DEVELOPMENT, CALIBRATION, AND TESTING OF GROUND-WATER FLOW MODELS FOR THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER IN EASTERN ARKANSAS USING ONE-SQUARE-MILE CELLS

by Gary L. Mahon and David T. Poynter

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CONTENTS

Page

PLATES

ILLUSTRATIONS

ILLUSTRATIONS (continued)

Page

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)[1]	0.0929	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
million gallons per day (Mgal/d)	1,121	acre-foot per year

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

[1] Transmissivity is reported in standard units of cubic foot per day per square foot times foot of aquifer thickness, $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d) is used for brevity.

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ABSTRACT

Development of digital ground-water flow models of the Mississippi River Valley alluvial aquifer in eastern Arkansas was prompted by the growing concern about large water-level declines in the alluvial aquifer and by the need to better understand the flow system. Several flow models have been developed previously, but at scales that are too large for analyzing the effect of future pumping at a farm or local scale. Models developed and described in this report are at a one-square-mile cell scale that can be used to define local conditions. Because of the size of the study area, two models (a north model and a south model) were developed; the Arkansas River divides the study area and functions as a hydrologic boundary to the models. Both models simulate ground-water flow in one layer with recharge entering the aquifer from surface infiltration through the overlying confining unit and from seepage through riverbeds.

Digital model simulations were made to quantify ground-water flow within the alluvial aquifer as well as flow into and out of the system. The dynamic ground-water system was simulated by using seven stress periods between 1918 and 1987. Pumpage used in the simulations ranged from about 83,400,000 to 412,000,000 cubic feet per day in the north model and from about 12,800,000 to 58,500,000 cubic feet per day in the south model.

Three scenarios were tested to spatially and temporally distribute pumpage in the models. This was necessary because water-use estimates did not adequately define the pumping distribution. Present-day water-use reporting gives a better representation of water use in the Mississippi Alluvial Plain, but historical distributions of pumping still are poorly defined.

Several criteria were used during model development and calibration to determine how well the model simulated conditions in the aquifer. Potentiometric maps of computed water levels were compared with observed water levels to check the computed water-level gradients and direction of flow. Hydrographs of selected observation wells were compared to computed water levels at corresponding model cells to assess the temporal distribution of pumpage. A root-mean-square error analysis was performed during calibration to serve as a criterion to minimize differences between observed and model computed water levels at the end of stress period 4 (1972). Root-mean-square error values of 4.93 and 4.50 feet were obtained for the 1972 analyses of the north and south model results, respectively. For further model calibration, observed and computed water levels for 1982 (stress period 6) were compared.

Analyses of the sensitivity of the models to changes in input parameters were made to gain insight to how a change in a given input parameter may affect the computed heads and volumetric budget of a model simulation. Sensitivity analyses were performed by making a model simulation with one parameter altered from the calibrated value and comparing the root-mean-square error computed from the water levels in the calibration simulation to the error computed from the sensitivity analysis. In general, the south model was less sensitive than the north model, especially when adjustments were made to values of aquifer recharge and pumpage.

INTRODUCTION

Since the early 1900's, eastern Arkansas has produced agricultural crops (rice, soybeans, and cotton) that are highly dependent on the availability of water for irrigation. Precipitation in Arkansas should be sufficient to support these crops, but much of the rainfall occurs in the fall and winter and rainfall during the growing season is often insufficient to meet the needs of these crops. Consequently, farmers have had to rely on irrigation for their crops.

The most areally abundant and available source of water for irrigation is the uppermost aquifers underlying the study area. The aquifers are part of the Mississippi embayment that extends from southern Illinois to the Gulf of Mexico (fig. 1). By far, the most productive of these aquifers is the Mississippi River Valley alluvial aquifer, herein referred to as the alluvial aquifer, that underlies most of the area. Overlying the alluvial aquifer in most of the study area is the Mississippi River Valley confining unit, herein referred to as the overlying confining unit.

Ground-water development in eastern Arkansas has increased rapidly since the mid 1940's and has resulted in long-term water-level declines in the alluvial aquifer. Water-level declines in the alluvial aquifer were first noticed in the Grand Prairie region (fig. 2), where large amounts of ground water were withdrawn for rice irrigation. Currently, much of the Mississippi Alluvial Plain has been agriculturally developed and ground-water withdrawals commonly are used to irrigate soybeans and cotton, as well as rice. As a result, water-level declines have been observed in many other areas of the alluvial plain.

The drought that occurred in the early 1980's caused a dramatically large increase in the use of ground water for crop irrigation in eastern Arkansas. The increase in ground-water use caused water levels to decline and created concern among local, State, and Federal agencies and among the farmers in the State. As a result, a work group was formed to evaluate the water resources, agricultural practices, and water use in eastern Arkansas, and to develop recommendations to solve the dilemma of declining ground-water levels. The U.S. Geological Survey (USGS), one of several State and Federal agencies represented on the work group, was given the responsibility of developing a ground-water level monitoring program needed to evaluate the extent of the ground-water declines. Additionally, the USGS was given the responsibility of developing digital models to simulate the alluvial ground-water system at a scale that could be used to predict the effects of changes in ground-water withdrawals at the local or county scale. The modeling efforts reported in this report were done as part of a cooperative agreement between the USGS and the Arkansas Soil and Water Conservation Commission.

Purpose and Scope

This report describes the framework, development, and results of the model simulations of ground-water flow in the alluvial aquifer. The report briefly describes the geohydrology of the study area, specifically in relation to application of model boundary conditions and hydraulic parameters. It is not the intent of this report to provide a detailed description of the geology of the study area because the geology has been described in great detail by previous investigators.

Because of the size of the study area, two models were developed with the Arkansas River dividing the study area and functioning as a hydrologic boundary to both models (figs. 2 and 3). The north model includes all or parts of 23 counties north of the Arkansas River in Arkansas and all or part of 5 counties in southeastern Missouri. The south model includes all or parts of six counties in Arkansas south of the Arkansas River and parts of three parishes in northeastern Louisiana. In both modeled areas, the study is limited to the flow regime and effects of pumping within the alluvial aquifer and its overlying confining unit.

Previous Investigations

Many investigators have described, to some degree, the hydrogeology of sediments underlying the Mississippi Alluvial Plain. One of the earliest reports describing the subsurface geology and ground-water resources in southern Arkansas and northern Louisiana was written by Veatch (1906). Notably, no mention was made in this early publication about any irrigation wells in the Grand Prairie. Ground-water resources of northeastern Arkansas were described and a detailed inventory was provided by Stephenson and Crider (1916). Fisk (1944) reported on extensive geologic investigations along the Mississippi Alluvial Valley made by the U.S. Army Corps of Engineers between 1941 and 1944. This compilation consists of text accompanied by more than 110 illustrations describing the alluvial sediments. Krinitzsky and Wire (1964) expanded on the hydrogeologic work of Fisk with a comprehensive treatment of ground-water conditions. Boswell and others (1968) provided an overview of the alluvial aquifer in their discussion of Quaternary aquifers in the Mississippi embayment. It was in this publication that the water-yielding sediments underlying the alluvial plain were first named the Mississippi River Valley alluvial aquifer.

Recently, several reports have been published documenting the results of model simulations of the flow system within and across the boundaries of the alluvial aquifer. Digital modeling of the alluvial aquifer-stream system in southern Arkansas was reported by Reed and Broom (1979). Broom and Lyford (1981) described the flow system of

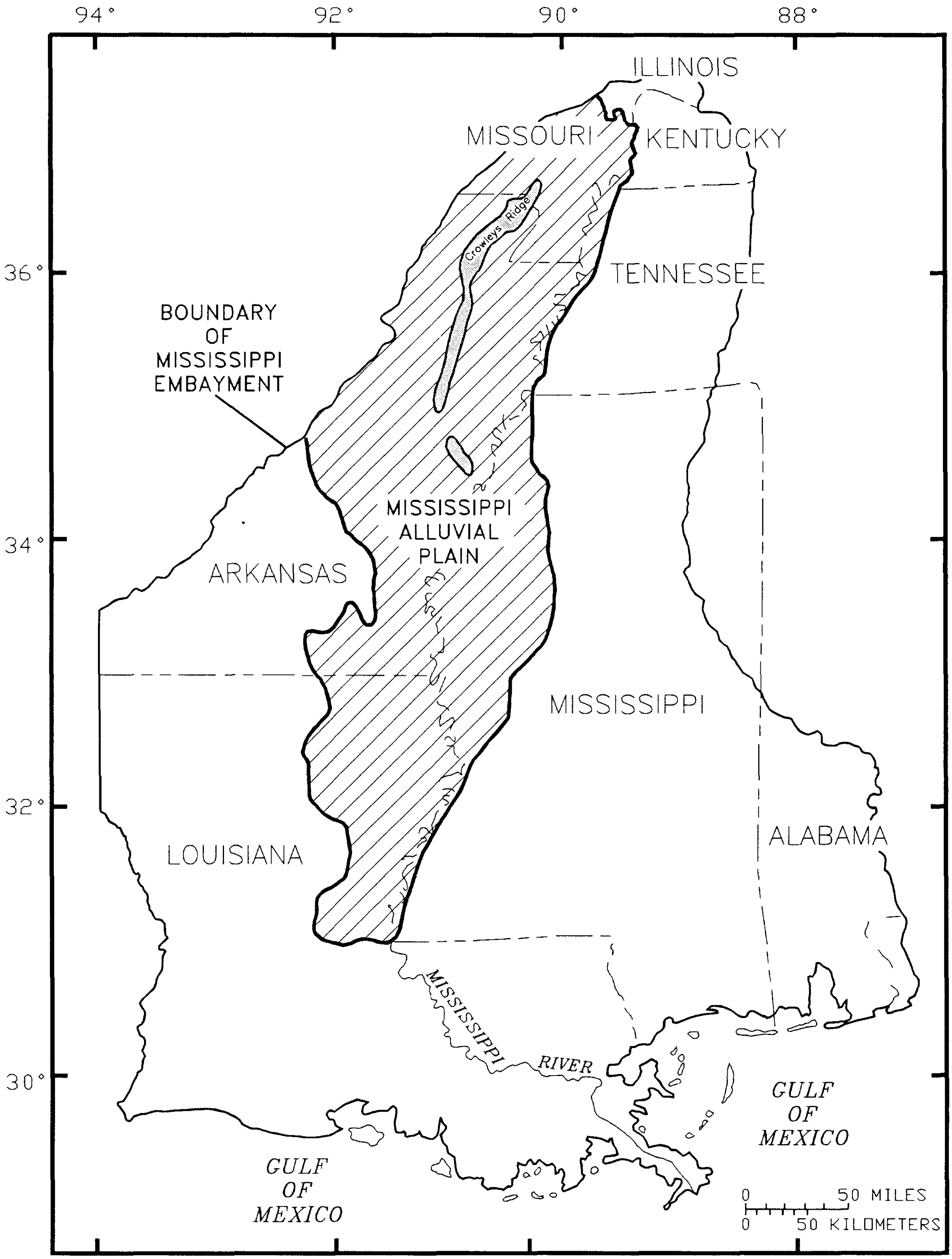

Figure 1.--Location of Mississippi Alluvial Plain within the Mississippi embayment.

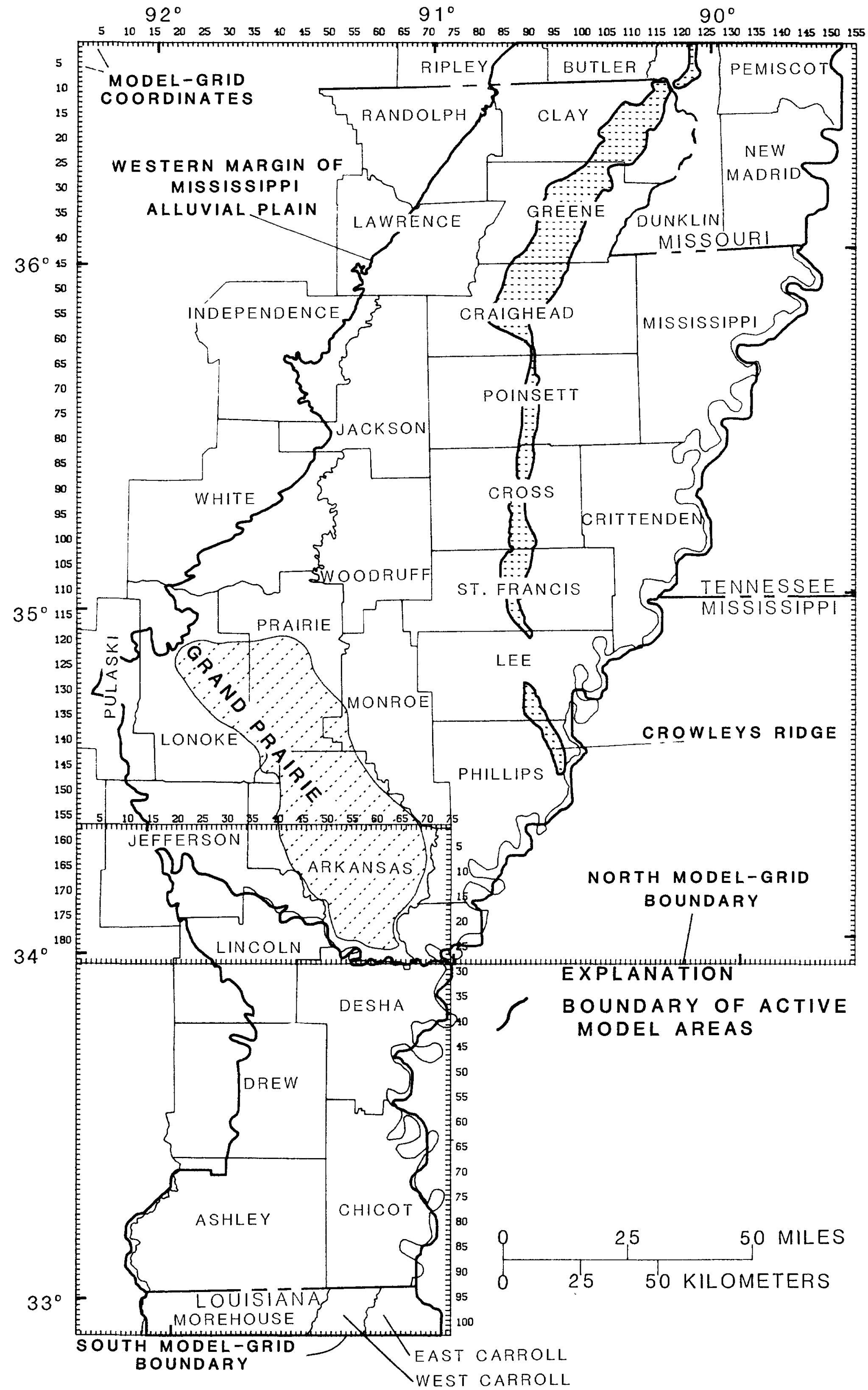

Figure 2.--Study area and model boundaries in eastern Arkansas, southeastern Missouri, and northeastern Louisiana.

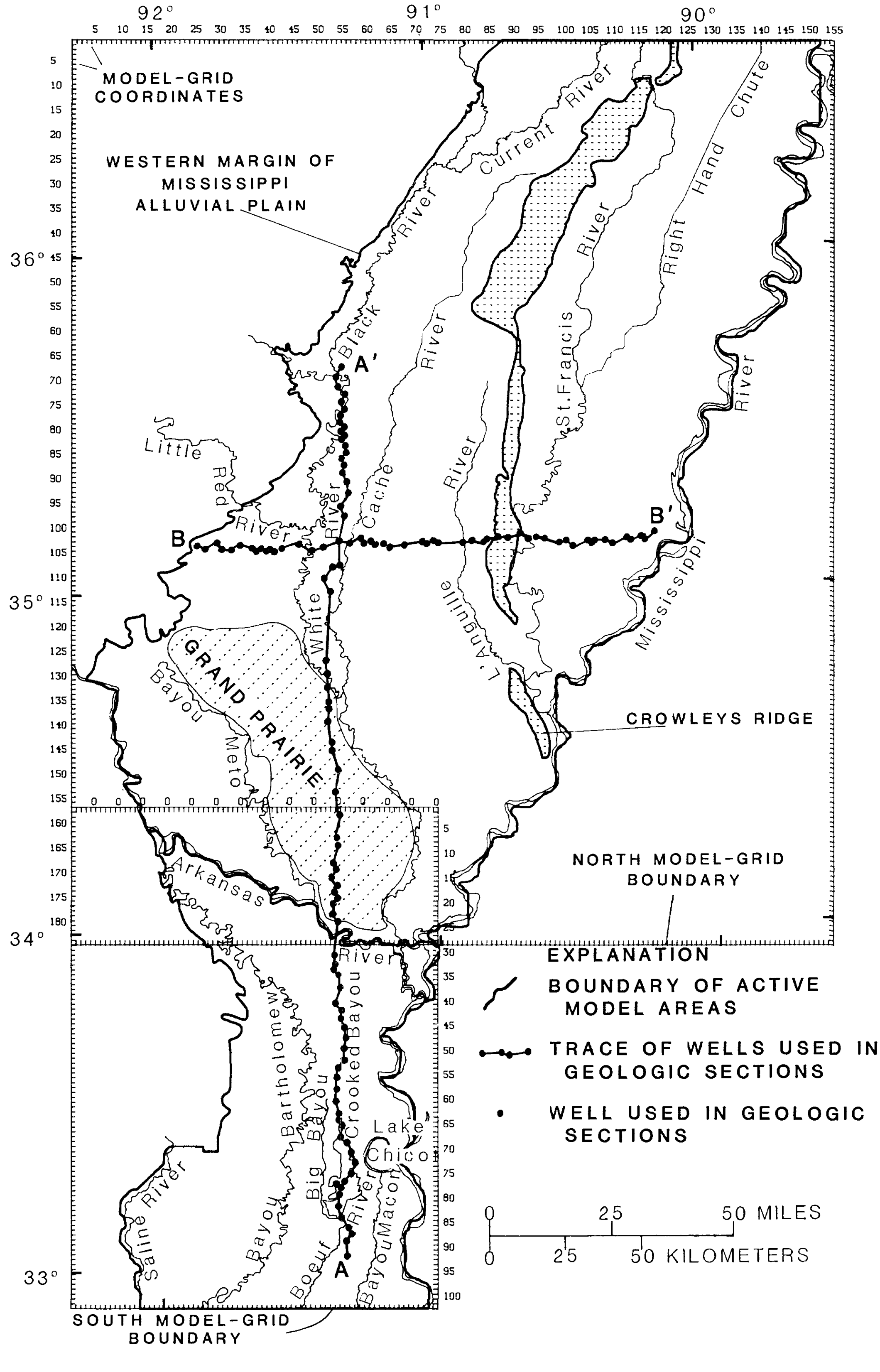

Figure 3.--Rivers, lake, and hydrologic boundaries simulated by digital models, and location of traces of geologic sections A-A' and B-B' in eastern Arkansas.

the alluvial aquifer based on the results of a model of the Cache and St. Francis River basins in northeastern Arkansas (fig. 3). Peralta and others (1985) estimated future Quaternary (alluvial aquifer) ground-water availability in the Grand Prairie region by using a flow model. Regional model investigations by Ackerman (1989a; 1990) were conducted within the framework of the Gulf Coast Regional Aquifer-System Analysis; these reports describe the model development and results and show the characteristics of the flow system on a regional scale. Predictive simulations presented by Ackerman were based on hypothetical increases in pumping. Mahon and Ludwig (1990) reported on simulations of flow in the alluvial aquifer north of the Arkansas River under steady-state and dynamic conditions. For their investigation, simulations were made to show the effects of pumpage increases to the year 2050.

GEOHYDROLOGY

The uppermost aquifer system in eastern Arkansas is part of a much larger sedimentary system known as the Mississippi embayment. The Mississippi embayment extends southward in a fan shaped geosyncline, plunges southward from southern Illinois to the Gulf of Mexico, and covers about 160,000 mi^2 in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee (fig. 1) (Cushing and others, 1964; Williamson and others, 1990). The ages of the embayment sediments range from Jurassic to Quaternary, but only units of Cretaceous age and younger crop out in Arkansas. The central axis of the Mississippi embayment nearly parallels the Mississippi River, and the embayment surface drainage in Arkansas is ultimately to the Mississippi River.

The Mississippi Alluvial Plain is a broad, flat plain that lies within the Coastal Plain physiographic province (Fenneman, 1938) and is part of the Mississippi embayment. The alluvial plain encompasses an area of about 32,000 mi^2, more than 54 percent occurring in eastern Arkansas. The alluvial plain in Arkansas is bounded on the west by sediments of Paleozoic age with very low hydraulic conductivity and by sediments of Tertiary age of the Mississippi embayment that have a distinctly lower hydraulic conductivity than sediments comprising the alluvial aquifer (Ackerman, 1990).

Deposition of sediment from the Mississippi and Arkansas Rivers during Pleistocene and Holocene time has produced a sequence of sands, silts, and clays that constitute the alluvial aquifers and semiconfining units in eastern Arkansas. From a regional perspective this collection of sediment can be divided into two units. The lower unit, which contains the alluvial aquifer, is composed of coarse sand and gravel that grades upward to fine sand. The upper unit consisting of clay, silt, and fine sand confines the alluvial aquifer. It is this regional aquifer and confining unit, along with its flow system, that has been defined and investigated previously (Broom and Lyford, 1981; Broom and Reed, 1973; Ackerman, 1989a, 1989b, 1990; Mahon and Ludwig, 1990).

The Mississippi River Valley alluvial aquifer underlies nearly all of eastern Arkansas, with the exception of Crowleys Ridge (fig. 3) which trends nearly north to south and divides the alluvium, north of the Arkansas River, into two hydraulically-separate flow regimes. The ridge averages about 10 mi in width and is an erosional remnant of strata of Tertiary age capped, in places, by several tens of feet of loess. In southern Craighead and northern Poinsett Counties the ridge is narrow, and the hydrologic units cropping out are the most transmissive of those comprising the ridge. Theoretically, this area would be the most likely to allow the transfer of ground water from one side of the ridge to the other. However, mapping of ground-water levels indicate that there is about 20 to 30 ft of head difference from one side of the ridge to the other which indicates that the ridge is a substantial barrier to flow. There is also a contrast between water levels in the alluvial aquifer and those in the ridge.

Because of the forementioned depositional conditions of the alluvial aquifer and confining unit, the top and bottom of the aquifer are not planar, but are marked by numerous highs and lows in their surfaces. Shown in plates 1 and 2 are contour maps of the top and bottom, respectively, of the aquifer based on more than 6,500 driller's logs provided by the Arkansas Geological Commission for wells in the study area. The driller's logs also were used to construct geologic sections (figs. 4 and 5) that show the great variability in the top and bottom surfaces of the aquifer.

Aquifer thickness resulting from a comparison of the top and bottom surfaces varies substantially in the study area. North of the Arkansas River thickness ranges from about 15 to 195 ft and averages about 100 ft. South of the Arkansas River the aquifer thickness ranges from about 40 to 160 ft and averages about 85 ft. The aquifer is thickest where the confining unit is thin or where depressions occur in the underlying Tertiary sediments.

Confining unit thickness varies within the study area and ranges from 0 where the unit is absent to slightly more than 80 ft in the Grand Prairie (plate 3). Thickness generally is 50 ft or less and the average thickness is about 25 ft. The integrity of the confining unit partly governs recharge to the aquifer and is a function of the thickness of the

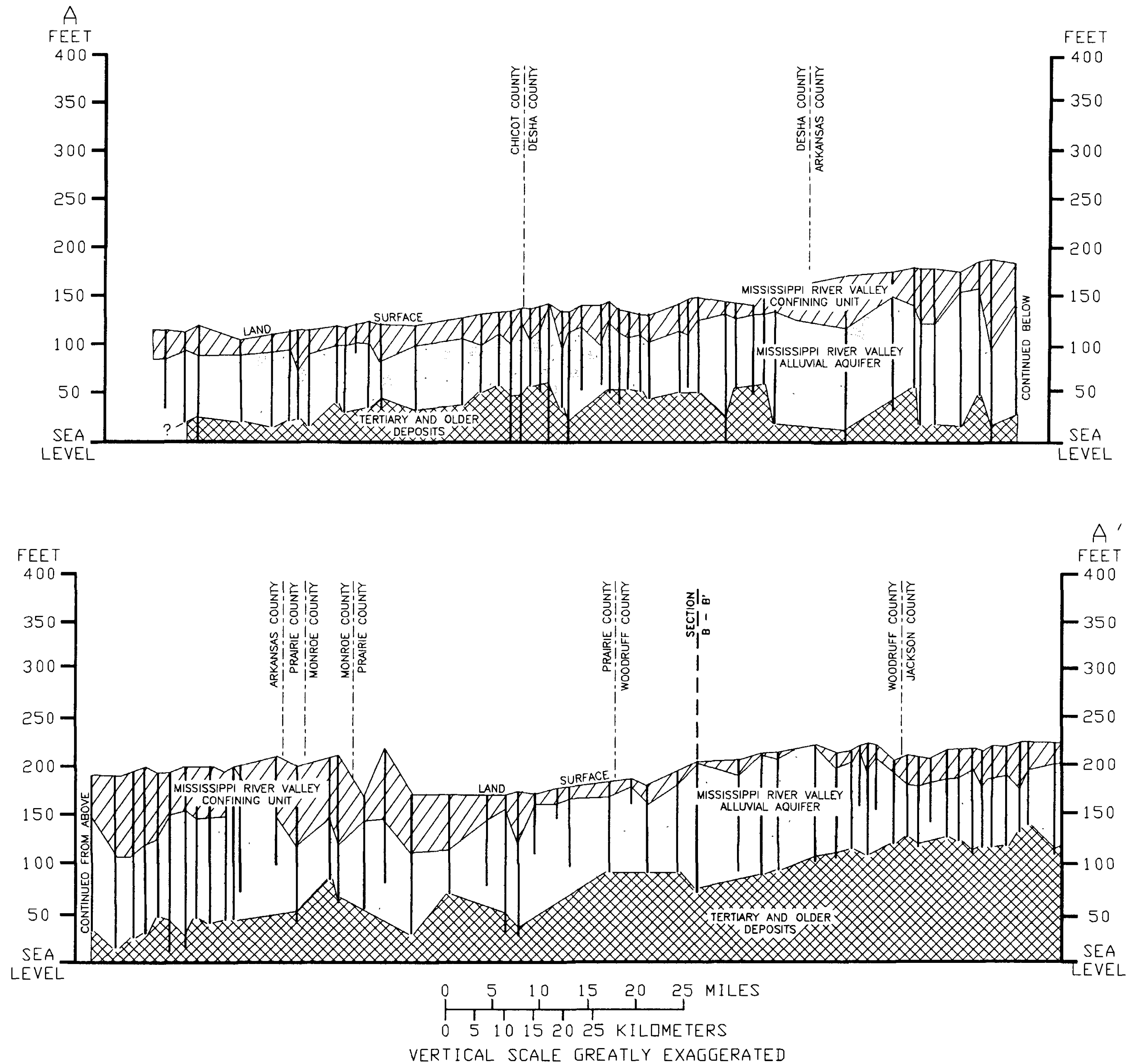

Figure 4.--Geologic section A-A' (G.J. Gonthier, U.S. Geological Survey, written commun., 1992). Line of section shown on figure 3.

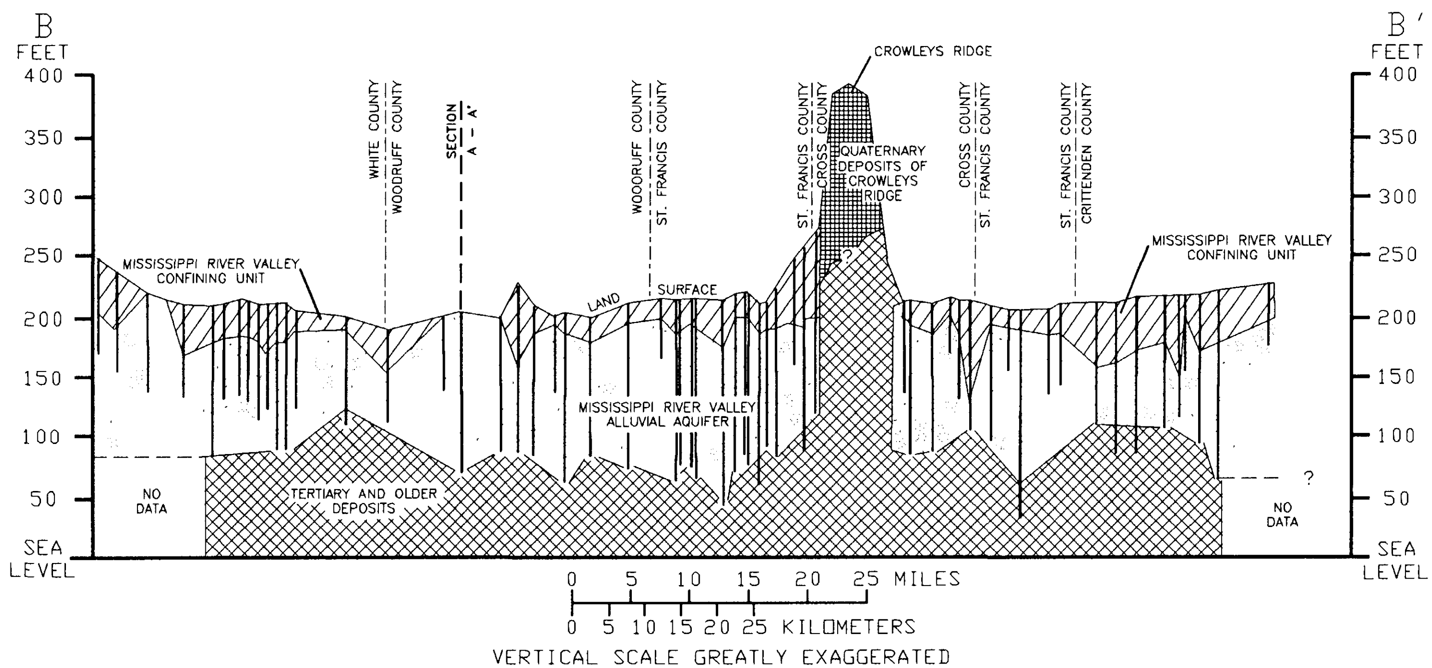

Figure 5.--Geologic section B-B' (G.J. Gonthier, U.S. Geological Survey, written commun., 1992). Line of section shown on figure 3.

sediments and the interconnection of transmissive sediments within the clay. As a result of the variability of confining unit thickness and the interconnection of the transmissive sediments, surficial recharge to the alluvial aquifer varies within the alluvial plain.

Hydraulic conductivity of the alluvial aquifer ranges from about 120 to 390 ft/d, based on estimates by Krinitzsky and Wire (1964) and Ackerman (1989a). The hydraulic conductivity is greatest in the coarse sand and gravel near the base of the aquifer. Because there are no laterally extensive confining units within the alluvial aquifer, the aquifer reacts hydraulically as a single unit from a regional perspective.

FLOW SYSTEM CHARACTERISTICS

The complexity of the geology within the alluvium is paralleled by that of the ground-water system; that is, small stringer sand and silt beds are dispersed laterally and vertically and represent local features of the aquifer and flow system. Ground-water flow related to these features may or may not be hydraulically independent on a local scale. Although flow is made more complex by the multitude of heterogeneities in the aquifer and upper confining unit, the flow system can be generalized and conceptualized as water moving laterally in a single zone or layer. This simplistic conceptualization of flow is compatible with conditions observed in the field.

Both regional and local flow systems exist in the alluvial sediments. Regional flow in the alluvial aquifer is considered to be water that has entered the deeper, coarse sand and gravel part of the aquifer and traveled for tens or hundreds of miles before discharging to major rivers such as the Mississippi, Arkansas, or White. Regionally, ground-water levels have been measured and mapped for several years (Ackerman, 1989b; Plafcan and Edds, 1986; Plafcan and Fugitt, 1987; Westerfield, 1990). These measurements indicate that ground water in the alluvial aquifer in northern Arkansas currently flows southward.

When examined in detail at a local scale this regional simplification of ground-water flow may be inappropriate. Channel fill, point bar, and backswamp deposits associated with present or former channels of the major rivers locally can produce abrupt differences in lithology, resulting in spatial variations in the hydraulic properties of both the aquifer and confining unit within small distances. The local lithologic variations allow for small scale or localized flow systems that may have flow characteristics that differ slightly from the regional flow system. Local flow systems may have recharge and discharge zones occurring within short distances, such as tens of feet to a few miles, from each other. Well yields in these shallow local aquifers are sufficient to provide for domestic sources of water but are much less than those from wells completed in the underlying regional system. For the purpose of this investigation, however, these local variations in lithology and flow characteristics are not considered.

It is presumed that before development of the ground-water resource began in the alluvial aquifer, flow was in a southward direction, with a general slope of about 1.2 ft/mi (Counts and Engler, 1954). Discharge from the aquifer most likely was to the major rivers such as the White, Arkansas, and Mississippi. Prior to development, regional flow probably was southward beneath the Grand Prairie and the Arkansas River into the southern part of the alluvial aquifer and into Louisiana.

Many rivers flow across the alluvial plain (fig. 3) and exchange water with the aquifer. The flow of water through the riverbeds is dependent on the transmissive properties of the riverbed and the differential between the head in the aquifer and the river stage. Rivers such as the Mississippi and the Arkansas are presumed to have a very high degree of hydraulic connection with the aquifer because they are deeply incised into the aquifer, and the water level in the aquifer adjacent to the river is nearly identical to the river stage (Ackerman, 1989a; 1990; Mahon and Ludwig, 1990). The White and St. Francis Rivers are not as well connected hydraulically with the aquifer, and hydrographs for wells near these rivers reflect attenuated changes in river stage. Field observations and water-level measurements indicate that other smaller streams in the alluvial plain generally have less hydraulic connection with the aquifer (Ackerman, 1990, fig. 8). Model simulations indicate that the general direction of water movement is from the rivers and streams to the aquifer and that streams provide a large amount of inflow to the aquifer since its development (Ackerman, 1990).

As a result of pumping since the early 1900's, the flow conditions and the potentiometric surface of the alluvial aquifer have changed considerably. Pumpage from the alluvial aquifer for irrigation of rice and other crops has produced several drawdown cones resulting in increased potentiometric gradients and reversal of the direction of predevelopment flow in some areas. Rice production began in the Grand Prairie because of two hydrological reasons: 1) the alluvial aquifer provided an abundant source of water for crop irrigation and 2) the thick clay cap overlying the alluvial aquifer inhibited infiltration of irrigation water when rice fields were flooded.

Because the Grand Prairie region was the first area to be irrigated, it is where the first major cone of depression formed in the potentiometric surface of the alluvial aquifer. The cone had developed before measurements were made to construct the potentiometric surface map depicting 1929 water levels (Engler and others, 1945, p. 31). Because of declining water levels, many farmers in the area have lowered their pumps, or in some cases, have had to drill to deeper aquifers to maintain their irrigation schedules. Water levels have declined as much as 90 ft in the Grand Prairie since pumping began, and the cone has extended northwestward toward the western boundary of the alluvial plain and northeastward beneath the White River. It is likely that the northeasterly propagation of this cone eventually will coalesce with another cone that has developed west of Crowleys Ridge (Westerfield, 1990). The effect of these drawdown cones illustrate the great influence that pumpage has had on flow in the alluvial aquifer.

Regional ground-water movement in the alluvial aquifer generally has maintained a southward direction but locally is toward areas of large withdrawals such as in the Grand Prairie area and in the upper L'Anguille River basin (fig. 3) (Westerfield, 1990). In many areas, flow is now from the streams and rivers to the aquifer, especially during periods of high streamflow and large ground-water withdrawals, and the aquifer is no longer discharging to rivers, but is being recharged by the rivers. Regional ground-water movement, however, is still controlled by the generally southward slope of the Mississippi Alluvial Plain (Ackerman, 1989a; Westerfield, 1990).

Recharge to the alluvial aquifer enters the aquifer from several sources. Precipitation averages about 49 in. annually, some of which seeps through the fine-grained material overlying the aquifer. Infiltration of precipitation probably accounts for the largest amount of recharge but varies areally within the study area. Other sources of recharge include seepage from rivers and streams and flow from adjacent and underlying units. A small amount, less than 5 percent, of the total recharge enters the aquifer from Tertiary and Cretaceous sediments underlying the aquifer and from the Paleozoic rocks flanking the western side of the valley (Ackerman, 1990). Recharge to the study area also includes the ground-water that moves southward from the alluvial aquifers in Missouri.

Data related to the movement of ground water between the alluvial aquifer and the underlying older hydrologic units during predevelopment time are sparse. Because outcrop areas of the older units are topographically higher than the alluvium, it is presumed that flow was upward from these older strata to the alluvium. However, water levels in the underlying aquifers recently have declined, and water-level measurements indicate that in some of the study area water levels in the alluvium are now greater than those in the underlying rocks indicating that flow is in the direction of the older units. As an example, in part of the Grand Prairie, even though water levels in the alluvial aquifer are depressed from predevelopment conditions, water levels in the alluvium in 1989 were 20 to 30 ft higher than those in the Cockfield and Sparta aquifers, indicating that flow was from the alluvium into the underlying hydrologic units.

In the north study area, Crowleys Ridge significantly obstructs the flow of ground water from one side of the ridge to the other, as evidenced by recent potentiometric maps of the alluvial aquifer (Westerfield, 1990). This hydraulic condition has been modeled in different ways by previous investigators. Broom and Lyford (1981) believed a fairly good hydraulic connection existed across the ridge, and modeled the ridge cells actively with hydraulic conductivity of the ridge sediments 1 to 2 orders of magnitude less than conductivities in the surrounding alluvial aquifer. Ackerman (1989a) conceptualized some contribution of flow from the ridge and modeled the condition with a head-dependent flow boundary condition. Mahon and Ludwig (1990) considered the flow from the ridge to be insignificant and modeled those cells inactively, although adjacent cells were modeled with head-dependent recharge that could account for an unspecified amount or flux of water from the ridge sediments.

In two parts of the study area saline water exists in the basal part of the alluvial aquifer. Although a determination of water quality in the alluvial aquifer was not an objective of this investigation, the presence of saline water may be indicative of variable density flow near the basal part of the alluvial aquifer. Saline water has intruded by some mechanism from underlying geohydrologic units in both the northern and southern parts of the alluvial aquifer. An area of approximately 56 mi^2 in Monroe County within the north model area had chloride concentrations of greater than 50 mg/L in 1984 (Morris and Bush, 1986). In the south model area an elongated zone which included about 50 percent of the alluvial aquifer area had chloride concentrations that exceeded 50 mg/L when sampled between the years of 1982 and 1984 (Fitzpatrick, 1985). Maximum concentrations in the north and south model areas were as high as 960 mg/L and 1,360 mg/L, respectively.

The modeling program used in this investigation does not account for variable-density flow, and water-quality variations can cause improper representation of the flow field by the model. The more saline water is denser and remains in the lower part of the aquifer, thus reducing the vertical extent of the freshwater flow field. When treating the freshwater/saltwater contact as a sharp interface, the net result is a decrease in the transmissivity of the aquifer. For this investigation, the water-quality conditions are considered to be inconsequential to the modeling effort and were neglected during model development. If water-quality conditions in these areas deteriorate as ground-water development expands, the effects could limit the utility and usefulness of the flow model.

DEVELOPMENT OF GROUND-WATER FLOW MODELS

The models developed to simulate ground-water flow in eastern Arkansas utilized the modeling program developed by McDonald and Harbaugh (1988). The program is commonly referred to as MODFLOW and is modular in structure to allow for easy modification of boundary conditions and hydraulic parameters. The program uses finite-difference approximations to solve the partial-differential equation (PDE) for the three-dimensional movement of constant-density ground water. The ground-water flow equation solved within MODFLOW is:

$$\frac{\delta}{\delta x}\left(K_{xx}\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(K_{yy}\frac{\delta h}{\delta y}\right) + \frac{\delta}{\delta z}\left(K_{zz}\frac{\delta h}{\delta z}\right) - W = S_s\frac{\delta h}{\delta t}, \qquad (1)$$

where K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z axes that represent, respectively, the major axes of flow (Lt^{-1});

h is potentiometric head (L);

W is a volumetric flux per unit volume and represents sources and sinks of water (t^{-1});

S_s is the specific storage of the material (L^{-1}); and

t is time (t).

The solver used to iteratively solve the PDE for both models developed for the alluvial aquifer in eastern Arkansas for this study is the Strongly Implicit Procedure.

Both of the areas simulated by MODFLOW were divided into a grid of cells that are classified as active or inactive. An active cell is one in which head varies or is a specified or constant value with respect to time. Flow potentially can occur within an active cell. Inactive cells are those in which no flow occurs and, consequently, a head is not computed during the simulation.

Another feature of MODFLOW is the ability to specify whether cells represent confined or unconfined aquifers. Confined aquifers represent a geologic unit under fully saturated conditions, bounded by a confining unit above and below. Unconfined aquifers represent a unit that is either exposed at the surface and is a water table aquifer, or is a confined aquifer in which the potentiometric level has dropped below the top of the aquifer (base of the confining unit), thus creating a partially saturated or unsaturated condition. MODFLOW allows for conversion between saturated and unsaturated conditions, and thus, between confined and unconfined aquifers during a simulation.

Grid spacing was designed to simulate the effects that changes in stress on a farm-size scale might have on the flow system. A cell size of 1 mile square was determined to meet the above requirement while, at the same time, maintaining a reasonable size to the simulated data bases, the size of input arrays, and requirements for computational resources. In addition to areal dimensions, MODFLOW computes the thickness of the aquifer by subtracting the altitude of the aquifer bottom from the altitude of the top.

A characteristic common to both the north and south models is the simulation of flow in the alluvial aquifer in two dimensions. Justification for simulating flow in two dimensions is based on several observations of vertical gradient in the alluvial aquifer. In Woodruff County (fig. 2), water levels in wells open to upper and lower zones of the aquifer differed by less than 0.25 ft in 1990 and 1991. The wells are located a few miles from the Cache River in a relatively undisturbed area of a hardwood swamp and are part of a nested-well network used for investigating ground- and surface-water interaction. In Mississippi County, differences in water levels in wells open to upper and lower zones also are within a few tenths of a foot, indicating a negligible vertical gradient of flow. These wells are located less than 0.15 mi from each other and have screened open intervals separated by more than 50 ft. These observations are considered representative of flow conditions throughout the alluvial aquifer, except in the immediate vicinity of large-capacity, pumping wells, and near major rivers and streams that are hydraulically well connected to the aquifer.

The thickness of the aquifer is used to compute a transmissivity value for each active model cell. The transmissivity distribution computed during the model simulations for a fully saturated aquifer and for water levels computed at the end of the last model stress period are shown in plates 4 and 5, respectively. Transmissivity under fully saturated conditions reflects the values appropriate to describe ground-water flow prior to development.

In preparing the data sets for model simulation, software external to MODFLOW was used. A preprocessing program was used to transform latitude and longitude coordinates to model coordinates of driller's log data for land surface altitude and aquifer top and bottom. Additionally, graphics software was used to assign altitude values of land surface and aquifer top and bottom to the center of each active grid cell. The software estimated the value for a cell by performing an octant and nearest neighbor search around the cell (Sampson, 1975). The octant search procedure divides the area around the cell into eight equal segments and the nearest prescribed number of data points are found in each octant. The software then uses the nearest neighbor search in which a group of closest surrounding data points are used to compute a single value at the cell center. The computed value is a function of the distance weighted average of projections of dips of the surface at the previously described nearby data points.

The selection of rivers and river reaches for simulation by the models was based on the likelihood of interaction with the alluvial aquifer. By using the RIVER package, a group of subroutines that compute flow through a riverbed (McDonald and Harbaugh, 1988), flow into or out of the aquifer is computed dependent on the water-level difference between the river and the aquifer, and the conductance of the riverbed sediments. The conductance (plate 6) of the riverbed sediments is a function of the length, width, and thickness of the river within the model cell, and the vertical hydraulic conductivity of the riverbed sediments. Vertical hydraulic conductivity was assumed to be $1x10^{-2}$ ft/d, based on model estimates by Ackerman (1989a). Bed-conductance values are input to the model and are specified per cell in the RIVER package for each stress period. Initial riverbed conductance values were computed from estimates of river geometry and vertical hydraulic conductivity, and were adjusted to achieve calibration of the model.

Because the Mississippi and Arkansas Rivers are presumed to fully penetrate the upper confining unit, the conductance value was preset to a relatively high value to simulate unrestricted flow between the rivers and the aquifer and was not adjusted during calibration. The head computed in the river cell during the simulation is similar to the stage in the river. This compares favorably with field data for river/aquifer pairs of measured water levels for concurrent periods.

Surficial recharge to the alluvial aquifer also was simulated using the RIVER package because the recharge process is head-dependent and is analogous to flow between the aquifer and major rivers. The rate and direction of flow for recharge to or discharge from the aquifer is dependent on the vertical conductance of the confining unit and the difference between a reference water level and the head in the aquifer. The elements of the modeled confining unit are analogous to those in the RIVER package as listed below:

Confining unit	RIVER package
Confining unit conductance	Riverbed conductance
Bottom of confining unit	Riverbed bottom
Reference water level	River stage

The confining unit conductance is a function of the thickness of the confining unit, the area of the model cell, and the vertical hydraulic conductivity of the predominantly clay material. The thickness of the confining unit is the difference between the altitudes of land surface and the bottom of the confining unit. Conductance of the confining unit (plate 7) was computed for each active cell assuming a value of $3x10^{-4}$ ft/d for vertical hydraulic conductivity (Ackerman, 1989a). The conductance values were adjusted during calibration to achieve an adequate representation of the ground-water flow. Adjustment of the conductance value also was necessary to compensate for the small amount of water entering the alluvial aquifer from adjacent and underlying aquifers of Paleozoic and Tertiary age.

The use of the riverbed bottom in the RIVER package to represent the bottom of the confining unit imposes a limitation on the recharge rate of water entering the alluvial aquifer. This limitation is analogous to a maximum flow rate between a river and an aquifer when the head in the aquifer is below the bottom of the riverbed (McDonald and Harbaugh, 1988). With the application of the RIVER package to the confining unit, a maximum recharge rate is attained when the head in the alluvial aquifer is below the bottom of the aquifer.

The reference water level for the surficial recharge cells represents the level of water in the small, discontinuous sand beds embedded in the upper confining unit. Few field data exist to map the water surface, so a value was assumed for the entire simulation for each cell in which recharge was added. The modeled level corresponds to the altitude of land surface and represents the maximum level for the computation of areal recharge. The value would apply more closely to wet conditions and, in the simulations, does not account for drought conditions. Under drought conditions in eastern Arkansas, the water level in the sand beds theoretically would be lower which would decrease the amount of recharge to the alluvial aquifer. Consequently, use of the altitude of land surface for the reference water level could result in overestimated recharge rates and water levels in the aquifer that are higher than those observed.

Several other geohydrologic characteristics are common to both the north and south models. Hydraulic conductivity of the aquifer was selected, within the reported range given in the geohydrologic description above, to be a constant value of 275 ft/d for the entire model area. The value is similar to that used by Ackerman (1989a) and Mahon and Ludwig (1990). Transmissivity is calculated during model simulation and is dependent on the difference between the altitudes of the aquifer top and bottom and on the hydraulic conductivity of the aquifer. Hydraulic conductivity probably does not vary substantially with direction of flow and isotropic conditions were assumed for all simulations.

Primary and secondary storage coefficients (McDonald and Harbaugh, 1988) for model simulations correspond to confined storage coefficient and specific yield, respectively. The calibrated primary storage coefficient value used in both models is 5.0×10^{-2}. In the south model a secondary storage value of 0.28 was used for the entire study area. In the north model the value was varied areally between 0.25 and 0.28 (fig. 6) as part of the calibration process.

Pumpage in eastern Arkansas varies annually, but generally has increased since early years of irrigation. Although these increases have been documented as county totals, category totals, and aquifer totals in water-use reports, the spatial distribution of pumpage within a county has not been very well documented. Computation of pumpage distributions was based on estimates of ground-water use for six, 5-year time periods beginning in 1960 (Stephens and Halberg, 1961; Halberg and Stephens, 1966; Halberg, 1972 and 1977; Holland and Ludwig, 1981; Holland, 1987). The total pumpage from the alluvial aquifer reported for each county in the alluvial plain was used to compute the distribution of pumpage within the county. Pumpage for the period of time prior to 1960 was estimated based on results of previous models in eastern Arkansas (Mahon and Ludwig, 1990). The total pumpage simulated in each stress period is given for both models in table 1. The distribution of pumpage is described later in the report.

North Model

The northern study area was subdivided into a cell network of 184 rows and 156 columns (fig. 2). Of the 28,704 model cells, 14,118 are active. The alluvial aquifer in all or parts of 23 counties in Arkansas is represented by the north model. Additionally, five counties in southeastern Missouri were included in the simulation as discussed below. The locations of the four corners of the model grid are listed in table 2. The grid distribution in the north model area is shown in figure 2.

Several boundary conditions depicting geohydrologic conditions in the alluvial flow system are simulated by the north model. There is only one layer for horizontal flow and no confining unit layers within the aquifer to simulate vertical flow. The top of the aquifer is represented partially by a flux boundary, where water is transferred to and from the recharge nodes (river nodes) from or to the aquifer. The bottom of the aquifer is simulated as a no-flow boundary. Because of the relatively low hydraulic conductivity of the sediments flanking the alluvial aquifer, no-flow conditions are also simulated on the western side of the model representing the western extent of the alluvial sediments. The eastern boundary of the model is simulated by river cells representing the Mississippi River (plate 8). The southern boundary of the north model is simulated by river cells representing the Arkansas River.

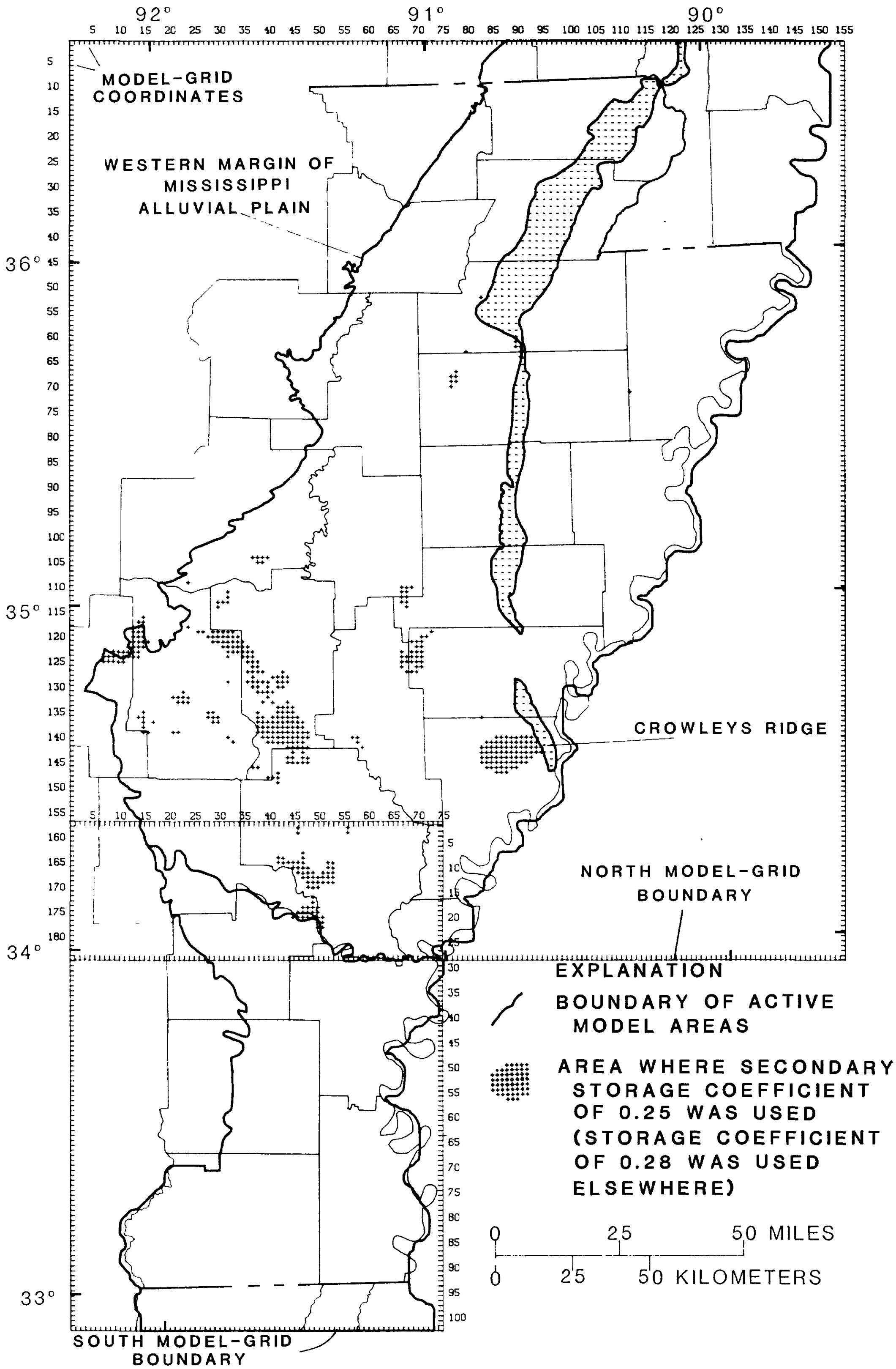

Figure 6.--Model simulated distribution of secondary (unconfined aquifer) storage coefficient.

Table 1.--*Total pumpage rates simulated by north and south models*

State	County or parish	Pumpage (x 10^6 cubic feet per day)						
		Stress period 1 (1918-57)	Stress period 2 (1958-62)	Stress period 3 (1963-67)	Stress period 4 (1968-72)	Stress period 5 (1973-77)	Stress period 6 (1978-82)	Stress period 7 (1983-87)
		North model area						
Arkansas								
	Arkansas	18.024	15.518	14.745	15.297	17.765	27.235	24.742
	Clay	1.875	2.398	2.965	2.540	8.071	20.060	23.512
	Craighead	2.830	3.799	6.533	8.816	19.449	29.798	27.118
	Crittenden	1.080	1.481	3.712	4.238	5.362	11.106	15.198
	Cross	5.478	7.587	9.110	11.441	22.721	30.321	34.893
	Desha	.264	.406	.750	1.351	1.907	2.435	17.195
	Greene	.846	1.038	2.096	2.466	9.047	18.571	17.619
	Independence	.139	.202	.302	.668	1.028	2.255	4.354
	Jackson	4.939	7.057	7.645	8.021	22.055	28.435	27.210
	Jefferson	2.375	3.304	4.196	5.192	10.697	14.083	17.910
	Lawrence	1.749	2.604	2.383	3.342	10.280	20.592	20.547
	Lee	1.340	1.776	3.317	2.848	5.194	15.037	12.914
	Lonoke	15.641	13.281	20.711	23.584	34.258	49.842	39.283
	Mississippi	.717	1.109	.703	1.100	1.172	2.697	6.733
	Monroe	2.276	4.137	7.597	6.230	10.963	20.680	16.592
	Phillips	1.023	1.865	1.941	1.881	2.254	10.487	9.598
	Poinsett	5.228	6.992	11.521	13.436	23.780	41.291	40.076
	Prairie	8.534	7.087	9.306	9.421	16.748	22.166	22.688
	Pulaski	.397	.733	1.705	2.273	2.910	4.473	3.949
	Randolph	.209	.424	.424	.535	2.521	5.663	5.622
	St. Francis	2.710	5.016	5.487	7.362	12.343	18.849	14.826
	White	.093	.176	.484	.669	1.935	6.333	6.751
	Woodruff	4.799	4.292	7.754	6.614	2.993	22.322	19.033
Missouri								
	Butler	0.168	0.259	0.345	0.590	1.924	7.300	8.400
	Dunklin	.173	.268	.642	.852	.770	.840	.945
	New Madrid	.079	.121	.345	.703	.895	1.279	1.535
	Pemiscot	.349	.548	.829	.668	.615	.601	.855
	Ripley	.102	.157	.185	.185	.346	.753	1.025

Table 1.--*Total pumpage rates simulated by north and south models* --Continued

State	County or parish	Pumpage (x 10^6 cubic feet per day)						
		Stress period 1 (1918-57)	Stress period 2 (1958-62)	Stress period 3 (1963-67)	Stress period 4 (1968-72)	Stress period 5 (1973-77)	Stress period 6 (1978-82)	Stress period 7 (1983-87)
		South model area						
Arkansas								
	Ashley	5.963	5.289	3.159	4.782	7.188	14.795	10.510
	Chicot	1.143	1.769	1.583	3.171	6.210	9.119	10.038
	Desha	1.833	2.841	5.248	9.458	13.352	17.048	14.826
	Drew	.546	.847	1.210	3.041	1.472	5.915	5.512
	Lincoln	1.420	2.202	3.303	8.792	10.724	11.337	10.968
Louisiana								
	East Carroll	.128	.198	.198	.342	.342	1.003	.866
	Morehouse	1.153	1.787	2.196	2.655	5.617	3.319	2.911
	West Carroll	.019	.029	.120	.198	.267	.390	.488

Table 2.--*Latitude and longitude of north and south model-grid corners*

	Corner	Latitude	Longitude
<u>North model</u>			
	Northwest	36°38′21″	92°17′01″
	Northeast	36°35′10″	89°27′54″
	Southwest	33°57′42″	92°18′32″
	Southeast	33°54′37″	89°35′23″
<u>South model</u>			
	Northwest	34°22′07″	92°18′18″
	Northeast	34°21′08″	90°59′25″
	Southwest	32°53′13″	92°19′07″
	Southeast	32°52′16″	91°01′45″

No natural geohydrologic boundary separates flow in the alluvial aquifer between Arkansas and southern Missouri. Accordingly, the alluvial aquifer in the "bootheel" of Missouri was included in the simulations because pumpage in that area may affect pumpage east of Crowleys Ridge in eastern Clay and Greene Counties, Arkansas. A specified-head boundary was placed in southern Missouri north of the "bootheel" even though this is not a natural boundary because agricultural development of ground water in this area is minimal compared to that in Arkansas. The boundary is placed about 10 mi (10 rows of cells) north of the Arkansas-Missouri border west of Crowleys Ridge and extends eastward to the Mississippi River. The placement of this boundary is sufficiently far from the areas of major pumping in Arkansas so as not to adversely affect computation of water levels in the area of interest. There are 63 specified-head nodes within the north model governing, in part, the flow of water from southern Missouri into Arkansas (plate 8).

Ten rivers were chosen to be actively simulated within the alluvial model (fig. 3). Below is a listing of these rivers and the number of "river cells" simulated by the model:

Arkansas River	100
Bayou Meto	77
Black River	86
Cache River	104
Current river	31
L'Anguille River	54
Little Red River	11
Mississippi River	306
St. Francis River	243
White River	149

Some potential for flow exists between the alluvial aquifer and sediments underlying and composing Crowleys Ridge. In particular, the Memphis Sand crops out on both sides of the ridge in southern Craighead, northern Cross, and Poinsett Counties. Hydraulic connection with the Memphis Sand below the alluvium could account for some flow between the hydrologic units. In 1990, water levels in the Memphis Sand beneath western Cross and Poinsett Counties (Westerfield, 1990) were higher than water levels in the alluvial aquifer indicating possible ground-water flow from the Memphis Sand into the alluvial aquifer. For purposes of this investigation, parts of the ridge were simulated with a head-dependent boundary condition in the same manner as modeled by Ackerman (1989a).

Areal (two dimensional) flow also is simulated by the south model. The small amount of flow from units below the aquifer is not accounted for and the base of the alluvial aquifer is simulated as a no-flow boundary. As described earlier, head-dependent flow between the aquifer and overlying sediments is accounted for by using the RIVER package.

The northern boundary of the south model is coincident with the Arkansas River, which functions as a large potential source of inflow and outflow to and from the aquifer (plate 8). The eastern boundary coincides with the Mississippi River. The southern boundary of the model is represented by specified-head cells representing the alluvial aquifer in northern Louisiana about 10 mi south of the Arkansas border and does not reflect any natural boundary condition (plate 8). The placement of this boundary is such that computation of ground-water flow conditions are unaffected in the area of interest. The western boundary is simulated with a no-flow boundary coinciding with the line of outcrop of sediments of Tertiary age. The exception to this no-flow condition is in western Ashley County where the western model boundary is the Saline River.

Eight rivers are simulated in the south model (fig. 3). One lake is also simulated in the model because of its hydraulic connection with the alluvial aquifer. Below is a listing of these rivers and the lake, and the number of "river cells" used during the simulations:

Arkansas River	90
Bayou Bartholomew	140
Bayou Macon	27
Big Bayou	23
Boeuf River	32
Crooked Bayou	31
Mississippi River	94
Saline River	35
Lake Chicot	14

SIMULATING FLOW IN THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER

Initial conditions for the north and south model simulations reflect water levels that probably existed before ground-water development began in the early 1900's. Earliest potentiometric maps for the study area are for the Grand Prairie and do not extend very far out of that area in any direction (Engler and others, 1945). Even these water levels reflect the ground-water development that already had begun. Consequently, very little water-level data exist, and a potentiometric map of prepumping conditions based on observed data was never constructed. Previously developed flow models (Ackerman, 1989a; Broom and Lyford, 1981) have produced a distribution of water levels that represents conditions prior to pumping in the alluvial aquifer (plate 9). It is these distributions that have been used as initial conditions for simulations of the north and south model areas.

Both models simulate the ground-water flow system for 70 years beginning in 1918 and ending in 1987. This period was divided into seven stress periods. The first stress period length is 40 years (1918-57); succeeding lengths of stress periods are 5 years to coincide with periods for which water-use data were collected. For each stress period (except stress period 1) the reported county total ground-water withdrawal was distributed to individual cells, as described in later sections, and was assumed to be constant for 2 years before and after the year for which water use was reported. Agricultural pumpage for stress period 1 was estimated because water use was not reported prior to 1960. Modeled pumpage values are discussed later in the sections describing aquifer withdrawals for both the north and south models.

Model Calibration

Synoptic water-level and long-term hydrograph data were used during model development to determine how well the model simulated observed ground-water flow conditions. One calibration goal was to simulate water levels that match reasonably well those that describe the 1972 potentiometric surface. Iterative comparisons of potentiometric maps constructed from heads at the end of stress period 4 with water levels measured in 1972 were made until a reasonable match of the potentiometric levels and flow directions was achieved. The potentiometric map for heads computed at the end of stress period 4 (1972) is shown in plate 10 for the north and south models along with observed water levels for 1972. Calibration of the models was further checked by comparing potentiometric maps of heads at the end of stress period 6 with water levels measured in 1982 (plate 11).

Additional calibration was achieved by matching computed heads with 19 long-term observation well hydrographs in the north model area and 11 hydrographs in the south model area (figs. 7-9). These comparisons indicate the ability of the model to simulate the long-term response of the alluvial aquifer to resource development. Hydrographs for the computed and observed water levels for selected cells and the effects of pumping distributions on the calibration of the model are discussed in the following section.

Statistical analyses were made on the computed water levels at the end of stress period 4 by comparing them to water levels for 1972 by means of root-mean-square error (RMSE) analysis. A similar analysis was made using water-level data for 1982 and model results at the end of stress period 6. An RMSE value, in feet, was computed for both the north and south models by comparing the computed value to an observed value at 227 cells in the north model and 270 cells in the south model for 1972; 217 and 52 cells were used for the north and south model RMSE analyses, respectively, for 1982. Listed below are the RMSE values for the calibrated models as compared to observed water levels in 1972 and 1982:

North model	
1972	4.93 ft
1982	7.65 ft
South model	
1972	4.50 ft
1982	4.66 ft

The relatively large difference between the 1972 and 1982 RMSE values in the north model is likely the result of the high rate of ground-water pumpage during stress period 6, especially in 1982, and the uncertainty concerning the spatial distribution of pumpage. In the southern area, the pumpage is less than in many of the northern counties, and the spatial distribution is more uniform resulting in a smaller difference between the 1972 and 1982 RMSE values. Model calibration was achieved when RMSE values for stress periods 4 and 6 were minimized using identical input arrays of boundary and river nodes and aquifer and confining unit hydraulic characteristics for all stress periods.

Determining a reasonable distribution of pumpage to adequately represent field conditions, respective of time and space, was an integral part of model calibration. However, it seems that distributing pumpage with 1-mile-square model cells provides a resolution that is too refined for the quality and accuracy of the available pumpage data because pumpage is not necessarily reported throughout the area. A discussion of specific model pumping scenarios and distributions is given in subsequent sections of this report.

During a model simulation, the model program computes a water budget for the entire modeled area as a check on the acceptability of the solution and to provide summarized information on the flow system (McDonald and Harbaugh, 1988). Model calibrated flows reflecting volumetric total flows for both the north and south model areas are presented in table 3.

An analysis of the volumetric model budget indicates that approximately 65 percent of the inflow to the aquifer in the north area is from areal recharge. This percentage of flow is approximately equivalent to an average recharge rate of 1.4 in/yr. In the south area, areal recharge accounts for 68 percent of the inflow, which also is approximately equivalent to 1.4 in/yr. A model by Broom and Lyford (1981) estimated between 0.4 and 2.0 in/yr of recharge to the

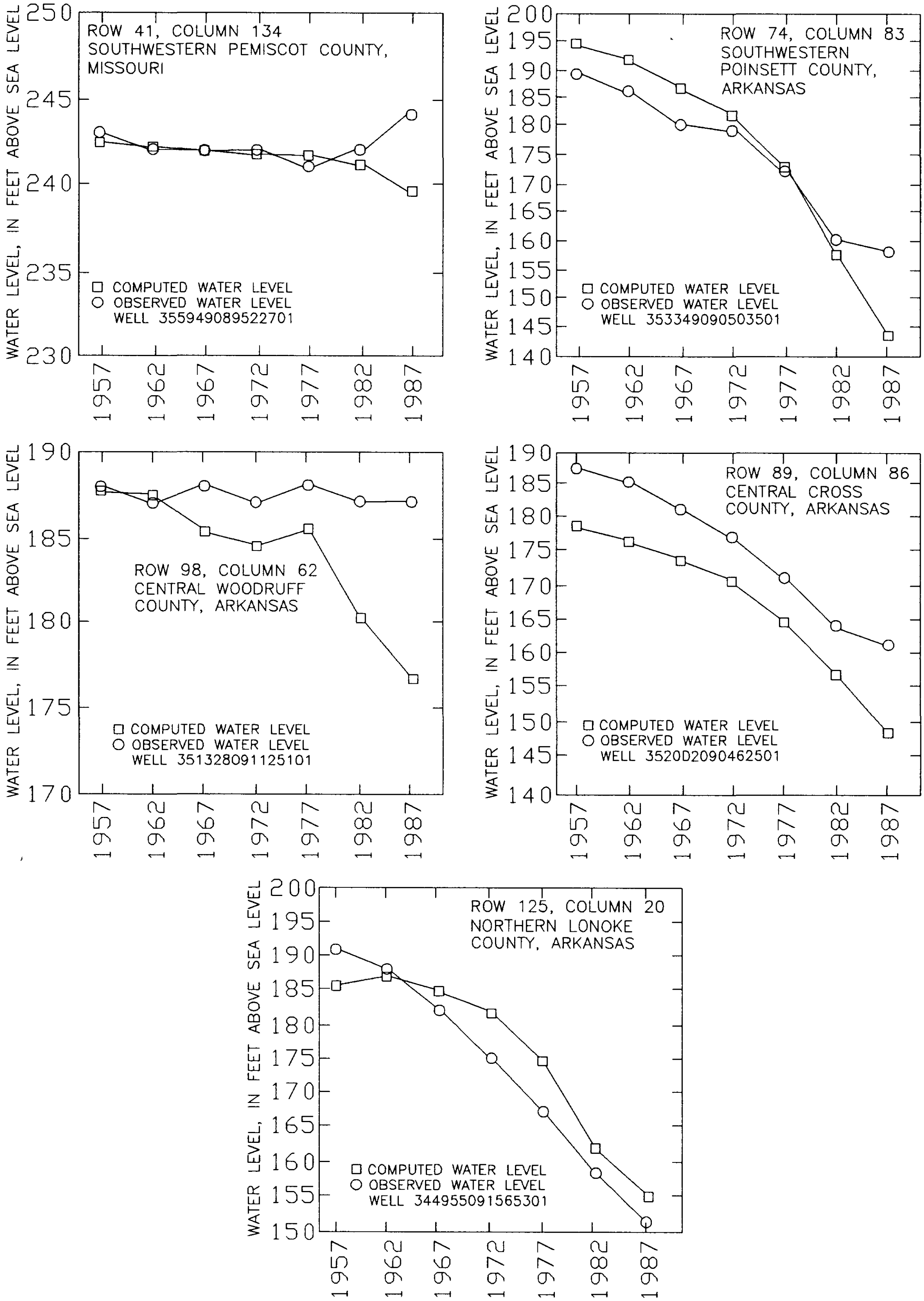

Figure 7.--Selected hydrographs of observed and model computed data for cells in the north model area.

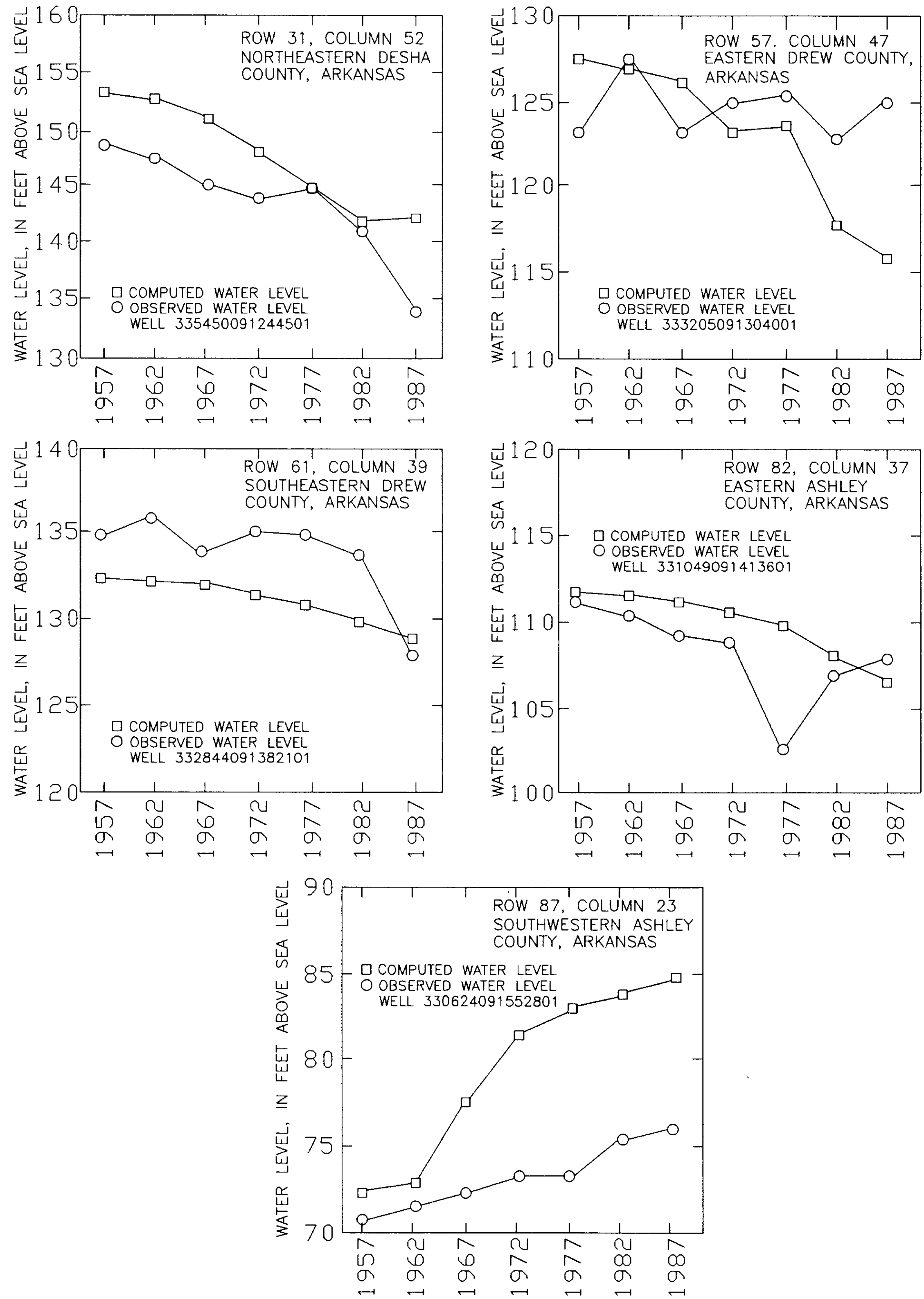

Figure 8.--Selected hydrographs of observed and model computed data for cells in the south model area.

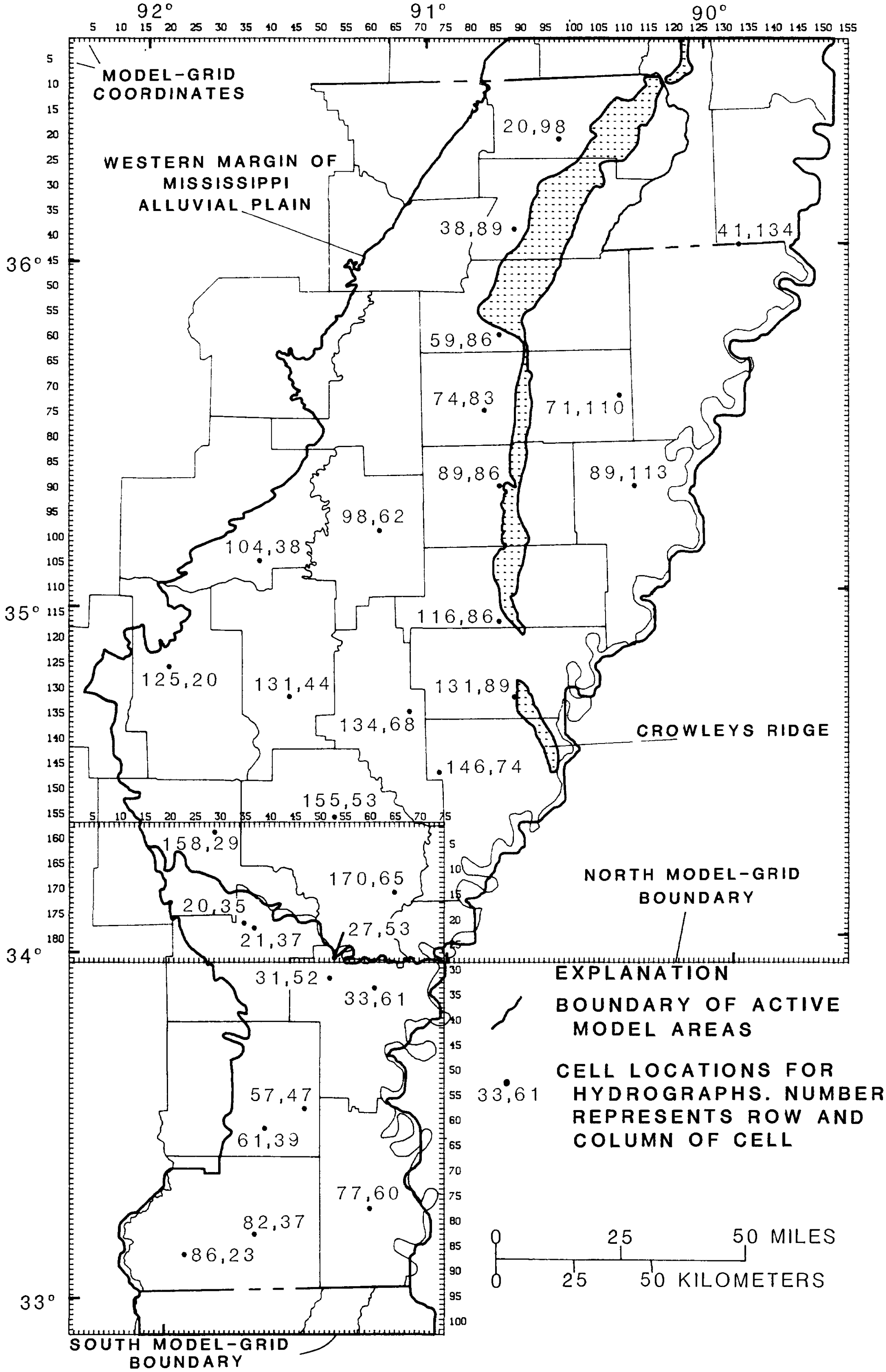

Figure 9.--Cell locations for hydrographs of observed and model computed data used in model calibration.

alluvial aquifer from flow across the upper confining unit. An analysis by Ackerman (1989a) of simulated flow into the aquifer indicated an average recharge rate across the upper confining unit to be 0.8 in/yr and an average rate of 0.7 in/yr for flow from underlying and adjacent sediments and rocks.

Table 3.--*Model calibrated flows into and out of the alluvial aquifer*

[ft^3/d, cubic feet per day; N/A, not applicable because general head boundary is not used in south model]

Model budget term	North model		South model	
	Flow into aquifer (ft^3/d)	Flow out of aquifer (ft^3/d)	Flow into aquifer (ft^3/d)	Flow out of aquifer (ft^3/d)
Storage[1]	4.2365×10^7	6.1739×10^4	7.2190×10^6	1.8407×10^6
Specified head[2]	2.3764×10^6	1.9971×10	1.1825×10^6	7.7314×10^5
Riverbed[3]	1.7827×10^7	3.7221×10^7	6.9841×10^6	1.1499×10^7
Confining unit[4]	1.1798×10^8	6.0268×10^4	3.2992×10^7	0.00
General head[5]	7.2171×10^5	1.3192×10^6	N/A	N/A
Pumpage	0.00	1.4244×10^8	0.00	3.3674×10^7

[1] Storage can reflect either confined or unconfined aquifer conditions. The flow is either into the aquifer from storage or out of the aquifer into storage.

[2] Specified head flow is the flow across the SPECIFIED HEAD BOUNDARY in southern Missouri for the north model and in northern Louisiana for the south model.

[3] Riverbed flow is flow across the riverbed of the modeled rivers.

[4] Confining unit flow is flow across the upper confining unit of the alluvial aquifer.

[5] General head flow is the flow across the GENERAL HEAD BOUNDARY along Crowleys Ridge in the north model area.

Sensitivity Analyses

Model simulations of a ground-water system do not produce a unique representation of the system. Thus, more than one combination of boundary conditions, initial conditions, geohydrologic parameter values, and stresses can produce the same representation of the potentiometric surface. For these reasons, it is desirable to test the sensitivity of the model to changes in input parameters by adjusting each parameter within its reasonable upper and lower limits. The resulting changes in head can provide insight as to the degree to which a change in a given parameter may affect the results of any simulation and, thus, the errors in the model resulting from the assumptions made during model calibration.

The process of sensitivity analysis involves uniformly varying one parameter of the calibrated model while all others remain unchanged. The model is rerun in the same manner as in the calibrated run, and changes in output head between the calibrated model run and the sensitivity test run for the changed parameter are noted. Any large differences in head between the calibrated output and the output from the sensitivity analysis indicate that the model is very sensitive to the magnitude of change of that parameter at that cell. Conversely, small head differences indicate insensitivity of the model to the magnitude of change of the parameter in the sensitivity run.

Model sensitivity was tested for both the north and south models with changes in parameters as listed in table 4. Shown in figures 10 and 11 are the results of the sensitivity analysis simulations using the RMSE analysis value from the calibrated model (1972) for comparison. In general, the south model is less sensitive than the north model to changes in parameters. This is especially apparent in comparing the output from changes made to hydraulic conductivity, aquifer recharge, and pumpage. Generally, both models show relatively little sensitivity to changes from isotropic to anisotropic conditions, and in changes in the primary storage coefficient. Unlike the north model, the south model shows little sensitivity to changes in hydraulic conductivity of the aquifer. Both models are relatively sensitive to changes in values of aquifer recharge and pumpage.

Table 4.--*Multiplication factors used in model sensitivity analyses*

[ft/d, feet per day; ft^2/d, feet squared per day; ft^3/d, cubic feet per day]

Hydrologic parameter	Calibration value	Sensitivity analysis values or multiplier
Hydraulic conductivity	275.0 ft/d	× 4.0, 2.0, 0.5, 0.25
Anisotropy	1.0	8.0, 4.0, 2.0, 0.50, 0.25, 0.125
Confining unit and riverbed conductance	0.1 to 1,160,000 ft^2/d	× 8.0, 4.0, 2.0, 0.50, 0.25, 0.125
Primary storage coefficient	0.05	0.200, 0.100, 0.010, 0.005
Secondary storage (see note below) coefficient	0.25-0.28 North 0.28 South	× 1.3, 1.2, 1.1, 0.91, 0.83, 0.77 × 1.3, 1.2, 1.1, 0.91, 0.83, 0.77
Pumpage	6 to 893,349 ft^3/d	× 4.0, 2.0, 1.25, 0.50, 0.25, 0.125

Sensitivity analyses were also made by noting the changes in volumetric budget for selected changes in input data. Budgets were not analyzed for all sensitivity analysis simulations because of the number of budget components and sensitivity analysis simulations. The results of the volumetric budget analysis are presented in table 5. The greatest sensitivity of the models is to changes in the conductance of the riverbed and confining unit.

Errors made in applying data for a particular input parameter or to assigning initial or boundary conditions to the physical system can create large errors in the model if the model is sensitive to that particular input parameter or condition. The effects of these errors in model development can be assessed when looking at the sensitivity analysis of a model.

The models for eastern Arkansas show sensitivity to riverbed and confining unit conductance. In terms of error in the model, incorrect assignment of conductance values could cause an error in the computation of heads and flow in the aquifer. Because few field data exist to quantify areal or river recharge, conductance and water-level values have been assumed for modeling purposes and are subject to a degree of uncertainty and error in the models for eastern Arkansas.

Other errors may exist because of assumptions made for values of hydraulic conductivity and for isotropic conditions of the aquifer. Because the alluvial aquifer was formed by deposition of fluvial deposits, the distribution of sand and gravel may be lenticular and discontinuous, with the direction of flow having a preferred direction. Again, because few field data are available to substantiate a well defined distribution of parameter values, single values were assumed for the entire aquifer for modeling purposes, assumptions that could introduce error into the model.

Pumpage stress in the eastern Arkansas models have been estimated from water-use reports for 1960 to 1985 as mentioned earlier. It is likely that inherent in the pumpage data are errors from the compilation of county pumpage totals. Inaccuracy of the estimates of total county pumpage will be reflected in the distributions used in the models. The accuracy of the data is unknown, but low pumpage estimates would produce higher water levels in the models than those observed in the field. The converse effect would be obtained for overestimating total county pumpage.

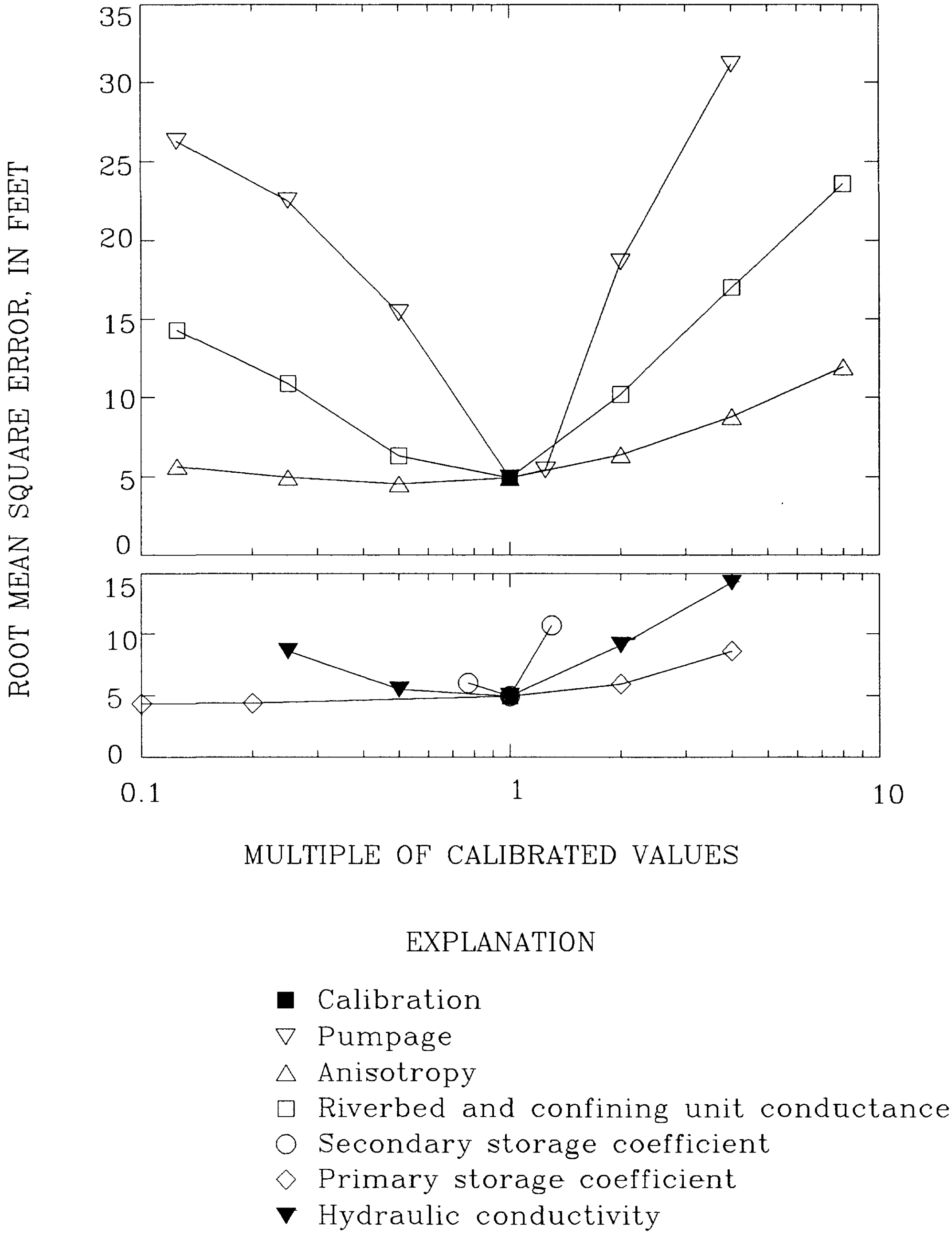

Figure 10. -- Sensitivity of the north model to changes in calibrated values of aquifer properties and pumpage.

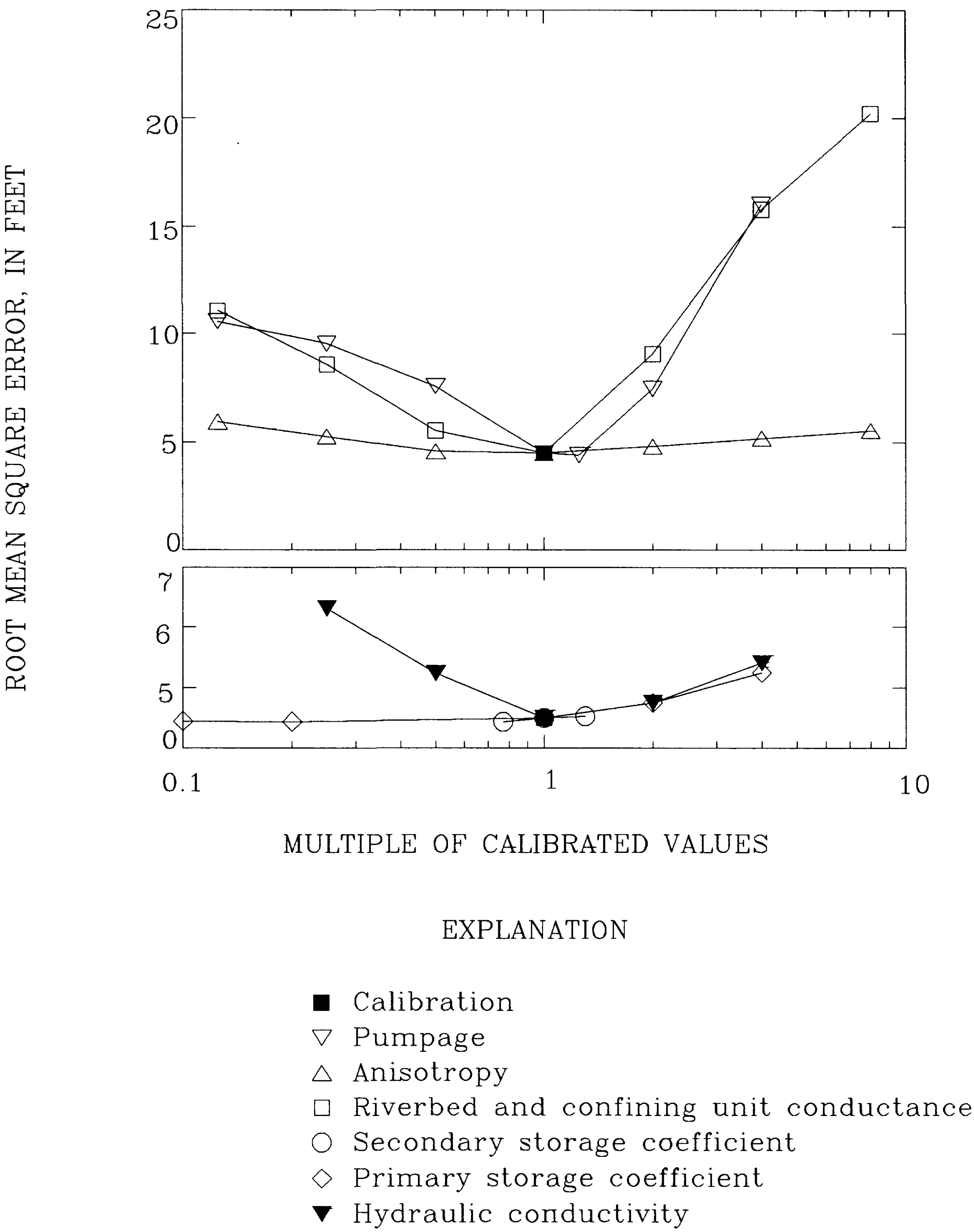

Figure 11. -- Sensitivity of the south model to changes in calibrated values of aquifer properties and pumpage.

Table 5.--*Percent change from calibrated flows into and out of the alluvial aquifer resulting from changes to model parameters during sensitivity analyses*

[+, indicates a percent increase in flow; -, indicates a percent decrease in flow; NA, category not applicable for the south model]

Model parameter	Factor	Into aquifer					Out of aquifer				
		From storage[1]	Across specified head boundary[2]	Across riverbed[3]	Across confining unit[4]	Across general head boundary[5]	Into storage	Across specified head boundary	Across riverbed	Across confining unit	Across general head boundary
North model area											
Pumpage	1.25	+40	+8	+33	+6	+139	+69	-10	-11	-32	-20
Pumpage	.125	-91	-28	-79	-33	-100	-17	+39	+71	+1,176	+295
Riverbed and confining unit conductance	8.0	-80	-45	-72	+208	-100	+638	+244	+486	+14,800	+467
Riverbed and confining unit conductance	.125	+133	+31	+29	-82	+181	-99	-10	-90	-100	-74
Hydraulic conductivity	4.0	-28	+254	+74	+114	-36	-77	+419	+54	-85	+154
Hydraulic conductivity	.25	+30	-71	-37	-17	+33	+344	-77	-38	+167	-61
South model area											
Pumpage	1.25	+33	+22	+31	+7	NA	+19	-35	-11	0	NA
Pumpage	.125	-89	-30	-69	-29	NA	-55	+187	+70	[6] 2.26×10^4 ft^3/d	NA
Riverbed and confining unit conductance	8.0	-77	-18	-63	+230	NA	-97	+861	+519	[6] 9.12×10^5 ft^3/d	NA
Riverbed and confining unit conductance	.125	+156	+120	+37	-81	NA	-48	-99	-82	0	NA
Hydraulic conductivity	4.0	-13	+169	+120	+8	NA	-59	+116	+106	0	NA
Hydraulic conductivity	.25	-94	-17	-38	-9	NA	-15	+14	-45	0	NA

[1] Storage can reflect either confined or unconfined aquifer conditions. The flow is either into the aquifer from storage or out of the aquifer into storage.
[2] Specified head flow is the flow across the SPECIFIED HEAD BOUNDARY in southern Missouri for the north model and in northern Louisiana for the south model.
[3] Riverbed flow is the flow across the riverbed of the modeled rivers.
[4] Confining unit flow is the flow across the upper confining unit of the alluvial aquifer.
[5] General head flow is the flow across the GENERAL HEAD BOUNDARY along Crowleys Ridge in the north model area.
[6] Actual increase in flow value given because there was no flow out of the aquifer in the calibrated model simulation.

Response of the Flow System to Pumpage Distributions

Calibration of the north model used three methods of distributing pumpage stress. All of the methods would produce potentiometric surfaces which were regionally similar by virtue of the fact that the total pumpage for each county is a constant regardless of which method was used to distribute pumpage within a county. The contrast among the methods of distributing pumping was evident, however, when looking at smaller scales such as flow in one or several counties. Best results were obtained by choosing the appropriate method on a county by county basis. Hydrographs in figures 8 and 9, in addition to computed and measured water levels illustrated in plates 10 and 11, show the results of model calibration and indicate, in part, the response of the flow system to pumpage distributions.

Computation of "county-averaged" pumpage for a cell in a county is based simply on the total annual pumpage within that county divided by the number of model cells in the county. In instances where cells were located in parts of more than one county, the pumpage assigned to the cell was based on the pumpage for the county in which most of the cell was located. Exceptions to the "county-averaged" pumpage distribution were made in counties where Crowleys Ridge divided the county. Pumpage values were adjusted on each side of the ridge to correspond to pumpage rates similar to those in adjacent counties.

Inconsistency of pumpage distributions across county lines is a possible consequence of "county-averaged" distributions. During the calibration process it was noticed that pumping rates in adjacent counties varied by an order of magnitude. This is an unlikely condition because typically neither the geohydrologic conditions nor the agricultural practices will change radically from county to county. "County-averaged" pumpage does not account for areas within counties where lower aquifer yields exist and pumpage values would be expected to be low. Consequently, the model would overstress these areas causing excessive or nonexistent cones of depression.

The concept and computation of crop-weighted pumpage values resulted from data collected and estimates made by the U.S. Soil Conservation Service and the U.S. Geological Survey (N.T. Baker, U.S. Geological Survey, written commun.,1989). For each active model cell a proportion of crop type was determined. Model pumpage rates were then computed for each cell by applying appropriate quantities of irrigation water to corresponding crop types. The crop-type data were compiled based on data collected during a field reconnaissance in 1985.

Site-specific water-use data collection began in 1985 as part of a cooperative effort between the Arkansas Soil and Water Conservation Commission and the U.S. Geological Survey (Baker, 1991). Data collected as a part of this effort are stored in a USGS data base with a specific latitude and longitude identifier. Through computer software programs written for this study, site-specific locations of slightly more than 30,000 wells (N.T. Baker, U.S. Geological Survey, oral commun., 1991) were converted to model cell locations, and all site-specific water-use data falling within the model cell boundaries were summed to produce a single pumpage value for the model cell.

Hydrographs, as mentioned previously, were constructed to aid in model calibration. Figures 7 and 8 illustrate 10 of the 30 comparisons made between observed hydrographs for selected wells in the alluvial aquifer and model simulated hydrographs for cells in which the observation wells are located (fig. 9). The modeled pumpage distribution produced water levels that provided fairly good matches to several observed hydrographs in areas that are highly stressed (ROW, COLUMN: North-89,86; 125,20; South-31,52) and in areas where the pumpage stresses are minimal (ROW, COLUMN: North-41,134; South-61,39). However, matches were not good in some cells indicating that the pumpage may have been inadequately distributed temporally or spatially. For example, assumed model pumpage in and around north model cell ROW 98, COLUMN 62 in central Woodruff County produced a water-level declines of 10 ft during the model simulation, whereas observed water levels have fluctuated 1 to 2 ft during the same time period. The aquifer in that area has been overstressed during model simulation because of the pumpage distribution based on county pumpage trends. Computed water levels in southern Prairie County (fig. 2) for the stress period corresponding to 1972 are higher than the observed levels shown in plate 10. Early model sensitivity analysis of pumpage indicated that increased pumpage in that area during the first stress period of the model could improve the match between computed and observed water levels.

When using "county-averaged" pumpage, the model cannot simulate local area pumpage changes which are likely to occur over time. For example, a model cell within a county may show a constant increase in pumpage over the simulation period because the pumpage total increased between 5-year reporting periods. Under actual field conditions, however, pumping in the area represented by that cell may have fluctuated or decreased as crops were rotated or some other agricultural practice was utilized. This condition probably is illustrated in figure 8 for a north model cell in Pemiscot County, Missouri, in which observed water levels rose between 1977 and 1987, whereas the computed water levels continued to decline because reported pumpage totals for Mississippi County, Arkansas, and Pemiscot County, Missouri, increased between 1975 and 1985 (Halberg, 1977; Holland and Ludwig, 1981; Holland, 1987; Mesko and others, 1990).

In Poinsett County, total county pumpage declined from approximately 309 to 300 Mgal/d between 1980 and 1985 (Holland and Ludwig, 1981; Holland, 1987). The observed water-level hydrograph in figure 8 for Poinsett County, Arkansas, shows that the water-level decline at this well slowed during the period 1982-87, whereas the computed hydrograph shows a much steeper decline. Because of the spatial and temporal distributions of pumpage in the model, the computed hydrograph does not compare well with the observed water-level hydrograph at the end of the last model stress period. The relatively poor match during the last stress period may be because of a greater portion of county pumpage actually occurred in the eastern part of the county than was reflected in the model pumpage distribution.

Pumpage scenarios using crop-weighted or site-specific distributions may improve upon the accuracy with which the model can simulate the ground-water system, however the methods for distributing pumping do not allow for the distribution to change between stress periods. In Woodruff County, Arkansas, pumpage between 1975 and 1980 increased by nearly 750 percent, but the observed water-level hydrograph (fig. 7) shows little change in water level for this period. Apparently the observation well is not located in the area of increased pumping. In the early stress periods, the pumpage distribution represented the field conditions fairly well, but in the later simulation periods the model tended to overestimate rates of water-level decline because the field conditions indicate pumpage is more uniformly distributed.

The accuracy of reported pumpage distributions was less than desirable for the south model area. Consequently, the development of the model data sets was based on a "county-averaged" distribution and a good match between observed and computed water levels for a particular cell was not always possible. The observed hydrograph also indicates that pumpage distributions, which are assumed constant during a stress period, often are not constant. The hydrograph for a well in eastern Drew County, Arkansas (fig. 8) illustrates this. Although water-use estimates indicate a steady increase in pumpage through 1970 (Stephens and Halberg, 1961; Halberg and Stephens, 1966; Halberg, 1972), the observed hydrograph show two rises in water levels for that period.

In eastern Ashley County, Arkansas, total alluvial aquifer pumpage declined by 42 percent between 1960 and 1965, but has steadily increased since that time (Stephens and Halberg, 1961; Halberg and Stephens, 1966; Halberg, 1972 and 1977; Holland and Ludwig, 1981; Holland, 1987). The total pumpage reported includes agricultural pumpage and also pumpage for municipal and industrial needs. Agricultural pumpage was distributed by the "county-averaged" method, but the municipal and industrial pumpage was distributed based on areas where drawdown cones existed in the potentiometric surfaces. Municipal and industrial pumpage estimates were largely from the lumber mills in the county which were somewhat transient in the early and middle 1900's. Accordingly, declines in water levels in an area were commonly for only a short time. It is very probable that the 5-ft decline in the observed hydrograph for the Ashley County well (fig. 8) is the result of a temporary increase in industrial pumpage in the area.

Although the RMSE error for the south model is somewhat less than that for the north model, many of the hydrograph comparisons of observed and computed water levels for the south model do not seem very close. Once again it is likely that this disparity reflects the effects of improper pumpage distribution for the model simulations.

Keeping in mind that the models show a great deal of sensitivity to increases and decreases in pumping stress, this observation can also give some indication of the sensitivity of the model to spatial changes in pumpage. The sensitivity of the model to pumping stress should not be interpreted to be a problem with the representation of the ground-water system with a flow model, but that the distribution of pumpage within the model can greatly affect the degree to which observed water levels can be matched. The significance of this is that with improved pumpage location in the alluvial aquifer, prediction of future water levels will be more accurate.

SUMMARY

Significant water-level declines in the Mississippi River Valley alluvial aquifer prompted the need to better understand the flow system in the aquifer which, in turn, led to the development of digital ground-water flow models of the alluvial aquifer. Although flow models have been developed previously, they were either at a scale that is too large to analyze the effects of projected pumpage scenarios or they were limited in their areal extent. Models developed and described in this report are at a one-square-mile cell scale that can be used to describe ground-water flow conditions for a local county area. Two models were developed in the eastern Arkansas study area with the Arkansas River dividing the study area and functioning as a hydrologic boundary to the models. Both models simulate ground-water flow in one layer with recharge entering the aquifer from head-dependent surface infiltration through the overlying confining unit and from seepage through riverbeds.

The alluvial aquifer ranges from 10 to 190 ft in thickness north of the Arkansas River and from 40 to 160 ft south of the river. Aquifer thickness averages about 100 ft and 85 ft north and south of the river, respectively. Thickness of the overlying confining unit is generally 50 ft or less, but ranges from 0 where the unit is absent to more than 80 ft in the Grand Prairie. Hydraulic conductivity of the aquifer ranges from about 120 to about 390 ft/d. Simulated primary storage coefficient (specific yield) values for unconfined aquifer conditions range between 0.25 and 0.28; for confined aquifer conditions, the secondary storage coefficient value averages about 5.0×10^{-2}.

Digital models were used to simulate flow in the aquifer during seven stress periods between 1918 and 1987. The models quantify flow into and out of the system based on the boundary conditions, hydraulic parameters, and initial conditions used to represent the system. Pumpage used in the simulations ranged from 83,400,000 to 412,000,000 ft^3/d in the north model and from 12,800,000 to 58,500,000 ft^3/d in the south model.

Three different spatial and temporal pumpage scenarios were tested to simulate pumpage stress in the models. Water-use estimates for the counties in eastern Arkansas did not adequately define the pumping distribution when the model pumpage files were developed, so the different pumpage scenarios were developed to determine which produced the most accurate representation of the 1972 and 1982 potentiometric surfaces and matches to hydrographs of wells open to the alluvial aquifer. The pumpage distribution used in the calibrated model was based on a combination of all three scenarios. The distribution was assumed to remain constant for each stress period, but the changes in pumpage rate between stress periods were based on changes in total pumpage for the county.

Several criteria were used during model development to determine how well the model simulated conditions in the aquifer. Potentiometric maps of model computed water levels were compared to measured data to check the computed water levels and direction of flow. Hydrographs of observation wells were compared to computed water levels at corresponding model cells to assess the temporal distribution of pumpage. A root-mean-square error analysis was performed during calibration by comparing observation well and model computed water levels for 1972 (stress period 4). Root-mean-square error values of 4.93 and 4.50 ft were obtained for the 1972 analyses of the north and south model results, respectively. A similar analysis was made for observed and model computed water levels for 1982 (stress period 6) to verify that the model simulated water-level changes with a reasonable degree of accuracy.

Sensitivity analyses were performed to determine the effects of changes in input parameters on computed heads (water levels). Analyses were made by making a model simulation with one parameter altered from the calibrated value and comparing the root-mean-square error value from the calibrated model to the value computed from the sensitivity analysis. Both models were sensitive to changes in recharge and pumpage but the south model generally was less sensitive than the north model.

SELECTED 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 Investigations Report 88-4028, 74 p.

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

----- 1990, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States: U.S. Geological Survey Open-File Report 90-358, 228 p.

Arthur, J. Kerry 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 90-4364, 97 p.

Baker, N.T., 1991, Summary and analysis of water-use data collection in eastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 90-4177, 25 p.

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

Boswell, E.H., Moore, G.K., MacCary, L.M., and others, 1965, Cretaceous aquifers in the Mississippi embayment, *with discussion of* Quality of the water by H.G. Jeffery: U.S. Geological Survey Professional Paper 448-C, 37 p.

Broom, M.E., and Lyford, F.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.

Broom, M.E., and Reed, J.E., 1973, Hydrology of the Bayou Bartholomew alluvial-aquifer stream system, Arkansas: U.S. Geological Survey Open-File Report, 91 p.

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

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

Edds, Joe, and Fitzpatrick, D.J., 1984, Maps showing altitude of the potentiometric surface and changes in water levels of the Sparta Sand and Memphis Sand aquifers in eastern Arkansas, spring 1983: U.S. Geological Survey Water-Resources Investigations Report 84-4265, 1 sheet.

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, Agricultural 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.

----- 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity: U.S. Army Corps of Engineers, Waterways Experiment Station, 82 p.

Fitzpatrick, D.J., 1985, Occurrence of saltwater in the alluvial aquifer in the Boeuf-Tensas Basin, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 85-4029, 1 sheet.

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

----- 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.

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

Hosman, R.L., Long, A.T., Lambert, T.W., and others, 1968, Tertiary aquifers in the Mississippi embayment, *with discussions of* Quality of the water by H.G. Jeffery: U.S. Geological Survey Professional Paper 448-D, 29 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., Terry, J.E., and Peralta, R.C., 1989, Water-resources development alternatives for the Mississippi Alluvial Plain in eastern Arkansas: Proceedings from the American Water Resources Association Conference "Water: Laws and Management", p. 11B-29 - 11B-43.

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 Investigations Report 89-4145, 26 p.

Mesko, T.O., Williams, T.A., Ackerman, D.J., and Williamson, A.K., 1990, Ground-water pumpage from the Gulf Coast aquifer systems, 1960-1985, south-central United States: U.S.Geological Survey Water-Resources Investigations Report 89-4145, 177 p.

McDonald, M.G., and Harbaugh, A.W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83-875, 528 p.

----- 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water Resources Investigations Book 6, Chapter A1.

Morris, E.E. and Bush, W.V., 1986, Extent and source of saltwater intrusion into the alluvial aquifer near Brinkley, Arkansas, 1984: U.S. Geological Survey Water-Resources Investigations Report 85-4322, 123 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, Agricultural 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 Investigations 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 Investigations Report 86-4178, 1 sheet.

Plebuch, R.O., 1961, Fresh-water aquifers of Crittenden County, Arkansas: Arkansas Geological and Conservation Commission Water Resources Circular 8, 65 p.

Reed, J.E., and Broom, M.E., 1979, Digital model of the Bayou Bartholomew alluvial aquifer-stream system, Arkansas: U.S. Geological Survey Open-File Report 79-685, 37 p.

Ryling, R.W., 1960, Ground-water potential of Mississippi County, Arkansas: Arkansas Geological and Conservation Commission Water Resources Circular 7, 87 p.

Sampson, R.J., 1975 [1978], Surface II graphics system (revision I): Kansas Geological Survey Series on Spatial Analysis no. 1, 240 p.

Saucier, R.T., 1964, Geological investigation of the St. Francis basin: U.S. Army Corps of Engineers, Waterways Experiment Station Technical Report 3-659.

Smith, F.L., and Saucier, R.T., 1971, Geological investigation of the western lowlands area, lower Mississippi Valley: U.S. Army Corps of Engineers, Waterways Experiment Station Technical Report S-71-5.

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

Sumner, D.M., and Wasson, B.E., 1984, Geohydrology and simulated effects of large ground-water withdrawals on the Mississippi River alluvial aquifer in northwestern Mississippi: U.S. Geological Survey Open-File Report 84-822, 82 p.

U.S. Department of Agriculture, Soil Conservation Service, 1987, Present and projected land and water use: Eastern Arkansas Region Comprehensive Study, 141 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.

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