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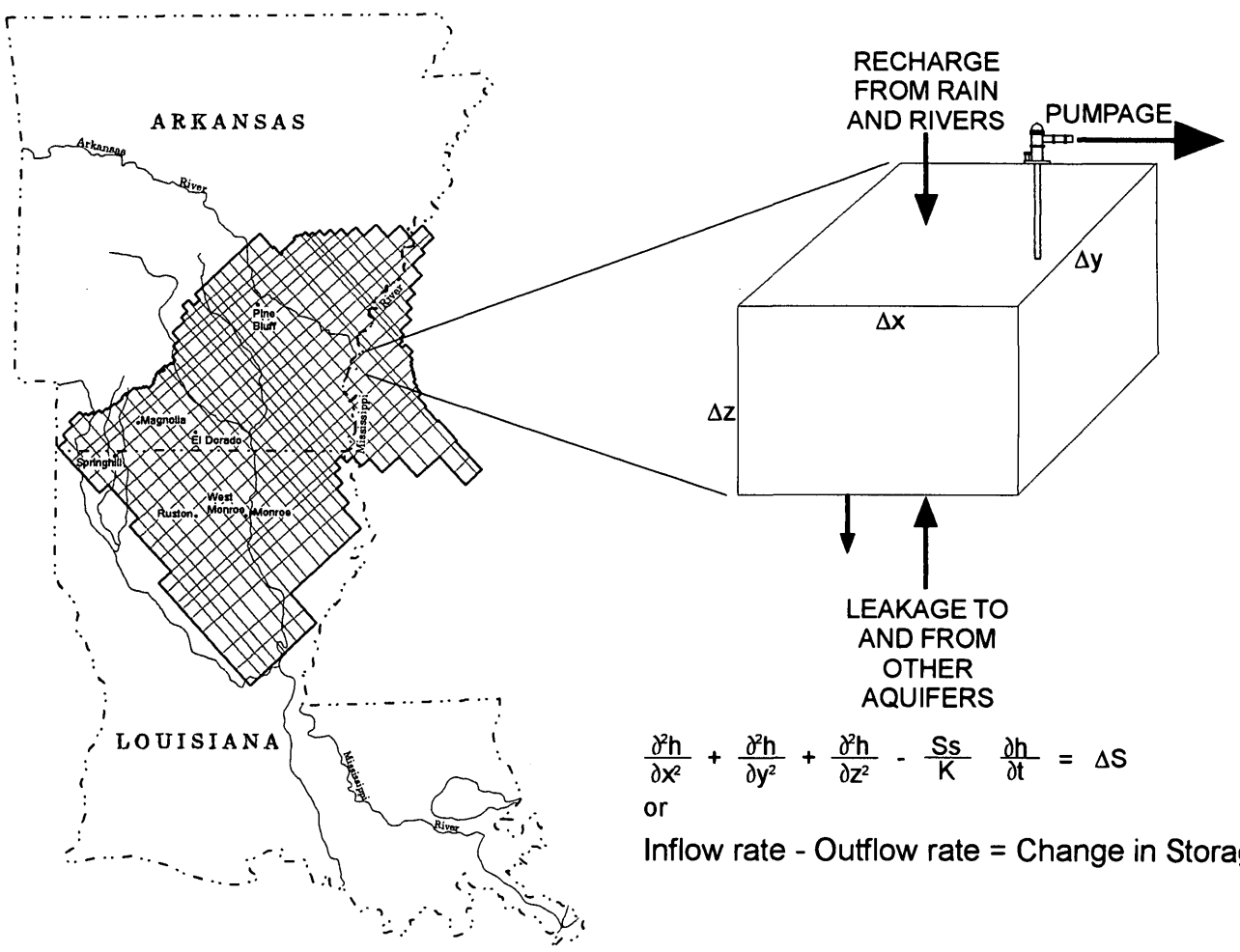
SIMULATED RESPONSE TO PUMPING STRESS IN THE SPARTA AQUIFER OF SOUTHEASTERN ARKANSAS AND NORTH-CENTRAL LOUISIANA, 1998-2027

Water-Resources Investigations Report 98-4121



$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} - \frac{Ss}{K}\frac{\partial h}{\partial t} = \Delta S$$

or

Inflow rate - Outflow rate = Change in Storage

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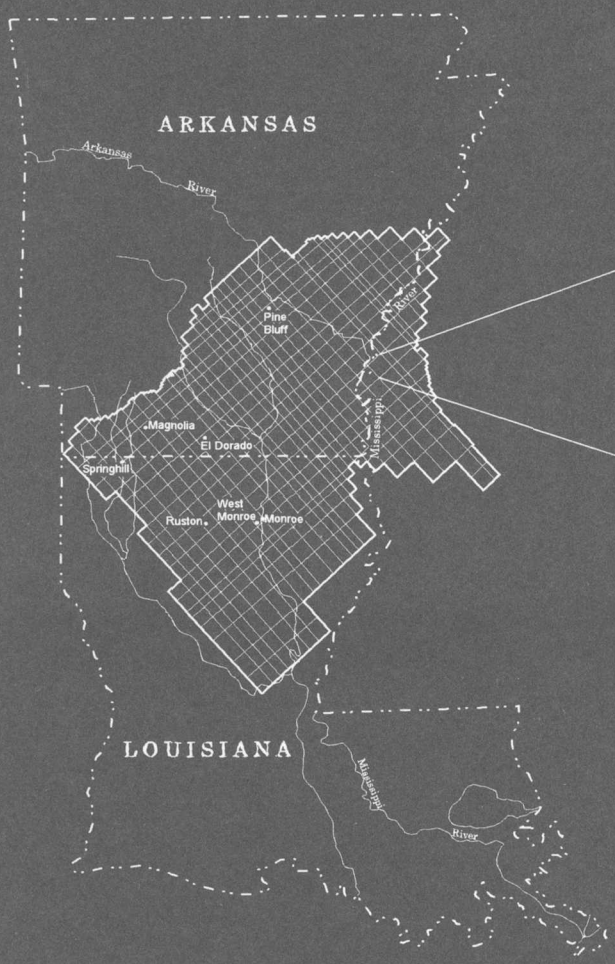

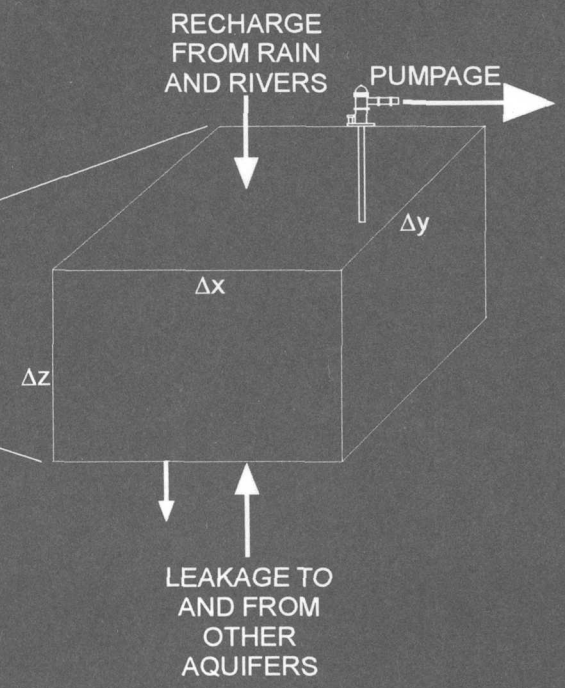

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By Phillip D. Hays, John K. Lovelace, and Thomas B. Reed

U.S. GEOLOGICAL SURVEY
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Little Rock, Arkansas
1998

U.S. DEPARTMENT OF THE INTERIOR
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Simulated Response to Pumping Stress in the Sparta Aquifer of Southeastern Arkansas and North-Central Louisiana, 1998-2027

By Phillip D. Hays, John K. Lovelace, and Thomas B. Reed

ABSTRACT

The Sparta aquifer in southeastern Arkansas and north-central Louisiana is a major water resource for municipal, industrial, and agricultural uses. In recent years, the demand for water in some areas has resulted in withdrawals from the Sparta that significantly exceed recharge to the aquifer. Considerable drawdown has occurred in the potentiometric surface, and water users and managers alike have begun to question the ability of the aquifer to supply water for the long term. Large cones of depression are centered beneath the Grand Prairie area and the cities of Pine Bluff and El Dorado in Arkansas, and Monroe in Louisiana. Water levels in the aquifer have declined at rates greater than 1 foot per year for more than a decade in much of southern Arkansas and northern Louisiana and are now below the top of the formation in parts of Union and Columbia Counties, Arkansas, and in several areas of Louisiana. Problems related to over draft in the Sparta could result in increased drilling and pumping costs, loss of yield, salt-water intrusion, and decrease in water quality in areas of large drawdown. The effects of current ground-water withdrawals and potential future withdrawals on water availability are major concerns of water managers and users as well as the general public in the two States.

The Sparta model—a regional scale, digital ground-water flow model—was first calibrated in the mid-1980's. The model was updated and reverified using 1995-97 data. Visual inspection of the observed (1996-97) and simulated potentiometric surfaces, statistical analysis of the error for the original calibration and current reverification, and comparison of observed versus simulated hydrographs indicates that the model is simulating conditions in the aquifer within acceptable error, and the quality of current (1998) model results is similar to the original model calibration results. When stressed with current withdrawal volumes and distributions, the model is able to simulate currently observed heads effectively as heads were simulated in the original calibration period.

Five pumping scenarios were simulated over a 30-year period based on (1) current pumping rates, (2) current rates of change in pumping, (3) decreased pumping in selected areas, (4) increased pumping in selected areas, and (5) redistribution and increase of pumping in selected areas.

Model results show that although continued pumping at current rates will result in relatively minor declines in water levels (scenario 1 above), continued pumping at currently observed rates of change will result in drastic declines across large areas of focused withdrawals (scenario 2). Under the first scenario—in which current pumping rates are input to the model for the 30-year simulation period—water levels in the middle of the cones of depression centered on El Dorado and Monroe decrease less than 10 feet. In the second scenario—in which the current rate of change in pumpage is applied to the model—substantial declines occur in the proximity of most major pumpage centers. During the 1998-2027 model period, predicted water levels decline from 307 feet below sea level to 438 feet below sea level near El Dorado, from 58 feet below sea level to

277 feet below sea level near Pine Bluff, but only by about 25 feet—from 202 feet below sea level to 225 feet below sea level near Monroe.

In the third scenario—in which minimum predicted water use figures supplied by selected facilities in Arkansas and decreased pumping estimates for Louisiana are applied to the model—simulated water levels are substantially higher at cones of depression around the major pumping centers of Monroe and El Dorado as compared to initial (1997) values. During the 1998-2027 model period, predicted water levels near Monroe increase from 202 feet below sea level to 133 feet below sea level; water levels near El Dorado increase from 307 feet below sea level to 123 feet below sea level.

For the fourth scenario—in which maximum predicted water use information supplied by selected facilities in Arkansas and increase pumping estimates for Louisiana are used in the model—water levels near Monroe decline from 202 feet below sea level to 279 feet below sea level over the period of simulation (1998-2027); water levels near El Dorado decline from 307 feet below sea level to 421 feet below sea level over the period of simulation. Thus, the potential differences in water-level distribution that could arise from various water-use strategies by major facilities are significant. Comparison of the minimum and maximum use scenarios (scenarios 3 and 4) demonstrates the effects that water-use patterns in a limited area can exercise on water levels across an extensive area and highlights the significance, importance, and potential efficacy of water-management planning.

In the fifth scenario, the current rate of change in pumping is doubled for Lonoke and part of Prairie County and selected pumping near El Dorado and Monroe is redistributed. The scenario illustrates the drastic, cumulative effect that long-term, rapidly growing demands for water can have on water levels (Lonoke and Prairie Counties, Arkansas) and the effects of redistributing pumpage from major pumpage centers. Redistribution of selected withdrawal points in the El Dorado and Monroe areas results in expansion of the cones of depression and higher water levels in the center of the cones of depression relative to scenario 2 as well as the initiation of new cones of depression at the new well fields. The increased pumpage in Lonoke and Prairie Counties results in drastic water-level decreases; water levels decline more than 100 feet in some areas of Lonoke County over the 1998-2027 simulation period.

INTRODUCTION

The Sparta aquifer in southeastern Arkansas and north-central Louisiana is a major water resource for municipal, industrial, and agricultural uses. Approximately 355 million gallons per day (Mgal/d) was pumped from the aquifer in Arkansas and Louisiana in 1995 (Joseph, 1998b). The Sparta extends through eastern and southeastern regions of Arkansas, northern Louisiana, and portions of Texas, Mississippi, and Tennessee (fig. 1). Historically, the Sparta aquifer has provided abundant water of high quality. In recent years, however, the demand for water in some areas has resulted in withdrawals from the Sparta that significantly exceed recharge to the aquifer. Considerable drawdown has occurred in the potentiometric surface, and water users and managers alike have begun to question the ability of the aquifer to supply water for the long term. Withdrawals have resulted in the development of large cones of depression centered beneath the Grand Prairie area and the cities of Pine Bluff and El Dorado in Arkansas, and Monroe in Louisiana (Joseph, 1998b). Water levels in the areas of these cones have declined at rates greater than 1 foot per year (ft/yr) for more than a decade in much of southern Arkansas and northern Louisiana and are now below the top of the formation (though not necessarily below the tops of the producing sand units) in parts of Union and Columbia Counties, Arkansas, and in several areas of Louisiana. The cones of depression centered beneath El Dorado and Monroe have coalesced to form a single, large, elongated depression. A smaller cone of depression centered beneath Magnolia, Arkansas, diminished substantially after the completion of Lake Columbia and installation of a surface-water supply system in March 1993 resulted in decreased withdrawals from the Sparta aquifer. The continued increase of drawdowns in areas of the Sparta aquifer, where alternative water sources are not available, probably will result in continued expansion of the cones of depression as well as increased drilling and pumping costs, decreased

aquifer yield, increased saltwater intrusion, and reduced water quality.

In 1985, the U.S. Geological Survey (USGS), in cooperation with the Arkansas Soil and Water Conservation Commission (ASWCC) and the Louisiana Department of Transportation and Development (DOTD), began a project to study the hydrogeologic characteristics of the Sparta aquifer and evaluate the regional effects of increased pumpage on water levels in the aquifer. The primary product of the project was a computer model of ground-water flow in the Sparta aquifer (Fitzpatrick and others, 1990; McWreath and others, 1991), hereafter, referred to as the "Sparta model". In 1991, this model was verified (Kilpatrick, 1992) by the USGS in cooperation with the ASWCC and selected scenarios of future ground-water withdrawals in Union County, Arkansas, were simulated. In 1997, the USGS, in cooperation with the ASWCC and DOTD, began a reverification study to update the modeled pumping stresses and evaluate five potential pumping scenarios.

Purpose and Scope

The effects of current ground-water withdrawals and potential future withdrawals on water availability are a major concern of water managers and users as well as the general public in the two States. This report describes the procedure for updating the previously completed computer model of ground-water flow in the Sparta aquifer and presents the results of five potential future pumping scenarios. The area simulated by the model includes most of southeastern Arkansas and north-central Louisiana. The five potential future pumping scenarios were designed to evaluate the effects of increased, decreased, and redistributed water withdrawals from the Sparta aquifer on water levels in the aquifer during the period 1998-2027.

Information on the model reverification, including a comparison with the observed potentiometric surface and an analysis of error, is presented. Maps are presented that show the simulated 1997 potentiometric surface and results of each hypothetical pumping scenario. Graphs showing observed and simulated water levels at selected wells also are presented.

Previous Studies

Model construction, calibration (1898-1985), and first application (1985-2005) are fully described in Fitzpatrick and others (1990) and McWreath and others (1991). These reports define the initial goals of the model and describe model testing and simulation results for the pumping scenarios posed. Detailed discussion of the history of Sparta aquifer water use, study area hydrogeologic setting, and a description of the aquifer system also are included in the two reports and are not repeated in detail here.

Development of the Sparta model was based on a large body of information available on the hydrogeology of the region. The Gulf Coast Regional Aquifer System Analysis (RASA) included a large-scale hydrogeologic analysis of the region within which the Sparta aquifer lies. Hydrogeologic framework characterization and initial parameter estimates for construction of the Sparta model largely were based upon Gulf Coast RASA results (Williamson and others, 1990; Arthur and Taylor, 1990). Additional data were obtained from reports by Broom and others (1984), Hosman (1982), Payne (1968), Trudeau and Buono (1985), and Petersen and others (1985). These reports present information on the distribution of hydrogeologic characteristics and ground-water conditions, and provide additional hydrogeologic information for the Sparta model; this information includes boundaries, faults, transmissivity, storage coefficients, specific yield, recharge, and water levels.

Kilpatrick (1992) updated pumping data in the model for 1985-89 and performed a verification. The model was used to predict the effects of six pumping scenarios (1990-2019) on water levels in the El Dorado, Arkansas, area.

For comparison of the water-level distribution and evaluation of specified-head boundaries during the current reverification as described in this report, recent potentiometric map reports were reviewed. Ackerman (1987), Joseph (1998a, 1998b), Oakley and Burt (1994), and Westerfield (1994) present potentiometric surface data for the Sparta aquifer and the Cockfield aquifer (Ackerman, 1987, 1996; Brantley and Seanor, 1996; Westerfield, 1994) in Arkansas, Louisiana, and Mississippi.

Study Area Description

The study area comprises terrain in southern and east-central Arkansas, northern Louisiana, and northwestern Mississippi (fig. 1). This area lies within the Mississippi Alluvial Plain and West Gulf Coastal Plain sections of the Coastal Plain Physiographic Province (Fenneman, 1938). Land-surface altitudes range from more than 500 feet (ft) along the western boundary and outcrop recharge zones to less than 100 ft along the Mississippi River. The principal drainages are the Mississippi, Arkansas, Saline, Ouachita, and Red Rivers, Bayou Dorcheat, and Bodcau Creek. Mean annual precipitation is approximately 50 inches (Freiwald, 1985). Water use from the Sparta aquifer in the study area reflects predominant land uses; ground water is intensively used for municipal supply, plant- and animal-based agriculture, aquaculture, and manufacturing of forest products, chemicals, and other industrial products.

SPARTA GROUND-WATER FLOW MODEL DESCRIPTION

The digital model code used by Fitzpatrick and others (1990) and McWreath and others (1991) for development of the Sparta model was the modular finite-difference ground-water flow model (MODFLOW) developed by McDonald and Harbaugh (1988). MODFLOW simulates flow in three dimensions using a block-centered, finite-difference equation approach to the solution of the partial-differential equation for flow. For this study, the Sparta model was converted to run in MODFLOWARC, a version of MODFLOW that allows interface with a geographical information system (Orzol and McGrath, 1992). After the model was converted to MODFLOWARC, it was run to ensure that functionality and output were unchanged from originally reported results.

The model consists of two layers discretized on a variably spaced grid of 113 rows and 95 columns, which represents a 267 mile (mi) by 218 mi area. Active model cells constitute 8,996 of 10,735 grid cells. Cell dimensions range from 1 mi by 1 mi to 10 mi by 23 mi. Hydraulic heads are calculated only in layer 2, which represents the Sparta aquifer. Layer 1, which represents the overlying Mississippi River Valley Alluvial and Cockfield aquifers, is modeled as a constant-head layer—heads remain unchanged throughout the simulation. Flow from layer 1 to layer 2, through the Cook Mountain confining unit, is controlled by the vertical hydraulic conductance assigned to layer 1. Because the Sparta aquifer is underlain by the relatively impervious Cane River confining unit, the base of layer 2 is modeled as a no-flow boundary. Lateral boundary conditions are a combination of no-flow and specified-head boundaries. The specified-head boundaries are at the north, east, and south boundaries of the model; specified heads are changed in certain stress periods. Calibrated hydraulic conductivities used for computation of transmissivity of the Sparta aquifer ranged from 1 to 35 feet per day (ft/d). Calibrated vertical hydraulic conductivities of the Cook Mountain confining unit ranged from 9×10^{-6} to 3×10^{-3} ft/d. The calibrated storage coefficient for the Sparta aquifer was 1×10^{-4} (Kilpatrick, 1992, p. 7). More comprehensive discussions of model construction and calibration are included in the Fitzpatrick and others (1990), McWreath and others (1991), and Kilpatrick (1992).

The model period for simulation is from 1898 (predevelopment) to 1997. During initial model construction and calibration, the period 1898 to 1985 was divided into 4 simulation periods and 25 stress periods (table 1). Kilpatrick (1992) represented the period 1986-91 with an additional simulation period and stress period. For this study, the period 1990-97 is represented by one additional simulation period and stress period.

Table 1. Model simulation periods, number of stress periods, and time periods represented

Model simulation period	Number of stress periods	Time periods represented
1	8	1898-1942
2	8	1943-1962
3	6	1963-1977
4	3	1978-1985
5	1	1986-1989
6	1	1990-1997

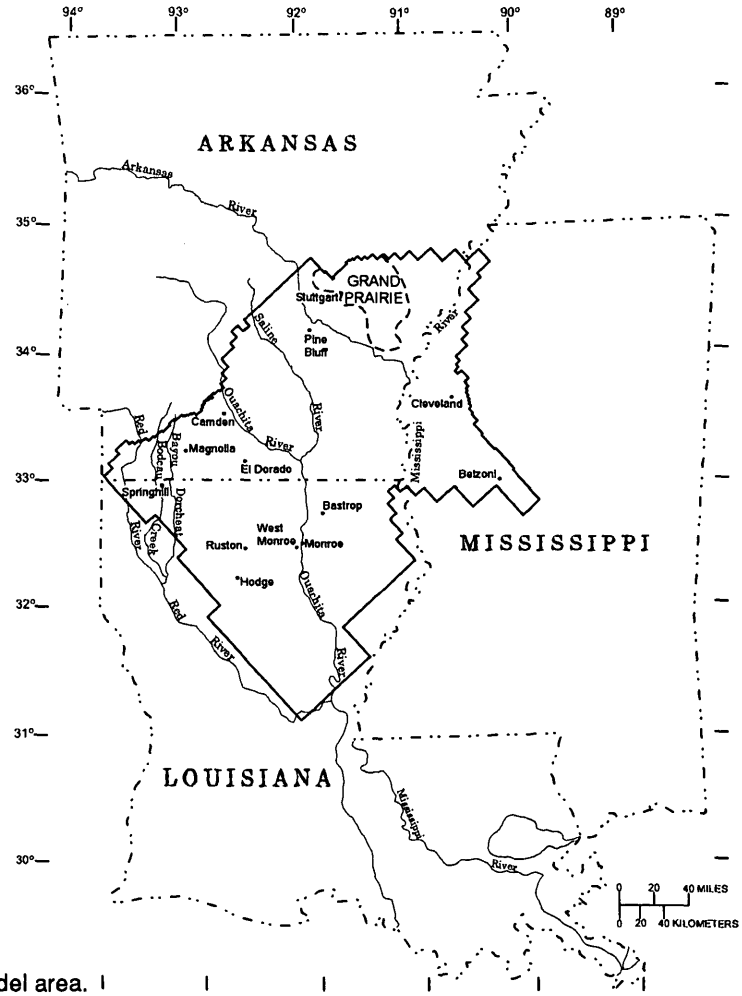


Figure 1. Location of study and model area.

Specified-head values were revised between each model simulation period for periods 1 through 4. Review of recent potentiometric maps for the Sparta aquifer (Joseph, 1998b; Oakley and Burt, 1994) indicated inconsequential changes in head near the specified-head boundaries during the time periods represented by simulation periods 5 and 6; no revision of specified-head values was required. Review of recent potentiometric maps for the Cockfield aquifer (Ackerman, 1987, 1996; Brantley and Seanor, 1996; Westerfield, 1994) also shows minimal changes in water levels, indicating no need to revise layer 1 constant-head values.

Ground-water withdrawal data totaling 248 Mgal/d (33.1 million ft^3/d) for the period 1990-97 were input to the Sparta model. A major focus of the current study was updating and validating the accuracy of water-withdrawal data used in the model. Prior to this study, the most recent estimate of water withdrawal from the Sparta was completed as part of the 1995 national water-use compilation. As previously mentioned, the 1995 total for Arkansas and Louisiana was 355 Mgal/d or 47.5 million ft^3/d. The difference in the amount of withdrawals reported for 1995 and the amount of withdrawals used in the model is due to several factors including: use of 1996 and 1997 data in the model, exclusion of water-use data for wells with unknown completion zones, exclusion of some gross livestock and irrigation estimates, and the fact that 18 Mgal/d are withdrawn from the Sparta aquifer in areas outside of the active model grid. Model well-data sets for simulation periods 4, 5, and 6 were constructed based on withdrawal and well location information available from Arkansas, Louisiana, and Mississippi water-use data bases for 1985, 1989, 1990, 1995, 1996, and 1997. An inventory of water withdrawals in these States is made on a 5-year basis. Pumpage data were distributed in the model over time by subdividing

pumpage into stress periods of relatively constant pumping rates. The allotment of stress periods through the simulation period with respect to pumpage are shown in figure 2. Site-specific withdrawal amounts (withdrawal data for individual wells) were compared with total water use (which includes estimates for livestock and other uses for which there are no site-specific data) reported for the Sparta aquifer by county for Arkansas. For counties in which the site-specific total did not agree with the reported total, wells for which no aquifer code was assigned were reviewed and assigned aquifer codes, bringing site-specific values closer to the estimated totals. To assure accuracy of withdrawal rates and well locations reported by individual facilities, field personnel contacted major water users (facilities pumping more than 1 Mgal/d from the Sparta aquifer) to verify reported data.

MODEL REVERIFICATION

Model reverification was conducted using a three-criteria approach comprising (1) comparison of simulated and observed potentiometric surfaces, (2) error analysis using root mean square error (RMSE), and (3) comparison of simulated and observed hydrographs. "Reverifying" the model essentially confirms that the calibrated model parameters are acceptable and that the model can reproduce, within the same acceptability criteria used for calibration, recently (1996-1997) observed water levels resulting from recent pumpage. The term "calibrated model" means that the model can reproduce, or simulate, within acceptable criteria, observed water levels in the Sparta aquifer resulting from pumping conditions that have existed up to that point in time. Thus the Sparta model was initially calibrated for the 1898-1985 period (Fitzpatrick and others, 1990), verified for the 1985-89 period by Kilpatrick (1992), and now reverified for the 1990-97 period.

Potentiometric Surface Comparison

The first criterion of model reverification was a comparison of simulated heads in the aquifer at the end of the 1997 stress period with observed head values for the water year 1997 (Joseph, 1998b). Simulated heads were contoured and directly compared to the contoured distribution of observed heads (plate 1). To complement simple visual comparison of the simulated and observed surfaces, a difference map was generated (plate 2). To calculate the difference, the contoured distribution of observed heads was used to generate an interpreted head value for each cell in the model in which water-level data were sufficiently near to allow for interpolation or extrapolation. The difference between the interpreted value and the simulated value was determined for each cell where these data were available. The results were color-coded and plotted in order to provide a useful, though qualitative, assessment of the distribution of model error. A difference map for the 1985 observed and simulated heads (plate 3) also was generated to provide a qualitative basis of comparison to 1997 simulation results. Visual comparison of these maps may indicate a slight improvement in the error distribution of the 1997 simulation.

Error Analysis

The second criterion of model reverification was error analysis. Potentiometric head values observed at wells located within model cells were compared with simulated head values generated in the model for the centers of those model cells. Root mean square error (RMSE) was used to judge the goodness of fit. This statistic was used for the previous calibration and verification analyses (Fitzpatrick and others, 1990; Kilpatrick, 1991) and was used to compare current model results with previously reported results. Error results for calibration and reverification analyses are summarized in table 2. RMSE is a statistical representation of variance, and, as such, minimum values of RMSE indicate better model calibration. RMSE is determined using the equation:

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

where n is number of observations,
h_o is observed potentiometric head, and
h_s is simulated potentiometric head.

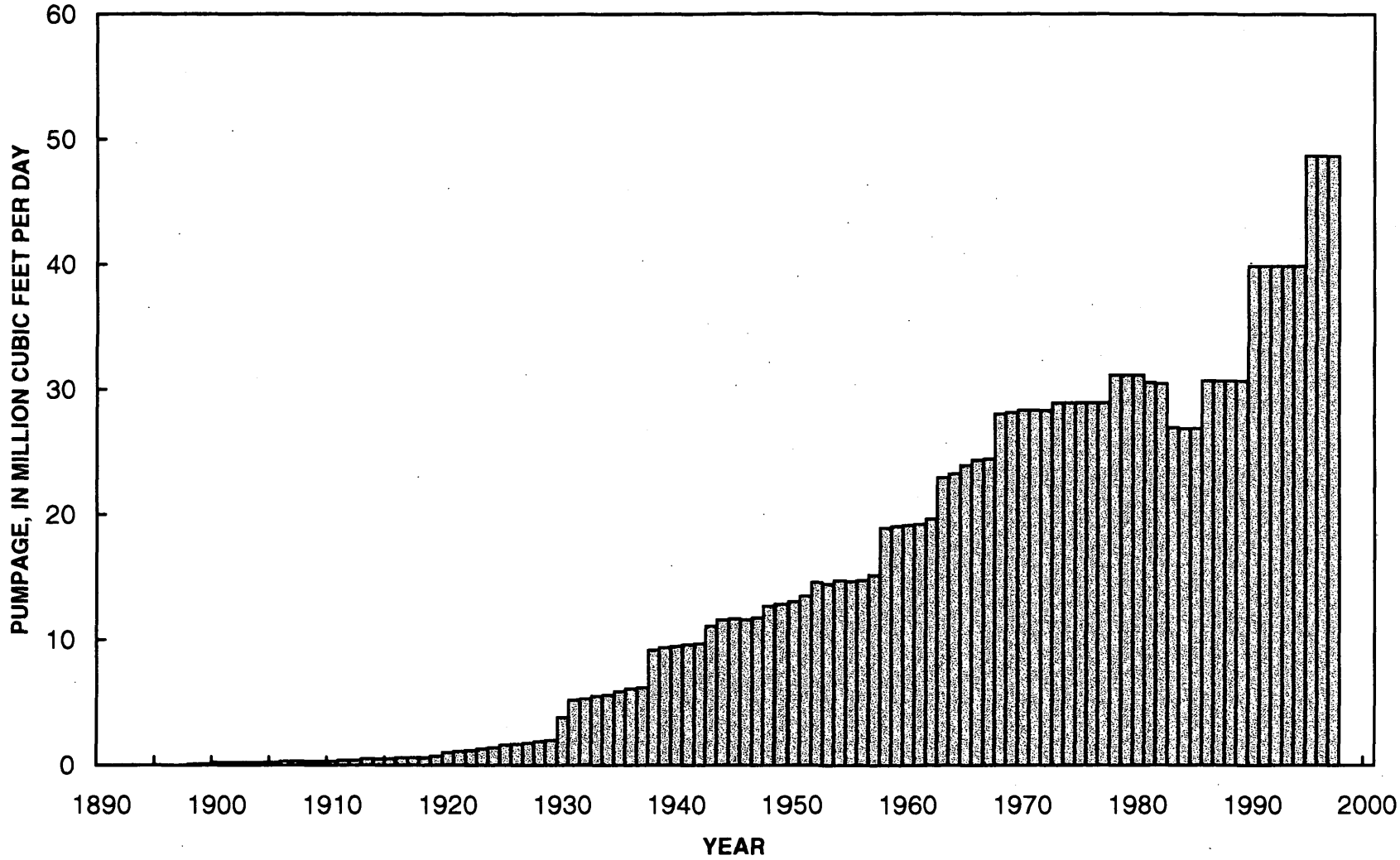


Figure 2. Stress period intervals and total pumpage from the Sparta aquifer, 1898 to 1997.

Table 2. Error analysis results for observed potentiometric heads versus simulated potentiometric heads for 1985, 1990, and 1997 model simulations

Statistic	1985a[1]	1985b[2]	1990[3]	1997a[4]	1997b[2]
Number of wells	233	197	113	283	197
Mean error (feet)	1.8	-12.1	18.3	-2.3	-0.8
Minimum absolute error (feet)	0.3	0.1	0.5	0.3	0.1
Maximum absolute error (feet)	70.6	148.1	68.4	143.0	143.3
Standard deviation (feet)	13.5	30.7	15.4	31.2	31.8
Variance (feet)	180.8	815.0	236.6	974.6	1,014.8
Root mean square error (feet)	21.2	32.9	24.0	31.3	31.7

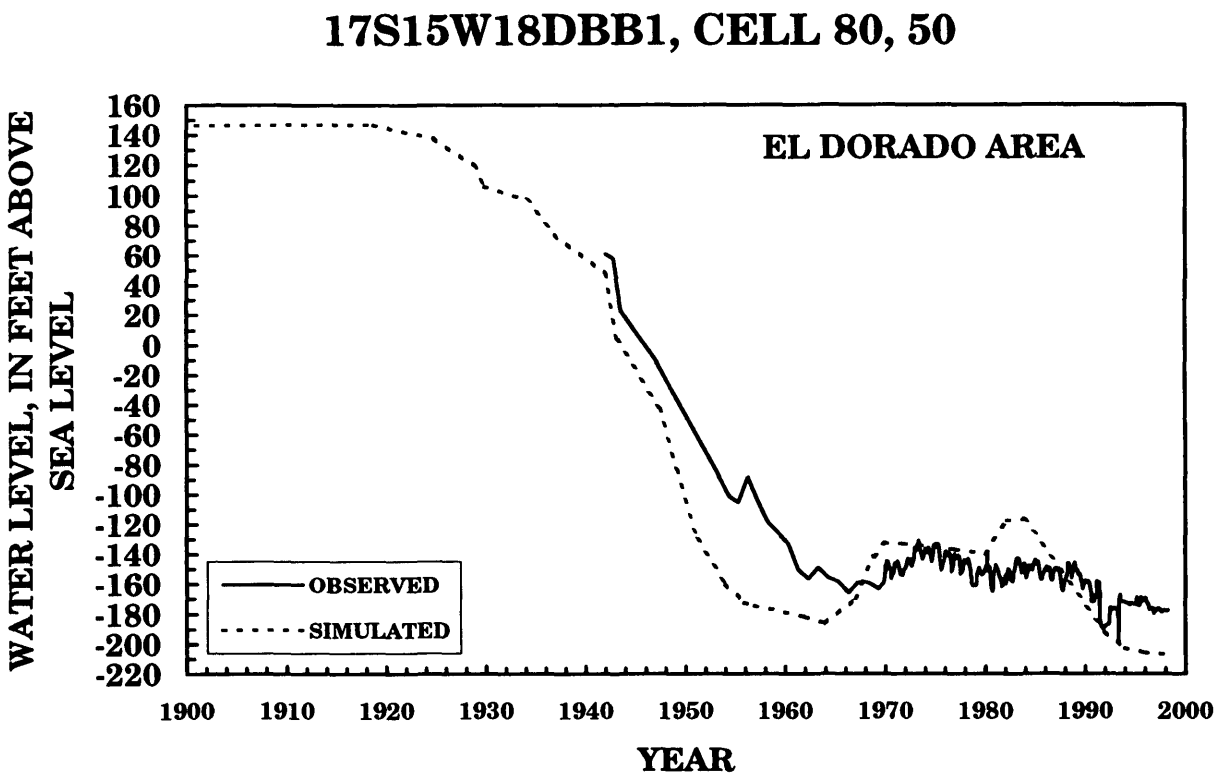
[1]Error results from Fitzpatrick and others (1990).
[2]Statistical determination using data derived from the USGS Ground-water Site Inventory system database for sites within the model area for which data were available for both 1985 and 1997, generating a common key well set for the two simulations.
[3]Error results of Kilpatrick (1992).
[4]Statistical determination using all well data available within the model area for 1997.

Water-level data for 283 wells were available within the active model area for 1997. This data set produced a RMSE of 31.3 ft (table 2). This value is higher than the reported 1985 and 1990 analyses of 21.2 ft and 24.0 ft, respectively (Fitzpatrick and others, 1990; Kilpatrick, 1992; table 2). However, this increase appears to be due to the location of the wells, and does not necessarily indicate a decline in model performance. During collection of water-level data used to construct the 1996-97 potentiometric map for the Sparta aquifer, additional measurements were made in areas of concern to the ASWCC. These areas included cones of depression in a five-county critical aquifer area (Bradley, Calhoun, Columbia, Ouachita, and Union Counties in Arkansas) and the faulted area located west of Magnolia, Arkansas. Greater model error is expected in areas of high gradient, such as the cones of depression found in Columbia and Union Counties. In addition, faults west of Magnolia are not accurately represented by the model, causing water-level simulation in the area to be problematic, as is mentioned in Fitzpatrick and others (1990, p. 30). Over-representation of these areas in the wells set could introduce differences to the error-analysis result. To illustrate this, when the wells in a 17 mi by 14 mi area (a polygon described by model rows 90-99, columns 20-33 containing 11 wells) within the faulted area are removed, RMSE for the 1997 model run drops to 24.6 ft—a value comparable to that reported previously.

A more direct comparison of the ability of the model to simulate potentiometric heads for the original calibration and the current reverification was derived by compiling water-level information from wells that were measured both in 1985 and in 1997, thus providing identical well sets for comparison. Using the identical well sets, RMSE for 1985 was 32.9 ft, comparing very closely with the RMSE result for 1997 of 31.7 ft (table 2).

Hydrograph Comparison

Observed and simulated hydrographs were compared for eight wells with long periods of record (fig. 3a-g). The observed and simulated hydrographs, representative of water levels in different regions of the model area, show good agreement for most locations. Hydrographs in figures 3a-d, and g show long-term declines associated with municipal and industrial withdrawals in the El Dorado (a and b), Pine Bluff (c), and Monroe (d and g) areas. The hydrographs in figures 3e and 3f show long-term declines associated with agricultural withdrawals in the Grand Prairie area of Arkansas.



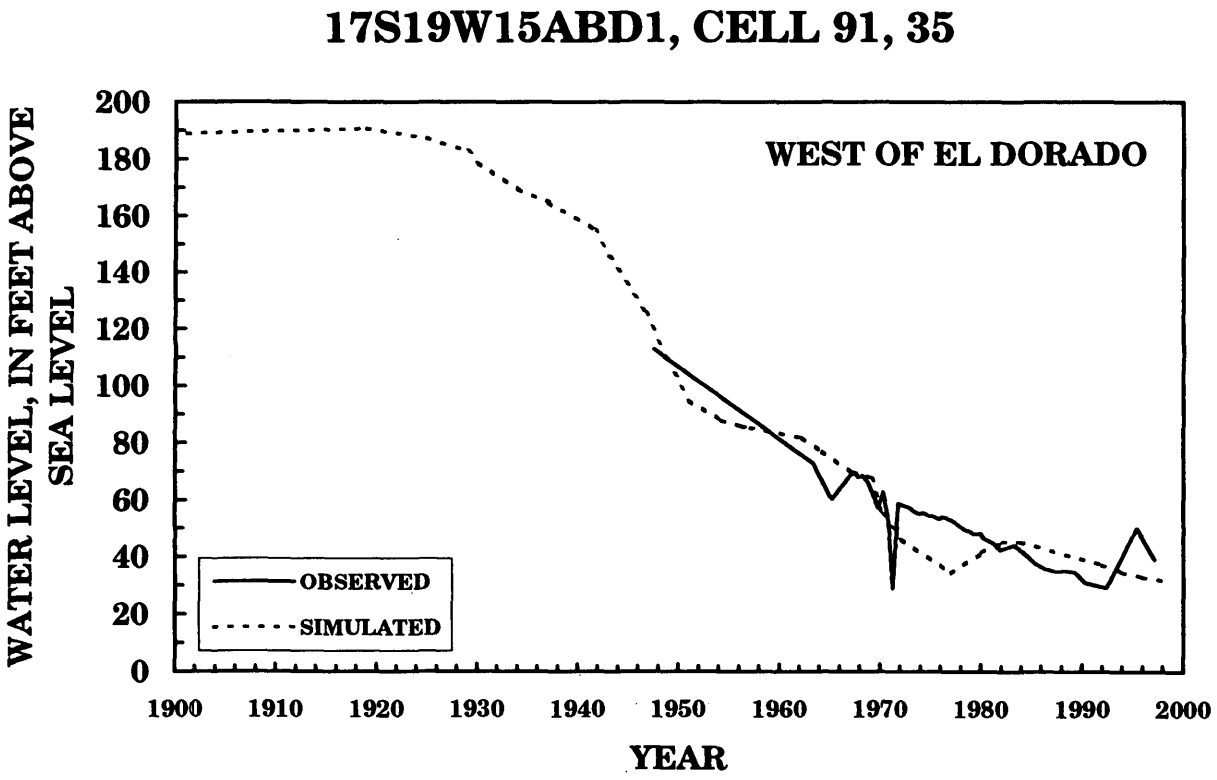
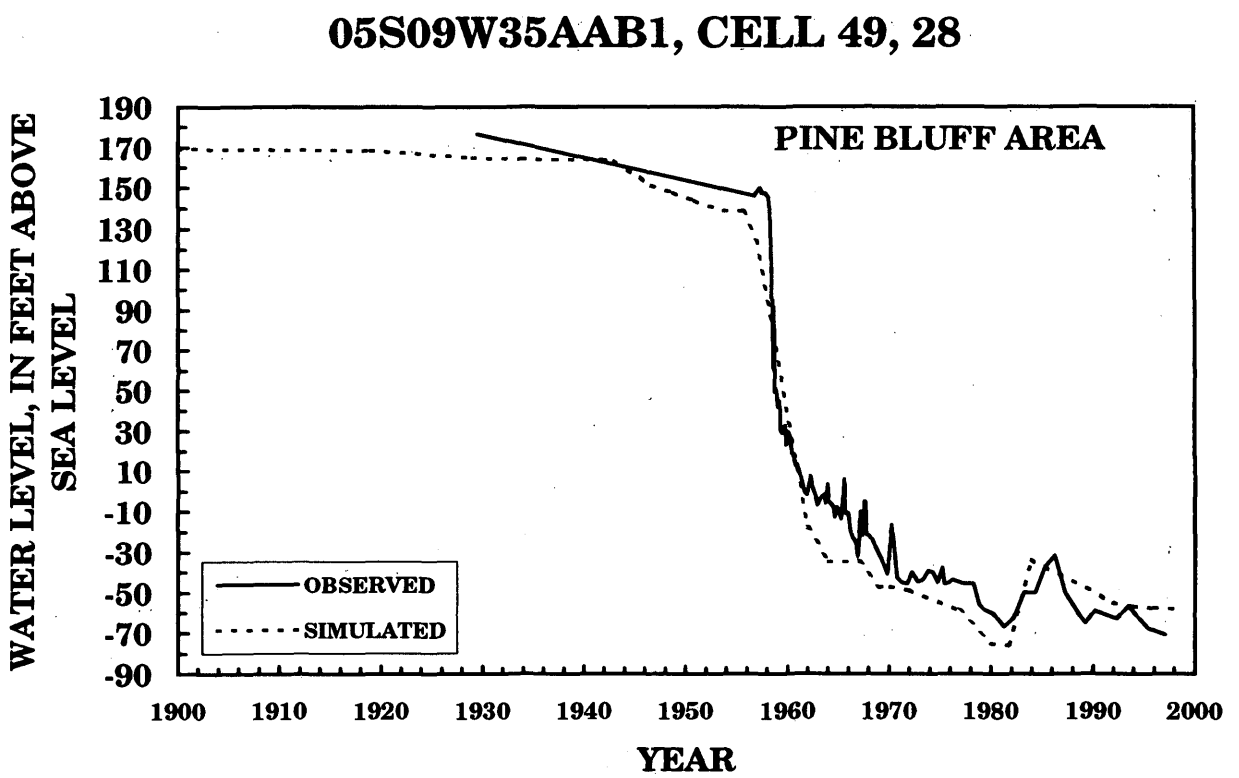


Figure 3. Selected hydrographs of simulated versus observed water levels, 1900 to 1997 (page 1 of 4).



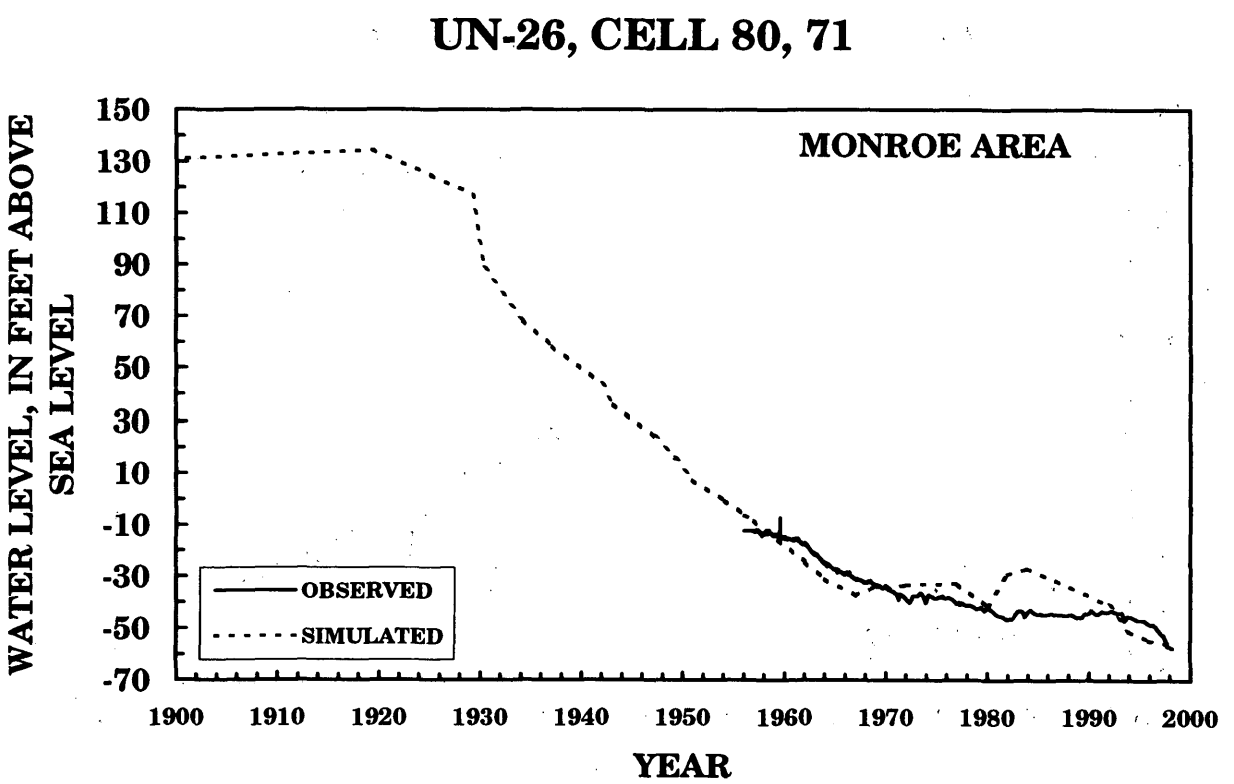
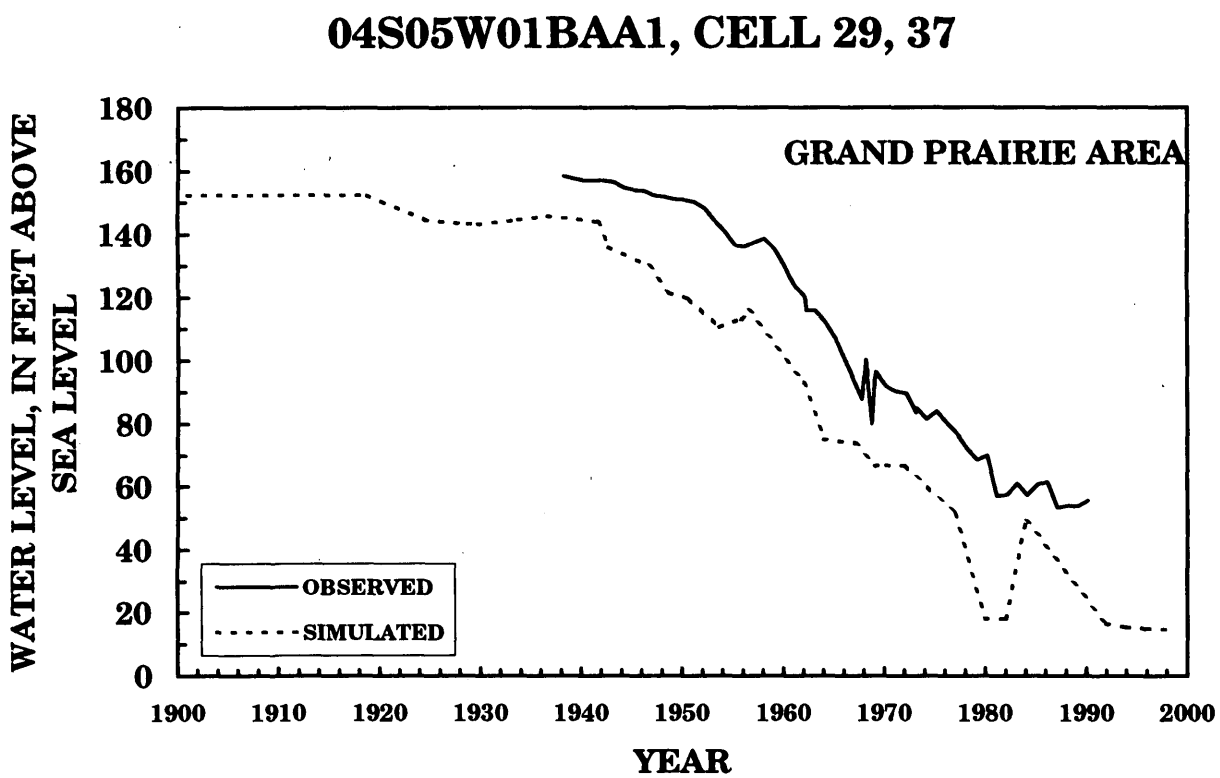


Figure 3. Selected hydrographs of simulated versus observed water levels, 1990 to 1997 (page 2 of 4).



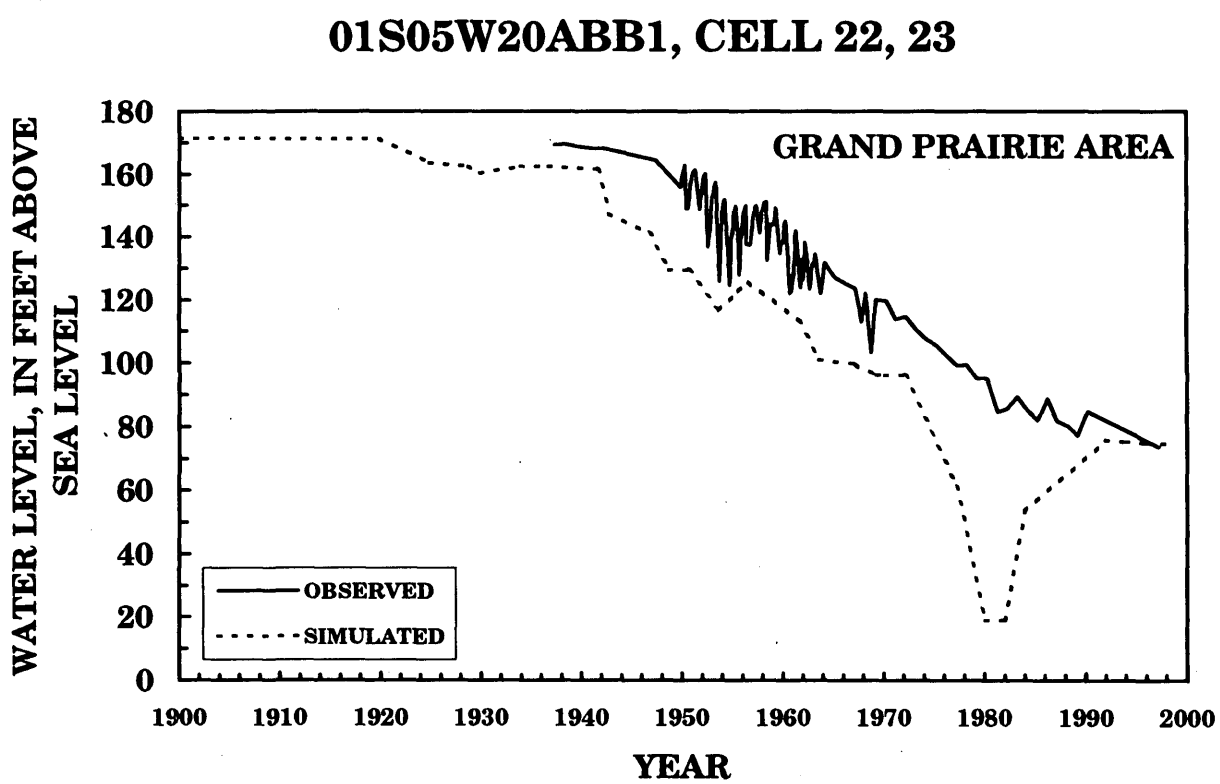


Figure 3. Selected hydrographs of simulated versus observed water levels, 1990 to 1997 (page 3 of 4).

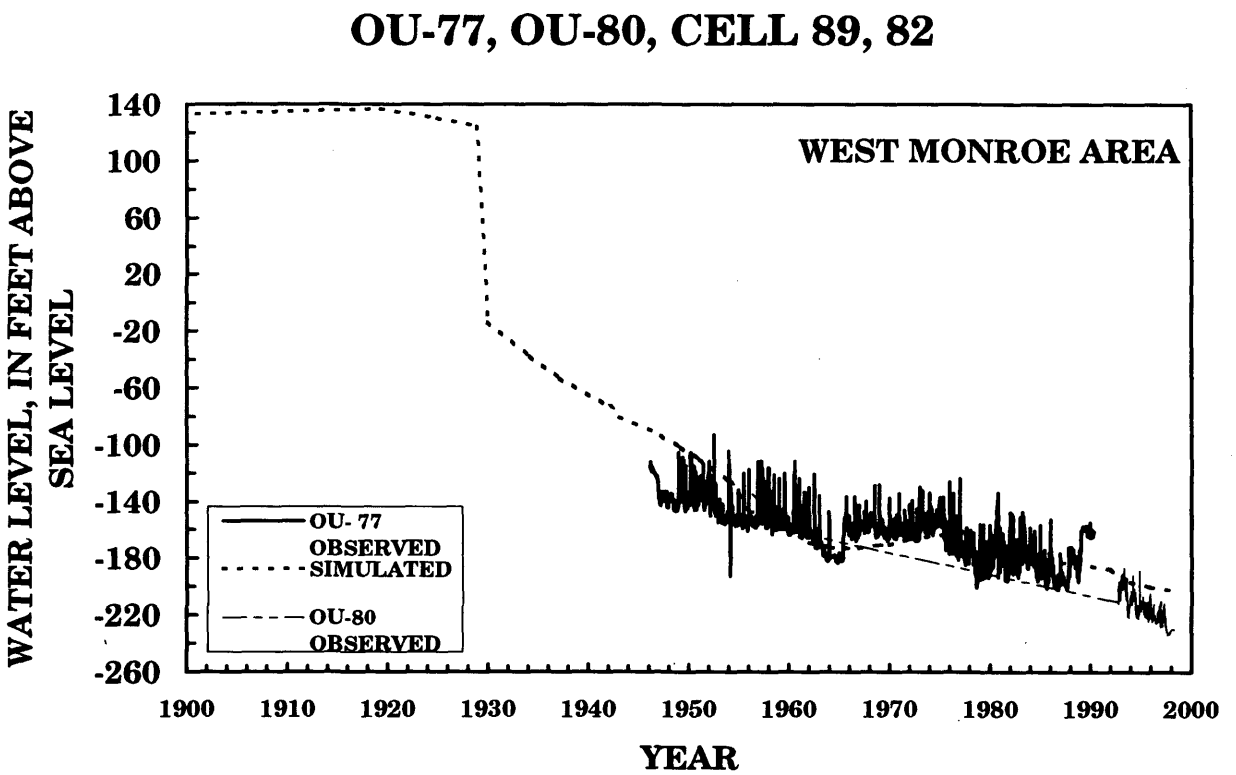


Figure 3. Selected hydrographs of simulated versus observed water levels, 1990 to 1997 (page 4 of 4).

Reverification Result

Comparison of observed and simulated potentiometric surfaces and hydrographs and comparison of current error analysis with previous work indicates that the model is simulating conditions in the aquifer within acceptable error, and the quality of current (1998) model results is similar to the original model calibration results. Reverification of the model indicates that results generated in the predictive runs can provide information useful to water-management planning needs and address the questions posed for this study.

A recalibration of the model (adjustment of basic model parameters such as hydraulic conductivity distribution, vertical conductance, boundary conditions, recharge, etc.) was not conducted nor deemed necessary for achieving study goals at this time. However, analysis of reverification results has identified specific areas where recalibration would improve the ability of the model to simulate aquifer behavior. Potential changes to the model would be based upon analysis of current model results and comparison to observed aquifer conditions as well as hydrogeologic data, such as aquifer test and geophysical logging data, collected since original model development. Changes to the model that would improve utility and performance include: (1) geophysical and aquifer test data currently being accrued that will help define needed alterations of hydraulic conductivity and vertical conductance distributions, (2) better simulation of faulted areas (particularly in the area west of Magnolia), (3) addition of newly completed reservoirs in or near outcrop and subcrop areas, (4) adding the ability to convert from storage coefficient to specific yield conditions where water levels drop below the top of the producing sands, and (5) refinement of the model grid. The model grid could be refined to incorporate more detailed hydrogeologic data as they become available and additional withdrawal points as water-use patterns change.

The questions posed to be answered by interpretation of Sparta ground-water flow model results have changed with the evolving needs of water users and managers in the region; the problems, and questions that must be answered to address those problems, have become more focused and site specific. This requires increasingly detailed input, results, and interpretations from the model. Recalibration of the model, incorporating some of the changes mentioned here, would

improve the utility of the model and make a more adaptable tool capable of addressing the evolving Sparta aquifer water-management problems of the region.

VOLUMETRIC FLOW BUDGET

Summary output of model volumetric flow-rate budget information for the 1985 (Fitzpatrick and others, 1990) and 1997 (this report) simulations are included in table 3 and are shown schematically in figure 4. Analysis of simulated flow shows that total flow through the Sparta aquifer has increased from about 38.6×10^6 cubic feet per day (ft^3/d) in 1985 to 43.6×10^6 ft^3/d in 1997. Leakage from the Cockfield aquifer (Layer 1) into the Sparta aquifer has increased from 15.0×10^6 ft^3/d to about 18.0×10^6 ft^3/d. Total stress on the aquifer by wells has increased by 6.0×10^6 ft^3/d, and now constitutes 76 percent of total flow out of the aquifer. Total leakage of river water into and out of the aquifer has decreased. The general, model-wide decline in leakage out of the aquifer to river cells is because of lower water levels due to increased pumping from the Sparta aquifer in areas where rivers overlie the aquifer. The decline in leakage into the aquifer from river cells may be explained by a major decrease in demand in the Magnolia area because of a switch from ground-water use to surface-water use. Intense pumping from the Sparta aquifer in the Magnolia area induces recharge to the aquifer from nearby rivers; the recent decrease in pumpage there has resulted in less water moving from the river into the aquifer in the area. Analysis of flow indicates that the aquifer is behaving as conceptualized under increased pumping stress throughout the model area.

Table 3. Sparta model volumetric budget comparison

1985 run		1997 run		
In	Volume rate (cubic feet per day)	In	Volume rate (cubic feet per day)	Component difference
Storage	3,872,927	Storage	5,150,900	1,277,973
Layer 1 leakage (constant head)	15,004,858	Layer 1 leakage (constant head)	17,979,736	2,974,878
Constant head boundary cells	4,759,267	Constant head boundary cells	5,661,264	901,997
Wells		Wells		
Recharge	13,297,338	Recharge	13,298,000	662
River leakage	1,702,362	River leakage	1,516,500	-185,862
Total in	38,636,752	Total in	43,606,400	4,969,648
Out	Volumetric rate (cubic feet per day)	Out	Volumetric rate (cubic feet per day)	Component difference
Storage	149,416	Storage	109,070	-40,346
Layer 1 leakage (constant head)	554,511	Layer 1 leakage (constant head)	495,112	-59,399
Constant head boundary cells	2,126,513	Constant head boundary cells	1,957,988	-168,525
Wells	27,137,568	Wells	33,128,000	5,990,432
Recharge		Recharge		
River leakage	8,677,128	River leakage	7,915,800	-761,328
Total out	38,645,136	Total out	43,605,970	4,960,834

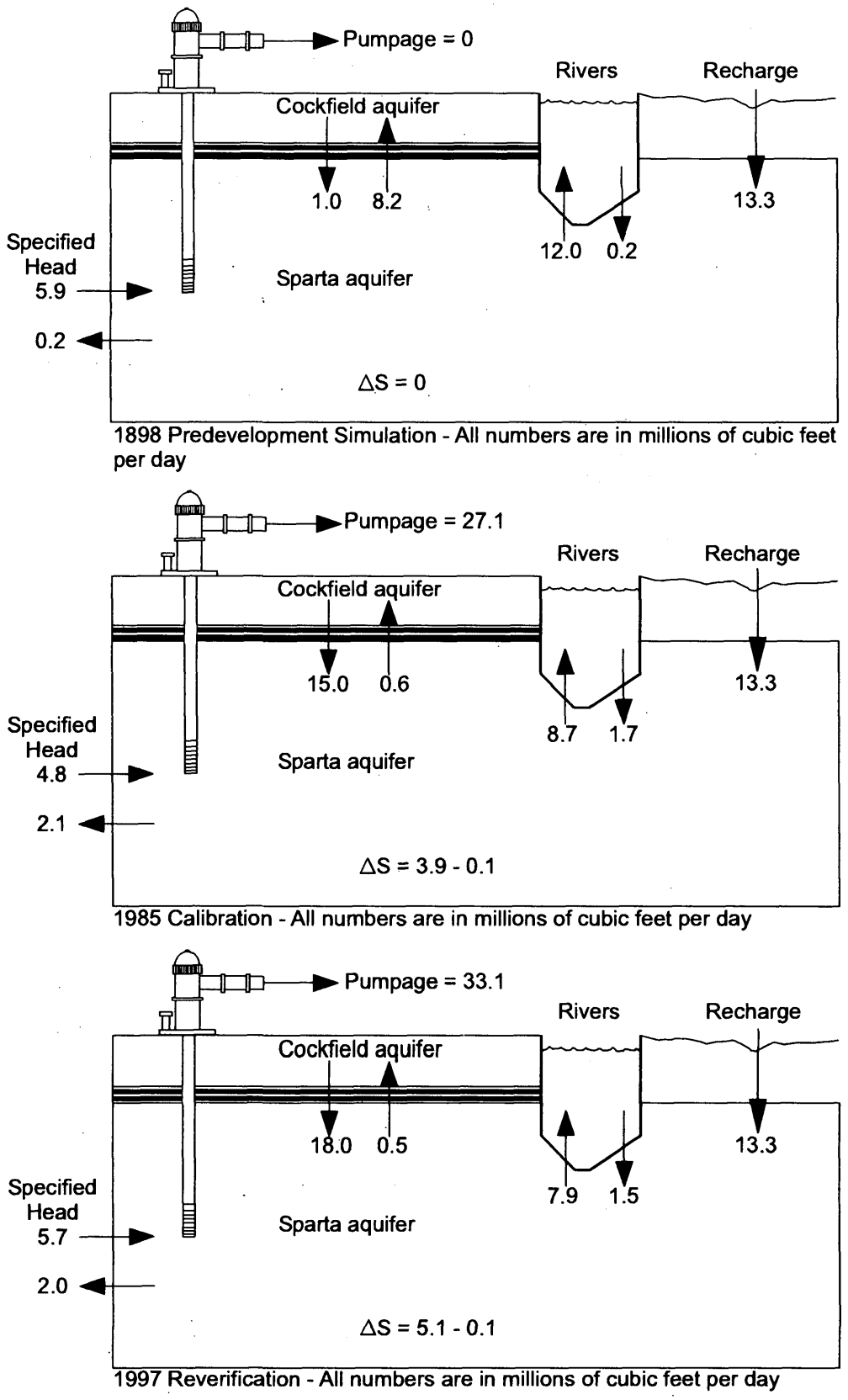


Figure 4. Volumetric budget components for 1898 predevelopment simulation, 1985 calibration, and 1997 reverification.

SIMULATED AQUIFER RESPONSE TO FUTURE PUMPING STRESS

The reverified model was used to predict the effects of five pumping scenarios on water levels over the period 1998-2027. Total pumpage for each scenario is listed in table 4. Development of the scenarios was based on input from Sparta aquifer water users and managers in Arkansas and Louisiana and was obtained through direct communication, questionnaires, public meetings, and discussion with ASWCC and DOTD representatives. To ensure that the predictive scenarios are realistic and could be instituted, representatives of several major water-using facilities were asked to describe possible water-use changes that could occur at their facilities in the future. Possible changes described include facility growth, water conservation, use of alternative water sources, and various other factors that could cause the amount or location of water pumped from the Sparta aquifer to change.

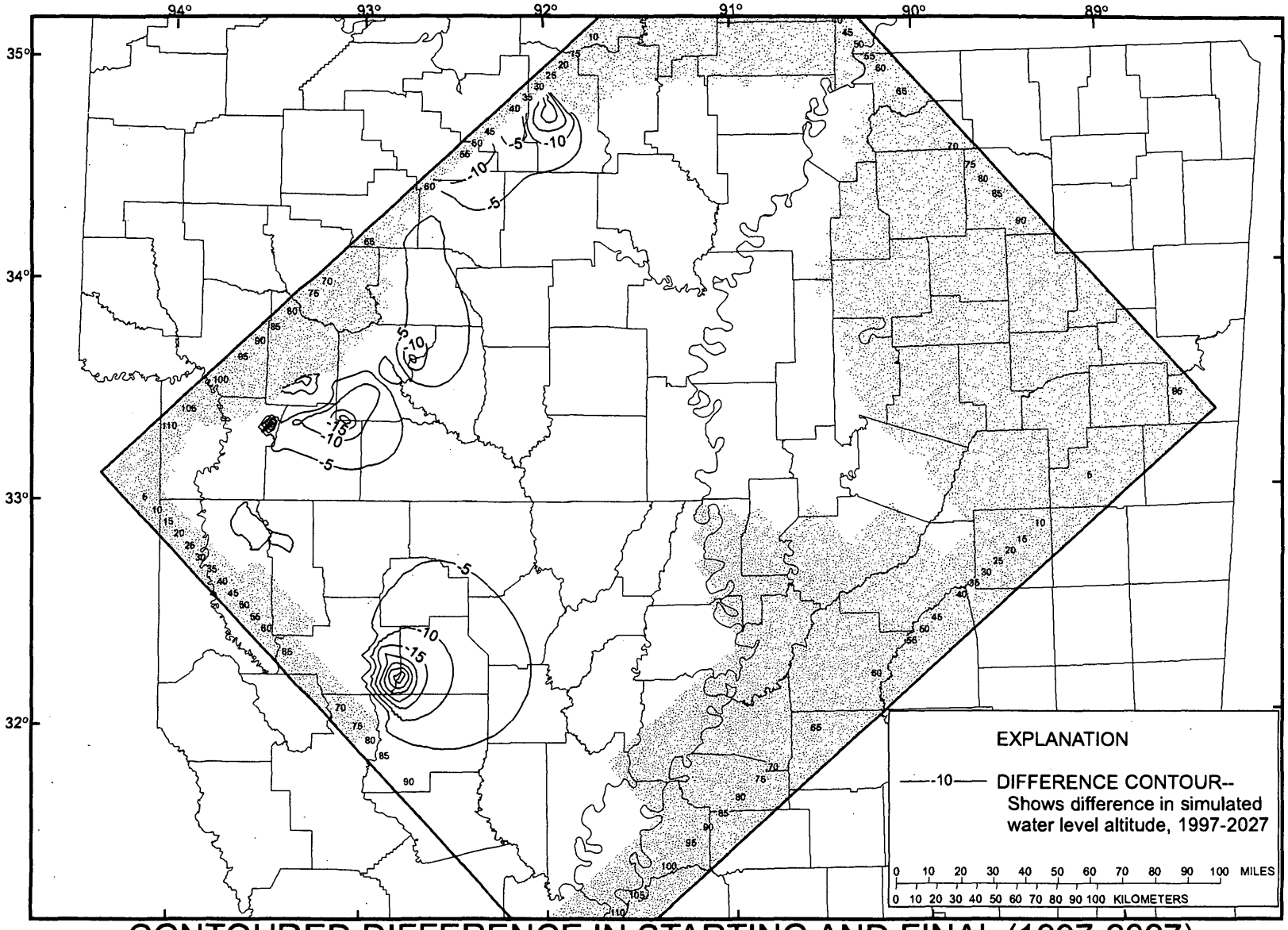
1- Baseline Scenario

A model simulation using pumpage values held constant at 1996 rates was conducted for the period 1998-2027. The potentiometric surface for 2027 from this scenario is presented in plate 4. This scenario provides a baseline for comparison of other simulations in which future withdrawals may increase, decrease, or change in location. In general, results of this scenario indicate that water levels will decline slightly in most areas of the model. To illustrate this, figure 5 shows contoured differences in starting and final water levels at cell nodes. For example, water levels in the center of the cone of depression centered on El Dorado decrease to 311 ft below sea level in 2027 from 307 ft below sea level in the 1997 simulation (table 4). Water-level elevations in the Monroe cone of depression show a similar decline from 202 ft below sea level to 207 ft below sea level in the center of the cone. Water-level values within the Pine Bluff cone of depression decline 3 ft over the simulation period.

Table 4. Selected volumetric budget and water-level altitude data from model cells representative of cone of depression centers for reverification run (1997) and for predictive scenario runs (2027)

	1997 reverification	2027 scenario 1	2027 scenario 2	2027 scenario 3	2027 scenario 4	2027 scenario 5
Pumpage (million cubic feet per day)	33.1	33.1	52.9	30.1	36.2	52.9
Net to rivers (million cubic feet per day)	2.7	5.6	4.7	6.3	5.0	5.1
Net from Cockfield (million cubic feet per day)	17.5	17.9	27.6	16.7	19.2	26.8
Change in storage (million cubic feet per day)	5.0	3.3	7.7	2.5	4.1	8.3
El Dorado water level (feet) (cell 82,53)	-307	-311	-438	-123	-421	-378
Monroe water level (feet) (cell 89,82)	-202	-207	-225	-133	-279	-155
Pine Bluff water level (feet) (cell 49,28)	-58	-61	-277	-60	-63	-261
Magnolia water level (feet) (cell 98,33)	-102	-106	-115	-86	-243	-109
Lonoke County water level[1] (feet) (cell 33,21)	72	69	-25	70	68	-35

[1]Lonoke County water-level data are representative of the area and are not from a cone of depression.



CONTOURED DIFFERENCE IN STARTING AND FINAL (1997-2027) WATER LEVEL DISTRIBUTION FOR SCENARIO 1

Figure 5. Contoured difference in starting and final (1997-2027) water-level distribution for scenario 1.

2- Continuing Current Rate of Change Scenario

A model simulation using the current rate of change of withdrawal rates was conducted for the period 1998-2027. This scenario provides information on the evolution of aquifer conditions in the region if the current rate of change in water withdrawal rates continues. For this scenario, a simple regression model for predicting total water use was constructed for each county and parish in the active model area using water-use data available since 1980. The trend in change of observed water-use rates over the period 1980-1995 was used to predict water use for each county or parish through 2027. The simulation period was segmented into six stress periods of 5 years each. The percentage contribution of each well to total pumpage within a county or parish was determined, and pumpage at each well was augmented according to the regression-derived county/parish- total multiplied by the well percentage for each stress period. Predicted future withdrawals based on declining water use in some Arkansas counties indicated that withdrawals from the Sparta aquifer would cease prior to 2027. Because this is probably unrealistic, water use in counties with negative water-use growth was held constant at 1996 rates.

In general, predicted water levels for this scenario (plate 5) are lower than levels predicted for the baseline scenario (plate 4) and substantial declines occur in the proximity of major pumpage centers under the second scenario. Figure 6 illustrates the declines observed over the scenario 2 model period. During the 1998-2027 model period, predicted water levels decline from 307 ft below sea level to 438 ft below sea level near El Dorado (table 4), from 58 ft below sea level to 277 ft below sea level near Pine Bluff, but only by about 25 ft from 202 ft below sea level to 225 ft below sea level near Monroe. Water use probably would be adversely affected by the declines predicted in this scenario; by 2027, water levels approach or drop further below the top of the Sparta Formation in several pumpage centers, including El Dorado, Monroe, Pine Bluff, and the Grand Prairie area.

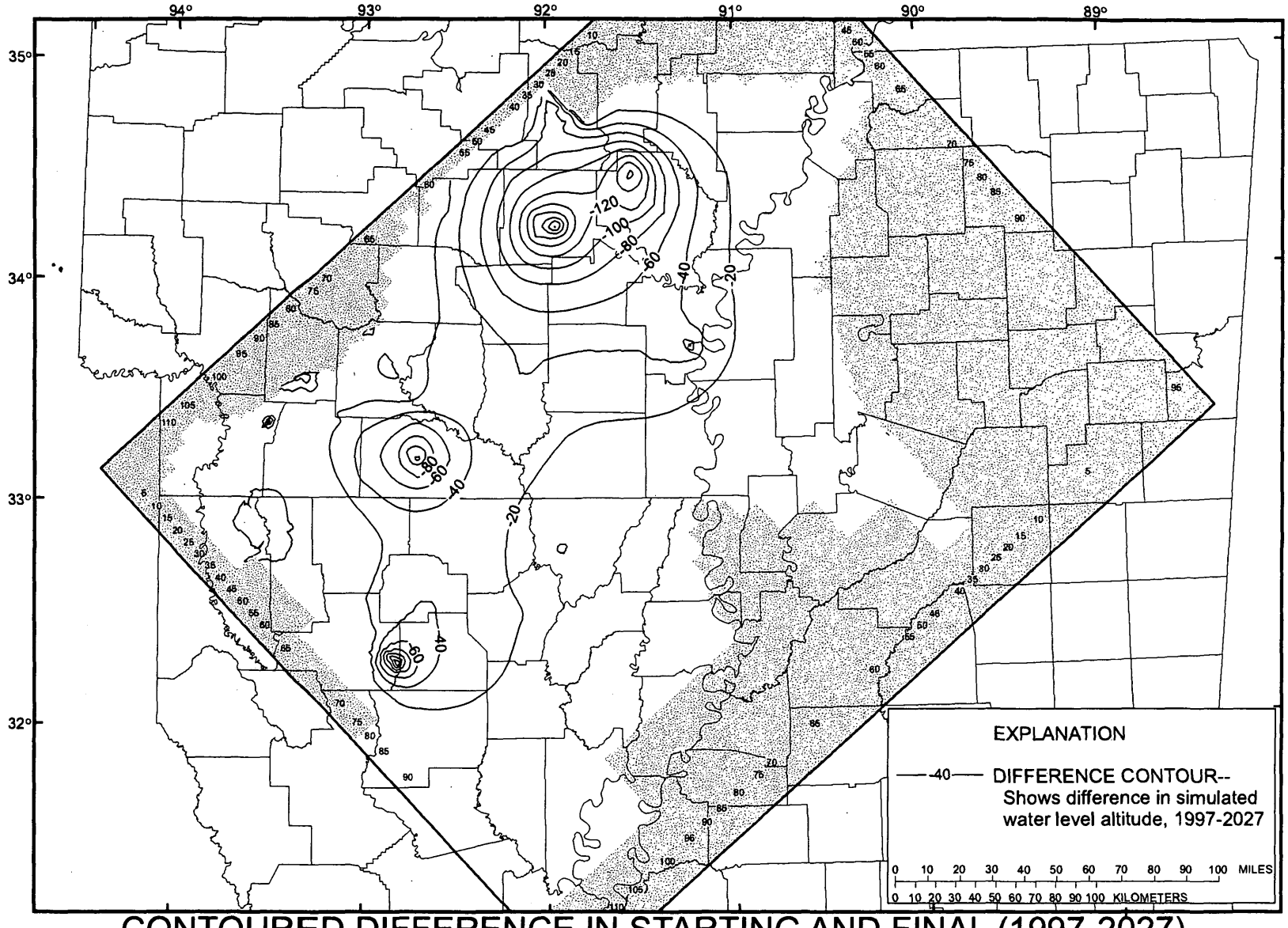
3-Minimum Estimated Water-Use Scenario

A model simulation was conducted using estimated minimum water-use rates for selected facilities in Arkansas and Louisiana. For Arkansas, minimum rates were estimated based on information collected from water users in the five-county critical aquifer area, which includes Bradley, Calhoun, Columbia, Ouachita, and Union Counties. Water managers at major water-use facilities, municipalities, and water associations provided data on potential future water use at their facilities and described multiple potential patterns for water use at their facilities for the next 30 years. A summation of the minimum predicted water use from all of these facilities was used to construct the minimum estimated water-use scenario. Pumpage values outside of the five-county area were maintained constant at 1997 levels. For Louisiana, minimum rates for major users (average withdrawals rates greater than 1 Mgal/d) were estimated to be 75 percent of rates used in scenario 1, which approximately corresponds to minimum withdrawal rates reported by many of these facilities since 1980.

This scenario was intended to estimate what effect the potential water-use minimization strategies currently identified by water managers will have. The potentiometric surface for 2027 is shown in plate 6. Simulated water levels are substantially higher at cones of depression around the major pumping centers of Monroe and El Dorado as compared to starting (1997) values. These changes are highlighted with the positive values shown on the difference map (fig. 7) for scenario 3. During the 1998-2027 model period, predicted water levels near Monroe increase from 202 ft below sea level to 133 ft below sea level (table 4); El Dorado water levels increase from 307 ft below sea level to 123 ft below sea level.

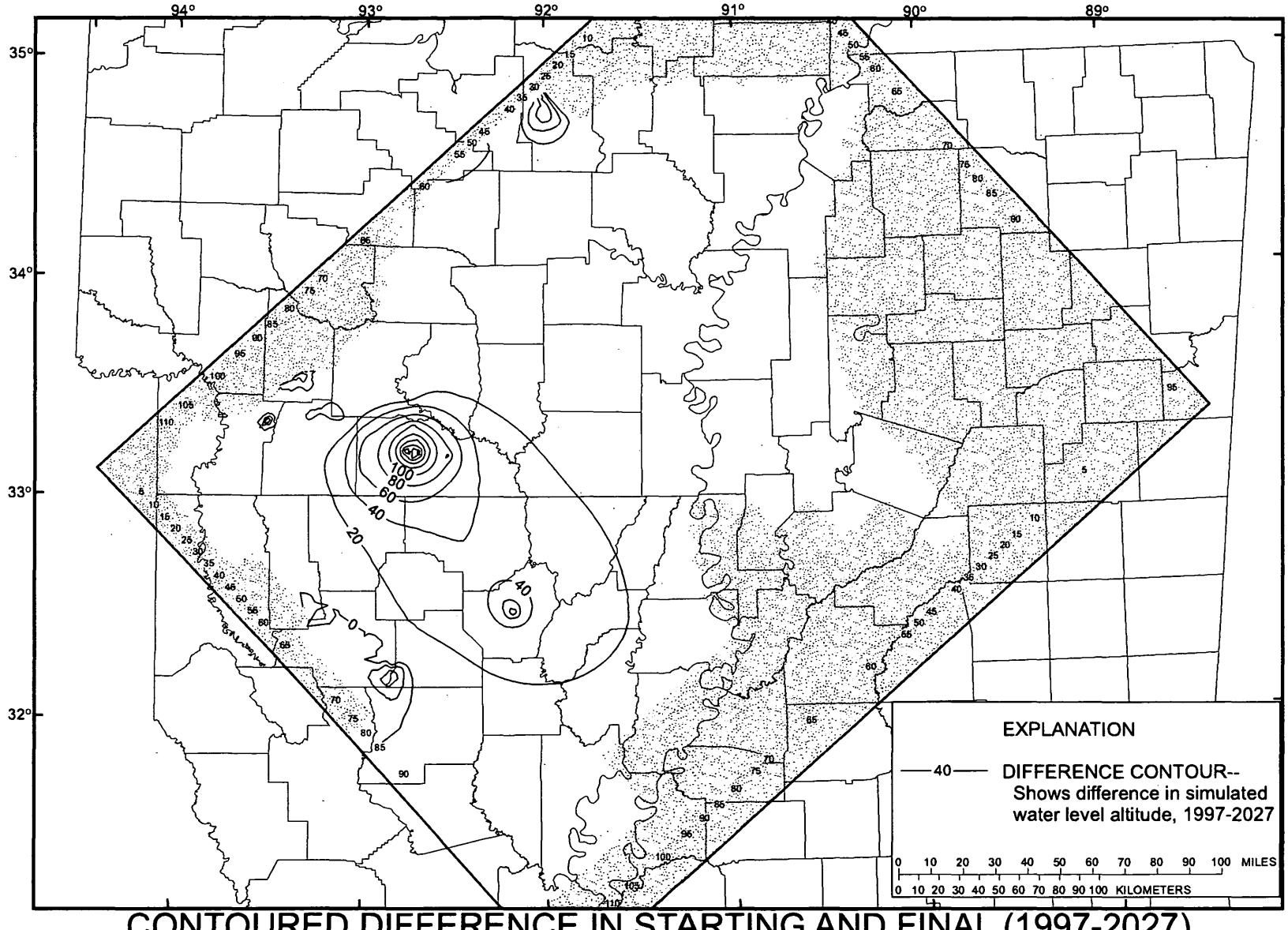
4-Maximum Estimated Water-Use Scenario

A model simulation was conducted using estimated maximum water-use rates for selected facilities in Arkansas and Louisiana. For Arkansas, maximum rates were estimated based on information collected from water users in the five-county critical area. Water managers at major water-use facilities, municipalities, and water associations provided data on potential future water use at their facilities and described multiple potential patterns for water use at their facilities for the next 30 years. A summation of the maximum predicted water use from all of the reporting facilities was used to construct the maximum estimated water-use scenario. Pumpage values outside of the five-county critical area were maintained constant at 1997 levels.



CONTOURED DIFFERENCE IN STARTING AND FINAL (1997-2027) WATER LEVEL DISTRIBUTION FOR SCENARIO 2

Figure 6. Contoured difference in starting and final (1997-2027) water-level distribution for scenario 2.



CONTOURED DIFFERENCE IN STARTING AND FINAL (1997-2027)
WATER LEVEL DISTRIBUTION FOR SCENARIO 3

Figure 7. Contoured difference in starting and final (1997-2027) water-level distribution for scenario 3.

For Louisiana, maximum rates for major users were estimated to be 125 percent of 1995 rates, which is approximately 10 percent higher than maximum withdrawal rates reported by many of these facilities since 1980.

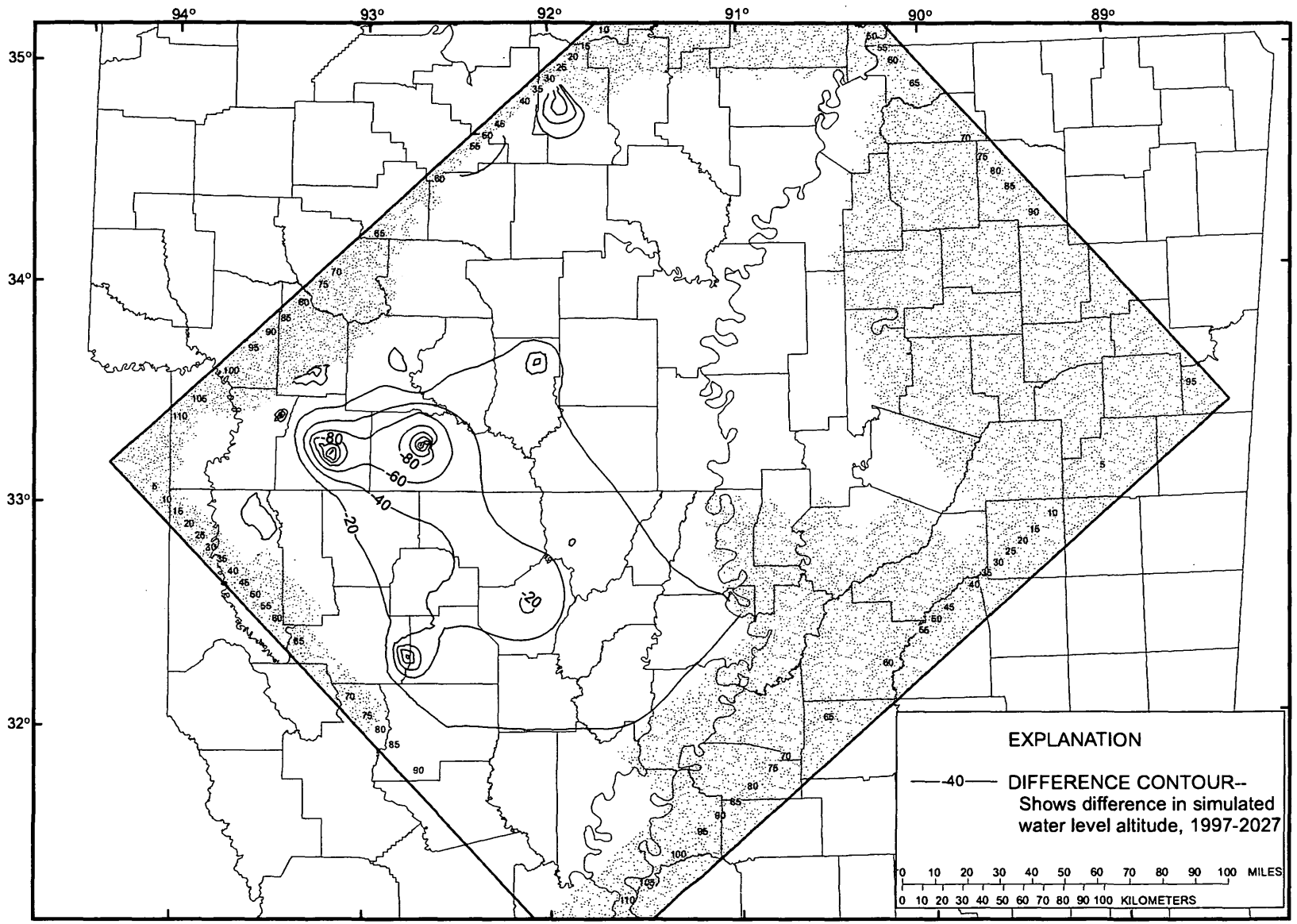
This scenario was intended to estimate the effect that potential water-use growth trends currently identified by water users will have on water levels. The potentiometric surface for 2027 is shown in plate 7; the contoured difference in water levels is shown in figure 8. These show sharp water-level declines at cones of depression around the major pumping centers of Monroe and El Dorado. Water levels near Monroe decline from 202 ft below sea level to 279 ft below sea level over the period of simulation (1998-2027) (table 4); water levels near El Dorado decline from 307 ft below sea level to 421 ft below sea level over the period of simulation. The declines resulting from the maximum growth in water use as predicted by the water-use facilities for this scenario are slightly less than the declines predicted by Scenario 2—the continuing current rate of change scenario. The ability to produce water from the aquifer would be adversely impacted. For example, pumping costs may increase with the drastic reductions in water levels predicted. As water levels drop below the tops of the producing sands, further withdrawal will begin to "mine" water from the once artesian system, and the ability of the aquifer to provide water will be described by specific yield instead of storage coefficient, resulting in increased potential for irretrievable damage to this clay and fines-rich aquifer by way of compaction of aquifer materials, loss of yield, and reduction of the water resource (Freeze and Cherry, 1979; Todd, 1980).

To facilitate comparison of the effects of the minimum and maximum pumpage scenarios, a difference map (plate 8) was created that shows the differences in water-level distributions in the year 2027 for the two scenarios (scenarios 3 and 4). Large areas around El Dorado and Monroe—where the changes in withdrawal rates were applied—show differences of greater than 100 ft, and a broad region encompassing the two cities exhibits differences of 25 to 100 ft. Maximum differences approaching 300 ft are seen near El Dorado. This map demonstrates the effects that water-use patterns in a limited area can exercise on water levels across an extensive area, and the comparison underscores the significance, importance, and potential efficacy of water-management planning and water-use minimization strategies.

5-Lonoke-, El Dorado-, Monroe-Shuffle Scenario

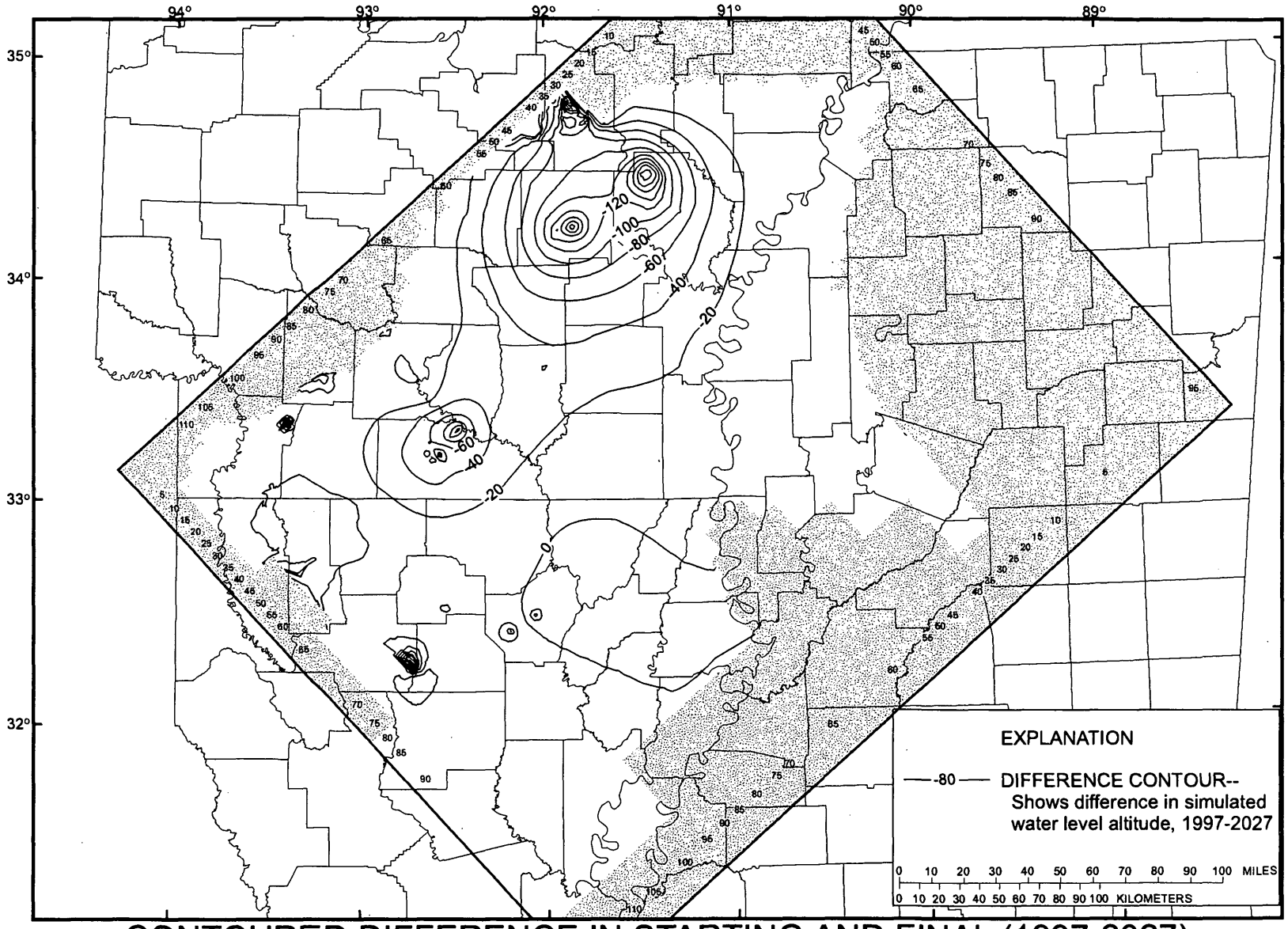
A model simulation was conducted to determine the effects of redistributing pumpage in the El Dorado and Monroe areas and increasing the current rate of pumpage in Lonoke and central Prairie Counties, Arkansas. Selected pumpage located in the El Dorado and Monroe cones of depression was redistributed away from the center of the cones. Pumpage in Lonoke and central Prairie Counties was increased by twice the currently observed rate of increase over the 30-year model simulation period to simulate the effects of burgeoning agricultural use. Pumpage applied in other counties and parishes was based on the current rate of change in water use on 5-year periods 1998-2027 (as in scenario 2).

Redistribution of selected withdrawal points in the El Dorado and Monroe areas results in shallower but more expansive cones of depression (plate 9) relative to scenario 2 (plate 5). Minimum water levels near El Dorado under this scenario are more than 375 ft below sea level (table 4); minimum levels near Monroe are more than 150 ft below sea level. New cones of depression begin to develop at the new well fields by the end of the 30-year model period. The increased pumpage in Lonoke and Prairie Counties results in drastic water-level decreases; declines in water levels exceed 100 ft in some areas of Lonoke County over the 1998-2027 simulation period (fig. 9).



CONTOURED DIFFERENCE IN STARTING AND FINAL (1997-2027) WATER LEVEL DISTRIBUTION FOR SCENARIO 4

Figure 8. Contoured difference in starting and final (1997-2027) water-level distribution for scenario 4.



CONTOURED DIFFERENCE IN STARTING AND FINAL (1997-2027) WATER LEVEL DISTRIBUTION FOR SCENARIO 5

Figure 9. Contoured difference in starting and final (1997-2027) water-level distribution for scenario 5.

SUMMARY

The Sparta aquifer in southeastern Arkansas and north-central Louisiana is a major water resource and provides water for municipal, industrial, and agricultural uses. In recent years, the demand in some areas has resulted in withdrawals from the Sparta that significantly exceed the aquifer's ability to recharge. Considerable drawdown has occurred in the potentiometric surface and water users and managers alike have begun to question the ability of the aquifer to supply water for the long term. Large cones of depression are centered beneath the Grand Prairie area and the cities of Pine Bluff and El Dorado in Arkansas, and the city of Monroe in Louisiana (Joseph, 1998b). Water levels in the aquifer have declined at rates greater than 1 ft/yr for more than a decade in much of southern Arkansas and northern Louisiana and are now below the top of the formation in parts of Columbia and Union Counties, Arkansas and in several areas of Louisiana. Problems related to overdraft in the Sparta could result in increased drilling and pumping costs, loss of yield, saltwater intrusion, and decrease in water quality in areas of large drawdown.

The effects of current ground-water withdrawal and potential future withdrawals on water availability are a major concern of water managers and users as well as the general public in the two States. The Sparta model provides a tool capable of testing potential water-use scenarios and aiding development of effective water-use management strategies. This report describes the procedure for testing the computer model of ground-water flow in the Sparta aquifer with updated pumpage and water levels and presents the results of five potential future pumping scenarios. The area simulated by the model includes most of eastern and southern Arkansas and north-central Louisiana. The five potential future pumping scenarios were designed to evaluate the effects of increased, decreased, and redistributed water withdrawals from the Sparta aquifer on water levels in the aquifer during the period 1998-2027.

The model was reverified using a three criteria approach, comprising 1) comparison of simulated and observed potentiometric surfaces, 2) error analysis using root mean square error (RMSE), and 3) comparison of simulated and observed hydrographs.

Analysis of the observed and simulated potentiometric surfaces, error for the original calibration and current reverification, and of observed versus simulated hydrographs indicates that the model is within acceptable error simulating conditions in the aquifer. Model results from the current updating of withdrawals and reverification effort are of a quality equal to those of the original calibration.

Analysis of reverification results has identified specific areas where recalibration could improve the ability of the model to simulate aquifer behavior. The questions posed to be answered by interpretation of Sparta ground-water flow model results have changed with the evolving needs of water users and managers in the region; the problems and questions that must be answered to address those problems have become more focused and site specific. This requires increasingly detailed input, results, and interpretations from the model. Recalibration of the model, incorporating some of the changes mentioned here, would improve the utility of the model and make a more adaptable tool capable of addressing the evolving Sparta aquifer water management problems of the region.

The reverified model was used to test pumping scenarios including: 1) pumpage rates continuing at current rates for the 30-year simulation period (1998-2027); 2) pumpage rates changing at the 1980 through 1995 rate of change; 3) minimum-forecast pumpages applied to facilities in Bradley, Calhoun, Columbia, Ouachita, and Union Counties in Arkansas and major water-use facilities in Louisiana; 4) maximum-forecast pumpages applied to facilities in Bradley, Calhoun, Columbia, Ouachita, and Union Counties in Arkansas and major water-use facilities in Louisiana; and 5) redistributing pumpage in the El Dorado and Monroe areas and increasing total pumpage in Lonoke and central Prairie Counties, Arkansas, by twice the current rate of increase. Model results show that while continuing pumpage at current rates will result in relatively minor declines in water levels (scenario 1), pumpage expanding at currently observed rates of change will result in drastic declines across large areas of focused withdrawals (scenario 2).

Under scenario 1, water levels in the middle of the cone of depression centered on El Dorado decrease to 311 ft below sea level in 2027 from 307 ft below sea level in the 1997 simulation. Water-level elevations in the Monroe cone of depression show a similar decline from 202 ft below sea level to 207 ft below sea level in the center of the cone.

In scenario 2, substantial declines occur in the proximity of major pumpage centers. During the 1998-2027 model period, predicted water levels decline from 307 ft below sea level to 438 ft below sea level near El

Dorado, from 58 ft below sea level to 277 ft below sea level in Pine Bluff, but only by about 25 ft—from 202 ft below sea level to 225 ft below sea level—near Monroe.

In scenario 3, simulated water levels are substantially higher at cones of depression around the major pumping centers of Monroe and El Dorado as compared to starting (1997) values. During the 30-year model period, predicted water levels near Monroe increase from 202 ft below sea level to 133 ft below sea level; El Dorado water levels increase from 307 ft below sea level to 123 ft below sea level.

For scenario 4, water levels near Monroe decline from 202 ft below sea level to 279 ft below sea level over the period of simulation (1998-2027); water levels near El Dorado decline from 307 ft below sea level to 421 ft below sea level over the period of simulation. Thus, the potential differences in water-level distribution that could arise from various water-use strategies by major facilities are significant. Comparison of the minimum and maximum use scenarios (scenarios 3 and 4) demonstrates the effects that water-use patterns in a limited area can exercise on water levels across an extensive area and highlights the significance, importance, and potential efficacy of water-management planning.

Scenario 5 illustrates the drastic cumulative effect that long-term, rapidly growing demands on water can have on water levels (Lonoke and Prairie Counties, Arkansas) and the effects of redistributing pumpage from major pumpage centers. Redistribution of selected withdrawal points in the El Dorado and Monroe areas results in an expansion of the cones of depression with a higher water level in the center of the cones of depression relative to scenario 2 as well as the initiation of new cones of depression at the new well fields. The increased pumpage in Lonoke and Prairie Counties results in drastic water-level decreases; declines in water levels exceed 100 ft in some areas of Lonoke County over the 1998-2027 simulation period.

REFERENCES

Ackerman, D.J., 1987, Generalized potentiometric surface of the aquifers in the Cockfield Formation, southeastern Arkansas, spring 1980: U.S. Geological Survey Water-Resources Investigations Report 87-4212, 1 sheet.

——— 1996, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States: U.S. Geological Survey Professional Paper 1416-D, 56 p.

Arthur, J.K., and Taylor, R.E., 1990, Definition of 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.

Brantley, J.A., and Seanor, R.C., 1996, Louisiana ground-water map no. 9: Potentiometric surface, 1993, and water-level changes, 1968-93, of the Cockfield aquifer in northern Louisiana: U.S. Geological Survey Water-Resources Investigations Report 95-4241, 2 sheets.

Broom, M.E., Kraemer, T.F., and Bush, W.V., 1984, A reconnaissance study of saltwater contamination in the El Dorado aquifer, Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 84-4012, 47 p.

Fenneman, N.M., 1938, Physiography of eastern United States: New York, McGraw-Hill Book Co., Inc., 689 p.

Fitzpatrick, D.J., Kilpatrick, J.M., and McWreath, Harry, 1990, Geohydrologic characteristics and simulated response to pumping stresses in the Sparta aquifer in east-central Arkansas: U.S. Geological Survey Water-Resources Investigations Report 88-4201, 50 p.

Freeze, R.A., and Cherry J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, 604 p.

Freiwald, D.A., 1985, Average annual precipitation and runoff for Arkansas, 1951-80: U.S. Geological Survey Water-Resources Investigations Report 84-4363, 1 sheet.

Hosman, R.L., 1982, Outcropping Tertiary units in southern Arkansas: U.S. Geological Survey Miscellaneous Investigations Series I-1405, scale 1:250,000.

Joseph, R.L., 1998a, Potentiometric surface of the Cockfield aquifer in southeastern Arkansas and the Wilcox aquifers in southern and northeastern Arkansas, October 1996-July 1997: U.S. Geological Survey Water-Resources Investigations Report 98-4084, 19 p.

———1998b, Potentiometric surface of the Sparta aquifer in eastern and south-central Arkansas and north-central Louisiana, and the Memphis aquifer in east-central Arkansas, October 1996-July 1997: U.S. Geological Survey Water-Resources Investigations Report 97-4282, 19 p.

Kilpatrick, J.M., 1992, Simulated response to future pumping in the Sparta aquifer, Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 91-4161, 25 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, Chapter A1, 586 p.

McWreath, H.C., III, Nelson, J.D., and Fitzpatrick, D.J., 1991, Simulated response to pumping stresses in the Sparta aquifer, northern Louisiana and southern Arkansas: Louisiana Department of Transportation and Development Water Resources Technical Report No. 51, 51 p.

Oakley, W.T., and Burt, D.J., Jr., 1994, Potentiometric-surface map of the Sparta aquifer in Mississippi, October through December 1989: U.S. Geological Survey Water-Resources Investigations Report 94-4048, 1 sheet.

Orzol, L.L., and McGrath, T.S., 1992, Modifications of the U.S. Geological Survey modular finite-difference, ground-water flow model to read and write geographic information system files: U.S. Geological Survey Open-File Report 92-50, 202 p.

Payne, J.N., 1968, Hydrologic significance of the lithofacies of the Sparta Sand in Arkansas, Louisiana, Mississippi, and Texas: U.S.Geological Survey Professional Paper 569-A, 17 p.

Petersen, J.C., Broom, M.E., and Bush, W.V., 1985, Geohydrologic units of the Gulf Coastal Plain in Arkansas: U.S. Geological Survey Water-Resources Investigations Report 85-4116, 20 p.

Todd, D.K., 1980, Groundwater Hydrology: New York, John Wiley, 535 p.

Trudeau, D.A., and Buono, Anthony, 1985, Projected effects of proposed increased pumpage on water levels and salinity in the Sparta aquifer near West Monroe, Louisiana: Louisiana Department of Transportation and Development Office of Water Resources Technical Report No. 39, 70 p.

Westerfield, P.W., 1994, Potentiometric-surface maps of the Cockfield and lower Wilcox aquifers in Arkansas, 1991: U.S. Geological Survey Water-Resources Investigations Report 93-4134, 2 sheets.

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.

Hays, Lovelace, and Reed—SIMULATED RESPONSE TO PUMPING STRESS IN THE SPARTA AQUIFER OF SOUTHEASTERN ARKANSAS AND NORTH-CENTRAL LOUISIANA, 1998-2027—U.S. Geological Survey WRIR 98-4121