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Simulation of Various Management Scenarios of the Mississippi River Valley Alluvial Aquifer in Arkansas

Prepared in cooperation with the
Arkansas Natural Resources Commission and the
U.S. Army Corps of Engineers, Vicksburg District

Scientific Investigations Report 2006-5052

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

Front Cover: Ground water pumped from the Mississippi River Valley alluvial aquifer being diverted through an alfalfa valve for irrigating adjacent rice fields near Lonoke, Arkansas. Photograph by John B. Czarnecki, U.S. Geological Survey.

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U.S. Department of the Interior
Gale A. Norton, Secretary

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Contents

Figures

1-5. Maps showing:

Tables

Conversion Factors and Abbreviations

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)

Simulation of Various Management Scenarios of the Mississippi River Valley Alluvial Aquifer in Arkansas

By John B. Czarnecki

Abstract

The Mississippi River Valley alluvial aquifer is a water-bearing assemblage of gravels and sands that underlies most of eastern Arkansas and several adjacent States. Ground-water withdrawals have caused cones of depression to develop in the aquifer's water-level surface, some as much as 100 feet deep. Rivers, such as the Arkansas, White, St. Francis, and Mississippi Rivers, are in hydraulic connection with the alluvial aquifer. Recharge to the alluvial aquifer from these rivers becomes induced as ground-water level declines. Long-term water-level measurements in the alluvial aquifer show an average annual decline of 1 foot per year in some areas. The expansion of the cones of depression and the consistent water-level declines indicate that ground-water withdrawals are occurring at a rate that is greater than the sustainable yield of the aquifer.

Ground-water flow models of two areas of the alluvial aquifer (north alluvial and south alluvial—divided by the Arkansas River) previously were developed for eastern Arkansas and parts of northern Louisiana, southeastern Missouri, and adjacent States. The flow models showed that continued ground-water withdrawals at 1997 rates for the alluvial aquifer could not be sustained indefinitely without causing water levels to decline below half of the original saturated thickness of the alluvial aquifer.

To develop estimates of withdrawal rates that could be sustained relative to the constraints of critical ground-water area designation, conjunctive-use optimization modeling previously was applied to the flow models. Optimization modeling was used to calculate the maximum sustainable yield from wells and rivers, while maintaining simulated water levels and streamflows at or above minimum specified limits.

Modifications to the optimization models were made to evaluate the effects of varying ground-water level constraints and surface-water withdrawals from rivers on the model-calculated sustainable yield of the aquifer and rivers. As ground-water-level constraints are relaxed, optimized sustainable yields from rivers decrease because more ground water is available for withdrawal, which would otherwise discharge to the rivers. In addition, sustainable yield of ground water was compared for four different management scenarios involving different water-level constraints and river withdrawal specifications. Scenario 1 is the baseline scenario in which river withdrawals were allowed from all river cells from 11 rivers specified in the north alluvial model, while maintaining ground-water levels at or greater than half the saturated thickness of the aquifer. Scenario 1 includes withdrawals from two irrigation project areas that would remove water from either the Arkansas or White Rivers. Scenario 2 differs from Scenario 1 in that the water-level constraints were relaxed so that the aquifer must have at least 30 feet of saturated thickness everywhere. In Scenario 3, optimized surface-water withdrawal is removed from the model specification in all 11 rivers; however, surface-water withdrawals are fixed at 2000 rates at select points, and no additional withdrawals are permitted. In addition, no withdrawals from either of two irrigation project areas that would remove water from either the Arkansas or White Rivers are specified in Scenario 3, as in Scenarios 1 and 2. Water-level constraints in the aquifer are set to half the saturated aquifer thickness. For Scenario 4, the same conditions as for Scenario 3 were specified, but water-level constraints were relaxed to have at least 30 feet of saturated aquifer thickness. Average differences in sustainable yield of ground water between baseline Scenario 1 and Scenarios 2, 3, and 4 show an increase of 6.74, 6.82, and 13.24 percent, respectively.

A large paper mill in Pine Bluff, Arkansas, currently pumps 30 million gallons per day from the Sparta aquifer, which underlies the alluvial aquifer. The alluvial aquifer has been considered by the mill operators as an alternative source of water, particularly if water were to be withdrawn from a well or wells constructed near the Arkansas River. One potential well site was simulated using an extant model of the south alluvial aquifer by adding it to the existing wells in the model beginning in 1998, and specifying it to pump at 30 million gallons per day for a period of 50 years. Pumping at that rate causes a cone of depression to occur in the alluvial aquifer with a maximum change in water level in the pumped cell of about 40 ft; no dry cells occur after 50 years. Saturated thickness in the pumped cell at 50 years is about 70 ft which is larger than half the original aquifer saturated thickness of 58 ft. Running the model to steady-state conditions with a pumping rate of 30 Mgal/d resulted in water levels dropping an additional 0.1 ft near the pumped well, indicating that conditions were near steady state at 50 years, and that pumping at that rate could be sustained without causing water levels to go below half the aquifer satu-

rated thickness, although this rate was near the maximum rate of about 38.9 million gallons per day, above which model cells would go dry.

Introduction

The Mississippi River Valley alluvial aquifer (hereafter referred to as the alluvial aquifer) is a water-bearing assemblage of gravels and sands that underlies most of eastern Arkansas and several adjacent States. Ground-water withdrawals have caused cones of depression to develop in the aquifer's water-level surface, some as much as 100 feet (ft) deep. Rivers, such as the Arkansas, White, St. Francis, and Mississippi Rivers, are in hydraulic connection with the alluvial aquifer. Recharge to the alluvial aquifer from these rivers becomes induced as ground-water level declines. Long-term water-level measurements in the alluvial aquifer show an average annual decline of 1 foot per year in some areas. The expansion of the cones of depression and the consistent water-level declines indicate that ground-water withdrawals are occurring at a rate that is greater than the sustainable yield of the aquifer.

For many years, the Arkansas Natural Resources Commission (ANRC) has worked with the U.S. Geological Survey (USGS) and other agencies in the development of ground-water flow models to be used as management tools to determine the sustainability of the water resource and the feasibility of various management scenarios. In a management scenario, specification of withdrawal locations from wells and from points along rivers (all with fixed withdrawal limits) are made, as are constraints with respect to water levels or stream flows that must be maintained for a feasible outcome. Ground-water flow models of two areas of the alluvial aquifer (north alluvial and south alluvial—divided by the Arkansas River (fig. 1)) were developed for eastern Arkansas and parts of northern Louisiana, southeastern Missouri, and adjacent States (Reed, 2003; Stanton and Clark, 2003). The flow models showed that continued ground-water withdrawals at 1997 rates for the alluvial aquifer could not be sustained indefinitely without causing water levels to decline below half of the original saturated thickness of the alluvial aquifer, a constraint that is consistent with Critical Ground-Water Area designation by the ANRC for certain counties in eastern Arkansas. To develop estimates of withdrawal rates that could be sustained relative to the constraints of critical ground-water area designation, conjunctive-use optimization modeling was applied to the flow models (Czarnecki and others, 2003a, 2003b). Optimization modeling was used to calculate the maximum sustainable yield from wells and rivers, while maintaining simulated water levels and streamflows at or above minimum specified limits. However, those analyses represented only a few of the possible management scenarios that might be considered for managing the ground- and surface-water resources. For example, if flows in rivers are maintained without additional withdrawals, a larger sustainable yield of ground water should be realized.

The purpose of this report is to describe additional applications of the models in which the effects of varying constraints on ground-water levels and surface-water withdrawals from rivers on the model-calculated sustainable yield of the aquifer and rivers were evaluated. Three scenarios were simulated and results compared to results from a baseline scenario simulation. Scenario 1 is the baseline scenario in which surface-water withdrawal was allowed from all 11 rivers specified in the north alluvial model, while maintaining ground-water levels at or greater than half the saturated thickness of the aquifer. Surface-water withdrawals from the Arkansas and White Rivers for two irrigation project areas are included in Scenario 1, as are withdrawals from relifts corresponding to 2000 withdrawal rates. Scenario 2 was selected to evaluate the effect of lowering the water-level constraint to 30 ft above the base of the aquifer, with all other conditions remaining the same as in Scenario 1. Scenario 3 was selected to evaluate the effect of removing additional water from rivers and not removing water from rivers for the Bayou Meto or Grand Prairie irrigation projects. Each of these projects (U.S. Army Corps of Engineers, 2006a; 2006b) is intended to divert water from either the Arkansas or the White River to supplement ground water in areas of need. Scenario 4 evaluated the combination of conditions for Scenarios 2 and 3. Each of the additional scenarios was expected to result in a larger value of sustainable yield for ground water. Additional simulations also were made to evaluate the hypothetical effects of a potential large well near Pine Bluff, Arkansas, on the hydrologic system.

Conjunctive-Use Optimization Models

This section provides a brief summary of the conjunctive-use optimization models previously developed for the alluvial aquifer; complete descriptions of the models are described in Czarnecki and others (2003a, 2003b). Integral to the conjunctive-use models is the concept of sustainable yield, which is the rate at which water can be withdrawn indefinitely from ground- and surface-water sources without violating specified constraints. This rate is calculated through the use of the conjunctive-use models. The models consist of an objective function, decision variables, and constraints. Specifically, the objective function is to maximize the total rate of withdrawal from ground-water and surface-water sources. The decision variables are the withdrawal rates calculated at managed well sites and river-diversion sites. Constraints consist of water levels and stream-flow rates that are specified at locations within the model domain. The sustainable yield from rivers represents a potential source of water that could supplement ground water. There were 9,979 managed well sites in the north alluvial model area and 1,841 well sites in the south alluvial model area. There were 1,165 river-withdrawal sites in the north alluvial model and 2 river-withdrawal sites in the south alluvial model.

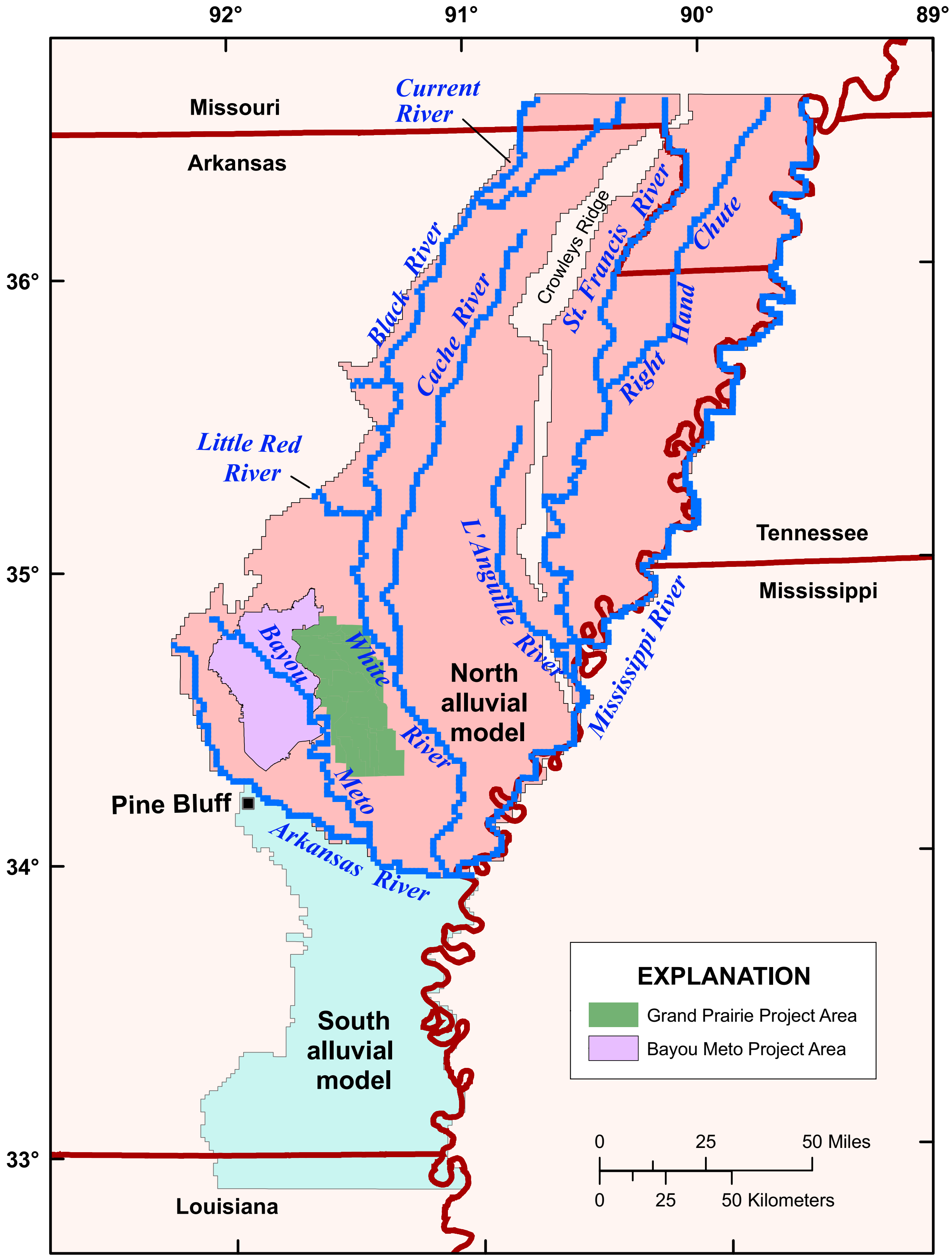


Figure 1. Location of north and south alluvial model areas.

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 ground-water withdrawals to a maximum of 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 9,979 model cells corresponding to well locations and at 1,165 river cells.

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:

$$\text{maximize } z = \Sigma q_{well} + \Sigma q_{river} \tag{1}$$

where z is the total managed water withdrawal, in cubic feet per day;

Σq_{well} is the sum of ground-water withdrawal rates from all managed wells, in cubic feet per day; and

Σq_{river} is the sum of surface-water withdrawal rates from all managed river reaches, in cubic feet per day.

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

$$h_c \geq h_{minimum} \tag{2}$$

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 ANRC 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. 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.

Streamflow is regulated in Arkansas by ANRC 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

$$q^R_{head} + \Sigma q^R_{overland} + \Sigma q^R_{groundwater} - \Sigma q^R_{diversions} - \Sigma q^R_{river} \geq q^R_{minimum} \tag{3}$$

where

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

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

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

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

Σq^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.

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 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

$$0 \leq q_{well_i} \leq M q_{well_{1997}} \tag{4}$$

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.

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 (that is, greater than the streamflow constraint) 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 at all river cells. Because each withdrawal amount is optimized, it is dependent on all of the model constraints and conditions, not just those in the immediate vicinity of the withdrawal.

For optimization, 9,979 one-square mile cells were used to represent pumping from 35,043 wells in 1997. Each cell was specified as a managed well (that is, a decision variable) within MODMAN (Greenwald, 1998). In 1997, the annual pumping rate for all wells was 635.6 million cubic feet per day (Mft^3/d). Note that in the north alluvial model (Reed, 2003), dry cells occurred in transient simulations with projected pumpage to 2049 causing pumping wells at the dry cells to become inactive, reducing total pumping to 631 Mft^3/d. For the sustainable-yield analysis, the optimized rate at each of the 9,979 cells was allowed to vary between a rate of zero to a maximum rate equal to a multiple between 1 and 2 to that which was pumped in 1997. An upper limit was specified because no limit on pumping led to unrealistic optimal withdrawal from wells adjacent to rivers.

To allow for both optimal conjunctive-use of surface water and ground water within the optimization model, 11 rivers were specified (table 1). Flow into the uppermost cell of each river is based on mean-annual flow for the period of record, which includes high, moderate, and low flow conditions. Overland flow is an estimate of water entering the river from tributaries and surface runoff within the area of the drainage. Overland flow less the amount of water diverted or withdrawn during 2000 and planned diversions from Bayou Meto and Grand Prairie irrigation projects are listed in table 1. Planned diversions are 63,339,248 ft^3/d for the Bayou Meto project area and 55,078,367 ft^3/d for the Grand Prairie project area, which factor in an additional 30 and 40 percent transmission loss, respectively. Of the 11 rivers specified, 3 (Arkansas, Cache, and Little Red) have streamflow constraints specified at each river cell as the 7-day, 10-year-recurrence low flows (7Q10) (Steve Loop, Arkansas Natural Resources Commission, written commun., 2001), which are derived from historical streamflow for the rivers. Five rivers (Bayou Meto, Black, L'Anguille, St. Francis, and White) were specified with a constraint that was substantially larger than the 7Q10 value for each of the rivers. Where a streamflow constraint was not provided by ANRC, an arbitrary value of zero was specified (Current and Right Hand Chute) except in the case of the Mississippi River where a value of 50 billion ft^3/d was specified. If a value of zero was specified, then a stream could be pumped dry; however, this condition occurred only in Right Hand Chute (see table 3). Note that if a minimum flow constraint was set equal to the 7Q10 value, the available streamflow within the optimization model would be limited all year long to an amount equal to or greater than 7Q10, although 7Q10 data reflect a statistically low flow that occurs only once every 10 years, and then for only 7 consecutive days.

Table 1. Rivers, streamflows, and streamflow constraints.

[ANRC, Arkansas Natural Resources Commission; Flow constraint from ANRC based on an annual minimum 7-consecutive-day average flow with a recurrence interval of 10 years; ft^3/d, cubic foot per day]

River name	Number of model cells	Flow into uppermost river cell of model (ft^3/d)	Overland flow less surface withdrawals per river (ft^3/d)	Flow constraint (ft^3/d)	Source for value of constraint
Arkansas	97	4,903,200,000	87,338,294	100,224,000	ANRC
Bayou Meto	77	17,020,800	69,289,254	605,000	ANRC
Black	88	148,996,800	960,301,031	27,302,400	ANRC
Cache	105	50,328,000	207,634,689	950,400	ANRC
Current	31	280,886,400	61,386,926	0	Arbitrary
L'Anguille	54	21,556,800	107,769,192	3,974,400	ANRC
Little Red	15	247,017,600	19,501,549	0	Arbitrary
Mississippi	305	50,185,440,000	911,455,120	50,000,000,000	Arbitrary
Right Hand Chute	74	244,944,000	44,997,010	0	Arbitrary
St. Francis	169	231,552,000	1,884,825,939	7,257,600	ANRC
White	150	1,248,480,000	1,807,462,700	665,000,000	ANRC
Total	1,165	57,579,422,400	6,161,961,704[1]	50,805,313,800	

[1] Summation assumes that overland flow less surface withdrawals are applied at river cell.

Management Scenarios

Several management scenarios involving different water-level constraints and river withdrawal specifications were evaluated using the conjunctive-use optimization model. As implied in the previous section, the sustainable yield calculated by the optimization model is dependent on the defined upper limits of withdrawal rates at wells and rivers that are specified in the model; consequently, sustainable yield is likely to change as the values of the specified withdrawal rates are varied. Rates of sustainable yield also depend on the values of ground-water levels specified in the optimization model; if the specified values are relaxed (that is, ground-water levels are allowed to be drawn down further), then the sustainable yield of the aquifer may be increased. This section describes management scenarios from optimization-model runs in which the specified values of river withdrawals and ground-water levels were varied for the north alluvial model. Also discussed are results using the south alluvial flow model to evaluate pumping adjacent to the Arkansas River near Pine Bluff.

Constraining River Withdrawals and Water Levels

Differences in sustainable yield from ground water at the county level illustrate the complex interplay of hydrologic conditions that exist throughout the model area, which are affected in part by model geometry, aquifer thickness, proximity to surface-water sources, and constraints imposed. Constraints or conditions specified in each of the four management scenarios are listed in table 2. A comparison of ground-water sustainable yield by county is shown in table 3 for various scenarios involving changes in river withdrawals and water-level constraints for the north alluvial model. Scenario 1 is the baseline scenario in which river withdrawals were allowed from all river cells from 11 rivers specified in the north alluvial model, while maintaining ground-water levels at or greater than half the saturated thickness of the aquifer. Scenario 2 differs from Scenario 1 in that the water-level constraints were relaxed so that the aquifer must have at least 30 feet of saturated thickness everywhere. In Scenario 3, optimized surface-water withdrawal is removed from the model specification in all 11 rivers; however, surface-water withdrawals are fixed at 2000 rates at select points, and no additional withdrawals are permitted. In addition, no withdrawals from either the Bayou Meto or Grand Prairie Project areas that would remove water from the Arkansas and White Rivers, respectively, are specified in Scenario 3. Water-level constraints in the aquifer are set to half the saturated aquifer thickness. For Scenario 4, the same conditions as for Scenario 3 were specified, but water-level constraints were relaxed to have at least 30 feet of saturated aquifer thickness.

Percentage of ground-water withdrawals that are sustainable relative to 1997 pumping rates for Scenario 1 in the conjunctive-use optimization model of the north alluvial aquifer (Czarnecki and others, 2003a) resulted in the distribution of sustainable yield shown in figure 2A. Note that the lowest percentage values of sustainable yield from ground water occur in Jackson and Phillips Counties (7 and 18 percent of the 1997 ground-water withdrawal rate). This is because the conjunctive-use optimization model is designed to maximize both ground-water and surface-water withdrawals. Jackson County is bordered by the Black River on its northwestern boundary; Phillips County is bordered by the Mississippi River on its eastern side. If no optimized surface-water withdrawal locations are specified, then some of that surface water that would otherwise be withdrawn directly from these two rivers is available for ground-water withdrawal.

Table 2. Constraints or conditions specified in each of the four management scenarios.

	Constraint or condition			
Scenario	Minimum ground-water level at or above half the thickness of the alluvial aquifer	Minimum ground-water level at or above 30 feet from the bottom of the alluvial aquifer	Surface water withdrawals allowable in all river cells; surface-water withdrawals specified for both Bayou Meto and Grand Prairie irrigation projects	No surface water withdrawals other than those occurring in 2000; no surface-water withdrawals for Bayou Meto or Grand Prairie irrigation projects
1	X		X	
2		X	X	
3	X			X
4		X		X

Table 3. Percentage of sustainable yield relative to 1997 ground-water withdrawal rates in selected counties in Arkansas in the north alluvial model area.

	Percentage of 1997 ground-water withdrawal that is sustainable				Percentage difference between Scenario 1 and:		
County	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Arkansas	46.57	47.82	47.18	48.97	1.24	0.61	2.40
Clay	98.91	99.06	100.00	100.00	0.15	1.09	1.09
Craighead	53.18	66.17	60.08	67.47	12.99	6.91	14.29
Crittenden	87.12	98.15	88.53	98.29	11.02	1.40	11.16
Cross	59.67	78.07	60.60	60.49	18.40	0.93	0.82
Desha	94.29	94.29	94.29	94.29	0.00	0.00	0.00
Greene	73.68	88.88	74.81	88.88	15.20	1.13	15.20
Independence	71.07	71.06	72.34	72.33	0.00	1.28	1.26
Jackson	6.81	6.81	74.14	87.38	0.00	67.34	80.58
Jefferson	75.72	78.62	77.44	78.19	2.90	1.72	2.47
Lawrence	60.43	84.03	78.84	88.48	23.60	18.41	28.05
Lee	45.71	79.14	34.62	74.17	33.43	-11.09	28.46
Lincoln	98.51	98.51	98.75	98.75	0.00	0.25	0.25
Lonoke	41.96	41.37	41.73	42.09	-0.59	-0.23	0.13
Mississippi	100.00	100.00	100.00	100.00	0.00	0.00	0.00
Monroe	73.61	77.23	85.46	83.21	3.62	11.85	9.60
Phillips	18.02	77.79	61.06	81.38	59.77	43.04	63.36
Poinsett	50.55	57.34	39.58	43.39	6.79	-10.97	-7.15
Prairie	50.38	48.11	53.97	55.92	-2.27	3.59	5.54
Pulaski	100.00	100.00	100.00	100.00	0.00	0.00	0.00
Randolph	91.22	96.27	96.71	100.00	5.05	5.48	8.78
St. Francis	35.74	39.95	32.94	48.90	4.21	-2.81	13.16
White	68.07	68.19	74.33	77.03	0.13	6.27	8.97
Woodruff	47.00	13.13	64.43	76.27	-33.86	17.44	29.27
Average	64.51	71.25	71.33	77.74	6.74	6.82	13.24

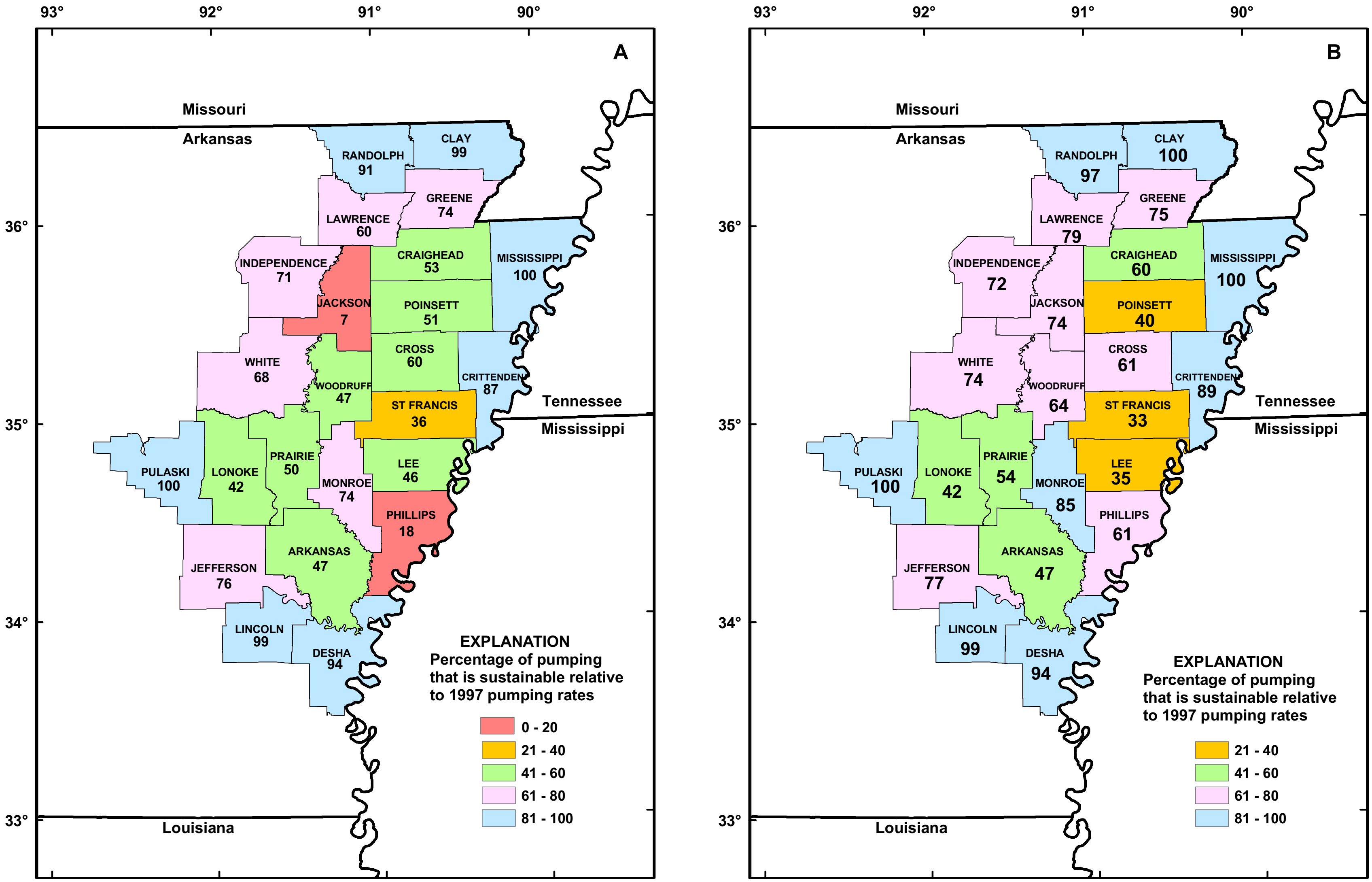


Figure 2. Counties in Arkansas showing the percentage of ground-water withdrawals that are sustainable relative to 1997 pumping rates using (A) optimized river withdrawals and (B) no optimized river withdrawals (that is, surface-water withdrawals are fixed at 2000 rates at select points, and no additional withdrawals are permitted).

If optimized surface-water withdrawal is removed from the model specification for Scenario 3, the distribution of sustainable yield from ground water relative to 1997 pumping rates is that shown in figure 2B. Note the substantial increase in the ground-water sustainable yields that result in Jackson and Phillips Counties with 74 and 61 percent, respectively, of the 1997 pumping rate.

Results from the conjunctive-use optimization model of the north alluvial aquifer for each of the four scenarios are shown in figures 3A-3D as a ratio of optimal withdrawal rates relative to 1997 withdrawal rates at model cells with a pumping well in 1997. When ground-water level constraints are relaxed (Scenarios 2 and 4), optimal ground-water withdrawal rates increase. When optimized river withdrawals are removed (Scenario 3), sustainable yield from ground water increases. When ground-water level constraints are relaxed (Scenario 4), sustainable yield from ground water increases further still. Jackson County, which has a common border with the Black River on its northwest boundary, exhibited the largest change in percentage of 1997 ground-water withdrawal that is sustainable relative to Scenario 1. This difference resulted largely from the removal of surface-water withdrawal. Sustainable yield from ground water in Phillips County also increases when surface-water withdrawals are removed; however, an even larger increase occurs by relaxing the water-level constraint (Scenario 2). When averaged over all of the counties (table 3), sustainable yield from ground water increases as water-level constraints are relaxed, or surface water withdrawals are removed. Average differences in sustainable yield of ground water between baseline Scenario 1 and Scenarios 2, 3, and 4 show increases of 1997 rates of 6.74, 6.82, and 13.24 percent, respectively.

Optimized sustainable yield from rivers is affected by aquifer water-level constraints. Table 4 shows that as ground-water-level constraints are relaxed (such as between Scenarios 1 and 2), optimized sustainable yields from rivers decrease because more ground water is available for withdrawal, which would otherwise discharge to the rivers. Values of water available listed in table 4 reflect mean-annual flow into the head of each stream and mean-annual overland flow to the stream, which are assumed to be continuous throughout the year, although low-flow periods likely would have less water available.

Analysis of a Potential Large Well Near Pine Bluff, Arkansas

A large paper mill in Pine Bluff, Arkansas, currently (2006) pumps 30 Mgal/d from the Sparta aquifer, which underlies the alluvial aquifer. This mill is the largest single user of ground water in Jefferson County. The alluvial aquifer has been considered by the mill operators as an alternative source of water, particularly if water was withdrawn from a well or wells constructed near the Arkansas River (fig. 4).

The hypothetical effect of one potential well site was simulated using the south alluvial model (Stanton and Clark, 2003). The potential well was added to the existing wells in the model beginning in 1998, and was specified to pump at 30 Mgal/d for a period of 50 years. Pumping at that rate causes a cone of depression to occur in the alluvial aquifer with a maximum change in water level in the pumped cell of about 40 ft; no dry cells occur after 50 years (fig. 5). Saturated thickness in the pumped cell at 50 years is about 70 ft which is larger than half the original aquifer saturated thickness (58 ft). Running the model to steady-state conditions with a pumping rate of 30 Mgal/d resulted in water levels dropping an additional 0.1 ft near the pumped well, indicating that conditions were near steady state at 50 years, and that pumping at that rate could be sustained without causing water levels to go below half the aquifer saturated thickness.

However, the increased pumping of 30 Mgal/d is near the threshold at which dry cells occur after 50 years. If pumping is increased to 40 Mgal/d at the potential well site, dry cells occur in the vicinity because the pumping rate is unsustainable. The pumping threshold for the occurrence of dry cells is between 38.9 and 39.0 Mgal/d.

Model Limitations

The values of sustainable yield should be considered maximum rates, in that head constraints were violated in some areas because of non-linear responses in hydraulic head to incremental changes in withdrawal rates within the flow model. When the sustainable yield rates were used in the flow model of Reed (2003), a few cells had values of hydraulic head at steady state that were 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 where this occurred. From a management standpoint, however, the values might be considered to be conservative because they apply to steady-state conditions that will not be reached for possibly hundreds of years. Values of sustainable yield from streams are based on an average annual flow into the head of a stream and overland flow to the stream that are continuous throughout the year, even during low-flow periods when less water would be available.

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.

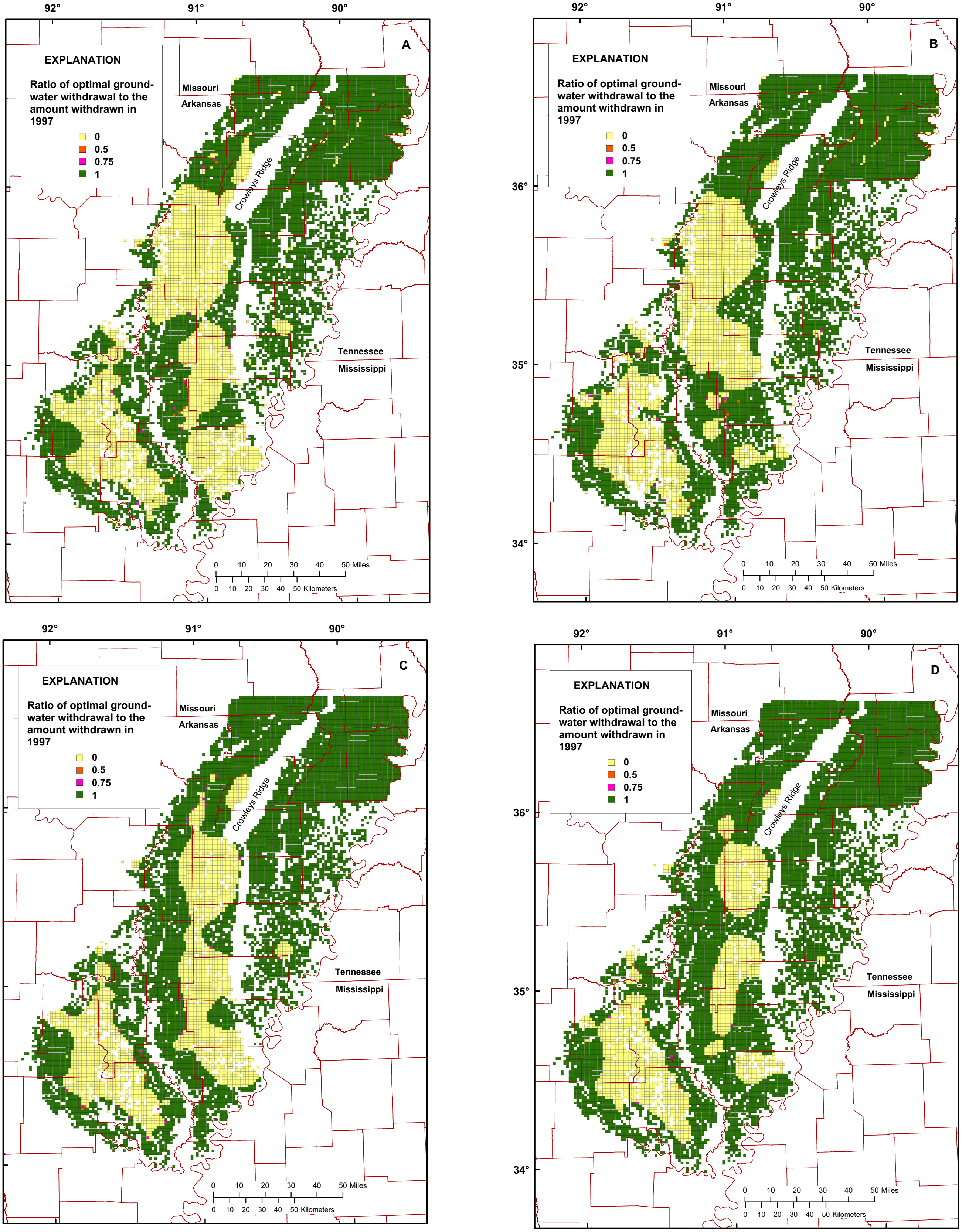
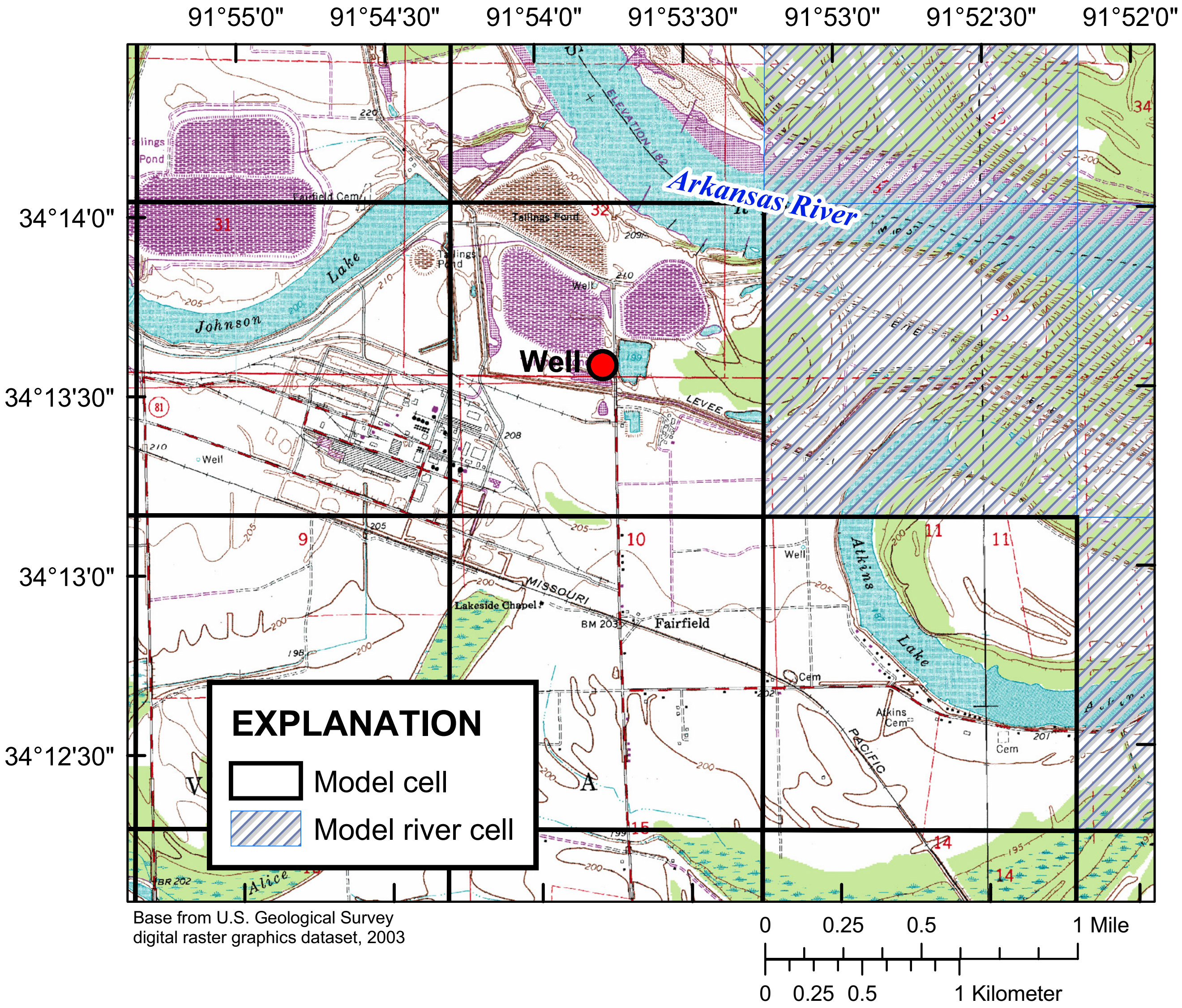


Figure 3. Ratio of optimal ground-water withdrawal calculated by the optimization model to the amount withdrawn in 1997: (A) Scenario 1 with optimized river withdrawals and water-level constraints set at half the saturated thickness of the aquifer; (B) Scenario 2 with optimized river withdrawals and water-level constraints set to a minimum of 30 feet of saturated aquifer thickness; (C) Scenario 3 with no optimized river withdrawals or withdrawals from Grand Prairie or Bayou Meto project areas and water-level constraints set at half the saturated thickness of the aquifer; and (D) Scenario 4 with no river withdrawals or withdrawals from Grand Prairie or Bayou Meto project areas and water-level constraints set to a minimum of 30 feet of saturated aquifer thickness.



Base from U.S. Geological Survey
digital raster graphics dataset, 2003

Figure 4. Location of potential large well about 10 miles east of Pine Bluff, Arkansas.

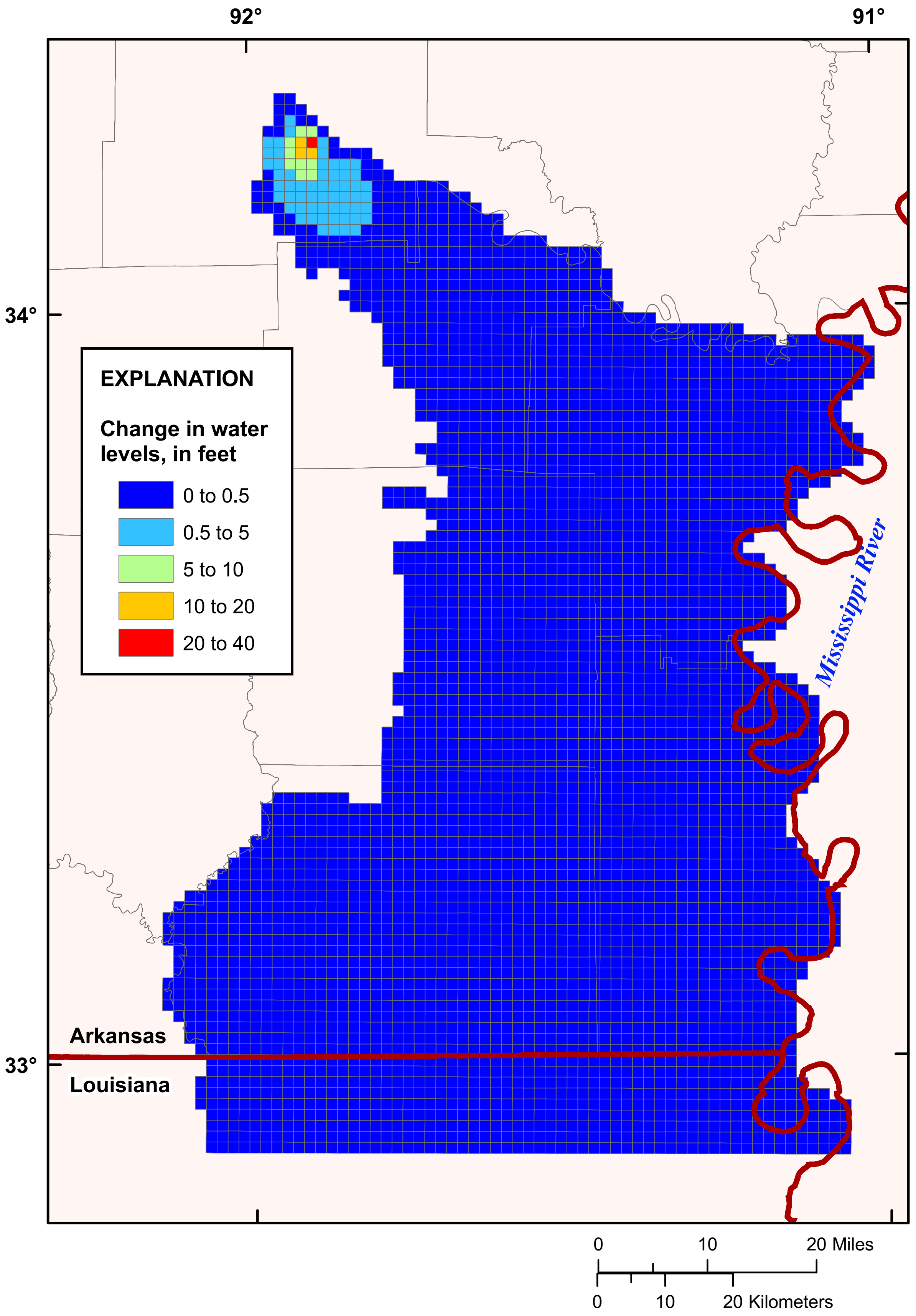


Figure 5. Simulated water-level change in the south alluvial aquifer model in 2049 resulting from the addition of one well pumping at 30 million gallons per day for 50 years.

Summary and Conclusions

The Mississippi River Valley alluvial aquifer is a water-bearing assemblage of gravels and sands that underlies most of eastern Arkansas and several adjacent States. Ground-water withdrawals have caused cones of depression to develop in the aquifer's water-level surface, some as much as 100 feet deep. Rivers, such as the Arkansas, White, St. Francis, and Mississippi Rivers are in hydraulic connection with the alluvial aquifer. Recharge to the alluvial aquifer from these rivers becomes induced as ground-water level declines. Long-term water-level measurements in the alluvial aquifer show an average annual decline of 1 foot per year in some areas. The expansion of the cones of depression and the consistent water-level declines indicate that ground-water withdrawals are occurring at a rate that is greater than the sustainable yield of the aquifer.

Ground-water flow models of two areas of the alluvial aquifer (north alluvial and south alluvial—divided by the Arkansas River) were developed for eastern Arkansas and parts of northern Louisiana, southeastern Missouri, and adjacent States. The flow models showed that continued ground-water withdrawals at 1997 rates for the alluvial aquifer could not be sustained indefinitely without causing water levels to decline below half of the original saturated thickness of the alluvial aquifer.

To develop estimates of withdrawal rates that could be sustained relative to the constraints of critical ground-water area designation, conjunctive-use optimization modeling was applied to the flow models. Optimization modeling was used to calculate the maximum sustainable yield from wells and rivers, while maintaining simulated water levels and streamflows at or above minimum specified limits.

Modifications to the models were made to evaluate the effects of varying ground-water level constraints and surface-water withdrawals from rivers on the model-calculated sustainable yield of the aquifer and rivers. As ground-water-level constraints are relaxed, optimized sustainable yields from rivers decrease because more ground water is available for withdrawal, which would otherwise discharge to the rivers. In addition, sustainable yield of ground water was compared for four different scenarios involving different constraints and river withdrawal specifications. Scenario 1 is the baseline scenario in which river withdrawals were allowed from all river cells from 11 rivers specified in the north alluvial model, which includes river withdrawals from the Arkansas and White River for the Bayou Meto and Grand Prairie irrigation project areas, while maintaining ground-water levels at or greater than half the saturated thickness of the aquifer. Scenario 2 differs from Scenario 1 in that the water-level constraints were relaxed so that the aquifer must have at least 30 feet of saturated thickness everywhere. In Scenario 3, optimized surface-water withdrawal is removed from the model specification in all 11 rivers; however, surface-water withdrawals are fixed at 2000 rates at select points, and no additional withdrawals are permitted. In addition, no withdrawals from either the Bayou Meto or Grand Prairie Project areas that would remove water from the Arkansas and White Rivers, respectively, are specified in Scenario 3. Water-level constraints in the aquifer are set to half the saturated aquifer thickness. For Scenario 4, the same conditions as for Scenario 3 were specified, but water-level constraints were relaxed to have at least 30 feet of saturated aquifer thickness. Average differences in sustainable yield of ground water between baseline Scenario 1 and Scenarios 2, 3, and 4 show an increase of 6.74, 6.82, and 13.24 percent, respectively.

A large paper mill in Pine Bluff, Arkansas, currently (2006) pumps 30 Mgal/d from the Sparta aquifer, which underlies the alluvial aquifer. The alluvial aquifer has been considered by the mill operators as an alternative source of water, particularly if water were to be withdrawn from a well or wells constructed near the Arkansas River. One potential well site was simulated using an extant model of the alluvial aquifer south of the Arkansas River by adding it to the existing wells in the model beginning in 1998, and specifying it to pump at 30 Mgal/d for a period of 50 years. Pumping at that rate causes a cone of depression to occur in the alluvial aquifer with a maximum change in water level in the pumped cell of about 40 ft; no dry cells occur after 50 years. Saturated thickness in the pumped cell at 50 years is about 70 ft which is larger than half the original aquifer saturated thickness of 58 ft. Running the model to steady-state conditions with a pumping rate of 30 Mgal/d resulted in water levels dropping an additional 0.1 ft near the pumped well, indicating that conditions were near steady state at 50 years, and that pumping at that rate could be sustained without causing water levels to go below half the aquifer saturated thickness, although this rate was near the maximum rate of about 38.9 Mgal/d, above which model cells would go dry.

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