Prepared in cooperation with the Arkansas Natural Resources Commission

Validation of a Ground-Water Flow Model of the Mississippi River Valley Alluvial Aquifer Using Water-Level and Water-Use Data for 1998–2005 and Evaluation of Water-Use Scenarios

Scientific Investigations Report 2009–5040

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

Front cover. Soybean field in central Arkansas. Photograph by Ralf Montanus, U.S. Geological Survey.

Validation of a Ground-Water Flow Model of the Mississippi River Valley Alluvial Aquifer Using Water-Level and Water-Use Data for 1998-2005 and Evaluation of Water-Use Scenarios

By Jonathan A. Gillip and John B. Czarnecki

In cooperation with the Arkansas Natural Resources Commission

Scientific Investigations Report 2009-5040

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Gillip, J.A., and Czarnecki, J.B., 2009, Validation of a ground-water flow model of the Mississippi River Valley alluvial aquifer using water-level and water-use data for 1998-2005 and evaluation of water-use scenarios: U.S. Geological Survey Scientific Investigations Report 2009-5040, 22 p.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above or below the vertical datum.

Validation of a Ground-Water Flow Model of the Mississippi River Valley Alluvial Aquifer Using Water-Level and Water-Use Data for 1998-2005 and Evaluation of Water-Use Scenarios

By Jonathan A. Gillip and John B. Czarnecki

Abstract

A ground-water flow model of the Mississippi River Valley alluvial aquifer in eastern Arkansas, developed in 2003 to simulate the period of 1918-98, was validated with the addition of water-level and water-use data that extended the observation period to 2005. The original model (2003) was calibrated using water-level observations from 1972, 1982, 1992, and 1998, and water-use data through 1997. The original model subsequently was used to simulate water levels from 1999 to 2049 and showed that simulation of continued pumping at the 1997 water-use rate could not be sustained indefinitely without causing dry cells in the model.

After publication of the original ground-water flow model, a total of 3,616 water-level observations from 698 locations measured during the period of 1998 to 2005 became available. Additionally, water-use data were compiled and used for the same period, totaling 290,005 discrete water-use values from 43,440 wells with as many as 39,169 wells pumping in any one year. Total pumping (which is primarily agricultural) for this 8-year period was about 2.3 trillion cubic feet of water and was distributed over approximately 10,340 square miles within the model area.

An updated version of the original ground-water flow model was used to simulate the period of 1998-2005 with the additional water-level and water-use data. Water-level observations for 1998-2005 ranged from 74 to 293 feet above National Geodetic Vertical Datum of 1929 across the model area. The maximum water-level residual (observed minus simulated water-level values) for the 3,616 water-level observations was 52 feet, the minimum water-level residual was 60 feet, the average annual root mean squared error was 8.2 feet, and the annual average absolute residual was 6.0 feet. A correlation coefficient value of 0.96 was calculated for the line of best fit for observed to simulated water levels for the combined 1998-2005 dataset, indicating a good fit to the data and an acceptable validation of the model.

After the validation process was completed, additional ground-water model simulations were run to evaluate the response of the aquifer with the 2005 water-use rate applied through 2049 (scenario 1) and the 2005 water-use rate increased 2 percent annually until 2049 (scenario 2). Scenario 1 resulted in 779 dry cells (779 square miles) by 2049 and scenario 2 resulted in 2,910 dry cells (2,910 square miles) by 2049. In both scenarios, the dry cells are concentrated in the Grand Prairie area and Cache River area west of Crowleys Ridge. However, scenario 2 resulted in dry cells to the east of Crowleys Ridge as well. A simulation applying the 1997 water-use rate contained in the original ground-water flow model resulted in 401 dry cells (401 square miles) in the Grand Prairie and Cache River areas.

Introduction

The Mississippi River Valley alluvial aquifer (hereafter referred to as alluvial aquifer) is a water-bearing assemblage of gravels and sands that underlies about 32,000 square miles (mi^2) of Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. In Arkansas, the alluvial aquifer occurs in an area generally ranging from 50 to 125 miles (mi) in east to west extent and about 250 mi north to south, adjacent to the Mississippi River (Holland, 2007). The alluvial aquifer behaves as a confined or unconfined aquifer depending on location (Czarnecki and others, 2003). Withdrawal of ground water from the alluvial aquifer for agriculture started in the early 1900's in the Grand Prairie area for the irrigation of rice and soybeans. Water-level declines in the alluvial aquifer were documented as early as 1927 (Engler and others, 1945). Long-term water-level measurements in the alluvial aquifer show an average annual decline of 1 foot per year in some areas (Czarnecki, 2006). From 1965 to 2005, water use in the alluvial aquifer increased 655 percent. In 2005, 834.5 million cubic feet per day (Mft^3/d) of water were pumped from the aquifer, primarily for irrigation and fish farming (Holland, 2007).

Several cones of depression in excess of 100 feet (ft) deep have formed in the potentiometric surface, resulting in lower well yields, and in some cases degraded water quality. Several counties in the Grand Prairie area have been designated as Critical Ground Water Areas (Arkansas Natural Resources Commission, 1991). Ground-water level declines have induced recharge into the aquifer from the Arkansas, White, St. Francis, and Mississippi Rivers (Czarnecki, 2006). A ground-water flow model by Reed (2003) showed that continued water-use at the 1997 rate was unsustainable. The U.S. Geological Survey (USGS) in cooperation with the Arkansas Natural Resources Commission conducted a study to validate and update the original model (Reed, 2003) and evaluate water-use scenarios.

Purpose and Scope

The purpose of this report is to validate and update the original north alluvial model (Reed, 2003) of the Mississippi River Valley alluvial aquifer using water-level and water-use observations now available for 1998-2005 without varying the other model variables used in the calibration of Reed (2003). Results from the updated ground-water flow model and two scenarios are presented for model runs through the end of 2049 for various pumping scenarios to evaluate the sustainability of current and potential water use. A comparison of dry cells between the model of Reed (2003) and the updated model are presented for two scenarios.

Previous Studies

The sediments of the Mississippi River Valley have been the subject of many previous reports. The subsurface geology and ground-water resources in southern Arkansas and northern Louisiana were described by Veatch (1906). The ground-water resources of northeastern Arkansas were further described by Stephenson and others (1916). Extensive geologic investigations were performed by the U.S. Army Corps of Engineers along the Mississippi River Valley between 1941 and 1944 (Fisk, 1944). Krinitzsky and Wire (1964) expanded on the geologic investigations of Fisk and examined the ground-water conditions. Cushing and others (1964) and Boswell and others (1968) studied Quaternary-age aquifers in the Mississippi River Valley, including the alluvial aquifer. Boswell and others (1968) first used the term Mississippi River Valley alluvial aquifer to refer to the water-yielding sediments in the alluvial plain of the Mississippi River.

Several reports have documented the results of model simulations of the flow system within and across boundaries of the alluvial aquifer (Ackerman, 1989a, 1989b, 1990; Broom and Lyford, 1981; Mahon and Poynter, 1993; Peralta and others, 1985; Reed, 2003). Ground-water flow models of two areas of the alluvial aquifer were developed: the north alluvial model (Reed, 2003) and the south alluvial model (Stanton and Clark, 2003), divided by the Arkansas River. Reed (2003) recalibrated and extended the MODFLOW ground-water flow model (hereafter referred to as the original flow model) of Mahon and Poynter (1993) to include hydraulic head observations to 1998. Reed used the original flow model to simulate ground-water levels in 2049 using 1997 water-use rates, resulting in 401 dry cells, with about 300 mi² going dry in the Grand Prairie area and about 100 mi² going dry in the Cache River area west of Crowleys Ridge by 2049. This indicated that 1997 water-use rates were not sustainable (Reed, 2003; Freiwald, 2005). The original flow model subsequently was used in the optimization modeling of Czarnecki and others (2003) and Czarnecki (2006, 2007) using MODMAN (Greenwald, 1998) and in the assessment of potential increased pumping in Lonoke County (Czarnecki, 2006, 2007).

Study Area

The study area (fig. 1) is the same as the model area and covers 14,104 mi², and includes all or parts of 23 counties in Arkansas and all or part of 5 counties in Missouri. The model simulates ground-water conditions in the unconsolidated Mississippi River Valley alluvial aquifer north of the Arkansas River, east of the consolidated Paleozoic-age formations, west of the Mississippi River, and including a small area in southeastern Missouri.

The study area lies within the Mississippi Alluvial Plain physiographic section, which is a broad, flat region that lies within the Coastal Plain physiographic province (Fennemen, 1938) and is part of the Mississippi embayment. In Arkansas, the Mississippi Alluvial Plain is bounded to the west by Paleozoic-age consolidated sediments that exhibit small values of hydraulic conductivity and by Tertiary-age sediment of the Mississippi embayment with distinctly lower conductivity than those of the alluvial aquifer (Ackerman, 1990).

Hydrogeologic Setting

The alluvial aquifer is the uppermost aquifer system in eastern Arkansas. It is a part of and contained within the Mississippi embayment. Because of continental extension, the Mississippi embayment lies within a plunging syncline with the axis roughly parallel to the present-day Mississippi River and plunges south toward the Gulf of Mexico (Hart and others, 2008). The Mississippi embayment is contained in the states of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee, covering an area of approximately 160,000 mi². The sediments of the Mississippi embayment range from Jurassic to Quaternary in age (Cushing and others, 1964; Williamson and others, 1990). The formations that crop out in Arkansas are Cretaceous age and younger.

During the Pleistocene and Holocene, deposition of sediment by the Arkansas and Mississippi Rivers produced deposits of alluvium consisting of gravels, sands, silts and

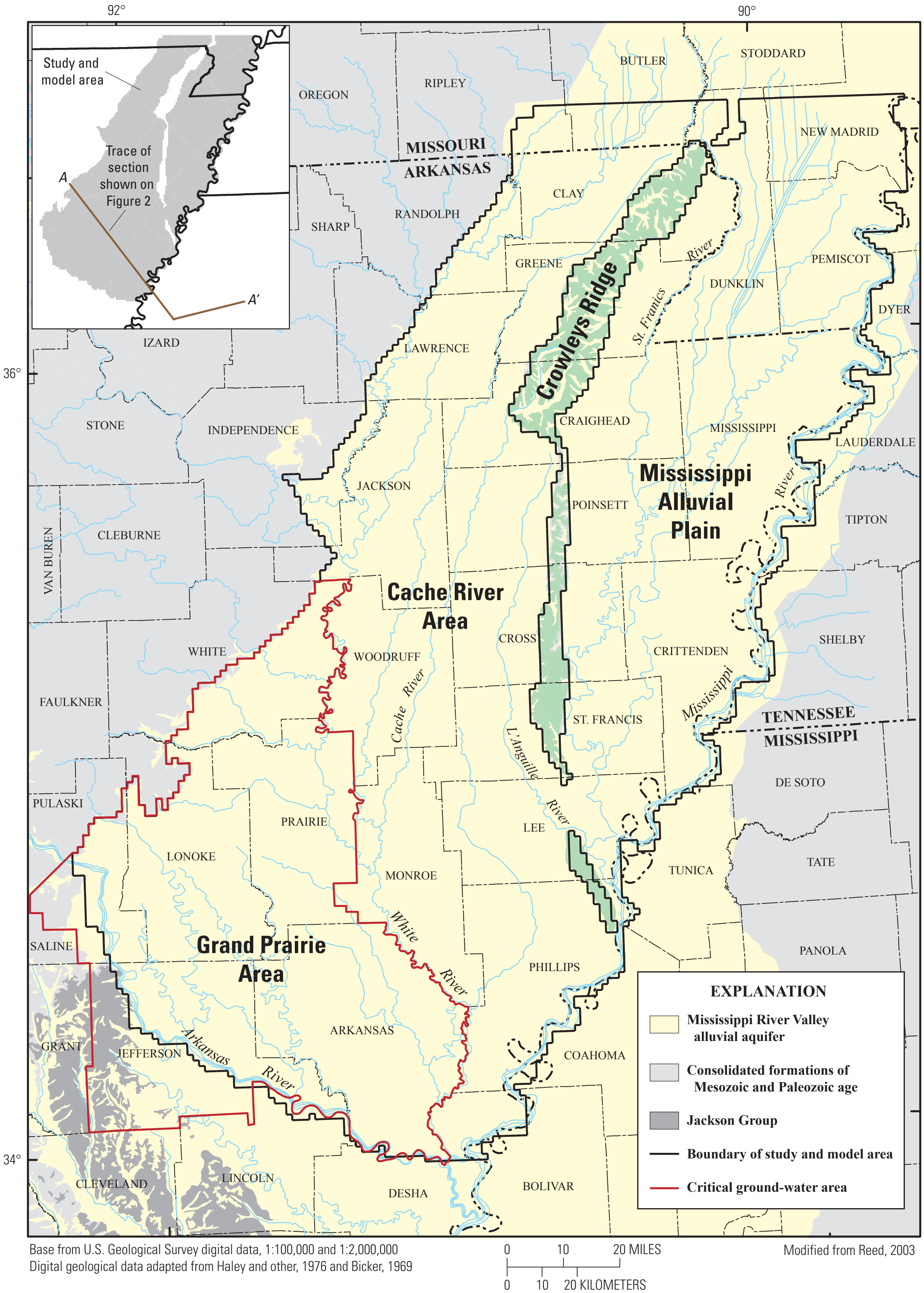

Figure 1. Location of study and model area.

clays that constitute the Mississippi River Valley alluvial aquifer and semi-confining units in eastern Arkansas (fig. 2). In Arkansas, these alluvial sediments can be divided into two layers. The upper layer is composed of clay, silt, and fine sands and has a small hydraulic conductivity. The lower layer of the alluvial aquifer is composed of coarse sands and gravels that grade upward to fine sands. The hydraulic conductivity is larger at the bottom of the formation and decreases upward as the sediment size decreases (Broom and Lyford, 1981; Ackerman, 1989a, 1989b, 1990; Mahon and Ludwig, 1990; Mahon and Poynter, 1993). The alluvial aquifer overlies older units including the Vicksburg-Jackson confining unit, the upper Claiborne aquifer, the middle Claiborne confining unit, the middle Claiborne aquifer, the lower Claiborne confining unit, the lower Claiborne aquifer, the middle Wilcox aquifer, and the lower Wilcox aquifer (Hart and others, 2008) (fig. 2).

The alluvial aquifer contains regional and local flow systems. Ground-water flow paths range from tens to hundreds of miles before intersecting major rivers such as the Mississippi, Arkansas, or White Rivers. Regional potentiometric-surface maps have been constructed for the alluvial aquifer (Ackerman, 1989b; Plafcan and Edds, 1986, Plafcan and Fugitt, 1987; Westerfield, 1990; Joseph, 1999; Reed, 2004; Schrader, 2001, 2006). The potentiometric surface ranges in altitude from nearly 300 ft in the north to less than 100 ft in the south. Ground water enters the alluvial aquifer from the north and west and flows south and east toward major rivers. Locally, ground-water flows towards cones of depression caused by water withdrawal (Schrader, 2006).

Predevelopment flow in the alluvial aquifer is presumed to have been in a southward direction with a general gradient of approximately 1.2 feet per mile (Counts and Engler, 1954). The alluvial aquifer likely discharged into the Arkansas, Mississippi, and White Rivers. To the south, regional flow probably was southward beneath the Grand Prairie and Arkansas River.

In the flow model area, the alluvial aquifer thickness varies from about 15 to 195 ft and averages about 100 ft (Mahon and Poynter, 1993). Pugh and others (1997) reported a thickness for the alluvial aquifer that varies from 0 to 180 ft with an average thickness of 100 ft. The thickness of the upper flow model layer varies within the study area, ranging between zero to nearly the entire thickness of the alluvial aquifer (Mahon and Poynter, 1993). Gonthier and Mahon (1993) reported the clay thickness in the upper flow model layer as ranging from 0 to 140 ft. The thickness of the clay is generally 50 ft or less and the average thickness is around 25 ft in the flow model area. The integrity of the upper flow model layer as a confining unit is controlled by the thickness of the clay cap. The interconnection of laterally discontinuous but transmissive lenses within the clay cap also affects the integrity of the upper flow model layer. The effective aquifer thickness (lower flow model layer) varies based on the thickness of the overlying flow model layer and the elevation of the underlying Tertiary-age sediments.

Crowleys Ridge (fig. 1), a north-south trending ridge, divides the alluvial aquifer into two hydraulically separate flow regimes. Crowleys Ridge is an erosional remnant

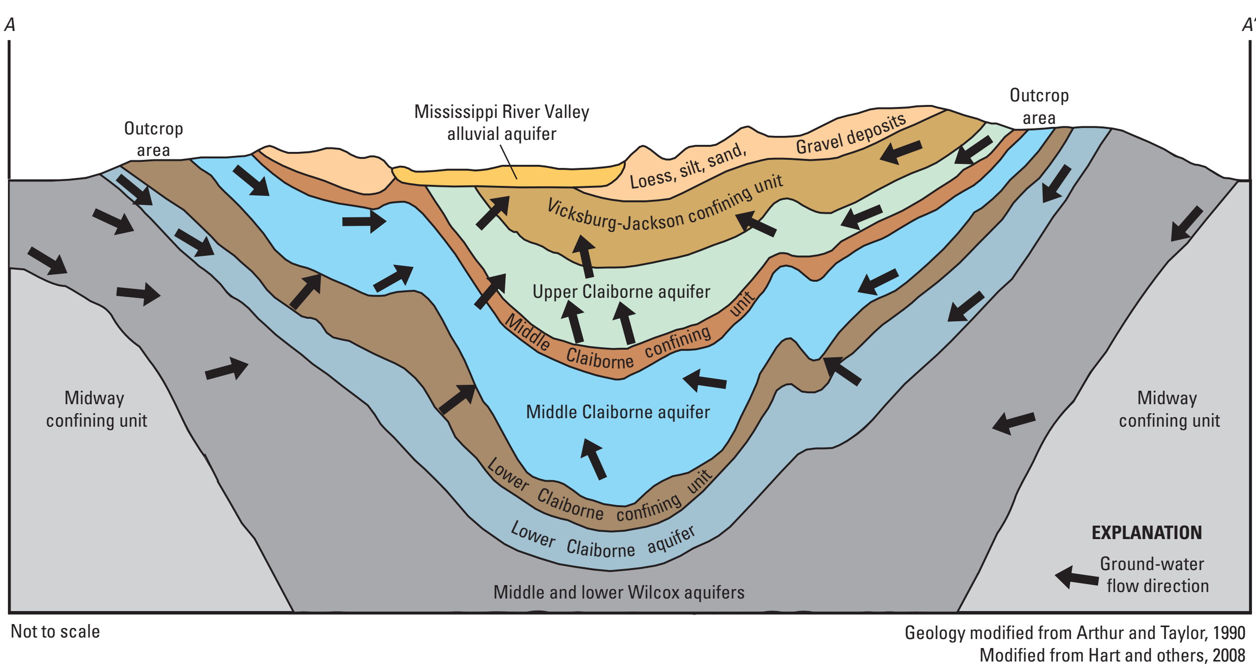

Figure 2. Idealized east-west hydrogeologic section through the alluvium and underlying units.

composed of Tertiary-aged strata capped in places by loess, averaging 10 mi in width (Cushing and others, 1964). The narrowest portion of Crowleys Ridge occurs in southern Craighead and northern Poinsett Counties. Potentiometric-surface maps (Joseph, 1999; Reed, 2004; Schrader, 2001, 2006) in the area indicate a head difference of 20 to 30 ft on opposite sides of Crowleys Ridge, which indicates that even in the area where ground-water throughflow would be most likely, Crowleys Ridge serves as a hydraulic barrier. Water levels from wells on the ridge generally are higher than those of the alluvial aquifer, indicating that the ridge is not part of the alluvial aquifer flow system (Reed, 2003).

Original Flow Model

The updated flow model described in this report is based on the original flow model of the alluvial aquifer documented by Reed (2003). Reed recalibrated the model developed by Mahon and Poynter (1993) using the U.S. Geological Survey (USGS) finite-difference, three-dimensional, ground-water flow model MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW-2000 was used to solve finite-difference ground-water flow equation approximations for the spatial distribution of hydraulic head over time. The Preconditioned-Conjugate-Gradient (PCG) solver within MODFLOW-2000 was used to solve the finite-difference equations for steady-state and transient conditions. Model variables are described in detail by Reed (2003). The aquifer geometry and hydraulic properties used in the updated flow model are identical to the original flow model described in Reed (2003).

Two model layers are used to represent the alluvial aquifer. Adjacent wells in the alluvial aquifer open to the upper and lower layers of the aquifer have similar heads, showing a hydraulic connection between the two layers (Mahon and Poynter, 1993). However, vertical variations in hydraulic conductivity are believed to be important, so two layers were used to represent the upper and lower layers in the alluvial aquifer in this model. The two layers of the alluvial aquifer used in the model are of equal thickness. Confined or unconfined flow conditions are used to model both layers and vary areally. All lateral boundaries are modeled as impermeable, except for parts of the western boundary, parts of Crowleys Ridge, and a boundary of specified hydraulic head values along the northern boundary (Reed, 2003).

The ground-water system is modeled as being isotropic, causing hydrologic properties to be spatially invariant. The model uses 1-mi² grid cells, creating other simplifying assumptions. All water use in a model cell can be simulated as coming from the cell center. Small-scale variations of hydraulic conductivity within cells are negligible. In the model, water use throughout a stress period is applied equally throughout the stress period. Recharge zones for the model were based on the same zones as used for hydraulic conductivity. Recharge values then were modified locally to improve model fit. Recharge values were similar for stress periods 10 and 11 in the original flow model, so the recharge was modeled as invariant throughout subsequent stress periods. All water-use and observation wells are modeled as being completed in the lower layer.

Stress Period Discretization

In the updated model described in this report, stress periods 1 through 10 are the same as those specified by Reed (2003). Stress period 1 was specified as steady state to allow flow throughout the model domain to come to equilibrium with the specified boundary conditions. Subsequent stress periods are transient. Reed’s stress period 11 began in 1994 and went through March 31, 1998, using 1997 water-use data. Stress period 11 was altered to end at December 31, 1997, instead of March 31, 1998, for this flow model validation. Eight additional 1-year stress periods (12-19) were added to include annual water-use data to 2005. Stress periods 20-24 were added to extend the simulation period to 2049, to be consistent with those used in the scenario evaluations of Reed (2003). The changes to stress period 11 and the additional discretization of stress periods 12-24 are shown in table 1.

Table 1. Discretization of additional stress periods.

Stress Period	Length (days)	Length (years)	Beginning	End
11	1,461	4	January 1, 1994	December 31, 1997
12	365	1	January 1, 1998	December 31, 1998
13	365	1	January 1, 1999	December 31, 1999
14	365	1	January 1, 2000	December 31, 2000
15	365	1	January 1, 2001	December 31, 2001
16	365	1	January 1, 2002	December 31, 2002
17	365	1	January 1, 2003	December 31, 2003
18	365	1	January 1, 2004	December 31, 2004
19	365	1	January 1, 2005	December 31, 2005
20	1,461	4	January 1, 2006	December 31, 2009
21	3,652	10	January 1, 2010	December 31, 2019
22	3,652	10	January 1, 2020	December 31, 2029
23	3,652	10	January 1, 2030	December 31, 2039
24	3,652	10	January 1, 2040	December 31, 2049

Water-Level Data

Water-level observations for each year from 1998 to 2005 were used for model validation, totaling 3,616 water-level observations from 698 locations. These data were retrieved from the USGS Ground Water Site Inventory (GWSI) database (http://waterdata.usgs.gov/nwis/gw). As a result of potentiometric surfaces being developed and updated for the alluvial aquifer for 2000, 2002, and 2004 (Schrader, 2001; Reed, 2004; Schrader, 2006), greater numbers of observations were available for these even numbered years.

Water-Use Data

Water use from the alluvial aquifer varies annually, but has generally increased since the early years of development and is used mostly for irrigation. Ground-water pumpage in the study area averaged about 83,000,000 ft^3/d during 1918-1957 (Mahon and Ludwig, 1990) and reached a maximum of about 929,431,000 ft^3/d in 2000 (Holland, 2004). Water-use rates within the flow model area for the alluvial aquifer in Arkansas are shown in figure 3. No trend was observed in annual water use for Arkansas or individual counties within Arkansas for the 1998-2005 time period.

Water use in Arkansas was updated to include available data through 2005. Water use in Missouri was assigned the same value for 1998 through 2005 as that specified for 1997 because updated water-use data were not available. Water use for 1918-1988 (stress periods 2-8) was obtained from Mahon and Poynter (1993). Water use from 1918 through 1982 was estimated based on the results of previous models in eastern Arkansas by Mahon and Ludwig (1990). Prior to 1997, documentation of the spatial distribution of water use within counties was lacking. Water use was documented as county totals, category totals, and aquifer totals in water-use reports. Therefore, water use for stress periods 3 through 8 was computed based on estimates of ground-water use for six, 5-year periods between 1958 and 1988 (Stephens and Halberg, 1961; Halberg and Stephens, 1966; Halberg, 1972, 1977; Holland and Ludwig, 1981; Holland, 1987). The total water-use reported by county was assigned equally to the cells within the county (Reed, 2003).

From 1989 to March 1998, water-use estimates were compiled for the model of Reed (2003) using site-specific water-use data and estimates of water use. Reported water-use values for 1991 were used for 1989 through 1993 and reported values for 1997 were used for 1994 through 1998.

Site-specific water-use data (Terry Holland, U.S. Geological Survey, written commun., 2007) for 1998 through 2005 were added to the updated model. Stress period 11 for the model of Reed (2003), ending in March of 1998, was replaced with actual 1998 water-use data. For the 1998 through 2005 period, water-use data were compiled annually, totaling 290,005 discrete water-use values from 43,440 wells, with as many as 39,169 wells specified in any one year. Total water use (which is primarily irrigation) for the period of 1998-2005 was about 2.3 trillion cubic feet of water, distributed over approximately 10,340 square miles within the model area.

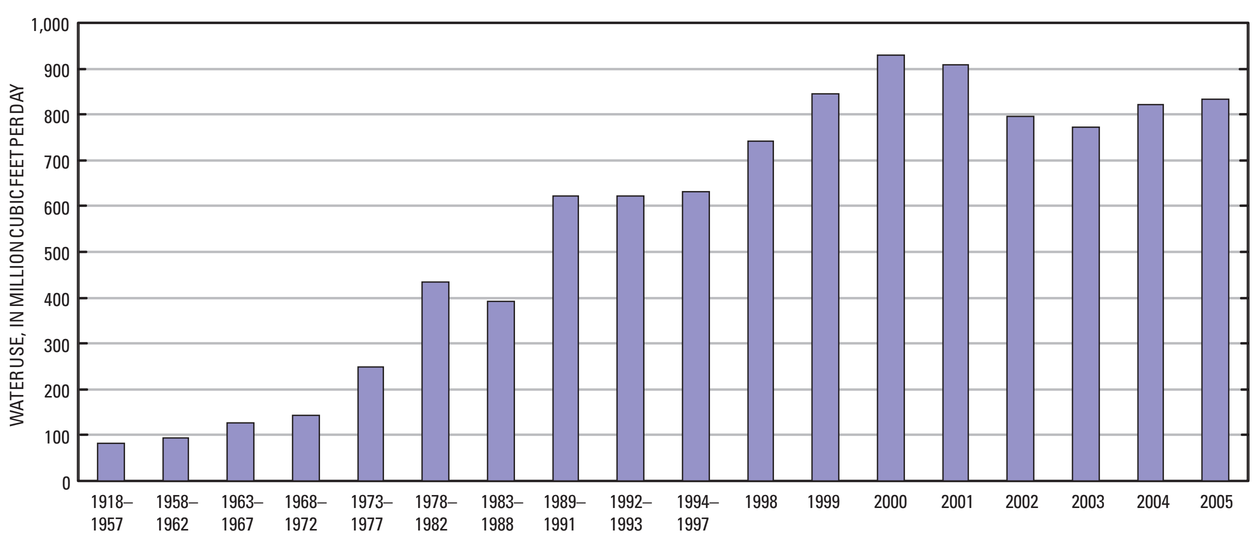

Figure 3. Alluvial aquifer water use in Arkansas within the flow model area for 1918-2005.

Model Results and Validation

To evaluate the validity of the updated flow model, the altitude of water levels simulated by the updated flow model were compared to observed water-level altitudes. The altitude of water-level observations for the period of 1998-2005 ranged from 74 to 293 feet above National Geodetic Vertical Datum of 1929 across the model area. The altitude of observed water levels is plotted against simulated water-level altitudes in figure 4. The correlation coefficient (R^2) for the line of best fit for observed to simulated water levels for the combined 1998-2005 dataset was calculated as 0.9604, indicating an excellent fit to the data.

The difference between observed and simulated water levels provides spatial and temporal measures of model accuracy and inherent model bias. Water-level residuals (the difference between the observed and simulated water-level values at each measurement location for a specific time) were calculated for all water-level observations (fig. 5). Negative residuals indicate that the observed water level was lower than the simulated water level. Conversely, positive residuals indicate that the observed water level is higher than the simulated water level. The maximum water-level residual for the 3,616 water-level observations was 52 feet, the minimum water-level residual was -60 feet, the average root mean squared error was 8.2 feet, and the annual average absolute residual was 6.0 feet. The water-level residuals were skewed slightly towards the positive (fig. 5). The spatial distribution of water-level residuals for stress periods 12 through 19 (1998-2005) are shown in figures 6 through 13.

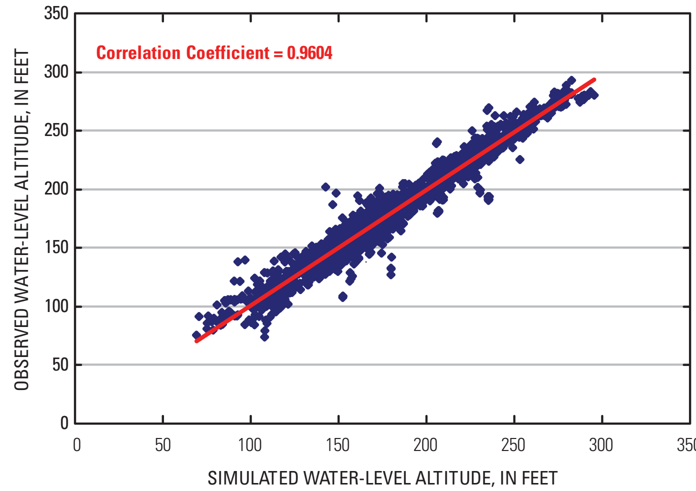

Figure 4. Comparison of observed and simulated water-level altitudes for 1998-2005.

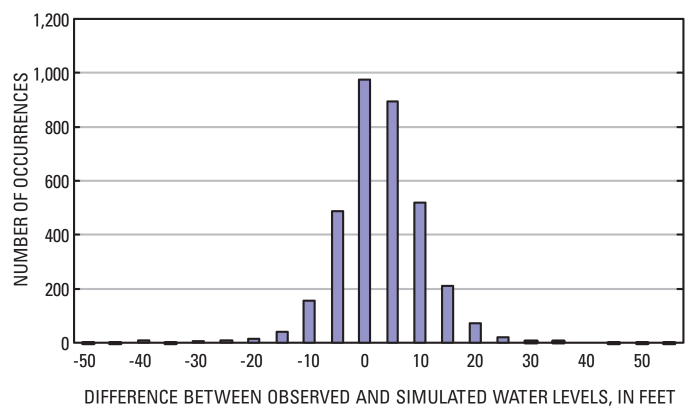

Figure 5. Water-level residuals from 1998-2005.

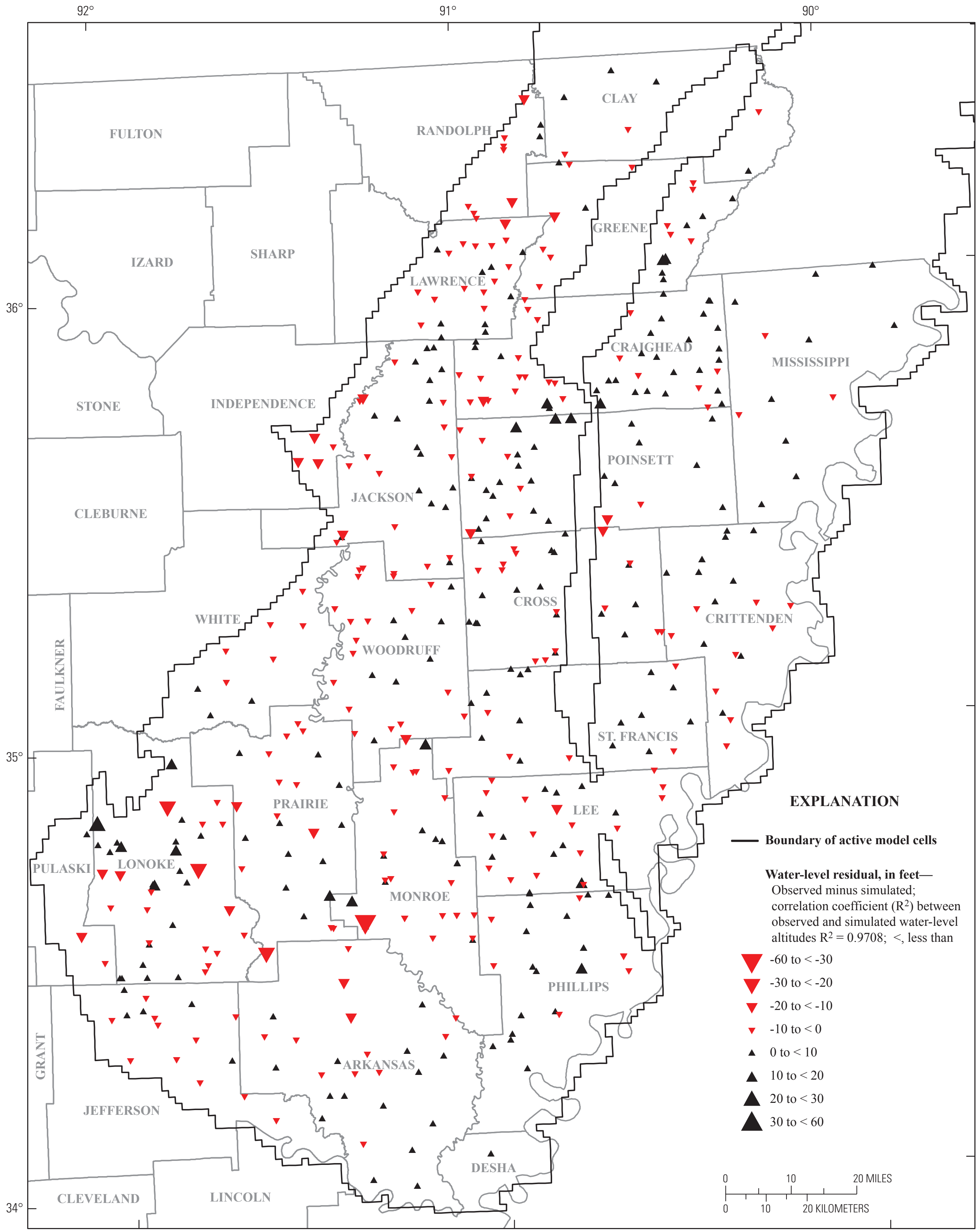

Figure 6. Water-level residuals for observation wells at the end of 1998 (stress period 12).

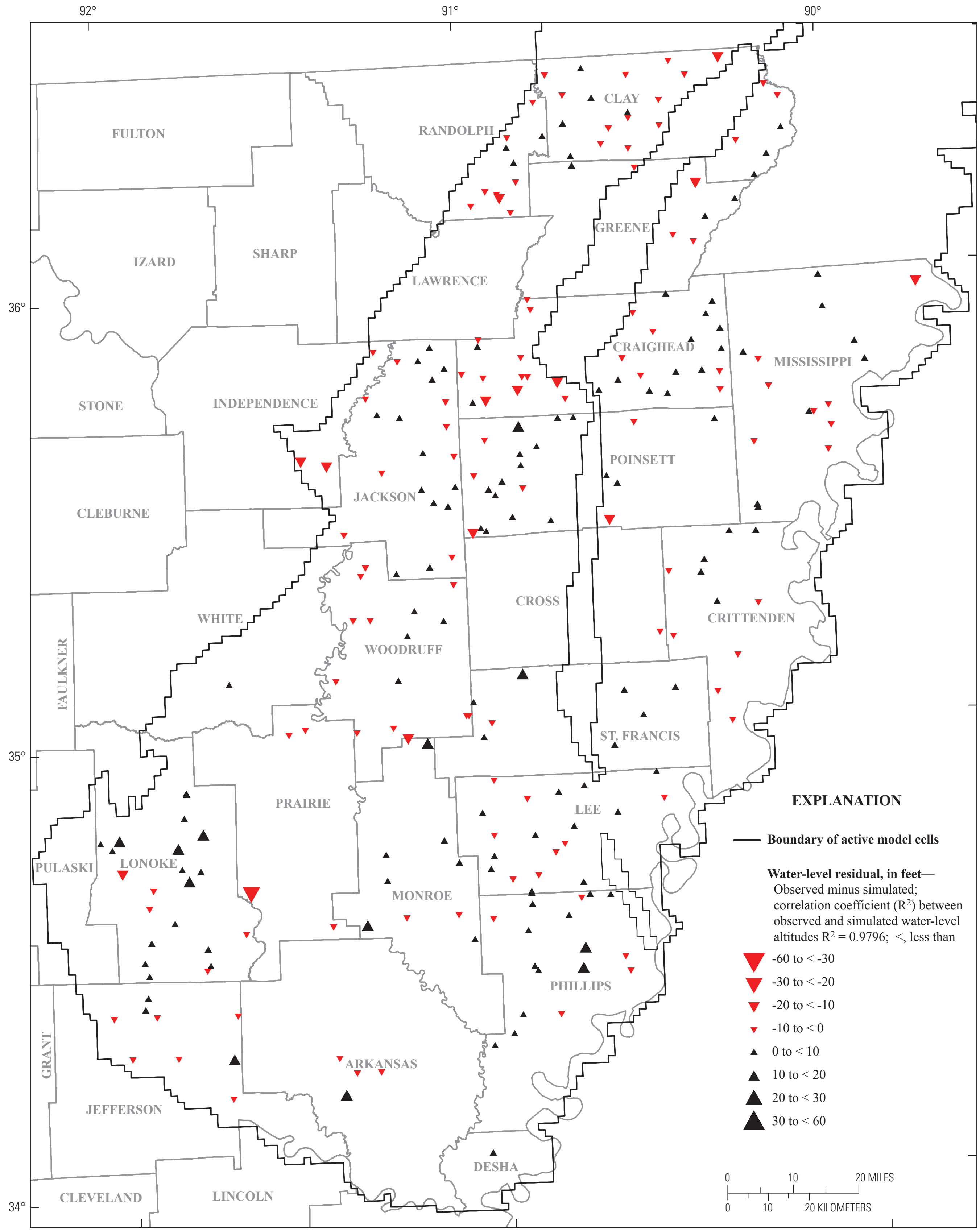

Figure 7. Water-level residuals for observation wells at the end of 1999 (stress period 13).

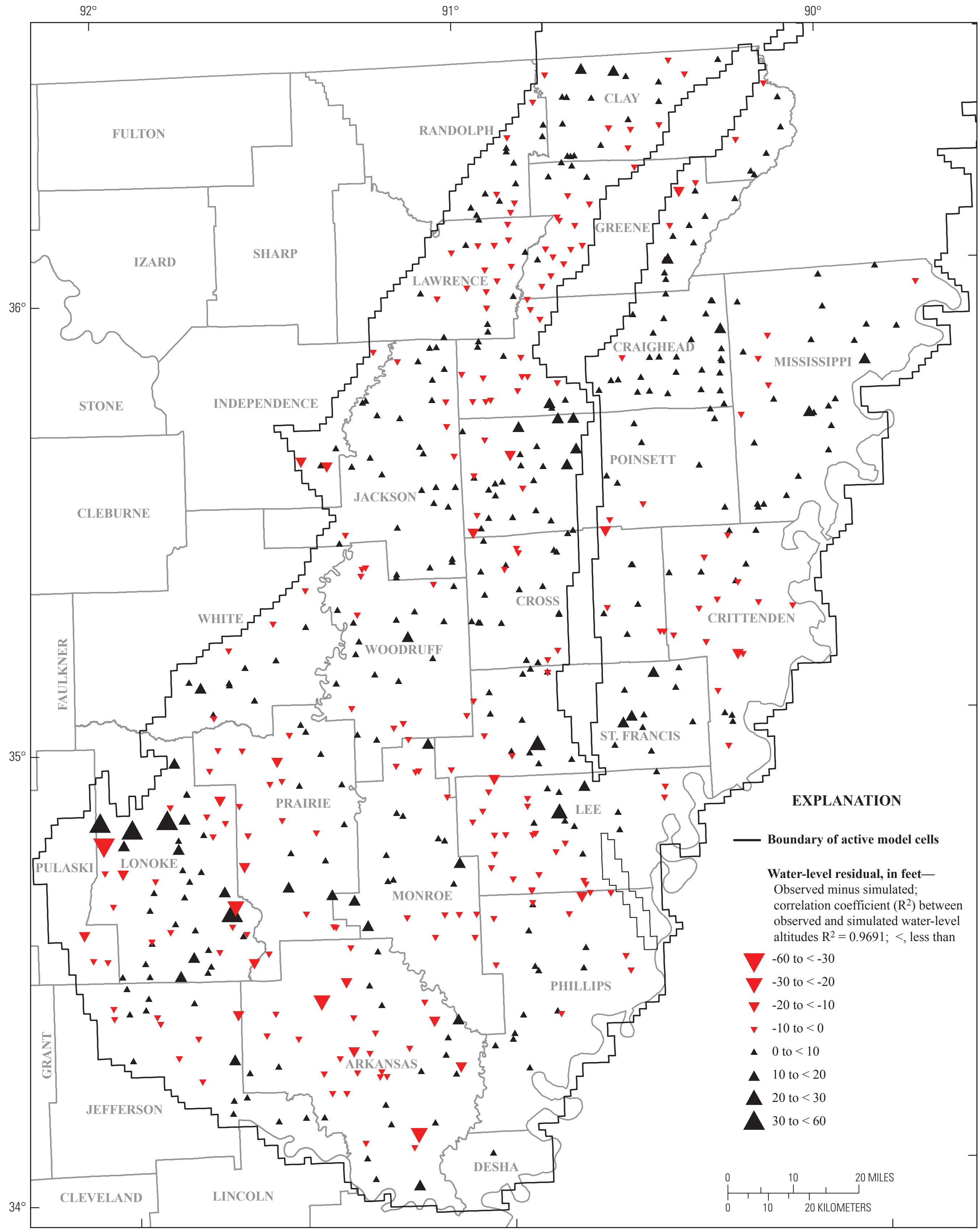

Figure 8. Water-level residuals for observation wells at the end of 2000 (stress period 14).

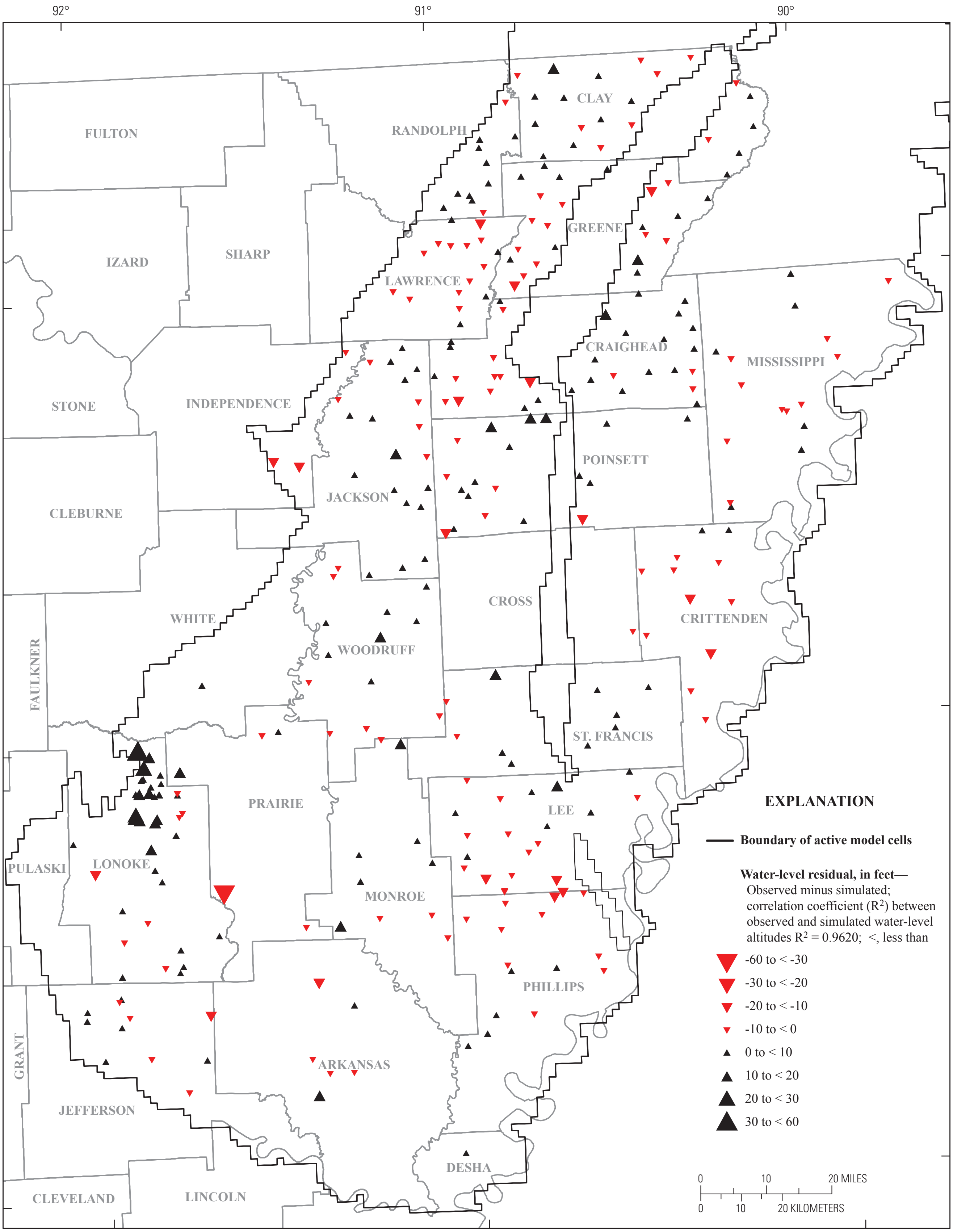

Figure 9. Water-level residuals for observation wells at the end of 2001 (stress period 15).

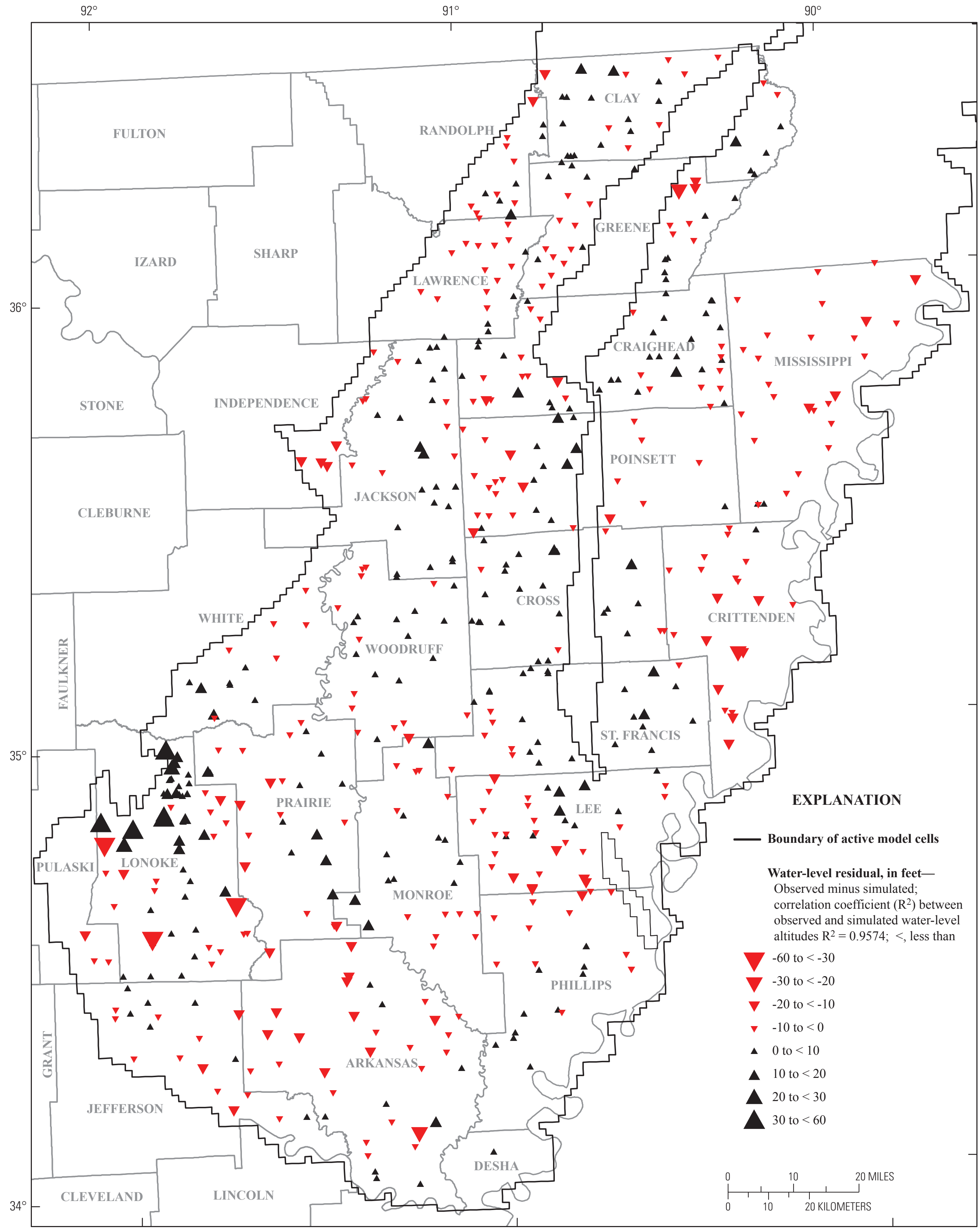

Figure 10. Water-level residuals for observation wells at the end of 2002 (stress period 16).

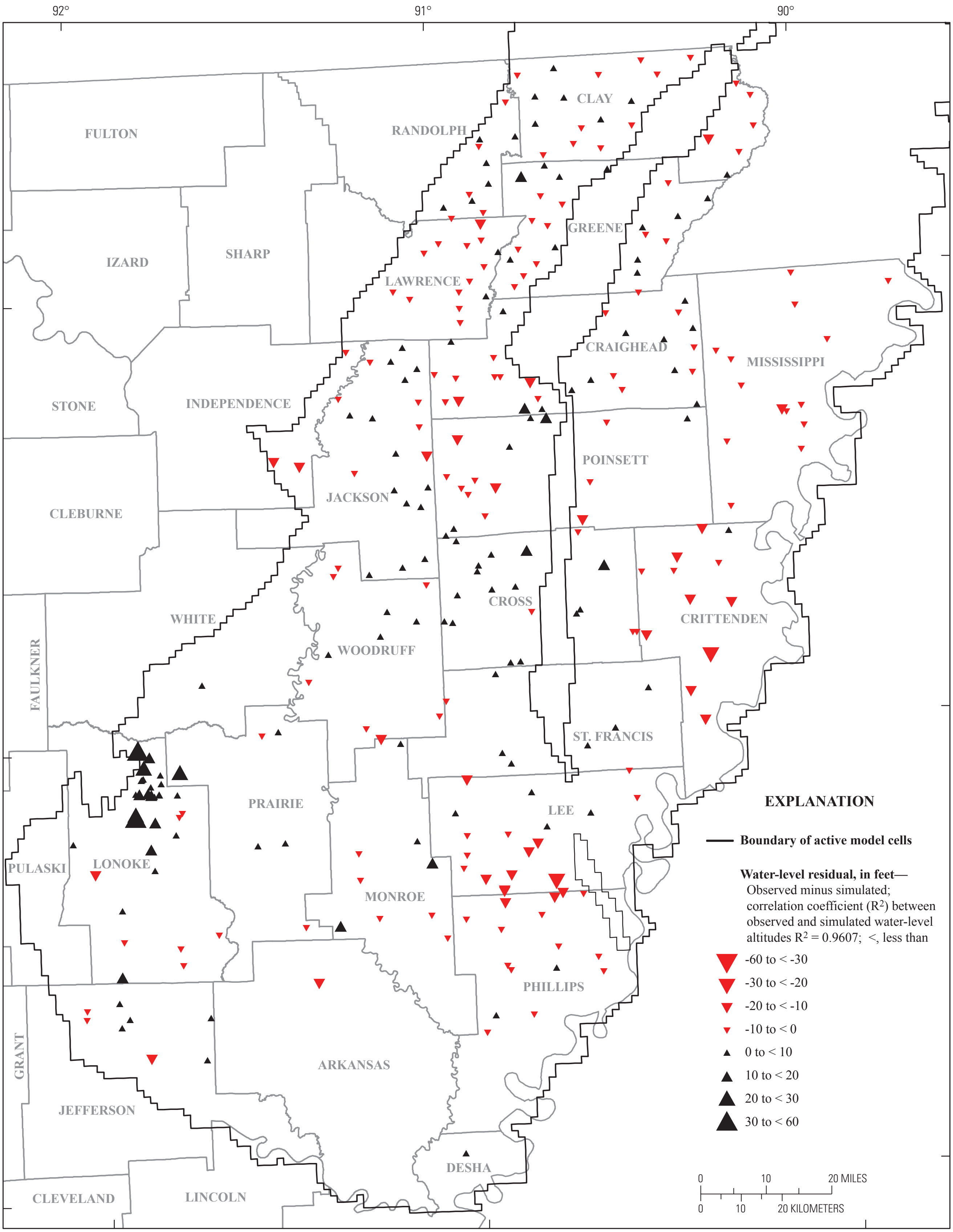

Figure 11. Water-level residuals for observation wells at the end of 2003 (stress period 17).

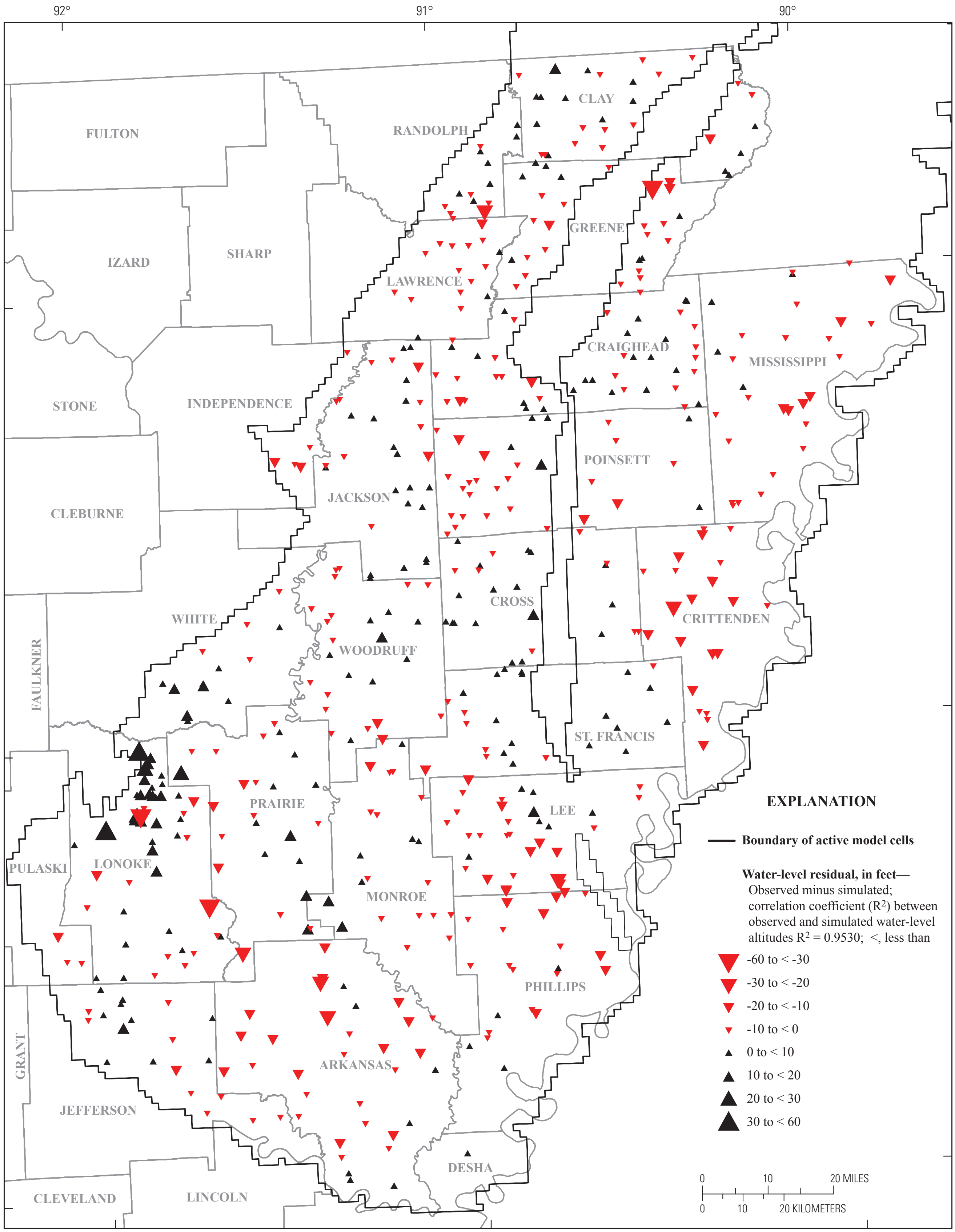

Figure 12. Water-level residuals for observation wells at the end of 2004 (stress period 18).

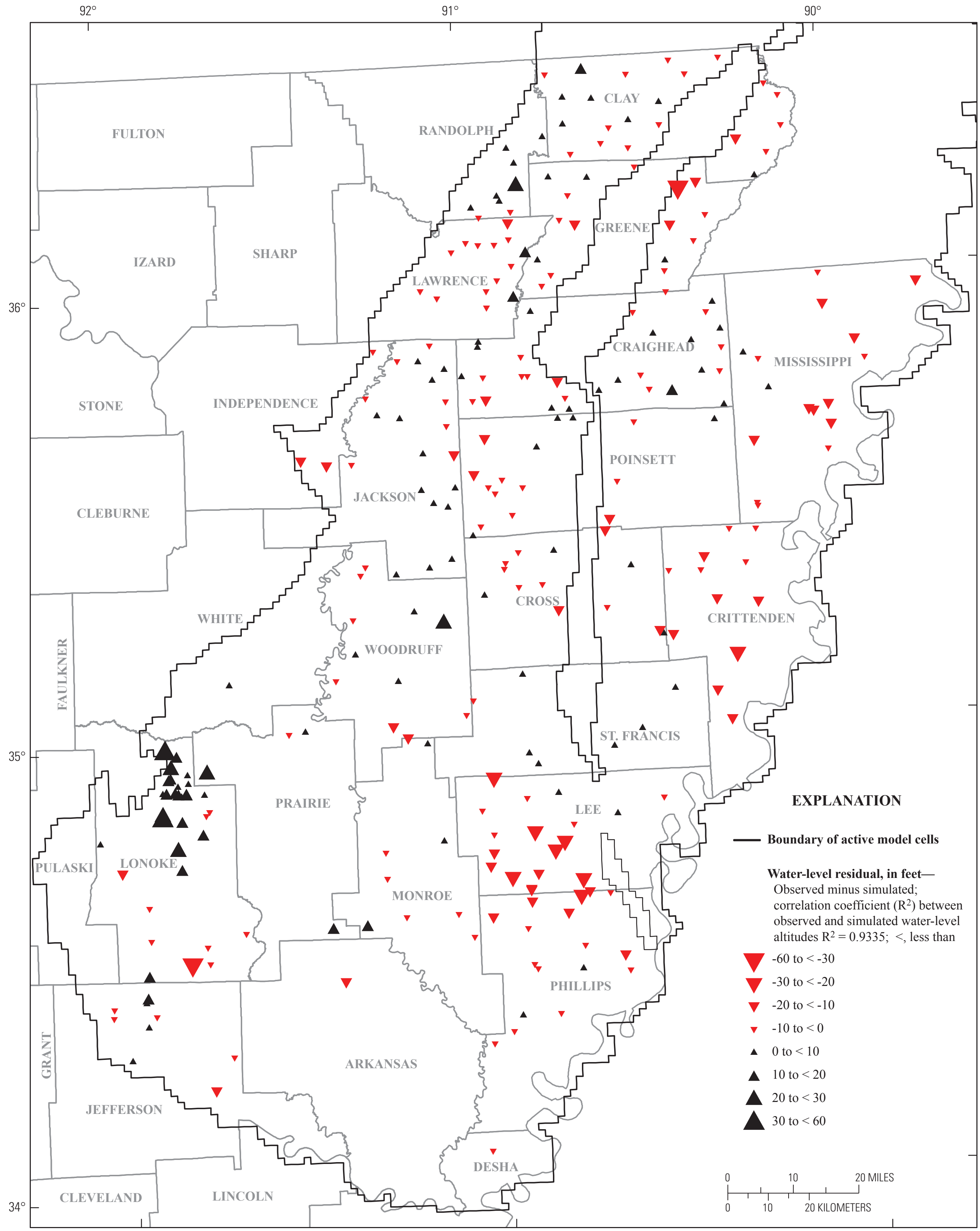

Figure 13. Water-level residuals for observation wells at the end of 2005 (stress period 19).

Evaluation of Water-Use Scenarios

Water-level declines caused by projected ground-water withdrawals were simulated using the calibrated model of Reed (2003) and updated water-use rates for 1998 through 2005, as described in the "Water-Use Data" section. Simulations represent ground-water conditions in 2049 using different water-use scenarios. In scenario 1, the 2005 water-use rate is applied through 2049 without change. Scenario 2 uses a 2 percent annual increase to existing wells from the 2005 water-use rate until the end of the model run in 2049. The 2 percent increase results in the water-use doubling in approximately 35 years. This rate increase is strictly hypothetical and is used merely to compare the effect that it has on the occurrence of dry cells. Dry cells in the model imply that the aquifer is completely dewatered and no water would be available for withdrawal. While the upper layer is also part of the alluvial aquifer, it has a small value of hydraulic conductivity. Wells are modeled in the lower layer; therefore, dry cells in the lower layer are more indicative of unsustainable water use. Dry cells in the lower layer in 2005 and from these scenarios 1 and 2 are shown in table 2 and figures 14, 15, and 16.

Table 2. Dry cells resulting from water-use scenarios.

Stress Period	End of Stress Period	Dry Cells (Scenario 1)	Dry Cells (Scenario 2)
12	1998	52	52
13	1999	63	63
14	2000	82	82
15	2001	99	99
16	2002	113	113
17	2003	125	125
18	2004	131	131
19	2005	135	135
20	2009	181	194
21	2019	451	944
22	2029	664	1,563
23	2039	728	2,231
24	2049	779	2,910

In 2005, simulated flow model results show that there were 135 dry cells (135 mi²) in the lower layer of the alluvial aquifer (fig. 14). These dry cells are concentrated in the Grand Prairie area. The scenario results show that with the 2005 water-use rate extended to 2049 (scenario 1), there are 779 dry cells (779 mi²) in the lower layer of the alluvial aquifer (fig. 15). These dry cells are concentrated in the Grand Prairie area and Cache River area west of Crowleys Ridge. If the 2005 water-use rate is increased at a rate of 2 percent annually (scenario 2), there are 2,910 dry cells (2,910 mi²) by 2049 (fig. 16). These dry cells also are concentrated in the Grand Prairie area and Cache River area west of Crowleys Ridge; however, a number of dry cells also occurred east of Crowleys Ridge. The original flow model simulation using 1997 water-use rates resulted in 401 dry cells, with about 300 mi² going dry in the Grand Prairie area and about 100 mi² going dry in the Cache River area on the west side of Crowleys Ridge (Reed, 2003; Freiwald, 2005) by 2049.

Limitations and Potential Sources for Errors

By definition, a model is a simplification of a complex system and, therefore, can not represent the system with exact detail. The ground-water system is modeled as being isotropic and the grid size is 1 mi² with water use in the model simulated as coming from the cell center. The original and updated flow models use two layers to represent the alluvial aquifer. Vertical variations in hydraulic conductivity are believed to be important, so two layers of equal thickness were used to represent the upper and lower layers in the alluvial aquifer in this model (Mahon and Poynter, 1993).

Proximity of pumping cells to flux boundaries may result in unrealistic water levels. The flow model uses several General Head Boundaries (GHB). The purpose of the GHB is to simulate a source of water some unspecified distance from the model boundary. However, this boundary condition may cause drawdown to be less than actual amounts. An examination of the conductance associated with the GHB cells shows it to be small compared to other values used in the model, lessening the effect that the GHB cell would have on simulated water levels interior to the model.

Water-use rates are important variables that have a large effect on simulated water levels. Errors in reported water use will affect the model. Over reported water use would result in a lower simulated water-level value and, therefore, a positive residual. Conversely, under reported water use would result in a higher simulated water-level value and, therefore, a negative residual.

Model cells that go dry during a simulation remain dry from that point in time until the simulation is finished. Cells that are near the threshold of going dry may respond non-linearly following abrupt changes in water-use rates causing numerical inaccuracies to occur within that part of the model. Cells that were no longer dry for some of the simulations likely occur in those cells that were near this threshold; consequently, their saturated thickness is small.

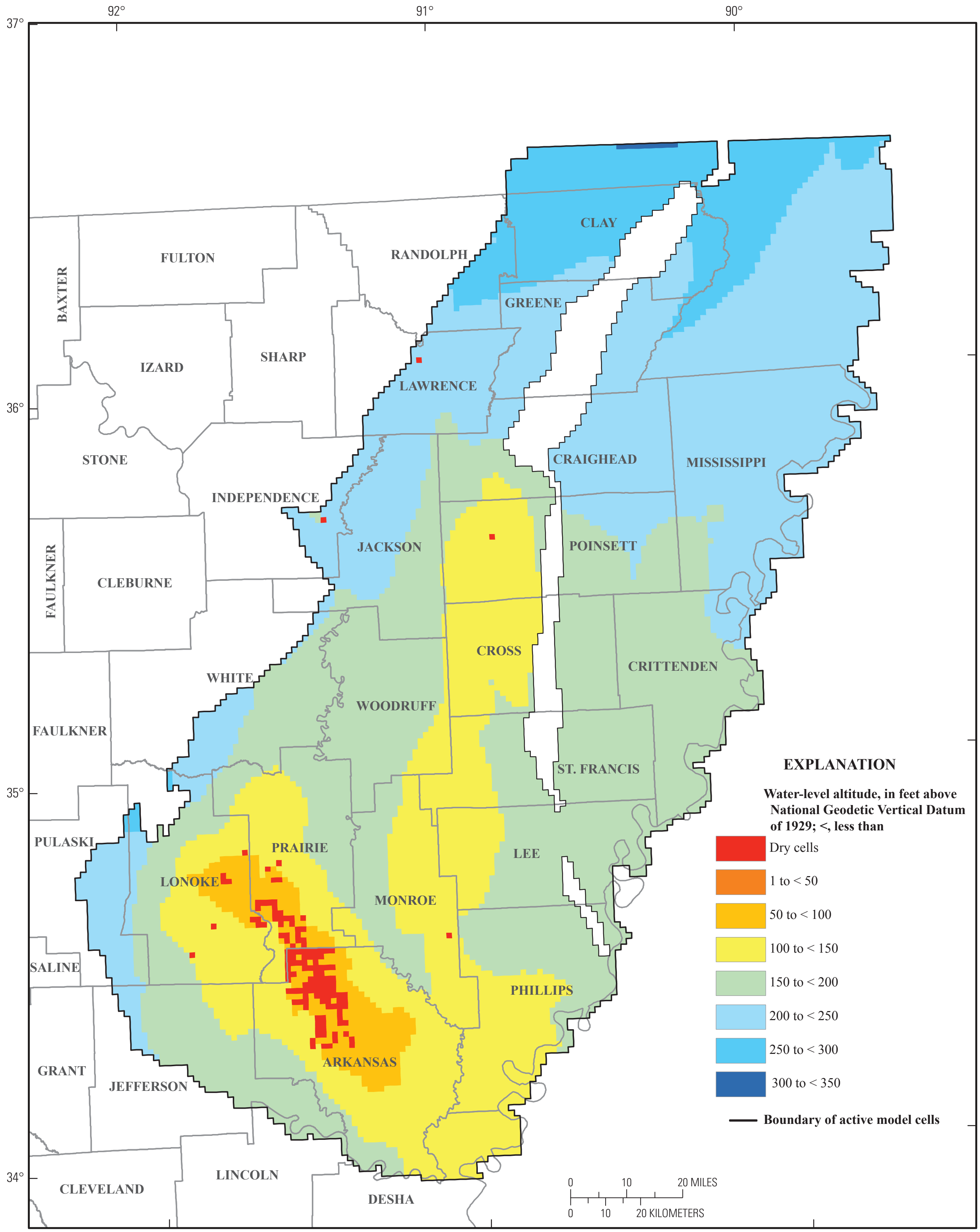

Figure 14. Water-level altitudes and dry cells in the lower layer of the alluvial aquifer in 2005.

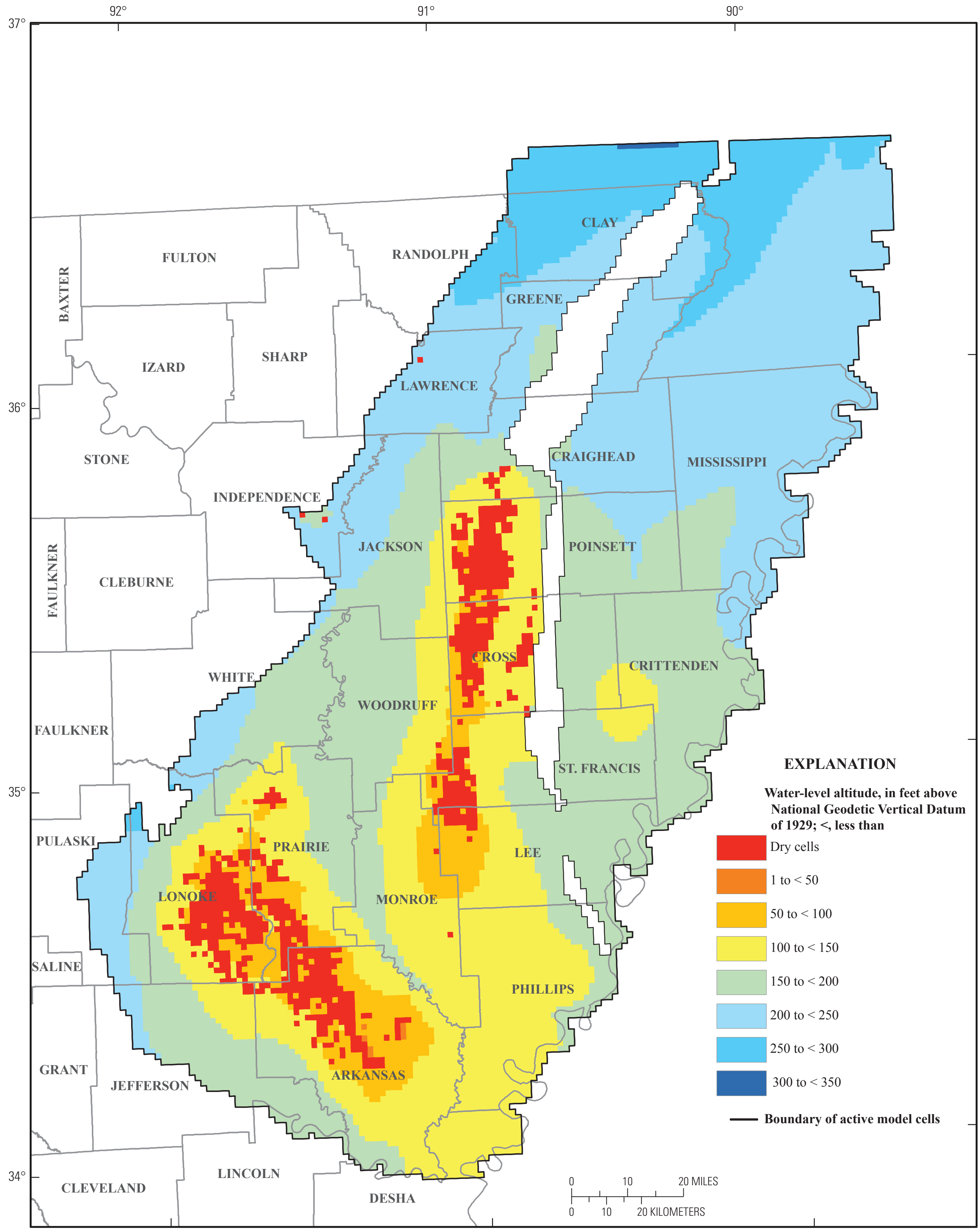

Figure 15. Water-level altitudes and dry cells in the lower layer of the alluvial aquifer in 2049 using Scenario 1.

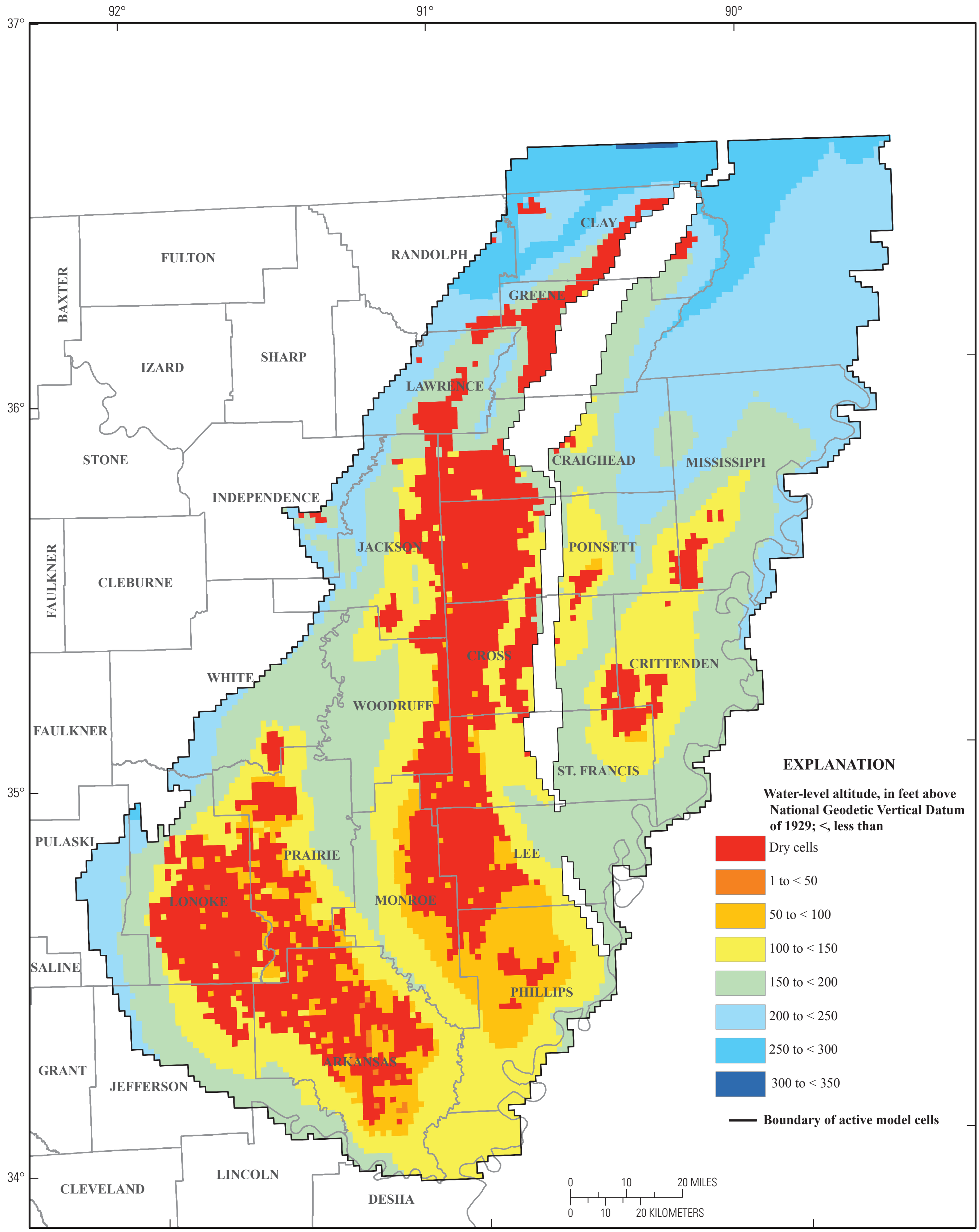

Figure 16. Water-level altitudes and dry cells in the lower layer of the alluvial aquifer in 2049 using Scenario 2.

Summary

The Mississippi River Valley alluvial aquifer is a water-bearing assemblage of gravels and sands that underlies most of eastern Arkansas and parts of several adjacent states. The Mississippi River Valley alluvial aquifer is the uppermost aquifer system in eastern Arkansas. The alluvial aquifer contains regional and local flow systems. Generally, ground water enters the alluvial aquifer from the north and west and flows south and east toward major rivers. Ground water flows from tens to hundreds of miles before discharging into major rivers such as the Mississippi, Arkansas, or White Rivers. Locally, water flows towards cones of depression caused by large ground-water withdrawal.

Ground-water withdrawals have caused cones of depression to develop in the water-level surface of the aquifer, some as much as 100 feet deep. The original ground-water flow model showed that continued ground-water withdrawals at 1997 rates were unsustainable. Recharge to the alluvial aquifer from the Arkansas, Mississippi, St. Francis, and White Rivers has been induced by ground-water level declines. Long-term water-level measurements show an average annual decline of 1 foot per year in some areas.

The original ground-water flow model completed in 2003 of the northern part of the alluvial aquifer was validated with the specification of additional water-level and water-use data that extended the end of the observation period to 2005. Water-level observations for each year from 1998 through 2005 were used for model validation, totaling 3,616 water-level observations from 698 locations. Water-use data were compiled and used for the same period, totaling 290,005 discrete water-use values from 43,440 wells, with as many as 39,169 wells pumping in any one year. Total pumping (which is primarily agricultural) for this period was about 2.3 trillion cubic feet of water, distributed over approximately 10,340 square miles within the model area.

The original ground-water flow model was updated with the 1998-2005 water-use data and validated by comparing the simulated water levels with observed water levels during the simulation. The 1998-2005 water-level observations ranged from 74 to 293 feet above National Geodetic Vertical Datum across the model area. The maximum water-level residual (observed minus simulated value) for the 3,616 water-level observations was 52 feet, the minimum water-level residual was 60 feet, the average annual root mean squared error was 8.2 feet, and the annual average absolute residual was 6.0 feet. A correlation coefficient (R^2) of 0.9604 was calculated for the line of best fit for observed to simulated water-levels for the combined 1998-2005 dataset indicated a good fit to the data.

The updated flow model simulated 135 dry cells (135 mi^2) at the end of 2005. Additionally, model simulations using two scenarios were run to evaluate the response of the aquifer with the 2005 water-use rate applied through 2049 (scenario 1) and the 2005 water-use rate increased 2 percent annually until 2049 (scenario 2). The results showed that at the 2005 water-use rate, there are 779 dry cells (779 mi^2) by 2049. If the 2005 water-use rate were to increase at a rate of 2 percent annually, resulting in a doubling of water use in approximately 35 years, there are 2,910 dry cells (2,910 mi^2) by 2049. In both scenarios, the dry cells are concentrated in the Grand Prairie and Cache River areas. However, scenario 2 resulted in dry cells to the east of Crowleys Ridge as well.

References

Ackerman, D.J., 1989a, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States – A preliminary assessment of the regional flow system: U.S. Geological Survey Water-Resources Investigation Report 88-4028, 74 p.

Ackerman, D.J., 1989b, Potentiometric surfaces of the Mississippi River Valley alluvial aquifer in eastern Arkansas, spring 1972 and 1980: U.S. Geological Survey Water-Resources Investigation Report 88-4075, 1 sheet.

Ackerman, D.J., 1990, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States: U.S. Geological Survey Water-Resources Investigation Report 90-358, 228 p.

Arkansas Natural Resources Commission, [1991], Critical Ground Water Designation: Arkansas Natural Resources Commission Fact Sheet, 1 p.

Arthur, J.K., and Taylor, R.E., 1990, Definition of the geohydrologic framework and preliminary simulation of ground-water flow in the Mississippi embayment aquifer system, Gulf Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 86-4364, 97 p.

Bicker, A.R., Jr., 1969, Geologic map of Mississippi: Mississippi Geological Survey.

Boswell, E.H., Cushing, E.M., Hosman, R.L., and Jeffery, H.G., 1968, Quaternary aquifers in the Mississippi embayment, with a discussion of quality of the water: U.S. Geological Survey Professional Paper 448-E, 15 p.

Broom, M.E., and Lyford, E.P., 1981, Alluvial aquifer of the Cache and St. Francis River basins, northeastern Arkansas: U.S. Geological Survey Open-File Report 81-476, 48 p.

Counts, H.B., and Engler, Kyle, 1954, Changes in water levels in deposits of Quaternary age in eastern Arkansas from 1938-1953: University of Arkansas, Agriculture Experiment Station Report Series 42, 11 p.

Cushing, E.M., Boswell, B.H., and Hosman, R.L., 1964, General geology of the Mississippi embayment: U.S. Geological Survey Professional Paper 448-B, 28 p.

Czarnecki, J.B., Clark, B.R., and Reed, T.B., 2003, Conjunctive-use optimization model of the Mississippi River Valley alluvial aquifer of northeastern Arkansas: U.S. Geological Survey Scientific Investigations Report 2003-4230, 29 p.

Czarnecki, J.B., 2006, Simulation of various management scenarios of the Mississippi River Valley alluvial aquifer in Arkansas: U.S. Geological Survey Scientific Investigations Report 2006-5052, 21 p.

Czarnecki, J.B., 2007, Simulated ground-water withdrawals by Cabot WaterWorks from the Mississippi River Valley alluvial aquifer, Lonoke County, Arkansas: U.S. Geological Survey Scientific Investigations Report 2007-5030, 39 p.

Engler, Kyle, Thompson, D.G., and Kazmann, R.G., 1945, Ground water supplies for rice irrigation in the Grand Prairie region, Arkansas: University of Arkansas, Agriculture Experiment Station Bulletin No. 457, 56 p.

Fenneman, N.M., 1938, Physiography of the eastern United States: New York and London, McGraw Hill Book Co., 714 p.

Fisk, H.N., 1944, Geological investigation of the alluvial aquifer of the lower Mississippi River: U.S. Department of the Army, Mississippi River Commission, 78 p.

Freiwald, D.A., 2005, Ground-water models of the alluvial and Sparta aquifers: Management tools for a sustainable resource: U.S. Geological Survey Fact Sheet 2005-3008, 4 p.

Gonthier, G.M., and Mahon, G.L., 1993, Thickness of the Mississippi River Valley confining unit, eastern Arkansas: U.S. Geological Survey Water-Resources Investigation Report 92-4121, 4 sheets.

Greenwald, R.M., 1998, Documentation and user's guide: MODMAN, An optimization module for MODFLOW version 4.0: Freehold, New Jersey, HIS GeoTrans, 112 p.

Haley, B.R., Glick, E.R., Bush, W.V., Clardy, B.F., Stone, C.G., Woodward, M.B., and Zachry, D.L., 1976, Geologic map of Arkansas: U.S. Geological Survey, scale 1:500,000

Halberg, H.N., 1972, Use of water in Arkansas, 1970: Arkansas Geological Commission Water Resources Summary Number 7, 17 p.

Halberg, H.N., 1977, Use of water in Arkansas, 1975: Arkansas Geological Commission Water Resources Summary Number 9, 28 p.

Halberg, H.N., and Stephens, J.W., 1966, Use of water in Arkansas, 1965: Arkansas Geological Commission Water Resources Summary Number 5, 12 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, The U.S. Geological Survey modular ground-water model – user guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 2000-92, 121 p.

Hart, R.M., Clark, B.R., and Bolyard, S.E., 2008, Digital surfaces and thicknesses of selected hydrogeologic units within the Mississippi Embayment Regional Aquifer Study (MERAS): U.S. Geological Survey Scientific Investigations Report 2008-5098, 33 p.

Holland, T.W., 1987, Use of water in Arkansas, 1985: Arkansas Geological Commission Water Resources Summary Number 16, 27 p.

Holland, T.W., 2004, Estimated water use in Arkansas, 2000: U.S. Geologic Survey Scientific Investigations Report 2004-5230, 38 p.

Holland, T.W., 2007, Water use in Arkansas, 2005: U.S. Geological Survey Scientific Investigations Report 2007-5241, 33 p.

Holland, T.W., and Ludwig, A.H., 1981, Use of water in Arkansas, 1980: Arkansas Geological Commission Water Resources Summary Number 14, 30 p.

Joseph, R.L., 1999, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 1998: U.S. Geological Survey Water-Resources Investigation Report 99-4035, 54 p.

Krinitzsky, E.L., and Wire, J.C., 1964, Ground water in alluvium of lower Mississippi Valley (upper and central areas): U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station Technical Report 3-658, v. 1 and 2, 400 p.

Mahon, G.L., and Ludwig, A.H., 1990, Simulation of ground-water flow in the Mississippi River Valley alluvial aquifer in eastern Arkansas: U.S. Geological Survey Water-Resources Investigation Report 89-4145, 26 p.

Mahon, G.L., and Poynter, D.L., 1993, Development, calibration and testing of ground-water flow models for the Mississippi River Valley alluvial aquifer in eastern Arkansas using one-square mile cells: U.S. Geological Survey Water-Resources Investigation Report 92-4106, 33 p.

Peralta, R.C., Yazdanian, A., Killian, P.J., and Shulstad, R.N., 1985, Future Quaternary groundwater accessibility in the Grand Prairie—1993: University of Arkansas, Agriculture Experiment Station Bulletin No. 877, 37 p.

Plafcan, Maria, and Edds, Joe, 1986, Water level and saturated thickness maps of the alluvial aquifer in eastern Arkansas, 1984: U.S. Geological Survey Water-Resources Investigation Report 86-4014, 1 sheet.

Plafcan, Maria, and Fugitt, D.T., 1987, Water level maps of the alluvial aquifer in eastern Arkansas, 1985: U.S. Geological Survey Water-Resources Investigation Report 86-4178, 1 sheet.

Pugh, A.L., Westerfield, P.W., and Poynter, D.T., 1997, Thickness of the Mississippi River Valley alluvial aquifer in eastern Arkansas: U.S. Geological Survey Water-Resources Investigation Report 97-4049, 1 sheet.

Reed, T.B., 2003, Recalibration of a ground-water flow model of the Mississippi River Valley alluvial aquifer of northeastern Arkansas, 1918-1998, with simulations of water levels caused by projected ground-water withdrawals through 2049: U.S. Geological Survey Water-Resources Investigation Report 03-4109, 58 p.

Reed, T.B., 2004, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2002: U.S. Scientific Investigations Report 2004-5129, 60 p.

Renken, R.A., 1998, Ground water atlas of the United States—Segment 5: Arkansas, Louisiana, Mississippi: U.S. Geological Survey Hydrologic Investigations Atlas 730-F, 13 p.

Schrader, T.P., 2001, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2000: U.S. Geological Survey Water-Resources Investigations Report 01-4124, 52 p.

Schrader, T.P., 2006, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2004: U.S. Geological Survey Scientific Investigations Report 2006-5128, 82 p.

Stanton, G.P., and Clark, B.R., 2003, Recalibration of a ground-water flow model of the Mississippi River Valley alluvial aquifer in southeastern Arkansas, 1918, with simulations of hydraulic heads caused by projected ground-water withdrawals through 2049: U.S. Geological Survey Scientific Investigations Report 2003-4232, 51 p.

Stephens, J.W., and Halberg, H.N., 1961, Use of water in Arkansas, 1960: Arkansas Geological and Conservation Commission Special Ground-Water Report Number 4, 8 p.

Stephenson, L.W., Crider, A.F., and Dole, R.B., 1916, Geology and ground water of northeastern Arkansas with a discussion of the chemical character of the waters: U.S. Geological Survey Water-Supply Paper 399, 315 p.

Veatch, A.C., 1906, Geology and underground water resources of northern Louisiana and southern Arkansas: U.S. Geological Survey Professional Paper 46, 422 p.

Westerfield, P.W., 1990, Water-level maps of the Mississippi River Valley alluvial aquifer in eastern Arkansas, 1987: U.S. Geological Survey Water-Resources Investigations Report 90-4089, 1 sheet.

Williamson, A.K., Grubb, H.F., and Weiss, J.S., 1990, Ground-water flow in the Gulf Coast aquifer systems, south-central United States—A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 89-4071, 124 p.

Publishing support provided by:
Lafayette and Rolla Publishing Service Centers

For more information concerning the research described in the report:

U.S. Geological Survey
Arkansas Water Science Center
401 Hardin Road
Little Rock, AR 72211-3528
(501) 228-3600

http://ar.water.usgs.gov

USGS

Gillip and Czarnecki—**Ground-Water Flow Model of the Mississippi River Valley Alluvial Aquifer**—Scientific Investigations Report 2009–5040