Prepared in cooperation with the

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Arkansas Soil and Water Conservation Commission

CONJUNCTIVE-USE OPTIMIZATION MODEL OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER OF SOUTHEASTERN ARKANSAS

Water-Resources Investigations Report 03-4233

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

Cover*:* Irrigation of cotton and rice fields in southeastern Arkansas represent two of the major uses of ground water from the Mississippi River Valley alluvial aquifer. Photographs by John B. Czarnecki, U.S. Geological Survey

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Little Rock, Arkansas
2003

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
million cubic feet per day (Mft^3/d)	7.481	million gallons per day (Mgal/d)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	7.481	gallon (gal)
cubic foot per day (ft^3/d)	0.0283	cubic meter per day (m^3/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.

Conjunctive-Use Optimization Model of the Mississippi River Valley Alluvial Aquifer of Southeastern Arkansas

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ABSTRACT

The Mississippi River Valley alluvial aquifer is a water-bearing assemblage of gravels and sands that underlies about 32,000 square miles of Missouri, Kentucky, Tennessee, Mississippi, Louisiana, and Arkansas. Because of the heavy demands placed on the aquifer, several large cones of depression have formed in the potentiometric surface, resulting in lower well yields and degraded water quality in some areas. A ground-water flow model of the alluvial aquifer was previously developed for an area covering 3,826 square miles, extending south from the Arkansas River into the southeastern corner of Arkansas, parts of northeastern Louisiana, and western Mississippi. The flow-model results indicated that continued ground-water withdrawals at rates commensurate with those of 1997 could not be sustained indefinitely without causing water levels to decline below half the original saturated thickness of the aquifer.

Conjunctive-use optimization modeling was applied to the flow model of the alluvial aquifer to develop withdrawal rates that could be sustained relative to the constraints of critical ground-water area designation. These withdrawal rates form the basis for estimates of sustainable yield from the alluvial aquifer and from rivers specified within the alluvial aquifer model. A management problem was formulated as one of maximizing the sustainable yield from all ground-water and surface-water withdrawal cells within limits imposed by plausible withdrawal rates, and within specified constraints involving hydraulic head and streamflow. Steady-state conditions were selected because the maximized withdrawals are intended to represent sustainable yield of the system (a rate that can be maintained indefinitely).

One point along the Arkansas River and one point along Bayou Bartholomew were specified for obtaining surface-water sustainable-yield estimates within the optimization model. Streamflow constraints were specified at two river cells based on average 7-day low flows with 10-year recurrence intervals.

Sustainable-yield estimates were affected by the allowable upper limit on withdrawals from wells specified in the optimization model. Withdrawal rates were allowed to increase to 200 percent of the withdrawal rate in 1997. As the overall upper limit is increased, the sustainable yield generally increases. Tests with the optimization model show that without limits on pumping, wells adjacent to sources of water, such as large rivers, would have optimal withdrawal rates that were orders of magnitude larger than rates corresponding to those of 1997. Specifying an upper withdrawal limit of 100 percent of the 1997 withdrawal rate, the sustainable yield from ground water for the entire study area is 70.3 million cubic feet per day, which is about 96 percent of the amount withdrawn in 1997 (73.5 million cubic feet per day). If the upper withdrawal limit is increased to 150 percent of the 1997 withdrawal rate, the sustainable yield from ground water for the entire study area is 80.6 million cubic feet per day, which is about 110 percent of the amount withdrawn in 1997. If the upper withdrawal limit is increased to 200 percent of the 1997 withdrawal rate, the sustainable yield from ground water for the entire study area is 110.2 million cubic feet per day, which is about 150 percent of the amount withdrawn in 1997. Total sustainable yield from the Arkansas River and Bayou Bartholomew is about 4,900 million cubic feet per day, or about 6,700 percent of the amount of ground-water withdrawn in 1997. The large, sustainable yields from surface water represent a potential source of water that could supplement ground water and meet the total water demand.

Unmet demand (defined as the difference between the optimized withdrawal rate or sustainable yield, and the anticipated demand) was calculated

using different demand rates based on multiples of the 1997-withdrawal rate. Assuming that demand is the 1997 withdrawal rate, and that sustainable-yield estimates are those obtained using upper limits of withdrawal rates of 100-, 150-, and 200-percent of 1997 withdrawal rates, then the resulting unmet demand for the entire model area is 3.3, -7.1, and -36.6 million cubic feet per day, respectively. Whereas, if the demand is specified as 100-, 150-, and 200-percent of the 1997 withdrawal rate, and the sustainable-yield estimates remain the same, then the resulting unmet demand for the entire model area is 3.3, 29.7, and 36.9 million cubic feet per day.

INTRODUCTION

The Mississippi River Valley alluvial aquifer, often termed simply the “alluvial aquifer,” is a water-bearing assemblage of gravels and sands that underlies about 32,000 mi^2 of Missouri, Kentucky, Tennessee, Mississippi, Louisiana, and Arkansas (fig. 1). In Arkansas, the alluvial aquifer occurs in an area generally 50 to 125 mi wide and about 250 mi long adjacent to the Mississippi River. The alluvial aquifer is the uppermost aquifer in this area, and generally ranges in thickness between 50 and 150 ft. The alluvial aquifer is under both confined and unconfined conditions depending on location (Czarnecki and others, 2002). The Mississippi River Valley alluvial aquifer supplies large volumes of water for agriculture in Arkansas. Withdrawal of ground water from the alluvial aquifer for agriculture started in the early 1900’s in the Grand Prairie area for irrigation of rice, and to a lesser extent, soybeans. Water-level declines in the alluvial aquifer were first documented in 1927 in the Grand Prairie (Engler and others, 1963, p. 21). From 1965 to 2000, water use from the alluvial aquifer in eastern Arkansas increased 637 percent. In 1997, 635.6 Mft^3/d of water were pumped from the aquifer, primarily for irrigation and fish farming. Most of the water use from the alluvial aquifer occurred north of the Arkansas River (outside the area of investigation of this report). In 2000, 97 percent of the ground water obtained in eastern Arkansas came from wells completed in the alluvial aquifer (Terry Holland, U.S. Geological Survey, written commun., 2002).

Because of heavy demands placed on the aquifer, several large cones of depression have formed in the potentiometric surface, resulting in lower well yields and degraded water quality from salinity increases in some areas. Several counties in southeastern Arkansas, which are within the extent of the alluvial aquifer, have been designated Critical Ground-Water Areas by the Arkansas Soil and Water Conservation Commission (ASWCC). One criterion associated with the designation of a Critical Ground-Water Area applies when water levels drop below half the original saturated thickness of the formation.

Ground-water flow models of the alluvial aquifer show that continued ground-water withdrawals at rates equal to those of 1997 could not be sustained indefinitely without causing water levels to decline below half the original saturated thickness of the formation (Stanton and Clark, 2003). To develop estimates of withdrawal rates that could be sustained in compliance with the constraints of critical ground-water area designation, the U.S. Geological Survey (USGS), in cooperation with the ASWCC and the Vicksburg District of the U.S. Army Corps of Engineers (USACE) applied conjunctive-use optimization modeling to an existing model of ground-water flow for the alluvial aquifer in southeastern Arkansas (fig. 1). Conjunctive use involves the withdrawal of both ground water and surface water. Conjunctive-use optimization modeling is a technique that can be used to determine maximum withdrawal rates from both surface water and ground water while meeting constraints with respect to water levels and streamflow. These withdrawal rates would form the basis for estimates of sustainable yield from the alluvial aquifer and from rivers specified within the alluvial aquifer model.

Purpose and Scope

The purpose of this report is to describe the application and evaluation of a conjunctive-use optimization model (hereafter referred to as the optimization model) of the Mississippi River Valley alluvial aquifer of southeastern Arkansas. The objective of this study is to provide estimates of sustainable yield from ground water and surface water using the optimization model. The optimization model was formulated as a linear programming problem, and utilized a ground-water model developed for the study area (Stanton and Clark, 2003) as a basis for evaluation. The purpose of the optimization model was to: (1) determine maximum withdrawal rates from model cells at which ground-water withdrawals occurred in 1997 and (2) determine maximum withdrawal rates from model cells at stream locations while maintaining ground-water levels at or

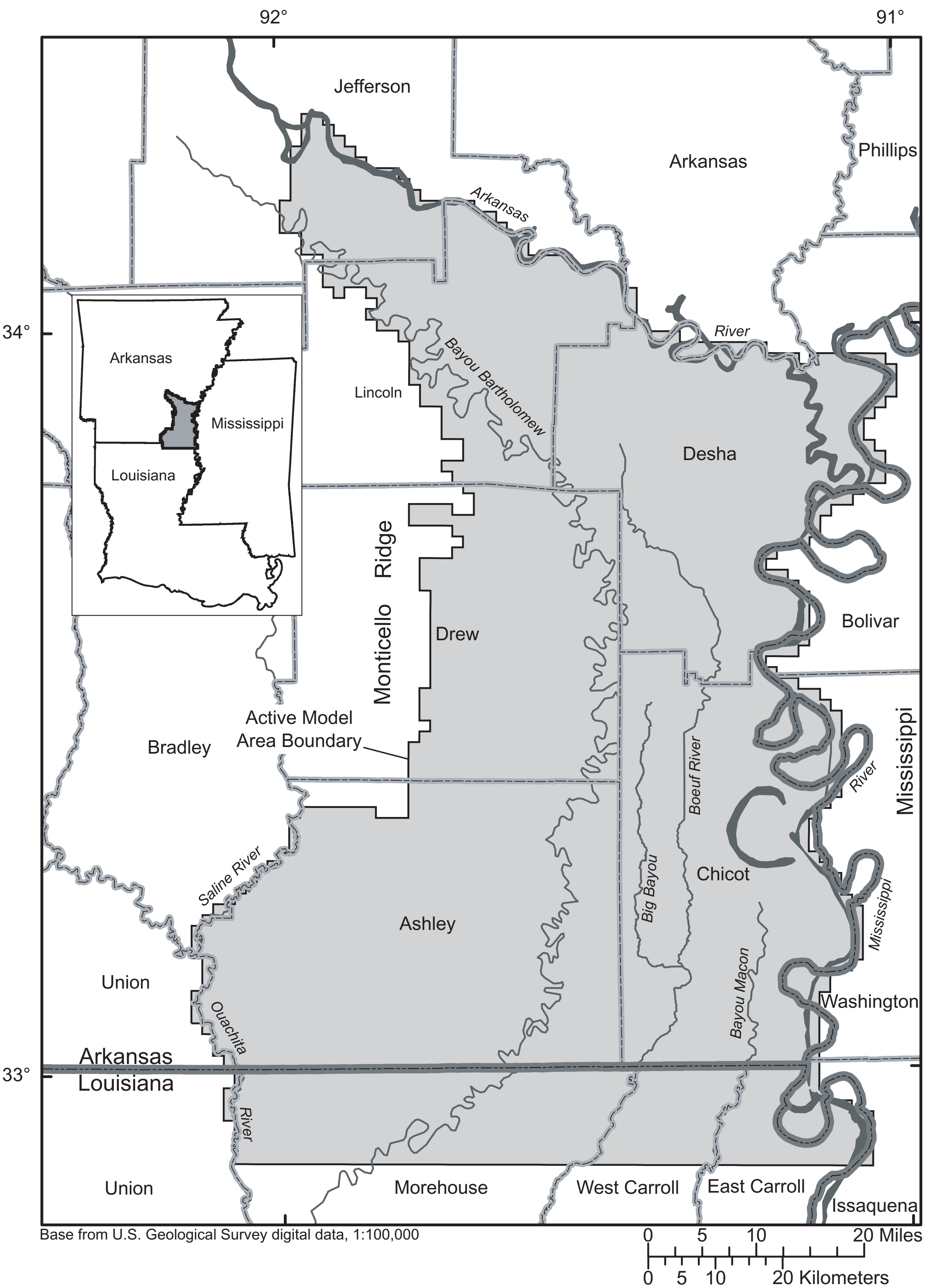

Figure 1. Location of study and modeled area.

above specified levels and streamflow at or above specified rates. The report describes the amount of projected total water demand that can be met by the alluvial aquifer and by available surface water while maintaining specified constraints. In this report, sustainable yield is defined as the amount of water that can be withdrawn indefinitely from ground water and from surface water without violating specified hydraulic-head or streamflow constraints. If an anticipated demand for water is known, an unmet demand may be calculated by subtracting the sustainable yield from the anticipated demand. Sustainable yield from ground water will be compared to anticipated demand for various withdrawal rates, because of concerns about water-level declines in the alluvial aquifer. The results of the optimization modeling can provide water managers and policy makers with information that can be used to assist in the management of the ground-water resources of the alluvial aquifer in southeastern Arkansas in a sustainable manner.

Previous Studies

Many investigators have described the underlying sediments of the Mississippi River Alluvial Plain. One of the earliest reports describing subsurface geology and ground-water resources in southern Arkansas and northern Louisiana was written by Veatch (1906). Ground-water resources of northeastern Arkansas were described and a detailed inventory was provided by Stephenson and Crider (1916). Fisk (1944) reported on extensive geologic investigations along the Mississippi River Valley made by the U.S. Army Corps of Engineers between 1941 and 1944. Krinitzsky and Wire (1964) expanded on the hydrogeologic work of Fisk with a comprehensive look at 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 of 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.

The MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) ground-water flow model (hereafter referred to as the flow model) used in the optimization modeling of this report is based on a recalibrated and extended model of Mahon and Poynter (1993), which included hydraulic-head observations for the years 1992 and 1998 (Stanton and Clark, 2003). Many researchers have applied conjunctive-use optimization models to the management of ground-water systems. Reichard (1995) provides a thorough review of many of these studies. Nishikawa (1998) used MODMAN 3.0 (Greenwald, 1998) (the precursor program to the one used for optimization in this report) to minimize the cost of supplying water during a design drought in Santa Barbara, California, by optimizing delivery of surface water and operation of the city’s reservoirs.

The first effort to estimate optimized ground-water withdrawals from the alluvial aquifer was done by Peralta and others (1985) who estimated future ground-water availability in the Grand Prairie area by using a flow model coupled to an optimization routine. Their analysis focused on a small subset of the alluvial aquifer north of the Arkansas River, and did not couple the conjunctive use of ground water and surface water. Barlow and others (2003) developed conjunctive-use management models for estimating sustainable yield from surface water and ground water within an alluvial-valley stream-aquifer system in Rhode Island.

Acknowledgments

The conjunctive-use optimization routine used in this report is an adaptation of enhancements to MODMAN (Greenwald, 1998) made by Brian Wagner (U.S. Geological Survey). Wesley Danskin (U.S. Geological Survey) provided guidance on the use of MODMAN and the large-scale optimization solver MINOS (Murtaugh and Saunders, 1998). Streamflow constraints used in the optimization model were compiled by Steve Loop (Arkansas Soil and Water Conservation Commission). Elton Porter (U.S. Geological Survey) computed mean annual flow rates and runoff estimates for the model streams used in this report.

Study Area

The study area (fig. 1), which is the same as the model area, is 3,826 mi^2, and includes all or part of six counties south of the Arkansas River in Arkansas, part of four parishes in northeastern Louisiana, and part of one county in Mississippi. The active cells of the model encompassed the area south of the Arkansas River, mostly west of the Mississippi River, and north of an arbitrary east-west line about 10 mi south of the Arkansas/Louisiana State line encompassing a small part of northeastern Louisiana (fig. 1).

Hydrogeology

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 and semiconfining units 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 clay, silts, and fine sand confines the alluvial aquifer. It is this regional alluvial aquifer and overlying confining unit, along with its flow system, that has been defined and investigated previously (Broom and Lyford, 1981; Broom and Reed, 1973; Ackerman, 1989a, 1989b, 1990; Mahon and Ludwig, 1990; Mahon and Poynter, 1993).

The geology 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 Tertiary-age Jackson Group in the study area (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. On a local scale, alluvial deposits are dominated by the complex heterogeneity of small, discontinuous sand and silt beds dispersed 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. A truncated erosional surface of the Jackson Group underlies the Mississippi River alluvium in the study area forming an effective underlying hydraulic confining unit (Cushing and others, 1964).

The Mississippi River alluvium consists of two distinct but gradational lithologies; clays and silts overlie coarse sands and gravels forming a fining upward sequence (Ackerman, 1989a). These two lithologies are used as a basis for subdividing the alluvium into the basal alluvial aquifer and the overlying confining unit. Figure 2 shows two hydrogeologic sections of the aquifer through the model area. The overlying confining unit ranges in thickness from 0 to 60 feet within the study area (Gonthier and Mahon, 1993). The sands and gravels that underlie the overlying confining unit and comprise the alluvial aquifer range from 50 to 100 feet thick.

CONJUNCTIVE-USE OPTIMIZATION

The following sections describe the development and application of the conjunctive-use optimization approach applied to the model area, beginning with a review of the flow model. The optimization model is described and results evaluated.

Flow Model

The flow model discussed in this report is based on a recalibrated and extended model of Mahon and Poynter (1993), which included hydraulic-head observations for the years 1992 and 1998 (Stanton and Clark, 2003). Characteristics for the flow model are listed in table 1. The flow model was developed using MODFLOW-2000 and incorporates river, no-flow, drain, and areally distributed recharge boundary conditions. The combinations of boundary conditions result in flow occurring from recharge sources to areas with extensive ground-water withdrawals and a consequent widespread lowering of the water table. The potentiometric surface within the alluvial aquifer for spring 1998 is shown in figure 3, which shows a substantial cone of depression near the boundary of Desha and Chicot Counties resulting from sustained pumping. Model parameters were estimated in part using MODFLOW-2000 (Hill and others, 2000) to assist model calibration to observed values of hydraulic head in 1972, 1982, 1992, and 1998. Values of the mean, mean absolute, and root-mean-square difference between observed and simulated hydraulic head for all observations for all periods simulated by the model are listed in table 1. The mean difference (-0.33 ft) is a sum of the differences, both positive and negative, divided by the total number of observations; for an unbiased model this value would be zero. The mean absolute difference (5.1 ft) is the sum of the magnitudes of the difference at each observation, divided by the total number of observa-

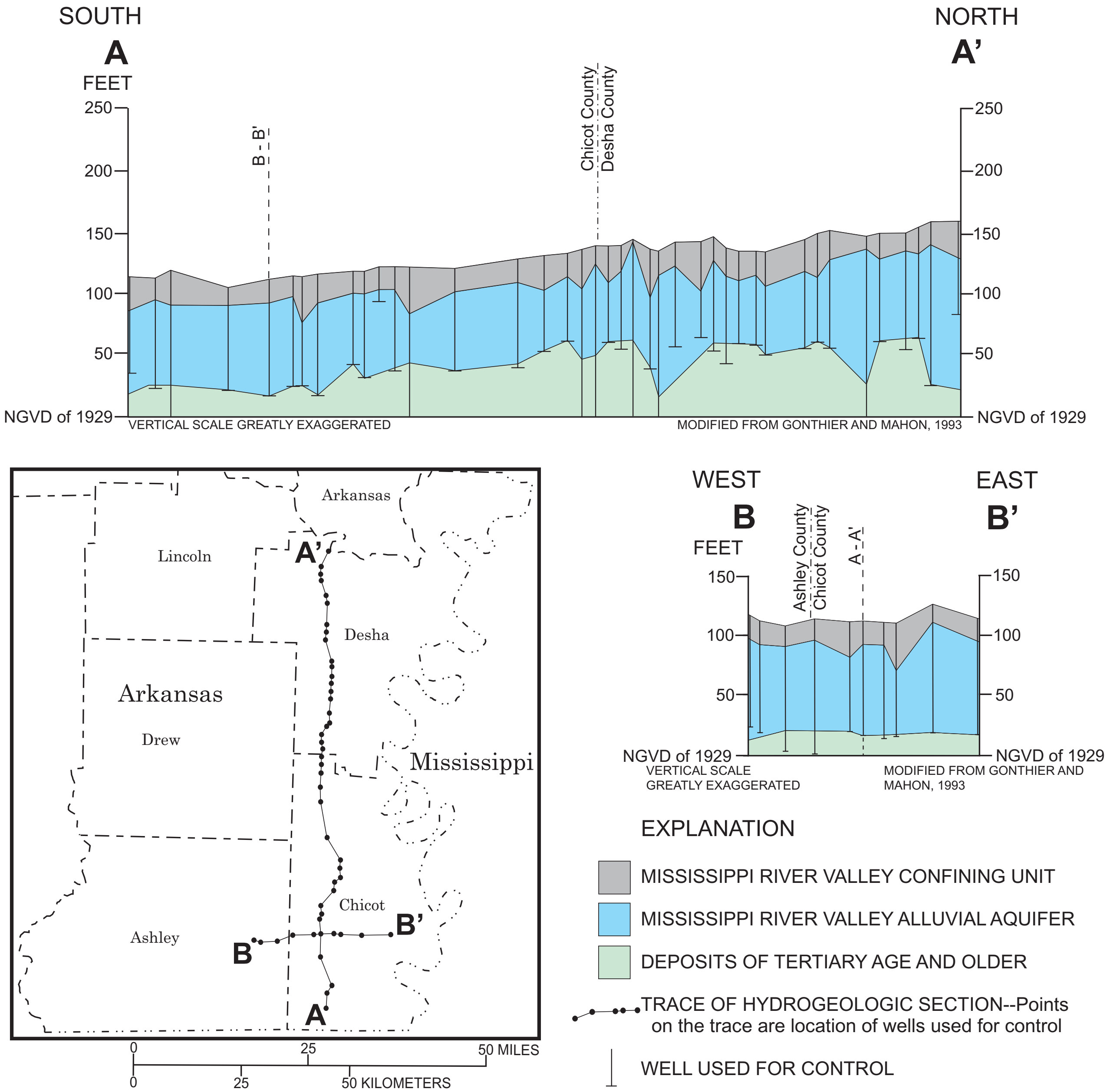

Figure 2. Hydrogeologic sections showing lithology and variation in thickness through the model area.

Table 1. Characteristics of the flow model (Stanton and Clark, 2003)

[mi^2, square mile; ft^3/d, cubic foot per day; ft/d, foot per day; ft^{-1}, inverse foot; ft, foot]

Characteristic	Value
Model area	3,826 mi^2
Cells with wells corresponding to 1997 withdrawals	1,841
Total pumpage in 1997	617,000 ft^3/d
Average hydraulic conductivity	250 - 450 ft/d
Specific yield	0.27 - 0.30
Specific storage	$3x10^{-5}$ - $9x10^{-4}$ ft^{-1}
River cells	470
Hydraulic-head observations	521
Hydraulic-head observation periods	1972, 1982, 1992, 1998
Range in observed hydraulic head values in 1998 (feet above National Geodetic Vertical Datum of 1929)	61.85 - 186.01 ft
Mean difference between observed and simulated hydraulic head, all four periods	-0.33 ft
Mean absolute difference between observed and simulated hydraulic head, all four periods	5.1 ft
Root-mean-square difference between observed and simulated hydraulic head, all four periods	6.5 ft

tions; a value of zero is preferable. Assuming a normal distribution, approximately 67 percent of the residual values (that is, the difference between observed and simulated water-level altitudes) would lie within positive or negative values of the root-mean-square difference (that is, +/-6.5 ft). Given the difference in the range in observed hydraulic-head values (220 ft), these differences are small and indicate a good fit to the observed values.

The flow model was used to simulate ground-water flow for the period from 1918 through 2049, and to evaluate effects from the demand for ground water from the alluvial aquifer, which has increased steadily for the last 40 years (Stanton and Clark, 2003). The flow model results indicated that continued ground-water withdrawals at rates commensurate with those of 1997 could not be sustained indefinitely without causing water levels to decline below half the original saturated thickness of the formation. Based on measured water levels, the saturated thickness of the alluvial aquifer has been greatly reduced in some areas (Schrader, 2001; Czarnecki and others, 2002). This has resulted in degraded water quality, decreasing water availability, increased pumping costs, and lower well yields.

Optimization Model

For the optimization model described in this report, modifications were made to MODMAN 4.0 to: (1) incorporate stream withdrawal cells as decision variables, (2) allow specification of streamflow constraints, and (3) account for streamflow water budgeting. Modifications to the MODMAN code were initially provided by Brian Wagner (U.S. Geological Survey) in a modification to MODMAN 3.0, and adapted to MODMAN 4.0. In addition, the ability to aggregate wells within a subarea of the model and to treat an aggregate-well pumping rate as a single decision variable was added to MODMAN 4.0. However, that ability was not utilized; instead, 9,979 ground-water-withdrawal decision variables and 1,165 surface-water-withdrawal decision variables were specified. The optimization modeling process (fig. 4) begins with the calibration and adaptation of a MODFLOW-based ground-water flow model to be compatible with the optimization modeling software (MODMAN 4.0).

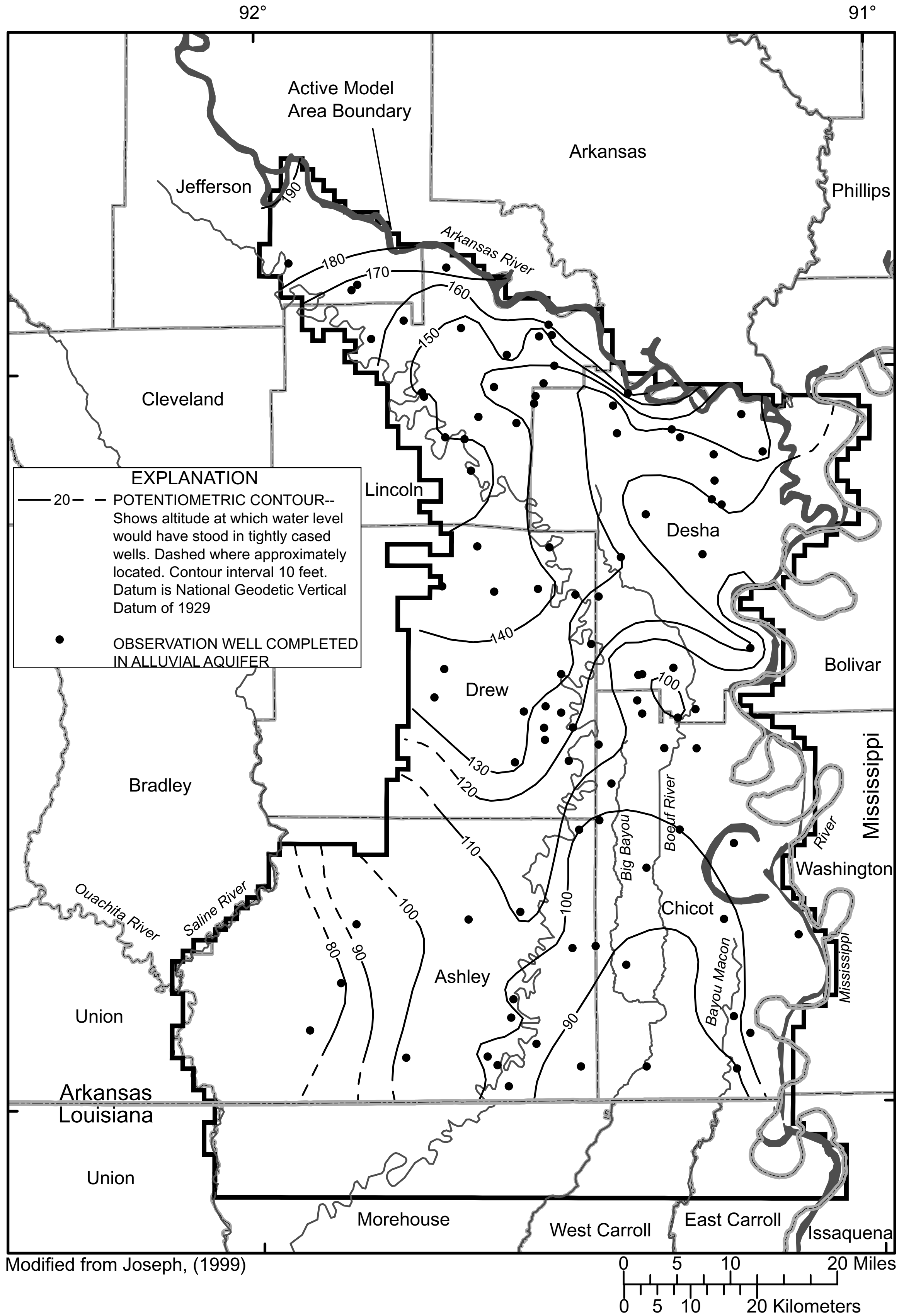

Figure 3. Potentiometric surface within the alluvial aquifer, spring 1998 (Stanton and Clark, 2003).

Adaptation entailed the conversion of the flow model from MODFLOW 2000 (Hill and others, 2000) to MODFLOW 96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), and verifying that the results were the same. Steady-state conditions were selected (as opposed to transient conditions) because the maximized withdrawals are intended to represent sustainable yield of the system (a rate that can be maintained indefinitely).

A management problem is formulated to maximize a parameter, such as water production from ground water and surface water, within selected constraints, such as maintaining hydraulic heads in the aquifer above a minimum altitude or maintaining a minimum amount of streamflow. The conjunctive-use version of MODMAN 4.0 was used to generate response coefficients for each specified withdrawal cell in the model. The response-coefficient matrix consists of changes in hydraulic head or streamflow at each constraint location that occur in response to pumping at a single well or river cell at a unit rate (Greenwald, 1998; Ahlfeld and Mulligan, 2000). The unit rate was specified at 10,000 ft^3/d. To accurately represent the response of the flow model to a unit rate of pumping under unconfined conditions, selection of starting hydraulic heads should be similar to those that would result when optimal withdrawal rates are applied. Starting hydraulic head values were selected as those simulated for 1997 from the model of Reed (2003). Because some dry cells occurred in that model at that simulated point in time, hydraulic-head values at dry cells were assigned similar values as adjacent model cells that were not dry.

After all the response coefficients are calculated, they are combined to form a data-input set along with hydraulic-head and streamflow constraints, and are formulated as a linear optimization program in mathematical programming system (MPS) format. The linear program is run under MINOS. If a feasible solution exists, MINOS will provide estimates of optimal (maximum) values of ground-water and surface-water withdrawals. MINOS also identifies points in the model where hydraulic-head or streamflow constraints have been reached.

Optimal ground-water withdrawal rates calculated using the optimization model were evaluated by applying them in the flow model, to compare the resulting simulated hydraulic head against the specified hydraulic-head constraints. Non-linear flow model behavior was expected for this model because of the unconfined condition of the aquifer and head-dependent flow boundary conditions at the rivers. For this reason, starting values of hydraulic head were specified as those simulated for 1997. In a strictly linear model, such as one for a confined aquifer, ground-water flow is a function of hydraulic head through only the hydraulic-gradient term in Darcy's law:

$$Q = -K\frac{dh}{dl}A \qquad (1)$$

where Q is ground-water flow, in cubic feet per day;
K is the hydraulic conductivity, in feet per day;
$\frac{dh}{dl}$ is the hydraulic gradient, dimensionless;
h is hydraulic head, in feet;
l is a distance over which the gradient is measured, in feet; and
A is the cross-sectional area through which flow occurs, in feet squared.

For unconfined conditions, A also is a function of hydraulic head. If changes in hydraulic head are small relative to the total saturated thickness, then A will remain about the same. However, if substantial change in saturated thickness occurs, A can change appreciably, because

$$A = bw \qquad (2)$$

where b is the saturated thickness, which varies with hydraulic head, in feet; and
w is the width through which flow occurs, in feet.

This is an important consideration in selecting starting values of hydraulic head for the flow model to produce a more efficient solution to the ground-water flow equation (McDonald and Harbaugh, 1988).

Problem Formulation

The optimization model was formulated as a linear programming problem with the objective of maximizing water production from wells and from streams subject to: (1) maintaining ground-water levels at or above specified levels; (2) maintaining streamflow at or above minimum specified rates; and (3) limiting

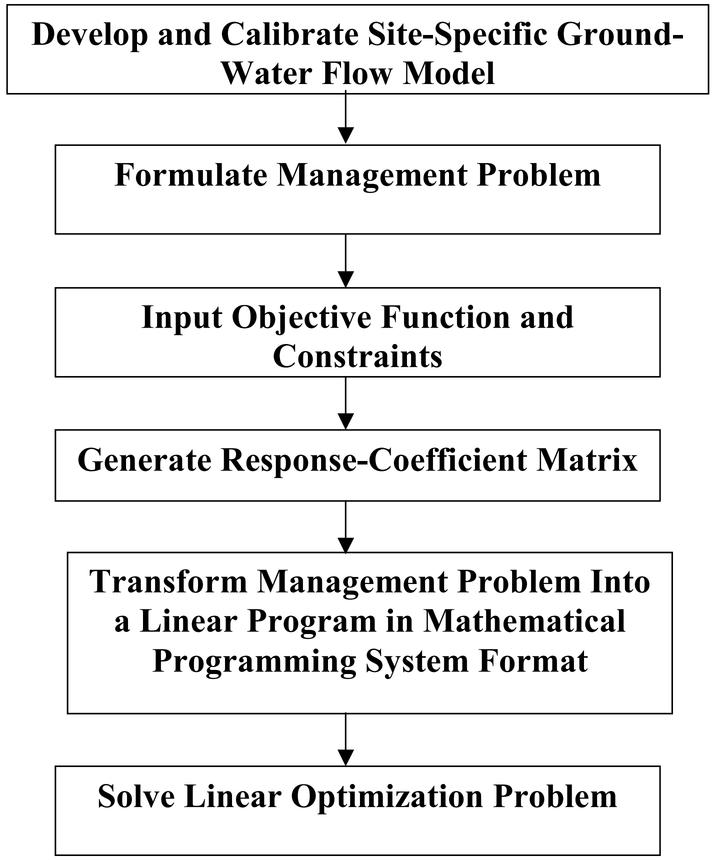

Figure 4. Flow chart of optimization modeling process (modified from Greenwald, 1998).

ground-water withdrawals to a maximum of either 100, 150, or 200 percent of the rate pumped in 1997. Steady-state conditions were selected (rather than transient conditions) because the maximized withdrawals are intended to represent sustainable yield of the system (a rate that can be maintained indefinitely). In this model, the decision variables (a term used in optimization modeling to identify variables that can be part of a management scheme) are the withdrawal rates at 1,841 model cells corresponding to well locations and at 2 river cells.

Objective Function

The objective of the optimization model is to maximize water production from ground-water and surface-water sources. The objective function of the optimization model has the form:

$$\text{maximize } z = \sum q_{well} + \sum q_{river} \qquad (3)$$

where z is the total managed water withdrawal, in cubic feet per day;
$\sum q_{well}$ is the sum of ground-water withdrawal rates from all managed wells, in cubic feet per day; and
$\sum q_{river}$ is the sum of surface-water withdrawal rates from all managed river reaches, in cubic feet per day.

Hydraulic-Head Constraints

Equation 3 is computed such that the following constraints are maintained:

$$h_c \geq h_{minimum} \qquad (4)$$

where h_c is the hydraulic head (water-level altitude) at constraint location c, in feet; and
$h_{minimum}$ is the water-level altitude at half the thickness of the aquifer, in feet.

To accommodate the ASWCC Critical Ground-Water Area criteria that water levels within the alluvial aquifer should remain above half the original saturated thickness of the aquifer, hydraulic-head constraints were specified at 2,804 model cells. For a few cells where the original saturated thickness of the aquifer is less than 60 ft but at least 30 ft, the hydraulic head constraint was specified as 30 ft, a minimum thickness considered necessary for the aquifer to remain viable in those areas. The spatial distribution of constraint points represents approximately every fifth model cell (fig. 5). If water levels were to drop everywhere to the level of the head constraint, then the resulting saturated thickness of the alluvial aquifer would range from 30 to 100 ft, and generally be thinnest in the Grand Prairie area (fig. 5).

Streamflow Constraints

Streamflow is regulated in Arkansas by ASWCC for purposes of maintaining water quality, navigation, and species habitat. Streamflow constraints for several rivers specified in the optimization model are based on 7-day, 10-year-recurrence low-flow data (7Q10). Streamflow constraints are specified as the minimum amount of flow required at individual river cells. The equation governing the relation between streamflow constraints and flow into and out of a stream is

$$q^R_{head} + \sum q^R_{overland} \pm \sum q^R_{ground\ water} - \sum q^R_{diversions} - \sum q^R_{river} \geq q^R_{minimum} \quad (5)$$

where q^R_{head} is the flow rate into the head of stream reach *R*, in cubic feet per day;

$\sum q^R_{overland}$ is the sum of all overland and tributary flow to stream reach *R*, in cubic feet per day;

$\sum q^R_{ground\ water}$ is the net sum of all ground-water flow to or from stream reach *R*, in cubic feet per day;

$\sum q^R_{diversions}$ is the sum of all surface-water diversions from stream reach *R*, in cubic feet per day;

$\sum q^R_{river}$ is the sum of all potential withdrawals, not including diversions, from stream reach *R*, in cubic feet per day; and

$q^R_{minimum}$ is the minimum permissible surface-water flow rate for stream reach *R*, in cubic feet per day.

Ground-Water Withdrawal Limits

The proximity of managed wells to model flow boundaries was taken into account to properly formulate the management objective. If no limit is imposed on the potential amount of water that can be pumped at each managed well, then those wells nearest model sources of water, such as rivers or general head-boundaries, will be the first to be supplied water, thus capturing flow that would otherwise reach wells further from the sources. Test simulations done with the optimization model show that without limits on pumping, wells adjacent to sources of water would have optimized withdrawal rates that were orders of magnitude larger than rates corresponding to those of 1997. Not only is it physically unlikely that individual wells could pump that much more water, but construction of sufficient additional wells in the one-square mile cells also is unlikely. The phenomenon of wells near rivers capturing induced recharge from the rivers and preventing sufficient water from flowing to interior wells is, however, consistent with current conditions (Czarnecki and others, 2002).

Test simulations using 1997 withdrawal rates applied to steady-state conditions yielded large areas with dry cells in the flow model. Therefore, ground-water demand limits were specified at each cell as a multiple of the amount pumped in 1997, such that

$$0 \leq q_{well_i} \leq M q_{well\ 1997} \quad (6)$$

where, q_{well_i} is the optimal ground-water withdrawal for well i, in cubic feet per day;

M is a multiplier between 1 and 2; and

$q_{well\ 1997}$ is the total amount withdrawn in 1997 from all wells, in cubic feet per day.

Surface-Water Withdrawal Limits

No limits were imposed on optimized withdrawals from rivers such that the range in optimal withdrawal was between zero and the maximum amount of water available (greater than 7Q10) at a given point in a given river. This specification permitted analysis of where water could be produced and the maximum amount available. Withdrawals were allowed only at the two points where river constraints were specified on both the Arkansas River and Bayou Bartholomew.

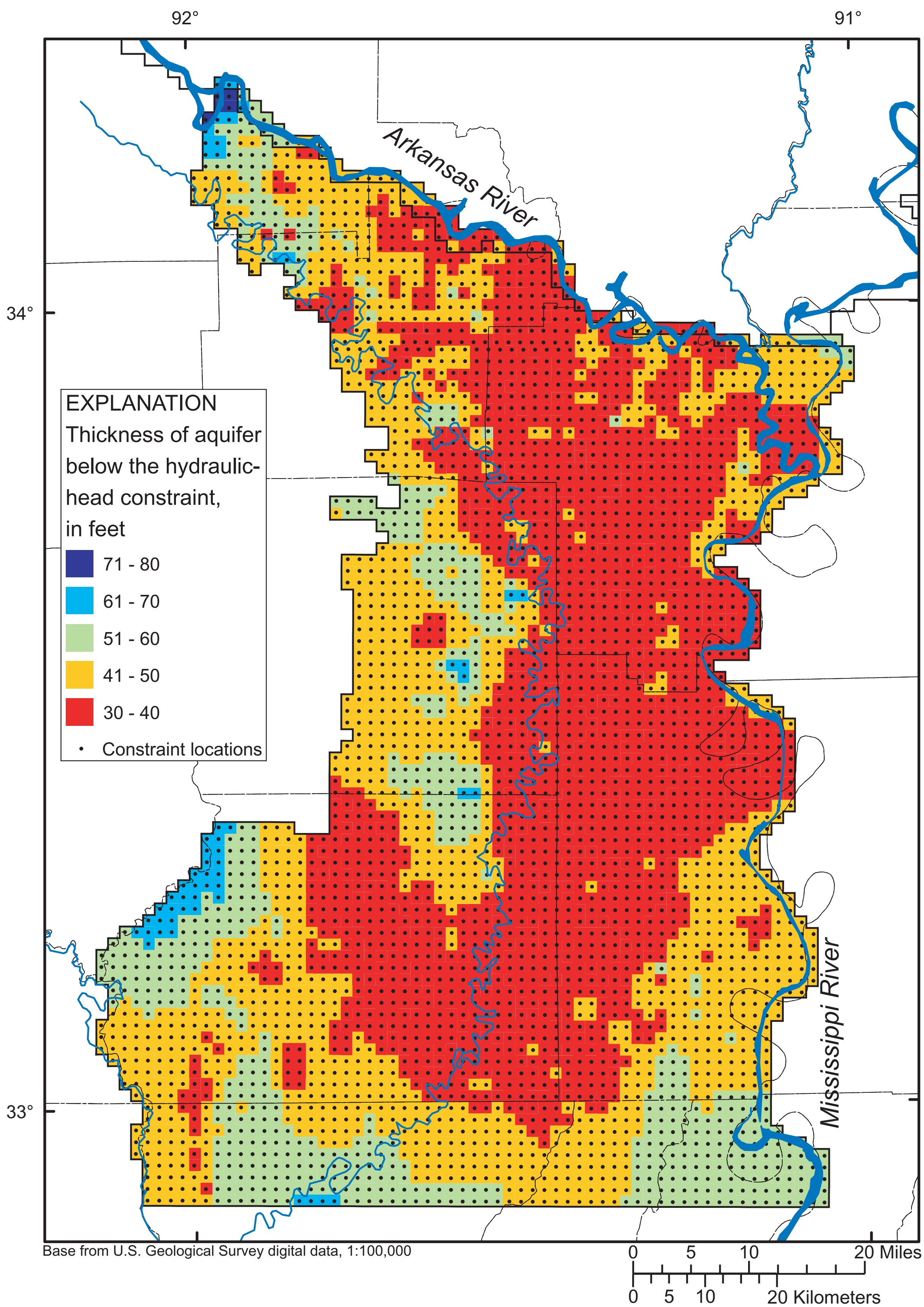

Figure 5. Location of hydraulic-head constraint points and thickness of aquifer below hydraulic-head constraint.

Wells Used in Optimization Model

For optimization modeling, 1,841 one-square mile cells were used to represent pumping in 1997. In Louisiana, pumping data were available only by parish, and were divided equally over all model cells corresponding to a given parish. Multiple wells can exist within any model cell, but the total pumping from all wells in a cell is the value specified. In 1997, the annual pumping rate for all wells was 73.5 million cubic feet per day. For the sustainable-yield analysis, the optimized rate was allowed to vary between a rate of zero to a maximum rate equal to twice that which was withdrawn in 1997. The latter condition was specified because no limit on withdrawal rates led to unrealistic optimal withdrawal rates from wells adjacent to rivers. Model cells used to denote ground-water withdrawals correspond to the distribution of wells in 1997. No additional wells other than those existing in 1997 are assumed. Because withdrawal rates in Louisiana are reported by parish rather than for individual wells as in Arkansas, withdrawal rates in Louisiana were evenly distributed by parish at every model cell within the flow model. This distribution gives the impression of a denser well distribution in Louisiana than probably exists.

Wells are optimized as individual wells, and therefore, have individual rates associated with each cell. For each optimization model run, the multiplier M is specified as a uniform value that applies to all 1,841 ground-water withdrawal cells.

Streamflow

To allow for both the optimal conjunctive use of surface water and ground water within the optimization model, streamflows from the two largest rivers (Arkansas River and Bayou Bartholomew) are specified for estimating optimal withdrawals (table 2). Streamflow constraints are specified at one cell from each river (fig. 6) based on 7-day low flows with 10-year recurrence intervals (7Q10) (Steve Loop, Arkansas Soil and Water Conservation Commission, written commun., 2001), which are derived from historical streamflow for the rivers. Streamflow constraints were unavailable for the other streams within the model. By specifying a minimum flow constraint based on 7Q10 values, available streamflow within the optimization model would be limited all year long to the amount of streamflow greater than the 7Q10; 7Q10 historically is expected to occur only once every 10 years, and then for only 7 consecutive days. Flow into the most upstream cell of each river contained within the model was specified based on mean annual flow, as were the cells at which tributaries connect. Because stream gages are not located at the start of the rivers simulated in the model, mean annual flow was prorated based on the drainage area upstream from that point. Overland flow (that is, surface-water runoff that would enter river cells from minor tributaries or sheet flow that was not explicitly represented in the model) was distributed equally at river cells within a river reach based on the difference in long-term average streamflow for a specific river

Table 2. Rivers, streamflows, and streamflow constraints

[ASWCC, Arkansas Soil and Water Conservation Commission. Flow constraint based on an annual minimum 7-consecutive-day average flow with a recurrence interval of 10 years]

River name	Number of model cells	Flow into uppermost river cell of model (million cubic feet per day)	Overland flow per river cell (million cubic feet per day)	Flow constraint (million cubic feet per day)	Source for value of constraint
Arkansas	83	3,500	18	100	ASWCC
Bayou Bartholomew	139	6.65	0.8	8.38	ASWCC

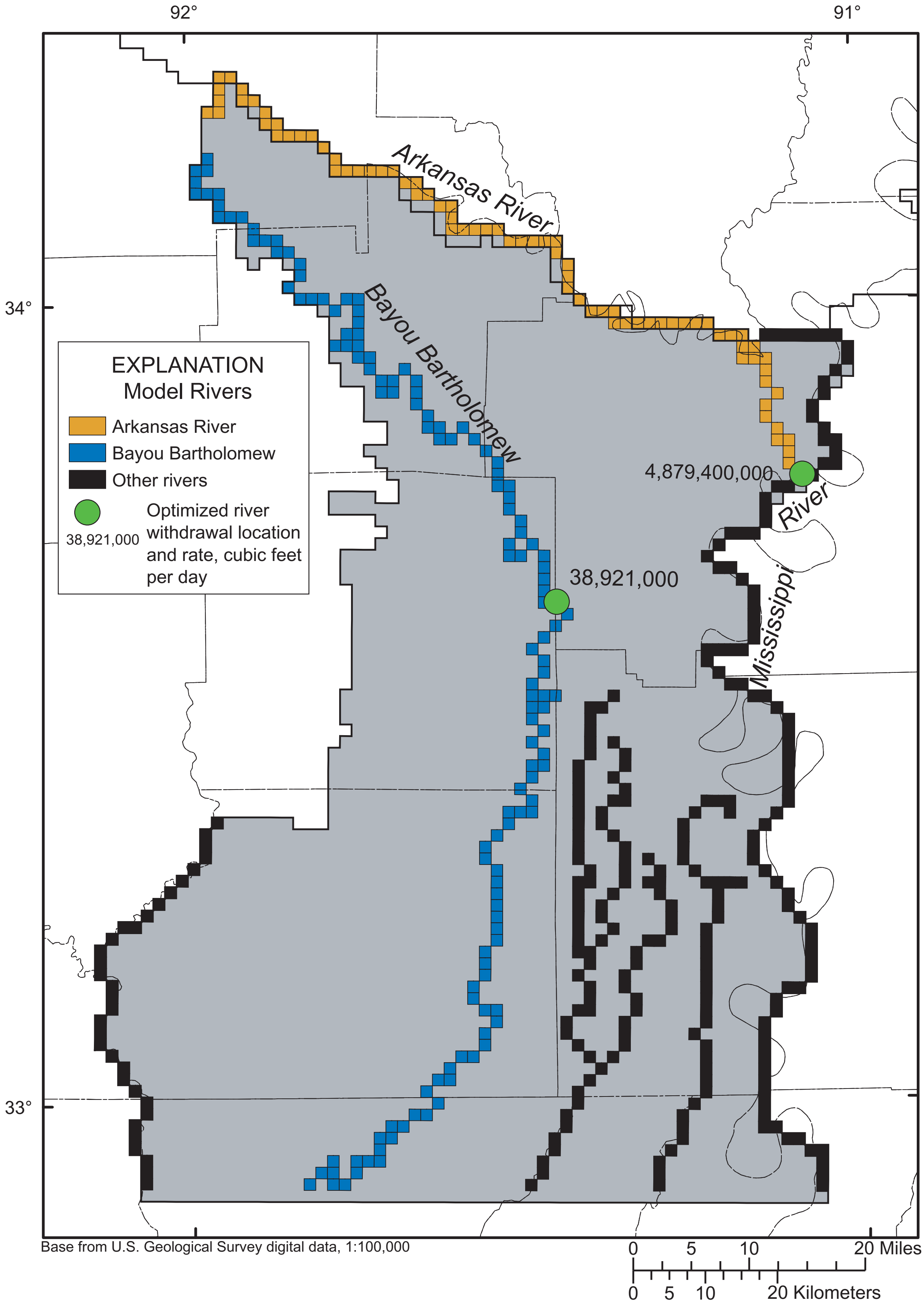

Figure 6. Location of streams within model showing cells and rates at which water could be withdrawn and still meet constraints within optimization model.

reach; or if such data were unavailable, areal estimates of runoff based on drainage areas were used (Elton Porter, U.S. Geological Survey, written commun., 2000). Surface-water diversion rates that occurred in 2000 were subtracted from specified overland flow at the appropriate river cells. Diversions totaling 1,787,103 ft^3/d were subtracted from Bayou Bartholomew, whereas no diversions from the Arkansas River were accounted for in this model.

Optimization Results

Sustainable Yield

The ultimate objective of the optimization model is to provide estimates of sustainable yield from both ground water and surface water. Sustainable yield is defined as a withdrawal rate from the aquifer or from a stream that can be maintained indefinitely (that is, to steady-state conditions) without causing violation of either hydraulic-head or streamflow constraints. Streamflow constraints (the 7Q10 streamflow) are specified in table 2.

Because sustainable yield from ground water is a function of the withdrawal limit specified for each managed well, multiples of the rate withdrawn in 1997 were used to set the maximum withdrawal limit. The distribution of optimal withdrawal rates using upper limits specified as 100-, 150-, and 200-percent multiples of the total 1997 ground-water withdrawal rates (scenarios 1, 2, and 3, respectively) are shown in figures 8-10. These limits, while arbitrary, are specified to examine the distribution of optimal withdrawals that would result for each scenario. The distribution of optimal withdrawal rates for each of these scenarios is such that most wells are withdrawing water at a rate equal to the upper limit or are not withdrawing water. This is convenient from a management standpoint because wells are generally on or off. As the withdrawal rate limit is increased, the total number of wells that can pump decreases (although the total amount withdrawn increases), with those wells withdrawing water being nearest to sources of water (major rivers) within the model. Test runs with the optimization model show that if no limits are placed on ground-water withdrawals, all of the withdrawals would come from wells adjacent to model sources of water, at rates that are orders of magnitude greater than were pumped in 1997. Although overall optimized withdrawal would be largest for such a scenario, the distribution of withdrawal cells would be unacceptable from a management standpoint because virtually all of the water production would come from wells adjacent to rivers, at the expense of the remaining interior wells being unable to pump at all. Not only is it physically unlikely that individual wells could pump that much more water, but construction of sufficient additional wells in the one-square mile cells also is unlikely.

Specifying an upper withdrawal limit of 100 percent of the 1997 withdrawal rate (scenario 1; fig. 7), the sustainable yield from ground water for the entire model area is 70.3 Mft^3/d (table 3), which is about 96 percent of the amount withdrawn in 1997 (73.5 Mft^3/d). If the upper withdrawal limit is increased to 150 percent of the 1997 withdrawal rate (scenario 2; fig. 8), the sustainable yield from ground water for the entire model area is 80.6 Mft^3/d (table 3), which is about 110 percent of the amount withdrawn in 1997. If the upper withdrawal limit is increased to 200 percent of the 1997 withdrawal rate (scenario 3; fig. 9), the sustainable yield from ground water for the entire model area is 110.2 Mft^3/d (table 3), which is about 150 percent of the amount withdrawn in 1997.

Sustainable yields from the Arkansas River and Bayou Bartholomew are much larger than those from ground water. Total sustainable yield from the Arkansas River and Bayou Bartholomew is about 4,900 Mft^3/d for scenarios 1, 2, and 3 (table 4) or about 6,700 percent of the amount of ground-water withdrawn in 1997. These large sustainable yields represent a potential source of water that could supplement ground water and meet total water demand, but to do so will require the construction of withdrawal and distribution facilities, which will have legal, political, economic, and social consequences.

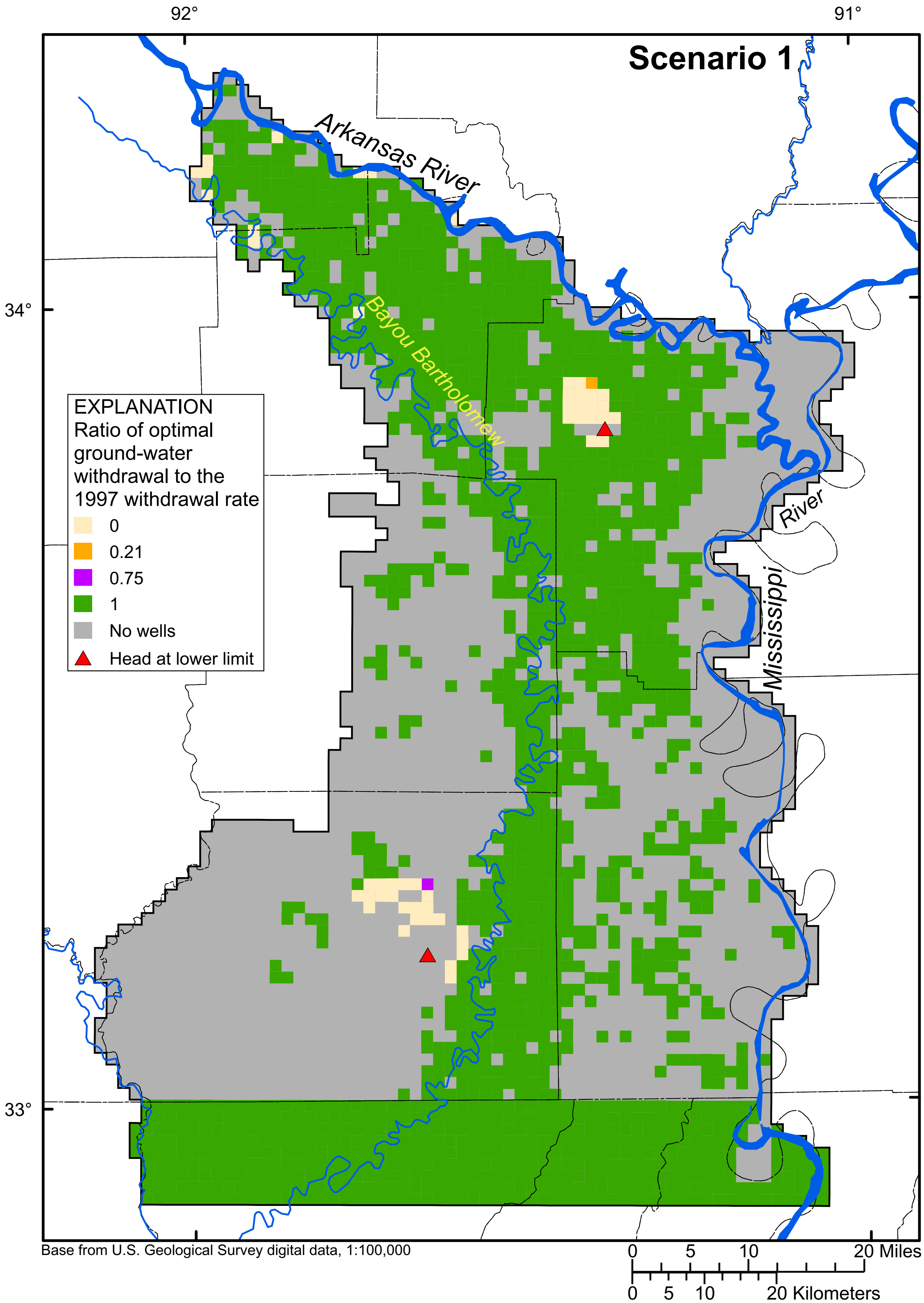

Figure 7. Ratio of optimal ground-water withdrawal calculated by the optimization model to the amount withdrawn in 1997 for withdrawal limits at each well set to 100 percent of the 1997 withdrawal rate.

Table 3. Sustainable yield and unmet demand by county or parish for different upper limits on withdrawals and different demand rates

[Negative unmet demand values indicate surplus water availability; Mft^3/d, million cubic feet per day]

			Sustainable yield (Mft^3/d) based on an upper withdrawal limit of:			Unmet demand (Mft^3/d) based on 1997 demand and a sustainable yield from:			Unmet demand (Mft^3/d) based on sustainable yields from scenarios 1,2, and 3, respectively, and a demand of:		
County or parish	State	1997 withdrawal rate (Mft^3/d)	100 percent of 1997 withdrawal rate (scenario 1)	150 percent of 1997 withdrawal rate (scenario 2)	200 percent of 1997 withdrawal rate (scenario 3)	Scenario 1	Scenario 2	Scenario 3	100 percent of 1997 withdrawal rate	150 percent of 1997 withdrawal rate	200 percent of 1997 withdrawal rate
Ashley	Arkansas	10.1	8.7	12.1	15.5	1.5	-2.0	-5.4	1.5	3.0	4.7
Chicot	Arkansas	7.9	7.9	11.8	15.7	0.0	-3.9	-7.9	0.0	0.0	0.0
Desha	Arkansas	20.9	19.6	22.2	22.1	1.3	-1.3	-1.2	1.3	9.1	19.7
Drew	Arkansas	6.8	6.8	9.7	11.9	0.0	-2.9	-5.1	0.0	0.5	1.7
Jefferson	Arkansas	8.6	8.2	12.3	16.5	0.3	-3.8	-7.9	0.3	0.5	0.7
Lincoln	Arkansas	16.1	15.9	7.7	22.1	0.2	8.4	-6.0	0.2	16.5	10.2
East Carroll	Louisiana	0.7	0.7	1.1	1.5	0.0	-0.4	-0.7	0.0	0.0	0.0
Morehouse	Louisiana	1.8	1.8	2.7	3.6	0.0	-0.9	-1.8	0.0	0.0	0.0
Union	Louisiana	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
West Carroll	Louisiana	0.6	0.6	0.9	1.2	0.0	-0.3	-0.6	0.0	0.0	0.0
Issaquena	Mississippi	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Total		73.5	70.3	80.6	110.2	3.3	-7.1	-36.6	3.3	29.7	36.9

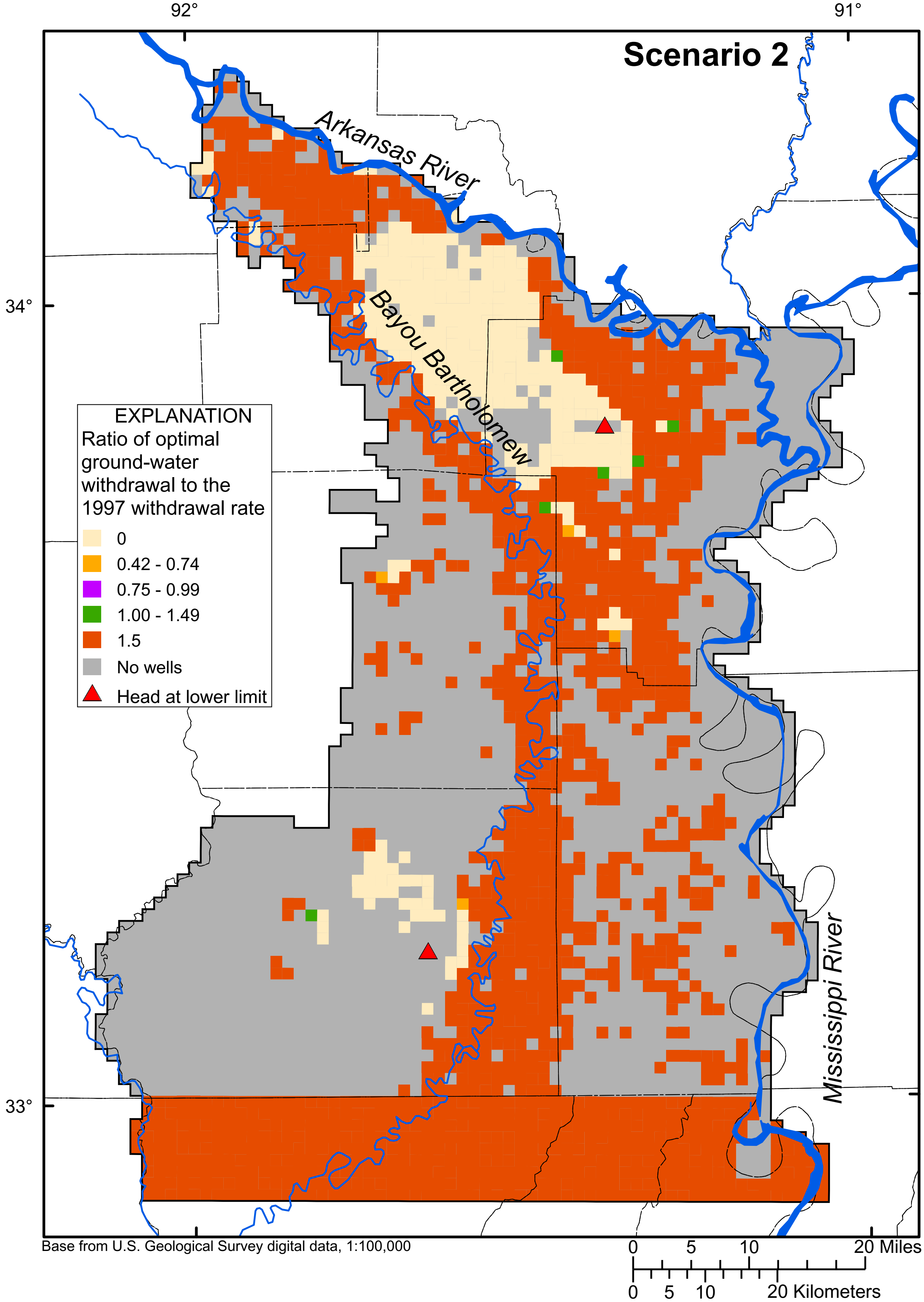

Figure 8. Ratio of optimal ground-water withdrawal calculated by the optimization model to the amount withdrawn in 1997 for withdrawal limits at each well set to 150 percent of the 1997 withdrawal rate.

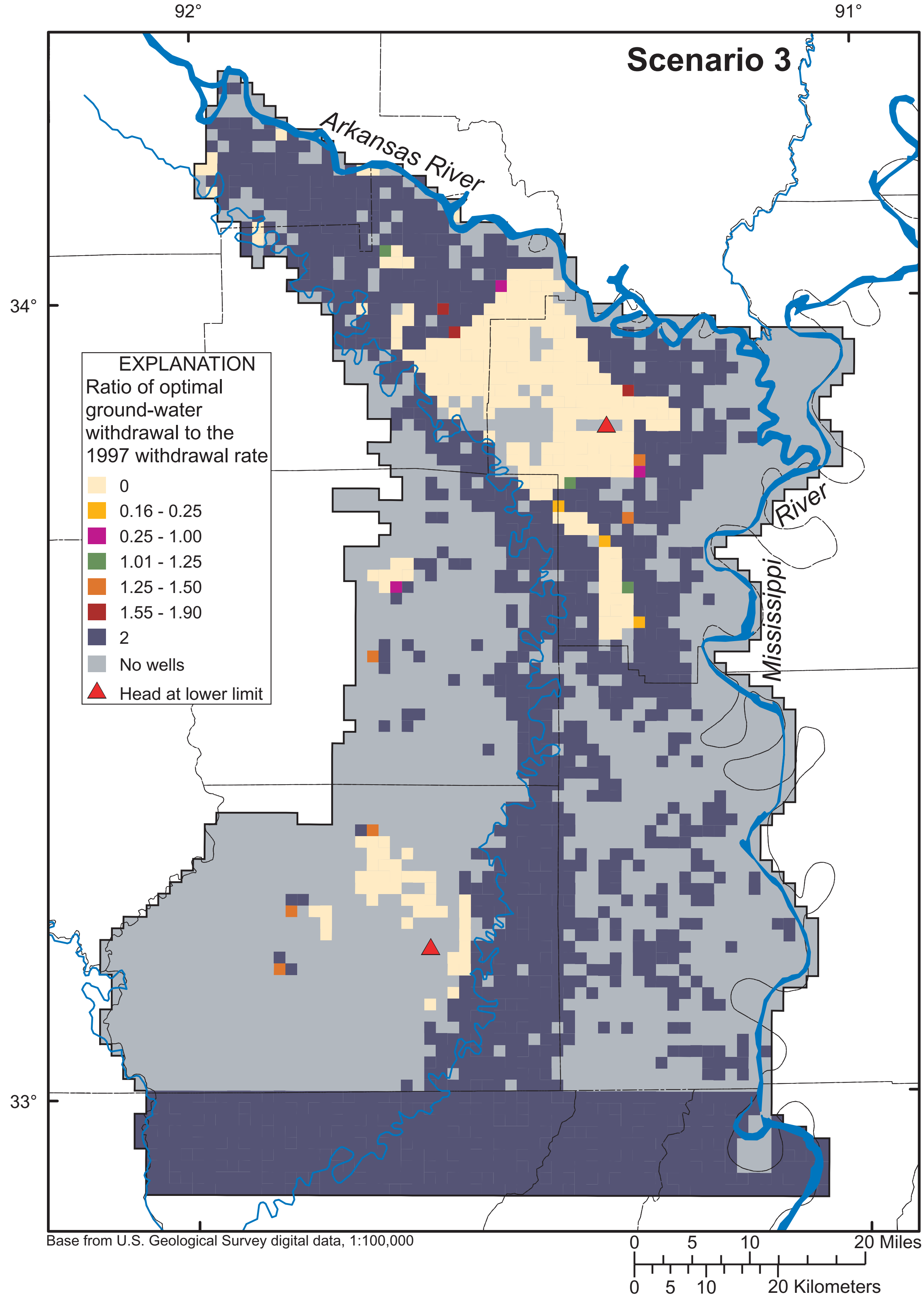

Figure 9. Ratio of optimal ground-water withdrawal calculated by the optimization model to the amount withdrawn in 1997 for withdrawal limits at each well set to 200 percent of the 1997 withdrawal rate.

Table 4. Optimized streamflow withdrawal

River name	Optimized streamflow withdrawal (million cubic feet per day)		
	100 percent of 1997 withdrawal rate (scenario 1)	150 percent of 1997 withdrawal rate (scenario 2)	200 percent of 1997 withdrawal rate (scenario 3)
Arkansas River	4,879.4	4,879.8	4,871.4
Bayou Bartholomew	38.9	40.7	30.7
Total	4,918.3	4,920.5	4,902.1

Unmet Demand

Unmet demand is defined in this report as the difference between the sustainable yield of ground water (or optimized withdrawal rate), and the anticipated demand:

$$U = D - S \tag{7}$$

where U is the unmet demand, in cubic feet per day;
D is the demand, in cubic feet per day; and
S is the sustainable yield, in cubic feet per day.

For example, if the demand is 73.5 Mft^3/d (the amount withdrawn in 1997), and the sustainable yield is calculated to be 70 Mft^3/d, the unmet demand is the difference of these two values, or 3.5 Mft^3/d. Because, unmet demand is not solely a function of the sustainable yield, unmet demand calculations are provided for different values of anticipated demand. Anticipated demand is specified as being either 100-, 150-, or 200-percent of the 1997 withdrawal rate for the entire model area (table 3).

Unmet demand was calculated using different demand rates based on multiples of the 1997 withdrawal rate. From a management perspective, it is useful to calculate the unmet demand under different anticipated demands and sustainable-yield estimates based on different limits on withdrawals. If the demand is specified as the 1997 withdrawal rate for the entire model area, and the sustainable-yield estimates for scenarios 1, 2, and 3 are used to calculate unmet demand, then the resulting unmet demand for the entire model area is 3.3, -7.1, and -36.6 Mft^3/d, respectively. Note that a negative value of unmet demand indicates surplus water availability. Whereas, if the demand is specified as 100-, 150-, and 200-percent of the 1997 withdrawal rate, and the sustainable-yield estimates for scenarios 1, 2, and 3 are used to calculate unmet demand, then the resulting unmet demand for the entire model area is 3.3, 29.7, and 36.9 Mft^3/d, respectively.

Hydraulic-head constraints restrict where and how much ground water and surface water can be extracted. The red triangles in figures 7-9 show the locations where the simulated value of hydraulic head, derived from the optimization model, reached the lower limits of the hydraulic-head constraint (known as a binding constraint). The ring of active pumping cells surrounding the binding constraint lower the potentiometric surface. These pumping cells are effective in reducing the flow toward the center of the model, and dropping the potentiometric surface as a result. If the hydraulic head at the binding constraint is relaxed or lowered, then more withdrawal cells would become active.

Pumping cells in the north-central part of the model, for which an optimized rate of zero was calculated, lie mostly between the Arkansas River and Bayou Bartholomew (figs. 7-9). An additional set of zero-pumping cells occurs to the west of Bayou Bartholomew. Both sets of zero-pumping cells are adjacent to points at which the hydraulic-head constraint (red triangles in figs. 7-9) prevented further withdrawals for all three scenarios.

Optimal Simulated Hydraulic-Head Altitude

Substantial differences occur between simulated hydraulic-head altitudes (or water-level altitudes) for steady-state flow-model simulations using 1997 withdrawal rates and for steady-state simulations using optimal withdrawal rates (sustainable yield) from scenario 1 (fig. 10). Because the 1997 withdrawal rates are unsustainable, some cells of the model are dry, particularly in the area between the Arkansas River and Bayou Bartholomew. In contrast, the optimal hydraulic-head altitude using sustainable yield from scenario 1 shows no dry cells.

The spatial distribution of the difference between simulated hydraulic-head altitude using optimized withdrawal rates from scenario 1 and the altitude corresponding to the half-aquifer-thickness hydraulic-head constraint is shown in figure 11. Over the vast majority of the model area, simulated hydraulic head is at or above the altitude of the constraint.

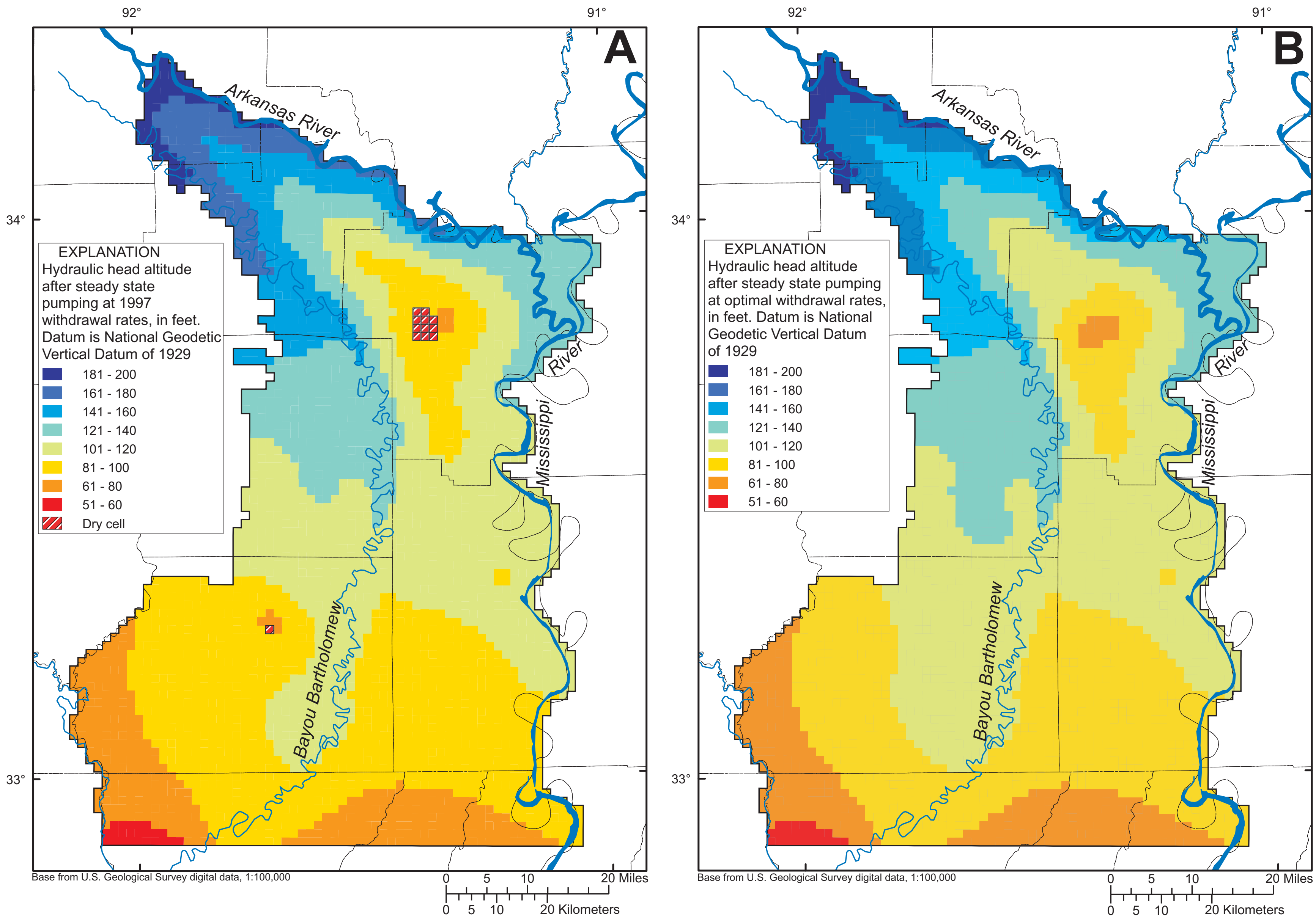

Figure 10. Simulated hydraulic-head altitude at steady state using (A) 1997 withdrawal rates and (B) sustainable yield.

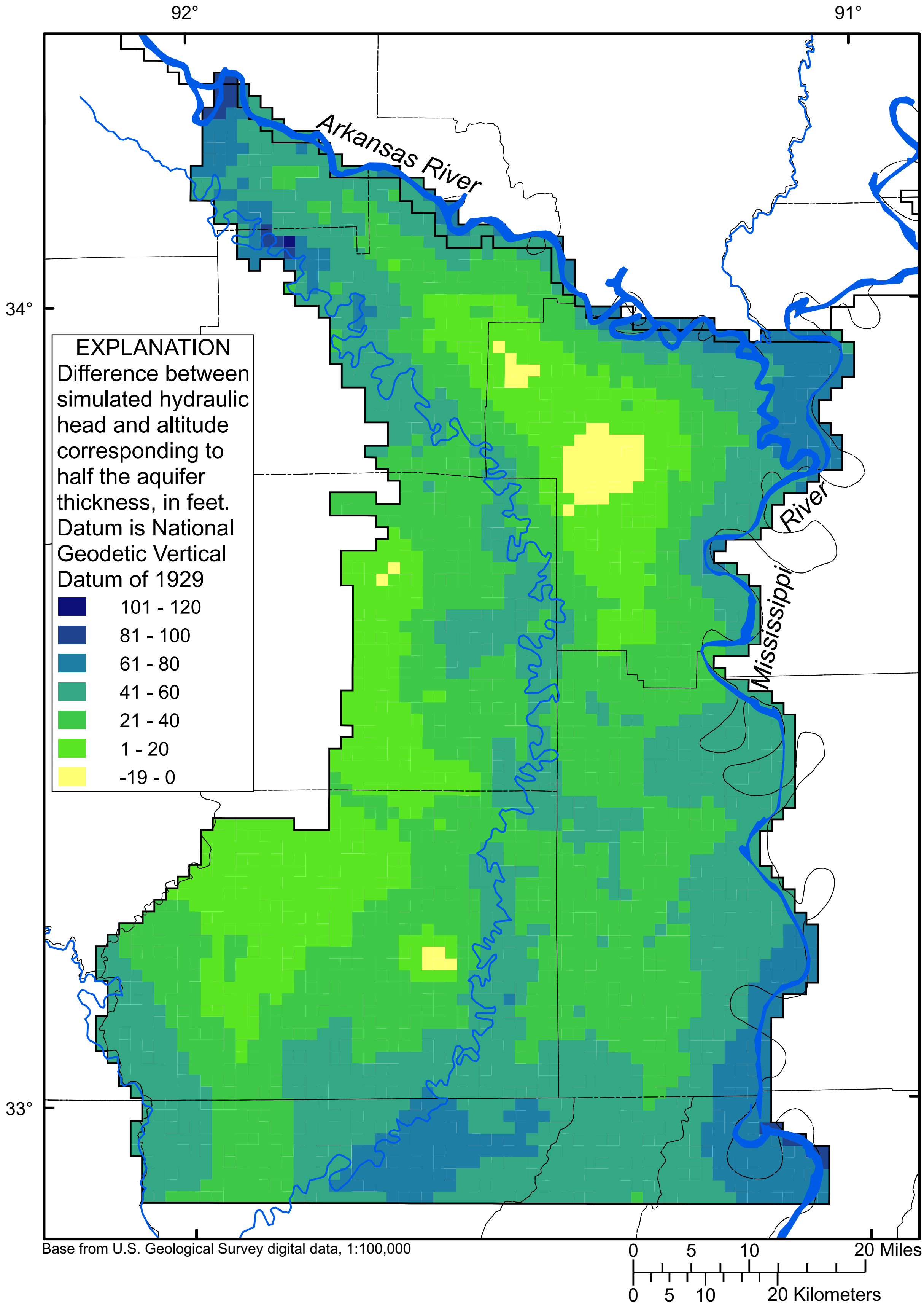

Figure 11. Difference between simulated hydraulic-head altitude using optimized withdrawal rates and altitude of half-the-aquifer-thickness hydraulic-head constraint.

Nonlinear Effects

Because sustainable yield is obtained with the assumption that the model behaves linearly (that is, the change in hydraulic head is a constant multiple of the change in withdrawal rate, regardless of the withdrawal rate), it is important to compare the resulting simulated hydraulic-head altitudes from the flow model derived using sustainable yield to the altitudes corresponding to the hydraulic-head constraints specified in the optimization model. This is done by using the sustainable yield from scenario 1 (upper limit of withdrawals set to 100 percent of the 1997 rates) in the flow model and simulating hydraulic-head altitudes at steady-state conditions. Less than 1.4 percent of the 3,826 hydraulic-head constraint points (that is, all of the active model cells) had flow-model derived values of hydraulic head that was below the hydraulic head constraint (fig.12). The optimized pumping distribution is a good approximation of sustainable yield, despite nonlinear behavior inherent in the model.

The values of sustainable yield should be considered maximum rates, in that hydraulic-head constraints are violated in some areas because of nonlinear responses in hydraulic head to incremental changes in withdrawal rates within the flow model. When the sustainable yield rates are used in the flow model, a few cells have hydraulic heads at steady state that are below the hydraulic-head constraints, which could have been corrected by reducing withdrawal rates further. This was not done, however, because of the few points affected.

Limitations

Sustainable yield results from the optimization model should be used cautiously, mindful that the model represents a simplification of a complex system. The assumption that the flow system behaves linearly is likely the largest discrepancy from actual conditions. Nonetheless, the optimization model does provide estimates of sustainable yield from both the ground-water and surface-water sources that result in hydraulic-head values remaining at or above an altitude corresponding to half the thickness of the aquifer throughout the bulk of the model area, and maintaining streamflows at or above specified minimum amounts.

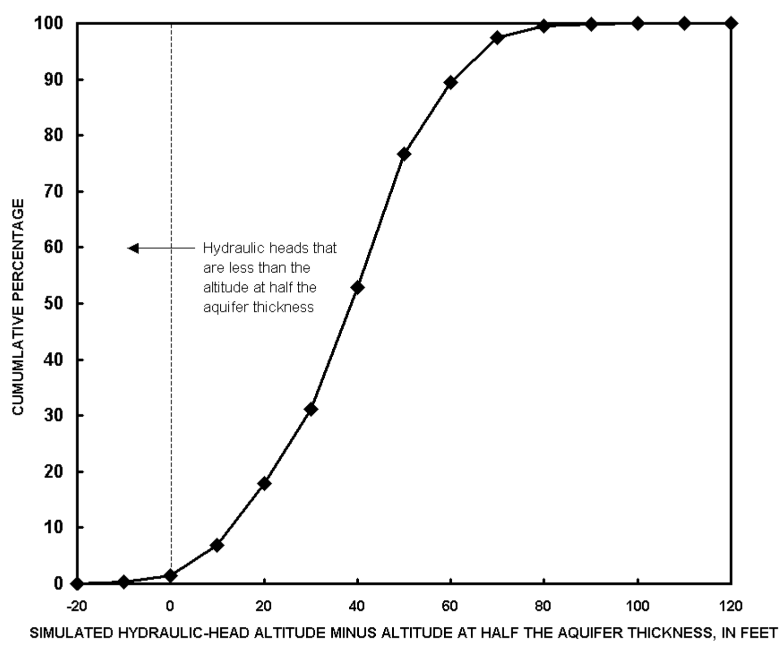

Figure 12. Cumulative percentage of hydraulic-head constraint points less than or equal to the difference between simulated hydraulic head and the altitude corresponding to half the aquifer thickness.

SUMMARY

The Mississippi River Valley alluvial aquifer is a water-bearing assemblage of gravels and sands that underlies about 32,000 mi^2 of Missouri, Kentucky, Tennessee, Mississippi, Louisiana, and Arkansas. The Mississippi River Valley alluvial aquifer supplies large volumes of water for agriculture in Arkansas. Because of the heavy demands placed on the aquifer, several large cones of depression have formed in the potentiometric surface, resulting in lower well yields and degraded water quality in some areas. Several counties, which are within the extent of the alluvial aquifer, have been designated Critical Ground-Water Areas by the Arkansas Soil and Water Conservation Commission (ASWCC). These criteria state that if water levels drop below half the original saturated thickness of the formation, then a “critical ground-water area” may be designated.

A ground-water flow model of the alluvial aquifer was developed for an area covering 3,826 mi^2, extending south from the Arkansas River into the southeastern corner of Arkansas, northeast Louisiana, and Mississippi. The flow model showed that continued ground-water withdrawals at rates commensurate with those of 1997 could not be sustained indefinitely without causing water levels to decline below half the original saturated thickness of the formation. To develop estimates of withdrawal rates that could be sustained relative to the constraints of critical ground-water area designation, the U.S. Geological Survey, in cooperation with the Arkansas Soil and Water Conservation Commission, and Vicksburg District of the U.S. Army Corps of Engineers, applied conjunctive-use optimization modeling to the flow model of the Mississippi River Valley alluvial aquifer in southeastern Arkansas. Conjunctive-use optimization modeling is a technique that can be used to simulate maximum withdrawal rates from both surface water and ground water while honoring constraints with respect to water levels and streamflow. These withdrawal rates form the basis for estimates of sustainable yield from the alluvial aquifer and from rivers specified within the alluvial aquifer model.

The purpose of this report is to describe the application and evaluation of a conjunctive-use optimization model of the Mississippi River Valley alluvial aquifer. A management problem was formulated as one of maximizing the sustainable yield from all ground-water and surface-water withdrawal cells within limits imposed by plausible withdrawal rates, and within specified constraints involving hydraulic head and streamflow. Steady-state conditions were selected because the maximized withdrawals are intended to represent sustainable yield of the system. The optimization model was used to generate response coefficients for each specified withdrawal cell in the model. After all the response coefficients were calculated, they were combined to form a data-input set along with hydraulic-head and streamflow constraints, and formulated as a linear program. Optimal sustainable yield values were obtained by running the linear program under MINOS.

Optimal sustainable-yield values are affected by the rate of recharge and limits to potential withdrawals assigned within the optimization model. Limits were assigned to ground-water withdrawals at individual model cells at multiples of 100, 150, and 200 percent of 1997 withdrawal rates. If no limit is placed on withdrawals, the majority of water production will be from wells proximal to model water sources such as rivers, depriving wells of water that are distant from these sources of water. No limit on withdrawals led to unrealistic optimal withdrawal from wells adjacent to rivers and most interior withdrawal cells had no withdrawal.

One point along the Arkansas River and one point along Bayou Bartholomew were specified for obtaining surface-water sustainable-yield estimates within the optimization model. Streamflow constraints were specified at two river cells based on average 7-day low flows with 10-year recurrence intervals.

Surface-water diversion rates that occurred in 2000 were subtracted from specified overland flow at the appropriate river cells. Diversions totaling 1,787,103 ft^3/d were subtracted from Bayou Bartholomew, whereas no diversions from the Arkansas River were accounted for in this model.

Sustainable-yield estimates for ground water are affected by the allowable upper limit on withdrawals from wells specified in the optimization model. Ground-water withdrawal rates were allowed to increase to 200 percent of the withdrawal rate in 1997. As the overall upper limit is increased, the sustainable yield generally increases. Tests with the optimization model show that without limits on pumping, wells adjacent to sources of water would have optimized withdrawal rates that were orders of magnitude larger than 1997 withdrawal rates. Not only is it physically unlikely that individual wells could pump that much more water, but construction of sufficient additional wells in the one-square mile cells also is unlikely.

Specifying an upper withdrawal limit of 100 percent of the 1997 withdrawal rate, the sustainable yield from ground water for the entire study area is 70.3 Mft^3/d, which is 96 percent of the amount withdrawn in 1997 (73.5 Mft^3/d). If the upper withdrawal limit is increased to 150 percent of the 1997 withdrawal rate, the sustainable yield from ground water for the entire study area is 80.6 Mft^3/d, which is about 110 percent of the amount withdrawn in 1997. If the upper withdrawal limit is increased to 200 percent of the 1997 withdrawal rate, the sustainable yield from ground water for the entire study area is 110.2 Mft^3/d, which is about 150 percent of the amount withdrawn in 1997.

Sustainable yields from the Arkansas River and Bayou Bartholomew are much larger than that from ground water. Total sustainable yield from the Arkansas River and Bayou Bartholomew is about 4,900 Mft^3/d or about 6,700 percent of the amount of ground water withdrawn in 1997. These large sustainable yields represent a potential source of water that could supplement ground water and meet the total water demand, but to do so will require the construction of withdrawal and distribution facilities, which will have legal, political, economic, and social consequences.

Unmet demand (defined as the difference between the optimized ground-water withdrawal rate or sustainable yield, and the anticipated demand) was calculated using different demand rates based on multiples of the 1997-withdrawal rate. Assuming that demand is the 1997 withdrawal rate, and that sustainable-yield estimates are those obtained using upper limits of withdrawal rates of 100-, 150-, and 200-percent of 1997 withdrawal rates, then the resulting unmet demand for the entire model area is 3.3, -7.1, and -36.6 Mft^3/d, respectively. Whereas, if the demand is specified as 100-, 150-, and 200-percent of the 1997 withdrawal rate, and the sustainable-yield estimates remain the same, then the resulting unmet demand for the entire model area is 3.3, 29.7, and 36.9 Mft^3/d. A negative value of unmet demand indicates surplus water availability.

A check of sustainable-yield rates was performed by applying these rates in the flow model run to steady state and comparing simulated hydraulic-head altitude to hydraulic-head constraints. Application of the sustainable-yield rates resulted in hydraulic-head values that were above 98.6 percent of the constraint values. At those points where hydraulic head is below the constraint, deviation from linear model response (that is, a unit incremental change in withdrawal rate results in a unit incremental change in hydraulic head) is suspected.

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