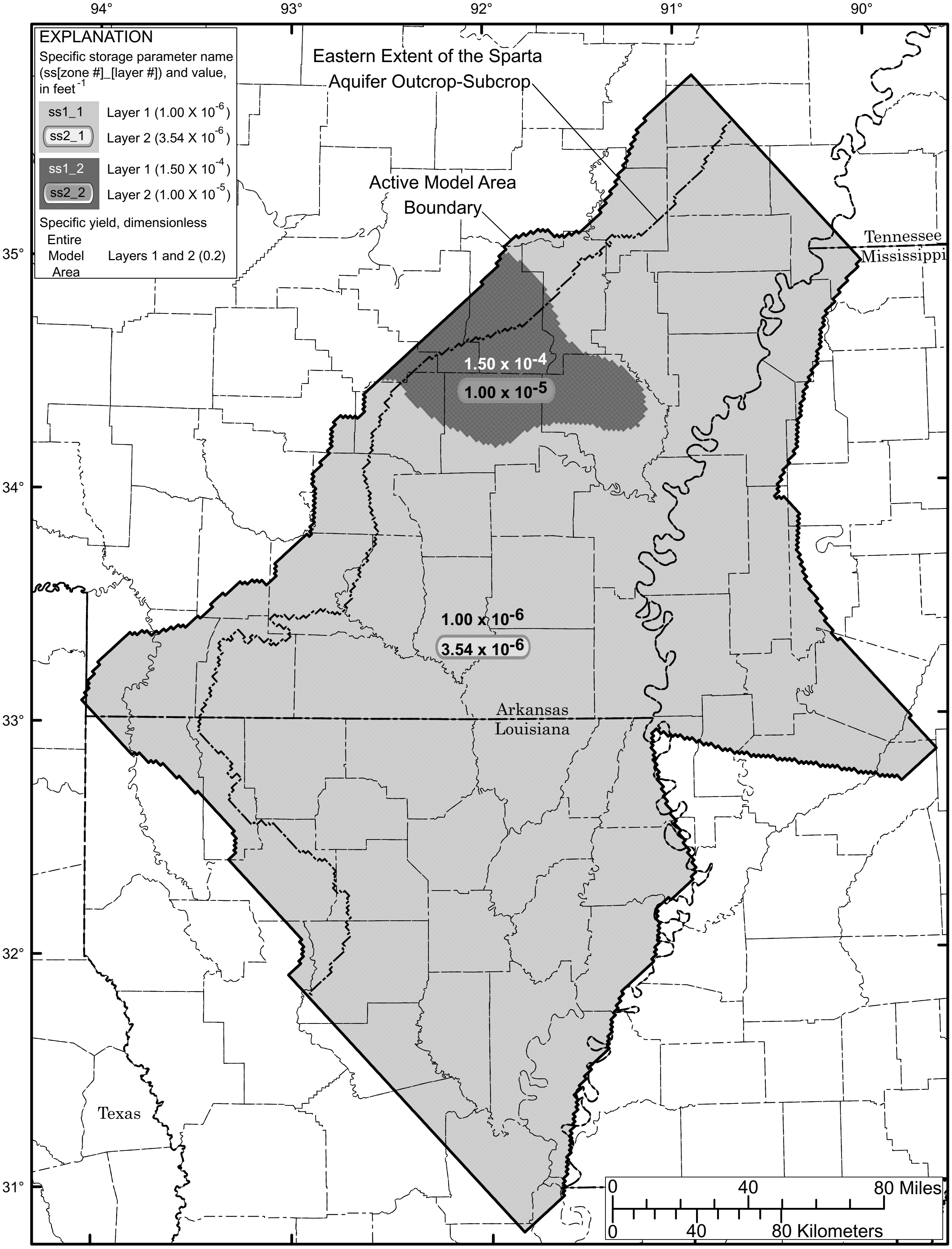


Figure 11. Storage parameter names and zonations.

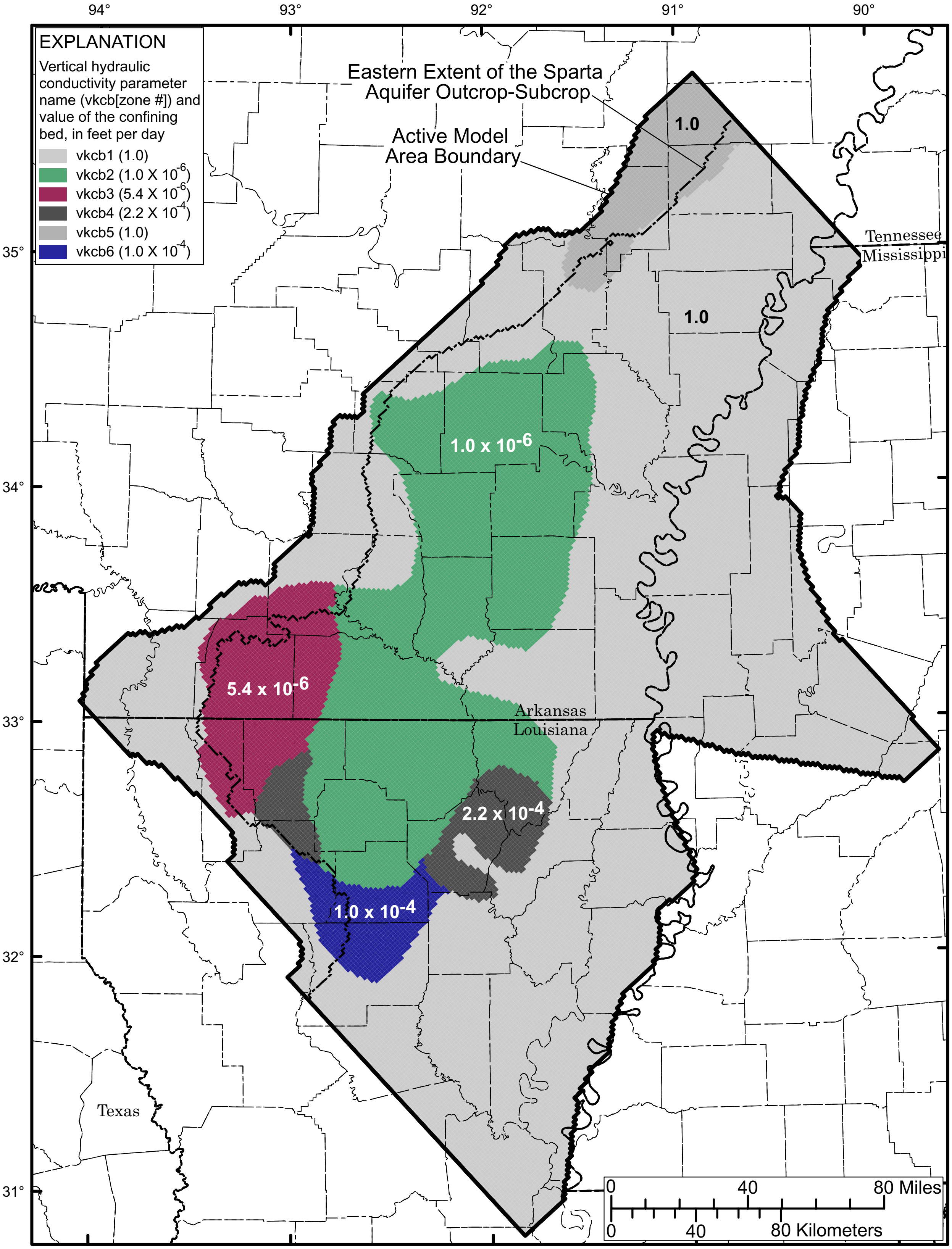


Figure 12. Hydraulic parameter names and zonations representing vertical hydraulic conductivity used to simulate confining beds in the Sparta aquifer.

called a residual. In the regression method, parameter values are estimated by minimizing the squared weighted residuals, called the objective function. The model is constructed to maintain parameter values within reason and plausibility. This method is explained with great detail in Cooley and Naff (1990); Hill (1992, 1994, and 1998); and Hill and others (2000).

Model Parameterization

In the model, grid cells assumed to have similar hydrologic properties are grouped together as a parameter zone and assigned a value that can be adjusted during the calibration process. The current Sparta model used a total of 56 hydraulic parameters (table 3). These parameters include horizontal hydraulic conductivity (hk), specific storage (ss), specific yield (sy), horizontal flow barriers, vertical hydraulic conductivity of Cook Mountain confining unit, riverbed conductance, vertical hydraulic conductivity of quasi-3D confining bed (vkcb), recharge (rch), and general-head boundary conductance (ghb). Many parameters are represented with the abbreviated name followed by the corresponding layer, when appropriate, and zone number. Thus hydraulic conductivity in layer 1, zone 1 is represented using hk1_1 and so on. Riverbed conductance parameters were named based on the corresponding river name. The value of ck_riv represents vertical hydraulic conductivity and is multiplied by length and width of each model cell, and divided by the thickness of the overlying Cook Mountain confining unit for input to the model. Horizontal flow barriers were named based on reference or spatial location. This is done for a number of aquifer properties, which will be discussed in detail in later sections of this report. For each boundary condition or hydraulic property, an associated parameter was considered for inclusion in the set of parameters to be estimated by the regression method during the calibration process, and an initial value for the parameter was assigned. Because the success of parameter estimation can be affected by the values of initial parameters, the values in the previous Sparta model and hydraulic-test data collected since that model was developed were used to assign initial parameter and model-input values. For parameters included in the estimated set, optimal parameter values were computed by the regression method.

Calibration Data Set

Hydraulic-Head Observations

A total of 795 hydraulic-head observations (water-level measurements) from 316 individual observation wells in Arkansas and Louisiana representing four time periods of 1970, 1985, 1990, and 1997 was used in the calibration data set (fig. 13). These observation periods were selected for two reasons: (1) they were used in potentiometric map reports for the Sparta aquifer (Edds and Fitzpatrick, 1986; Fitzpatrick and others, 1990; Joseph, 1998a; Kilpatrick, 1992); and (2) these observation years correspond to those used in the calibration and subsequent verifications of the previous Sparta model. The previous Sparta model was calibrated only to hydraulic-head observations in 1970 and verified with observations from each of the other 3 years. The 316 observation wells were selected from the wells used to generate the 1997 potentiometric map of the Sparta aquifer by Joseph (1998b). All hydraulic heads measured in the spring for any or all of the four time periods were used in the calibration. Spring measurements are least likely to be affected by localized drawdown caused by summertime pumping. All wells from which observations were used are assumed to be screened in the lower, higher producing section of the Sparta aquifer and assigned to model layer 2. These data provide broad spatial and temporal coverage of aquifer conditions.

Weights

The purpose of weighting the model calibration data is to reduce the influence of hydraulic-head observations that are less accurate and to increase the influence of observations that are more accurate. Weights on observation data account for measurement error associated with the method of determining land surface, affects of recent pumpage, unknown screened intervals of wells, presence of faults, and other factors. In theory, weights on the observations used in the regression procedure can be calculated from estimates of the variance or standard deviation of measurement error (Hill, 1998). The weights are calculated by dividing 1 by the variance of the measurement errors for the observation. To estimate these variances, the measurement errors can be assumed to have a normal distribution, and a 95-percent confidence interval for the measurement can be constructed. The 95-percent confidence interval spans a range equal to the measurement +/-1.96 times the

Table 3. Parameter names with corresponding optimal parameter estimates and composite-scaled sensitivities

[Numbers in parameter names indicate layer and zone as described in the parameter description. Composite scaled sensitivities as defined by Hill (1998). ft/d, foot per day; hk, horizontal hydraulic conductivity; ft^2/d, foot squared per day; in/yr, inch per year; NA, not applicable; vk, vertical hydraulic conductivity]

Parameter name	Parameter description (units)	Reasonable parameter values	Optimal parameter estimate	Composite-scaled sensitivity
hk1_1	Horizontal hydraulic conductivity of layer and zone (ft/d)	10-200[a] 0.1-600[b]	2.5	2.7
hk1_2			40.5	7.8
hk1_3			14	1.5
hk2_1			17.2	35.6
hk2_2			47.9	31.0
hk2_3			16.1	32.3
ss2_1	Specific storage of layer and zone (ft^{-1})	$1x10^{-7}$-$1x10^{-6}$[a] $<1x10^{-4}$[c]	$3.54x10^{-6}$	7.0
ss2_2			$1.0x10^{-6}$	3.0
ss1_1			$1.0x10^{-6}$	0.3
ss1_2			$1.5x10^{-4}$	11.5
sy_1	Specific yield of layer (dimensionless)	0.01-0.30[b]	0.2	2.1
sy_2			0.2	0
ghb_3	General head boundary conductance of zone (ft^2/d)	NA[d]	1	$1.5x10^{-3}$
ghb_1			1	$3.6x10^{-4}$
ghb_2			1	$3.3x10^{-4}$
ghb_4			1	$1.0x10^{-2}$
ghb_5			1	$2.2x10^{-3}$
ghb_6			1	$4.9x10^{-3}$
ghb_7			1	$5.6x10^{-3}$
ck_riv	Vertical hydraulic conductivity of Cook Mountain confining unit (ft/d)	$9x10^{-6}$-$3x10^{-4}$	$3.1x10^{-5}$	10.6
absent_ck			$9.3x10^{-3}$	0.3
Arkansas River	Riverbed conductance of rivers and streams in outcrop (ft^2/d)	100,000[d,e]	115,000	$3.2x10^{-2}$
Bayou Deview			0	$2.8x10^{-10}$
Black Lake Bayou			500	0.1
Bodcau Creek			2,494	1.0
Cache River			86,200	$2.0x10^{-2}$
Caney Creek			0	$3.6x10^{-11}$
Cypress Bayou			10,000	$5.8x10^{-3}$
Bayou Dorcheat			40,900	$7.3x10^{-2}$

Table 3. Parameter names with corresponding optimal parameter estimates and composite-scaled sensitivities--Continued

[Numbers in parameter names indicate layer and zone as described in the parameter description. Composite scaled sensitivities as defined by Hill (1998). ft/d, foot per day; hk, horizontal hydraulic conductivity; ft^2/d, foot squared per day; in/yr, inch per year; NA, not applicable; vk, vertical hydraulic conductivity]

Parameter name	Parameter description (units)	Reasonable parameter values	Optimal parameter estimate	Composite-scaled sensitivity
Dugdemona River			10,000	$1.7x10^{-2}$
Ouachita River			575,000	$1.5x10^{-2}$
Red River			305,000	$7.0x10^{-3}$
Saline River			538,000	$7.8x10^{-3}$
Saline Bayou			300	1.2
White River			137,000	$9.6x10^{-3}$
Smackover Creek			200	0.7
all-vk	Vertical hydraulic conductivity of both layers (ft/d)	hk divided by 10[f]	1.62	$6.4x10^{-2}$
vkcb6	Vertical hydraulic conductivity of quasi-3D confining bed zone (ft/d)	NA[d,g]	$1.0x10^{-4}$	2.2
vkcb5			1	$4.3x10^{-3}$
vkcb4			$2.2x10^{-4}$	5.6
vkcb3			$5.4x10^{-6}$	4.0
vkcb2			$1.0x10^{-6}$	1.0
vkcb1			1	$6.9x10^{-2}$
mrdata_1	Horizontal flow within a fault zone (ft/d)	NA[d,h]	$1.0x10^{5}$	$2.6x10^{-8}$
mrdata_2			1	$2.6x10^{-3}$
mod_mck1			1	$4.2x10^{-5}$
mod_mck2			$1.0x10^{-4}$	5.4
th_fault			$5.0x10^{-6}$	0.2
union_fault			$5.0x10^{-3}$	$8.9x10^{-2}$
rch_2	Recharge of zone (in/yr)	0-4[e]	0.39	4.4
rch_3			0.88	10.4
rch_4			0.11	2.2
rch_5			0.45	4.6
rch_6			1.10	3.5
rch_7			0.71	12.6
rch_8			0.77	6.7

[a] Multi-well hydraulic tests (Payne, 1968; Hosman and others, 1968).

[b] Comparable hydrologic units (Fetter, 1994).

[c] Common values (Freeze and Cherry, 1979).

[d] No data available to estimate reasonable range.

[e] Previous Sparta model (Fitzpatrick and others, 1990).

[f] Assumed vk one-tenth of hk in stratified depositional environment.

[g] Delineation of zones based on geophysical logs around Union County and hydrologic judgement elsewhere.

[h] Barrier locations based on mapped faults (Hosman, 1988) and hydrologic judgement.

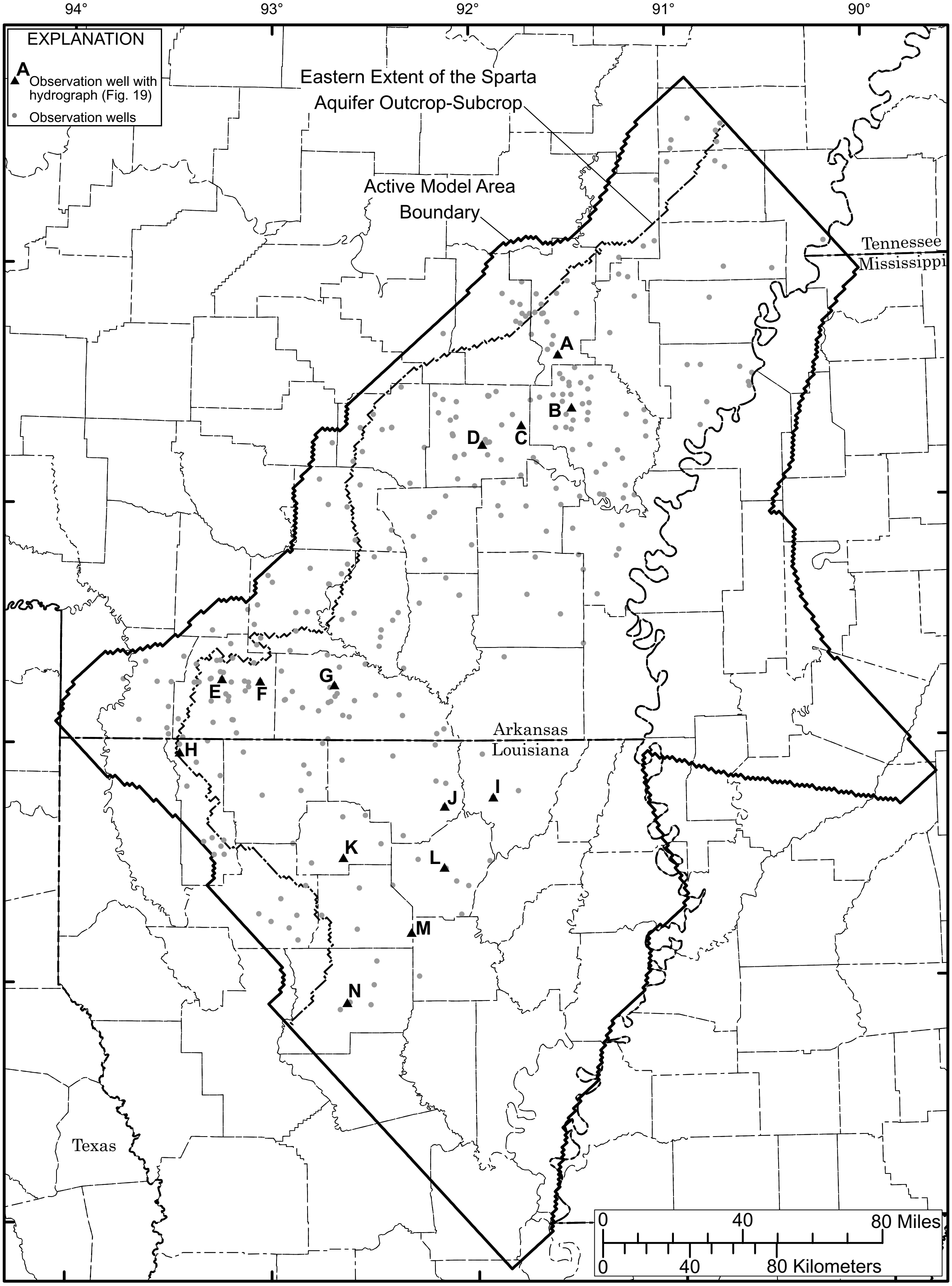


Figure 13. Locations of 316 wells for which hydraulic-head measurements for 1970, 1985, 1990, and 1997 are included in the calibration data set with hydrographs from 14 wells labeled A-N.

standard deviation (square root of the variance). Examples and detailed calculations of weights are given by Hill (1998).

For this report, a variance of 1.0025 ft^2 was used for all but 28 observations with a calculated weight of 0.998 (practically 1.0). Based on a 95-percent confidence interval, these measurements are assumed to be within approximately +/- 2 ft. The other 28 observations were weighted using estimated variances of 5 ft^2 and 10 ft^2 because of measurement uncertainty for reasons described above. These two variances result in calculated weights of 0.20 and 0.10 and 95-percent confidence intervals of approximately +/- 4.4 and 6.2 ft, respectively. These 28 observations were from only 13 of 316 observation wells used in the model calibration.

Sensitivities

The sensitivity of hydraulic heads with respect to various model parameters was calculated using the sensitivity-equation method (Hill and others, 2000). Composite scaled sensitivities (CSS) were calculated for each parameter (table 3). CSS values aid in determining if there is adequate information in the calibration data to estimate a particular parameter. CSS values less than about 0.01 times the largest CSS indicate that the regression may not be able to estimate the parameter (Hill, 1998). In many initial calibration attempts, estimations of various parameters were adjusted toward physically unreasonable values. In these cases, the parameter value was fixed at a reasonable value based on published studies in the area or literature review of similar hydrogeologic units. As the calibration improved, so did the ability of the parameter-estimation process to adjust parameters to reasonable values. Therefore, parameters that were initially fixed were allowed to be estimated by the parameter-estimation process later in the calibration.

Reasonable Parameter Ranges

The parameter-estimation process does not allow for upper and lower bounds on estimates to be specified; thus, it is possible for model-computed parameter estimates to lie outside of expected or reasonable ranges. A check for reasonableness of the optimal parameter estimates is an important step in the analysis of regression results.

Reasonable ranges of values for most of the parameters included in the set to be estimated by the regression procedure were determined (table 3). These ranges were determined from existing hydrologic information, including previous studies and model results, hydraulic tests, and material properties of similar aquifers and confining units. It was not possible to identify plausible ranges of flux values for each general-head boundary and horizontal-flow barrier prior to parameter estimation.

MODEL EVALUATION

Optimal Parameter Estimates

The final optimal parameter estimates of the model are considered reasonable estimates for the type of material and conditions found in the Sparta aquifer. Horizontal hydraulic conductivity values of 2.5 to 47.9 ft/d occur within the expected range of hydraulic conductivities for silty to clean sand (Freeze and Cherry, 1979). The smallest value of hydraulic conductivity occurs in the upper layer (table 3). This may be the result of fining upward in the stratigraphic sequence (Payne, 1968; Hosman and others, 1968). In any case, overall values for hydraulic conductivity are within the same order of magnitude and represent average values for large areas in the aquifer. Horizontal hydraulic conductivities of horizontal flow barriers, representing faults, range from 5 x 10^{-6} to 1.0 ft/d. In one case, the fault (mod_mck1 and 2) is thought to be a growth fault. Therefore, it may exist only in the lower portion of the Sparta aquifer. To simulate this, the fault was given a hydraulic conductivity of 1 x 10^{-4} ft/d in the lower layer (mod_mck2), and 1 ft/d in the upper layer (mod_mck1) (fig. 10). Another fault, mrdata_1 was found to be insensitive to the calibration data set because of the position of the fault near the western model boundary. Therefore, the value of mrdata_1 was set to 1 x 10^5 ft^2/d to simulate a lesser effect on the ground-water system. Specific yield values throughout the model were fixed at 0.2. Specific storage values range from 1 x 10^{-6} to 1.5 x 10^{-4} per foot (fig.10). Riverbed conductances for Bayou Deview and Caney Creek effectively were removed from the calibration by setting the riverbed conductance to 0 after determining their minor impact on calibration. The next smallest value of riverbed conductance is in a portion of Smackover Creek, which reflects the size and depth of the small stream. The largest value of riverbed conductance is in the Ouachita River, probably because of the large size of the river. Riverbed conductance typically varied by river size, however field measurements of streambed properties do not exist to estimate riverbed conductance for comparison. The vertical hydraulic-conductivity value used in the calculation of riverbed conductance for parameter ck_riv, which represents leakance through overlying units, ranged from 9.3 x 10^{-3} to 3.1 x 10^{-5} ft/d. The larger value of parameter absent_ck is associated with an area overlying the Sparta aquifer where the Cook Mountain confining unit does not exist (Hosman and Weiss, 1991) and represents impeded flow through overlying hydrogeologic units (fig. 5). Recharge from infiltration of precipitation ranges from 0.11 to 1.10 in/yr. Although these rates are less than 2 percent of the average precipitation, the total recharge rate for the outcrop is greater than that used in the previous Sparta model. Recharge rates from precipitation in the Sparta outcrop have not been quantified by field measurements. Table 3 lists all parameter names.

Parameter correlations for each calibration were computed using the approximate covariance matrix for the parameters, which is calculated as part of the nonlinear-regression method (Hill and others, 2000). If a pair of parameters has a correlation coefficient near 1.0 or -1.0, independent estimation of the two parameters is not possible given the calibration data set used in the regression. In the calibration, five parameter pairs have correlations greater than 0.85 (table 4).

Table 4. Parameter pairs of five largest correlation coefficients

[Correlation dimensionless]

Parameter pair[a] (see table 3 for explanation)			Correlation coefficient
Bayou Deview	:	rch_4	-0.96
Black Lake	:	rch_8	0.97
ghb_5	:	ghb_6	-0.88
Cache River	:	vkcb5	-0.89
Saline Bayou	:	rch_8	0.89

[a] See table 3 for explanation.

Typically, correlations greater than 0.95 suggest problems with parameter non-uniqueness (Hill, 1998) and that there was not enough observation data to independently estimate the model parameters. In these cases, the model may only be estimating the ratio or sum of the highly correlated parameters. Bayou Deview: rch_4 and Black Lake Bayou: rch_8 have the largest absolute correlations of any parameter pair at -0.96 and 0.97, respectively. The other parameter correlations are not large enough to be problematic. Therefore, the river parameters in each of the two parameter pairs were set at fixed values while the other parameters were allowed to adjust during calibration.

The CSS calculated using initial parameter values provided an indication of which model parameters to estimate in the nonlinear-regression procedure and which to set to fixed values. However, the CSS values are dependent on the parameter values because the sensitivities are a nonlinear function of the model parameters. The CSS values calculated using the optimal parameter estimates for the calibrated model also are listed in table 3. Less than half of the defined parameters (23 of 56) have CSS values greater than 1.0 (fig. 14). The three hydraulic conductivity zones of the lower layer have a CSS more than double any other parameters. The next highest parameters with a CSS over 10 are rch_7, ss1_2, ck_riv, and rch_3. Parameters with very low CSS values (less than 1.0) were fixed instead of adjusted because of their minimal effect on the calibration.

Model Fit and Model Error

Statistical Analysis of Residuals

Analysis of residual statistics, such as maximum, minimum, and root mean square error (RMSE), provides a measure of model fit and expected model performance as a management tool. RMSE is a statistical representation of variance, and, as such, smaller values of RMSE indicate better model calibration. RMSE is determined using the equation:

$$RMSE = [\Sigma(h_o - h_s)^2 / n]^{1/2} \qquad (2)$$

where h_o is observed hydraulic head,

h_s is simulated hydraulic head, and

n is number of observations.

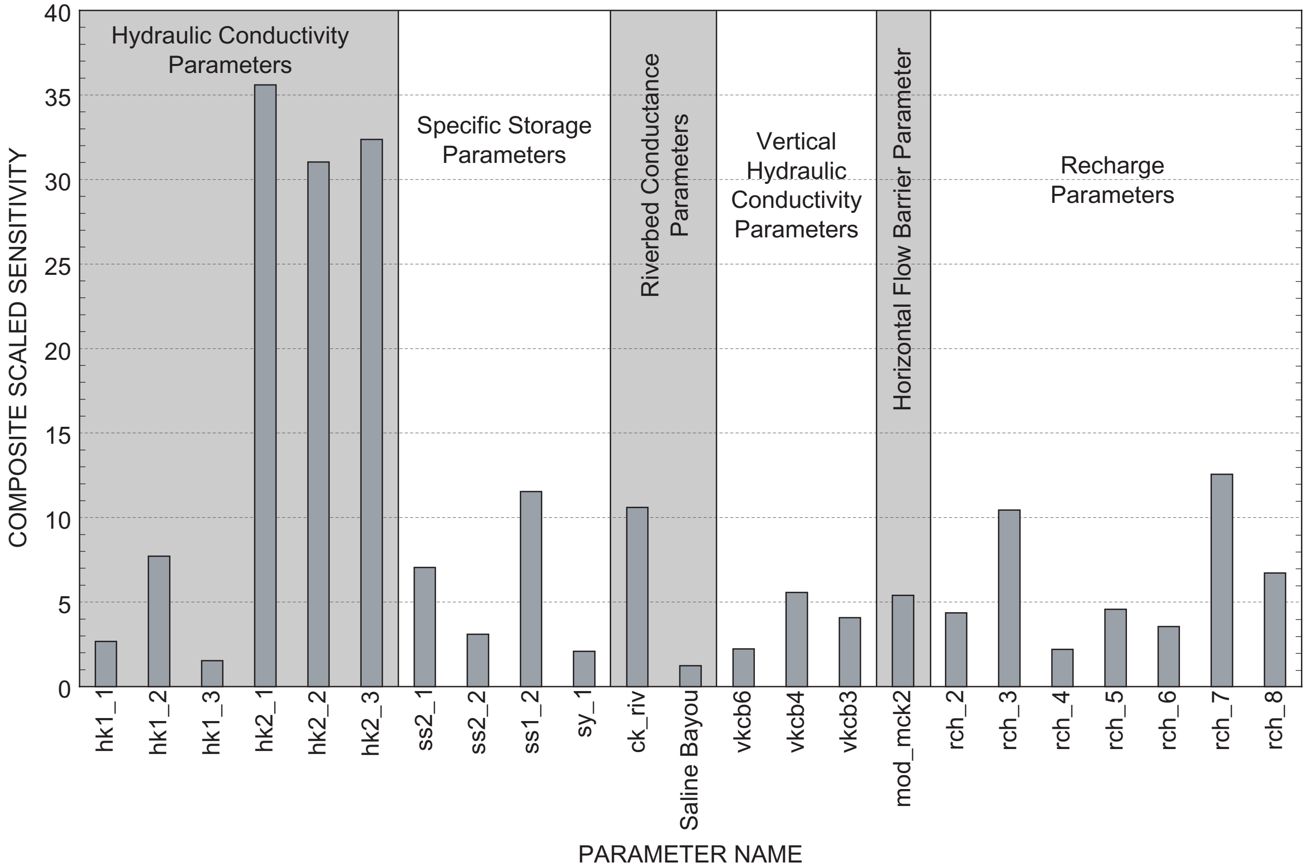


Figure 14. Composite scaled sensitivities (CSS) calculated using the optimal parameter estimates of the Sparta model calibration for CSS greater than 1.0.

RMSE's for the current model range from 16.0 to 18.9 ft for individual time periods, varying only slightly throughout time with no apparent trend (table 5).

Table 5. Weighted residual statistics for model calibration

Year	Number of wells	Mean (feet)	Mini-mum (feet)	Maxi-mum (feet)	Mean absolute (feet)	Root mean square error (feet)
1970	119	-2.7	-39.0	52.0	13.9	17.5
1985	197	0.6	-41.3	53.3	12.3	16.0
1990	163	-0.3	-54.9	47.4	14.3	18.9
1997	316	1.7	-56.5	48.4	14.5	18.9
All	795	0.4	-56.5	53.3	13.8	18.0

This indicates the ability of the model to simulate observed hydraulic heads under different sets of pumping stress and strengthens prediction confidence for future pumping stress scenarios. The RMSE for all 795 observations is 18.0 ft over a range in observed hydraulic-head altitudes from -224 to 306 ft. For only 1997 observations, the RMSE is 18.9 ft compared to 31.3 ft for the previous Sparta model reverification (Hays and others, 1998) using 316 and 283 observation wells, respectively. Additional comparisons of residual statistics for all years between the models are shown in table 6.

Standard error of the regression is a similar statistic that corrects the degrees of freedom for the number of parameters being estimated. The “n” in equation 2 is replaced by “n-p” where p is the number of parameters estimated. The standard error is 18.7 ft for all observations.

The mean or average of residuals is a simple measure of skewness from zero and indicates model bias depending on the magnitude and direction of the mean away from zero. The more closely the mean is to zero and more evenly divided between positive and negative residuals, the less model bias. A negative mean indicates the model tends to overpredict (simulated hydraulic heads greater than observed), and a positive mean indicates underprediction (simulated hydraulic heads less than observed). Out of 795 observations, 393 residuals were greater than or equal to zero (underprediction) and 402 residuals were less than zero (overprediction) resulting in a mean weighted residual of +0.4 ft

Table 6. Model residual statistics for the current and previous Sparta models

Statistic	1970[a]	1970[b]	1985[a]	1985[c]	1985[b]	1990[d]	1990[b]	1997[e]	1997[c]	1997[b]
Number of wells	192	119	233	197	197	113	163	283	197	316
Mean (feet)	1.8	-2.7	5.8	-12.1	0.6	18.3	-0.3	-2.3	-0.8	1.7
Minimum absolute (feet)	0.3	0.4	0.0	0.1	0.1	0.5	0.3	0.3	0.1	0.0
Maximum absolute (feet)	70.6	52.0	78.2	148.1	53.3	68.4	54.9	143.0	143.3	56.5
Standard deviation (feet)	13.5	17.3	14.2	30.7	16.0	15.4	18.9	31.2	31.8	18.9
Variance (feet squared)	180.8	300.0	202.3	815.0	255.1	236.6	355.7	974.6	1014.8	355.5
Root mean square error (feet)	21.2	17.5	22.3	32.9	16.0	24.0	18.9	31.3	31.7	18.9

[a] Results from Fitzpatrick and others (1990).

[b] Results for current model; wells used to generate 1997 Sparta potentiometric surface map (Joseph, 1998b) having data available for 1970, 1985, 1990, 1997.

[c] Results from Hays and others (1998); wells within the model area having data available for both 1985 and 1997, generating a common key well set for the two simulations.

[d] Results from Kilpatrick (1992).

[e] Results from Hays and others (1998); all well data available within the model area for 1997.

(table 5). The minimum and maximum weighted residuals were closely balanced at -56.5 and +53.3 ft, respectively. In addition, the mean for individual years shows no appreciable trend in increasing value from zero in either direction. This residual balance both in magnitude and direction and through time without trend is another desirable characteristic of model calibration that gives confidence to use of the model as a management tool.

Weighted Hydraulic-Head Residuals

Graphical analyses of the weighted residuals facilitate assessment of model bias or error and of model fit to the calibration data. These analyses include plots of the weighted residuals and weighted simulated values and of the spatial and temporal distribution of the weighted hydraulic-head residuals.

The plot of weighted residuals and weighted simulated equivalents for an unbiased model ideally should show a random distribution of the weighted residuals above and below zero for all weighted simulated equivalents. In this case, the model fit is generally similar over the entire range of available hydraulic head values, and the calibration has, in general, the desired random distribution of weighted residuals (fig. 15).

Additional assessments of model error are accomplished through analysis of the spatial and temporal distribution of weighted residuals (fig. 16) for years 1970, 1985, 1990, and 1997. Residuals representing 1997 observation data provided the best guide during model calibration because (1) improved water-use data for later years, (2) highest number and uniform distribution of wells, and (3) the last observation time before prediction scenarios begin. Negative residuals, shown in blue, indicate simulated hydraulic heads that are higher than observed, while positive residuals, shown in red, indicate simulated hydraulic heads that are lower than observed. Different ranges in residuals are represented by a variety of geometric symbols for visual analysis of model bias.

Ideally, negative and positive weighted residuals should be small and randomly distributed in space. Clustering of residuals with similar magnitudes and signs is indicative of model bias. Overall, residuals (fig. 16) appear to be well distributed in both magnitude and sign (+/-). Some clustering of residuals occurs in the Grand Prairie area with a trend through time from negative to positive residuals, which may be the result of inaccurate water-use data. Inaccurate assessment of water use in the Grand Prairie area may occur because of wells incorrectly reported as being completed in the alluvial aquifer that are actually completed in the Sparta aquifer, or wells with screened intervals in both the alluvial and Sparta aquifers. In many cases, insufficient reporting of well completion data makes it difficult to determine (1) in which aquifer the well is screened or (2) whether it is screened in both aquifers.

Another possible cause of model bias occurs in Columbia and Union Counties where geologic studies suggest considerably more heterogeneity in geologic

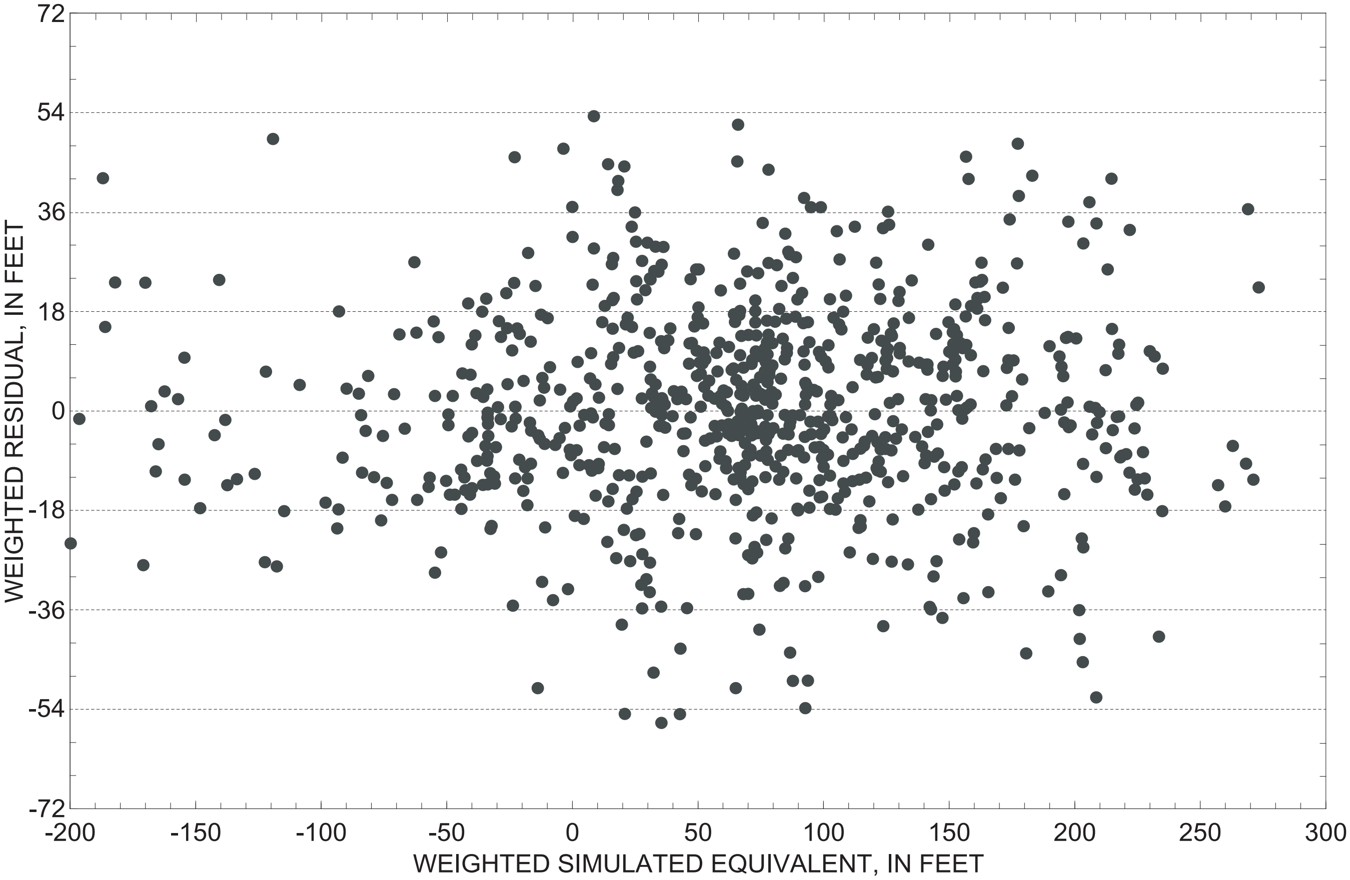


Figure 15. Weighted residuals and weighted simulated values.

conditions and faulting than is presently mapped and represented by the simple zonations and flow boundaries in the current model. In addition, model bias through time may be caused by (1) the temporal averaging of ground-water withdrawals to obtain the mean annual pumpage used in each stress period, and (2) the spatial averaging of pumpage from several wells located in a single model cell.

The weighted residuals ideally should show no temporal trends and be balanced around zero. All of the weighted residuals (fig. 17) are less than 56.5 ft in absolute value. Increasing trends with time may occur because of some wells having hydraulic-head measurements only at later times in the simulation. For each year, the number of positive residuals is approximately equal to negative residuals, and there appears to be a slight trend through time from underprediction to overprediction as indicated (fig. 17).

Normality of Weighted Residuals

Normality of weighted residuals is a prerequisite for a valid regression. If the model accurately represents the system, the weighted residuals are expected to be random, independent, and normally distributed (Hill, 1998). The normality and independence of the weighted residuals can be assessed through use of (1) the correlation coefficient R2N between the ordered weighted residuals and order statistics from the normal probability distribution function (Hill and others, 2000) and (2) a histogram of the weighted residuals. The weighted residuals are thought to be independent and normally distributed if the computed value of R2N for a calibration is higher than the tabulated critical value. The critical value of R2N is 0.987 for a set of 200 observations (maximum number of observations for which a value has been tabulated). This value will be even larger for the 795 observations used in the current model calibration because the critical value increases with the number of observations. The value of R2N for the model calibration is 0.993, which is larger than the critical value, indicating that the weighted residuals are independent and normally distributed. This is additionally supported by a histogram (fig. 18) of all 795 weighted residuals showing normal distribution (typical bell curve) about zero.

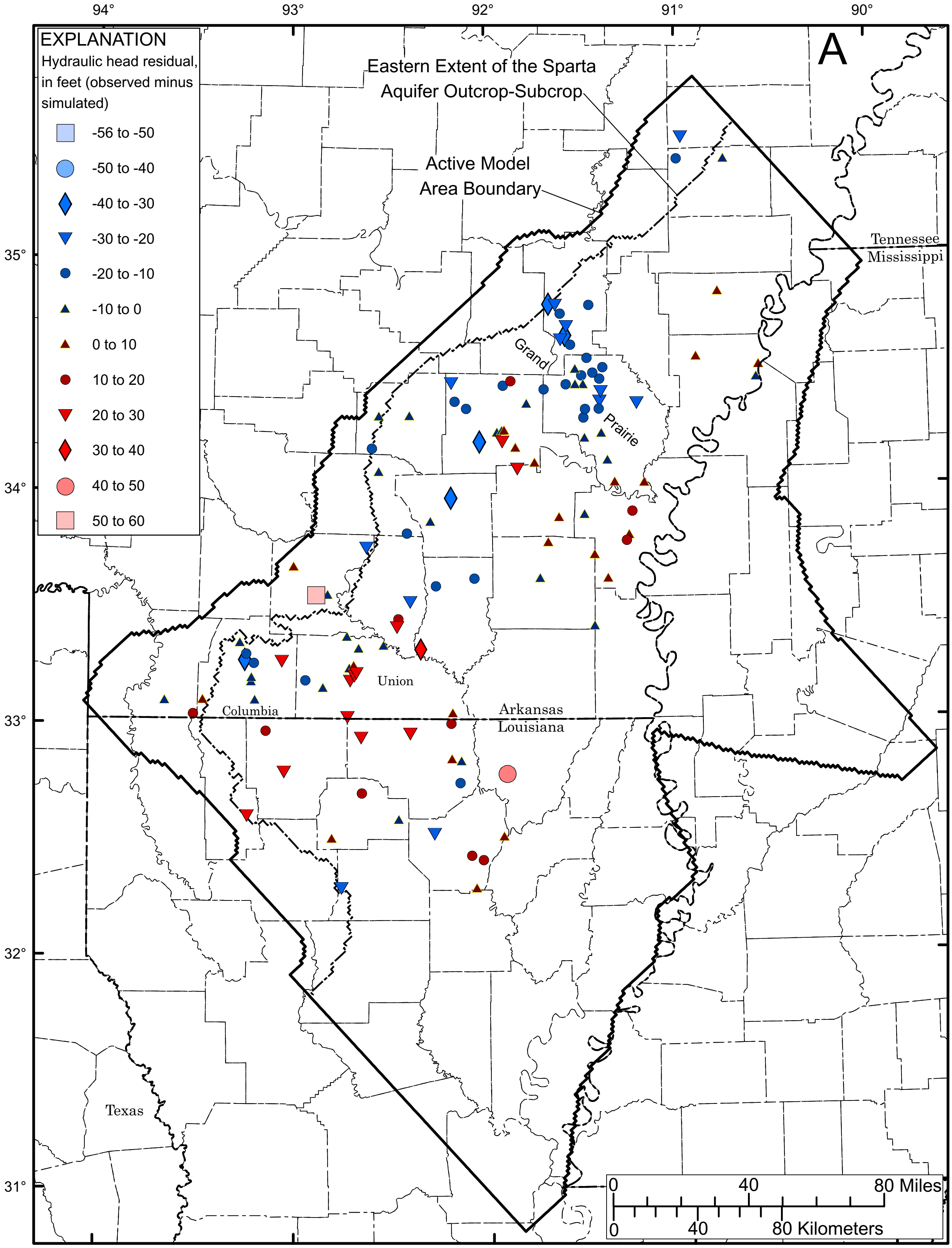


Figure 16. Spatial distribution of weighted hydraulic-head residuals for (A) 1970, (B) 1985, (C) 1990, and (D) 1997.

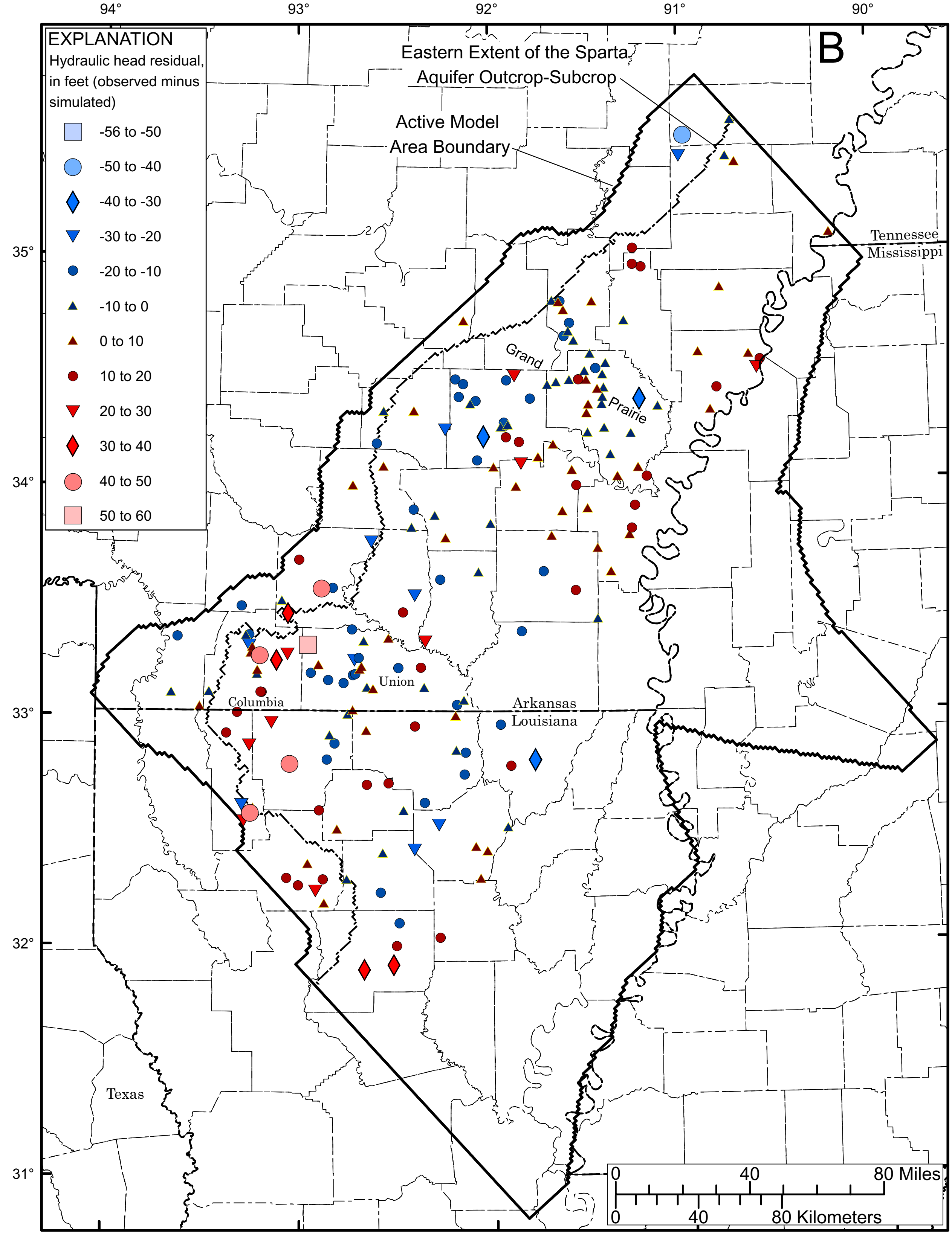


Figure 16. Spatial distribution of weighted hydraulic-head residuals for (A) 1970, (B) 1985, (C) 1990, and (D) 1997—Continued.

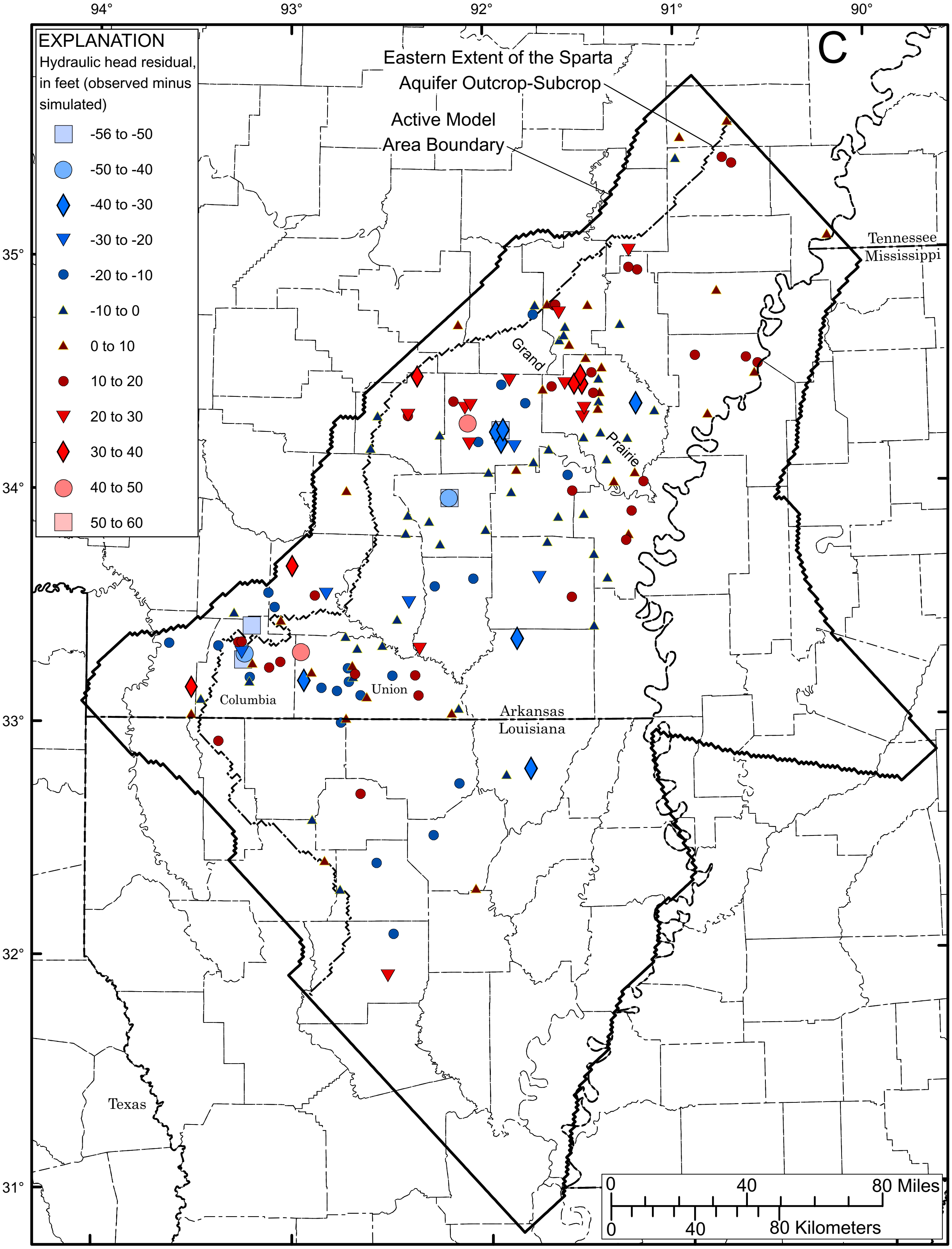


Figure 16. Spatial distribution of weighted hydraulic-head residuals for (A) 1970, (B) 1985, (C) 1990, and (D) 1997—Continued.

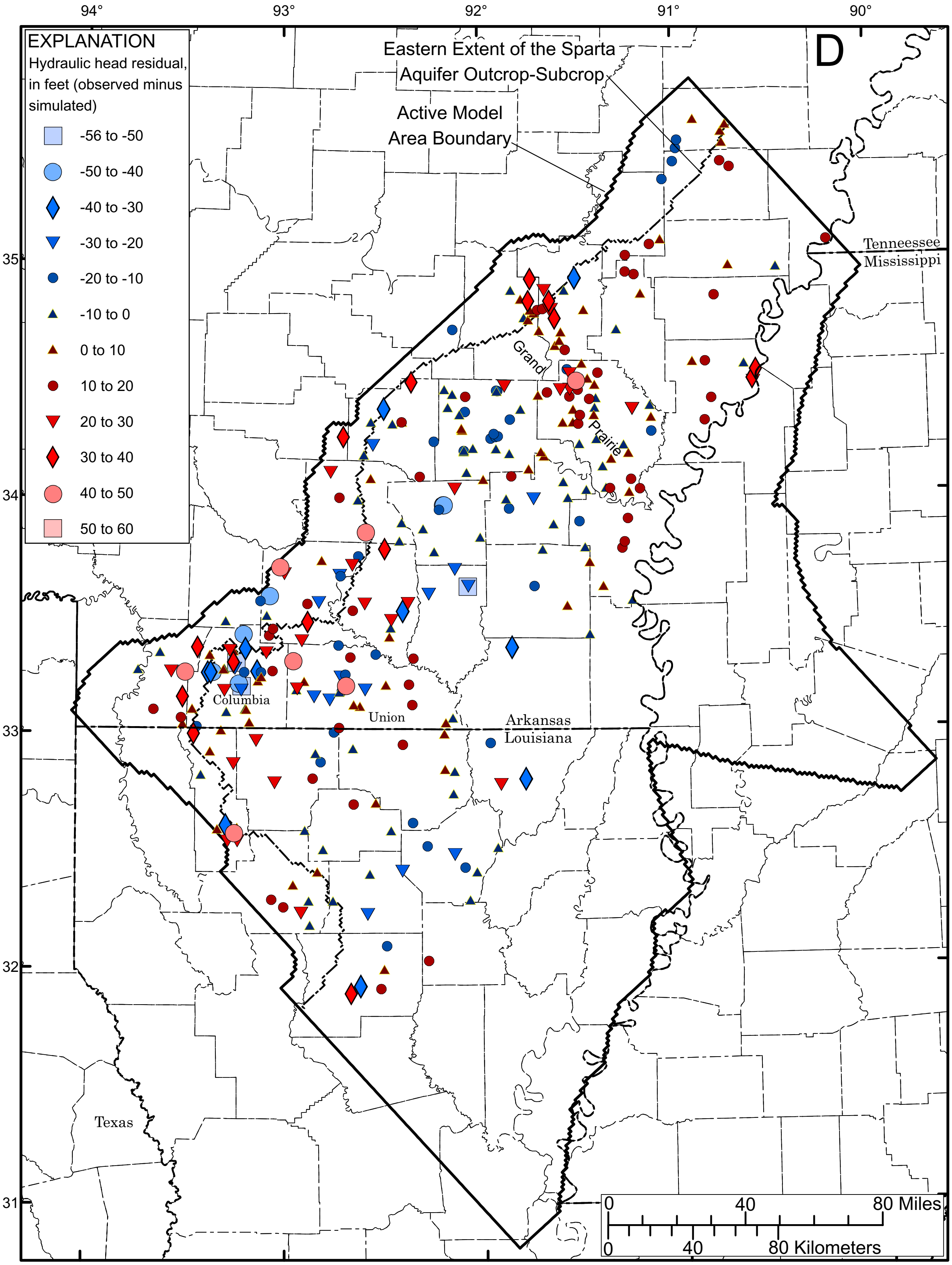


Figure 16. Spatial distribution of weighted hydraulic-head residuals for (A) 1970, (B) 1985, (C) 1990, and (D) 1997—Continued.

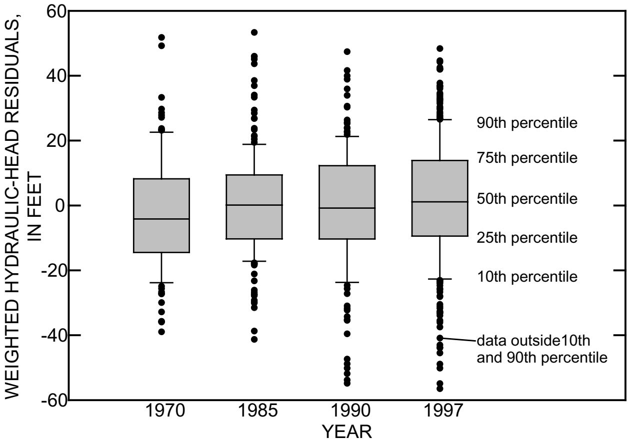


Figure 17. Distribution of weighted hydraulic-head residuals.

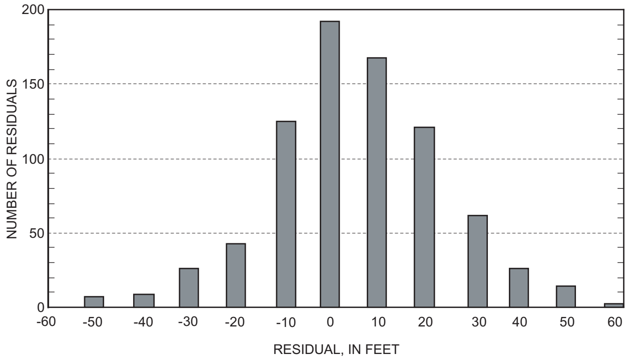


Figure 18. Histogram of residuals for entire calibration data set of 795 observations from 1970, 1985, 1990, and 1997.

Simulated and Observed Hydrographs of Hydraulic Heads

Simulated and observed hydrographs were compared for fourteen wells with long periods of record (fig. 19 A-N). These wells were originally selected by Fitzpatrick and others (1990) based on location in or near areas of large hydraulic-head gradients of cones of depressions formed from large, long-term withdrawals. The simulated and observed hydrographs, representative of hydraulic heads in the lower Sparta aquifer (layer 2) in different regions of the model area, show good agreement for most locations.

Simulated and Observed Potentiometric Surfaces

Potentiometric surfaces representing the lower Sparta aquifer (layer 2) are used to determine similarities and differences in general hydraulic head and flow direction between simulated and observed potentiometric surfaces. Predevelopment potentiometric surface contours (Reed, 1972) show good correlation to the simulated predevelopment potentiometric surface (steady-state model run with no pumping stresses applied) (fig. 20). Although sparse predevelopment hydraulic-head observation data limit the qualitative comparison in the outcrop area, the data are still useful to support the conceptual model of generalized predevelopment flow directions. Potentiometric-surface contours for spring 1997, overlain on simulated hydraulic heads, give reasonable qualitative match to cones of depression in Jefferson, Union, and Columbia Counties, and Ouachita Parish (fig. 21). The simulated hydraulic heads also approximate large gradients in Columbia County, thought to be influenced by faulting in the area (Hosman, 1988; Pugh and others, 2000) (fig. 21).

The simulated and observed (Joseph, 1998b) 1997 potentiometric surface in the Sparta aquifer is already below the top of the Sparta Sand (fig. 22) in much of southwestern Arkansas and north-central Louisiana. This area includes much of Columbia and Union Counties and parts of Ouachita, Lonoke, Prairie, and Monroe Counties in Arkansas and much of Webster, Claiborne, Lincoln, Bienville, and Jackson Parishes, and parts of Ouachita, Union, and Bossier Parishes in Louisiana. Based on the 1997 simulated hydraulic heads and the top of the Sparta Sand represented in the model, the percent area of the aquifer with hydraulic heads below the top of the Sparta Sand in Arkansas and Louisiana was 7.9 and 19.4, respectively. In Union County, Arkansas, over 50 percent of the county had hydraulic heads below the top of the Sparta Sand; Jefferson County had no area with hydraulic heads below the top of the Sparta Sand.

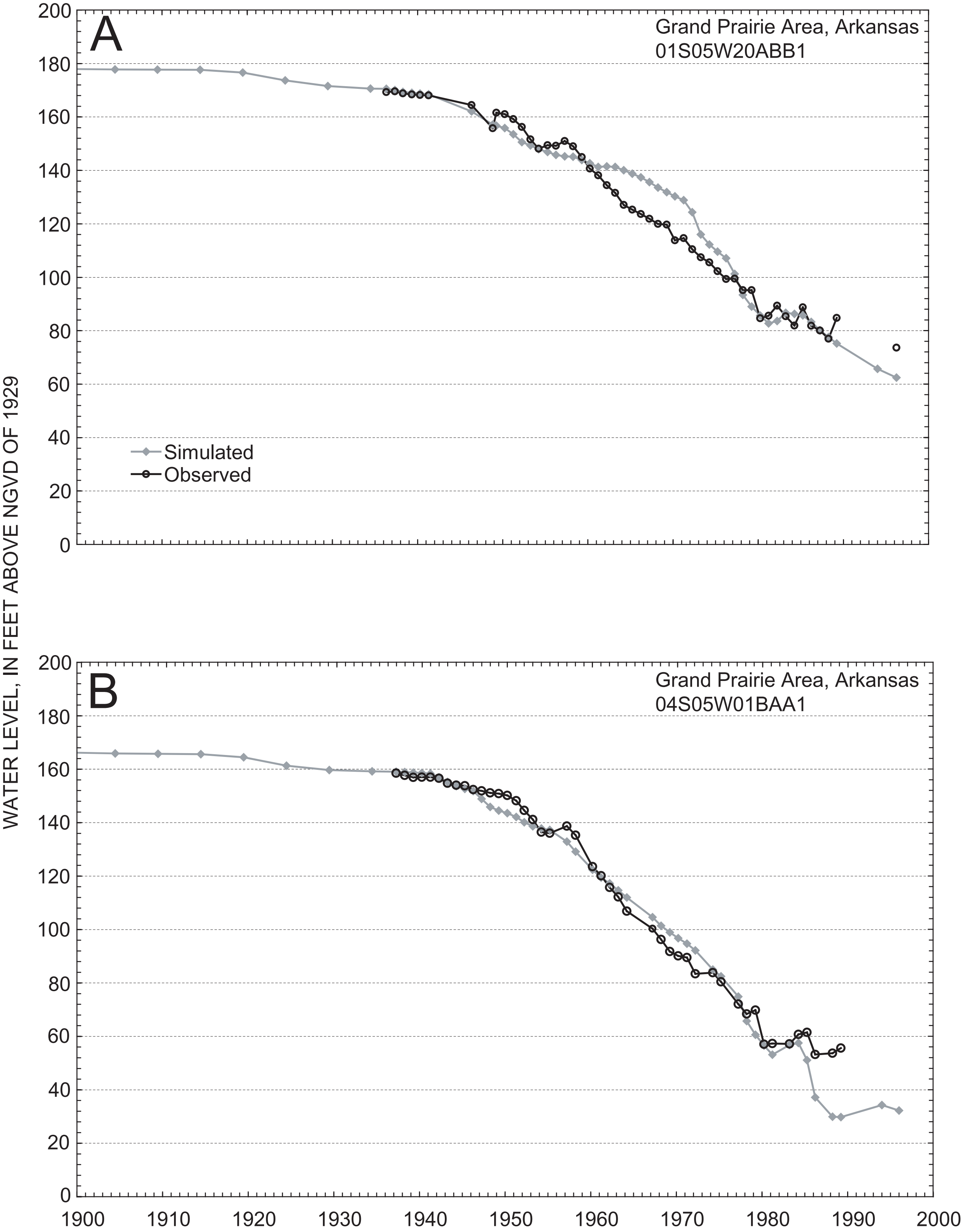


Figure 19. Simulated and observed hydraulic heads at selected observation wells, 1900-1997. Observation well locations are shown in figure 13.

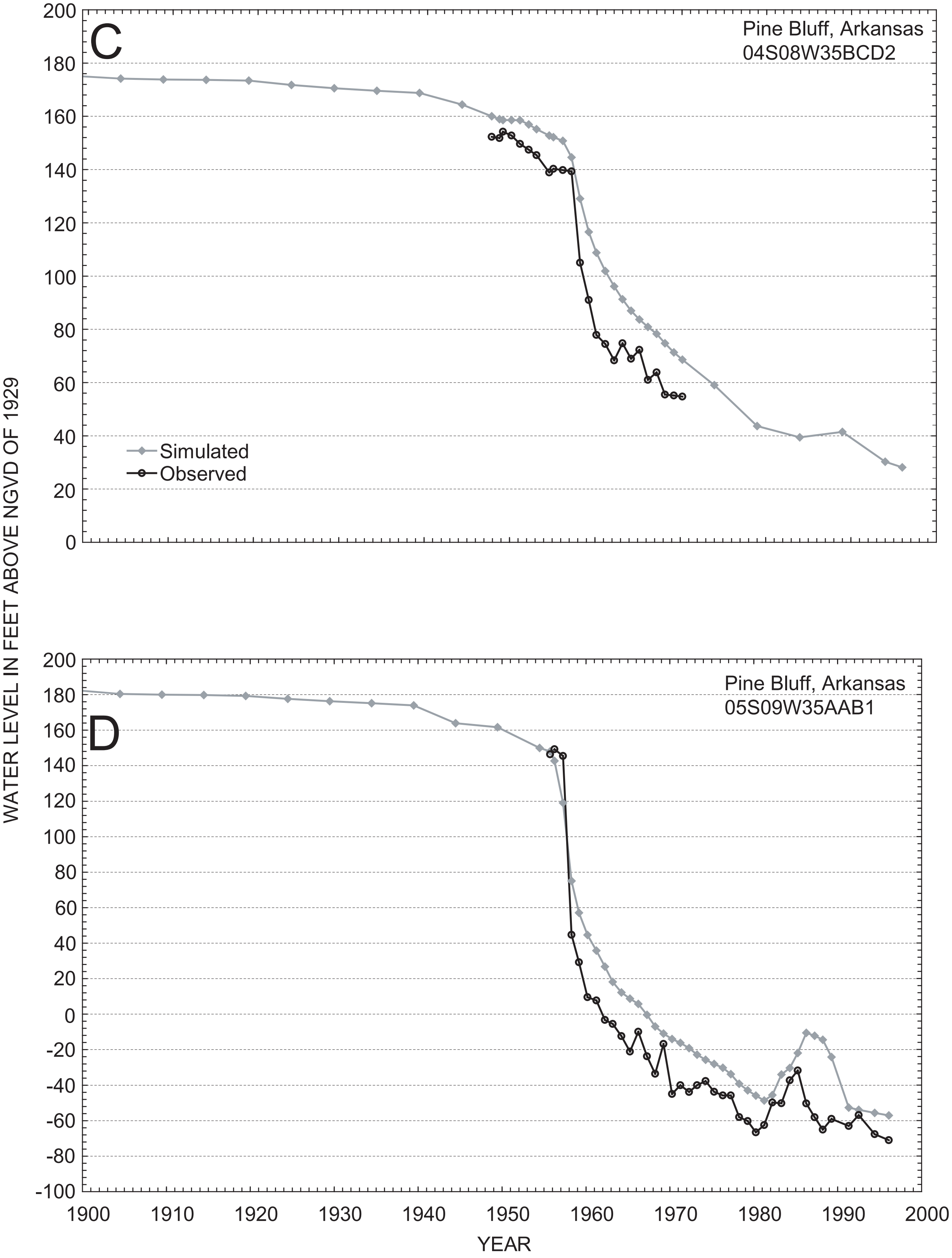


Figure 19. Simulated and observed hydraulic heads at selected observation wells, 1900-1997. Observation well locations are shown in figure 13—Continued.

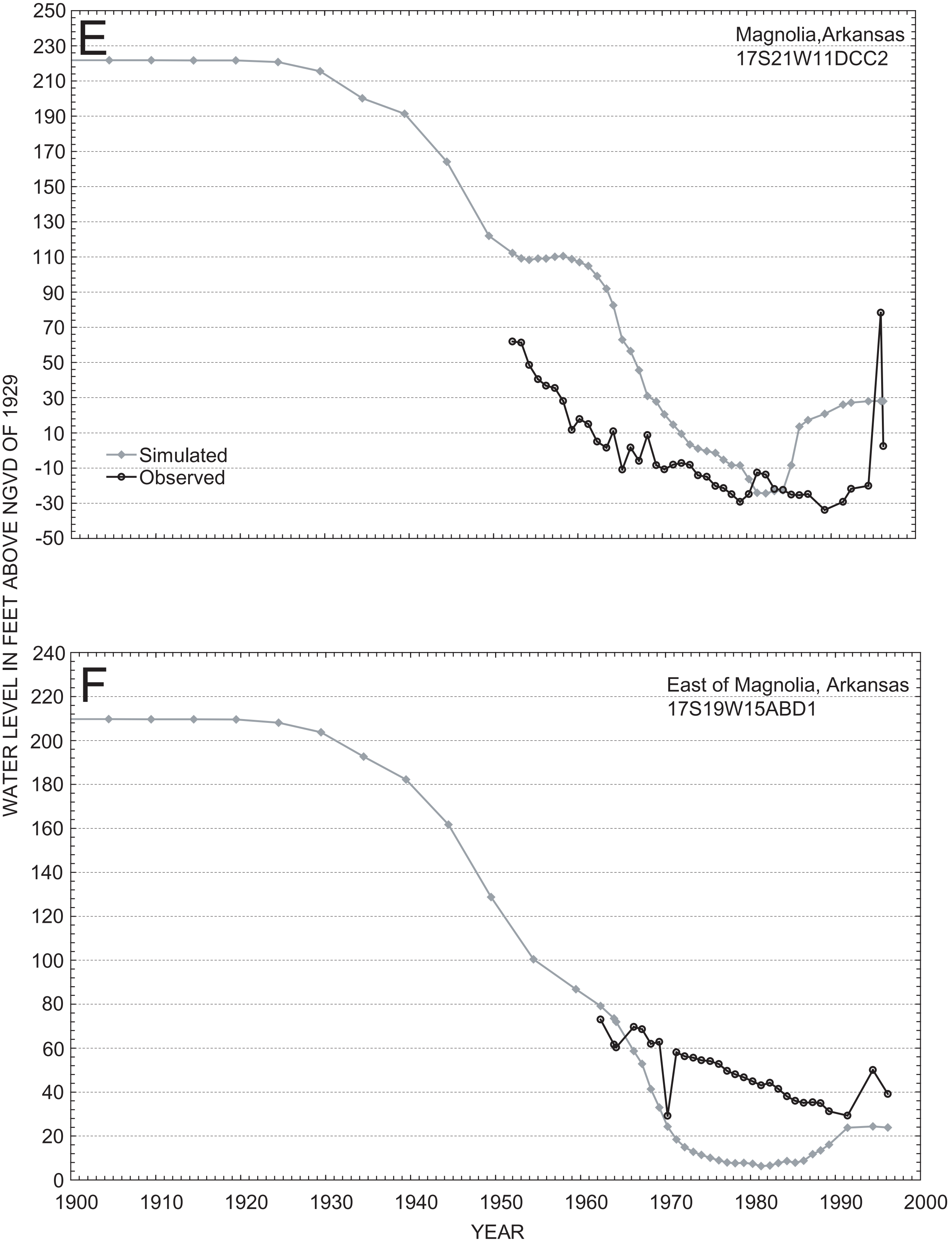


Figure 19. Simulated and observed hydraulic heads at selected observation wells, 1900-1997. Observation well locations are shown in figure 13—Continued.

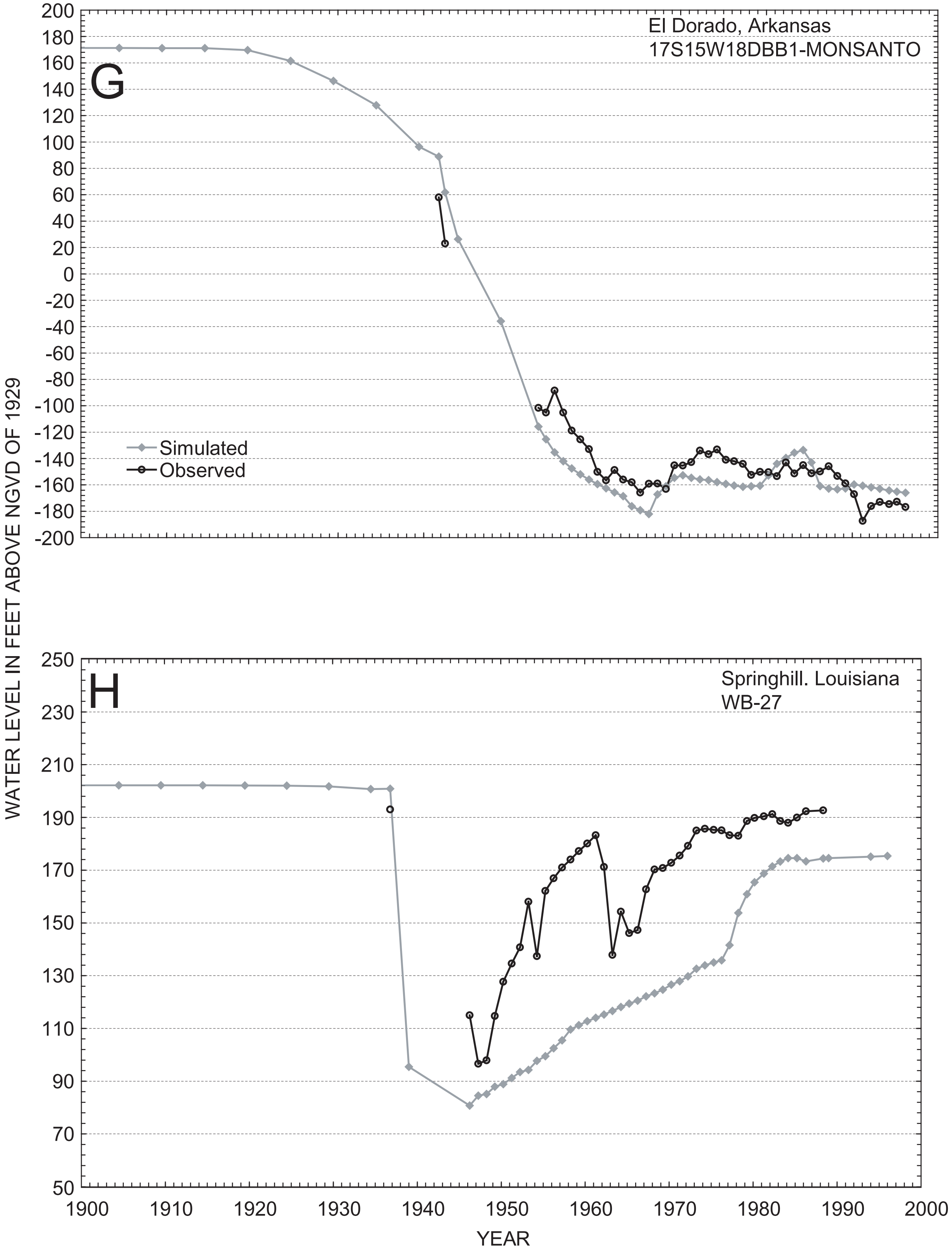


Figure 19. Simulated and observed hydraulic heads at selected observation wells, 1900-1997. Observation well locations are shown in figure 13—Continued.

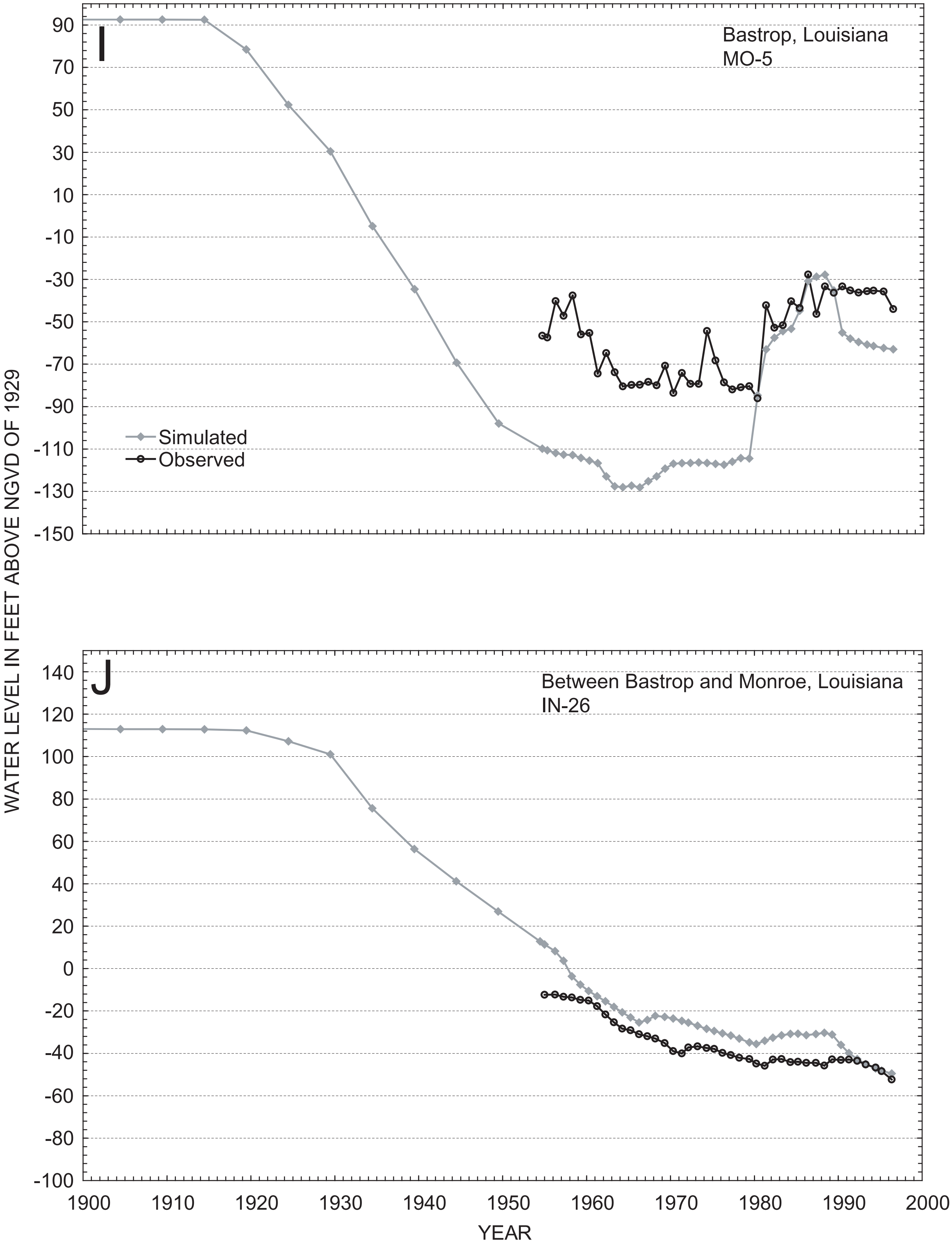


Figure 19. Simulated and observed hydraulic heads at selected observation wells, 1900-1997. Observation well locations are shown in figure 13—Continued.

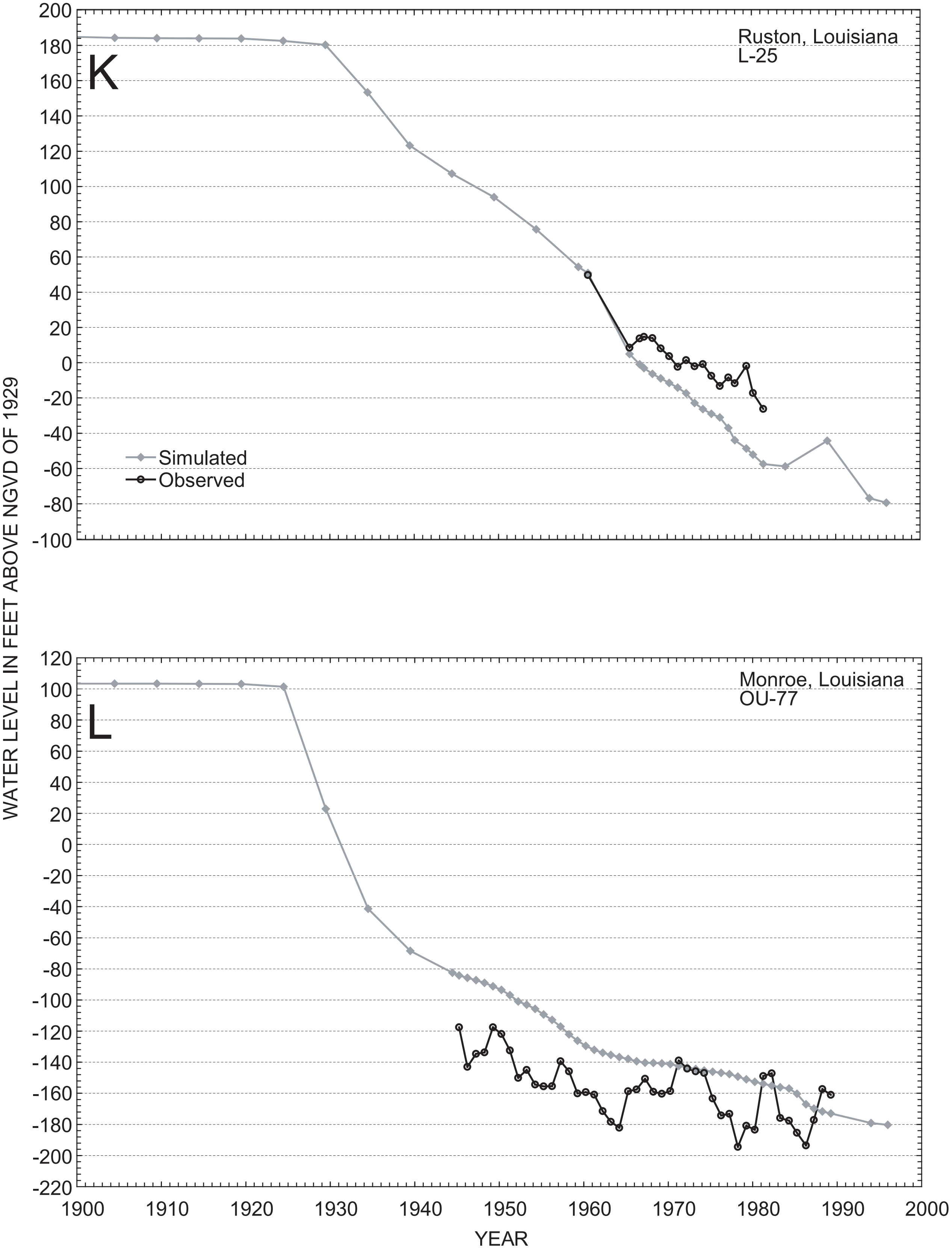


Figure 19. Simulated and observed hydraulic heads at selected observation wells, 1900-1997. Observation well locations are shown in figure 13—Continued.

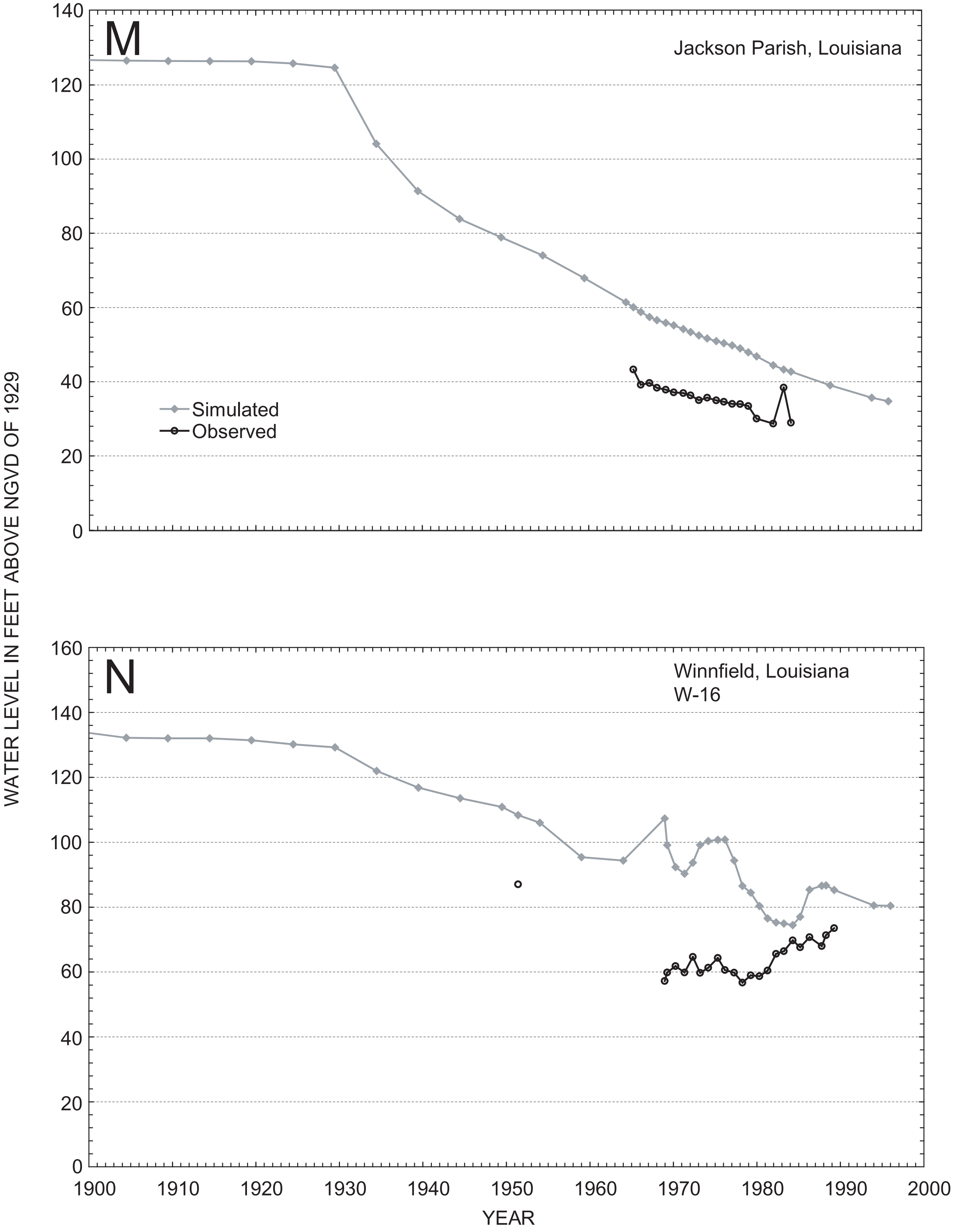


Figure 19. Simulated and observed hydraulic heads at selected observation wells, 1900-1997. Observation well locations are shown in figure 13—Continued.

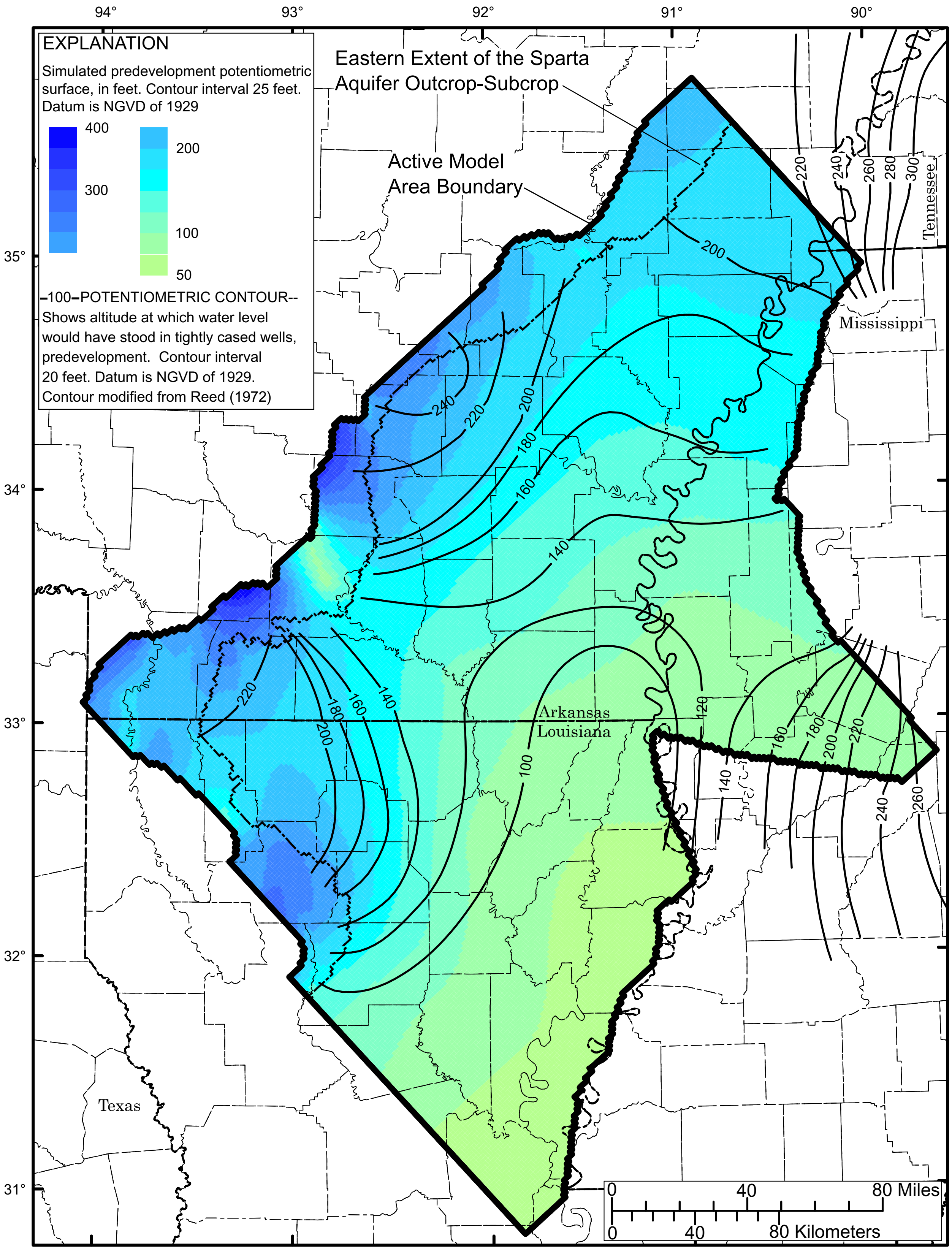


Figure 20. Simulated and observed potentiometric surface for the Sparta aquifer, predevelopment.

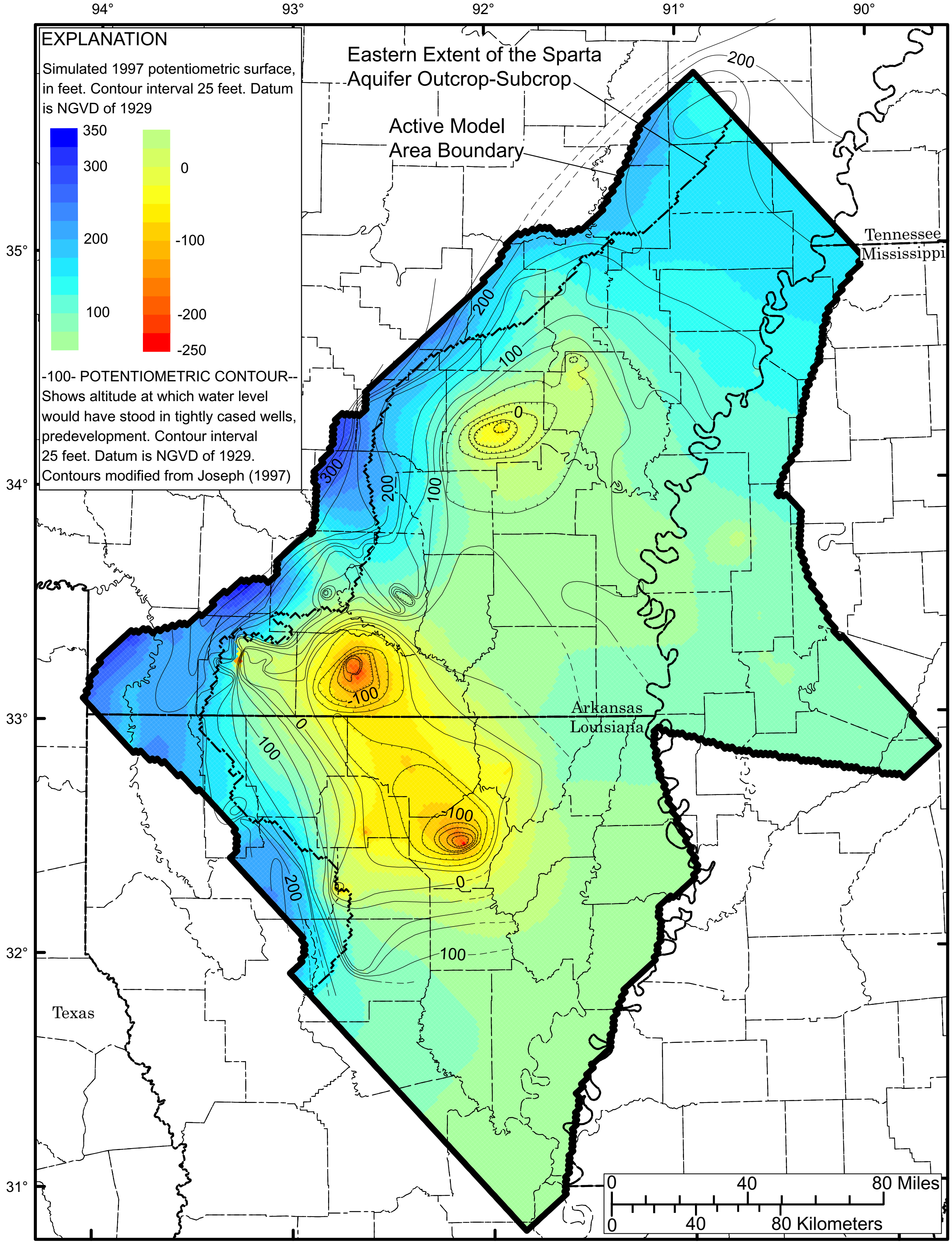


Figure 21. Simulated and observed potentiometric surface for the Sparta aquifer, 1997.

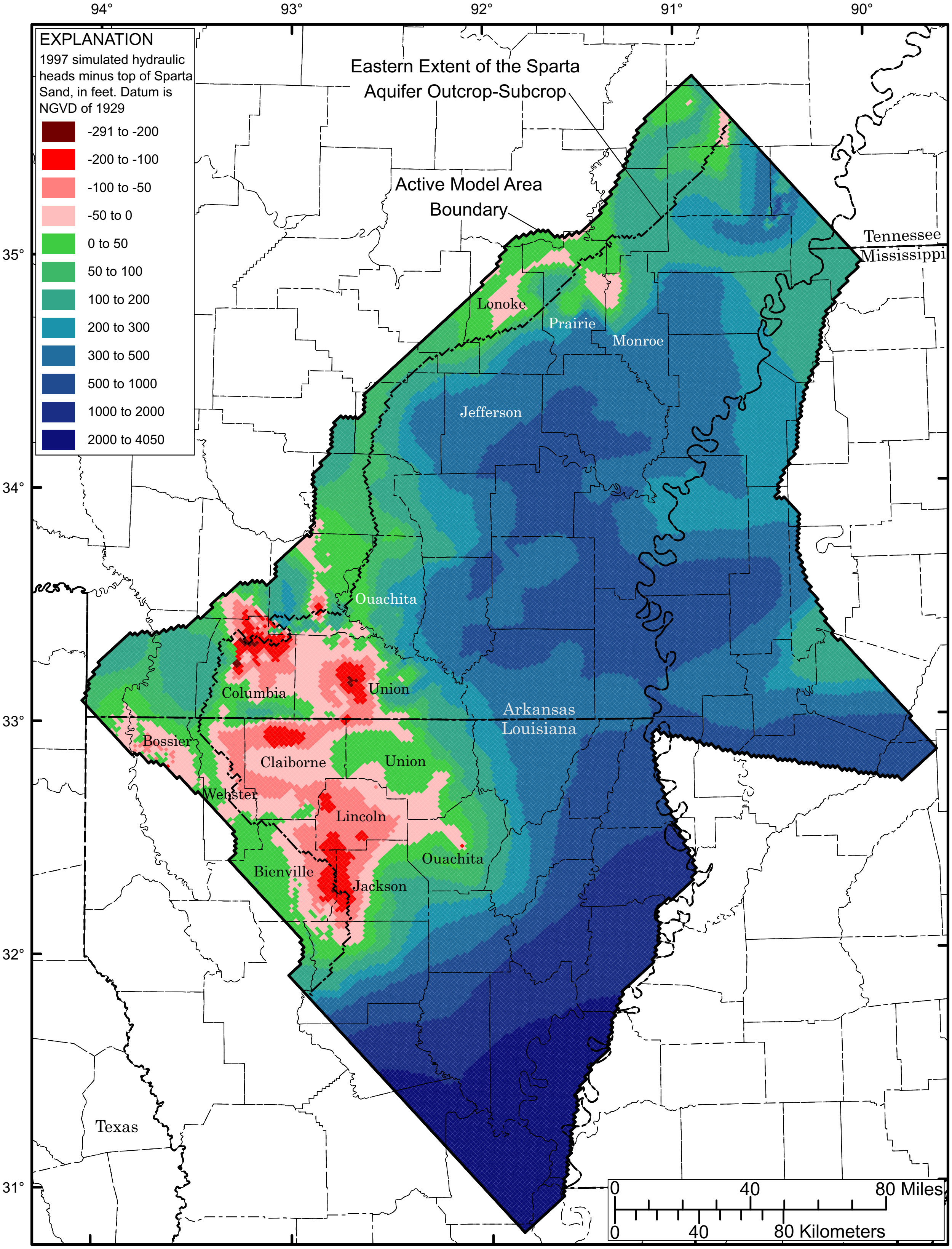


Figure 22. Contoured difference between 1997 simulated hydraulic heads and top of the Sparta Sand.

Ground-Water Budget

The ground-water flow budget from predevelopment to 1997 indicates changes in flow into (inflows) and out of (outflows) the Sparta aquifer (fig. 23). Negative rates indicate outflows from the ground-water system, and positive rates indicate inflows to the ground-water system. The net flow is computed by inflows minus outflows. Total flow through the Sparta aquifer in the model was about 18.9 million ft^3/d before development, and about 40.6 million ft^3/d in 1997 (table 7). There are five inflows to the model: recharge, river leakage through streambeds, leakage through the Cook Mountain confining unit, aquifer storage, and head-dependent boundaries. There are five discharges or outflows: withdrawals from wells, river leakage through streambeds, leakage through the Cook Mountain confining unit, aquifer storage, and head-dependent boundaries. Wells remove the most water of any outflow component with a volumetric rate of 32.0 million ft^3/d by the end of the model simulation in 1997. Ground-water withdrawals from wells are offset by river leakage, leakage through the Cook Mountain confining unit and changes in storage in the Sparta aquifer. The amount of water removed from storage increases throughout the simulated time as withdrawals increase to balance the water budget. Analysis of flow indicates that the aquifer is behaving as conceptualized under increased pumping stress throughout the model area. Fitzpatrick and others (1990) discuss analysis of the ground-water budget in greater detail for the previous Sparta model, but much of the same observations still apply, only the magnitudes of the components change.

Table 7. Ground-water budget comparison between predevelopment and 1997

	Predevelopment	**1997**	
Inflow	**Volumetric rate (cubic feet per day)**	**Volumetric rate (cubic feet per day)**	**Component difference**
Storage	0	8,366,842	8,366,842
Leakage through Cook Mountain confining unit	1,926,614	13,180,139	11,253,525
Head-dependent boundaries	24,422	32,375	7,953
Wells	0	0	0
Recharge	16,754,894	16,754,894	0
River leakage	202,951	2,237,671	2,034,720
Total in	18,908,881	40,571,921	21,663,040

Outflow	**Volumetric rate (cubic feet per day)**	**Volumetric rate (cubic feet per day)**	**Component difference**
Storage	0	170,507	170,507
Leakage through Cook Mountain confining unit	5,397,643	643,234	-4,754,409
Head-dependent boundaries	871	249	-622
Wells		31,995,434	31,995,343
Recharge	0	0	0
River leakage	13,520,117	7,761,769	-5,758,348
Total out	18,918,631	40,571,193	21,652,562

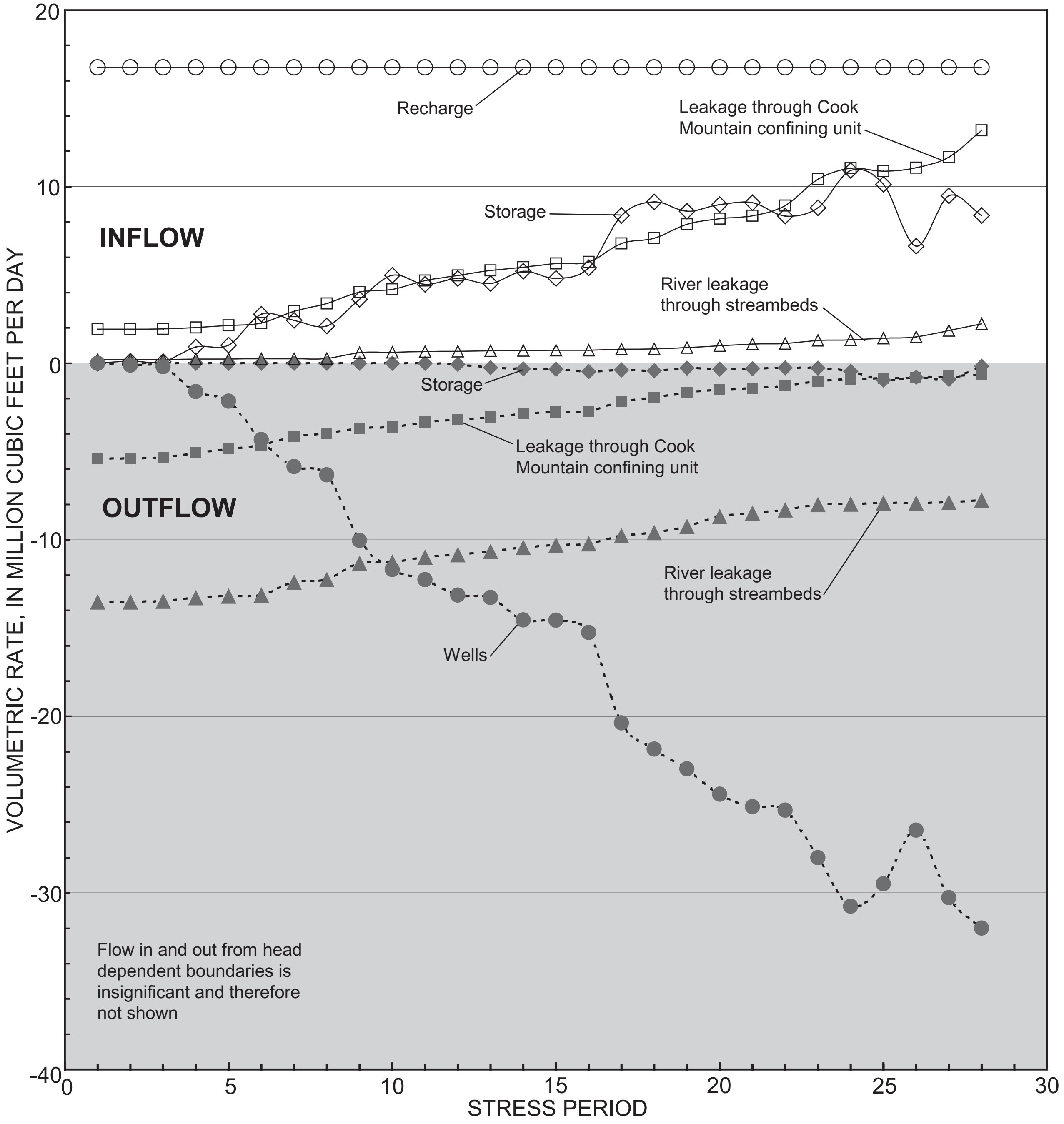


Figure 23. Simulated transient ground-water budget for the Sparta aquifer, predevelopment - 1997.

Comparison of ground-water budgets for the current model and the previous Sparta model show similarity in total volumetric flow rates for the ground-water system with only a 7 percent decrease from the previous model for both predevelopment and 1997. Therefore, this supports the conclusion that the basic conceptualization of the ground-water flow system has remained relatively unchanged. Major differences appear between individual budget components (fig. 24 A-B), primarily with flows from head-dependent boundaries (lateral boundaries and overlying aquifers) and to lesser degree flows from recharge and rivers. The use of general-head and river boundaries in the current model instead of constant-head boundaries as in the previous Sparta model to represent flows from lateral boundaries and overlying aquifers is the reason for this difference. With constant-head boundaries, the only restriction on amount of water provided to the aquifer is the hydraulic head difference between the constant head and the simulated hydraulic head in the cell. The other boundary types provide greater control on the amount of water allowed into the ground-water system through hydraulic conductance in the cell and limits on hydraulic-head gradients. Minor differences of flow from recharge and rivers can be explained within reasonable error with which these boundaries are known.

SIMULATED AQUIFER RESPONSE TO THREE HYPOTHETICAL FUTURE WITHDRAWAL RATE SCENARIOS

The current model was used to predict the effects of three hypothetical future withdrawal rate scenarios on hydraulic heads over a 30-year period from 1998-2027 and one scenario with withdrawals extended indefinitely until equilibrium conditions are attained (steady-state conditions). The 30-year transient simulation period was segmented into six stress periods of 5 years each. Total withdrawals for each scenario are listed in table 8 with other selected volumetric budget information and hydraulic-head altitude data from model cells representative of cone of depression centers for model calibration (1997) and for predictive scenarios. Development of the scenarios was based on information collected from Sparta aquifer water users and managers in Arkansas, Louisiana, and Mississippi, and in collaboration with ASWCC and MCOE representatives.

The future withdrawal rate scenarios were designed to address various management schemes and the sustainability of current withdrawal rates. Sustainability is the development and use of ground water for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley

Table 8. Selected volumetric budget and hydraulic-head altitude data from model cells representing cone of depression centers for model calibration (1997) and for predictive scenario runs (2027 and steady state)

[Net flow is inflow minus outflow; cell 193,64 represents cell at row 193 and column 64; dry cell indicates where hydraulic head computed in model is below bottom of layer 2; hydraulic head as altitude in feet above National Geodetic Vertical Datum of 1929; NA, not applicable]

	1997 calibration	2027 scenario 1a	Steady-state scenario 1b	2027 scenario 2	2027 scenario 3
Pumpage (million cubic feet per day)	32.0	32.0	32.0	27.4	33.9
Net flow to rivers (million cubic feet per day)	-5.5	-4.6	-2.4	-5.5	-4.6
Net flow from Cockfield aquifer (million cubic feet per day)	12.5	14.6	17.6	-12.7	14.5
Change in storage (million cubic feet per day)	8.2	5.2	NA	3.4	7.1
El Dorado hydraulic head (feet) (cell 193,64)	-212	-222	-229	-47	-88
Pine Bluff hydraulic head (feet) (cell 114,40)	-61	-78	-104	61	-41
Magnolia hydraulic head (feet) (cell 216,38)	-184	-194	-220	-184	dry cell
Arkansas County hydraulic head[a] (feet) (cell 87,42)	14	-8	-44	11	-15
Monroe hydraulic head (feet) (cell 204,122)	-250	-258	-264	-255	-307

[a] Arkansas County hydraulic-head data are representative of the area and are not from a cone of depression.

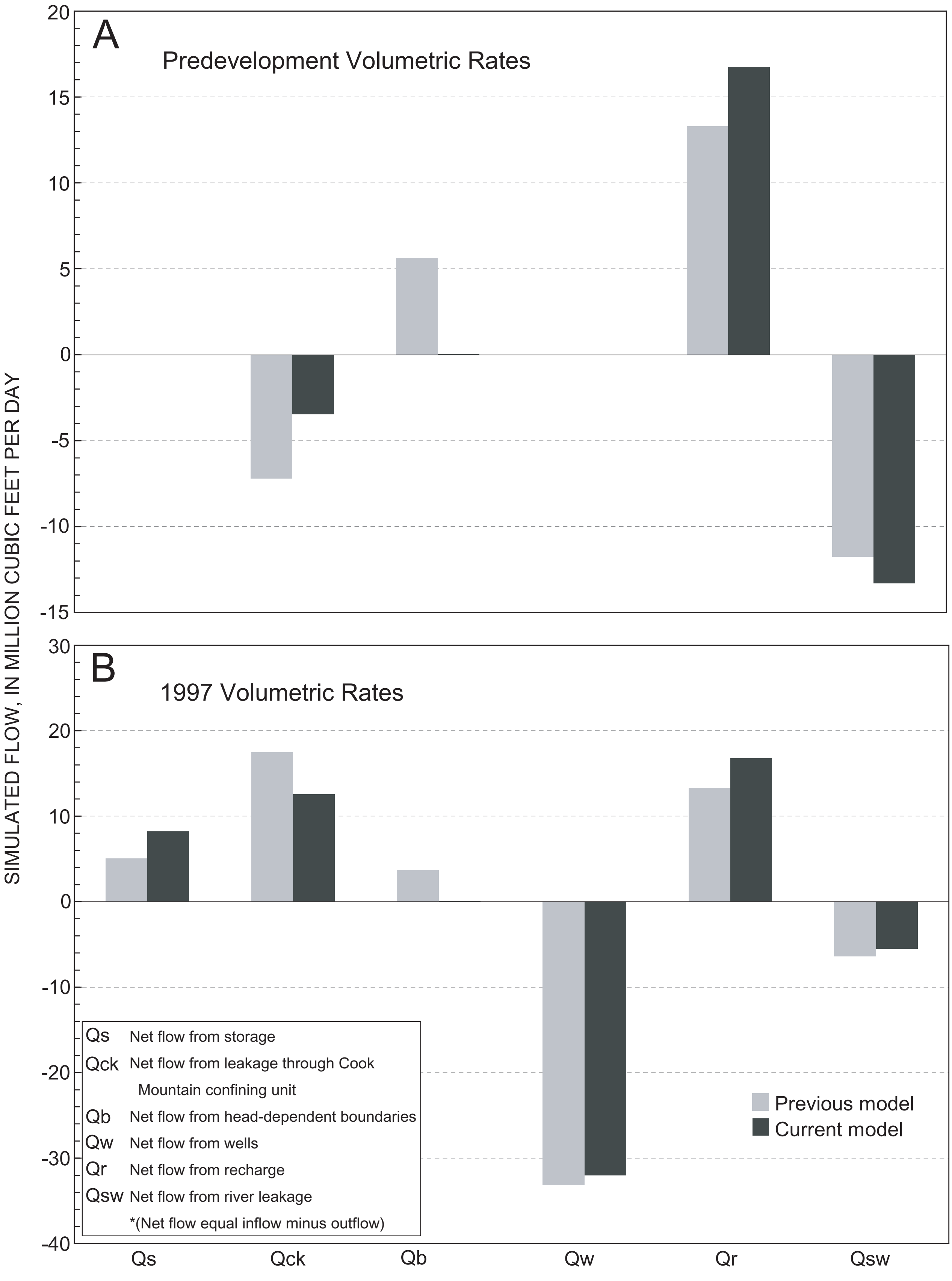


Figure 24. Simulated (A) predevelopment and (B) 1997 ground-water budget for the Sparta aquifer from current and previous Sparta models.

and others, 1999). In Arkansas, the ASWCC has established criteria for designating a "Critical Ground-Water Area" based on significant ground-water declines or water-quality degradation. For a confined aquifer like the Sparta, the criteria include (1) hydraulic heads in wells below the top of the aquifer formation and (2) the rate of decline in hydraulic heads in wells is more than 1 ft /yr over a 5-year period. This designation is used to promote education and public awareness for protection of the ground-water system. As indicated by the 1997 simulated hydraulic heads and observations, hydraulic heads in the Sparta aquifer are below the top of the Sparta Sand in some areas. Continued pumping at 1997 withdrawal rates causes further hydraulic-head decline (shown later in Scenario 1) and therefore, 1997 withdrawal rates are by definition unsustainable.

Each scenario description includes figures to illustrate (1) simulated hydraulic heads for 2027 or steady-state, (2) change in simulated hydraulic heads from 1997 to 2027 (or to steady-state), and (3) the difference between simulated hydraulic heads for 2027 and the top of the Sparta Sand. Three-dimensional animations of simulated hydraulic heads from each of the three scenarios are included on the enclosed compact disk in the appendix. An explanation of software used and a description of each animated scenario is included in the appendix.

Scenario 1- Baseline 1990-1997 Withdrawal Rates

A model simulation using constant withdrawal rates from 1990-1997 was conducted for the period 1998-2027 (scenario 1a), and then extended to steady state (scenario 1b). The potentiometric surfaces for 2027 and steady state from this scenario are presented in figures 25a and 25b. This scenario provides a baseline for comparison of other simulations in which future withdrawals may increase or decrease. Results of the steady-state baseline scenario (fig. 25b) indicate a substantial number of dry cells (simulated hydraulic head in a cell drops below the cell bottom) in northern Lonoke County and a few in south Nevada County, all within the Sparta outcrop/subcrop area. In general, dry cells result from withdrawal rates exceeding available water. Dry cells in the Grand Prairie area could indicate that, based on model assumptions and results, recent increased withdrawals from the Sparta aquifer for irrigation cannot be indefinitely continued. In addition, the cone of depression in the Grand Prairie area expands from 2027 to steady state toward the northwest (fig. 25b) as a result of continued withdrawal from the Sparta aquifer for agricultural crop irrigation in lieu of dwindling alluvial aquifer supplies (Joseph, 1998b; T.P. Schrader, U.S. Geological Survey, written commun., 2003).

Results of this scenario indicate that simulated hydraulic heads continue to decline (fig. 26a and 26b) and drop below the top of the Sparta Sand (fig. 27a and 27b). Dry cells affect simulated hydraulic heads by eliminating withdrawals and acting as barriers to flow. As a result, hydraulic head rises occur upgradient of dry cell areas where recharge boundary conditions exist (fig. 26b). Through 2027, hydraulic heads continue to decline in the center of cones of depression in areas of El Dorado, Pine Bluff, Magnolia, and Arkansas County, and in areas of Monroe, Louisiana (table 8). Cones of depression continue to deepen and expand, increasing the areas where hydraulic heads have dropped below the top of the Sparta Sand in Arkansas from 7.9 percent in 1997 to 9.6 percent in 2027, a 20.5 percent increase (table 9). For steady-state conditions, this area increases to 12.0 percent, a 50.6 percent increase from 1997.

Table 9. Percentage of selected areas where the potentiometric surface of the Sparta aquifer is below the top of the Sparta Sand

	Percent of model area below top of Sparta Sand				
Selected area	**1997**	**Scenario 1a[a]**	**Scenario 1b[b]**	**Scenario 2[c]**	**Scenario 3[d]**
Arkansas	7.9	9.6	12.0	5.8	6.9
Louisiana	19.4	20.5	22.4	17.6	20.7
Union County	51.9	55.5	57.4	7.3	16.6

[a] Scenario 1a - Baseline 1990-1997 withdrawal rates extended 30 years through 2027.

[b] Scenario 1b - Baseline 1990-1997 withdrawal rates extended indefinitely until equilibrium conditions are attained (steady-state).

[c] Scenario 2 - Baseline 1990-1997 withdrawal rates with reductions in Pine Bluff and El Dorado through 2027.

[d] Scenario 3 - Increased withdrawal rates with reductions in Pine Bluff and El Dorado through 2027.

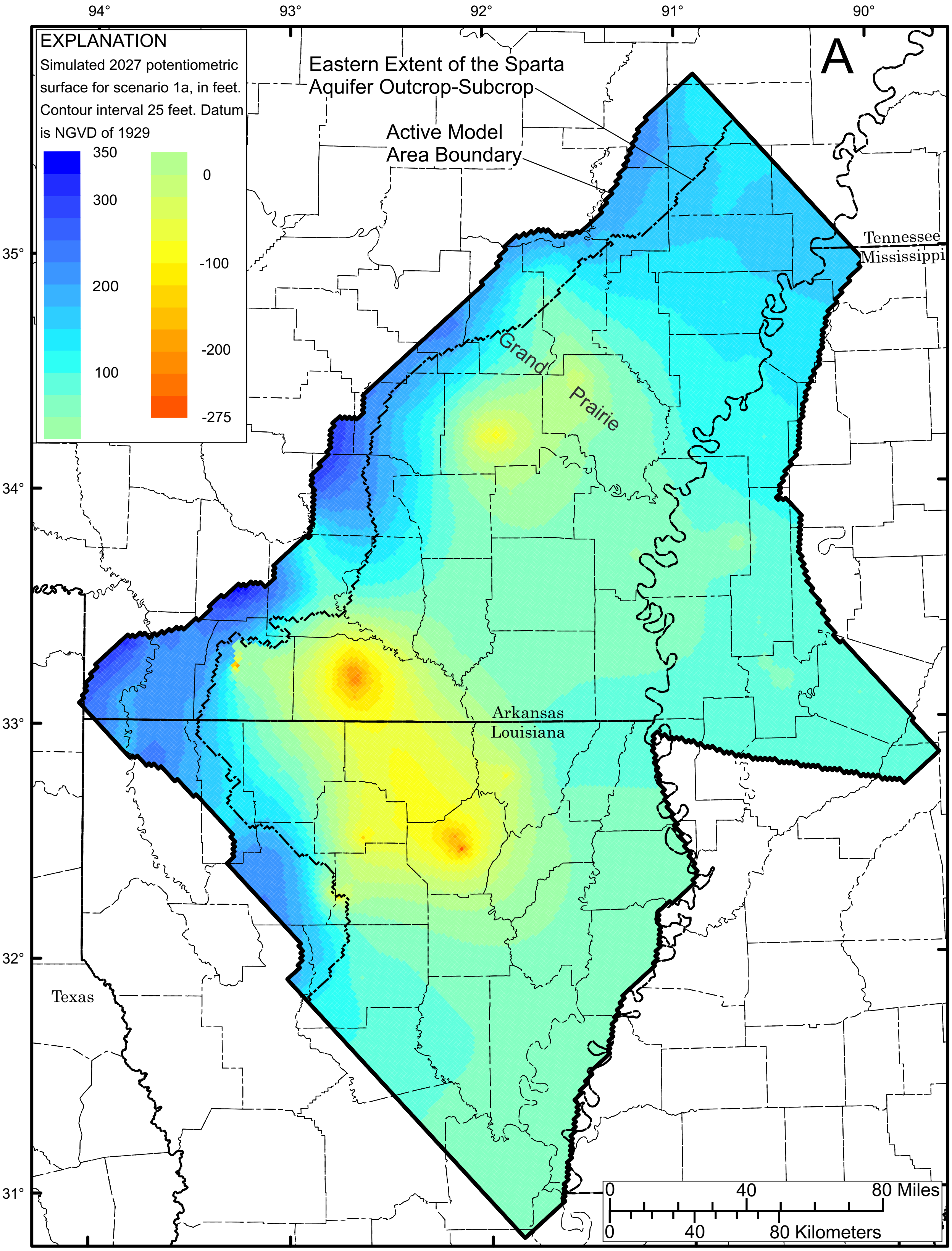


Figure 25. Simulated potentiometric surface (layer 2) for the Sparta aquifer using baseline 1990-1997 withdrawal rates through (A) 2027 [scenario 1a] and to (B) steady state [scenario 1b].

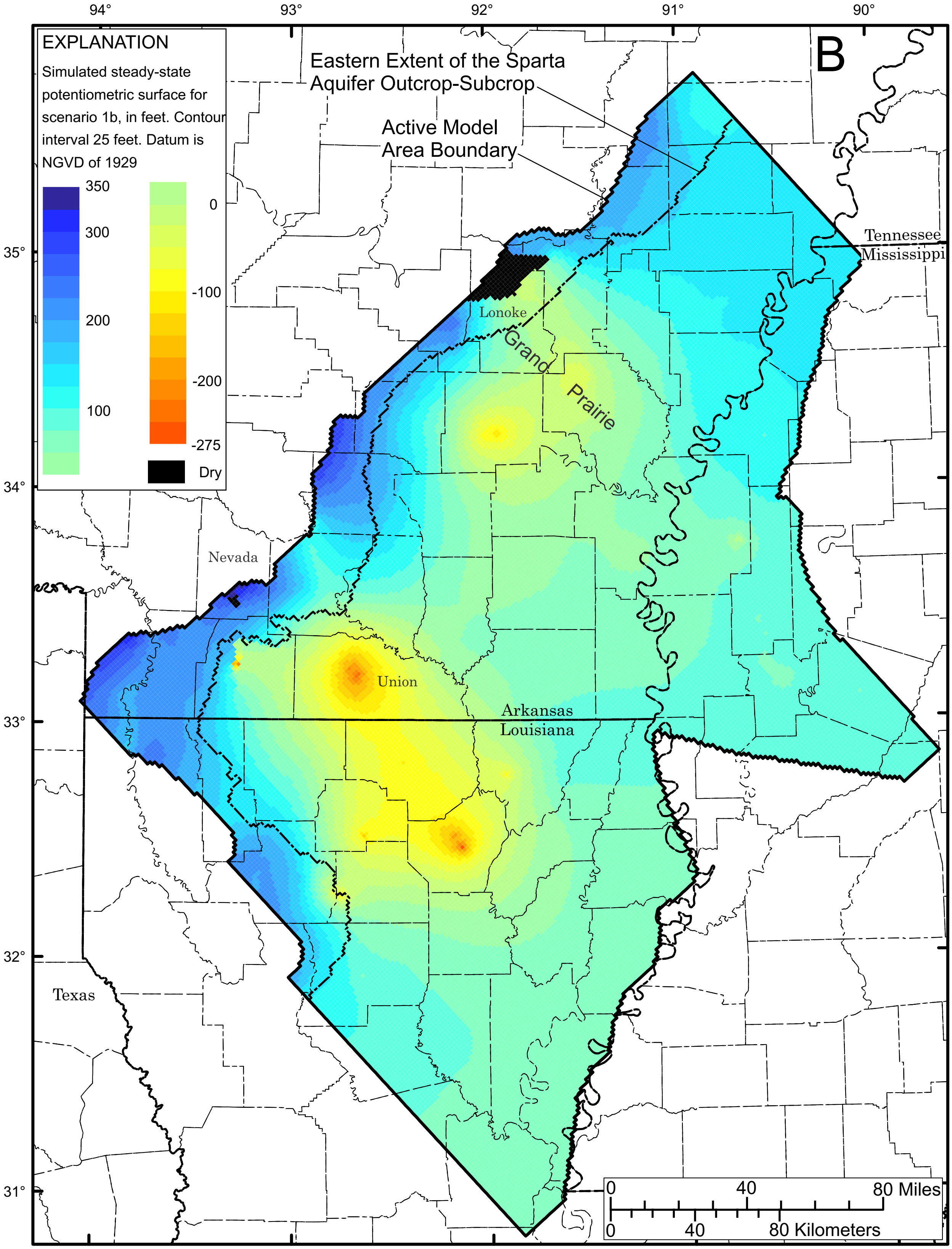


Figure 25. Simulated potentiometric surface (layer 2) for the Sparta aquifer using baseline 1990-1997 withdrawal rates through (A) 2027 [scenario 1a] and to (B) steady state [scenario 1b]—Continued.

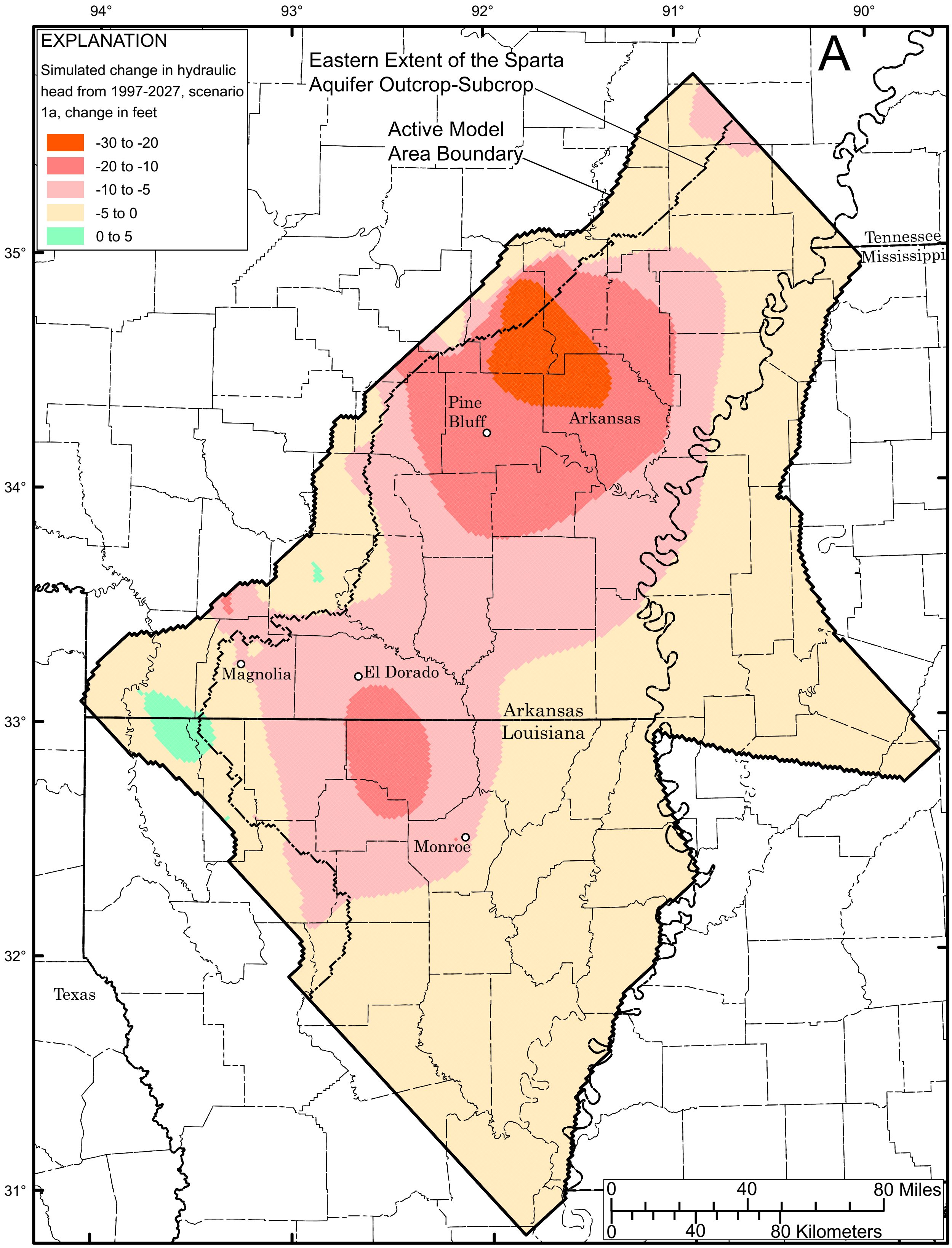


Figure 26. Contoured change in simulated hydraulic heads for the Sparta aquifer from 1997 to (A) 2027 [scenario 1a] and (B) steady state [scenario 1b] using baseline 1990-1997 withdrawal rates.

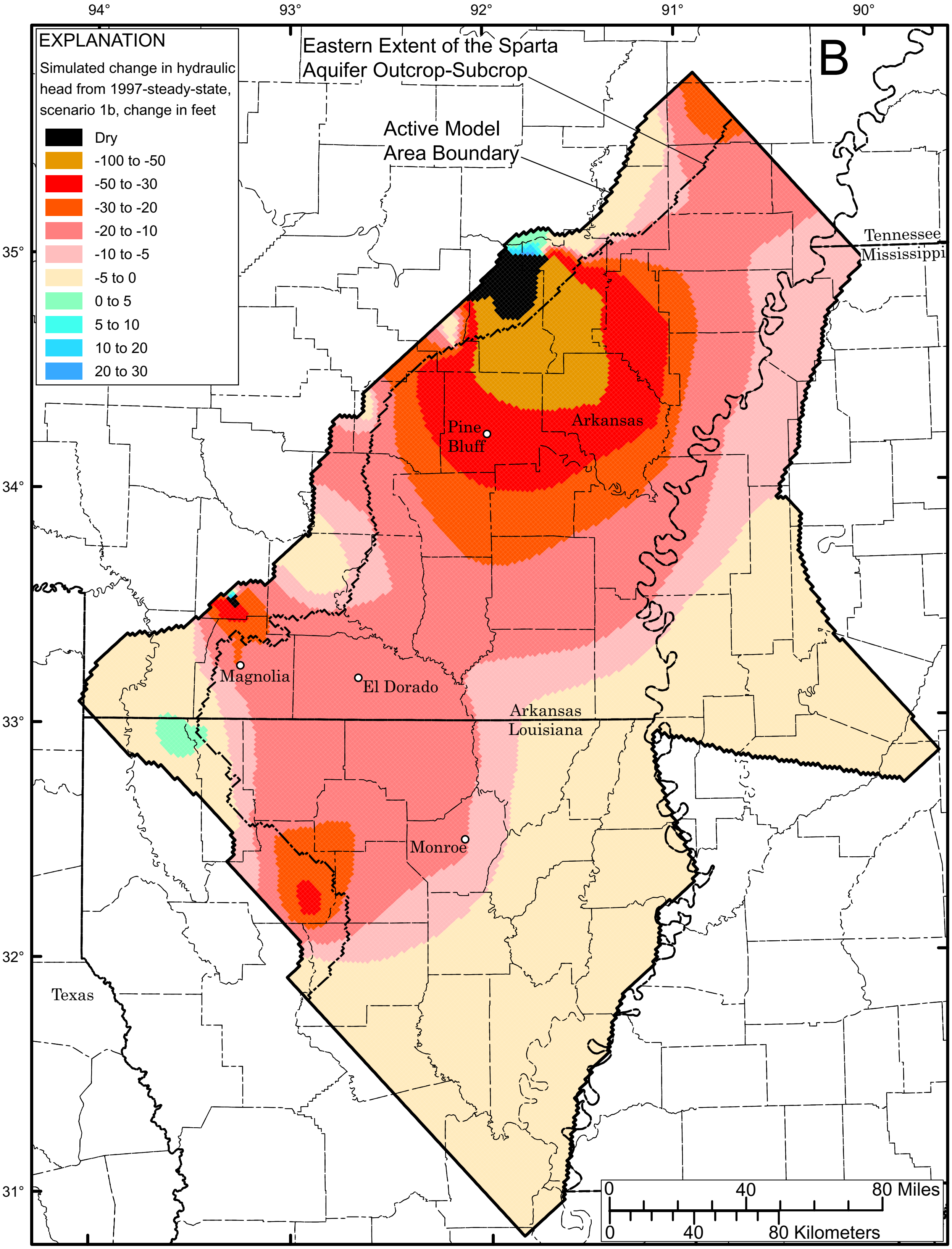


Figure 26. Contoured change in simulated hydraulic heads for the Sparta aquifer from 1997 to (A) 2027 [scenario 1a] and (B) steady state [scenario 1b] using baseline 1990-1997 withdrawal rates—Continued.

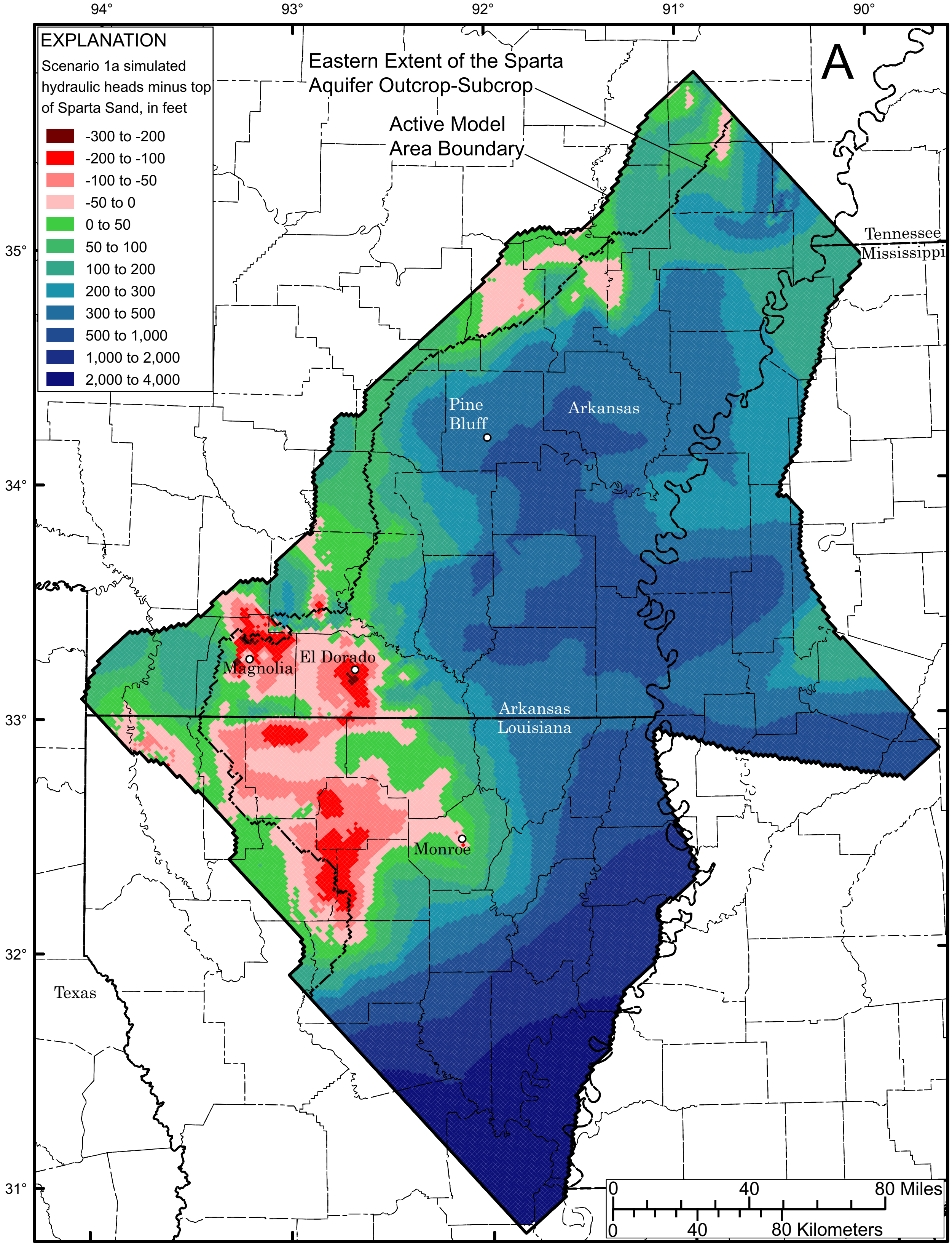


Figure 27. Contoured difference from (A) 2027 [scenario 1a] and (B) steady-state [scenario 1b] simulated hydraulic heads to the top of the Sparta Sand using baseline 1990-1997 withdrawal rates.

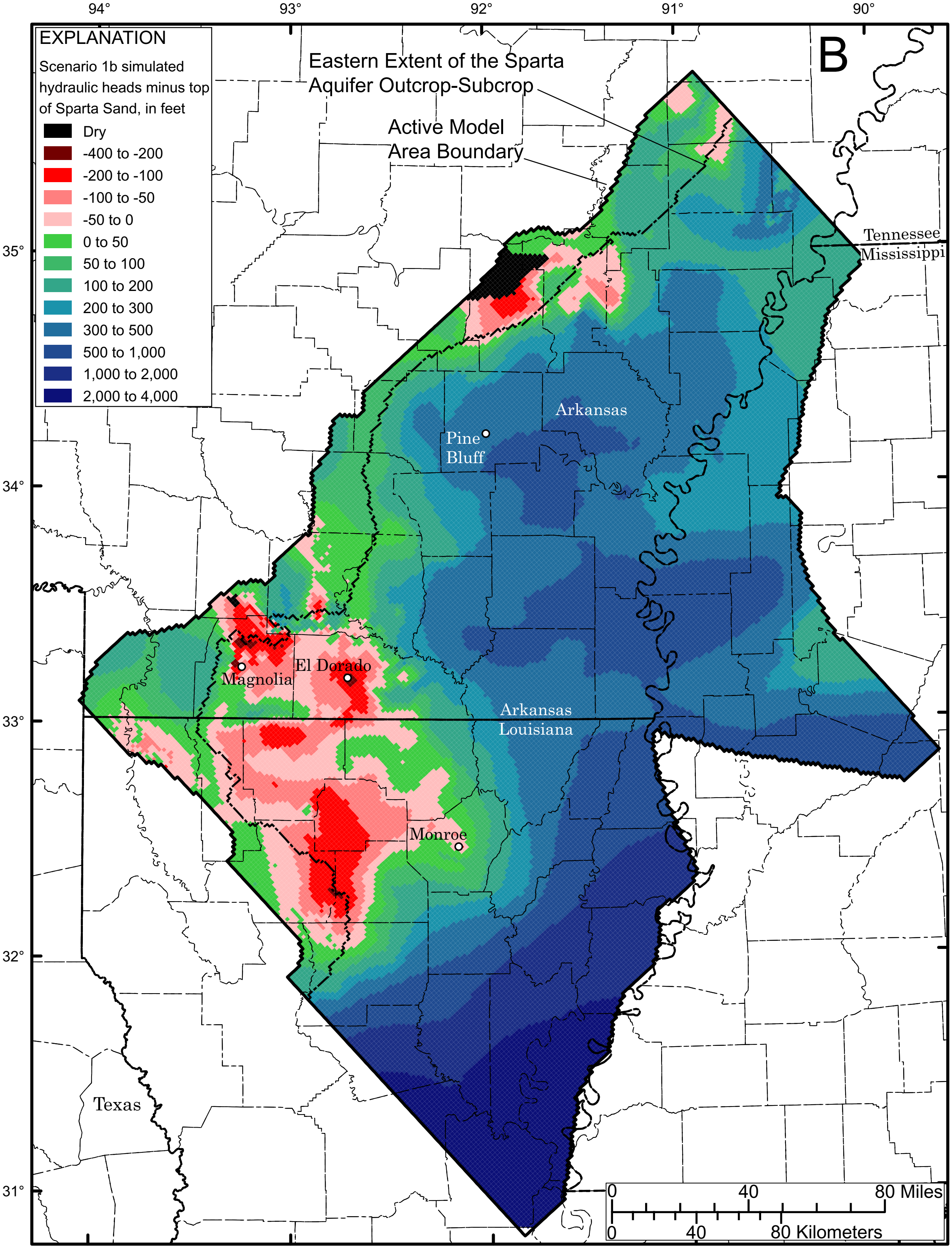


Figure 27. Contoured difference from (A) 2027 [scenario 1a] and (B) steady-state [scenario 1b] simulated hydraulic heads to the top of the Sparta Sand using baseline 1990-1997 withdrawal rates—Continued.

Scenario 2 - Baseline 1990-1997 Withdrawal Rates with Reductions in Pine Bluff and El Dorado

Scenario 2 presents a model simulation that was conducted to determine the effects of continued baseline 1990-97 withdrawal rates throughout most of the model area while reducing the withdrawal in the industrial areas in Pine Bluff and El Dorado. Selected industrial withdrawals in the Pine Bluff and El Dorado cones of depression were removed to simulate effects of industry changing to alternate sources of water (water reuse, surface-water diversions). These withdrawals represent the three largest industrial users of water from the Sparta aquifer in El Dorado and single largest industrial user in Pine Bluff.

The results of scenario 2 indicate that the removal of selected industrial withdrawals in the Pine Bluff area results in a shallower and less expansive cone of depression (fig. 28) relative to the baseline scenario (fig. 25A). In the center of the cone, hydraulic heads rise more than 120 ft by 2027 (fig. 29). Removal of selected industrial withdrawals in the El Dorado area also results in a shallower and less expansive cone of depression (fig 28) relative to the baseline scenario (fig 25A). In the center of the cone, hydraulic heads recover more than 165 feet by 2027 (fig. 29). Hydraulic heads recover above the top of the Sparta Sand by 2027 over most of Union County (fig. 30). The area of Union County where hydraulic heads are below the top of the Sparta Sand decreases from 51.9 percent in 1997 to 7.3 percent in 2027 (table 9).

The effects of withdrawal removal in Pine Bluff and El Dorado on areas outside of Jefferson and Union Counties appear to be minimal because of the great distance between these cities and the hydrogeologic properties of the flow system. Although substantial hydraulic-head recovery occurs in these counties, the change map (fig.29) indicates continued hydraulic-head decline in the Grand Prairie area as withdrawal rates remain at the 1990 to 1997 rate. A maximum decline of about 30 ft occurs in central Lonoke County. Hydraulic-head recovery occurs in much of north-central Louisiana, with a maximum decline of less than 10 ft in Ouachita Parish.

Scenario 3 - Increased Withdrawal Rates with Reductions in Pine Bluff and El Dorado

A model simulation was conducted to determine the effects of increased pumpage throughout most of the model area with removal of selected industrial withdrawals in Pine Bluff and El Dorado for the period 1998-2027. This scenario provides information on aquifer conditions in the region if the water withdrawal rates continue to increase while conservation initiatives in Pine Bluff and El Dorado support a reduction in industrial use as in scenario 2. The baseline 1990-97 withdrawal rate was linearly increased by 25 percent over the 30-year period from 1998 to 2027. The simulation period was segmented into six stress periods of 5 years each. Withdrawal rates at each well were multiplied by an appropriate percentage for each stress period that totals a 25 percent increase over 30 years.

The results of scenario 3 show that throughout most of the model area the predicted hydraulic heads for this scenario (fig. 31) are higher than levels predicted for the baseline scenario (fig. 25a) and that substantial recovery results in the cones of depression located in the Pine Bluff and El Dorado areas. Similar to scenario 2, the removal of selected withdrawals in the Pine Bluff and El Dorado areas results in shallower, less expansive cones of depression (fig. 31) relative to the baseline scenario (fig. 25a); however, recovery is less because of continued increases in pumping elsewhere in the aquifer. Hydraulic heads recover more than 100 ft by 2027 in Pine Bluff and more than 124 ft by 2027 in El Dorado (fig. 32). Hydraulic heads also recover above the top of the Sparta Sand, as in Scenario 2, by 2027 over most of Union County (fig. 33). However, the percentage area of Union County where hydraulic heads are below the top of the Sparta Sand is greater compared to Scenario 2 (16.6 percent compared to 7.3 percent in 2027) (table 9).

Even though substantial hydraulic-head recovery occurs in this scenario, the change map (fig. 32) indicates continued hydraulic-head decline not only in the Grand Prairie area, as in Scenario 2, but also noticeably in much of north-central Louisiana because withdrawals increase through 2027 in areas outside Pine Bluff and El Dorado. The maximum decline in Scenario 3 increases to 36 ft in central Lonoke County. North-central Louisiana hydraulic-head declines are substantially more compared to Scenario 2 with a maximum decline of 56 ft in Ouachita Parish.

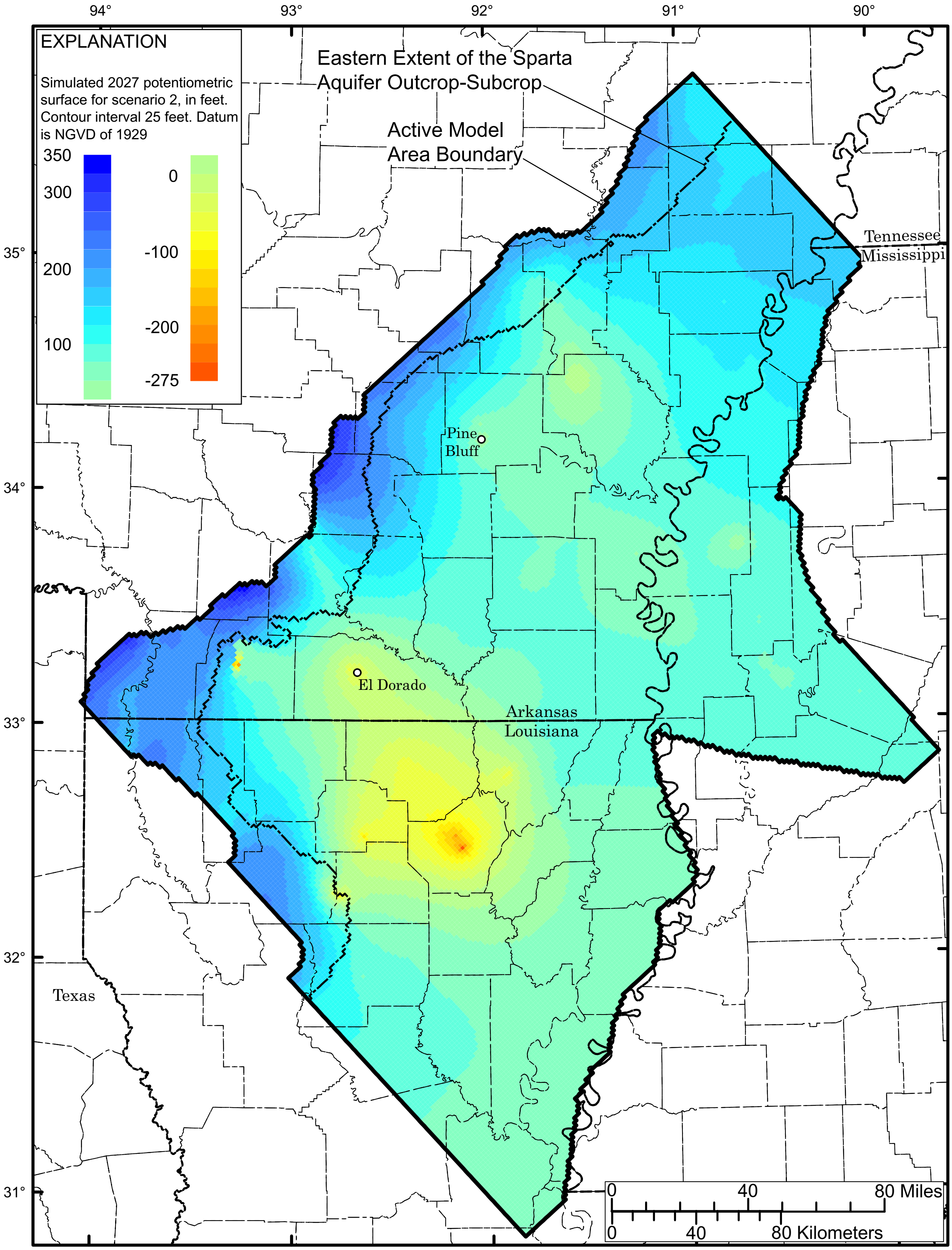


Figure 28. Simulated potentiometric surface for the Sparta aquifer using baseline 1990-1997 withdrawal rates with reductions in Pine Bluff and El Dorado through 2027, scenario 2.

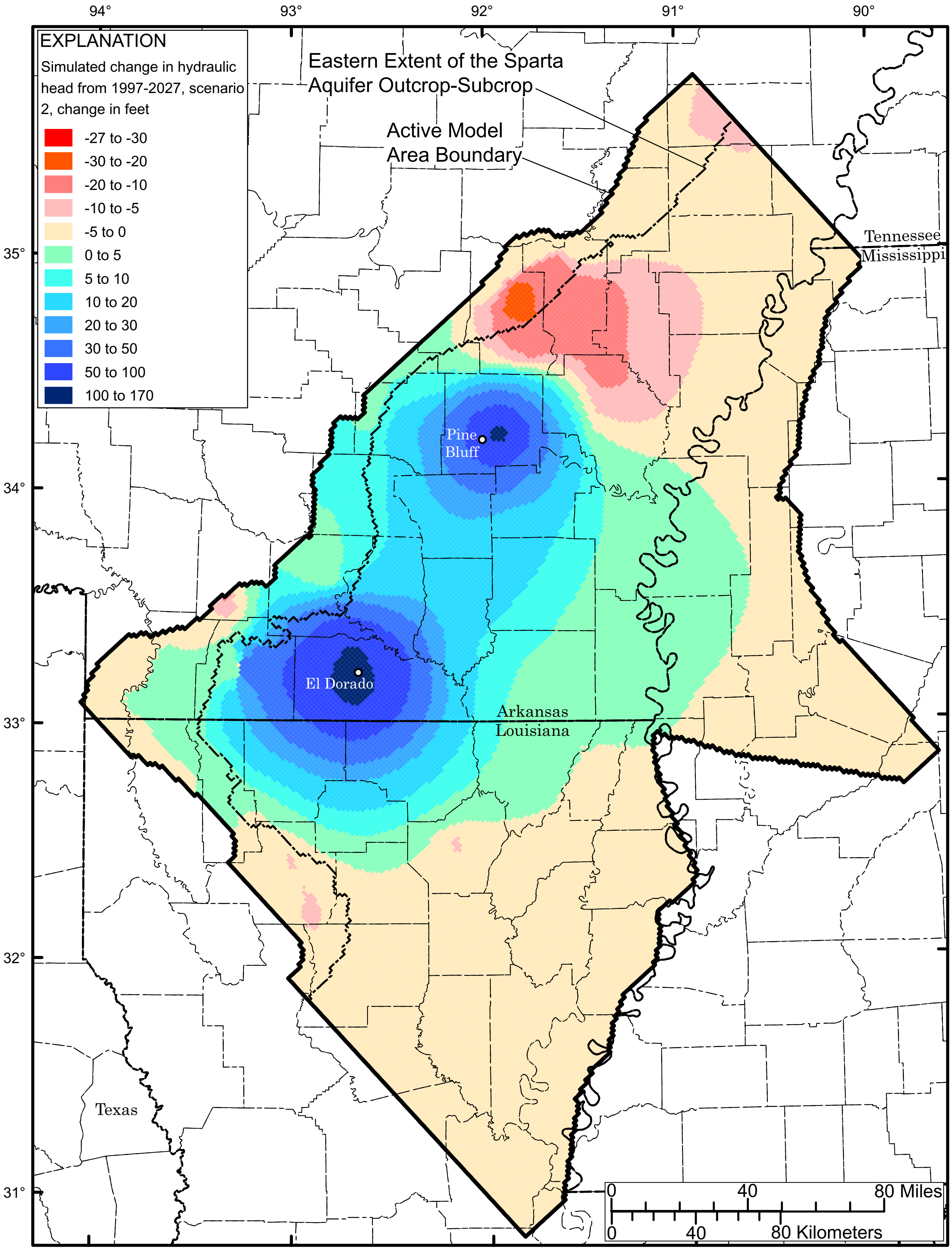


Figure 29. Change in simulated hydraulic head between 1997 and 2027 using baseline 1990-1997 withdrawal rates with reductions in Pine Bluff and El Dorado through 2027, scenario 2.

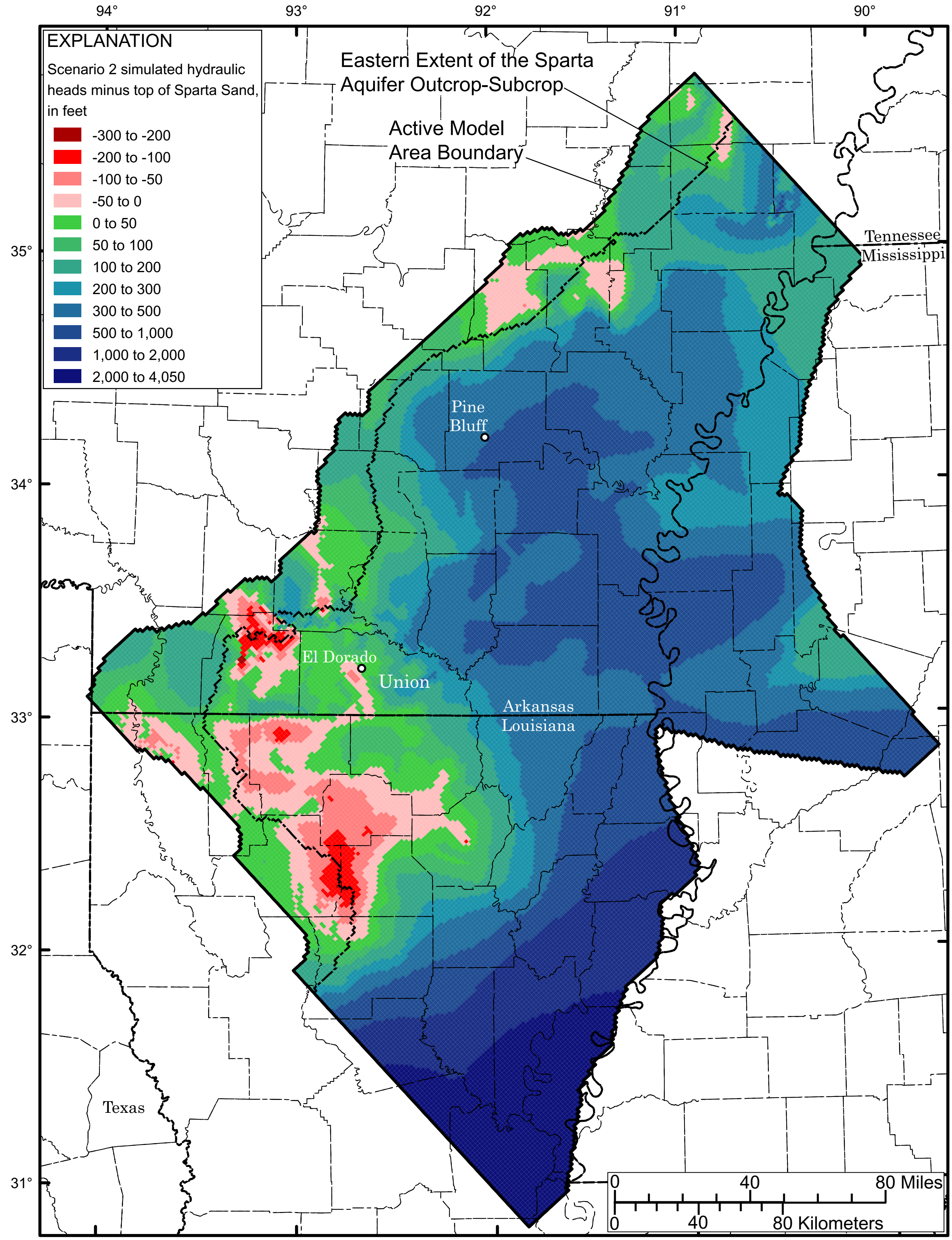


Figure 30. Difference between 2027 simulated hydraulic heads and top of the Sparta Sand using baseline 1990-1997 withdrawal rates with reductions in Pine Bluff and El Dorado through 2027, scenario 2.

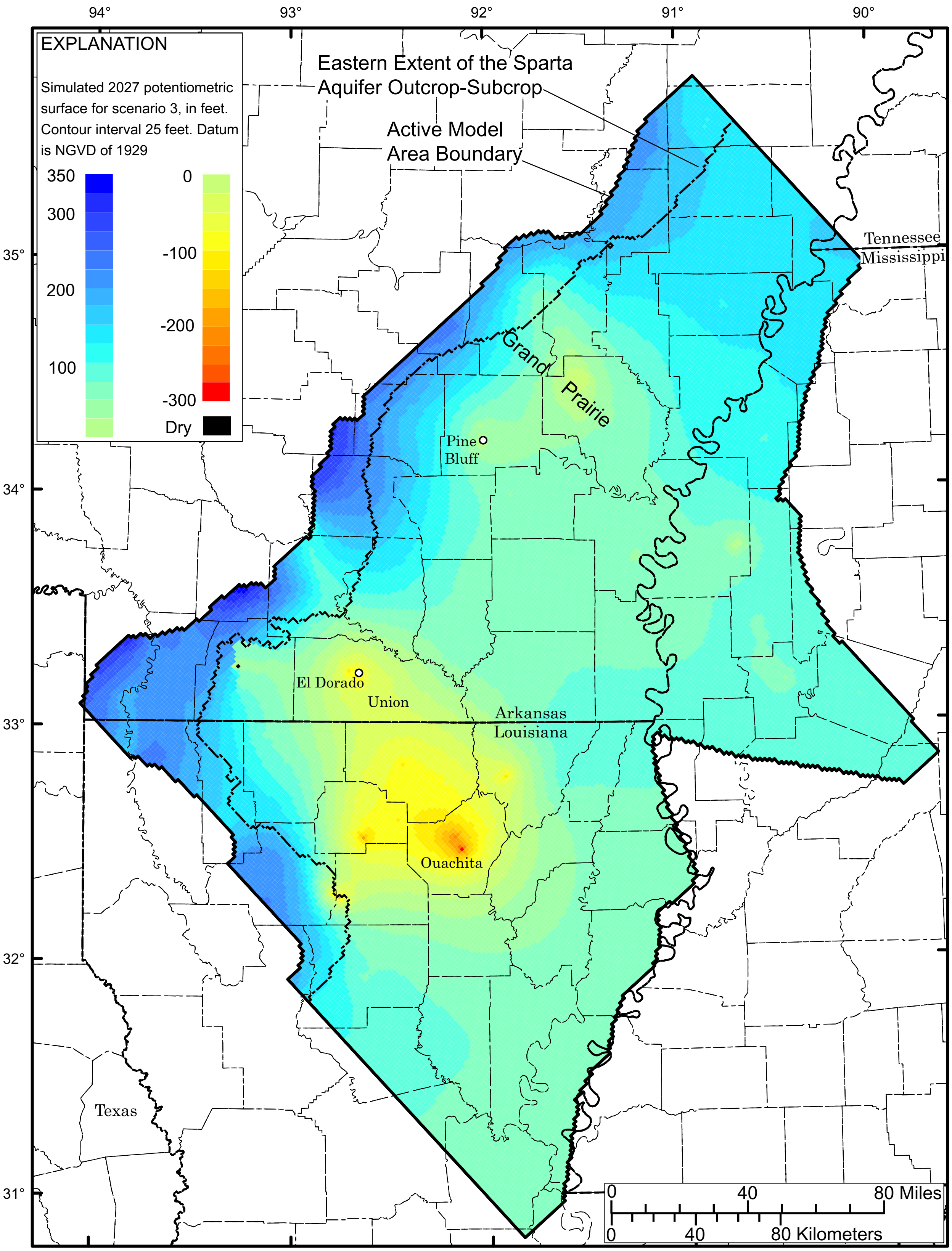


Figure 31. Simulated potentiometric surface for the Sparta aquifer using baseline 1990-1997 withdrawal rates increased by 25 percent with reductions in Pine Bluff and El Dorado through 2027, scenario 3.

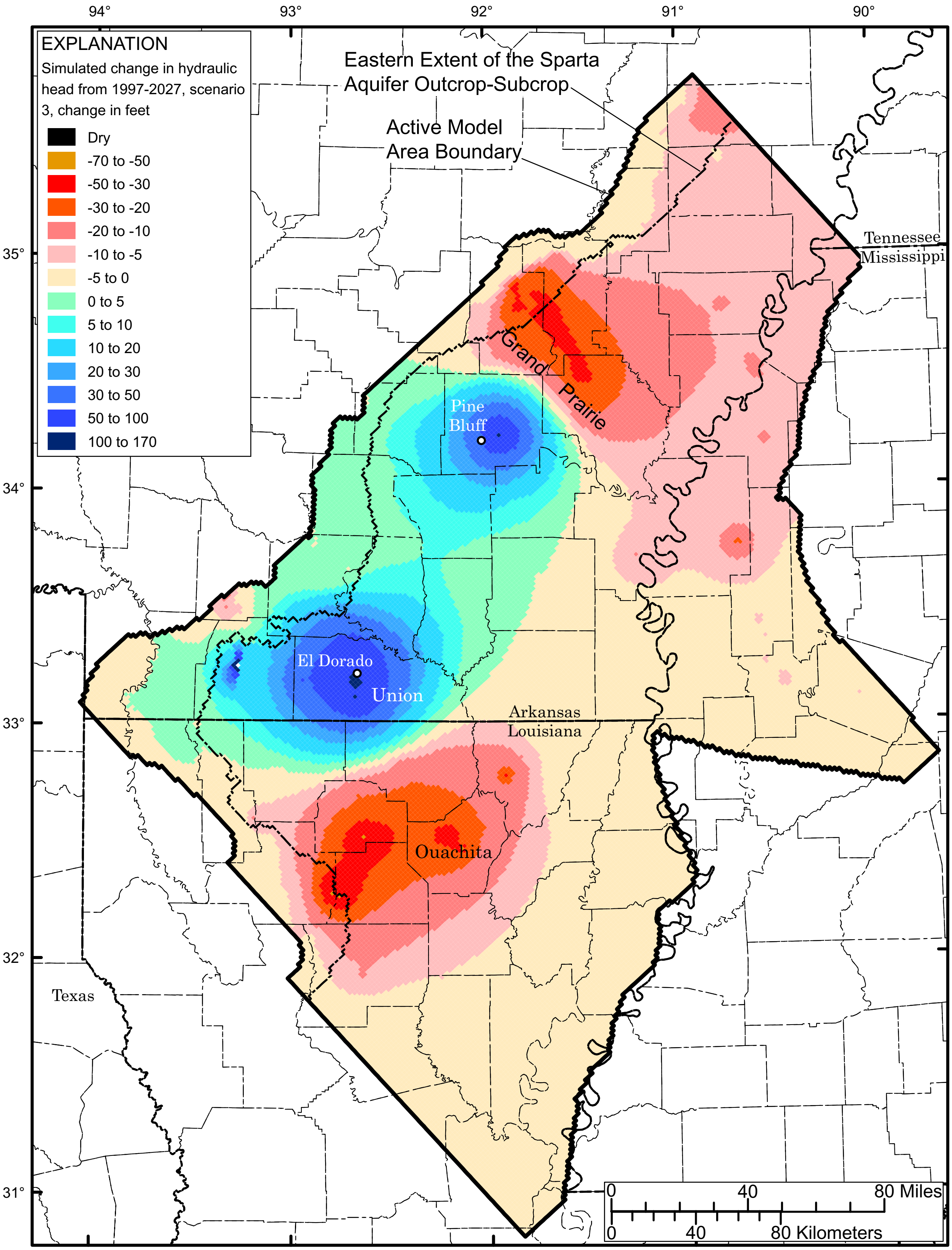


Figure 32. Changes in hydraulic head between 1997 and 2027 using baseline 1990-1997 withdrawal rates increased by 25 percent with reductions in Pine Bluff and El Dorado through 2027, scenario 3.

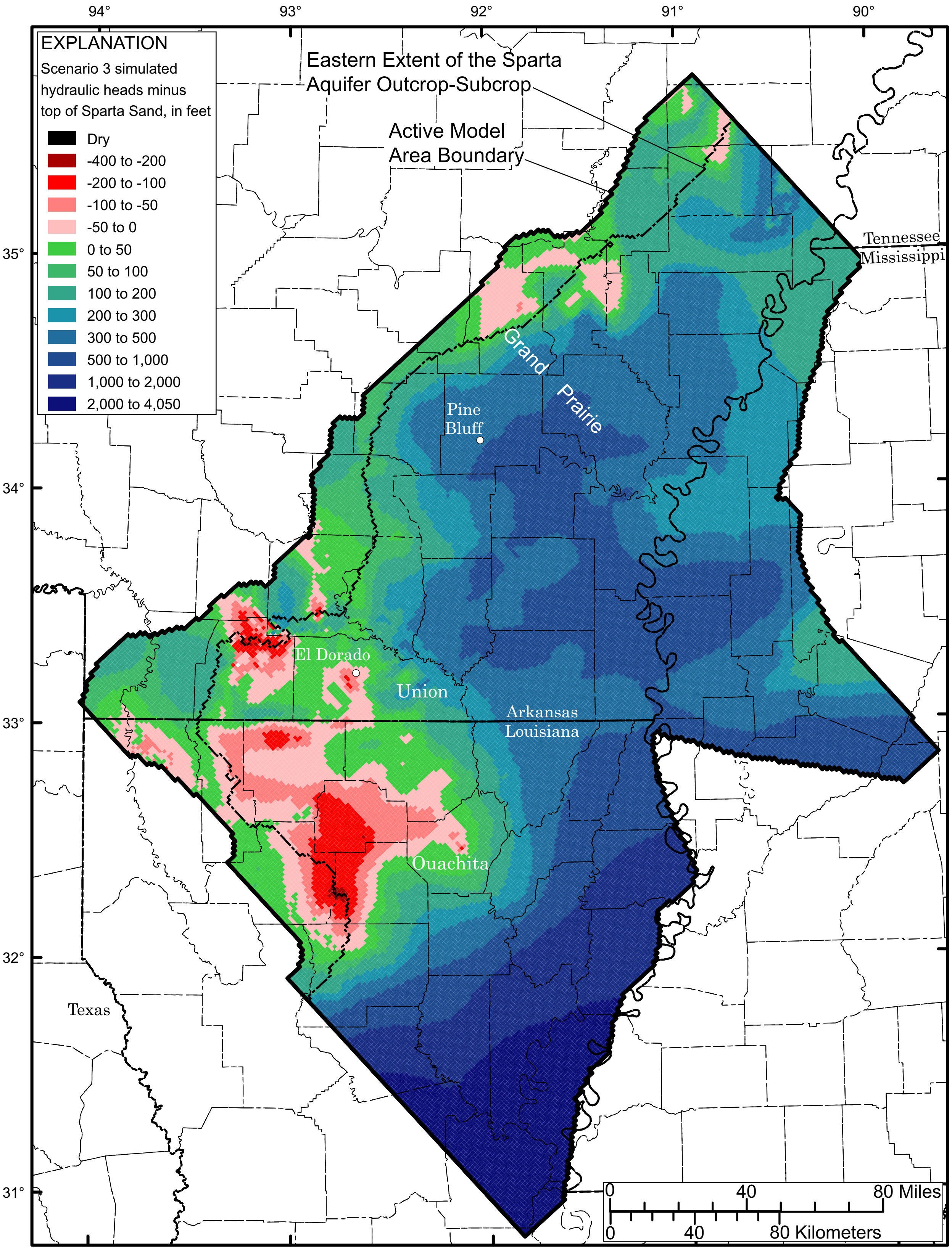


Figure 33. Difference between 2027 simulated hydraulic heads and top of the Sparta Sand using baseline 1990-1997 withdrawal rates increased by 25 percent with reductions in Pine Bluff and El Dorado through 2027, scenario 3.

MODEL LIMITATIONS

An understanding of model limitations is essential to effectively use flow model results. The accuracy of ground-water models is limited by simplification of complexities within the flow system, by space and time discretization effects, and by assumptions made in the formulation of the governing flow equations. Model accuracy is limited by cell size, number of layers, boundary conditions, accuracy and availability of data on hydraulic properties, accuracy of calibration, accuracy of pumpage estimates, historical data for calibration and verification, and parameter sensitivity. Model accuracy also is limited by the availability of data and by the interpolations and extrapolations that are inherent in using data in a model. Although a model might be calibrated, the calibration parameter values are not necessarily unique in yielding acceptable distributions of hydraulic head.

Surface discretization of the study area into a rectangular grid of square cells and vertical discretization of the Sparta aquifer requires an averaging of hydraulic properties. The model developed in this report is suitable for analyzing regional ground-water flow and simulating hydraulic heads resulting from local and regional stresses of ground-water withdrawal within a scale of 1 mi^2. Local variations and distributions of pumping stress within a 1 mi^2 area are not well represented in this model. Also, hydraulic heads simulated by the model represent the hydraulic head at the cell center of the 1 mile square grid, not at the pumping well.

Some of the water that enters the ground-water flow system travels only a short distance before being discharged locally into streams and other drains. The digital model does not simulate all the localized flow because of the 1-mi discretization. The model simulations represent the intermediate- and regional-scale flow system. Because of the minimum stress period length of 1 year, seasonal changes in hydraulic-head measurements were not simulated. Average withdrawal rates are used in the model, and simulated hydraulic heads could be higher or lower than actual hydraulic heads measured during different seasons.

As the validation period of the model increases, the greater is the probability of generating more reliable model results. Maintaining the model by incorporating continued hydraulic-head observations and hydraulic-test data increases the length of the validation period and enhances the model's capability to generate realistic projection results.

Hydraulic properties in the model do not vary with time. However, substantial desaturation of the aquifer can result in reduction in storage and hydraulic conductivity due to compaction of sediments. Analysis of such processes is possible (Galloway and others, 2000; Kasmarek and Strom, 2002) but was not done for this model.

SUMMARY AND CONCLUSIONS

Concern over long-term declining hydraulic heads in the Sparta aquifer has resulted in a continued, cooperative effort by the Arkansas Soil and Water Conservation Commission, the U.S. Army Corps of Engineers, and the U.S. Geological Survey to develop, maintain, and use numerical ground-water flow models to manage and further analyze the ground-water system. The Sparta aquifer in southeastern Arkansas and north-central Louisiana is a major water resource and provides water for municipal, industrial, and agricultural uses. In recent years, the demand in some areas has resulted in withdrawals from the Sparta aquifer that substantially exceed recharge to the aquifer. Hydraulic-head declines have caused water users and managers to question the ability of the aquifer to supply water for the long term. Large cones of depression are centered beneath the Grand Prairie area and the cities of Pine Bluff and El Dorado in Arkansas, and the city of Monroe in Louisiana. Hydraulic heads in the aquifer have declined at rates greater than 1 ft/yr for more than a decade in much of southern Arkansas and northern Louisiana and are now below the top of the Sparta Sand in parts of Columbia and Union Counties, Arkansas and in much of north-central Louisiana (Joseph, 1998b, T.P. Schrader, U.S. Geological Survey, written commun., 2003). Problems related to overdraft in the Sparta could result in increased drilling and pumping costs, decreased aquifer yield, and reduced water quality in areas of large drawdown.

This report describes the development and calibration of a ground-water flow model representing the Sparta aquifer to simulate observed hydraulic heads and presents the results of three hypothetical future withdrawal scenarios. The Sparta aquifer occurs within the Sparta Sand consisting of interbedded sand, silts, and clays. The aquifer is confined above by the Cook Mountain confining unit and below by the Cane River confining unit. Generalized ground-water flow in the Sparta aquifer is from the outcrop areas to the axis of the Mississippi Embayment and to the south. Sources of recharge to the Sparta aquifer are precipitation and flow from rivers in the outcrop, and leakage from adjacent aquifers through confining layers.

A ground-water flow model of the Sparta aquifer was originally developed by Fitzpatrick and others (1990) and McWreath and others, (1991), and was subsequently validated twice by Kilpatrick (1992) and by Hays and others (1998). Although the last verification indicated that the Sparta model was simulating conditions in the aquifer within acceptable error for study goals at that time, analysis of reverification results identified specific areas where recalibration could improve the ability of the model to simulate behavior in areas with steep hydraulic gradients and increasing withdrawals (Hays and others, 1998). Because the Sparta model is being maintained as a tool to improve understanding of the aquifer and help with management issues, it was necessary to develop, construct, and calibrate a new Sparta model. Modifications from the previous Sparta model incorporated more hydrologic data since the 1985 calibration and are designed to meet the current needs of Federal, State, and local water managers and planners.

The transient, three-dimensional numerical model of ground-water flow simulates ground-water flow in the Sparta aquifer from 1898 to 1997. Although the conceptual model of the ground-water system has not changed from the previous Sparta model, the delineation and construction of hydrogeologic units in the flow model were revised. Currently, the numerical model has two layers representing upper and lower water-bearing zones of the Sparta aquifer separated by a quasi-three dimensional confining bed representing a clay confining unit in much of southwestern Arkansas and north-central Louisiana. Other substantive changes from the previous Sparta model include grid refinement, extension of the active model area northward beyond the Cane River Formation facies change, and representation of model boundaries, primarily lateral boundaries and representation of overlying aquifers. The current model area covers 38,220 mi^2 with a uniform grid of 1mi^2 cell size.

The current model was calibrated with the aid of parameter estimation, a nonlinear regression technique, combined with trial and error parameter adjustment using a total of 795 observations from 316 wells over 4 different years—1970, 1985, 1990, and 1997. Model results indicate the current calibration to be an appreciable improvement over the previous model calibration and subsequent verifications with a RMSE of 18.0 ft for all observations and a RMSE of 18.9 ft in 1997. This compares with a RMSE of approximately 31 ft for observation data sets used in the previous Sparta model, an improvement of almost 39 percent.

The current model was used to predict the effects of three pumping scenarios on hydraulic heads over the period 1998-2027 with one extended indefinitely until equilibrium conditions were attained. The 30-year transient simulation period was segmented into six stress periods of 5 years each. By 1997, hydraulic heads in the Sparta aquifer were below the top of the Sparta Sand in much of southwestern Arkansas and north-central Louisiana. In Union County, Arkansas, over 50 percent of the county had hydraulic heads below the top of the Sparta Sand; Jefferson County, Arkansas, had no area with hydraulic heads below the top of the Sparta Sand.

In scenario 1a, withdrawals were held constant for 30 years at baseline 1990-97 rates. Hydraulic heads in El Dorado, Arkansas, decreased by 10 ft from the 1997 simulation to 222 ft below NGVD of 1929 in 2027. Hydraulic-head altitudes in the Pine Bluff cone of depression showed a greater decline in the center of the cone than at El Dorado from 61 ft below NGVD of 1929 in 1997 to 78 ft below NGVD of 1929 in 2027. With these withdrawals extended indefinitely (scenario 1b), hydraulic heads in the Pine Bluff cone of depression declined another 26 feet to 104 feet below NGVD of 1929; however, hydraulic-head decline in the El Dorado cone of depression center was only an additional 7 ft compared to scenario 1a.

In scenario 2, withdrawals were extended as in scenario 1a while industrial withdrawals were reduced in Pine Bluff and El Dorado. Selected withdrawals were removed to simulate effects of industry changing to alternate sources of water. Removal of selected withdrawals in both the Pine Bluff and El Dorado areas results in shallower, less expansive cones of depression relative to scenario 1a. In the cone of depression centers, hydraulic heads recover more than 120 and 165 ft, respectively, in the depression centers of these two areas. With this recovery, the area of Union County where hydraulic heads are below the top of the Sparta Sand decreases from 51.9 percent in 1997 to 7.3 percent by 2027.

In scenario 3, withdrawals were gradually increased over 30 years by 25 percent while reducing withdrawals in industrial areas of Pine Bluff and El Dorado. The results are similar to scenario 2; however, recovery is less because of continued increases in withdrawals elsewhere in the aquifer. In the cone of depression centers for Pine Bluff and El Dorado, hydraulic heads recovered more than 100 and 124 ft, respectively. Even though substantial hydraulic-head recovery occurred in both scenarios 2 and 3, hydraulic heads continued to decline in the Grand Prairie area (scenario 2 only) and in much of north-central Louisiana.

Understanding the conceptual model of the ground-water system is essential to effectively use the model as a management tool. The numerical model is a simplification of a complex flow system; therefore, understanding the model limitations is essential in analyzing results of predictive scenarios. The Sparta model is a dynamic tool that needs to be maintained and updated as data are collected. Periodic model verification increases user confidence in the model's ability to generate realistic long-term simulations.

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APPENDIX - DIGITAL THREE-DIMENSIONAL ANIMATIONS OF SIMULATED HYDRAULIC-HEAD SURFACES FOR THE THREE PREDICTIVE SCENARIOS

Animations illustrating each of the three hypothetical future water demand scenarios described in the report are included in AVI format on the enclosed compact disk. A README file also explains how to install and view the AVI on a PC.

The animations contained on the CD were created using Tecplot version 9.2-0-3 for MS-WINDOWS Copyright (c) 1988-2002 Amtec Engineering, Inc.

Hydraulic-head data for the animations were read from the HDS output file from MODFLOW-2000 and reformatted using code written with the Microsoft Visual Basic 6.0 editor within Microsoft Access 2000 (9.0.2720) Copyright (c) 1992-1999.

Animations included on the CD are simulated hydraulic heads for the following:

sc1.avi - scenario 1a, baseline 1990-1997 withdrawal rates extended through 2027 and then to steady-state.

sc1_oblq.avi - same as scl.avi, but with an oblique view.

sc2.avi - scenario 2 extended through 2027, but reduction in withdrawals from industrial areas of Pine Bluff and El Dorado

sc2_oblq.avi - same as sc2.avi, but with an oblique view.

sc3.avi - scenario 3, 25 percent increase in baseline 1990-1997 withdrawal rates over 30 years, with reduction in withdrawals from industrial areas of Pine Bluff and El Dorado

sc3_oblq.avi - same as sc3.avi, but with an oblique view.