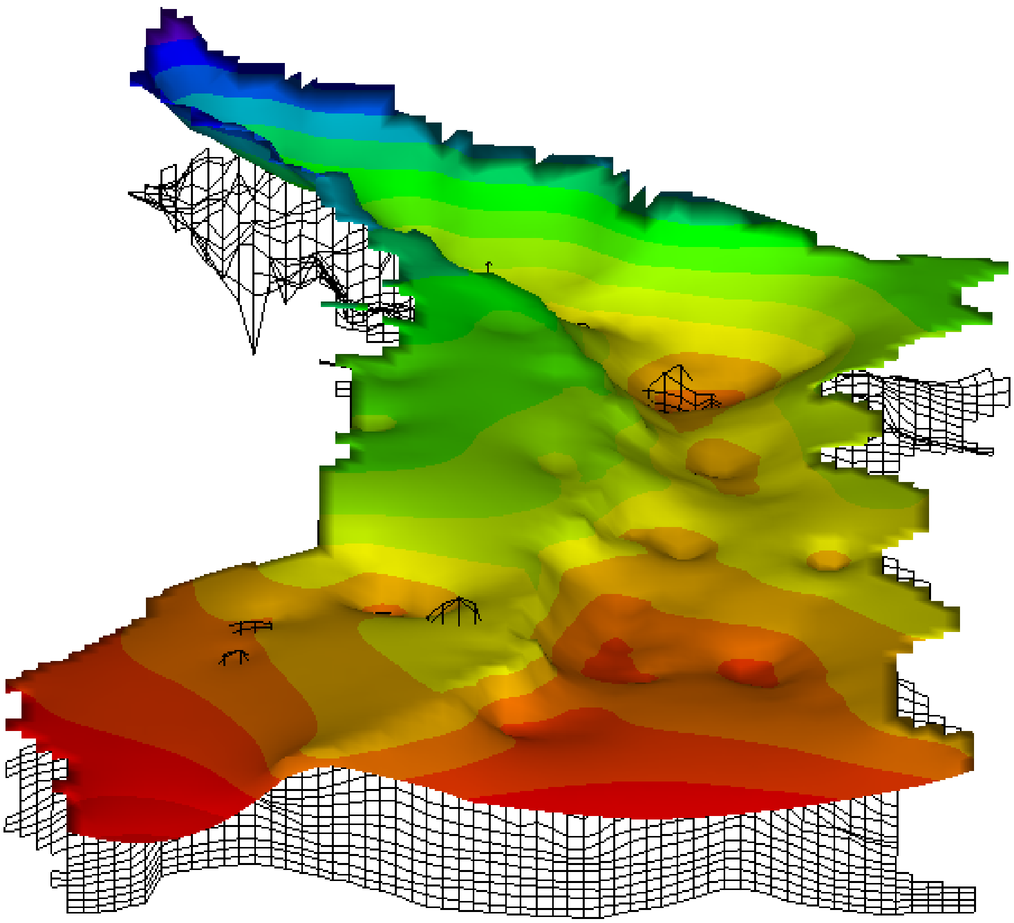
Prepared in cooperation with the

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

Arkansas Soil and Water Conservation Commission

RECALIBRATION OF A GROUND-WATER FLOW MODEL OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER IN SOUTHEASTERN ARKANSAS, 1918-1998, WITH SIMULATIONS OF HYDRAULIC HEADS CAUSED BY PROJECTED GROUND-WATER WITHDRAWALS THROUGH 2049

Water-Resources Investigations Report 03-4232



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

Cover*:* Oblique view of scenario 3 showing 2009 simulated heads of the alluvial aquifer with the 50 percent saturated thickness shown as a transparent grid, also shown in animations included on the compact disk in the back of the report.

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By Gregory P. Stanton and Brian R. Clark

U.S. GEOLOGICAL SURVEY
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Little Rock, Arkansas
2003

U.S. DEPARTMENT OF THE INTERIOR

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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)
	Rate	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per day (ft^3/d)	0.02932	cubic meter per day (m^3/d)
billion gallons per day (Mgal/d)	43.81	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)

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.

RECALIBRATION OF A GROUND-WATER FLOW MODEL OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER IN SOUTHEASTERN ARKANSAS, 1918-1998, WITH SIMULATIONS OF HYDRAULIC HEADS CAUSED BY PROJECTED GROUND-WATER WITHDRAWALS THROUGH 2049

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ABSTRACT

The Mississippi River Valley alluvial aquifer, encompassing parts of Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee supplies an average of 5 billion gallons of water per day. However, withdrawals from the aquifer in recent years have caused considerable drawdown in the hydraulic heads in southeastern Arkansas and other areas. The effects of current ground-water withdrawals and potential future withdrawals on water availability are major concerns of water managers and users as well as the general public. A full understanding of the behavior of the aquifer under various water-use scenarios is critical for the development of viable water-management and alternative source plans. To address these concerns, the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, Vicksburg District, and the Arkansas Soil and Water Conservation Commission developed and calibrated a ground-water flow model for the Mississippi River valley alluvial aquifer in southeastern Arkansas to simulate hydraulic heads caused by projected ground-water withdrawals.

A previously published ground-water flow model for the alluvial aquifer in southeastern Arkansas was updated and recalibrated to reflect more current pumping stresses with additional stress periods added to bring the model forward from 1982 to 1998. The updated model was developed and calibrated with MODFLOW-2000 finite difference numerical modeling and parameter estimation software. The model was calibrated using hydraulic-head data collected during 1972 and 1982 and hydraulic-head measurements made during spring (February to April) of 1992 and 1998. The residuals for 1992 and 1998 have a mean absolute value of 4.74 and 5.45 feet, respectively, and a root mean square error of 5.9 and 6.72 feet, respectively.

The effects of projected ground-water withdrawals were simulated through 2049 in three predictive scenarios by adding five additional stress periods of 10 years each. In the three scenarios, pumpage was defined by either continuing 1997 pumpage into the future (scenario 1) or by continuing water-use trends into the future (scenario 2), and increasing water-use trends with a 10 percent reduction in pumpage in selected areas (scenario 3). Scenario 1 indicates a cone of depression centered in Desha County and extensive dewatering with areas of simulated hydraulic heads dropping below 50 percent saturated thickness. Scenario 2 indicates a larger area of simulated hydraulic heads dropping below 50 percent saturated thickness and additional dewatering with model cells going dry and smaller cones of depression appearing in Ashley and Chicot Counties. Scenario 3 indicates overall reduction in depth and extent of the cones of depression of those in scenario 2, and the number of dry cells are only about two-thirds that of dry cells in scenario 2.

INTRODUCTION

Since the early 1900’s, southeastern Arkansas has produced agricultural crops (rice, soybeans, and cotton) that are highly dependent on ground water for irrigation. More recently, fish farming and other types of aquaculture are becoming major users of ground water. The most areally extensive and abundant source of water for irrigation in the Mississippi Embayment is the Mississippi River Valley alluvial aquifer. The Mississippi River Valley Alluvial aquifer, herein will be referred to as the alluvial aquifer. Overlying the alluvial aquifer in most of the study area is the Mississippi River Valley confining unit (Gonthier and Mahon, 1993), herein referred to as the overlying confining unit.

The alluvial aquifer, located in eastern Arkansas, and parts of Kentucky, Louisiana, Mississippi, Missouri, and Tennessee, supplies an average of 5 billion gallons of water per day (Grubb, 1998). Historically, the aquifer has been an important water resource for agriculture, business, and community growth in eastern Arkansas by providing abundant water of high quality. However, in recent years, demand has exceeded recharge to the aquifer, and water users and water managers are concerned about the ability of the aquifer to meet increasing long-term water demands. Withdrawals from the aquifer have caused considerable drawdown in the potentiometric surface. The effects of current ground-water withdrawals and potential future withdrawals on water availability are major concerns of water managers and users as well as the general public. A full understanding of the behavior of the aquifer under various water-use scenarios is critical to development of viable water-management and alternative source plans. To address these concerns, the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, Vicksburg District (USACE) and the Arkansas Soil and Water Conservation Commission (ASWCC) has developed and calibrated a ground-water flow model for the alluvial aquifer in southeastern Arkansas that is used to simulate hydraulic heads (often used interchangeably with water-level altitude or potentiometric surface) and flow in response to various projected ground-water withdrawal scenarios.

Purpose and Scope

This report describes the flow model and calibration, and results of simulations of hydraulic heads caused by projected ground-water withdrawals for the alluvial aquifer in southeastern Arkansas. The model described in this report is an updated and recalibrated version of the Mahon and Poynter (1993) “south model” with updated pumpage and recalibrated hydraulic values. This report briefly describes the hydrogeology of the model area, specifically in relation to application of model boundary conditions and hydraulic parameters. The model was calibrated using hydraulic heads from 1918 to 1998, and various scenarios of projected ground-water withdrawals were simulated for 1998-2049.

This report is limited to the digital modeling of ground-water flow in the alluvial aquifer and the effects of pumping within the alluvial aquifer. The conjunctive-use optimization modeling using this flow model is published in a separate report (Czarnecki and others, 2003).

Model Area

The model area includes all or parts of six counties in Arkansas south of the Arkansas River (Ashley, Chicot, Desha, Drew, Jefferson, and Lincoln) and parts of three parishes in northeastern Louisiana (East Carroll, West Carroll, and Morehouse) (fig. 1). The flow model of the alluvial aquifer north of the Arkansas River is described in a separate report (Reed, 2003).

Previous Studies

The unconsolidated sediments of the Mississippi alluvial plain have been described in several publications. One of the earliest reports describing subsurface geology and ground-water resources in southern Arkansas and northern Louisiana was written by Veatch (1906). Fisk (1944) reported on extensive geologic investigations along the Mississippi River Valley made by the USACE between 1941 and 1944. This compilation consists of text accompanied by more than 110 illustrations describing the alluvial sediments. Krizinsky and Wire (1964) expanded on the hydrogeologic work of Fisk with a comprehensive study of the ground-water conditions. Cushing and others (1964) and Boswell and others (1968) provided an overview of the alluvial aquifer in their discussions of Quaternary-age aquifers on the Mississippi Embayment. Boswell and others (1968) first referred to the water-yielding sediments underlying the alluvial plain as the Mississippi River Valley Alluvial aquifer.

Several reports have been published documenting the results of model simulations of the flow system within and across boundaries of the alluvial aquifer. A two-dimensional planar model of the alluvial aquifer-stream system in southern Arkansas was published by Reed and Broom (1979). This model simulated stream-aquifer interaction and streamflow with the finite-difference equation (Pinder and Bredehoeft, 1968) and was the first digital model of the alluvial aquifer south of the Arkansas River. Regional model investigations were conducted by Ackerman (1989a, 1990) under the framework of the USGS Gulf Coast Regional Aquifer-System Analysis; these reports describe the model development and results and show the characteristics of the flow system on a regional basis. Predictive sim-

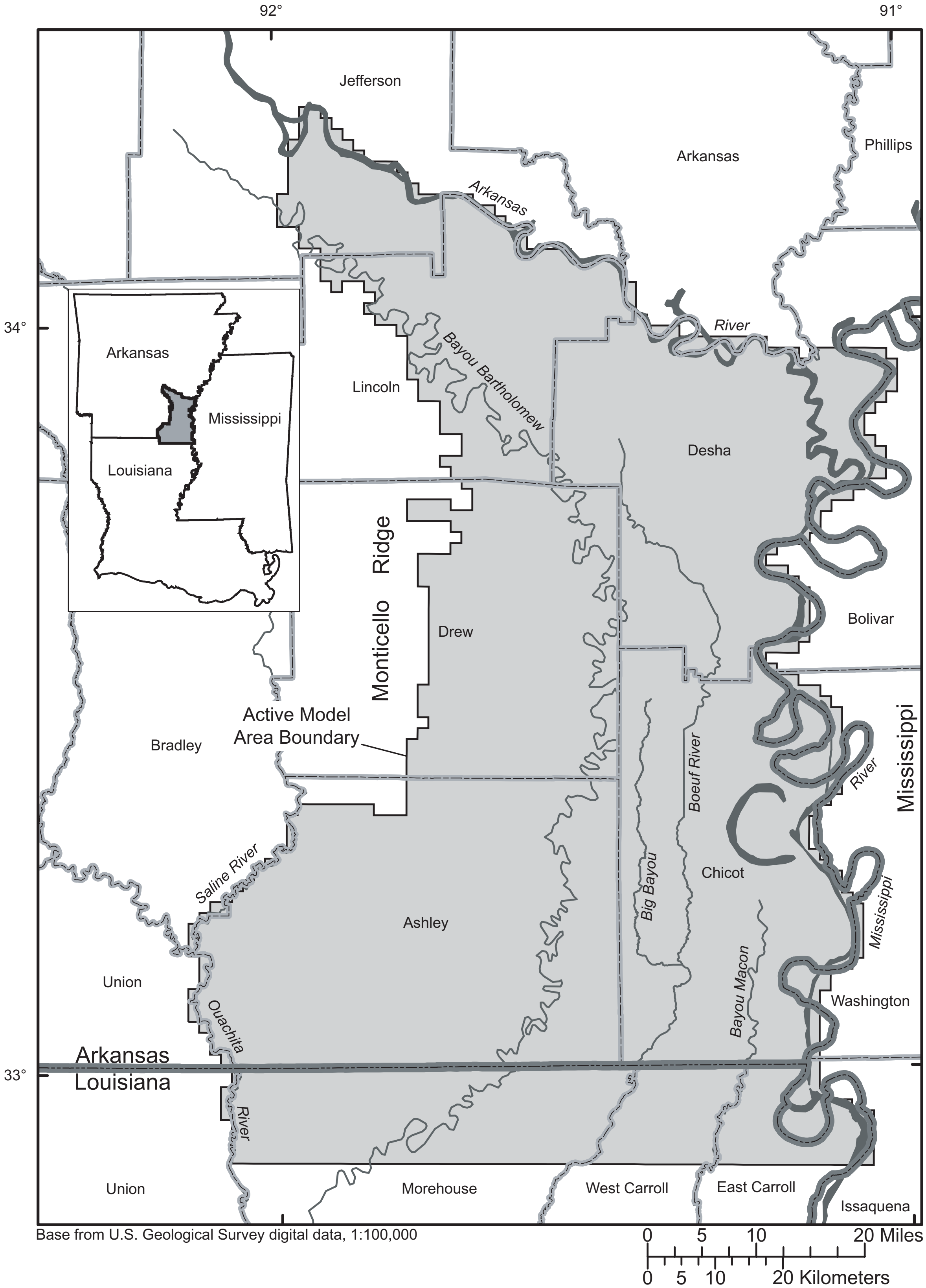

Figure 1. Active model area.

ulations presented by Ackerman (1989a, 1998) were based on hypothetical increases in pumping.

Previous Model

Substantial hydraulic-head declines in the alluvial aquifer in the 1980's (Ackerman, 1989b; Westerfield and Poynter, 1994) prompted the need to better understand the flow system in the aquifer which, in turn, led to the development of digital ground-water flow models of the alluvial aquifer. The previously published model of the alluvial aquifer used in this report was authored by Mahon and Poynter (1993). Mahon and Poynter (1993) described the development, calibration, and results of two separate models for eastern Arkansas: one for the area north of the Arkansas River and one for the area south of the Arkansas River (herein referred to as the north model and the south model, respectively). The north and south models utilized the MODFLOW finite difference numerical-modeling software (McDonald and Harbaugh, 1988). The models were calibrated using hydraulic-head data from 1972 and 1982. Model grids had a cell size of 1 square mile. Recharge to the aquifer was simulated using head-dependent surface infiltration through the overlying confining unit and seepage through riverbeds. The active cells of the south model encompassed the area in Arkansas south of the Arkansas River, west of the Mississippi River, east of the Monticello Ridge, the Saline River, and the Ouachita River, and south into northern Louisiana for about 10 miles (fig. 1).

HYDROGEOLOGIC SETTING OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER

The alluvial aquifer is the uppermost aquifer system in eastern Arkansas and is part of a much larger sedimentary system known as the Mississippi Embayment (Cushing and others, 1964). The Mississippi Embayment plunges southward from Illinois to the Gulf of Mexico in a fan shaped trough, and covers about 160,000 square miles in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee (Cushing and others, 1964; Williamson and others, 1990). The ages of the embayment sediments range from Jurassic to Quaternary, but only units of Cretaceous age and younger are exposed in Arkansas. The central axis of the Mississippi Embayment nearly parallels the Mississippi River, and the embayment surface drainage in Arkansas is ultimately to the Mississippi River (Mahon and Poynter, 1993).

The Mississippi Alluvial Plain is a broad, flat plain that lies within the Coastal Plain physiographic province (Fenneman, 1938) and is part of the Mississippi Embayment. The alluvial plain encompasses an area of about 32,000 square miles, with more than 54 percent occurring in eastern Arkansas. The alluvial plain in Arkansas is bounded on the west by sediments of Paleozoic age with very low hydraulic conductivity and by sediments of Tertiary age of the Mississippi Embayment that have a distinctly lower hydraulic conductivity than sediments composing the alluvial aquifer (Ackerman, 1990; Mahon and Poynter, 1993).

Deposition of sediment from the Mississippi and Arkansas Rivers during Pleistocene and Holocene time (herein referred to as Mississippi River alluvium) has produced a sequence of sands, silts, and clays that constitute the alluvial aquifer in eastern Arkansas. From a regional perspective, this collection of sediment can be divided into two units. The lower unit, which contains the alluvial aquifer, is composed of coarse sand and gravels that grade upward to fine sand. The upper unit consisting of fine sand, silt, and clay confines the alluvial aquifer over most of the area. The alluvial aquifer and overlying confining unit, along with its flow system, has been defined and investigated previously (fig. 2) (Broom and Lyford, 1981; Broom and Reed, 1973; Ackerman, 1989a, 1989b, 1990; Mahon and Ludwig, 1990; Mahon and Poynter, 1993). The overlying confining unit ranges in thickness from 0 to 60 feet within the model area (Gonthier and Mahon, 1993). The sands and gravels that underlie the overlying confining unit and comprise the alluvial aquifer range from about 50 to about 100 feet thick.

The geology of most of the model area typically is characterized by clay and sand beds of the Mississippi River alluvium of Pleistocene and Holocene time overlying the silt and clay sequence of the Jackson Group of Tertiary age (Ackerman, 1989a). Channel fill, point bar, and backswamp deposits, associated with present or former channels of the major rivers, locally can produce abrupt differences in lithology of alluvial deposits, that result in spatial variations in the hydraulic properties of both the aquifer and confining unit within small distances (fig. 2). Alluvial deposits are dominated by the complex heterogeneity of small, discontinuous clay, silt, sand, and gravel beds dispersed

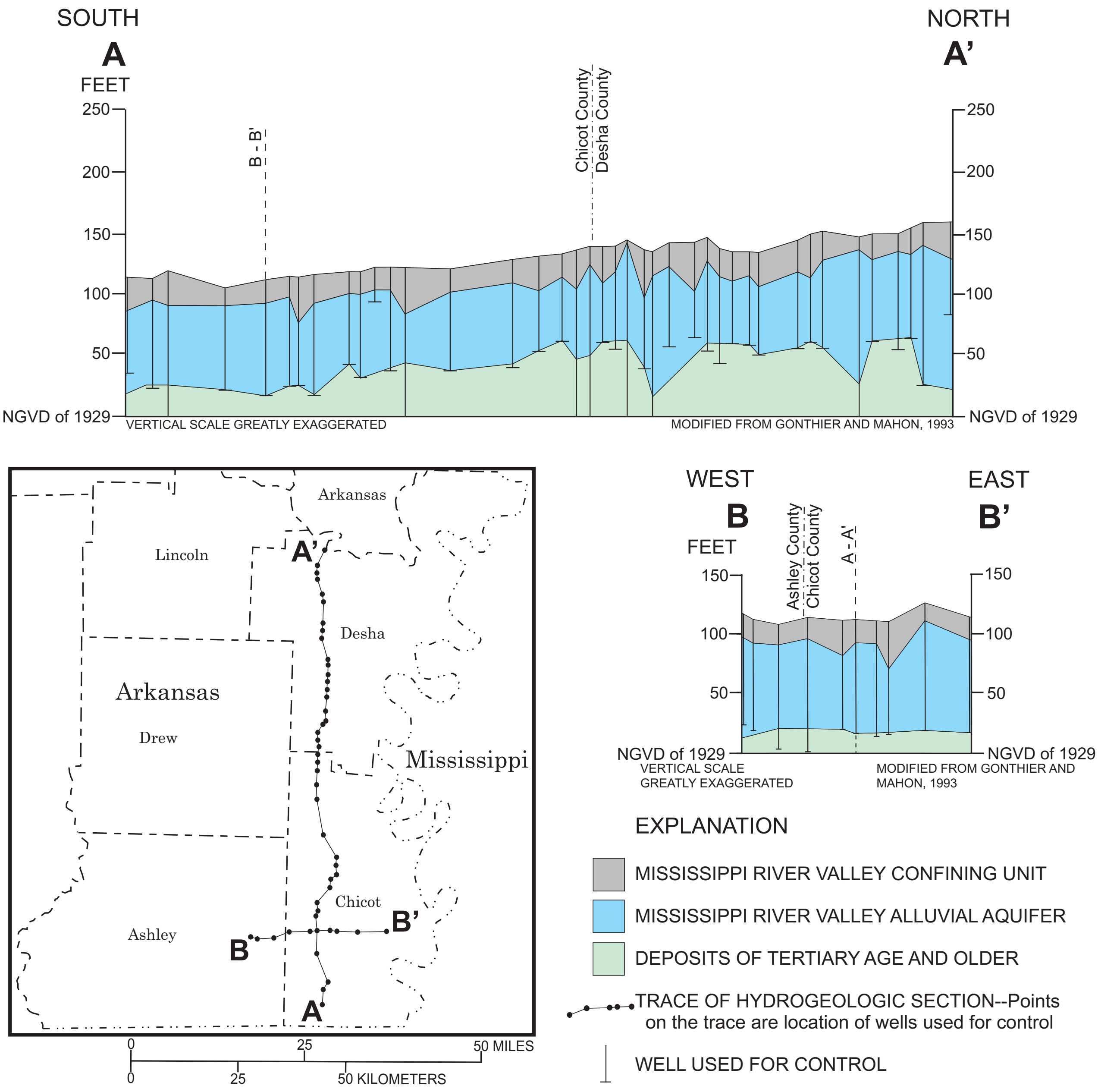

Figure 2. Hydrogeologic sections across the model area.

laterally and vertically, which represent local features of the aquifer and flow system. Laterally to the west, the contact between alluvial deposits and older strata is masked by terrace deposits (Ackerman, 1989a), which form a slight topographic high, locally referred to as the Monticello Ridge. During Tertiary time, the last marine inundation of the Mississippi Embayment occurred depositing the clays and silts of the Jackson Group. The Jackson Group underlies the Mississippi River alluvium in most of the model area forming an effective underlying hydraulic confining unit (Cushing and others, 1964).

The complexity of the geology within the alluvium is paralleled by that of the ground-water system. Although ground-water flow is made more complex by the heterogeneities in the aquifer and overlying confining unit, the flow system can be generalized and conceptualized as water moving laterally in a single zone or layer. This simplistic conceptualization of flow is compatible with conditions observed in the field (Mahon and Poynter, 1993).

The hydrologic conditions of the alluvial aquifer in the model area are the result of both regional and local flow systems in the alluvial sediments. Regionally, ground-water levels have been measured and mapped for several years (Ackerman, 1989b; Plafcan and Edds, 1986; Plafcan and Fugitt, 1987; Westerfield, 1990; Westerfield and Poynter, 1994; Stanton and others, 1998; Joseph, 1999; Schrader, 2001). These measurements indicate that ground water in the alluvial aquifer in southeastern Arkansas currently flows southward with local flow toward the areas of depressed hydraulic heads. A depressed hydraulic-head trough presently (2000) exists as a north-south feature between the Arkansas and Mississippi Rivers and Bayou Bartholomew on potentiometric maps (fig. 3) (Stanton and others, 1998; Joseph, 1999; Schrader, 2001). This trough induces local flow toward the axis of the trough, but regionally, a southeast flow direction is dominant.

Throughout most of the model area, the overlying silts, clay, and fine-grained sands of the overlying confining unit impede areal recharge (Krinitzsky and Wire, 1964) into the alluvial aquifer. Recharge to the top of the alluvial aquifer has been estimated by previous model studies. The most recent previous model by Mahon and Poynter (1993) estimated a recharge rate of 1.4 inches/year. A model by Broom and Lyford (1981) estimated between 0.4 and 2.0 inches/year of recharge to the alluvial aquifer through the overlying confining unit. Results of simulation analysis by Ackerman (1989a) indicated an average recharge rate through the overlying confining unit to be 0.8 inches/year.

Hydraulic heads in the aquifer have decreased with the increase in pumpage from the aquifer. Portions of the aquifer that had been under confined conditions now are under unconfined conditions. The aquifer is presently unconfined in most of the eastern part of the model area (fig. 4). The aquifer is confined in most of the western part of the model area.

The alluvial aquifer is hydraulically connected to major rivers and lakes resulting in considerable volumes of water being contributed to or taken from these surface-water bodies. Prior to the development of the alluvial aquifer, most major rivers and lakes in eastern Arkansas received part of their water from ground water. This ground-water derived component of flow constituted a significant part of total flow in major rivers (Ackerman, 1989a). Increased pumping from wells induces greater rates of recharge from rivers to the aquifer (Ackerman, 1989a; Czarnecki and others, 2002). Most rivers now lose water to the aquifer (recharge), and minimum observed flows in the rivers have decreased (Elton Porter, U.S. Geological Survey, written commun., 2002).

DESCRIPTION OF THE GROUND-WATER FLOW MODEL

The USGS finite-difference, three-dimensional, ground-water flow model MODFLOW-2000 (Harbaugh and others, 2000) was used to develop and calibrate the ground-water flow model for the alluvial aquifer. The calibrated model was used to simulate ground-water flow in the aquifer and to evaluate the range of plausible values for hydraulic characteristics (hydraulic conductivity, specific storage, storativity, and recharge). MODFLOW-2000 was used to solve finite difference, ground-water flow equation approximations for spatial distributions of hydraulic head over time with certain simplifying assumptions. The preconditional-conjugate-gradient (PCG) solver option was used within MODFLOW-2000 to solve the finite-difference equation.

A map of the alluvial aquifer in southeastern Arkansas was overlain by a rectangular, one square mile grid that discretized the aquifer into cells (fig. 5). Spatial and vertical variations in hydraulic characteristics and the aquifer framework are represented by discrete values in model cells. The model grid consists of

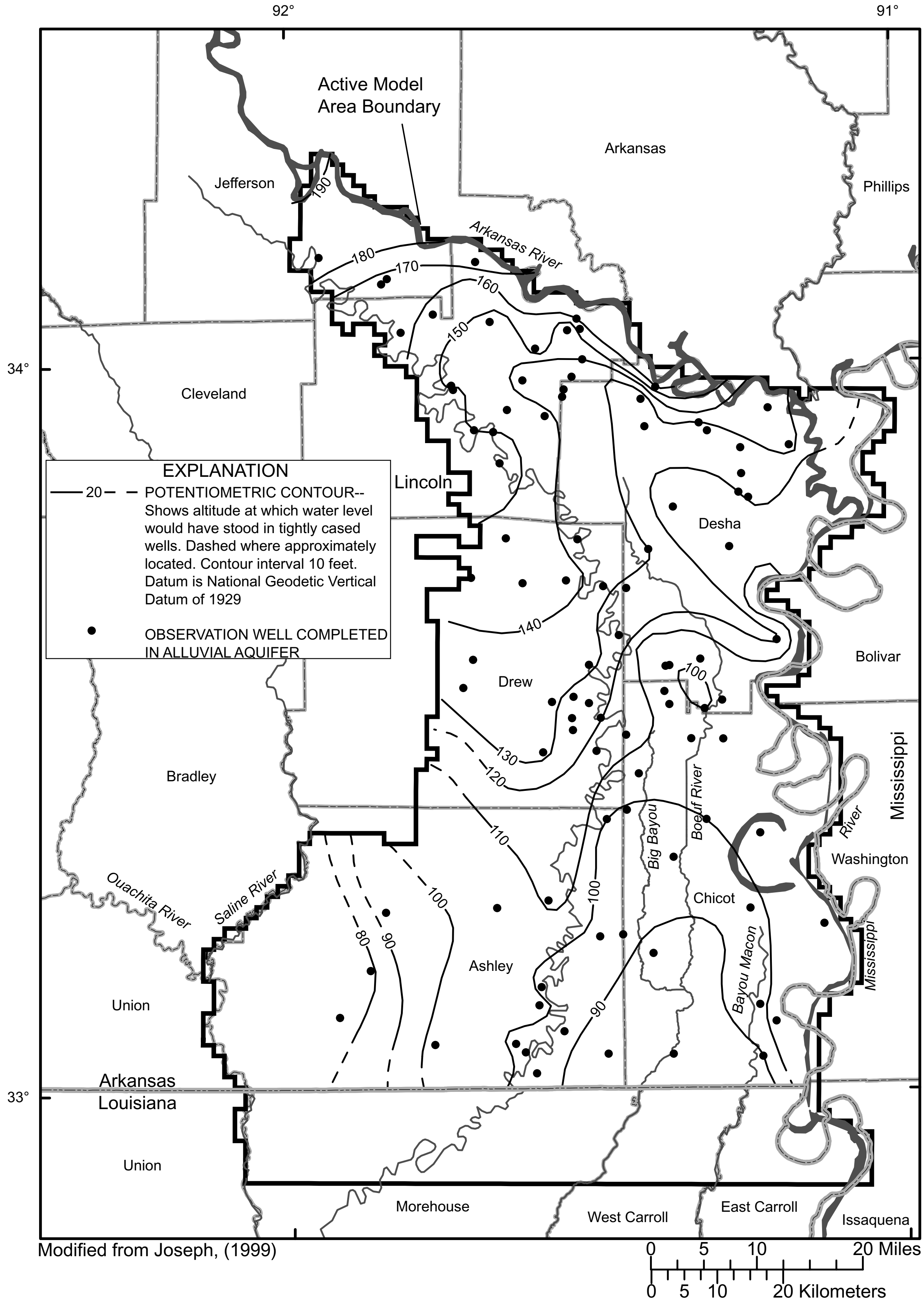

Figure 3. Ground-water levels in the alluvial aquifer in spring 1998 in the model area.

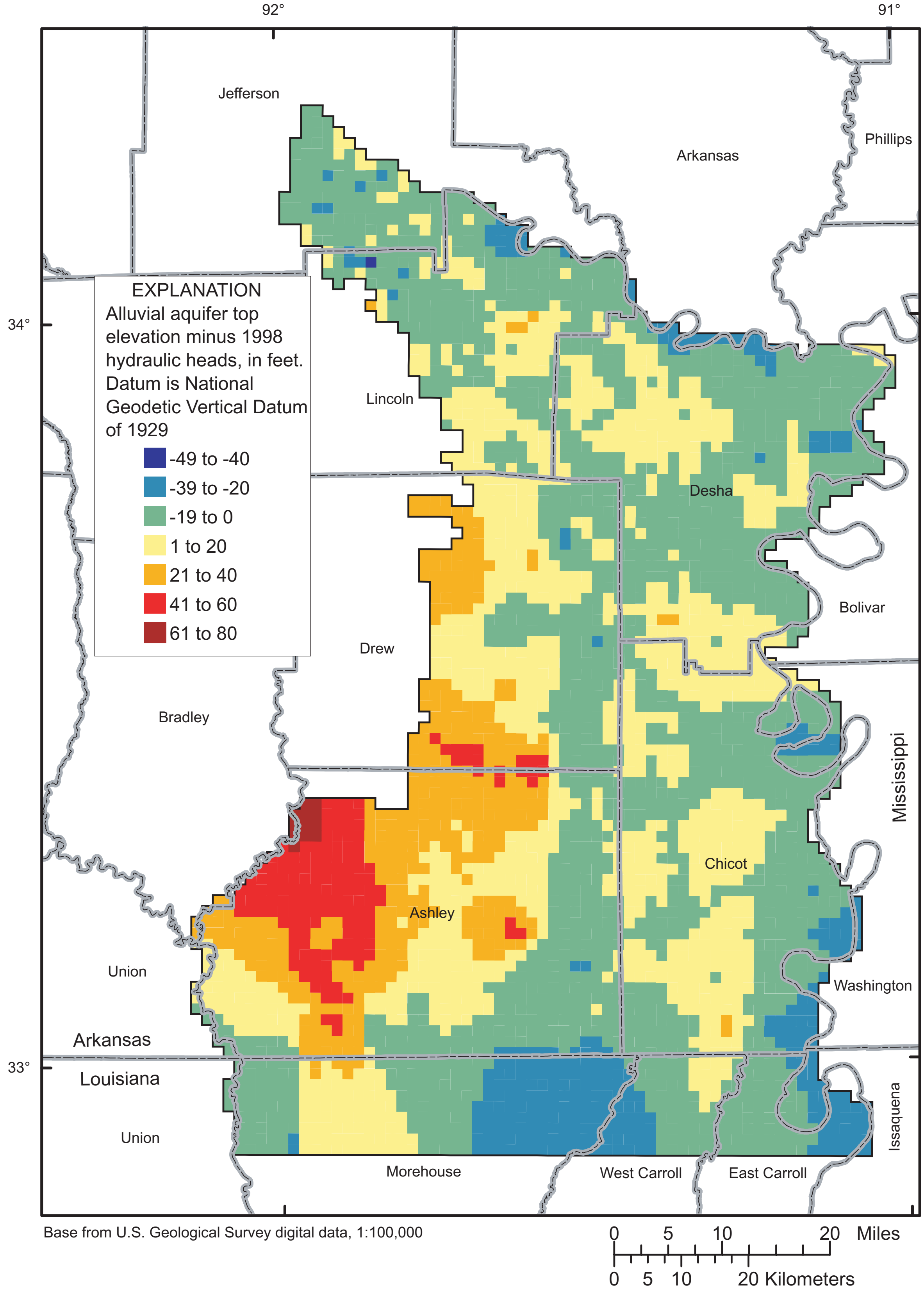

Figure 4. Difference between model top of the alluvial aquifer and 1998 hydraulic heads.

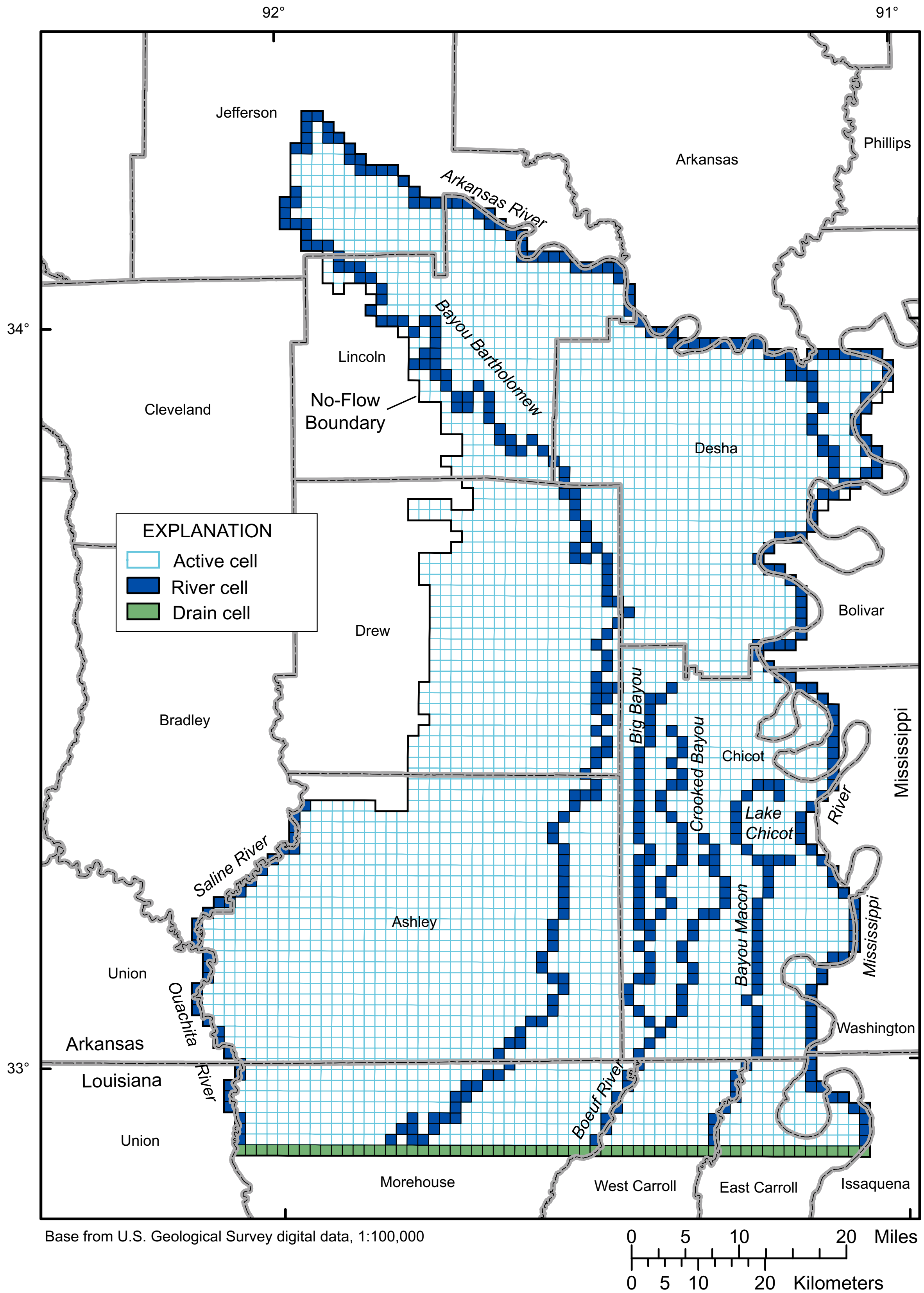

Figure 5. Active model grid and boundary conditions.

a single layer of variable thickness, with 102 rows and 75 columns, which represents only the alluvial aquifer.

Simplifying Assumptions

By necessity, a ground-water flow model is a simplification of the actual system. Several simplifying assumptions were made in the construction of the model: 1) a single layer is adequate to represent the alluvial aquifer; 2) flow is horizontal; 3) each cell is homogeneous and isotropic with respect to aquifer properties; 4) a finite grid is adequate for defining the vertical and lateral changes in aquifer properties; 5) recharge through streambeds is a function of river stage which is fixed in time; and 6) areal recharge is invariant in time and uniform over large areas. Mahon and Poynter (1993) describe wells close to one another in the alluvial aquifer and open to both the upper and lower zones in the aquifer as having negligible hydraulic-head differences. Thus, vertical flow as compared to lateral flow within the alluvial aquifer likely is small and using a single layer to represent the alluvial aquifer in the model is reasonable. Hydraulic-head altitude data indicate that pumping has drawn down hydraulic heads below the overlying confining bed throughout much of the alluvial aquifer. Streams supply recharge to the aquifer and receive discharge from the aquifer. Other potential recharge to the aquifer occurs as infiltration from the surface and as upward flow from the underlying Jackson confining unit, and these two recharge sources are simulated as a combined inflow term by the recharge package.

Model Specifications

Initial Conditions

Initial conditions for the model simulations are hydraulic heads estimated to have existed before ground-water development began in the early 1900's. The earliest potentiometric maps for the alluvial aquifer are for the Grand Prairie Region, north of the study area (Engler and others, 1945). Very little hydraulic-head data exist before the beginning of ground-water development, and no predevelopment potentiometric maps are available. Results from previously developed flow models (Ackerman, 1989a; Broom and Lyford, 1981) include hydraulic heads that represent conditions prior to pumping in the alluvial aquifer (fig. 6). These hydraulic heads were used as initial conditions for simulations of the Mahon and Poynter (1993) south model and were used as initial heads in the model described in this report. Ackerman (1989a) indicated that predevelopment of recharge to the alluvial aquifer was from underlying aquifers and from the overlying confining unit. Nearly all regional discharge was to rivers (Ackerman, 1989a).

Boundary Conditions

The model includes several rivers that exchange water with the ground-water system, and also is adjacent to areas that conceptually distribute little or no flow to or from the aquifer. The boundary conditions represented in the model reflect these conditions (fig. 5). The northern and eastern boundaries of the model are river cells representing the Arkansas River and Mississippi River, which function as large potential sources of inflow and outflow to and from the aquifer. The southern boundary of the model is about 10 miles south of the Arkansas border and is comprised of drain cells representing water flowing south in the alluvial aquifer into northern Louisiana. The western boundary is simulated with a no-flow boundary coinciding with a surface-water divide and the line of outcrop of sediments of Tertiary age. The exception to this no-flow condition is in western Ashley County where the western model boundary is river cells representing the Saline and Ouachita Rivers.

The flow from the apparent confining unit below the aquifer (Jackson Group), is assumed to be negligible and the base of the alluvial aquifer is simulated as a no-flow boundary. Data related to the movement of ground water between the alluvial aquifer and the deeper underlying units during predevelopment time are sparse. Because outcrop areas of the units are topographically higher than the alluvium, it is presumed that flow was upward from these underlying older rocks to the alluvium. However, hydraulic heads in the underlying aquifers recently have declined, and hydraulic-head measurements indicate that in some of the model area, hydraulic heads in the alluvium are now higher than those in the underlying rocks indicating that if flow does exist, it is downward to the underlying units (Grubb, 1998).

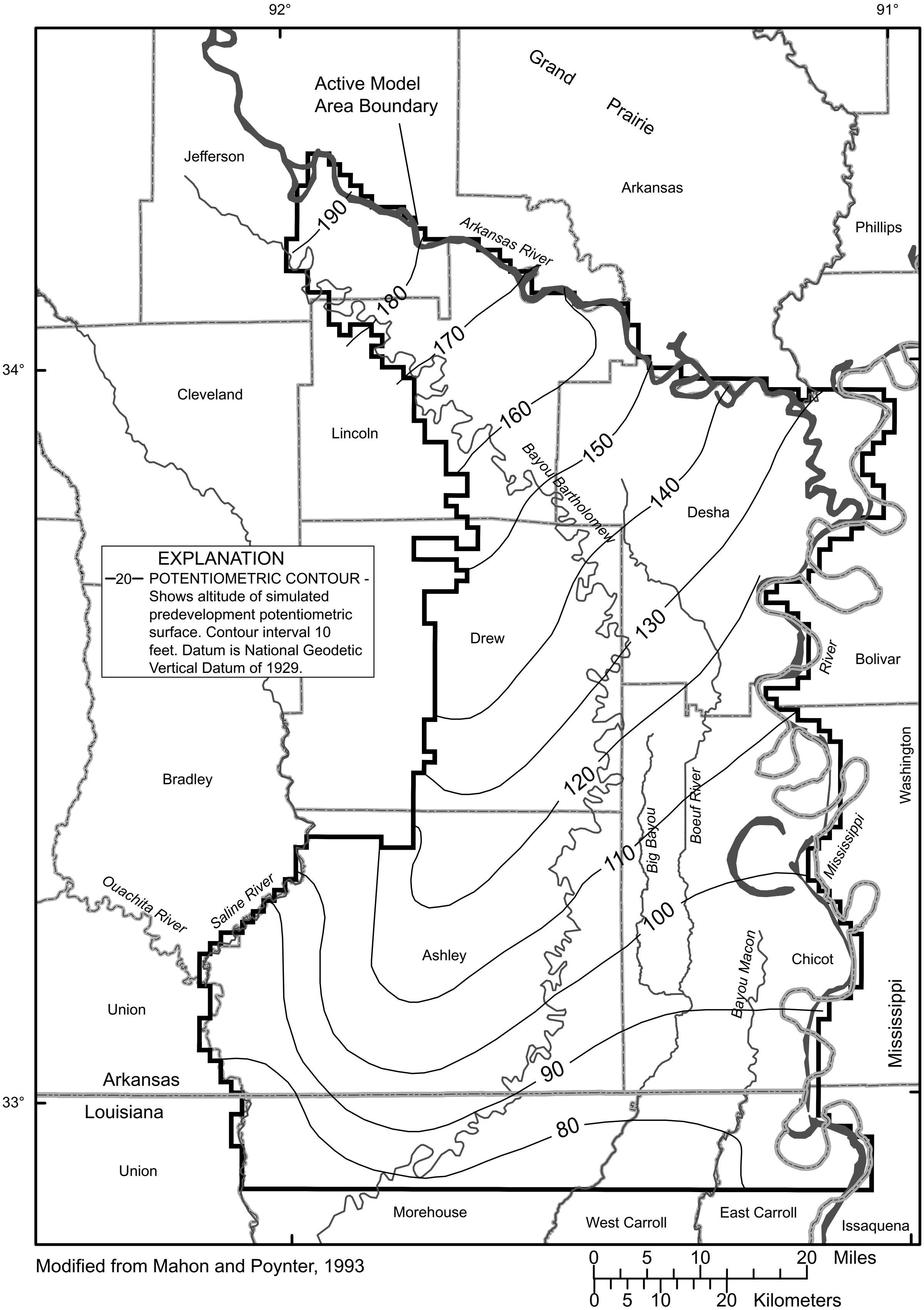

Figure 6. Simulated predevelopment potentiometric surface of the alluvial aquifer used as initial hydraulic-head conditions.

Surface-Water Parameters

Rivers, streams, and lakes contribute water to or drain water from the ground-water system based on the gradient between the surface-water body and the ground-water system and the hydraulic characteristics of the separating materials. Many rivers flow across the alluvial plain and exchange water with the alluvial aquifer (fig. 3). Rivers act as both sources of recharge and areas of discharge at different times of the year and at different locations along their reaches (Ackerman, 1989a). Rivers such as the Mississippi and the Arkansas are assumed to be in good hydraulic connection with the aquifer because they are deeply incised into the aquifer. The hydraulic head in the aquifer adjacent to the river is nearly identical to the river stage (Ackerman, 1989a; 1990; Mahon and Ludwig, 1990). The Saline and Ouachita Rivers and Bayou Bartholomew are not as well connected hydraulically with the aquifer, and hydrographs for wells near these rivers reflect attenuated changes in river stage. Field observations, hydraulic-head measurements, and model simulations indicate that other smaller streams such as the Boeuf River and Big Bayou in the alluvial plain generally have less hydraulic connection with the aquifer than the larger rivers (Ackerman, 1990).

The river package in the model allows simulation of a surface-water body separated from the ground-water system by a layer of lower permeability material. River-stage elevation was calculated using the mean annual stage data obtained from USGS stream gages. Stage elevations for river cells were prorated between gaging stations to create a realistic gradient. Stage elevation is constant through the model simulation time for all river cells. The river package is used only to simulate actual surface-water bodies.

Ten rivers and one lake are simulated in the model to be hydraulically connected with the alluvial aquifer (fig. 7). The rivers and the lake and the number of river cells, and riverbed conductances used during the simulations are listed in table 1.

Table 1. Surface-water bodies simulated in the model and corresponding river codes and riverbed conductances

Surface-water body	Number of cells	River code	Riverbed conductance (feet squared per day)	Parameter names
Arkansas River	76	3	2.51×10^6	ark_miss
Bayou Bartholomew	139	2	1.51×10^6	bart_saline
Big Bayou	26	5	5.0×10^3	boeuf_big
Boeuf River	25	5	5.0×10^3	boeuf_big
Lake Chicot	31	4	2.03×10^6	lk_chicot
Crooked Bayou	14	5	5.0×10^3	boeuf_big
Bayou Macon	30	5	5.0×10^3	boeuf_big
Mississippi River	93	3	2.51×10^6	ark_miss
Ouachita River	18	1	1.32×10^6	ouachita
Saline River	15	2	1.51×10^6	bart_saline
White River	3	3	2.51×10^6	ark_miss

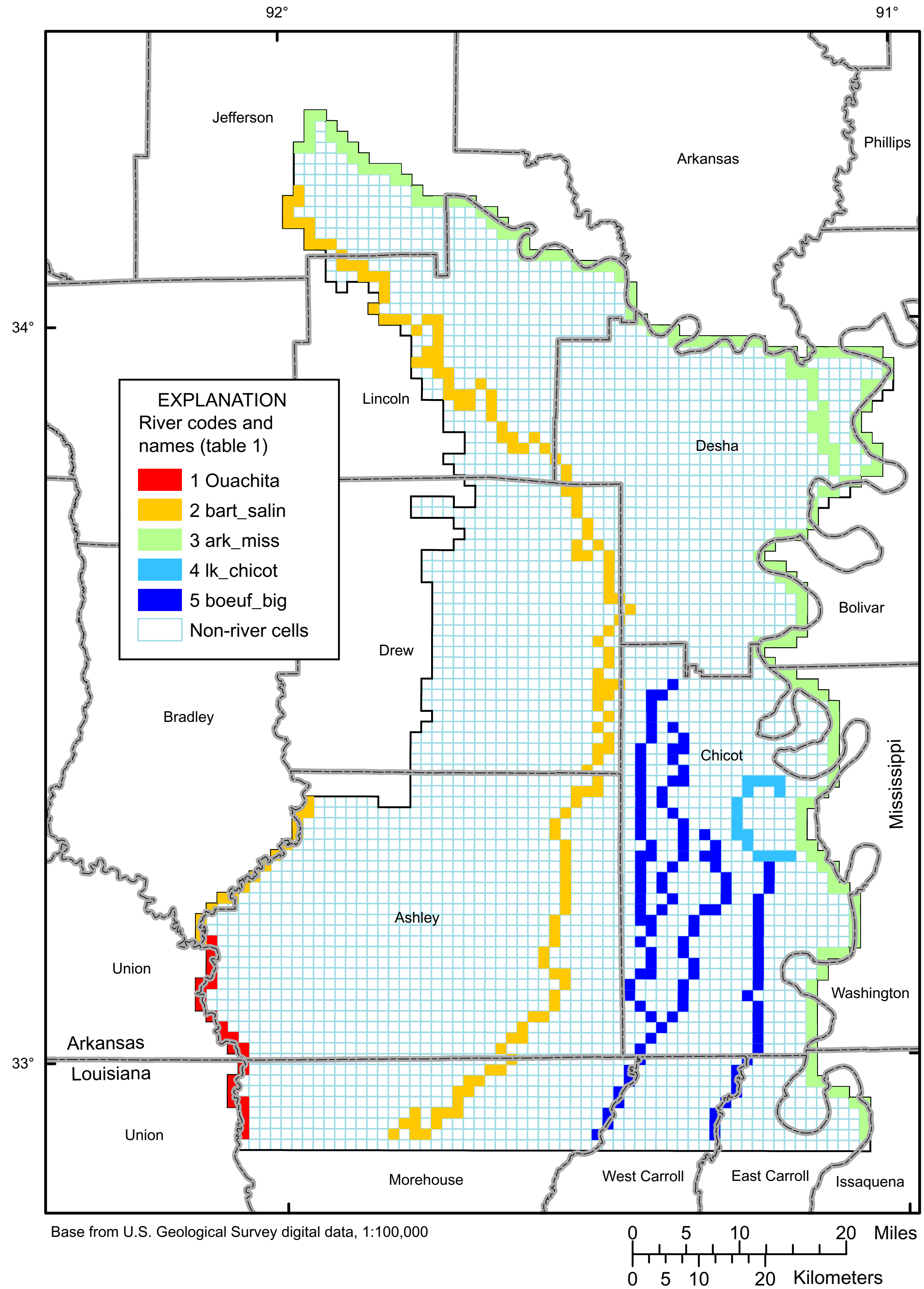

Figure 7. River cell groupings based on riverbed conductance and geometry.

Riverbed conductance was calculated assuming conditions of stage and dimensions of the river channels in the model and estimates of thickness and hydraulic conductivity of the riverbed using the equation:

$$C = KLW/\ M \qquad (1)$$

where C is riverbed conductance, in feet squared per day;

K is hydraulic conductivity of the riverbed material, in feet per day;

L is length of the reach, in feet;.

W is width of the river, in feet; and

M is thickness of the riverbed, in feet.

Rivers (or segments of rivers) were assigned one of five riverbed conductance values. These values ranged from 5.0×10^3 feet squared per day to 2.51×10^6 feet squared per day (fig. 7 and table 1). A portion of the Ouachita River is represented by river code 1. Bayou Bartholomew and a portion of the Saline River are represented by river code 2. The Arkansas, Mississippi and White Rivers are represented by river code 3, Lake Chicot is represented by river code 4, and the Boeuf River, Crooked Bayou, Bayou Macon and Big Bayou are represented by river code 5 (fig. 7 and table 1).

Recharge

The overlying confining unit limits recharge entering the alluvial aquifer from the surface. Previous models have estimated areal recharge to be 0.4 to 2.0 inches in eastern Arkansas. However, these values have not been corroborated by field studies. The alluvial aquifer is reported as obtaining most of its recharge from surface-water bodies (Ackerman, 19891; Mahon and Poynter, 1993).

Areal recharge zones for the model were based on five zones of surficial geology (Haley, 1993) and soil type (Schwarz and Alexander, 1995) (fig. 8). Variations in soil type and soil permeability have the potential to affect recharge to the underlying alluvial aquifer, thus parameter zones based on soil type and geology were used to vary the estimates of recharge within reasonable limits.

Discretization

Spatial Discretization

The model is spatially discretized by dividing the model area into a grid of 1 square- mile cells (fig. 5). The grid is identical to the grid used in the south model (Mahon and Poynter, 1993). The total model grid is 102 cells by 75 cells, with the active area encompassing 3,819 cells.

Temporal Discretization

The model was initially discretized into 10 stress periods each with 10 time steps, which reflect the seven stress periods of the south model (Mahon and Poynter, 1993), and 3 additional stress periods that bring the model forward in time to 1998 (fig. 9). One 11-year stress period and four 10-year stress periods were later added for predictive scenarios (years 1998 through 2049) to create a total of 15 stress periods for the scenario model.

Pumping Stress - Water Use

Pumpage in eastern Arkansas varies annually, but generally has increased since the early 1900's. The pumping stress for the model is distributed areally and temporally to simulate reported water use. The source of the pumping stress distribution and amounts for stress periods 1-7 (1918-1988) is the south model (Mahon and Poynter, 1993). The source of the pumping stress distribution and amounts for stress periods 8-10 (1989-1998) is the site-specific water-use information in the USGS and ASWCC Water-Use Database (T.W. Holland, U.S. Geological Survey, written commun., 2000). The database contains site-specific water-use rates as reported by farmers, municipalities, and industrial users.

Stress Periods 1-7 (1918-1988)

Simulated pumpage for stress periods 1-7 (1918-1988) was transferred from the south model (Mahon and Poynter, 1993). Computation of pumpage distributions was based on estimates of ground-water use for six, 5-year time periods beginning in 1960 (Stephens and Halberg, 1961; Halberg and Stephens, 1966; Halberg, 1972 and 1977; Holland and Ludwig, 1981; Holland, 1987). Pumpage distribution for stress periods 1-7 was determined by Mahon and Poynter (1993) (table 2, fig. 10). Pumpage for the period of time prior to 1960 was estimated based on results of previous models in eastern Arkansas (Mahon and Ludwig, 1990).

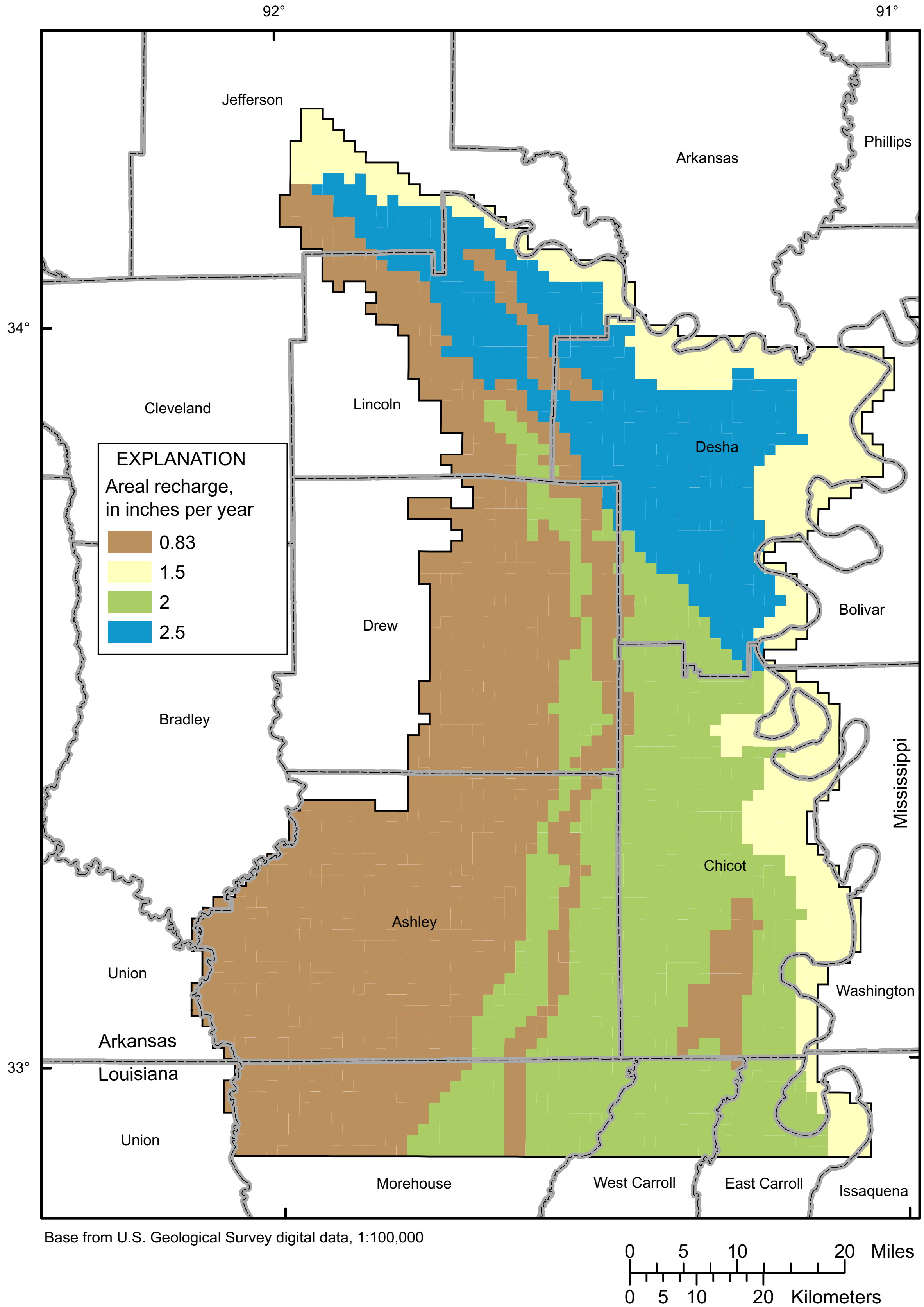

Figure 8. Areal recharge zones in the model.

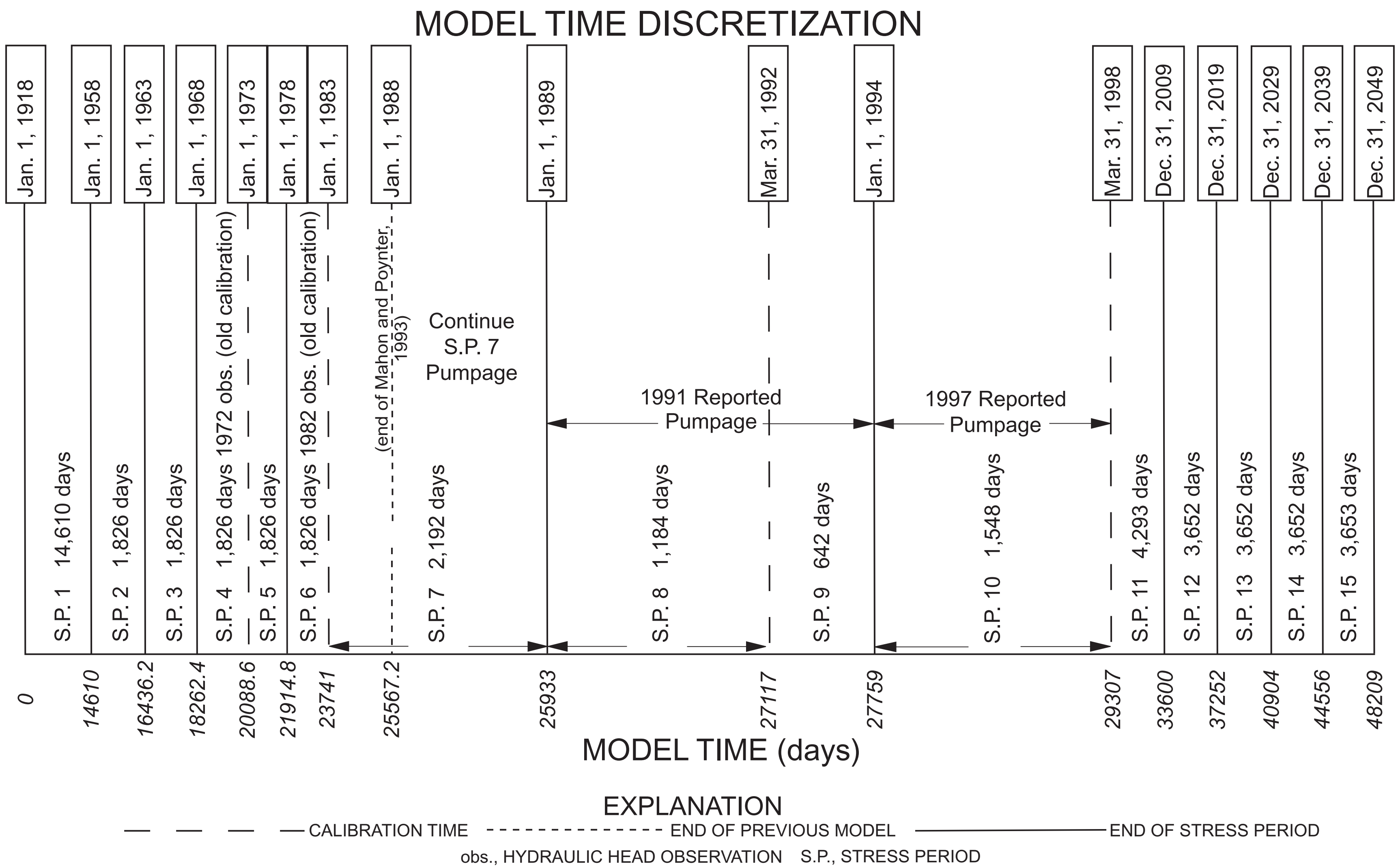

Figure 9. Model time, stress periods, and pumpage descriptions.

Table 2. Total pumpage rates simulated in stress periods 1-10

[Units are in cubic feet per day; negative designates outflow from the model]

State	County or parish	Stress period 1 (1918-1957)	Stress period 2 (1958-1962)	Stress period 3 (1963-1967)	Stress period 4 (1968-1972)	Stress period 5 (1973-1977)	Stress period 6 (1978-1982)	Stress Period 7 (1983-1988)	Stress Period 8 (1989-3/31/1992)	Stress Period 9 (4/1/1992-1993)	Stress period 10 (1994-3/31/1998)
Arkansas	Ashley	-5,880,694	-5,162,436	-2,976,426	-4,480,370	-6,691,450	-13,615,510	-9,713,190	-9,099,961	-9,099,961	-10,183,582
	Chicot	-1,215,002	-1,881,027	-1,744,270	-3,499,854	-6,538,087	-10,043,610	-10,752,910	-16,844,487	-16,844,487	-8,760,839
	Desha	-1,920,746	-2,977,729	-5,436,854	-9,903,450	-13,734,731	-17,770,490	-15,513,720	-19,955,596	-19,955,596	-22,513.748
	Drew	-483,472	-749,614	-1,072,044	-2,697,840	-1,348,066	-5,209,340	-4,856,160	-4,355,999	-4,355,999	-6,124,647
	Jefferson	-649,076	-1,003,899	-1,173,600	-1,466,340	-2,992,290	-3,929,100	-2,672,750	-4,035,457	-4,035,457	-8,780,402
	Lincoln	-1,538,143	-2,345,496	-3,417,860	-8,737,530	-10,653,590	-11,304,540	-10,939,470	-12,794,742	-12,794,742	-14,662,836
Louisiana	East Carroll	-128,251	-198,802	-202,168	-348,323	-350,552	-1,015,569	-881,604	-542,272	-542,272	-784,483
	Morehouse	-1,142,604	-1,771,485	-2,176,285	-2,631,851	-5,565,665	-3,290,439	-2,884,800	-1,430,115	1,430,115	-1,116,703
	West Carroll	-28,543	-44,278	-136,369	-216,108	-309,140	-407,793	-498,508	-277,988	-277,988	-599,101
	Total	-12,986,531	-16,134,766	-18,335,876	-33,981,666	-48,183,571	-66,586,391	-58,713,112	-69,336,617	-69,336,617	-73,526,341

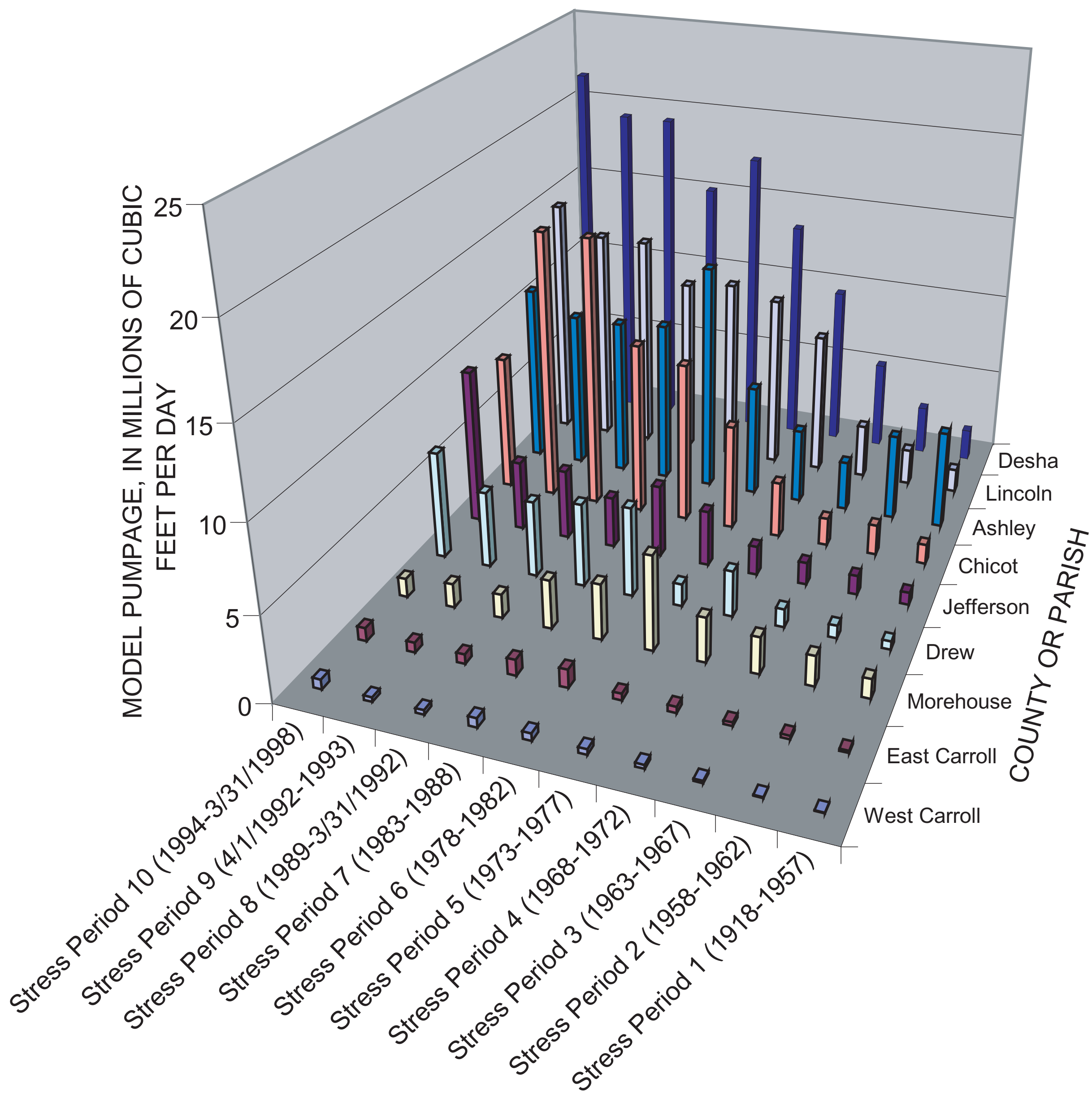

Figure 10. Pumpage by county in stress periods 1-10.

Stress Periods 8-10 (1989-March 31, 1998)

Simulated pumpage distribution for stress periods 8-10 (1989-1998) was derived from the reported pumpage for 1991 and 1997 (table 2 and fig. 10). The water-use data were verified by reported crop-type water-use amounts before being used in the model. Reported pumpage for 1991 was used for stress periods 8 and 9, encompassing 1989 through 1993 and reported pumpage for 1997 was used for stress period 10, encompassing 1994 through March 31, 1998.

Hydraulic Properties

The model was divided into five parameter zones (fig. 11) based on the surficial geology map of Arkansas (Haley, 1993) and the state soil geographic (STATSGO) (Schwarz and Alexander, 1995) database utilizing a similar geologic/soil type zonation developed for recharge into the aquifer. These surficial geologic and soil units were considered to adequately represent the spatial variability of hydraulic properties from which to assign or estimate hydraulic conductivity and other hydrogeologic properties.

Hydraulic Conductivity

Horizontal hydraulic conductivity values for model cells were estimated using the parameter-estimation process of MODFLOW-2000 (Hill and others, 2000; discussed in the Model Calibration section). The south model (Mahon and Poynter, 1993) used a value of 275 feet per day for hydraulic conductivity of the alluvial aquifer in Arkansas. Arthur (2001) used a value of 425 feet per day for hydraulic conductivity in the calibration of a model of the alluvial aquifer east of the Mississippi River in Mississippi. Values of hydraulic conductivity used in the current model range from 250 to 450 feet per day and are discussed in detail in the Model Calibration Procedure section.

Storage

Specific storage and specific yield parameter values for model cells were estimated using the parameter-estimation process of MODFLOW-2000. The parameter zones were based on the same zonation as used with horizontal hydraulic conductivity (fig. 11). The south model (Mahon and Poynter, 1993) used values of 2.50×10^{-4} to 3.76×10^{-3} per foot for specific storage and 0.28 for specific yield. Arthur (2001) used values of 1.60×10^{-3} per foot for specific storage and 0.32 for specific yield in calibration of a model of the alluvial aquifer east of the Mississippi River in Mississippi. These values were used as a guide for a range of plausible values during the calibration process for this model. Values of specific storage used in the current model range from $3x10^{-5}$ to $9x10^{-4}$ and are discussed in detail in the Model Calibration Procedure section.

MODEL CALIBRATION PROCEDURE

Calibration is the process of adjusting the model parameters to produce the best match between simulated and observed hydraulic heads. During calibration, parameters representing aquifer hydraulic properties were adjusted both manually and using automatic parameter-estimation techniques to match observed hydraulic heads. 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 parameter-estimation process represent the hydrologic properties distributed as constant values over large areas and, therefore, are not intended to represent specific values of field tests at individual points within the model area.

Non-Linear Least-Squares Regression Method

Non-linear least-squares regression is more efficient and objective compared to trial-and-error calibration because parameter values are adjusted automatically to obtain the best possible fit between observed and simulated values. The numerical difference between simulated minus observed values is called a residual. In the regression procedure, parameter values are estimated by minimizing the squared weighted residuals thus reducing residuals throughout the model, 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).

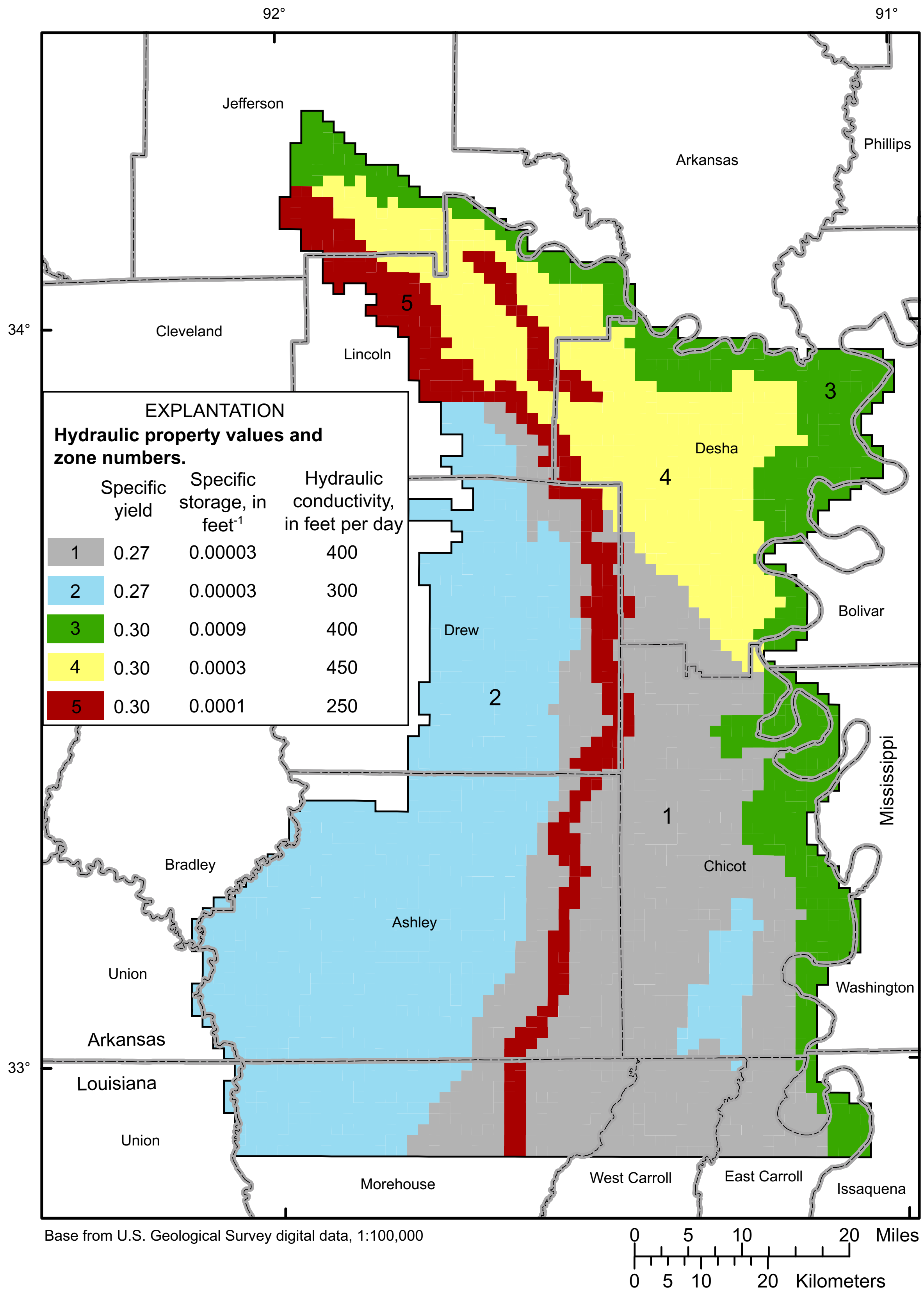

Figure 11. Zones with uniform values of hydraulic conductivity, specific storage, and specific yield.

Calibration Strategy

In the model, grid cells assumed to have similar hydrologic properties are grouped together as a parameter zone and assigned a constant value that is adjusted during the calibration process. The model used 5 hydraulic properties and 5 different zones for a total of 25 parameters. These properties include horizontal hydraulic conductivity (hk), specific storage (ss), specific yield (sy), riverbed conductance, and recharge (rch). Many parameters are represented with the abbreviated name followed by the corresponding zone number. Thus, hydraulic conductivity in zone 1 is represented using hk_1 and so on. Each parameter was considered for estimation by the nonlinear-regression procedure. In the initial calibration process, estimations of various parameters were adjusted toward physically unreasonable values. In these cases, the parameter values were fixed at a reasonable value based on published studies in the area or literature review of similar hydrogeologic units.

Calibration Data Set

The calibration data set consisted of 1972, 1982, 1992, and 1998 hydraulic-head observations (Mahon and Poynter, 1993, Ackerman, 1989b; Edds, 1982; Westerfield and Poynter, 1994; and Joseph, 1999). All published hydraulic-head observations (531) measured during the simulation period were used in the calibration process as head observations, but nine of these observations were omitted during the simulation because they were near the edge of the model boundary. The hydraulic head could not be interpolated between an inactive cell and the center of the active cell where the observation existed. Almost half of these omitted observations occurred in 1972.

Scaled Sensitivities

MODFLOW-2000 calculates sensitivities for values of hydraulic head throughout the model using the sensitivity-equation method (Yeh, 1986). These sensitivities then are used to calculate 1 percent scaled sensitivities. One percent scaled sensitivities are the change in hydraulic head at each observation point that would occur with a 1 percent change in the parameter and are helpful in determining which parameter will invoke the most change in hydraulic head. The 1 percent scaled sensitivities are multiplied by 100, which results in a 100 percent increase, to approximate the change in hydraulic head by doubling the value of a parameter. The least sensitive parameter is Ouachita, likely due to the distance from this parameter to observations. The average hydraulic-head change value for two parameters, hk_2 and boeuf_big, are negative (fig. 12). Negative values indicate the average hydraulic head would decline if the values of hk_2 and boeuf_big were doubled. This decline would be negligible because of the small negative values of average hydraulic-head change. Consequently, this indicates that the model is not as sensitive to changes in hk_2 and boeuf_big as it may be with other parameters. However, a doubling in the value of hk_3, rch_1, rch_2, or rch_4 could result in approximate hydraulic-head changes greater than 1 foot, with the most sensitive parameter rch_4 inducing hydraulic-head changes up to 3.2 feet. These parameters tend to be more sensitive because of their spatial location with respect to large numbers of observations.

CALIBRATION RESULTS AND MODEL EVALUATION

A calibrated model results in reasonable aquifer property values and a reasonable fit to observed field measurements. Values of aquifer properties in the model fall within ranges found in aquifer tests in the alluvial aquifer and similar aquifer materials. Hydraulic conductivity values of 250 to 450 feet per day were simulated and fall within the range of hydraulic conductivities for silty to clean sand (Freeze and Cherry, 1979). The lowest value (250 feet per day) of hydraulic conductivity occurs near Bayou Bartholomew in zone 5 (fig. 11). This may be the result of model reaction to differences in riverbed conductance, or the introduction of silt and clay into the aquifer by leakage from the bayou. Overall values for hydraulic conductivity are within the same order of magnitude and represent average values for large areas in the aquifer. Values for specific yield in the model range from 0.27 to 0.30. Specific storage values range from 3.0×10^{-5} to 9.0×10^{-4} per foot. The riverbed conductances range from 5×10^{3} to 2.51×10^{6}. Areal recharge ranged from 0.83 to 2.5 inches per year with the highest recharge applied to the northern portion of the model area between the Arkansas River and Bayou Bartholomew.

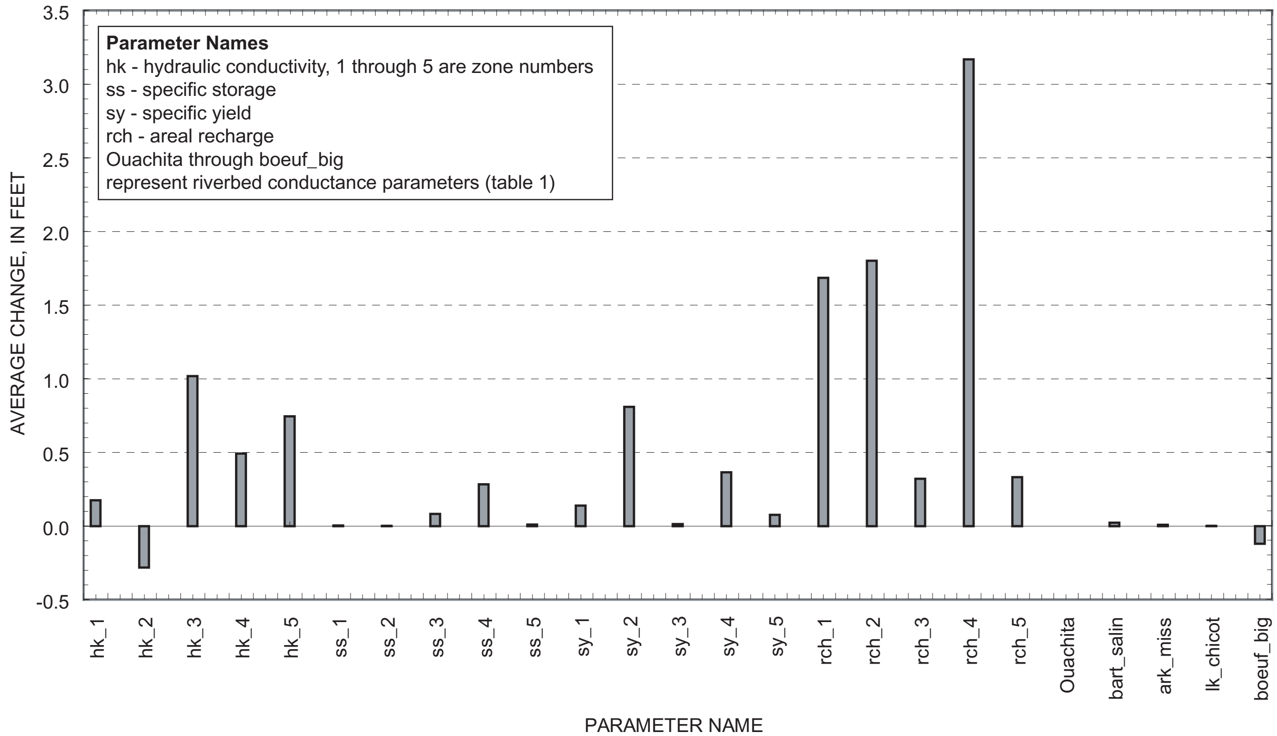

Figure 12. Average change in hydraulic head by doubling a parameter.

Drain elevation and conductance also were adjusted to represent flow southward into Louisiana. The drain elevation was set at an arbitrary altitude of -10 feet and was given a conductance value of 1,900 feet squared per day to allow the “best fit” of simulated heads based on comparison with published potentiometric-surface maps.

Water Budget

Examination of the ground-water model water budget indicates cells where ground-water flow enters or leaves in the active model area. Negative volumes indicate water removed from the model (outflow), and positive volumes indicate water introduced to the model (inflow) (fig. 13). There are three basic inflows to the model: release of water from aquifer storage, areal recharge, and riverbed leakage; and four withdrawals or outflows: aquifer storage, riverbed leakage, drains, and wells. Wells remove the most water with a total volume of 8.94×10^{11} cubic feet by the end of the simulation (table 3). Water removed by pumpage is offset by river leakage and water released from storage into the model.

Table 3. Cumulative volumes of inflow and outflow in the model at the end of stress period 10

[Units are in cubic feet]

	Inflow	Outflow
Storage	1.68×10^{11}	5.48×10^{10}
Wells	0	8.94×10^{11}
Drains	0	2.63×10^{11}
River leakage	4.38×10^{11}	5.17×10^{11}
Recharge	1.12×10^{12}	0
Totals	1.73×10^{12}	1.73×10^{12}

Hydraulic-Head Residuals

Residuals can indicate how well a ground-water flow model represents actual ground-water conditions in the aquifer. Residuals for the MODFLOW-2000 model software are calculated by subtracting the simulated hydraulic head from the observed hydraulic head. Negative residuals, colored in blue on figures 14 and 15, indicate simulated hydraulic heads that are higher than observed. Positive residuals, colored in red

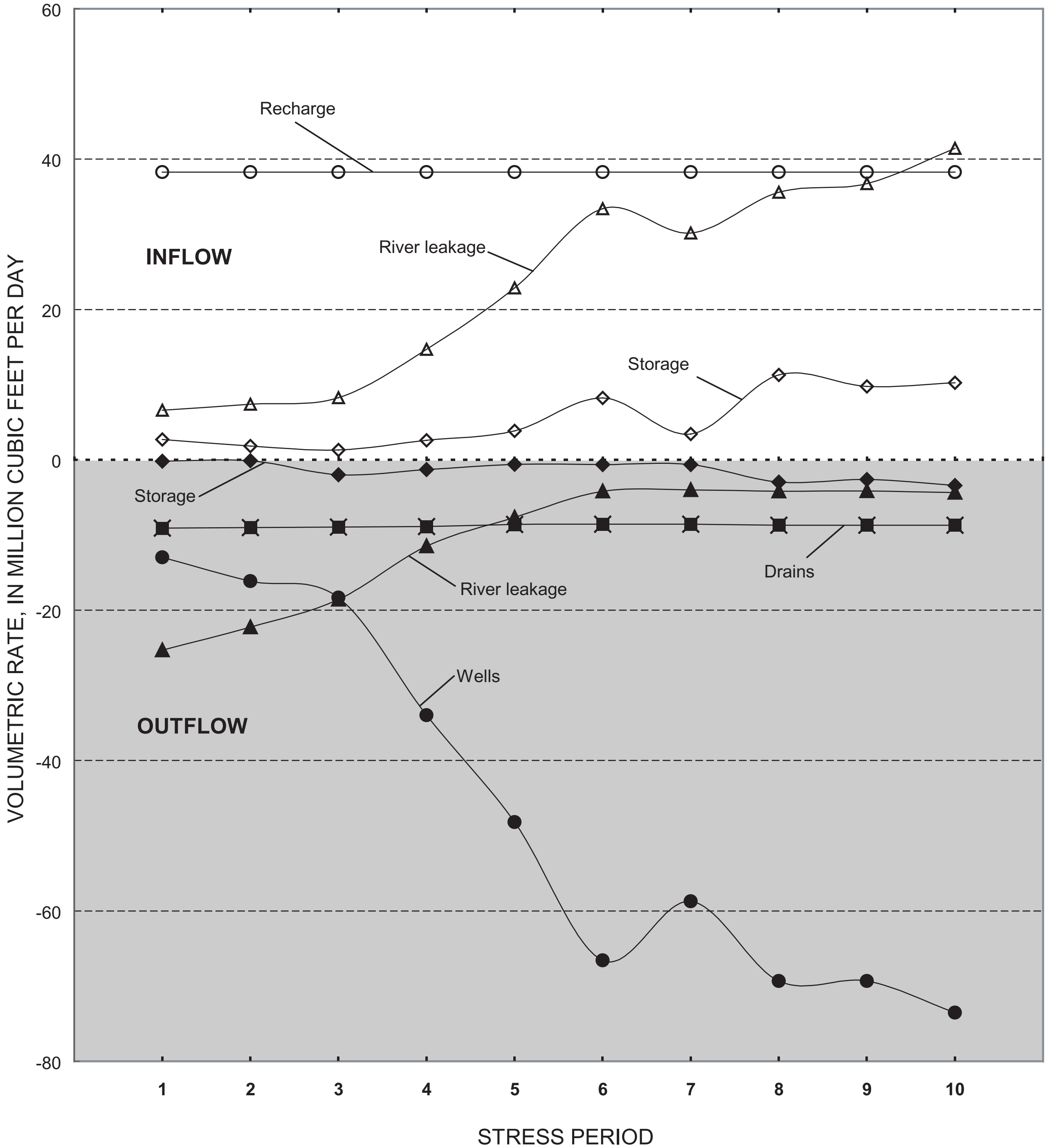

Figure 13. Ground-water model budget by stress period.

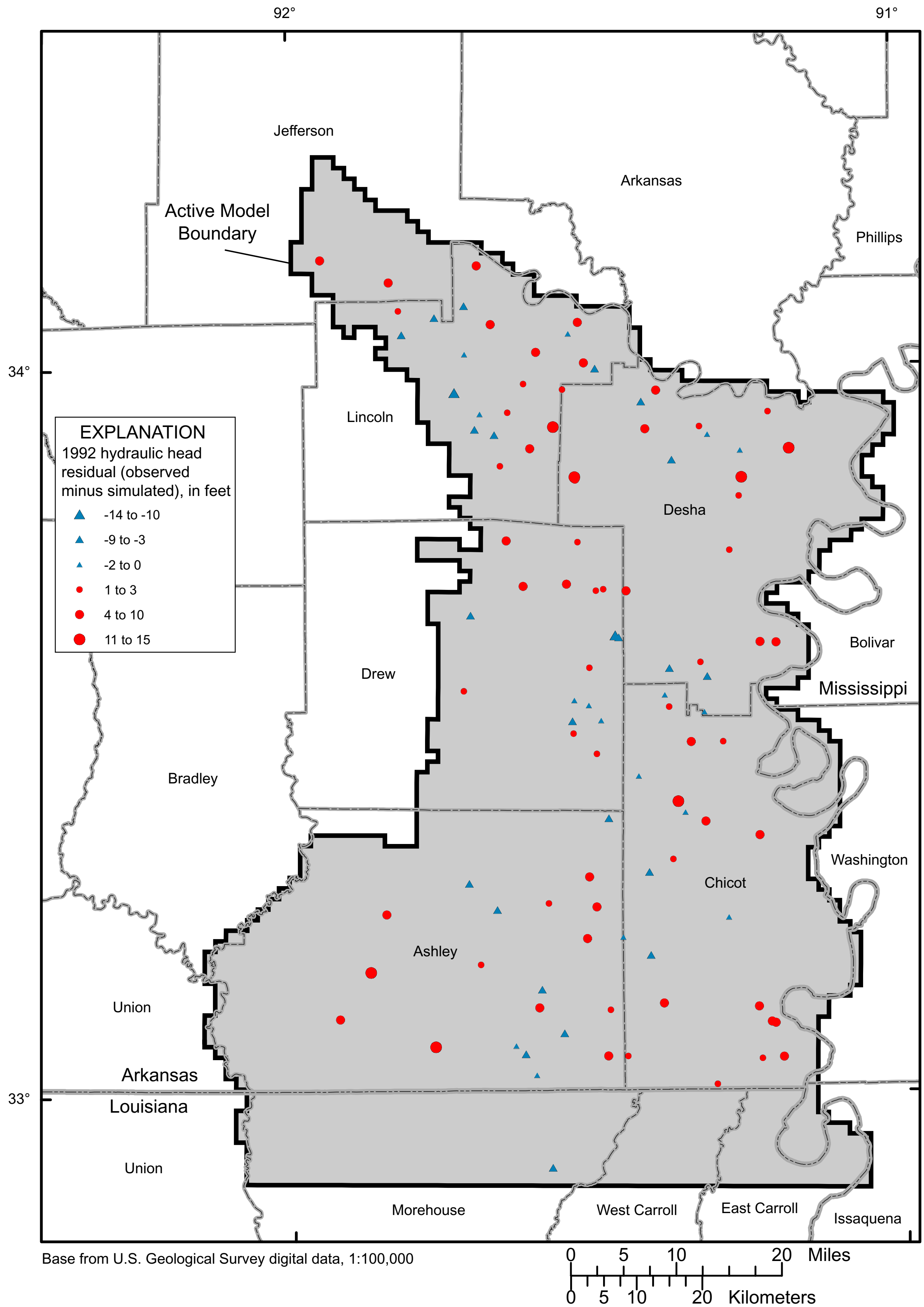

Figure 14. Residuals—difference between simulated hydraulic heads and 1992 observed hydraulic heads.

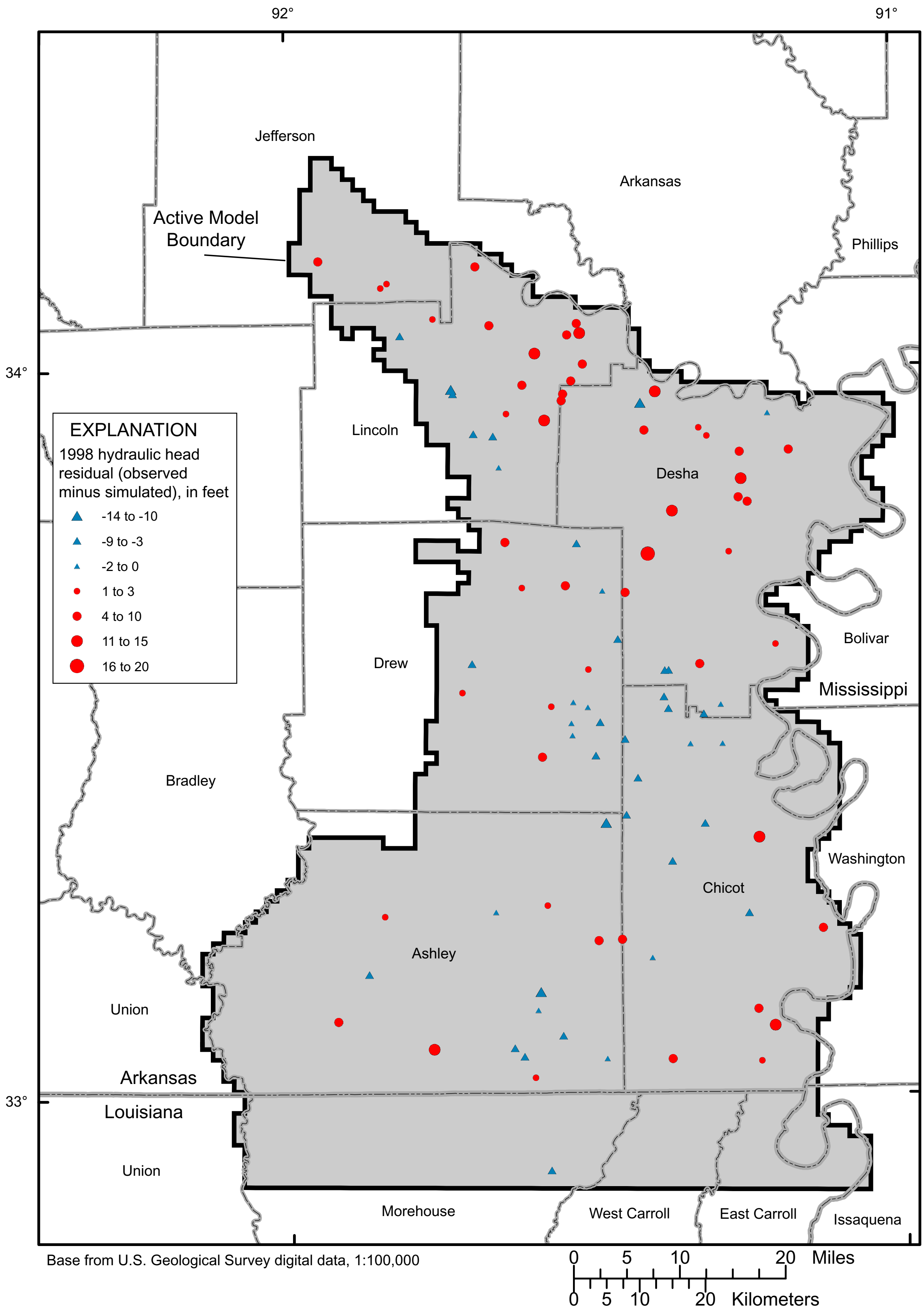

Figure 15. Residuals—difference between simulated hydraulic heads and 1998 observed hydraulic heads.

on figures 14 and 15, indicate simulated hydraulic heads that are lower than observed. Residuals calculated for 1992 and 1998 spring measurements primarily were used to guide model calibration because of better constrained site-specific water-use data collected during this period of time (figs. 14 and 15). The histograms for 1992 and 1998 residuals in the model show a slight positive bias partially resulting from model error in stressed areas of higher withdrawals (fig. 16). However, the overall fit of simulated heads were considered reasonable in the current calibration.

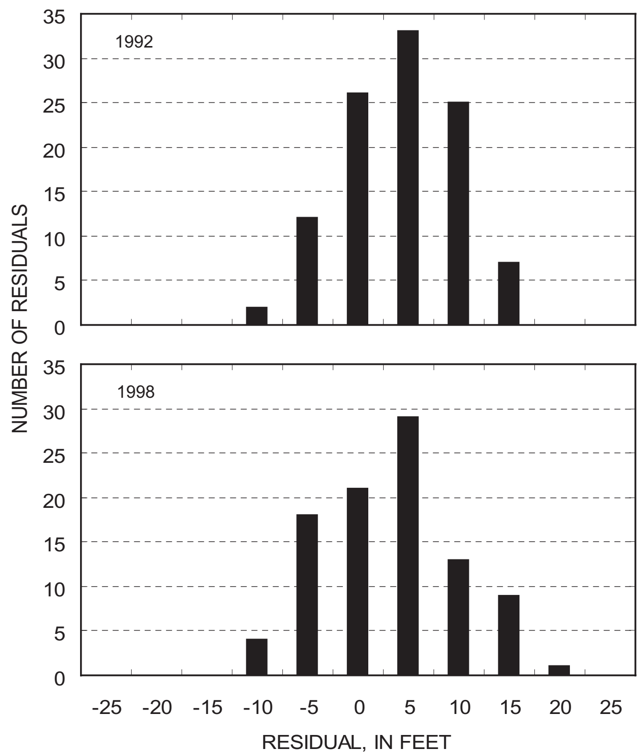

Figure 16. Frequency of residuals (plus or minus 2.5 feet of the value shown) for 1992 and 1998 observations.

Error Analysis

Statistics on hydraulic-head residuals, such as mean, minimum, maximum, root mean squared error (RMSE), and mean of absolute values aid in evaluation of model calibration. The RMSE for the four observation periods ranged from 5.90 to 6.72 indicating relatively good and consistent fit to observed values of hydraulic head (table 4).

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Table 4. Summary of the model residual statistics

Year	Mean	Minimum	Maximum	Root mean squared error	Mean absolute
1972	-2.56	-19.62	21.87	6.69	5.15
1982	-1.02	-12.25	12.74	6.49	5.03
1992	1.61	-12.58	14.89	5.90	4.74
1998	0.66	-13.43	19.98	6.72	5.45
All	-0.98	-19.62	21.87	6.51	5.11

The sign of the mean value can indicate skewed residuals depending on the magnitude of the mean away from zero. A more negative mean value indicates that the model tends to simulate hydraulic heads too high, and a more positive mean indicates a tendency to simulate hydraulic heads too low. The mean residual for the model in 1992 and 1998 is 1.61 and 0.66 feet, respectively. The mean absolute value is calculated as the mean for the absolute value of all residuals for a given year. The residuals for 1992 and 1998 have a mean absolute value of 4.74 and 5.45 feet, respectively, and an RMSE of 5.9 and 6.72 feet, respectively. The most negative residual value in the model is -19.62 feet (north-central Ashley County) and the most positive residual is 21.87 feet (on the Louisiana/Arkansas State line in Ashley County and Morehouse Parish). Both the minimum and maximum residuals occurred in 1972.

Potentiometric Surfaces

Potentiometric-surface maps are used to determine similarities and differences in general hydraulic head and flow direction between simulated and observed potentiometric surfaces. Potentiometric-surface contours for spring 1998 (Joseph, 1999) overlain on simulated hydraulic heads show similar results with ground-water flow southward into Louisiana, westward to the Ouachita River, and flow from the Arkansas River into the aquifer (fig. 17).

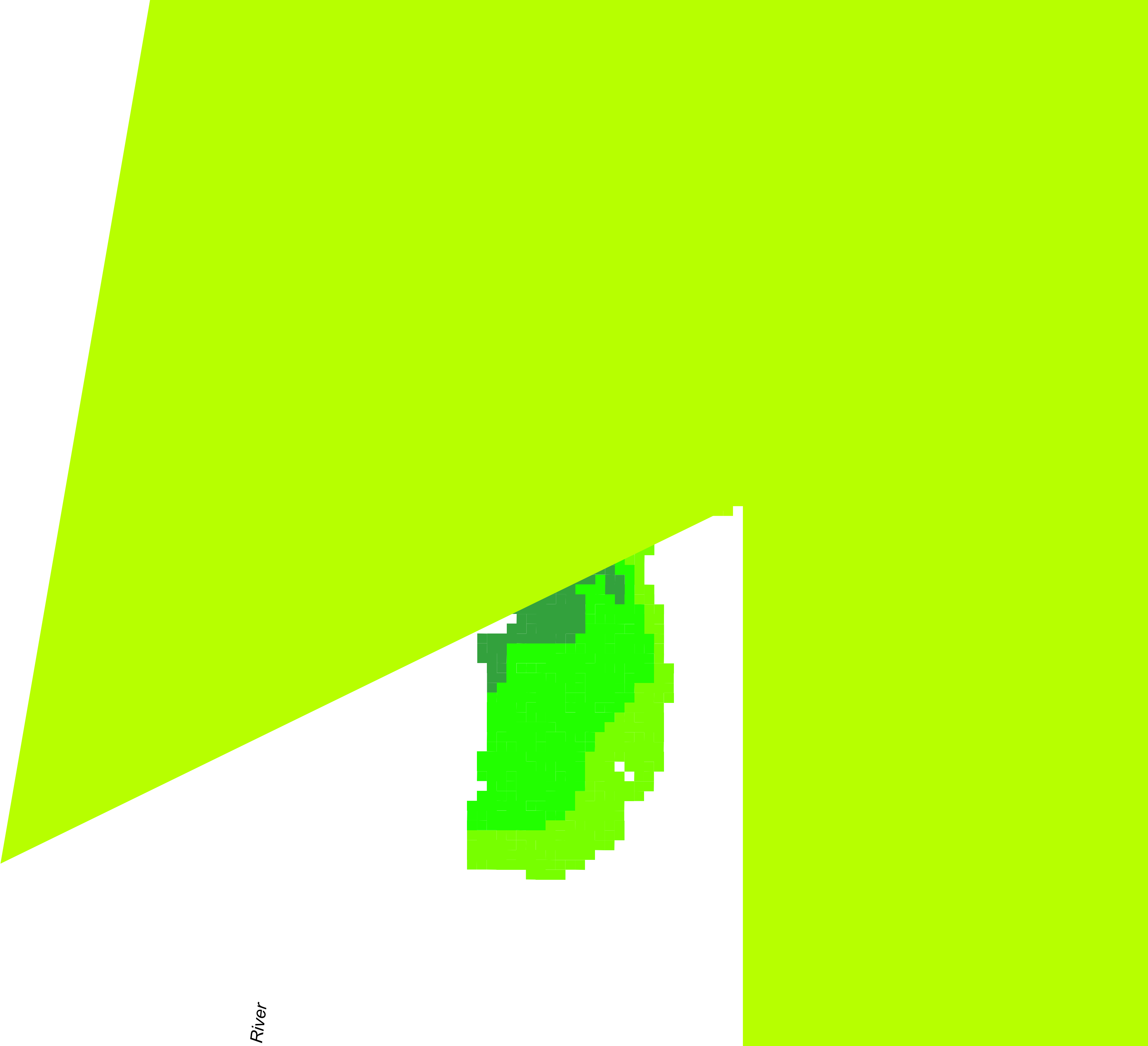

Figure 17. Potentiometric map and simulated hydraulic heads for 1998.

Simulated and Observed Hydrographs

Hydrograph comparison allows for the evaluation of simulated hydraulic heads over time at a given observation point. Sixteen wells with hydraulic-head data for each calibration period, 1972, 1982, 1992, and 1998, were selected. All available hydraulic-head data were used for the 16 wells. Much of these data included an intense collection period in the 1960’s during the construction of the lock and dam system on the Arkansas River. Because the model was calibrated to spring (January to April) observations, only measurements from January to April were used in the hydrographs to allow for consistency with other observation data and to ensure having a static hydraulic head. These data then were used to calculate residuals for each observation. Hydrographs were constructed to compare the simulated hydraulic head to the observed hydraulic head. Eight hydrographs from various sites in the model area are shown to illustrate the differences and similarities in the simulated and observed hydraulic head (fig. 18). Most simulated hydrographs coincide with the general trend of observed data. Intense data collection during the lock and dam construction on the Arkansas River from the late 1950s to the early 1990s can be seen in wells F and G. The effects of lock and dam construction were not explicitly simulated. Erratic changes in the hydrographs, such as those for well A, during 1988 and 1990 are not simulated. These spikes in the hydrograph may be because of short-term, localized recharge events or conditions that cannot be simulated with the available data.

SIMULATIONS OF PROJECTED GROUND-WATER WITHDRAWALS

To evaluate the effects on hydraulic heads caused by projected ground-water withdrawals, three scenarios were used to simulate a range of possible pumping demands. Five additional stress periods of 10 years each were added to the model to simulate conditions to 2049. Pumpage used in the predictive scenarios were either 1997 pumpage continued into the future (scenario 1) or increased pumpage based on water-use trends into the future (scenario 2) or increased pumpage with reductions in a selected area (scenario 3). The ASWCC Critical Ground Water area designation includes a requirement that a 50-percent saturated formation thickness be maintained. For this reason, the hydraulic head that would result in 50-percent of the thickness of the formation being saturated is used as a reference hydraulic head evaluating the simulated hydraulic heads. The model results from the scenarios are presented in maps of simulated hydraulic heads for 2049, and maps showing simulated hydraulic heads minus 50 percent saturated formation thickness for each stress period (ending in 2009, 2019, 2029, 2039, and 2049). Where less than 50 percent saturated formation thickness occurs, the total saturated thickness is shown. Animations showing simulated hydraulic heads changing through time are included on the enclosed compact disk. In the animations, the hydraulic head of 50 percent saturated formation thickness is indicated by a mesh surface and the dry cells appear as voids in the model surface. Pumpage rates for the predictive scenarios are shown in table 5 and figure 19. The decrease in pumpage is caused by dry cells that develop from 2019 to 2049 (stress periods 12, 13, 14, and 15), thereby eliminating pumping in those cells. Figure 20 shows the amount of model area that is simulated as being dry, less than 30 feet of the total saturated thickness, and less than 50 percent saturated of the formation thickness. The 30 feet of saturated thickness was used as a minimum thickness needed to pump a sufficient amount of water for uses such as irrigation.

Table 5. Total pumpage rates simulated in predictive scenario model runs, stress periods 11-15

[Units are in cubic feet per day]

Stress period	Dates simulated	Scenario 1	Scenario 2	Scenario 3
11	3/31/1998-2009	73,526,344	100,669,800	91,747,944
12	2010-2019	73,526,344	117,609,744	108,789,104
13	2020-2029	73,526,344	115,227,304	108,408,192
14	2030-2039	73,526,344	111,180,616	105,171,352
15	2040-2049	73,526,344	109,454,576	103,327,144

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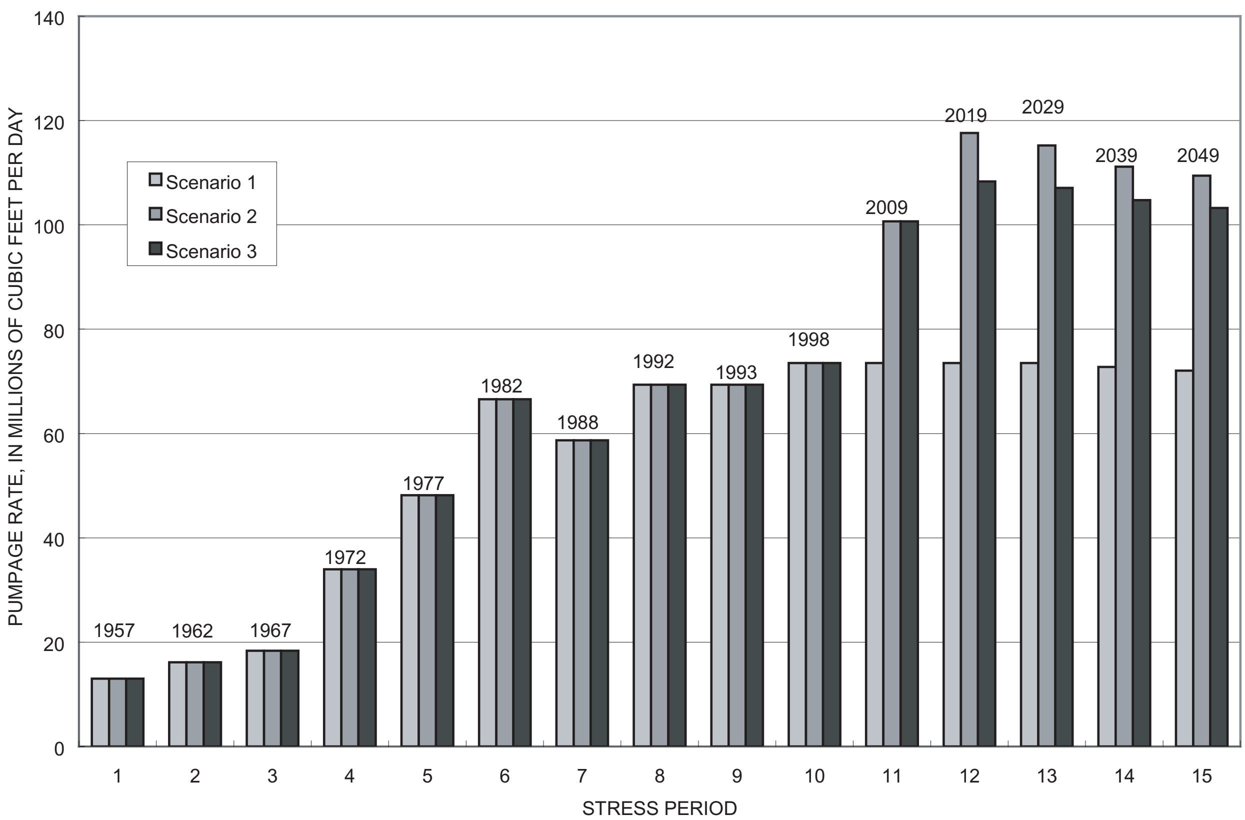

Figure 19. Rates of pumpage for the three scenarios by stress period.

Scenario 1

In the first scenario, 1997 pumpage was extended unchanged through 2049. No cells in the model became dry in this scenario (fig. 20), however, many cells (square miles) have simulated hydraulic heads below 30 feet and 50 percent of the saturated formation thickness. Simulated hydraulic heads drop below 30 feet of saturated thickness over an area 7 square miles in 2009 to 53 square miles in 2049. The model area with simulated hydraulic heads below 50 percent of the saturated formation thickness range from 12 square miles in 2009 to 81 square miles in 2049.

In 2009, a few areas where simulated hydraulic heads that are below the level of 50 percent saturated formation thickness occur in Ashley and Desha Counties (fig. 21). The two southernmost areas in Ashley County approaching and falling below 50 percent saturated formation thickness that appear at the 2009 timeframe are in areas where the aquifer is thinnest. The simulated hydraulic heads in these two areas in Ashley County are below 50 percent saturated formation thickness over the entire model simulation period. Other areas in Ashley County that approach less than 10 feet above or fall below 50 percent saturated formation thickness are related to high-density pumping. The area centered in Desha County that ranges between 0 and 20 feet above 50 percent saturated formation thickness and falls below 50 percent saturated formation thickness in two model cells is a pumpage-induced depression in simulated hydraulic heads. The two cells that fall below 50 percent saturated formation thickness indicate a simulated total saturated formation thickness of 30 to 40 feet. This pumpage-induced depression extends northwest from the center of Desha County and northeast into Lincoln County. The 2019 simulated hydraulic heads (fig. 21) indicate enlargement and deepening of the depressions seen in the 2009 simulated hydraulic heads.

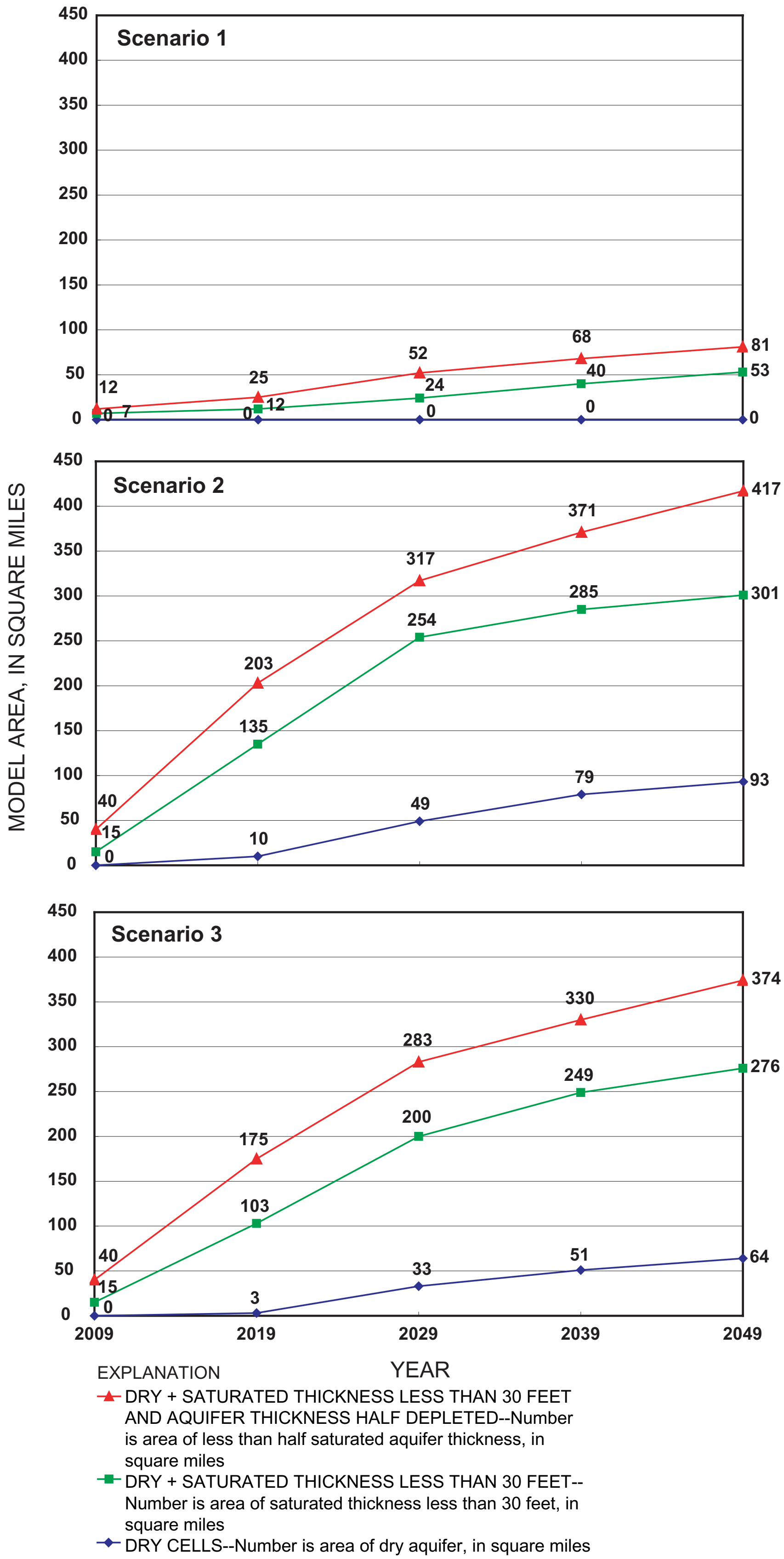

Figure 20. Comparison of model area where the simulated hydraulic heads fall below predefined levels for each scenario.

Click here to open figure 21.

Two areas of less than 50 percent saturated thickness in northwestern Desha County and north-central Ashley County not seen in the 2009 and 2019 timeframe appear in 2029, 2039, and 2049. The area of depressed simulated hydraulic heads centered in Desha County shows extensive aquifer dewatering with areas of simulated hydraulic heads continuing to drop below 50 percent saturated formation thickness reducing the total saturated formation thickness to less than 10 feet. Simulated hydraulic heads for 2049 shown in figure 22 indicate the hydraulic-head altitudes range from 200 feet above NGVD of 1929 in central Jefferson County to less than 70 feet above NGVD of 1929 in the center of the Desha County cone of depression.

Scenario 2

In scenario 2, pumpage was increased according to current water-use trends to simulate likely demands in the future. A regression was developed to determine a trend in the rate of increase for each county using water-use data from 1988 through 2000 (Holland, 1993; Holland, 1999; T.W. Holland, U.S. Geological Survey, written commun., 2002). The water-use trend was applied to the 1997 pumpage to increase pumpage for successive stress periods to a maximum value of 1.25 times the estimated 2000 pumpage for each county. Scenario 2 limits pumpage to 1.25 times the estimated 2000 pumpage rates because most of the land in the model area suitable for growing crops is already in agricultural production and little increase in agricultural acreage or changes in farm practices is anticipated. Rates of model pumpage for scenario 2 decrease after 2019 (stress period 12) (fig. 19). The decrease in pumpage is caused by dry cells that develop from 2019 to 2049 (stress periods 12, 13, 14, and 15), thereby eliminating pumping in those cells (fig. 20).

The results of scenario 2 show a number of cells that fall below the fixed criteria of 30 feet saturated thickness and 50 percent saturated formation thickness. The model area that becomes dry during the simulation of scenario 2 ranges from 0 square miles in 2009 to 93 square miles in Desha, Lincoln, and Ashley Counties. However, there are many cells (square miles) that have simulated hydraulic heads that fall below 30 feet saturated thickness and 50 percent of the saturated formation thickness (figs. 20 and 23). The model area that simulated hydraulic heads drop below 30 feet of saturated thickness ranges from 15 square miles in 2009 to 301 square miles in 2049. Simulated hydraulic heads drop below 50 percent saturated formation thickness over an area of 40 square miles in 2009 to 417 square miles in 2049. Figure 23 shows areas of simulated hydraulic heads that are below 50 percent saturated formation thickness in 2009 in Ashley and Desha Counties. A similar pattern of pumpage-induced areas below 50 percent saturated formation thickness simulated by scenario 1 in year 2039 (fig. 21) appears in 2009 scenario 2 (fig. 23). An additional area of less than 50 percent saturated formation thickness appears in Lincoln County in the 2009 simulated hydraulic head. The simulated total saturated thickness where the aquifer is less than or equal to half saturated in 2009 varies from 40 to 60 feet in western Ashley County and northeastern Lincoln County to 10 to 20 feet in eastern Ashley County.

The simulated hydraulic heads (fig. 23) for scenario 2 indicate enlargement and deepening of the area of depressed simulated hydraulic heads and the presence of dry cells in Desha County in 2019. A total of 10 dry cells appears in the 2019 timeframe all in Desha County. The pumpage-induced area of depressed simulated hydraulic heads elongates further to the southeast and to the northwest into Lincoln County from 2019 through 2049. An area in southern Desha County that was previously greater than 50 percent saturated formation thickness drops below the 50 percent saturated formation thickness level to a total thickness of 11 to 30 feet in 2019.

During the period of 2029 to 2049, areas of depressed simulated hydraulic heads are further deepened and enlarged and the number of dry cells increased in Desha, Lincoln, and Ashley Counties (fig. 23). The area of depressed simulated hydraulic heads centered in Desha County deepens and 77 model cells go dry by 2049 compared to scenario 1 where no dry cells are simulated by 2049. Smaller areas of depressed simulated hydraulic heads that appear in Ashley and Chicot Counties also show increased deepening. Simulated hydraulic heads for scenario 2 ranged from 200 feet above NGVD of 1929 in central Jefferson County to below 50 feet above NGVD of 1929 with dry cells appearing in Ashley, Desha, and Lincoln Counties (fig. 24).

Scenario 3

For the third scenario, the pumpage was reduced by 10 percent from that of scenario 2 in a selected area (fig. 25) that represents a proposed replacement of ground water by surface-water diversion in that area

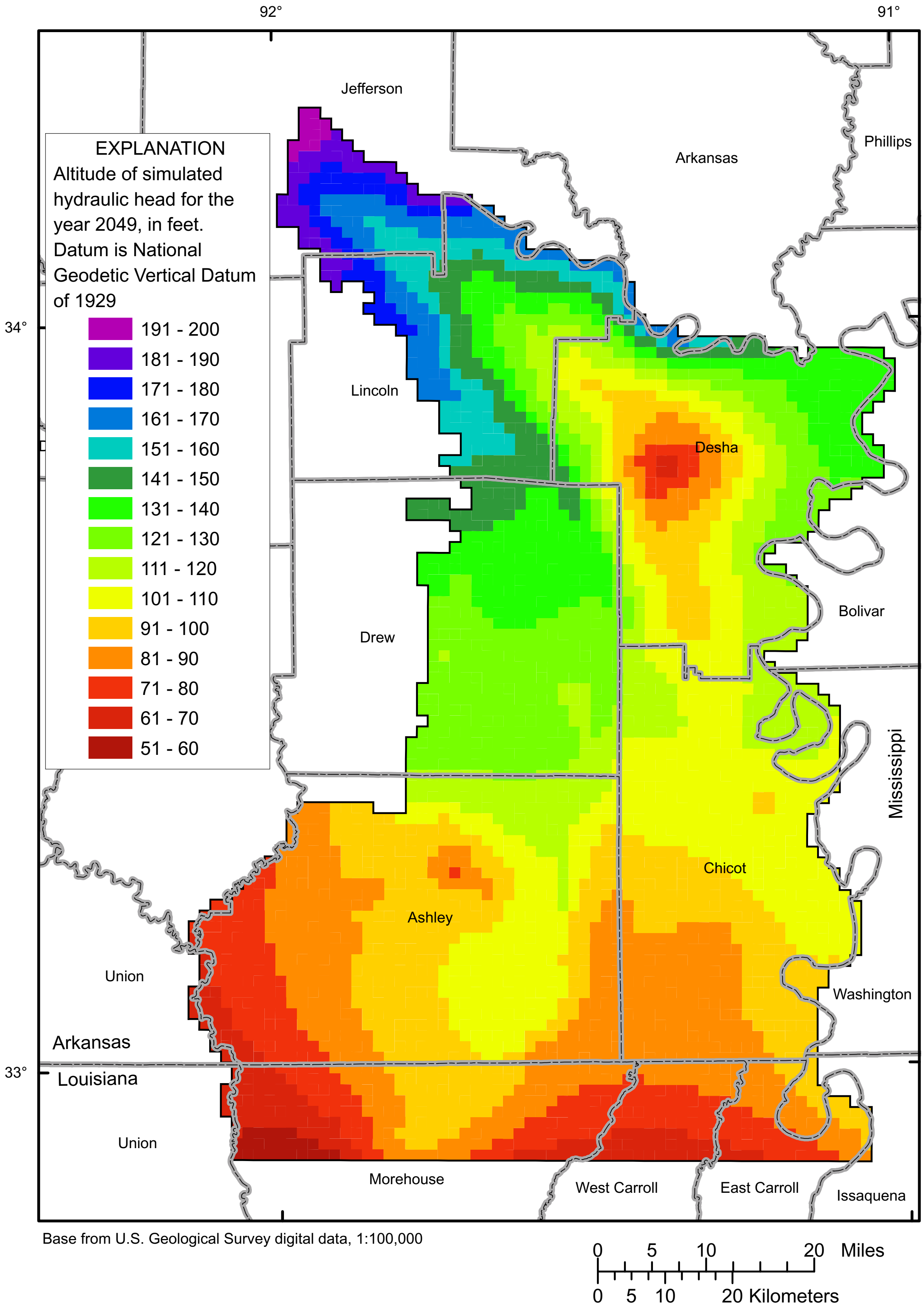

Figure 22. Simulated hydraulic heads for the year 2049, scenario 1.

Click here to open figure 23.

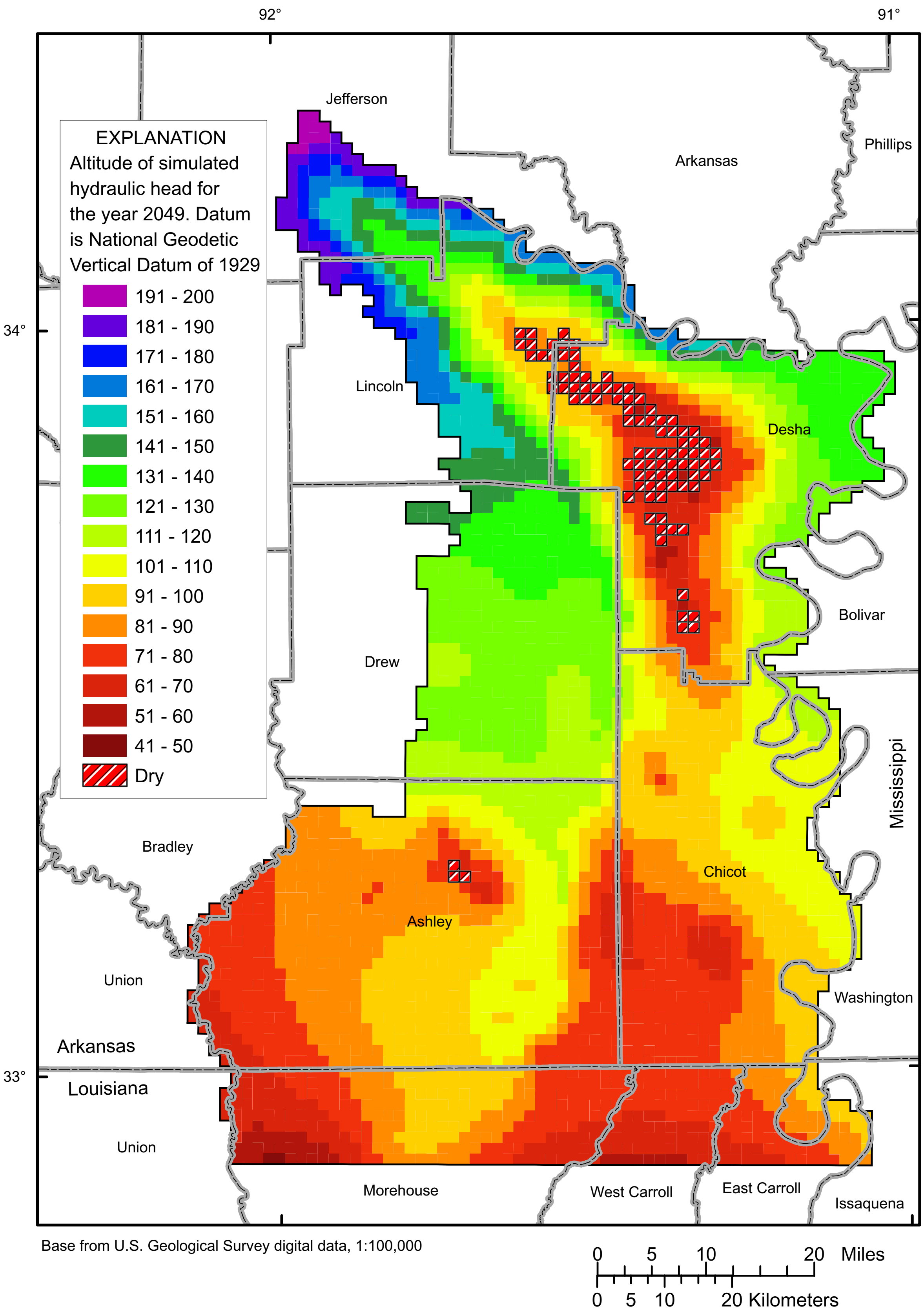

Figure 24. Simulated hydraulic heads for the year 2049, scenario 2.

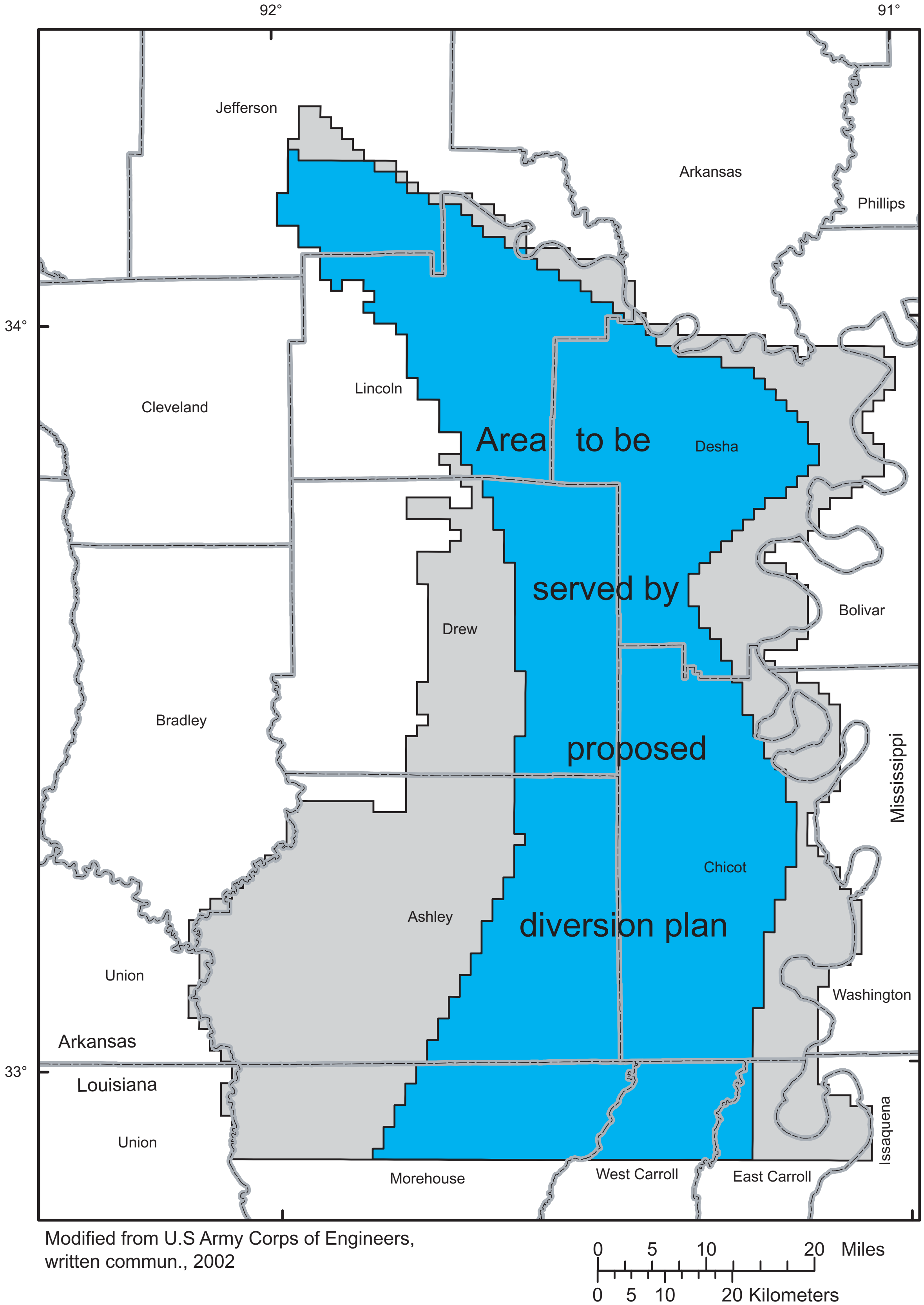

Figure 25. Model area and area to be served by proposed diversion plan.

(U.S. Army Corps of Engineers, written commun., 2002). The 10 percent reduction was applied only to the stress periods ending in years 2019, 2029, 2039, and 2049.

The result of scenario 3 shows a number of cells that fall below the fixed criteria of 30 feet saturated thickness, 50 percent of the saturated formation thickness, or become dry. Dry cells covered an area of 3 square miles in 2019 in Desha County to 64 square miles in 2049 (fig. 20). Simulated hydraulic heads drop below 30 feet of saturated thickness over an area of 15 square miles in 2009 to 276 square miles in 2049 and below 50 percent saturated formation thickness over an area of 40 square miles in 2009 to 374 square miles in 2049.

Reducing pumpage by 10 percent (scenario 3) resulted in areas of depressed simulated hydraulic heads similar to those simulated in scenario 2 with fewer dry cells (figs. 20 and 23). By 2019, scenario 3 simulated 3 dry cells compared with scenario 2, which simulated 10 dry cells (fig. 23). In the remaining three stress periods (2029, 2039, and 2049), scenario 3 had about two-thirds the number of dry cells simulated in scenario 2 (fig. 20). The 10 percent reduction appears to have delayed the development of dry cells by about 10 years as exhibited by the similarities of hydraulic heads and dry cells by 2029 for scenario 2 (fig. 23) and by 2039 for scenario 3 (fig. 26). Overall, the areas of depressed simulated hydraulic heads are somewhat reduced in scenario 3 by the proposed ground-water replacement from surface water. Simulated hydraulic heads for scenario 3 show the hydraulic-head altitudes in 2049 range from 200 feet above NGVD of 1929 in central Jefferson County to below 50 feet above NGVD of 1929 with dry cells appearing in Ashley, Desha, and Lincoln Counties (fig. 27).

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 model area into a rectangular grid of square cells and vertical discretization of the alluvial 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 surface-water features. 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 pumpage 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 report.

Click here to open figure 26.

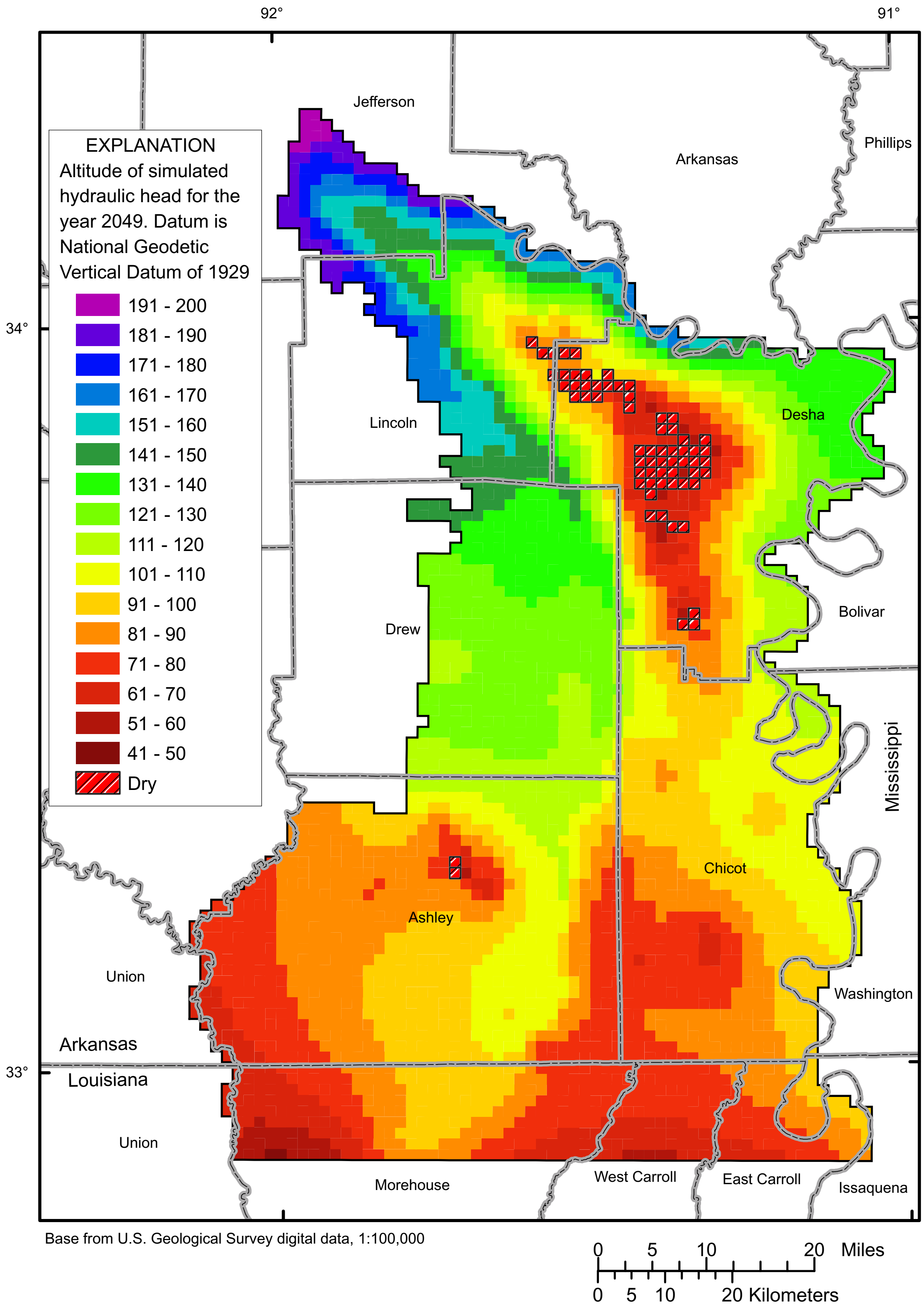

Figure 27. Simulated hydraulic heads for the year 2049, scenario 3.

SUMMARY

The Mississippi River Valley alluvial aquifer, encompassing parts of Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee supplies an average of 5 billion gallons of water per day. The aquifer is a valuable resource for agriculture, aquaculture, business, and community growth in eastern Arkansas by providing abundant water of high quality. However, withdrawals from the aquifer in recent years have caused considerable drawdown in the potentiometric surface. The effects of current ground-water withdrawals and potential future withdrawals on water availability are major concerns of water managers and users as well as the general public. A full understanding of the behavior of the aquifer under various water-use scenarios is critical to development of viable water-management and alternative source plans. To address these concerns, the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, Vicksburg District, developed and calibrated a ground-water flow model, which has been used to simulate hydraulic heads caused by projected ground-water withdrawals.

The previously published ground-water flow model of the alluvial aquifer, the “south model” by Mahon and Poynter (1993), was updated and recalibrated to reflect present pumping stresses. The south model utilized the MODFLOW finite-difference numerical-modeling software in a transient state, and simulated time from 1918 to 1988 in seven stress periods. Updated water-use information was input to the model and additional stress periods were added to bring the model forward to 1998. The new model was developed and calibrated with MODFLOW-2000 finite-difference numerical-modeling and parameter-estimation software. The south model was calibrated to spring 1972 and spring 1982 observations. The new model was calibrated to two additional observation times measured in the spring (January to April) of 1992 and 1998, in addition to the previous calibration times. The residuals for 1992 and 1998 have a mean absolute value of 4.74 and 5.45 feet, respectively, and a RMSE of 5.9 and 6.72 feet, respectively.

The effects of projected ground-water withdrawals were simulated through 2049 in three predictive scenarios. Five additional stress periods of 10 years were added to the model to facilitate predictive scenario generation. Pumpage for the three predictive scenarios was either 1997 pumpage continued into the future (scenario 1) or increased pumpage based on water-use trends into the future (scenario 2) or increased pumpage with reductions in a selected area (scenario 3). Scenario 1 resulted in an area of depressed simulated hydraulic heads centered in Desha County with simulated hydraulic heads in two cells dropping below 50 percent saturated thickness between 1998 and 2009. Simulated hydraulic heads for 2029, 2039 and 2049 indicate enlargement and deepening of the areas of depressed hydraulic heads with areas of simulated hydraulic heads continuing to drop below 50 percent saturated formation thickness, reducing the total saturated formation thickness to less than 10 feet. No dry cells were simulated in scenario 1. Scenario 2 simulated hydraulic heads over an area of 40 square miles below 50 percent saturated thickness by 2009 and 10 square miles going dry between 2009 and 2019 in Desha County and smaller areas of depressed hydraulic heads appearing in Ashley and Chicot Counties. In scenario 2, there were 93 dry cells (92 square miles) simulated by 2049 in Desha, Lincoln, and Ashley Counties. In scenario 3, the model area that simulated hydraulic heads below 50 percent saturated formation thickness ranged from 40 square miles in 2009 to 374 square miles by 2049. Dry cells first occur between 2009 and 2019 covering an area of 3 square miles in 2019 in Desha County to 64 square miles in 2049. Overall, the depth and extent of the areas of depressed hydraulic heads are reduced and the area is only about two-thirds of that simulated in scenario 2.

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