HYDROLOGY OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER, SOUTH-CENTRAL UNITED STATES--A PRELIMINARY ASSESSMENT OF THE REGIONAL FLOW SYSTEM

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4028

A contribution of the

Regional Aquifer-System Analysis Program

Little Rock, Arkansas

1989

DEPARTMENT OF THE INTERIOR

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CONTENTS

	Page
Abstract	1
Introduction	2
Purpose and scope	3
Approach	3
Geography	3
Previous investigations	5
Hydrogeology	5
Hydrogeologic units and hydraulic properties	8
Mississippi River Valley alluvial aquifer	8
Mississippi River Valley confining unit	14
Underlying units	16
Flow systems	20
Predevelopment conditions	26
Present-day (1985) conditions	26
Conceptual model of regional ground-water flow	28
Preliminary digital model	34
Boundary conditions	34
Model input data	36
Data manipulation and presentation	36
Sources of input data	38
Calibration	45
Procedure	45
Results	48
Sensitivity analysis	53
Application	53
Preliminary analysis of regional flow	56
Predevelopment	56
1972	62
Summary	69
References	72

ILLUSTRATIONS

		Page
Figure 1.	Map showing location of study area	4
2.	Map showing geographic locations in and near the study area	6
3.	Graphs showing rainfall at four places in the study area	7
4-7.	Geologic sections:	
	4. A-A'	10
	5. B-B'	11
	6. C-C'	12
	7. D-D'	13
8.	Map showing units subcropping below and adjacent to the Mississippi River Valley alluvial aquifer	15
9.	Map showing distribution of observations of hydraulic conductivity of the Mississippi River Valley alluvial aquifer	17

ILLUSTRATIONS (continued)

		Page
Figure 10.	Graph showing thickness of the Mississippi River Valley confining unit and penetration of the Mississippi River into the Mississippi River Valley alluvial aquifer......	18
11.	Map showing thickness of the Mississippi River Valley confining unit..	19
12.	Diagram showing configuration of and predevelopment flow in regional aquifers at the latitude of Memphis.........	22
13.	Graph showing seasonal fluctuations in stage for selected rivers..	25
14.	Hydrographs of selected wells in the Mississippi River Valley alluvial aquifer.............................	27
15.	Graph showing acreage of rice planted for selected counties and States in the study area..................	29
16.	Generalized hydrogeologic section along A-A'..............	30
17.	Generalized hydrogeologic section along D-D' showing 1972 flow..	31
18.	Map showing locations of geophysical logs used in hydrogeologic data base and locations of geologic and hydrogeologic cross sections..............................	32
19.	Map showing finite difference grid and types of boundary nodes..	33
20.	Diagrams showing conceptual and digital model of head-dependent boundaries..................................	35
21-25.	Maps showing:	
	21. Topography in and near the study area................	39
	22. Altitude of the bottom of the Mississippi River Valley alluvial aquifer..........................	40
	23. Altitude of the top of the Mississippi River Valley alluvial aquifer................................	41
	24. Distribution of discharge from wells in the Mississippi River Valley alluvial aquifer for 1970......................................	43
	25. Areal distribution of vertical hydraulic conductivity of the Mississippi River Valley confining unit.....	44
26.	Diagrams showing digital model simulation along row 50....	47
27.	Map showing distribution of observed hydraulic head data used in calibration of steady-state model...............	49
28.	Map and histogram showing distribution of difference between observed and simulated 1972 hydraulic head for the Mississippi River Valley alluvial aquifer...........	51
29.	Graph showing sensitivity of model to changes in calibration parameters and pumpage.........................	54
30.	Graph showing comparison of calibration criteria for model of 1972 as steady state..............................	55
31.	Map showing simulated predevelopment potentiometric surface of the Mississippi River Valley alluvial aquifer...	57
32.	Diagrams showing simulated predevelopment and 1972 steady-state ground-water flow along row 50..................	58

Page

33-35. Map and histogram showing simulated predevelopment distribution of recharge and discharge:
33. At the top of the Mississippi River Valley alluvial aquifer excluding that from rivers.................. 59
34. At the bottom of the Mississippi River Valley alluvial aquifer.................................. 60
35. From rivers to the Mississippi River Valley alluvial aquifer.................................. 61
36. Map showing simulated 1972 potentiometric map for the Mississippi River Valley alluvial aquifer................ 63
37-39. Map and histrogram showing simulated 1972 distribution of recharge and discharge:
37. At the top of the Mississippi River Valley alluvial aquifer excluding that from rivers.................. 64
38. At the bottom of the Mississippi River Valley alluvial aquifer.................................. 65
39. From rivers to the Mississippi River Valley alluvial aquifer.. 66
40. Map showing net drawdown between simulated predevelopment potentiometric surface and observed 1972 potentiometric surface for the Mississippi River Valley alluvial aquifer 67

TABLES

Table 1. Correlation of lithostratigraphic and hydrostratigraphic nomenclature for the study area........................... 9
2. Gain in discharge of rivers crossing the Mississippi Alluvial Plain.. 24
3. Values of river width used in simulation of rivers........... 46
4. Hydrologic budgets for preliminary simulation of steady-state regional flow in the Mississippi River Valley alluvial aquifer.. 50
5. Simulated regional aquifer flow to and from rivers for steady-state conditions.................................. 52

CONVERSION FACTORS

For use of readers who prefer to use metric (International System) units, rather than the inch-pound units used in this report, the following conversion factors may be used:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02932	cubic meter per second) (m^3/s)

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5(°F-32)/9$$

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

HYDROLOGY OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER, SOUTH-CENTRAL UNITED STATES--A PRELIMINARY ASSESSMENT OF THE REGIONAL FLOW SYSTEM

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ABSTRACT

The Mississippi River Valley alluvial aquifer is a part of the Mississippi Embayment aquifer system in the Gulf of Mexico Coastal Plain. The alluvial aquifer is prolific; ground-water withdrawals from it totaled 7,600 cubic feet per second in 1985, mostly for irrigation of rice, and accounted for nearly 60 percent of all ground-water pumpage in the Gulf Coastal area. The alluvial aquifer consists of 60 to 140 feet of sand and gravel of Quaternary age, grading from gravel at the bottom to fine sand near the top, and underlying 32,000 square miles in parts of Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. Throughout most of the area the alluvial aquifer is overlain by the Mississippi River Valley confining unit--10 to 50 feet of silts, clays, and fine-grained sands. The thickness of the confining unit is highly variable. The underlying beds consist of alternating sands and clays of the Mississippi Embayment aquifer system.

A three-layer finite-difference model was constructed and calibrated to simulate two-dimensional steady-state regional confined or unconfined flow. Measurements of head for 1972 and pumpage from wells for 1970 were chosen for a steady-state calibration. Calibration values of hydrogeologic properties were achieved by adjusting hydraulic conductivities of each of the three layers (the confining unit, the alluvial aquifer, and underlying units) and of the riverbed materials to minimize the root-mean-squared error of observed head and simulated head for 1972 data. Calibrated values of conductivity are as follows:

1. hydraulic conductivity of the alluvial aquifer, 300 feet/day,
2. vertical hydraulic conductivity of the confining unit, 0.0003 feet/day,
3. ratio of vertical hydraulic conductivity to bed thickness for riverbed materials, 0.05 day^{-1}, and
4. ratio of vertical hydraulic conductivity to bed thickness for underlying units three times that used by the Mississippi embayment and Cretaceous and Paleozoic subregional models.

After calibration, the mean difference between simulated and observed heads was 0.8 feet; 76 percent of 812 observed heads were within 10 feet. The two areas of greatest difference between observed and simulated values probably are the result of errors in estimating pumpage distribution and bias from the steady-state assumption. After calibration of the model of steady-state flow for 1972, pumpage was removed from the alluvial aquifer and predevelopment flow was simulated.

The predevelopment ground-water flow system can be summarized as follows: (1) flow probably followed the land surface (southerly and toward major rivers along the axes of river basins), (2) recharge was from underlying aquifers and the confining unit, and (3) nearly all river reaches were gaining flow from the alluvial aquifer and accounted for almost all discharge. The 1972 ground-water flow system, listed in order of the magnitude of net changes from predevelopment, is summarized as follows: (1) pumpage from the alluvial aquifer for irrigation has caused regional flow to move toward pumping centers (depressions in the potentiometric surface), (2) discharge to rivers decreased, (3) recharge from rivers increased, (4) recharge from the confining unit increased, (5) discharge to underlying aquifers increased, and (6) recharge from underlying aquifers decreased. In 1972, recharge from the Mississippi River Valley confining unit averaged about 0.8 inch/year for the modeled area but was at a maximum of 1.3 inch/year for large parts of the alluvial aquifer. Large sections of the Arkansas, lower White, lower Cache, and lower Mississippi Rivers and smaller sections of other rivers were losing streams in 1972.

Drawdown greater than 20 feet occurred primarily at two locations in Arkansas--the Grand Prairie region and the area west of Crowleys Ridge. In these areas the combination of heavy long-term pumpage and limited ability of the alluvial aquifer to increase recharge have resulted in long-term declines in water levels. The model results indicate the importance of leakage from both rivers and the confining unit to provide recharge to sustain the large amounts of pumpage from the alluvial aquifer.

INTRODUCTION

Use of ground water for agricultural, industrial, and municipal purposes in the Gulf Coastal Plain has caused regional declines in water levels in major aquifers. Increases in ground-water use are expected to continue during the next decade. The Regional Aquifer-System Analysis program of the U.S. Geological Survey was initiated to define the regional hydrology and geology and establish a framework of background information of geology, hydrology, and geochemistry of the nation's important aquifer systems (Sun, 1986).

This study is part of the Gulf Coastal Regional Aquifer-System Analysis (GC RASA), a study of aquifer systems composed of Upper Cretaceous and younger sediments in the Gulf of Mexico Coastal Plain west of Florida (fig. 1). The objectives of the GC RASA are to define the hydrogeologic framework in which the aquifers exist, describe the chemistry of the ground water, and analyze the regional ground-water flow patterns within the flow system (Grubb, 1984, p. 6). Three aquifer systems have been identified (Grubb, 1984): (1) the Mississippi Embayment aquifer system, (2) the Coastal Lowlands aquifer system, and (3) the Texas Coastal Uplands aquifer system. A complete discussion of the regional study and maps showing the extent of these aquifer systems is given in Grubb (1984). The definition of the aquifer framework and the analysis of regional ground-water flow patterns in the western Gulf Coastal Plain has been subdivided into five subregional assessments: (1) the Cretaceous and Paleozoic aquifers of the northern Mississippi embayment, (2) the Tertiary aquifers of the Mississippi Embayment aquifer system, (3) the Coastal Lowlands aquifer system, (4) the Texas Coastal Uplands aquifer system, and (5) the Mississippi River Valley alluvial aquifer (this study). A regional study at a larger scale considering variable-density flow will be used to investigate regional flow within all five aquifer systems.

The Mississippi River Valley alluvial aquifer (Boswell and others, 1968, p. 4), referred to as the alluvial aquifer or simply the aquifer in this report, underlies an area of about 32,000 mi^2 in parts of Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee (fig. 1). Most of the aquifer underlies eastern Arkansas, northwestern Mississippi (locally called "the Delta"), northeastern Louisiana, and the Bootheel of southeastern Missouri. The alluvial aquifer is a highly productive aquifer accounting for 60 percent of the ground-water pumpage in the Gulf Coastal study area. More than 90 percent of the withdrawal from the alluvial aquifer is for agricultural use (primarily the irrigation of rice). The large withdrawals have resulted in regional water-level declines and local water-quality degradation.

Purpose and Scope

The purpose of this report is to describe the hydrogeology of the Mississippi River Valley alluvial aquifer, to present a conceptual model for steady-state regional flow analysis, to document the preliminary calibration of a steady-state digital model of regional flow, and to analyze the regional flow system based on the application of the preliminary model. Understanding flow paths, fluxes, aquifer interaction, or the effects of development on a local scale is not a purpose of this study. The study area (fig. 1) is limited to the portion of the Mississippi River Valley alluvial aquifer north of the southern extent of the subcrop of the Vicksburg-Jackson confining unit (fig. 1).

Approach

A conceptual model of regional flow in the alluvial aquifer was proposed following compilation and synthesis of existing data in U.S. Geological Survey files and other Federal, State, and local agency files, from private (generally oil and gas) industry sources, and from interpretive reports. Project data bases describing the hydrogeologic framework, head distributions in aquifers, and hydrogeologic parameters were assembled. A common discretization and computer simulation model were chosen for all subregional assessments. The boundary conditions, equations of flow, hydrogeologic framework, and distribution of hydrogeologic parameters from the conceptual model and data bases were fitted to the discretization and computer model.

Model calibration was based on objective criteria of head matching for steady-state flow in 1972. Results of the preliminary calibration were analyzed by examination of model output and by sensitivity analysis. The calibrated model was used to simulate predevelopment flow. A preliminary description of steady-state predevelopment and 1972 regional flow was made.

Geography

The Mississippi Alluvial Plain section (fig. 1) of the Coastal Plain province (Fenneman, 1938) coincides with the valley and some adjacent drainages of the Mississippi River from Cairo, Illinois, south approximately 600 mi to the Gulf of Mexico.

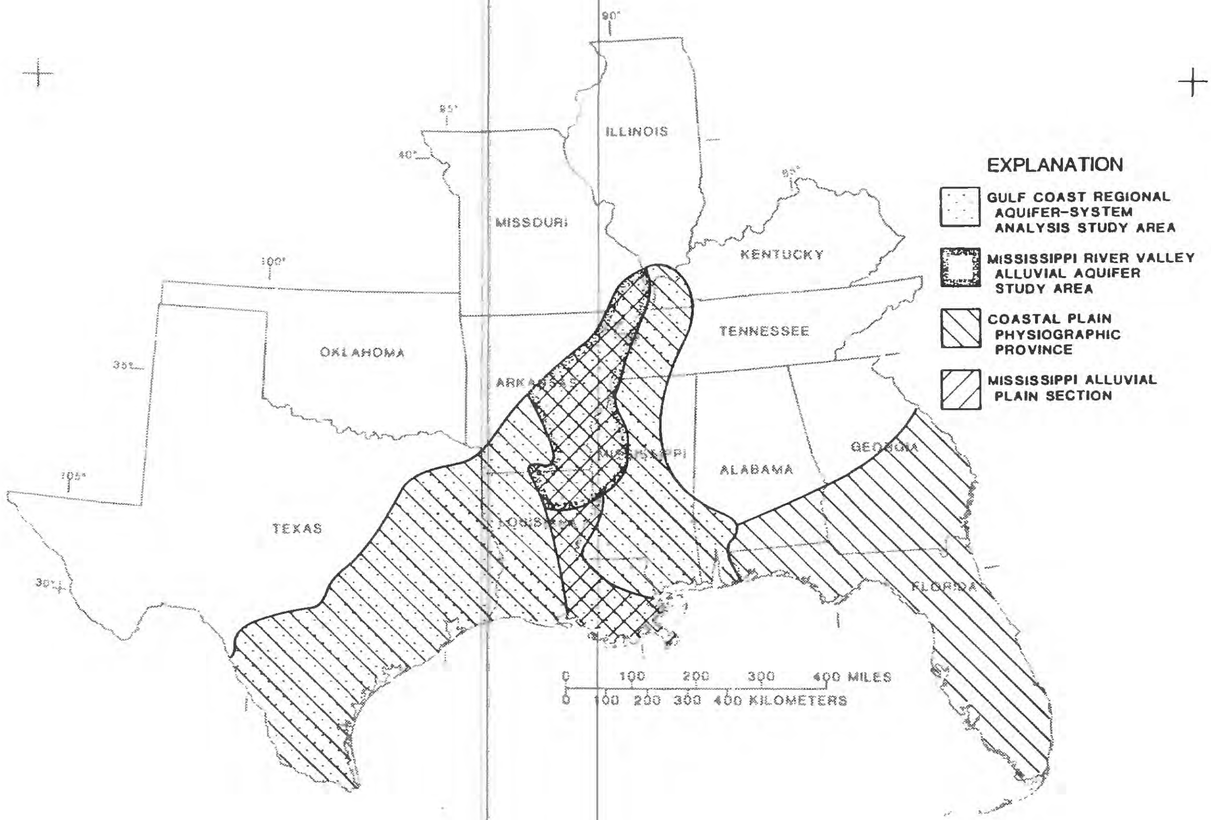


Figure 1.--Location of study area.

The land surface is a vast low, flat plain with one significant topographic interruption, Crowleys Ridge (fig. 2). The land surface generally slopes south from an altitude of about 330 ft above sea level in the north to about 50 ft above sea level near Vicksburg at the southern end of the study area. A few river basins (notably the St. Francis, Yazoo, and Tensas basins) generally are lower in altitude than the Mississippi River.

Crowleys Ridge trends north to south and bisects the northern half of the alluvial plain. The ridge width averages about 3 mi in the southern half of the ridge where the height is 100 to 150 ft above the plain, and 10 mi in the northern half of the ridge where the maximum height is about 250 ft above the plain.

Several major rivers drain the alluvial plain. The Mississippi, St. Francis, White, Arkansas, Yazoo, Ouachita, and Tensas are principal drainages. Modern engineering has changed the character of the rivers and the drainage basins in the alluvial plain. The rivers have been extensively channelized and their flood plains have intricate drainage and flood-control systems.

A physiographic region in the Mississippi Alluvial Plain, the Grand Prairie of Arkansas, is a natural treeless prairie that has been an area of intensive rice cultivation since about 1904 (Engler and others, 1945). The approximate outline of the Grand Prairie as used by most authors is shown on figure 19; some authors include more area to the north and west (see fig. 2).

The climate of the alluvial plain is moderate. Annual precipitation ranges from about 47 inches in the north to 52 inches near Vicksburg. Mean annual air temperature ranges from 58 °F in the north to about 66 °F near Vicksburg. Rainfall is not evenly distributed throughout the year (fig. 3), and droughts are common during late summer and early fall.

Previous Investigations

Many reports describing local hydrologic conditions have been published by the U.S. Army Corps of Engineers, the U.S. Geological Survey and other Federal and State agencies. Two reports discuss regional aspects of the alluvial aquifer and contain references to many of the reports describing local conditions (Krinitzsky and Wire, 1964; Boswell and others, 1968). More recent reports describing the results of modeling of ground-water flow for parts of the alluvial aquifer are Griffis (1972), Reed and Broom (1979), Broom and Lyford (1981), Sumner and Wasson (1984), and Peralta and others (1985).

HYDROGEOLOGY

At a regional scale, the hydrogeology of the Mississippi River Valley alluvial aquifer in the study area is very simple. The Quaternary alluvium overlies and is laterally adjacent to aquifers and confining beds in older rock units. (Pre-Quaternary geologic units are commonly referred to as bedrock in the project area, although most are not indurated.) The Quaternary alluvium has two distinct but gradational lithologies; clays and silts overlie coarse sands and gravels. These different lithologies form the hydrogeologic framework of the alluvial aquifer.

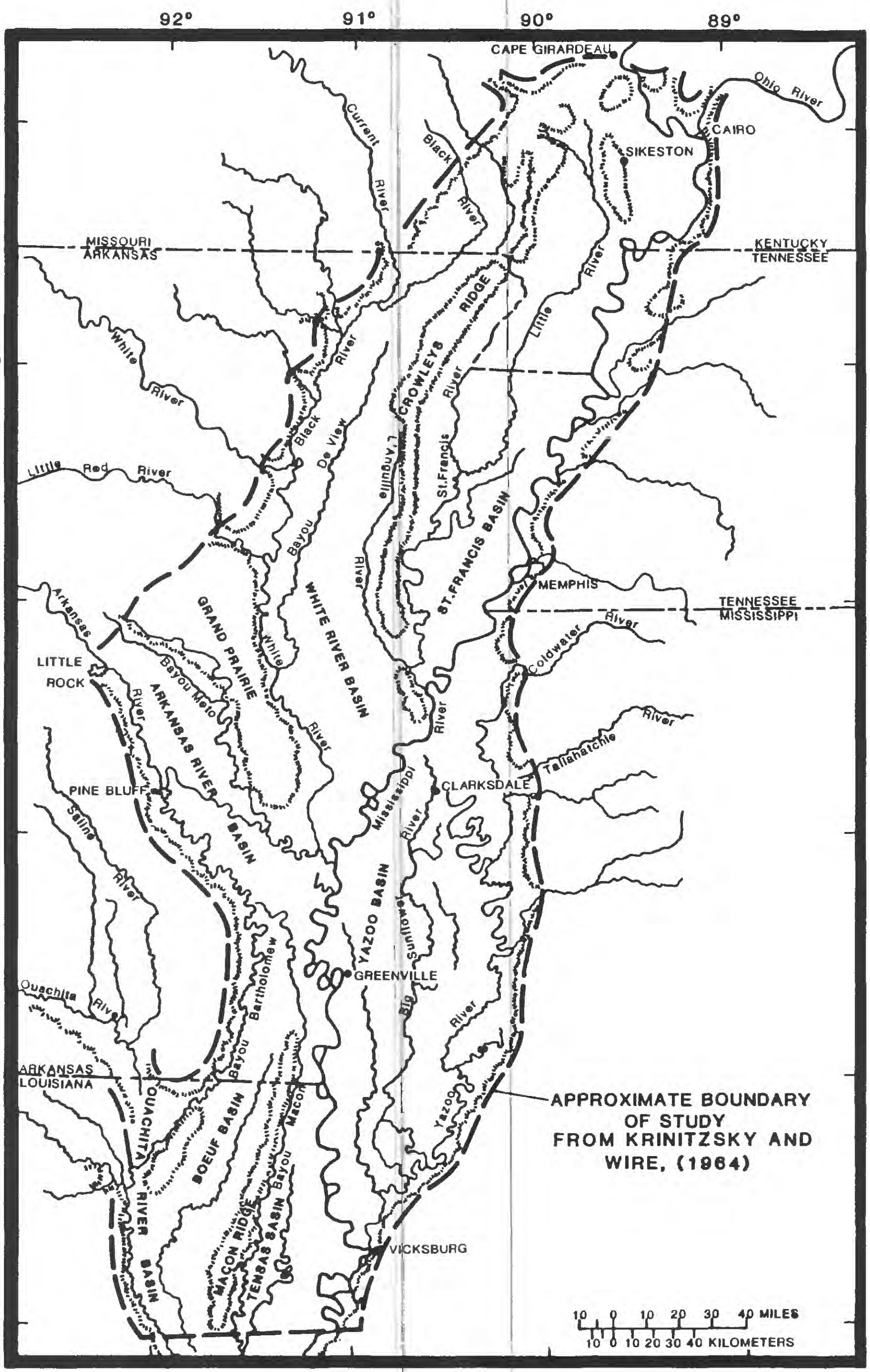


Figure 2.--Geographic locations in and near the study area. Modified from Krinitzsky and Wire (1964, fig. 2).

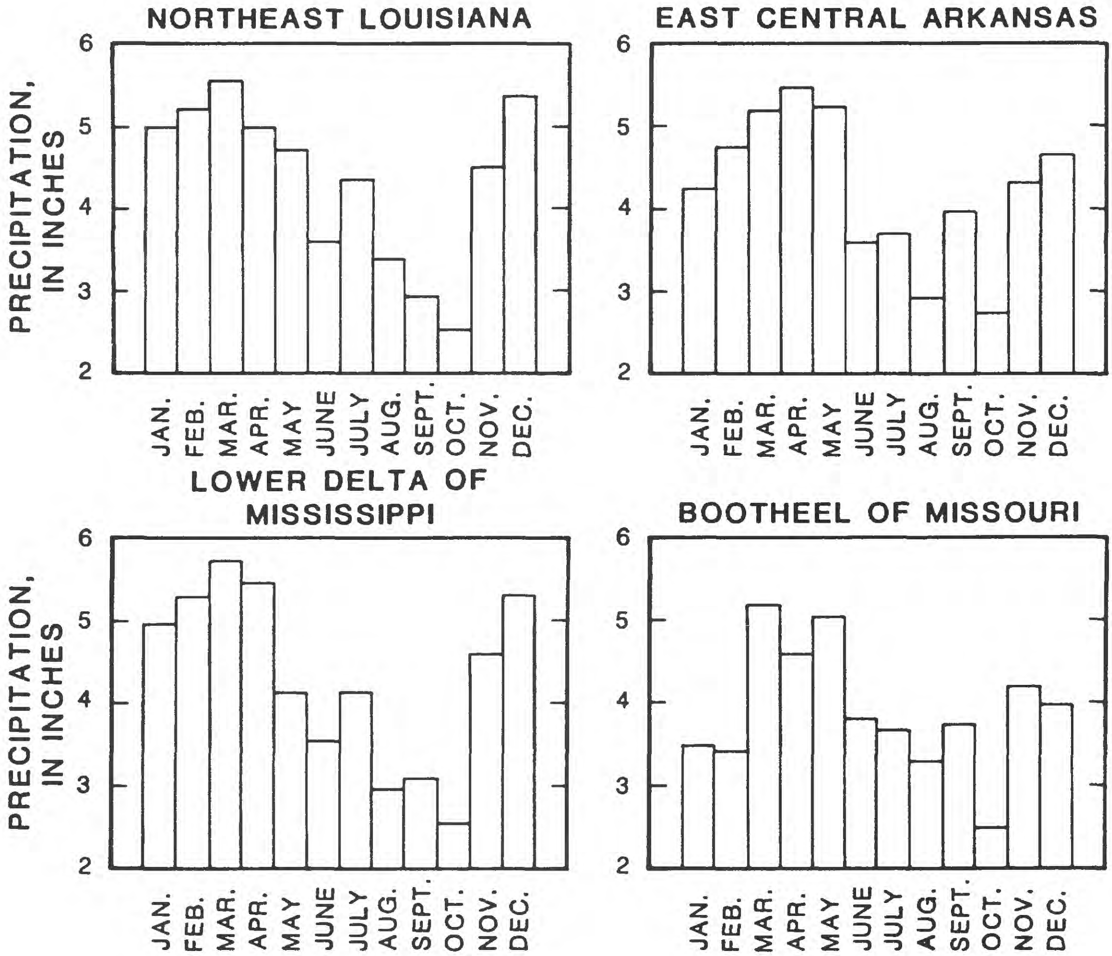


Figure 3.--Rainfall at four places in the study area. Data represent normal precipitation for period 1951-80. (U.S. Department of Commerce, 1952-81).

The base of the alluvial aquifer is a series of valleys entrenched in a pre-Quaternary eroded bedrock surface (Fisk, 1944). During Quaternary time the ancestral Mississippi and Ohio Rivers and their tributaries filled the valleys with sediment to the present level. In some places modern rivers have rearranged the upper part of the alluvial fill materials. The texture of the fill material gradually changes from the dominantly coarse-grained aquifer materials at the bottom to the dominantly fine-grained confining-unit materials at the top.

For additional discussions of the geologic history and geologic nature of the alluvial aquifer and associated geologic units, the reader is referred to Fisk (1944), Fisk (1947), Cushing and others (1964), Krinitzsky and Wire (1964), and Saucier (1974).

The stratigraphic position and nomenclature of the alluvial aquifer and underlying units in the study area are summarized in table 1. The hydrostratigraphic nomenclature and numbering system for aquifers and confining units used by the GC RASA are used for this report. Figures 4 through 7, that are modified from Fisk (1944) or from data in Krinitzsky and Wire (1964), show the geology at representative locations in the alluvial aquifer. Geologic section locations that also were used for hydrogeologic and model simulation sections are shown on figures 18 and 19.

Analysis of available potentiometric maps indicates that regional ground-water flow in the alluvial aquifer generally is southward and may be either toward or away from the Mississippi River. At some locations regional flow is toward major rivers such as the Arkansas, White, Sunflower, Yazoo, and Tensas. Notable exceptions are flow toward major perennial drawdown cones in eastern Arkansas. Seasonal variations in local and intermediate flow patterns occur in response to changing river stages and summer irrigation pumpage.

Additional discussion of local flow patterns in the alluvial aquifer can be found in Krinitzsky and Wire (1964), Broom and Reed (1973), Whitfield (1975), Dalsin (1978), Broom and Lyford (1981), and Luckey (1985).

Hydrogeologic Units and Hydraulic Properties

Three components of contrasting permeability comprise the Mississippi River Valley alluvial aquifer flow system. These are: (1) the alluvial aquifer, (2) an overlying unit, the Mississippi River Valley confining unit, and (3) the underlying or adjacent older strata. The silt and clay of the confining unit of the Quaternary alluvium confine the alluvial aquifer in most places. The underlying confining units impede the hydraulic connection with underlying deeper aquifers over much of the area. Where aquifers directly underlie the alluvial aquifer the contrast between the higher permeability of the coarse lower part of the alluvial aquifer and the lower permeability of underlying aquifers is sufficient to differentiate the aquifers.

Mississippi River Valley Alluvial Aquifer

The Mississippi River Valley alluvial aquifer consists predominately of sands and gravels that are coarser northward and with depth. Maximum grain sizes grade from about 8 inches in the north to 3 inches in the south (Fisk, 1947). The lower part of the aquifer generally is a coarse sand matrix with

Table 1.--Correlation of lithostratigraphic and hydrostratigraphic nomenclature for the study area

(Numbers in parentheses are part of the Gulf Coast RASA system of numbering hydrostratigraphic units and are for cross reference or labeling of map and sections only; X or cross-rule pattern indicates units not present, not adjacent to, or not subcropping below the Mississippi River Valley alluvial aquifer)

Erathem	System	Series	Arkansas Northeastern	Arkansas Southeastern	Illinois	Kentucky	Louisiana	Mississippi	Missouri	Tennessee	Hydrostratigraphic units in this study
Cenozoic	Quaternary	Holocene	Alluvium and terrace deposits	Alluvium and terrace deposits	Alluvium and terrace deposits	Alluvium and loess deposits	Alluvium and terrace deposits	Alluvium, terrace, and loess deposits	Alluvium and terrace deposits	Alluvium and loess deposits	Mississippi River Valley confining unit (11a)
Cenozoic	Quaternary	Pleistocene	Alluvium and terrace deposits	Alluvium and terrace deposits	Alluvium and terrace deposits	Alluvium and loess deposits	Alluvium and terrace deposits	Alluvium, terrace, and loess deposits	Alluvium and terrace deposits	Alluvium and loess deposits	Mississippi River Valley alluvial aquifer (11)
Cenozoic	Tertiary	Oligocene	X	X	X	X	Vicksburg Formation	X	X	X	Vicksburg-Jackson confining unit (15)
Cenozoic	Tertiary	Eocene	X	Jackson Group: Undifferentiated	X	X	Jackson Group: Undifferentiated	Jackson Group: Undifferentiated	X	X	Vicksburg-Jackson confining unit (15)
Cenozoic	Tertiary	Eocene	Claiborne Group: Cockfield Formation	Claiborne Group: Cockfield Formation	X	Claiborne Group: Cockfield Formation	Claiborne Group: Cockfield Formation	Claiborne Group: Cockfield Formation	Claiborne Group: Cockfield Formation	Claiborne Group: Cockfield Formation	Upper Claiborne aquifer (6)
Cenozoic	Tertiary	Eocene	Claiborne Group: Cook Mountain Formation	Claiborne Group: Cook Mountain Formation	X	Claiborne Group: Cook Mountain Formation	X	Claiborne Group: Cook Mountain Formation	Claiborne Group: Cook Mountain Formation	Claiborne Group: Cook Mountain Formation	Middle Claiborne confining unit (14)
Cenozoic	Tertiary	Eocene	Claiborne Group: Memphis Sand	Claiborne Group: Sparta Sand	X	Claiborne Group: Sparta Sand	X	Claiborne Group: Sparta Sand	Claiborne Group: Memphis Sand	X	Middle Claiborne aquifer (5)
Cenozoic	Tertiary	Eocene	Claiborne Group: Memphis Sand	Claiborne Group: Cane River Formation	X	Claiborne Group: Tallahatta Formation	X	Claiborne Group: Zilpha Clay	Claiborne Group: Memphis Sand	X	Lower Claiborne confining unit (13)
Cenozoic	Tertiary	Eocene	Claiborne Group: Memphis Sand	Claiborne Group: Carrizo Sand	X	Claiborne Group: Tallahatta Formation	X	X	Claiborne Group: Memphis Sand	X	Lower Claiborne-upper Wilcox aquifer (4)
Cenozoic	Tertiary	Eocene	Wilcox Group: Flour Island Formation	Wilcox Group: Undifferentiated	Wilcox Formation	Wilcox Formation	X	X	Wilcox Group: Flour Island Formation	X	Middle Wilcox aquifer (3)
Cenozoic	Tertiary	Paleocene	Wilcox Group: Fort Pillow Sand	Wilcox Group: Undifferentiated	X	X	X	X	Wilcox Group: Fort Pillow Sand	X	Lower Wilcox aquifer (2)
Cenozoic	Tertiary	Paleocene	Wilcox Group: Old Breastworks Formation	Wilcox Group: Undifferentiated	X	X	X	X	Wilcox Group: Old Breastworks Formation	X	Midway confining unit (12)
Cenozoic	Tertiary	Paleocene	Midway Group: Porters Creek Clay	Midway Group: Porters Creek Clay	Midway Group: Porters Creek Clay	Midway Group: Porters Creek Clay	X	X	Midway Group: Porters Creek Clay	X	Midway confining unit (12)
Cenozoic	Tertiary	Paleocene	Midway Group: Clayton Formation	Midway Group: Clayton Formation	Midway Group: Clayton Formation	Midway Group: Clayton Formation	X	X	Clayton Formation	X	Midway confining unit (12)
Mesozoic	Cretaceous	Upper Cretaceous	Arkadelphia Marl	X	McNairy Sand	McNairy Sand	X	X	Owl Creek Formation	X	Midway confining unit (12)
Mesozoic	Cretaceous	Upper Cretaceous	Nacatoch Sand	X	McNairy Sand	McNairy Sand	X	X	McNairy Sand	X	McNairy-Nacatoch aquifer (1)
Paleozoic	X	X	Paleozoic rocks	X	X	X	X	X	Paleozoic rocks	X	Unnamed units (0)

Mississippi embayment aquifer system: units (15) through (2).

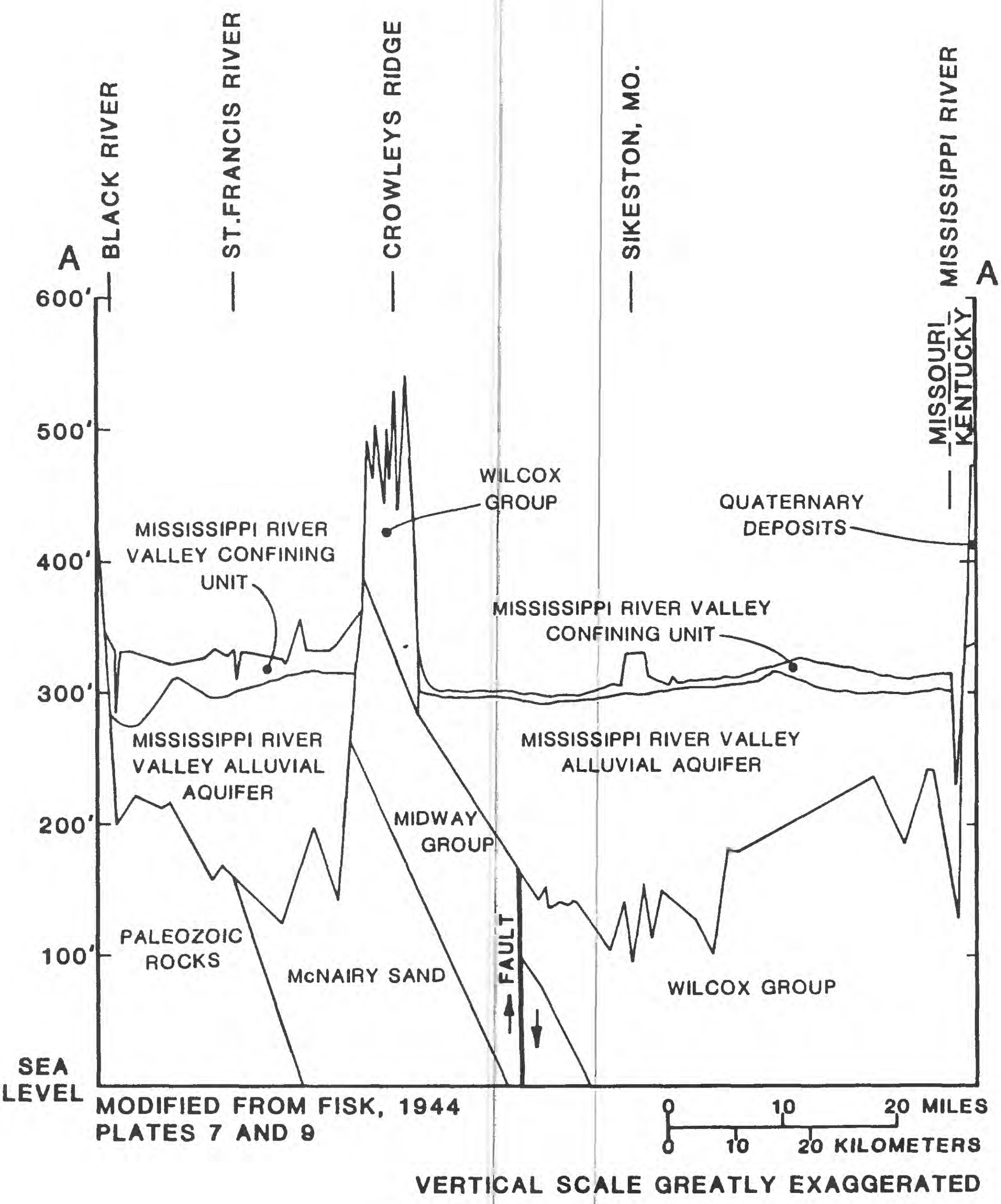


Figure 4.--Geologic section A-A'.

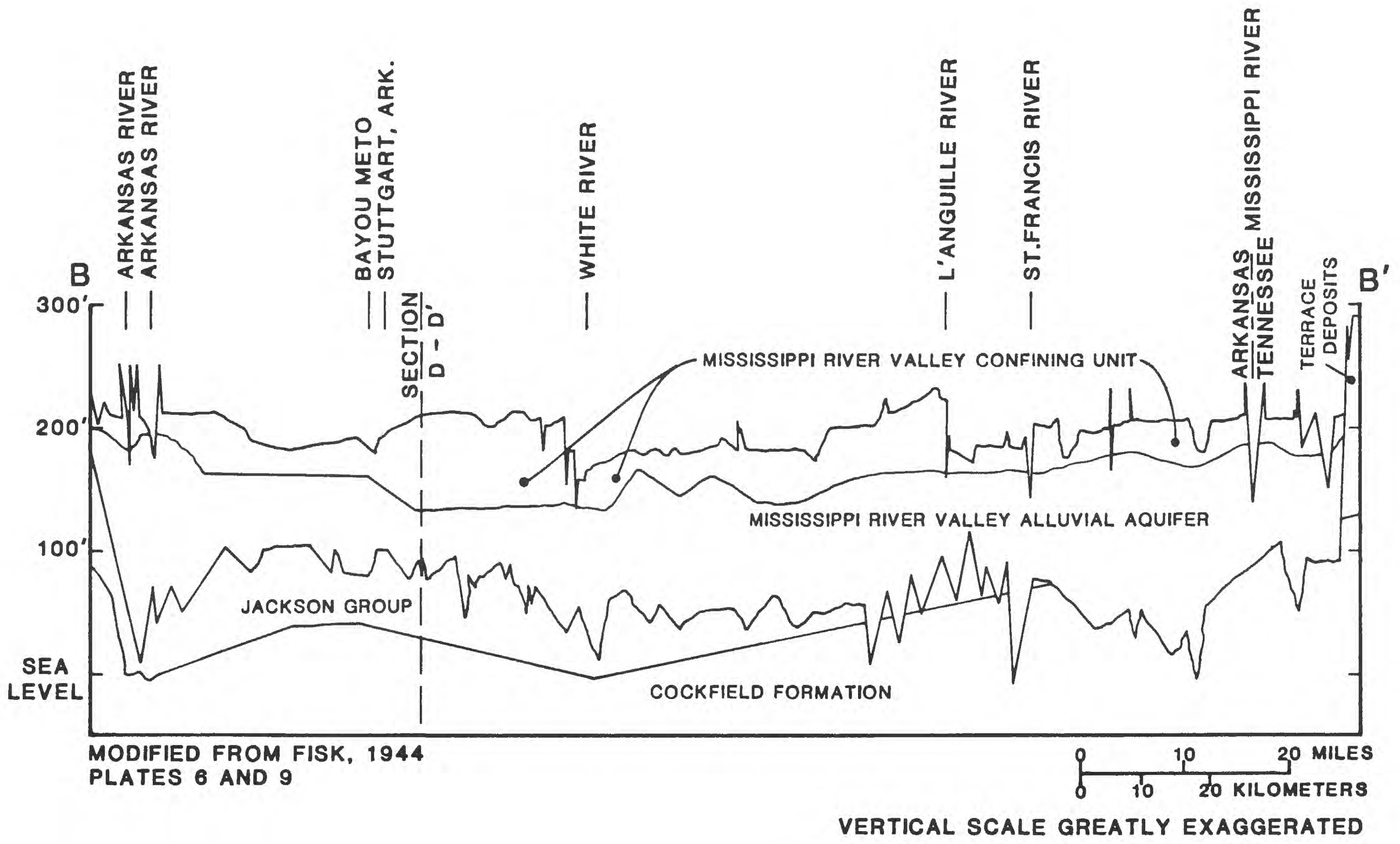


Figure 5.--Geologic section B-B'. Section D-D' is from a different source, location shown is approximate.

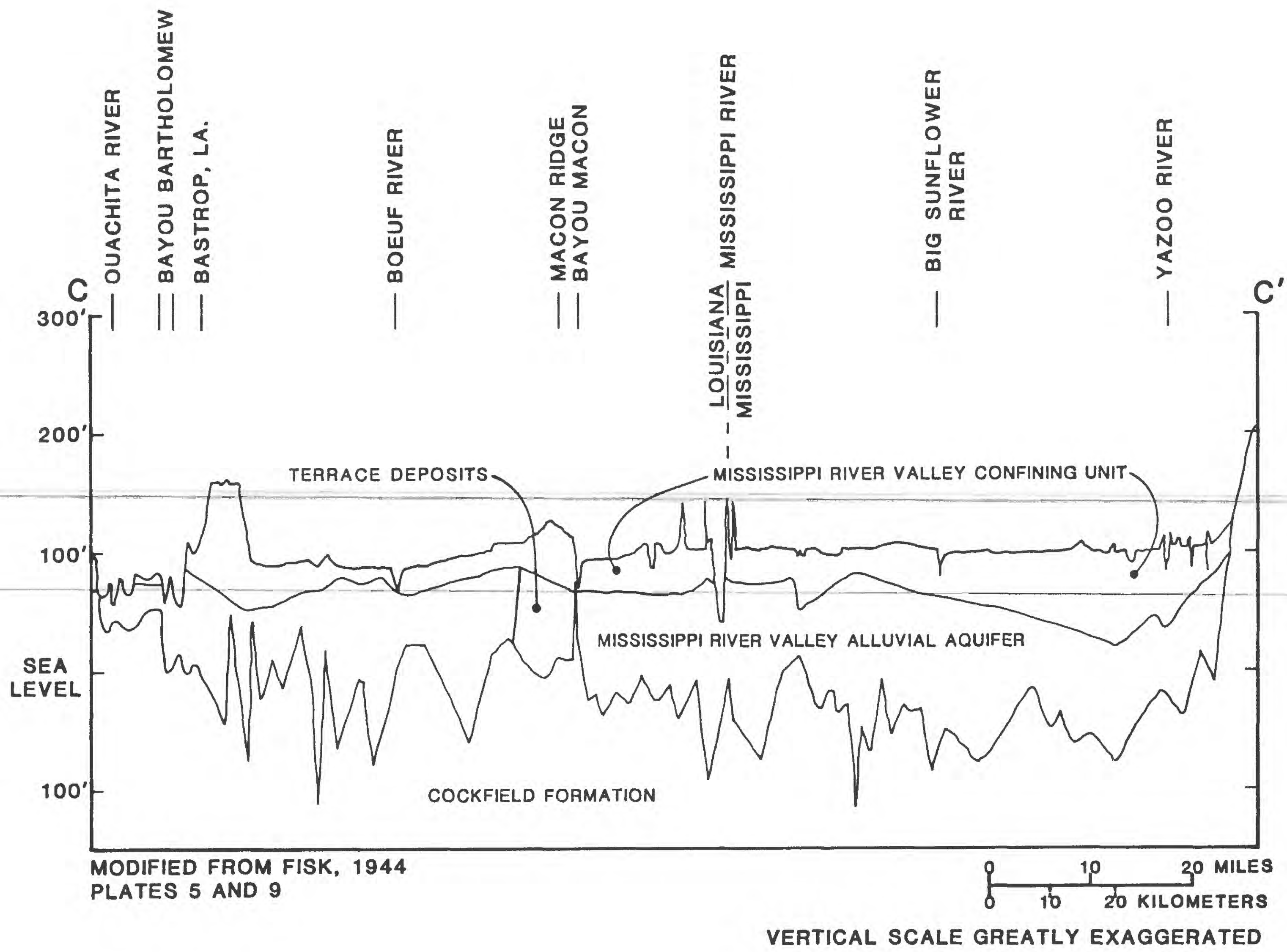


Figure 6.--Geologic section C-C'.

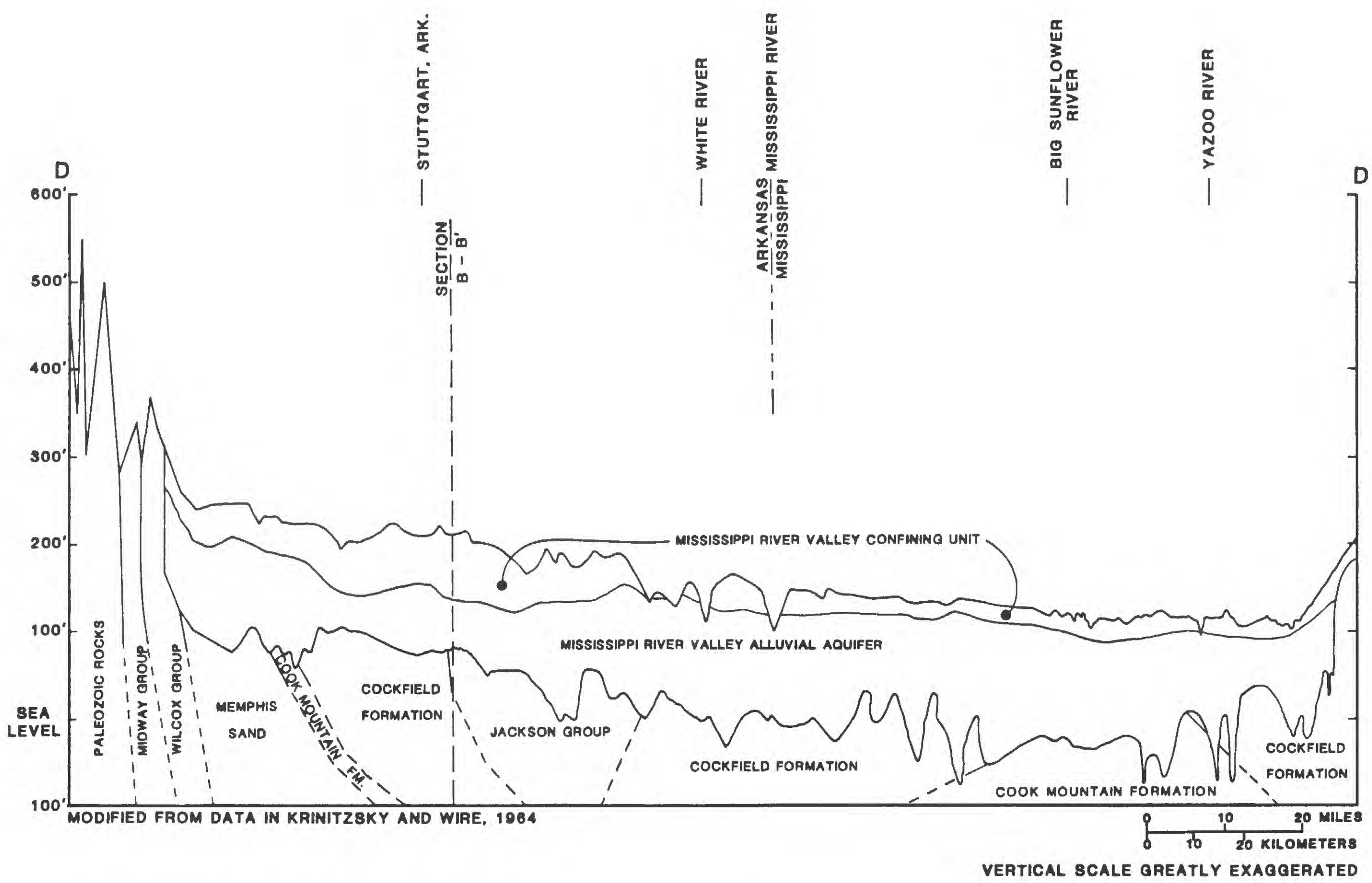


Figure 7.--Geologic section D-D'. Geology of underlying units from R.L. Hosman (written commun., 1986). Section B-B' is from a different source, location shown is approximate.

varying amounts of coarse gravel. In places, the base of the aquifer is predominately gravel. The gravelly sand is overlain by a medium to fine-grained non-graveliferous sand commonly referred to as the "clean" sand. Lenses of clay, silt, or sandy silt are found at many places in the aquifer, but are rarely continuous.

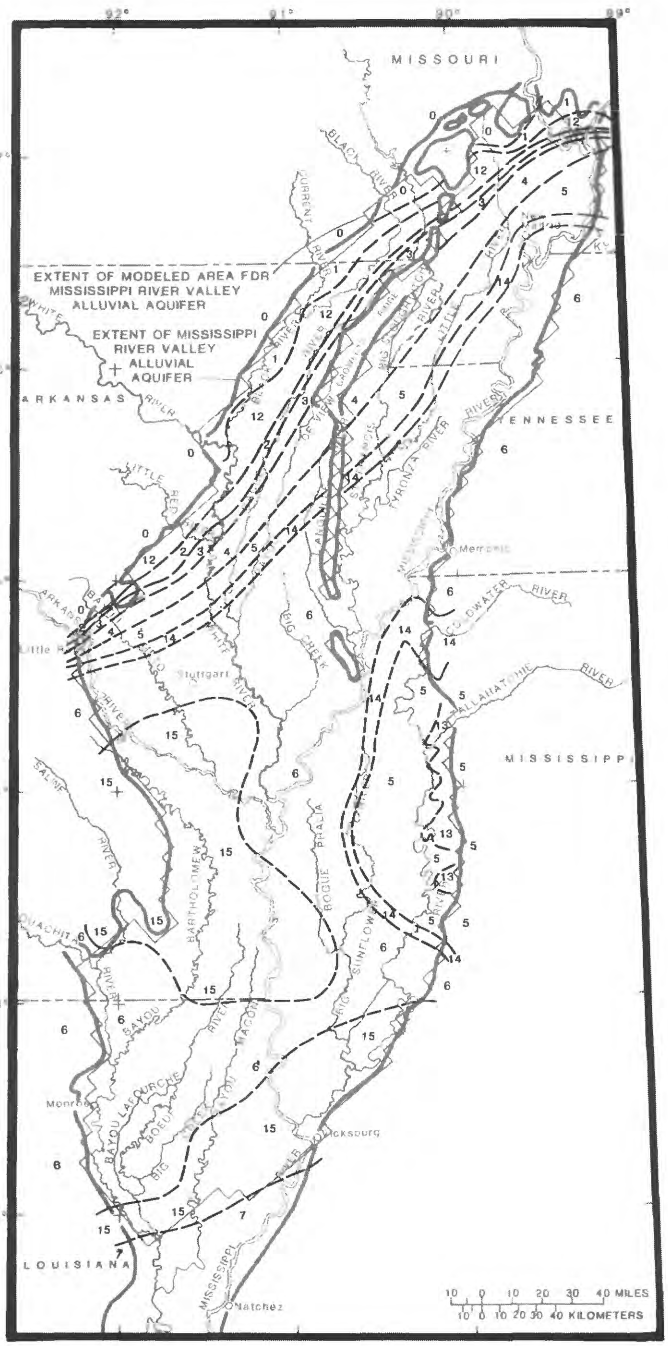
Although the alluvial aquifer extends south under the Mississippi Alluvial Plain to the Gulf of Mexico, this study concentrates on the portion of the aquifer north of the southern limit of the subcrop of the Vicksburg Formation and Jackson Group (fig. 11), a distance of nearly 400 mi. The aquifer has an average width of about 80 mi in the study area, has a maximum width of 125 mi near Helena, Arkansas, and a minimum width of 25 mi south of the study area near Natchez, Mississippi. The lateral limits of the aquifer generally are the outcrops of Eocene and older rocks. The alluvial aquifer does not exist on Crowleys Ridge, an errosional remnant of Tertiary strata. In some places the contact of the alluvial aquifer with older strata is masked by a thin covering of older and somewhat higher terrace deposits. The lateral boundaries shown on figure 11 are modified from an unpublished map (R.L. Hosman, U.S. Geological Survey, written commun., 1986) and agree with the many local studies that in turn are based on many logs of test holes and locations of high-capacity wells. However, the boundary is not certain in the western Ashley County, Arkansas, area due to a lack of detailed information.

The thickness of aquifer materials generally ranges from 60 to 140 ft, averages 100 ft and decreases to the south. Extremes of thickness for the alluvial aquifer will occur where the Mississippi River Valley confining unit is locally absent or very thick. Except in areas where large cones of depression have developed, the potentiometric surface of the alluvial aquifer is above or near the top of the aquifer. Therefore, saturated thickness usually is equal to the thickness of aquifer materials.

Aquifer hydraulic conductivities and transmissivities used in this project were assembled from a variety of sources. Hydraulic conductivity values for 51 aquifer tests in the alluvial aquifer (fig. 8) generally range from 120 to 330 ft/d and have a geometric mean of 205 ft/d (A.K. Williamson, U.S. Geological Survey, written commun., 1985). This is in agreement with 38 values of hydraulic conductivity in table 2 of Krinitzsky and Wire (1964); values generally were between 120 and 390 ft/d and had a geometric mean of 210 ft/d. Newcome (1971) gave an average of 200 ft/d and a range of 90 to 400 ft/d for alluvial aquifers in Mississippi.

Mississippi River Valley Confining Unit

Throughout most of the study area the overlying silts, clay, and fine-grained sands of the confining unit confine the Mississippi River Valley alluvial aquifer and impede recharge (Krinitzsky and Wire, 1964, p. 90). The overlying beds of fine-grained material are here named the Mississippi River Valley confining unit. For the purposes of this report the term "confining unit" (singular) will refer to the Mississippi River Valley confining unit that overlies the Mississippi River Valley alluvial aquifer. Although the confining unit is locally absent, the thickness averages 30 ft, generally ranges from 10 ft to 50 ft, and may be as much as 150 ft. In the study area three major types of depositional environment can be described for the



EXPLANATION

COASTAL LOWLANDS AQUIFER SYSTEM		ZONE E (LOWER MIOCENE-UPPER OLIGOCENE DEPOSITS)	7
MISSISSIPPI EMBAYMENT AQUIFER SYSTEM		VICKSBURG-JACKSON CONFINING UNIT	15
		UPPER CLAIBORNE AQUIFER	6
		MIDDLE CLAIBORNE CONFINING UNIT	14
		MIDDLE CLAIBORNE AQUIFER	5
		LOWER CLAIBORNE CONFINING UNIT	13
		LOWER CLAIBORNE-UPPER WILCOX AQUIFER	4
		MIDDLE WILCOX AQUIFER	3
		LOWER WILCOX AQUIFER	2
		MIDWAY CONFINING UNIT	12
		McNAIRY-NACATOCH AQUIFER	1
		UNNAMED UNITS	0

---- SUBCROP BOUNDARY

OUTCROP BOUNDARY

—— Outcrop and subcrop boundaries by R.L. Hosman (written commun., 1986).

Figure 8.--Units subcropping below and adjacent to the Mississippi River Valley alluvial aquifer. Numbers refer to hydrostratigraphic units. See also figure 12 and correlation table.

confining unit: (1) braided stream, (2) meander belt, and (3) backswamp (Fisk, 1944, 1947; Krinitzsky and Wire, 1964). Deposition in all three environments was dominated by silts and clays or lenticular clays and sand. Only the braided stream deposits contain any significant amount of sand (Fisk, 1947, plate 70). More recent work by geologists studying the confining unit describes the "braided stream" deposits of Fisk (1944, 1947) as "valley outwash plain" deposits (L.W. Smith, U.S. Army Corps of Engineers, oral commun., 1986).

The confining unit is thinnest in the north and near the margins of the study area (Fisk, 1944, 1947). Although confining-unit thickness is highly variable, the general increase in thickness from north to south can be seen in figure 9. The variation in the thickness of the confining unit can be seen in figure 10. The confining unit is thickest beneath the Grand Prairie region (fig. 19) near Stuttgart, Arkansas, where it is consistently greater than 50 ft over a large area. The sources of data and method of construction of figure 10 are described in the section of the report describing model input data.

Laboratory determinations of permeability for samples of the confining unit in the clay to silty sand textures ranges from 1×10^{-4} to 0.5 ft/d (M.S. Bedinger, U.S. Geological Survey, written commun., 1960). These values are reasonable for the grain sizes they represent (Freeze and Cherry, 1979, p. 29).

For a more complete discussion of the geology of the confining unit the reader is referred to Fisk (1944, 1947), Krinitzsky and Wire (1964), and Saucier (1974). Detailed maps showing the surficial geology and cross sections can be found in Kolb and others (1958), Saucier (1964, 1967), Fleetwood (1969), and Smith and Saucier (1971).

Underlying Units

Nomenclature for aquifers and confining units subcropping the Mississippi River Valley alluvial aquifer in the study area is shown on table 1 and figure 11 and the subcrop patterns are shown in figure 11. As shown on table 1, the Paleozoic units are the oldest strata underlying the alluvial aquifer. The Paleozoic rocks consist of limestones, dolomites, quartzites and shales of uncertain but probably low permeability. The remaining subcropping aquifers and confining units, which correspond to hydrologic units of the Mississippi Embayment aquifer system, are alternating beds of sand and clay with some interbedded silt, lignite, and limestone (Grubb, 1984).

The continuous sands of the Mississippi Embayment aquifer system that underlie the alluvial aquifer often are prolific regional aquifers. Horizontal permeabilities of these underlying aquifers generally ranges from 10 to 200 ft/d (A.K. Williamson, U.S. Geological Survey, written commun., 1985).

Underlying confining units of the Mississippi Embayment aquifer system generally range from 60 to 600 ft in thickness and are composed of shales, clays, and silty clays (Cushing and others, 1964). Date are not available on the hydrologic conductivity of these materials, but a common range for similar materials would be 10^{-3} to 10^{-7} ft/d (Freeze and Cherry, 1979, p. 29).

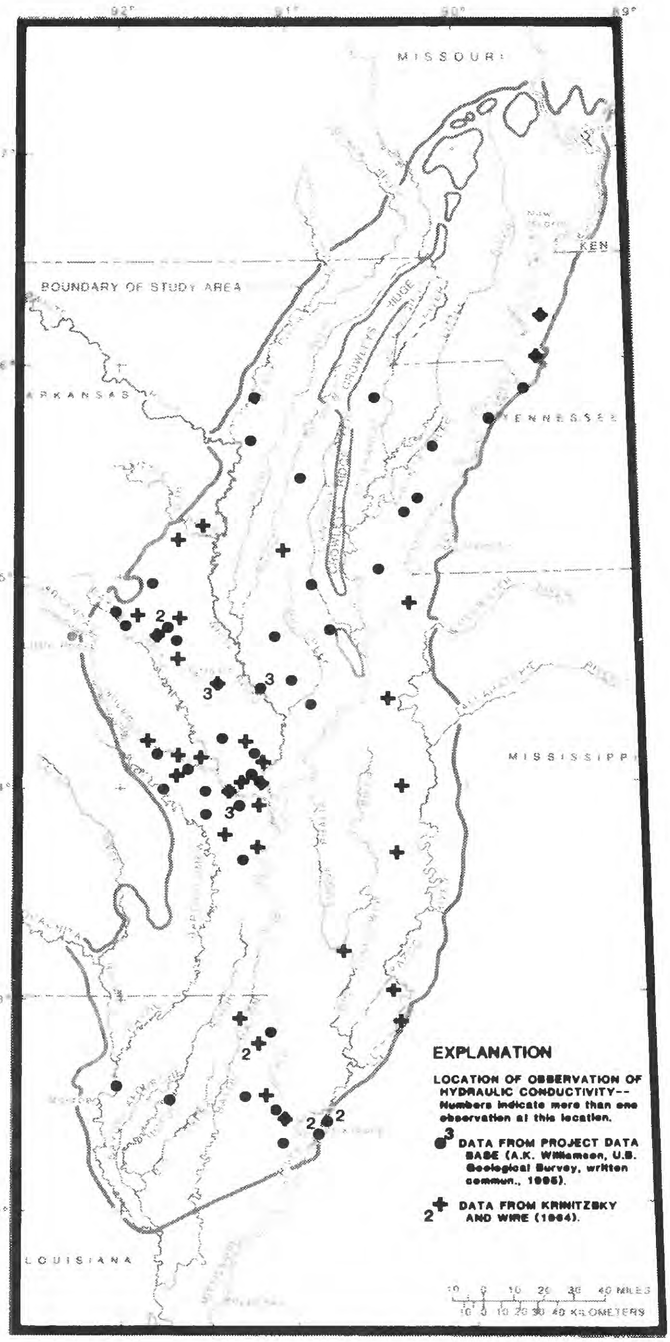


Figure 9.--Distribution of observations of hydraulic conductivity of the Mississippi River Valley alluvial aquifer. Overlapping symbols may represent the same data. Data are plotted in the center of the 5-mile model block.

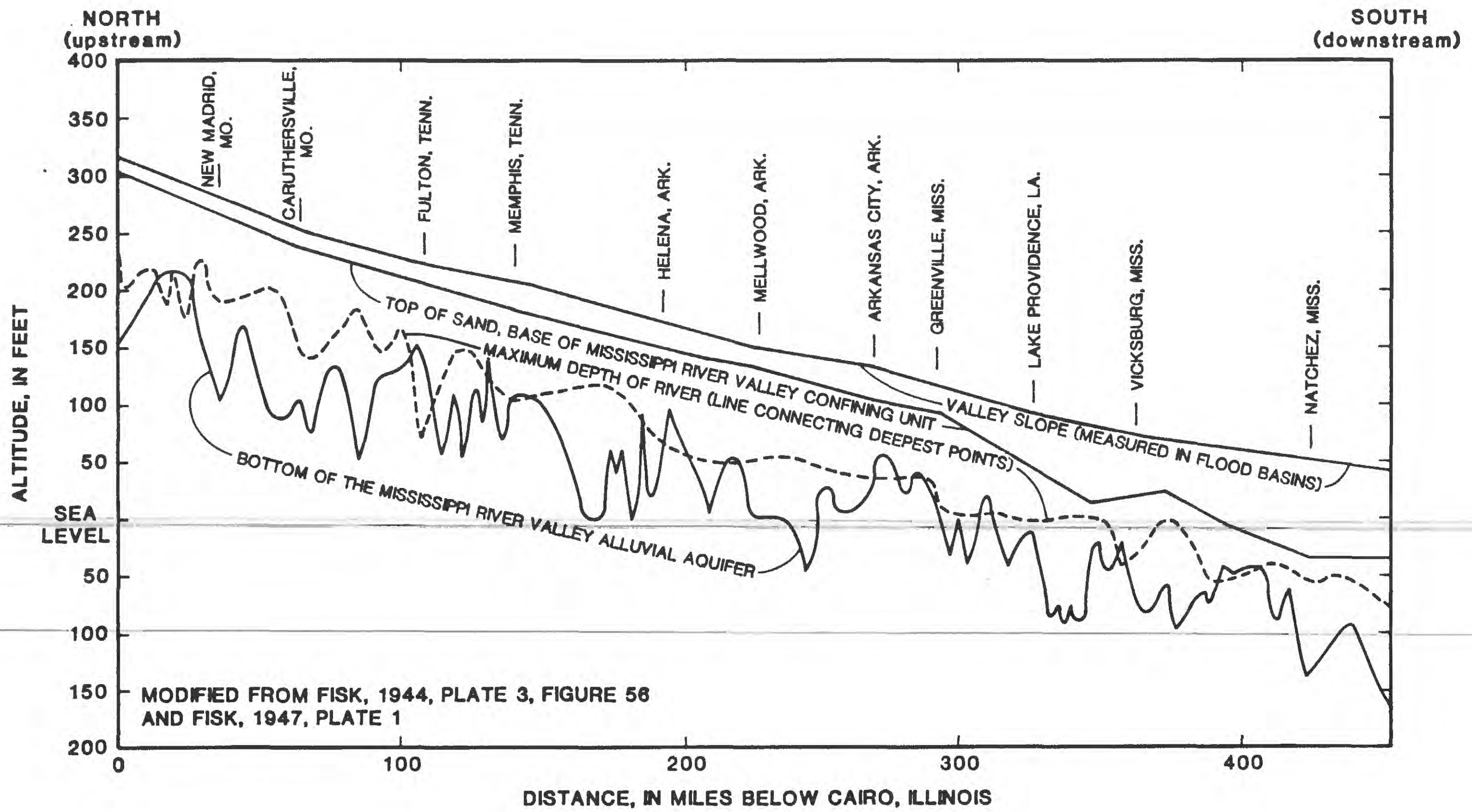


Figure 10.--Thickness of the Mississippi River Valley confining unit and penetration of the Mississippi River into the Mississippi River Valley alluvial aquifer.

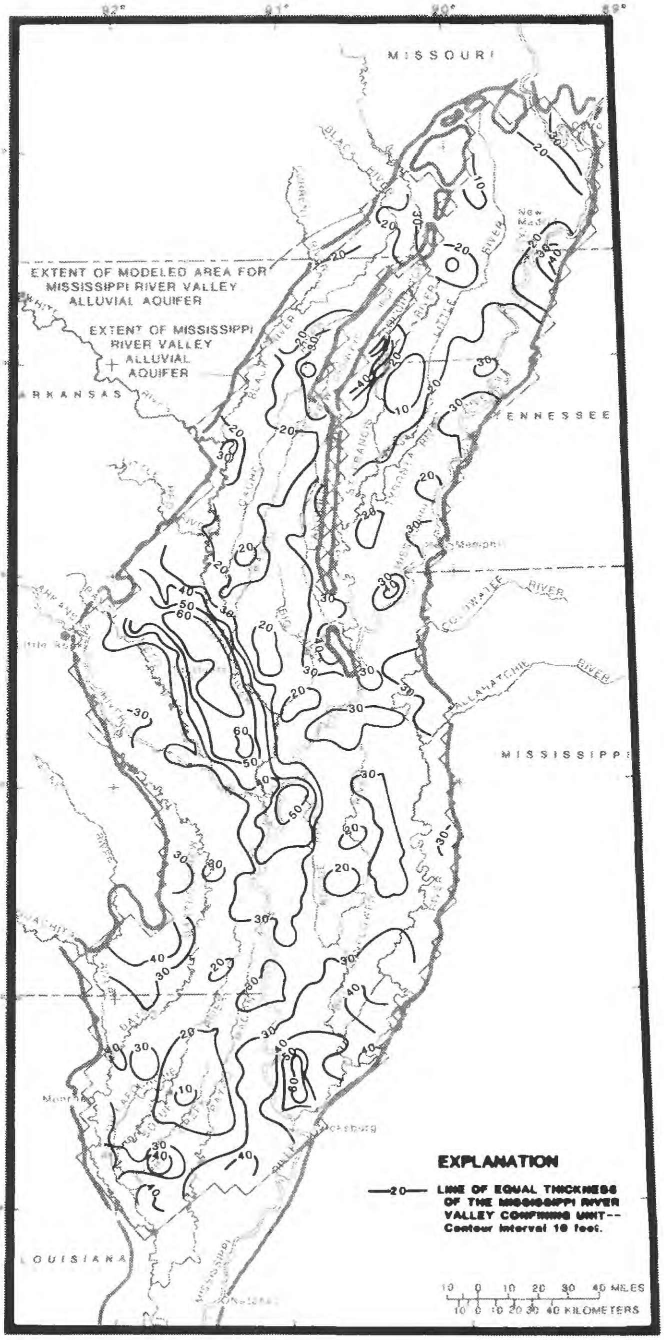


Figure 11.--Thickness of the Mississippi River Valley confining unit.

For a more complete discussion of the hydrogeology of aquifers underlying the alluvial aquifer the reader is referred to Boswell and others (1965) and Hosman and others (1968).

Flow Systems

Recharge to the Mississippi River Valley alluvial aquifer generally originates as leakage from the confining unit or direct infiltration of rainfall, rivers, underlying aquifers, and adjacent hydrogeologic units. The alluvial aquifer discharges to wells, evapotranspiration, and by leakage to the confining unit, rivers, underlying aquifers, and adjacent hydrogeologic units. Over most of its extent the alluvial aquifer receives water by leakage from the less pervious confining unit. Previous studies have described all movement of water to the top of the aquifer as percolation or recharge from rainfall. Where the alluvial aquifer is overlain by the confining unit this movement of water is leakage from the water table in the confining unit to the aquifer and not infiltration or recharge to the water table in the aquifer. Although the position of the water table in the confining unit is not documented it is probably near or above the potentiometric surface of the alluvial aquifer in most of the area over most of the year. The logical consequence is that the net flow would be downward into the alluvial aquifer.

Recharge to the top of the alluvial aquifer has been estimated by previous model studies. Broom and Lyford (1981, p. 35) estimated that the recharge in northeastern Arkansas generally was 0.4 inch/year except in some sandy areas where it was estimated to be nearly 2 inches/year. Sumner and Wasson (1984, p. 46) estimated uniform areal recharge to be 0.5 inch/year. Griffis (1972) and Peralta and others (1985) assumed no recharge across the top of the alluvial aquifer.

Leakage from the Mississippi River Valley confining unit is considered to be the dominant method by which water enters the top of the Mississippi River Valley alluvial aquifer in this report. This is supported by the nearly continuous presence of the fine-grained confining unit that serves as a source layer for flux to the aquifer. Recent research by the Soil Conservation Service, U.S. Department of Agriculture (USDA, SCS) has documented the existence of perched seasonal water tables above a layer of low hydraulic conductivity 1 1/2 to 2 ft below land surface (Larry Ward, USDA, SCS, written commun., 1985). This layer generally is a fragipan but is in some soils an argillic horizon. Soils at a depth of 6 to 7 ft below this horizon rarely were saturated and may be limiting recharge by leakage to much of the alluvial aquifer. In Arkansas about 13 percent of the alluvium surface is covered by soils classified as having a fragipan. These soils derived from loess, cover much of the older valley outwash plain (braided-stream) deposits with a thickness of 4 to 20 ft.

The fine-grained confining unit is not continuous and where it is thin or sandy direct recharge to the alluvial aquifer by infiltration of precipitation may occur. In northwestern Mississippi County, Arkansas, between the Black and Cache Rivers, and along major river courses there are extensive areas where the confining unit is thin or sandy. These river courses and parts of the nearby flood plains may be sites of either recharge to or evapotranspiration from the alluvial aquifer, however, the recharge and evapotranspiration cannot be quantified or identified as being distinct from flow between the aquifer and river. In general, areas where the confining unit is thin or sandy are not widespread or continuous at a regional scale.

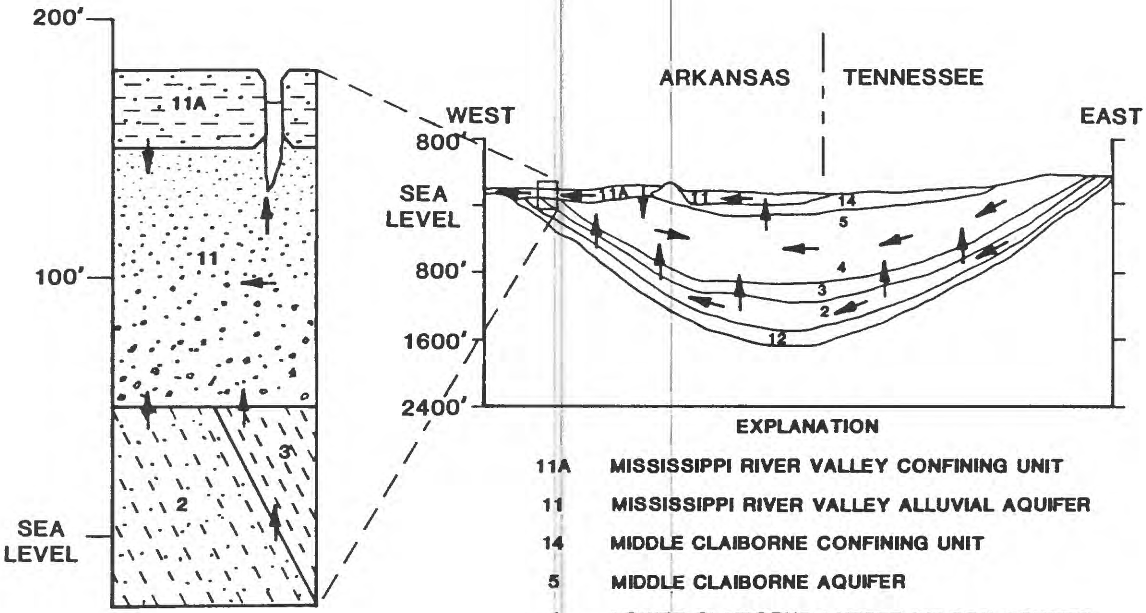
Along the eastern edge of the alluvial aquifer in parts of Mississippi and Tennessee the confining unit is overlain by more sandy alluvial apron deposits. Also, some of the confining unit is of the more sandy valley outwash plain (braided-stream) deposits. Hydrographs of wells in the alluvial aquifer near the uplands show large and rapid response to local precipitation (Krinitzsky and Wire, 1964, p. 60; Darden, 1981). Krinitzsky and Wire (1964) attribute recharge to the alluvial aquifer in this area to be a response to increased underflow from streams draining the uplands and geologic cross sections (Kolb and others, 1958; Saucier, 1964) show that most streams crossing the alluvium-upland contact are deeply incised through the confining unit into the alluvial aquifer allowing ample opportunity for flow to the aquifer.

Water also enters or leaves the alluvial aquifer as flux from or to underlying aquifers. Predevelopment head data for underlying aquifers are rare. The subcrop area of the aquifers of the Mississippi Embayment aquifer system represented the discharge area for much of the predevelopment regional flow originating in the surrounding highlands to the east (Weiss, 1983). Therefore, at most locations the predevelopment heads in underlying aquifers were probably greater than the heads in the alluvial aquifer. An analysis of available head data and comparisons with simulated heads in underlying aquifers from other subregional models shows that gradients are upward for slightly more than half the project area. Again, data are insufficient to quantify the flux between the alluvial aquifer and underlying aquifers.

The general relation of the Mississippi River Valley alluvial aquifer to the Mississippi River Valley confining unit and underlying units is illustrated by figure 12. The general direction of steady-state regional predevelopment flow in a cross-section simulation (Weiss, 1983) is illustrated by the direction of arrows. The alluvial aquifer is shown as the area of discharge for regional flow originating in the outcrop of underlying units. The relative position and presumed dominant vertical flow directions also are illustrated for the alluvial aquifer in the enlarged section.

Along the lateral edges of the aquifer where the alluvial aquifer is bounded by other hydrogeologic units some water may be exchanged by horizontal flow to or from the aquifer. For much of the lateral boundary the adjacent hydrogeologic units have a much lower horizontal hydraulic conductivity. Some are regarded as confining units where they subcrop the alluvial aquifer and some are regarded as aquifers in the subcrop. For most of the western boundary of the aquifer north of the Arkansas River, rocks of Paleozoic age are adjacent to the alluvial aquifer. The hydraulic conductivity of these rocks is probably of distinctly lower permeability than the alluvial aquifer. In nearly all cases the head in laterally adjacent and topographically higher hydrogeologic units is probably higher than that in the alluvial aquifer resulting in flux to the aquifer.

Within the last 15 years, studies using digital and analog models (Broom and Reed, 1973; Reed and Broom, 1979; Broom and Lyford, 1981; and Sumner and Wasson, 1984) indicate that leakage from rivers is a larger component of the alluvial aquifer budget than is direct recharge from precipitation. However, field verification of the major source of recharge is not possible at this



EXPLANATION

11A	MISSISSIPPI RIVER VALLEY CONFINING UNIT
11	MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER
14	MIDDLE CLAIBORNE CONFINING UNIT
5	MIDDLE CLAIBORNE AQUIFER
4	LOWER CLAIBORNE / UPPER WILCOX AQUIFER
3	MIDDLE WILCOX AQUIFER
2	LOWER WILCOX AQUIFER
12	MIDWAY CONFINING UNIT

Figure 12.--Configuration of and predevelopment flow in regional aquifers at the latitude of Memphis. Numbers refer to hydrostratigraphic units. See also figure 8 and correlation table. Modified from Weiss (1983).

time. Rivers are probably both sources of recharge and places of discharge at different times of the year and at different locations along their reaches.

Rivers are a focus for discharge from the alluvial aquifer. The Mississippi River and its major tributaries (the Arkansas, Boeuf, Ouachita, St. Francis, White, Yazoo Rivers and Bayou Macon) show gains in discharge as they traverse the alluvial aquifer. Mean daily discharge excluding flow originating upstream from the alluvial aquifer is shown in table 2 for August through October for rivers draining the alluvial plain.

The data in table 2 are included to show the approximate magnitude of discharge during a period of lower direct runoff. Ground-water contributions probably are a large proportion of river discharge at this time of the year. The proportion of this discharge representing regional steady-state ground-water discharge is not known. Some of the ground-water discharge represents part of the annual cycle of gains and losses from ground-water storage in local flow systems.

The seasonal change in stages of rivers (fig. 13) illustrates the timing and magnitude of potential changes in flux to or from the alluvial aquifer. The normal range in fluctuation of Mississippi River stage is quite large in comparison to the fluctuation of stage for other rivers. As a result, the changes of head in the alluvial aquifer and flux to or from the aquifer are larger than the changes resulting from stage changes of smaller rivers. The efficiency of the transfer of large fluxes between the aquifer and the Mississippi River also is greatly increased by its greater width and by the depth to which the river penetrates the aquifer (fig. 9). The seasonal changes in flux to and from the aquifer often change in magnitude and direction during the year, but result in no long-term net change of storage in the aquifer or change in flux to or from the aquifer under predevelopment or steady-state conditions.

The Mississippi River shows a large gain in discharge across the alluvial plain during the late summer (table 2). Sumner and Wasson (1984, p. 10, figs. 7 and 8) illustrated the profile of water levels in the alluvial aquifer adjacent to the Mississippi River in Mississippi. The profiles showed that at low river stages steep gradients from the aquifer to the river exist and that a short distance away from the river gradients in the aquifer were away from the river. At high river stages flow was to the aquifer from the river. Ryling (1960, p. 26) and Plebuch (1961, p. 37) noted a similar condition for northeastern Arkansas. Much of the water leaving the Mississippi River at high stages returns to the river from bank storage.

Discharge to wells is the only water budget item for the alluvial aquifer that has been measured. Measurements of well discharge, crop application rates, and consumption estimates have been synthesized and published as water-use figures for each of the States. The total pumpage from the alluvial aquifer in the Mississippi Embayment aquifer system area for 1980 is about 8,100 ft^3/s (5,200 million gallons per day) (Sun, 1986, p. 157).

Table 2.--Gain in discharge of rivers crossing the Mississippi Alluvial Plain

[Gain in discharge is the flow at stations nearest the mouth of the river (or boundary of the study area) minus any flow originating upstream from the Mississippi Alluvial Plain. Period of record 1964-1978 calendar years]

Drainage basin	Rivers used for computation	Gain in discharge August-October (cubic feet per second)	
		Mean	Standard deviation
Mississippi River mainstem	Mississippi River Yazoo River Arkansas River White River St. Francis River L'Anguille River Big Creek	30,000	20,000
Arkansas River	Arkansas River	500	1,000
White River	White River Big Creek Little Red River Black River Current River	6,000	2,000
St. Francis River	St. Francis River L'Anguille River	4,000	1,000
Yazoo River	Yazoo River Coldwater River Little Tallahatchie River Yocona River Yalobusha River Sunflower River	5,000	2,000
Boeuf-Tensas River	Bayou Macon Boeuf River Ouachita River Saline River	3,000	3,000
Total for study area		50,000	30,000

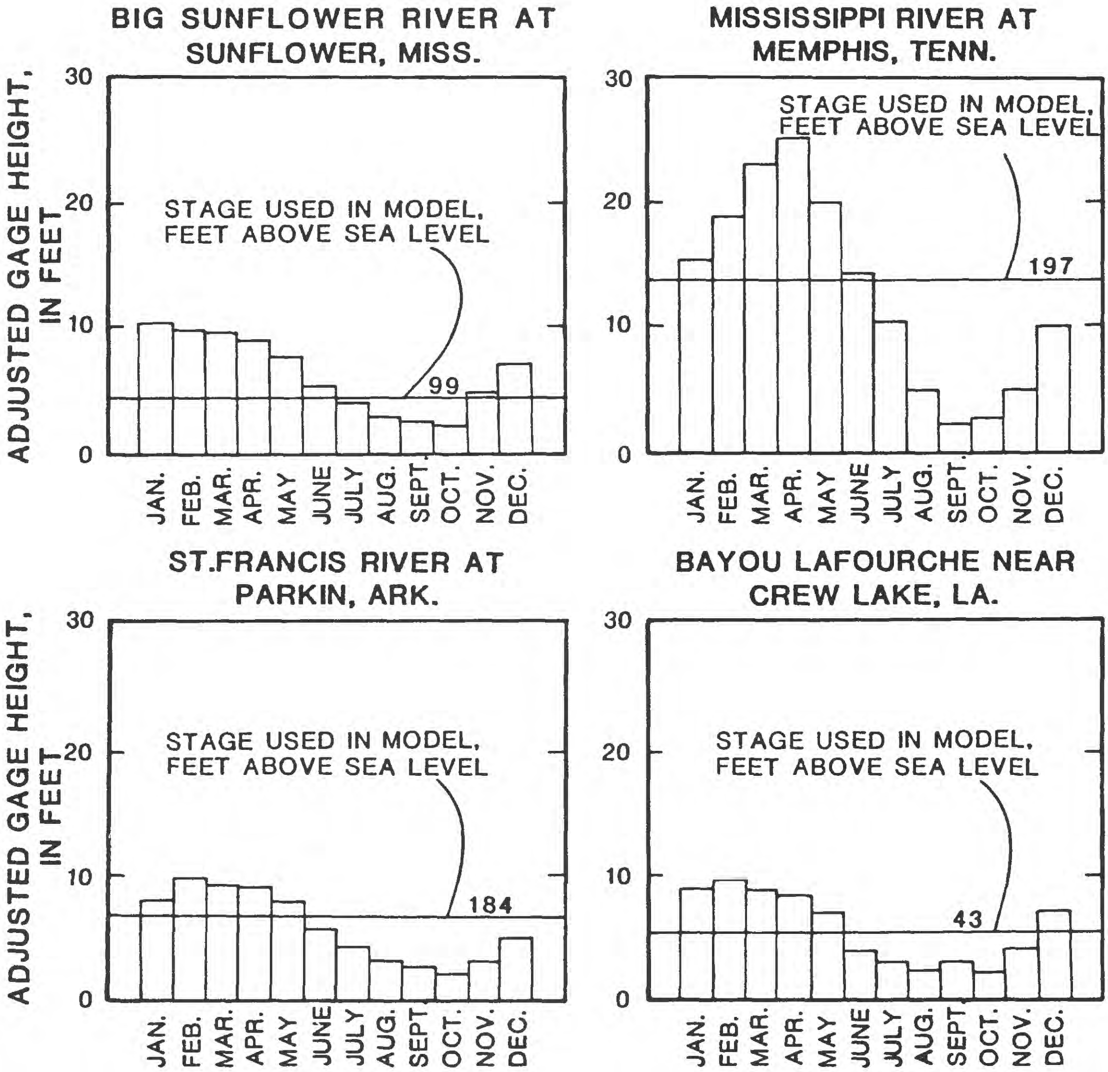


Figure 13.--Seasonal fluctuations in stage for selected rivers. Normal monthly mean gage height for period of record is shown. Gage height datum has been adjusted and is not station datum. Location of station can be found on figure 19.

Predevelopment Conditions

The predevelopment potentiometric surface is approximated by the average of water levels that might have existed in wells prior to large-scale withdrawals for irrigation and after current wetlands drainage. Activities such as wetlands drainage and changes in land use have had significant regional effects on the potentiometric surface of the Mississippi River Valley alluvial aquifer, but these effects can not be estimated nor are they likely to be reversed. The earliest records of irrigation withdrawals from the alluvial aquifer are for the Grand Prairie of Arkansas. Significant pumpage started about 1910 in Arkansas County, Arkansas. Water-level declines were documented in 1929 (Engler and others, 1945). Only one predevelopment potentiometric map has been presented for any large area of the alluvial aquifer. That map (Broom and Lyford, 1981, plate 10) was the result of a model simulation and describes the source of some data used in judging the map's accuracy. Broom and Lyford (1981) state that most wells unaffected by pumpage have water levels less than 20 ft below land surface. Engler and others (1945) give several water levels for wells in and near the edge of the Grand Prairie that may represent predevelopment conditions. These maps and data show the potentiometric surface following the land surface and sloping toward major rivers. If this observation generally is true then the flow generally was south and toward major rivers near the axes of the St. Francis, White, Arkansas, Yazoo,and Boeuf-Tensas basins.

Present-Day (1985) Conditions

The potentiometric surface of the Mississippi River Valley alluvial aquifer has been lowered significantly in some areas by pumpage, about 7,600 ft^3/s (1,600 million gallons per day) in 1985, for predominantly agricultural uses. In the Grand Prairie region of Arkansas a trough in the potentiometric surface stretches from southern Arkansas County to central Lonoke County. Comparison of 1985 water levels (Plafcan and Fugitt, 1987) and predevelopment water levels (Engler and others, 1945, p. 29) shows a maximum lowering of the predevelopment potentiometric surface of about 80 ft in Lonoke County, Arkansas. The minimum saturated thickness currently is about 20 ft (Plafcan and Fugitt, 1987) near the center of the Grand Prairie potentiometric trough. West of Crowleys Ridge, in Poinsett and Cross Counties, Arkansas, water levels have declined about 50 ft (Plafcan and Fugitt, 1987; Broom and Lyford, 1981, Plate 10). According to a model simulation, water levels may have declined more than 20 ft in the alluvial aquifer for a small area in the central part of northwestern Mississippi (Sumner and Wasson, 1984, p. 63, fig. 41). With the exception of drawdown cones in the immediate vicinity of municipal water-supply wells and wells for industrial centers most other declines probably are less than 20 ft.

Long-term hydrographs of several wells are shown for various locations in the study area on figure 14. The Arkansas County, Arkansas, well shows a long-term decline until the mid 1950's followed by steady water levels. The Lonoke and Poinsett County, Arkansas, wells show long-term declines especially in the late 1970's and early 1980's. Other wells show only seasonal fluctuations.

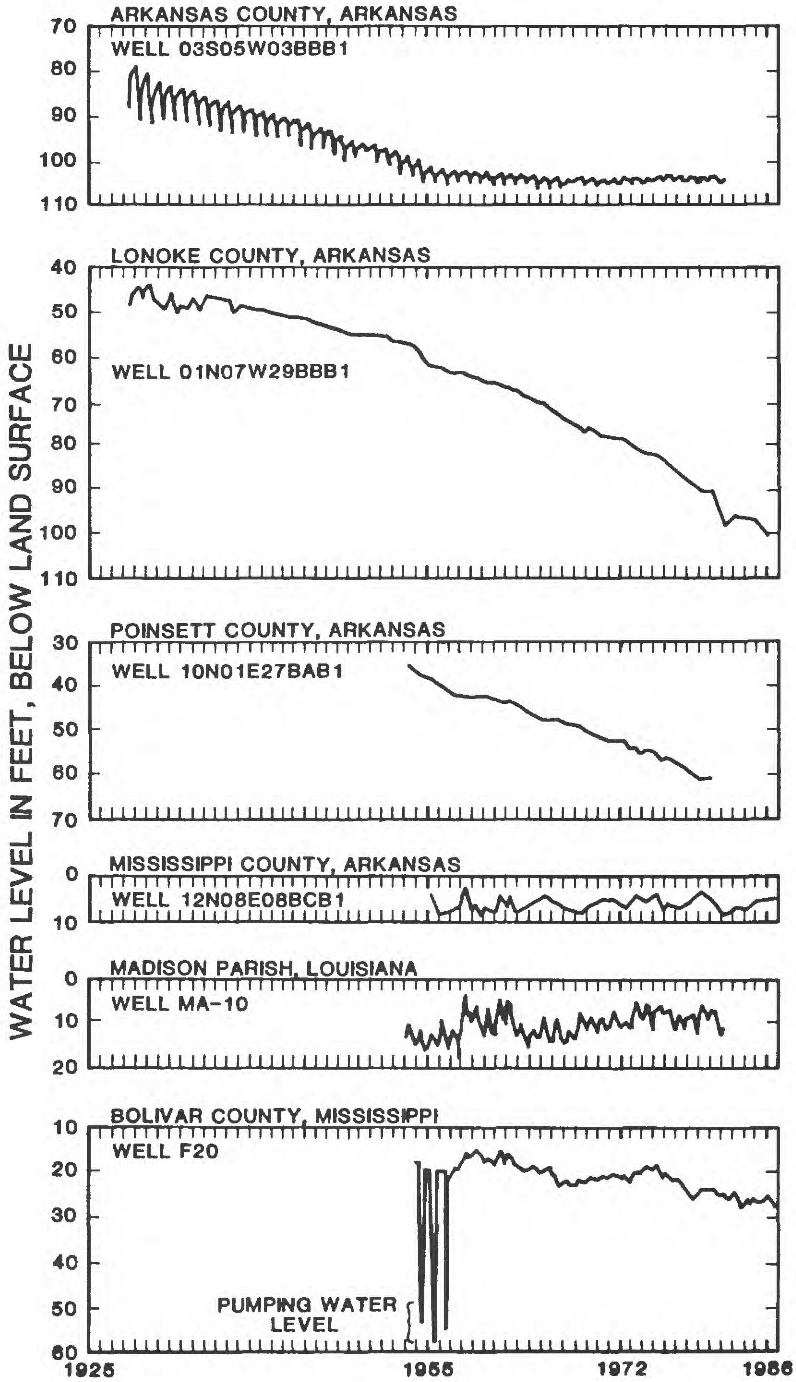


Figure 14.--Hydrographs of selected wells in the Mississippi River Valley alluvial aquifer.

The history of water-level declines is directly related to the stress on the alluvial aquifer from pumpage, mostly for the irrigation of rice. Therefore, the history of pumpage from the aquifer can be visualized by observing the trends in rice acreage. Broom and Lyford (1981, fig. 2) and Sumner and Wasson (1984, p. 18) show how closely pumpage follows rice acreage. Figure 15 shows the history and relative magnitude of rice acreage for various counties and States in the study area. Most counties show similar trends in rice acreage since about 1950, especially the large increases and fluctuations of rice acreage since 1974 when rice acreage limitations were removed. In Arkansas County, Arkansas, rice acreage has been relatively steady since 1920 changing slightly after 1974.

CONCEPTUAL MODEL OF REGIONAL GROUND-WATER FLOW

The concepts of the hydrogeologic framework and ground-water flow used to construct a digital model to analyze steady-state regional ground-water flow are illustrated in figures 16 and 17. The framework of the Mississippi River Valley alluvial aquifer system was derived from available data according to concepts mentioned in previous sections. The framework also reflects the discretization of the digital model, sources of data, and methods of synthesis as is discussed in the next section. The hydrogeologic sections represent interpretations developed by this project whereas the geologic sections (figs. 4-7) and figure 9 represent separate interpretations found in the literature. Since the locations (figs. 18 and 19) of the hydrogeologic sections (figs. 16 and 17) are approximately the same as the geologic sections (figs. 4 and 7), conceptualization and discretization may be directly compared. The general direction of flow based on available head data and model input is indicated by arrows, but since the vertical scale is greatly exaggerated, vertical components of flow are also exaggerated. The relative magnitude of flux is not indicated.

In general, water flows into the Mississippi River Valley alluvial aquifer from the Mississippi River Valley confining unit, underlying aquifers, or rivers and out of the alluvial aquifer to wells or rivers. Components of flow through the plane of the cross sections are not shown but generally are out of the plane (a southerly direction).

For the purposes of preliminary analysis the regional flow was assumed to be at steady-state conditions in 1972. Most of the alluvial aquifer probably was at steady-state conditions due to a long period of uniform stress (fig. 15). In some areas, such as the northwestern end of the Grand Prairie in Lonoke County, water levels do not indicate steady-state conditions (fig. 14). However, the rate of change in water levels was lower (-0.5 ft/yr) than for the previous and the subsequent 15-year periods (-1.1 and -1.7 ft/yr, respectively). The 1972 potentiometric data were chosen as the best combination of the following criteria: (1) at the end of a long period of uniform stress, (2) close to a time when pumpage data were compiled (1970), and (3) at a time for which adequate potentiometric data were compiled.

The conceptual model of regional predevelopment flow as applied to steady-state flow analysis of the Mississippi River Valley alluvial aquifer can be summarized in the following statements and working assumptions concerning the mass balance, flow equations, and boundary conditions of the alluvial aquifer.

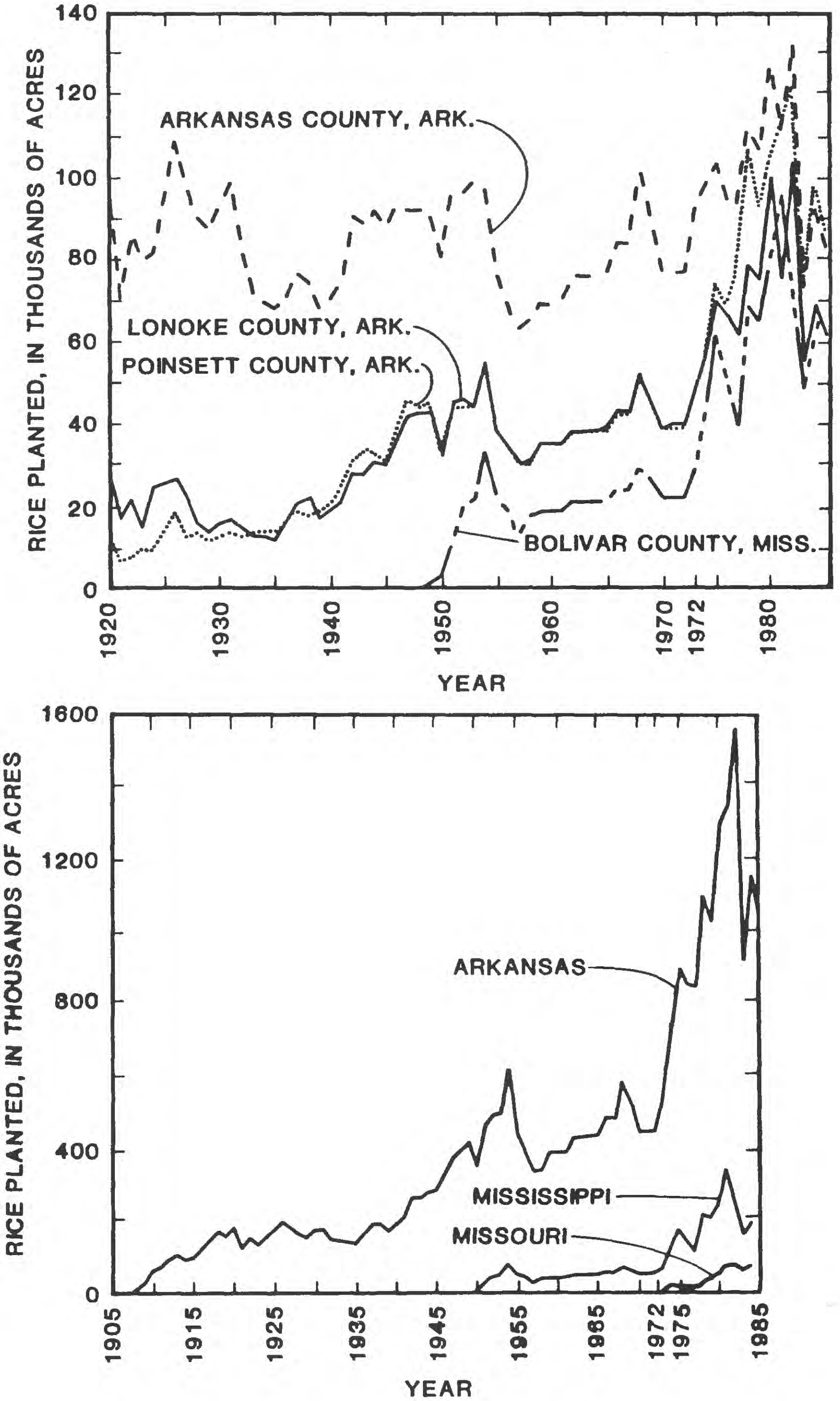


Figure 15.--Acreage of rice planted for selected counties and States in the study area.

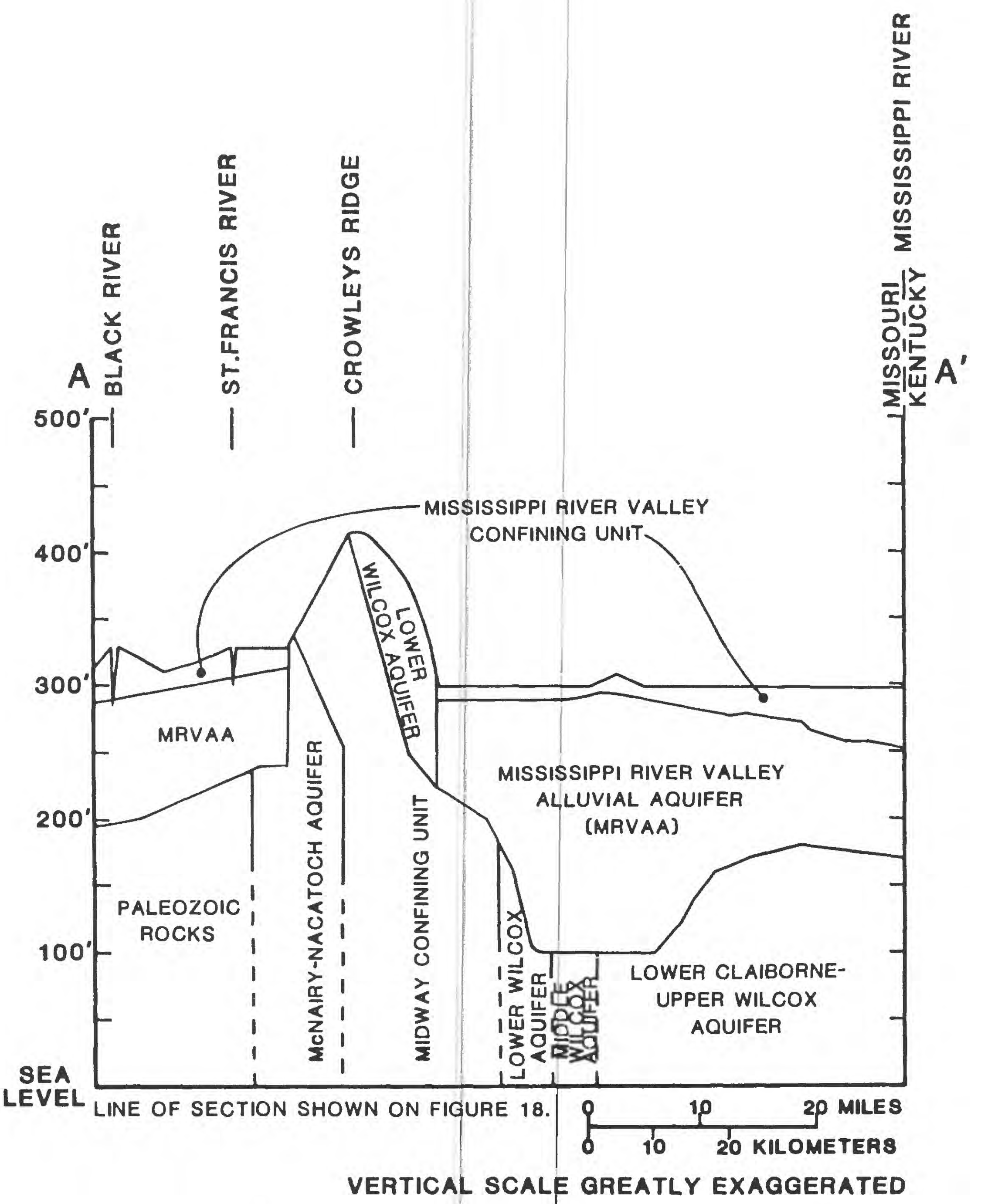


Figure 16.--Generalized hydrogeologic section along A - A'.

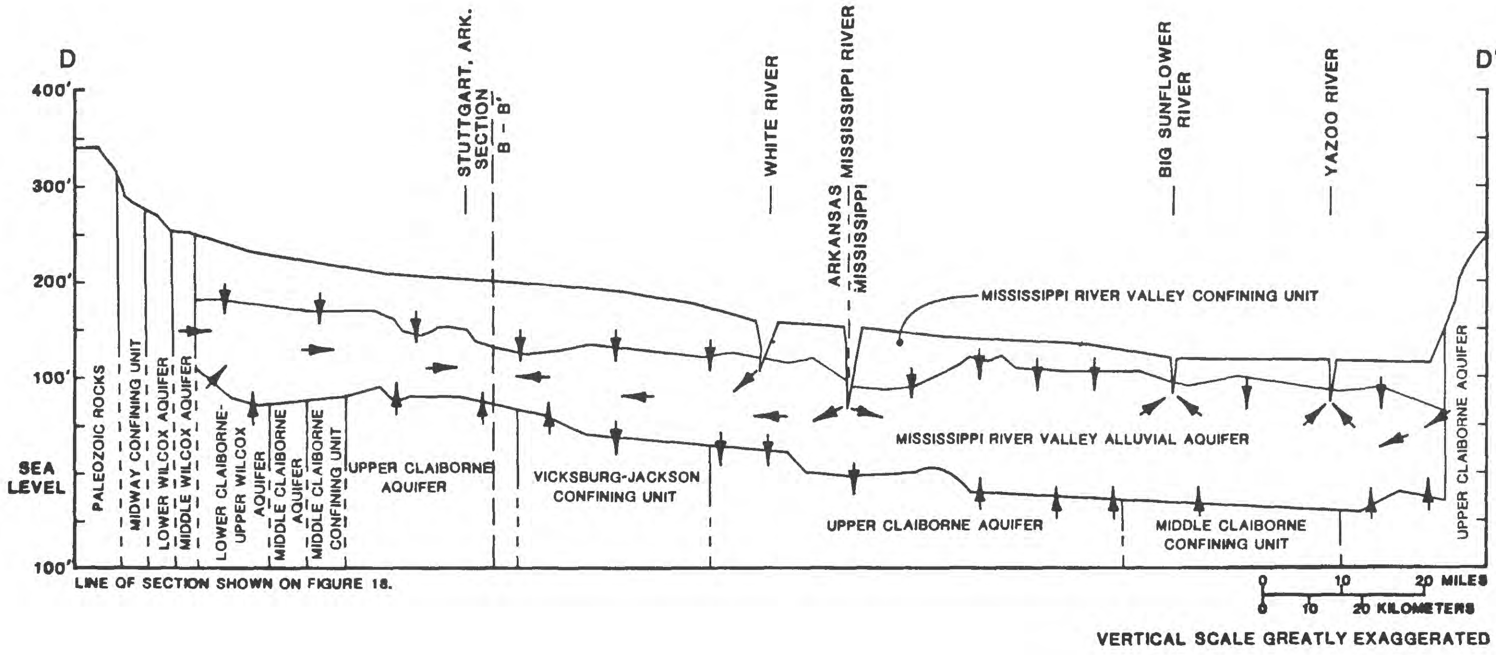
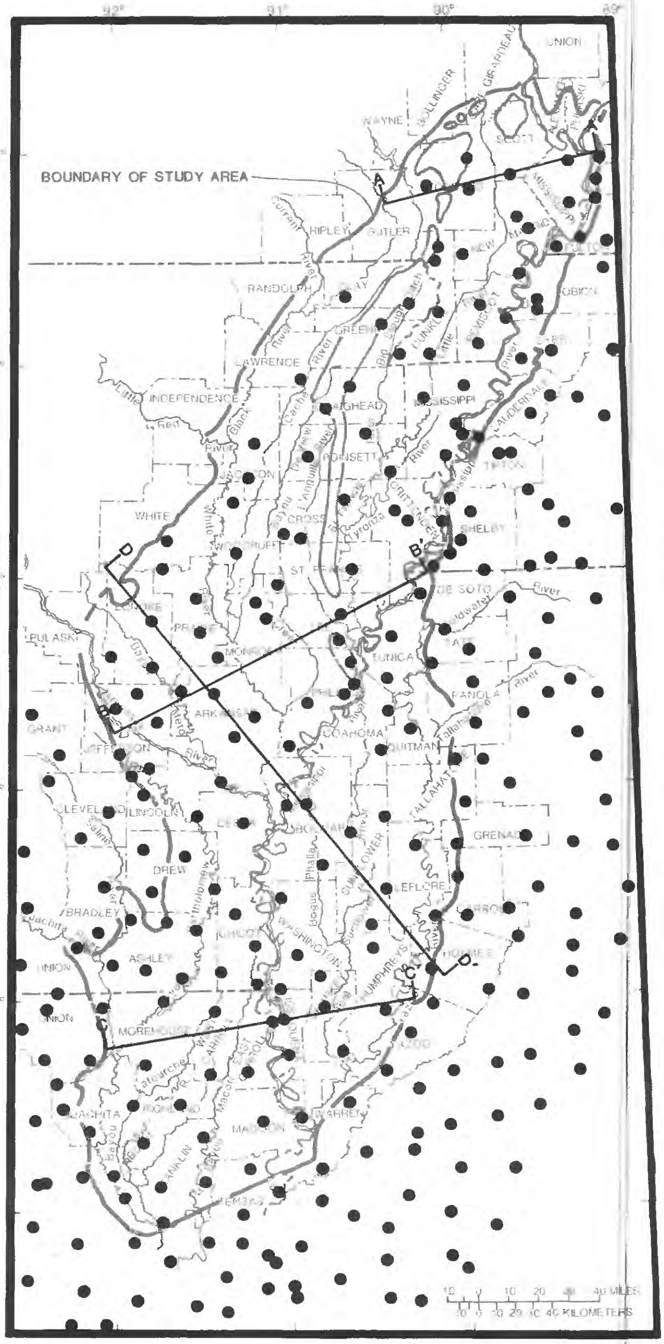


Figure 17.--Generalized hydrogeologic section along D - D' showing 1972 flow.



EXPLANATION

A——A' LINE OF GEOLOGIC OR HYDROGEOLOGIC SECTION

● LOCATION OF WELL WITH GEOPHYSICAL LOGS

Figure 18.--Locations of geophysical logs used in hydrogeologic data base and locations of geologic and hydrogeologic cross sections.

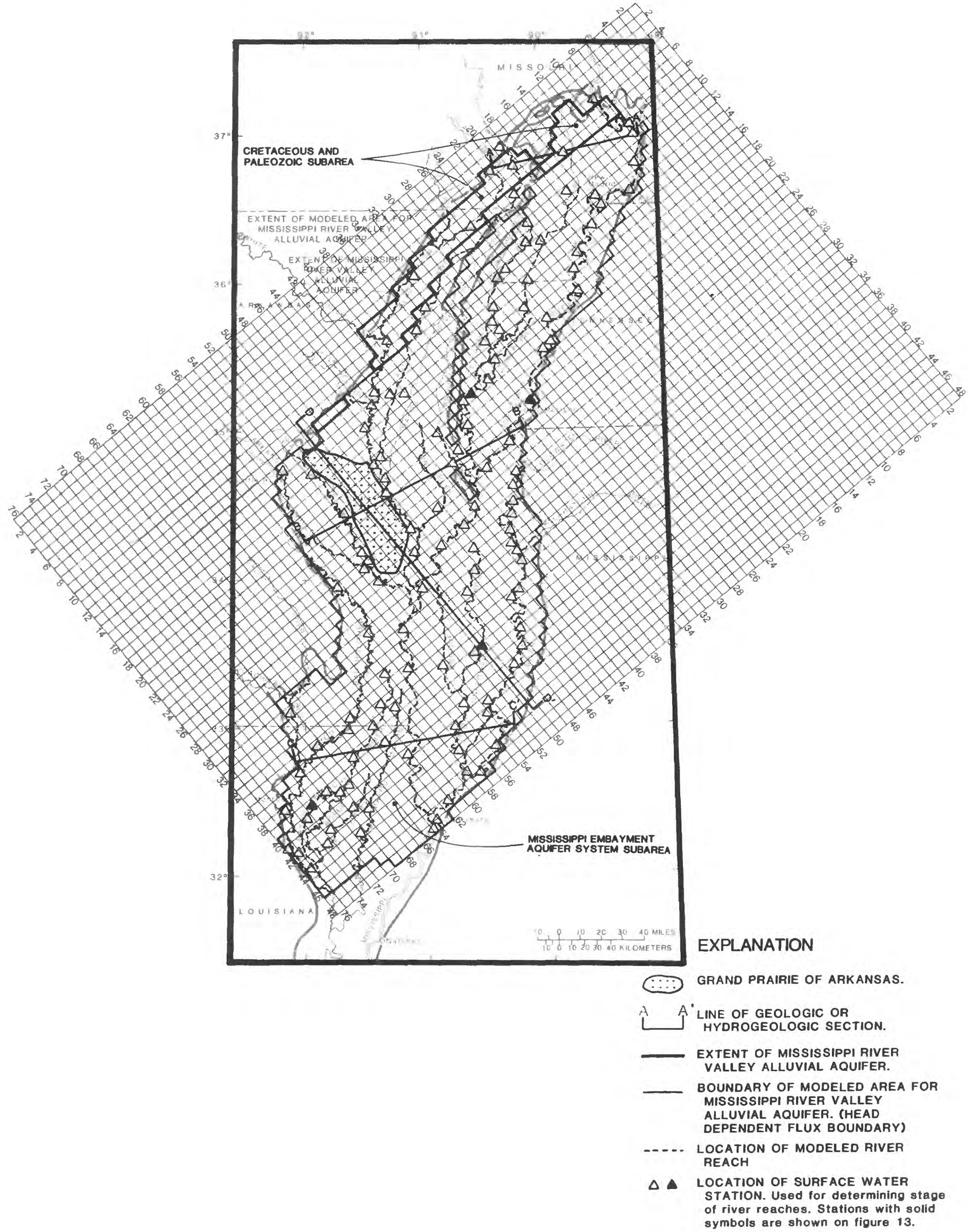


Figure 19.--Finite difference grid and types of boundary nodes.

1. Recharge to the aquifer occurs by leakage from the Mississippi River Valley confining unit, rivers, or adjacent aquifers, and from direct infiltration of precipitation where the confining unit is absent.
2. Discharge from the aquifer occurs by leakage to rivers, the confining unit, adjacent aquifers, wells, or to evapotranspiration.
3. Transmissivity varies areally in proportion to saturated thickness.
4. Predevelopment conditions are considered as steady state.
5. Confining units have vertical permeabilities much smaller than aquifers.
6. Flow to and from the aquifer is head dependent.

PRELIMINARY DIGITAL MODEL

A three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1984) was chosen for simulating the predevelopment and 1972 flow system. The finite-difference grid used for this model (fig. 19) consists of the first 76 rows and first 48 columns of the regional project grid. To simulate the areal extent of the Mississippi River Valley alluvial aquifer (layer 2) 1,256 blocks 5 mi on a side (out of 3,648 total blocks) were used; the remainder of the grid was inactive. The areal extent of the Mississippi River Valley confining unit (layer 1) and the underlying confining units (layer 3) were simulated for all alluvial aquifer (layer 2) blocks. A common areal discretization shared by all GC RASA project models was used to simplify comparisons of fluxes between the various models and to allow the efficient reduction of common input data from the variety of data sources.

The model simulates steady flow in the alluvial aquifer for two periods: (1) the time before significant development of the aquifer and (2) 1972. Steady-state flow equations chosen for the mathematical model represent either confined or unconfined flow in the alluvial aquifer. The Strongly Implicit Procedure was used to solve the flow equations. (See McDonald and Harbaugh, 1984, p. 370.)

The choice of steady-state conditions for predevelopment and for 1972 simplifies the construction of the model for simulation by eliminating consideration of storage terms and initial conditions in the equations of flow. It is assumed that the resultant potentiometric surface simulated by the model will represent the average distribution of head in the aquifer resulting from the average of boundary values. Stress resulting from withdrawal by wells is simulated for 1972 only.

Boundary Conditions

For the purpose of preliminary simulation of steady-state flow in the Mississippi River Valley alluvial aquifer, two boundary conditions were modeled: (1) head-dependent flux, and (2) constant flux.

Five separate head-dependent boundary conditions of the conceptual model were represented in the model (fig. 20). All surfaces of the aquifer were modeled as head-dependent flux boundaries. Leakage from the Mississippi River Valley confining unit, infiltration of rainfall, and leakage from underlying aquifers was simulated as leakage from sources in layers 1 and 3. Leakage from rivers and evapotranspiration was simulated as head-dependent flux using the

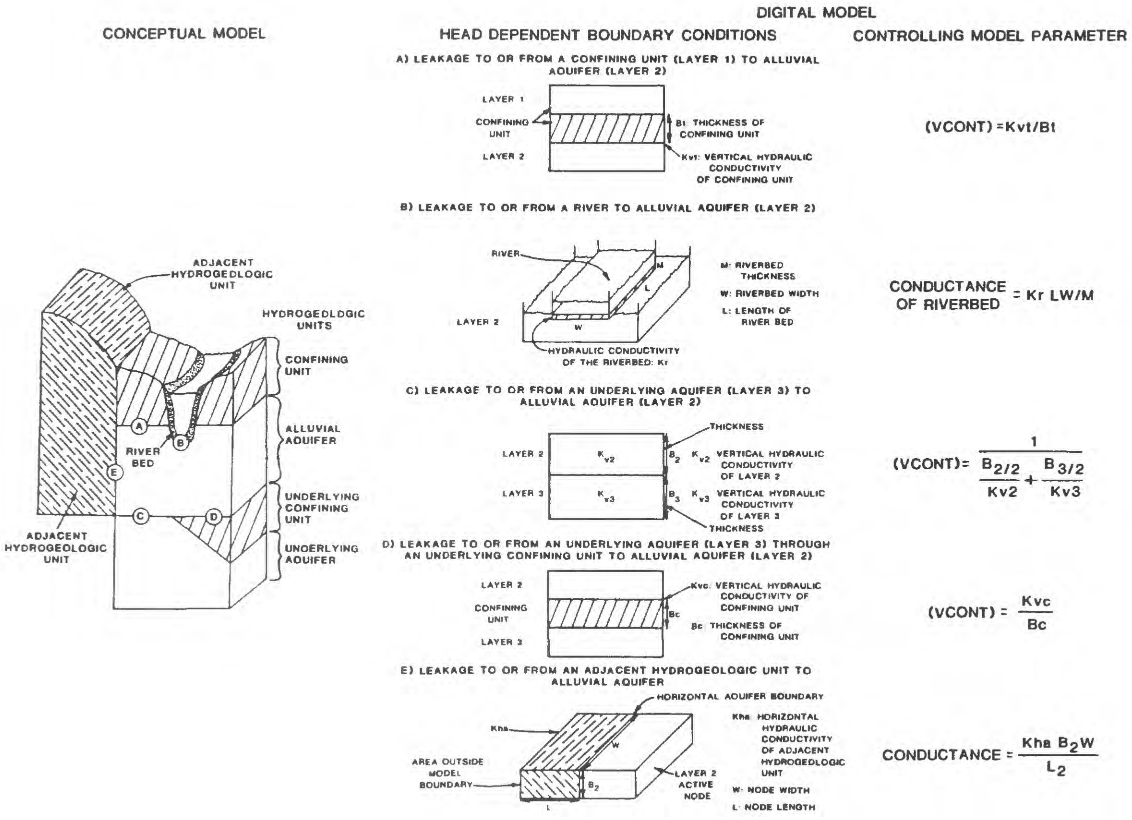


Figure 20.--Conceptual and digital model of head-dependent boundaries.

river package of the model. Leakage from adjacent hydrogeologic units was simulated using the general head boundary package of the model.

For the purpose of preliminary modeling of steady-state flow a head-dependent flux boundary was simulated for the entire lateral boundary of the alluvial aquifer using the general head boundary package of the model. The short section of the lateral boundary of the model on the south (representing the continuation of the alluvial aquifer outside the modeled area) was also modeled as head dependent flux. Most of the remainder of the lateral boundary represents the transition from the highly permeable alluvial aquifer to the lower permeability units that border the aquifer (fig. 11). Along parts of the lateral boundary, the Mississippi River, the White River and its tributaries, the Yazoo River and its tributaries, and the Ouachita River and its tributaries are within a few model blocks of the lateral boundary. The proximity of the river boundary to the lateral boundary may compensate for errors in the lateral boundary assumptions and data, particularly for the unstressed predevelopment conditions. Constant flux boundary conditions for 1972 (pumpage from wells) were simulated using the well package of the model.

Model Input Data

For the boundary conditions and the flow equations used the following input was required by the model:

1. the size and shape of the region of flow;
    a. bottom of the alluvial aquifer,
    b. top of the alluvial aquifer,
2. head values at the following boundaries;
    a. head in underlying aquifers,
    b. head in confining unit,
    c. stage in rivers,
    d. head in nodes outside the lateral model boundary,
3. the spatial distribution of hydrogeologic parameters that control the flow;
    a. hydraulic conductivity of the alluvial aquifer,
    b. thickness and vertical hydraulic conductivity of the confining unit,
    c. thickness and vertical hydraulic conductivity of underlying aquifers and confining units,
    d. length, width, thickness, and hydraulic conductivity of riverbed reaches,
    e. horizontal hydraulic conductivity of hydrogeologic units laterally adjacent to the alluvial aquifer,
4. the average 1972 pumping rate for wells in each node.

Data Manipulation and Presentation

This discussion will briefly describe (1) how scattered observations and maps were reduced to model input, (2) how model input and output were presented in a set of maps consistent with the discretization (scale) and assumptions of the model, and (3) how output values of node centers were compared to scattered locations of observed data. Data input to the model are often described as values located at the center of a model block representing the whole block. Model output (head and flux) also generally is represented at the center of a model block. The input and output data for the model were prepared and presented using the Surface II[1] graphic system of the Kansas Geological Survey (Sampson, 1975).

The preparation of input data and the first step in preparing a map to illustrate the data or model output was to create a rectangular grid matrix corresponding to nodes at the center of model blocks. The various grid matrices were assembled by one of the following methods:

1. Values at node centers were found by overlaying the locations of model nodes on maps. Examples are the land surface in northwestern Mississippi and soil permeability indices.
2. Values were averaged from many regularly distributed points located within model blocks. An example is the altitude of the land surface outside of the model boundaries in Arkansas and Mississippi.
3. Values were estimated at node centers by nearest-neighbor analysis (local-fit methods) of irregularly spaced data points scattered across the study area (Sampson, 1975, p. 8). Examples are the land surface in Arkansas and thickness of the Mississippi River Valley confining unit.
4. Values were determined by simple arithmetic manipulation of other grid matrices. Examples are the calculation of the top and bottom of the alluvial aquifer from the altitude of the land surface and the thickness of the confining unit or alluvial materials.
5. Values representing model output were used directly or converted to appropriate units. Examples are simulated head and flux across boundaries.

Figure 10 and most map illustrations on the following pages were prepared from the respective grid matrices using the following method (Sampson, 1975, p. 5): (1) linear interpolation between grid nodes was used to locate points of equal value where contour lines or other lines of equal value intersected the edge of a grid cell, (2) the string of successive map coordinates of these intersections defined the contour line or line of equal value that was drawn. The resulting illustrations were modified to conform to hydrologic relations represented but were not modified to describe hydrologic features occurring at a scale smaller than could be represented by the original data or by the scale of the discretization. When maps showing data in this report are compared with illustrations from other reports, most of which are at a larger scale, the data from this report will appear "smooth." That is to say extremes, both high and low, are attenuated due to the large (5-mi) grid spacing used in this study. To visualize the interpretation at this scale, imagine hand contouring a set of data points located at the centers of 25 mi^2 nodes on figure 19 representing the alluvial aquifer. The hydrogeologic cross sections (figs. 16 and 17) and the diagrams illustrating the simulation (figs. 26 and 32) were prepared directly from the map illustrations or data matrices or both.

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[1]The use of the trade name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Model output values of head at node centers were not compared directly with the scattered observations of head at control points. For the purposes of calibration and sensitivity analysis deviations from observed head were back calculated at control point locations by double linear interpolation from the grid nodes that enclose the locations being evaluated (Sampson, 1975, p. 81).

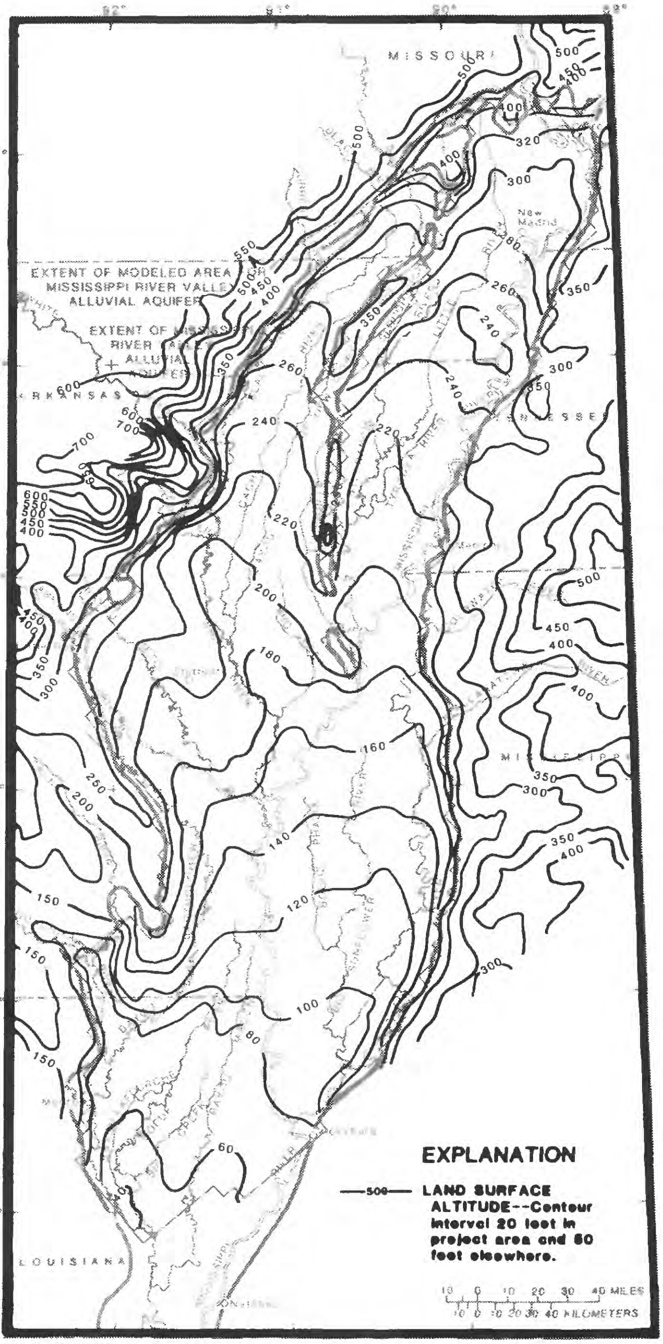
Sources of Input Data

The thickness of alluvial deposits (representing the confining unit plus the alluvial aquifer) was obtained from a project data base describing the hydrogeologic units in the project area (R.L. Hosman and J.S. Weiss, U.S. Geological Survey, written commun., 1985). These data were derived from geophysical locations on logs (fig. 18) with a spacing of approximately one well per 320 mi^2.

The thickness of the Mississippi River Valley confining unit (fig. 10) was calculated from a combined data set from two data sources: (1) from approximately 3,100 control points for the whole project area (Krinitzsky and Wire, 1964, vol. II) and (2) from approximately 6,600 logs found on well completion reports on file with the Arkansas Waterwell Construction Committee. For each of the 6,600 logs a value of land-surface altitude was picked from topographic maps with 5-foot contour intervals. These values plus more than 5,000 observations of land-surface altitude found in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) ground-water file were used to calculate land-surface altitude (fig. 21) for the area underlain by the alluvial aquifer in Arkansas. Land-surface data from northwestern Mississippi were taken from the model data set used by Sumner and Wasson (1984). Elsewhere the altitude of land surface for each 25 mi^2 block was calculated by averaging approximately 90 values per block from data based on digitized 1:250,000 scale topographic maps (Godson, 1981).

The depth of the bottom of the aquifer was given for about 5,100 of the 6,600 water-well completion reports and was used to calculate the altitude of the bottom of the aquifer in Arkansas. In northwestern Mississippi the data from Sumner and Wasson's (1984) model were used. Elsewhere the altitude of the bottom of the aquifer (fig. 22) was calculated by subtracting alluvium thickness from altitude of land surface. The altitude of the top of the alluvial aquifer (fig. 23) was calculated by subtracting the thickness of the confining unit from the land-surface altitude.

The head for underlying aquifers was obtained from the most recent steady-state simulation of the Mississippi Embayment subregional model (J.K. Arthur, U.S. Geological Survey, written commun., 1986) and of the Paleozoic and Cretaceous subregional model (J.V. Brahana, U.S. Geological Survey, written commun., 1986). The altitude of land surface was used to estimate the head in the confining unit. For the simulation of river stage the mean annual stage at gaging stations locations (fig. 19) for 1978 (the latest year for which complete data exist) was used where available. Examples of the stage used for selected rivers is shown on figure 13. Linear interpolation and 7.5 minute topographic maps were used to extend the stage data between or upstream from gaging stations.



MAP BASED IN PART
ON DIGITAL TERRAIN
DATA BY (GODSON, 1981)

Figure 21.--Topography in and near the study area.

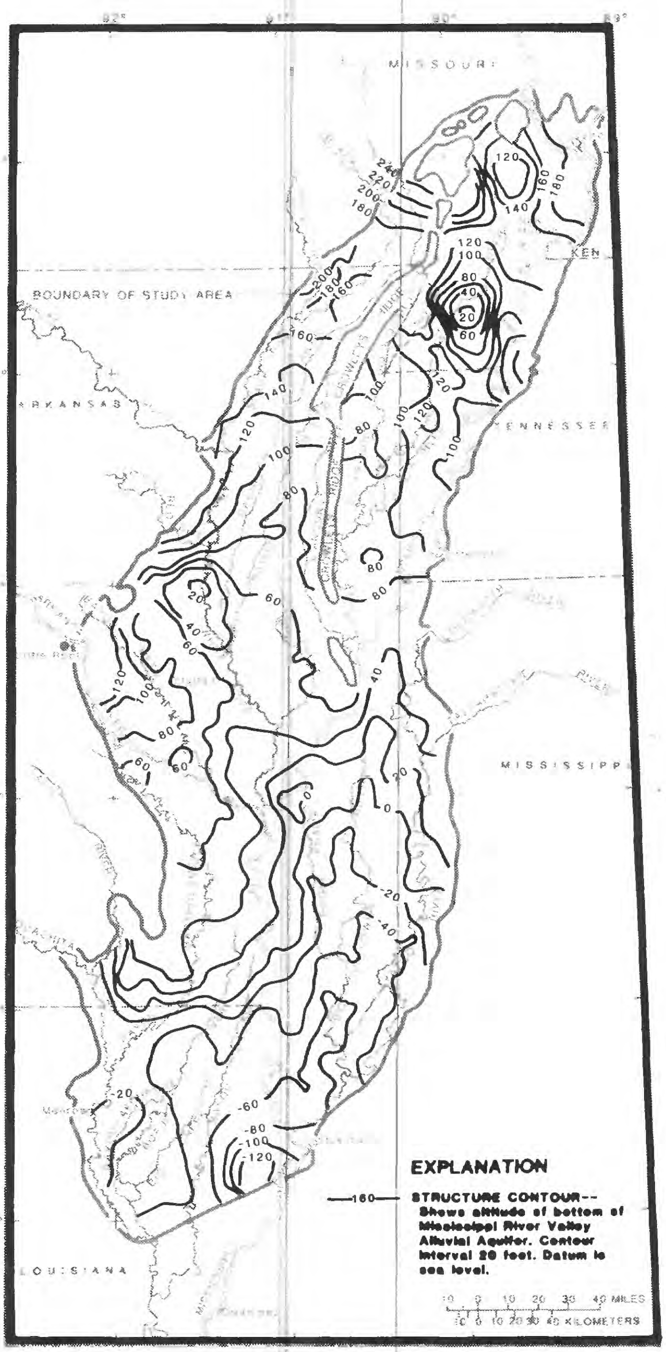


Figure 22.--Altitude of the bottom of the Mississippi River Valley alluvial aquifer.

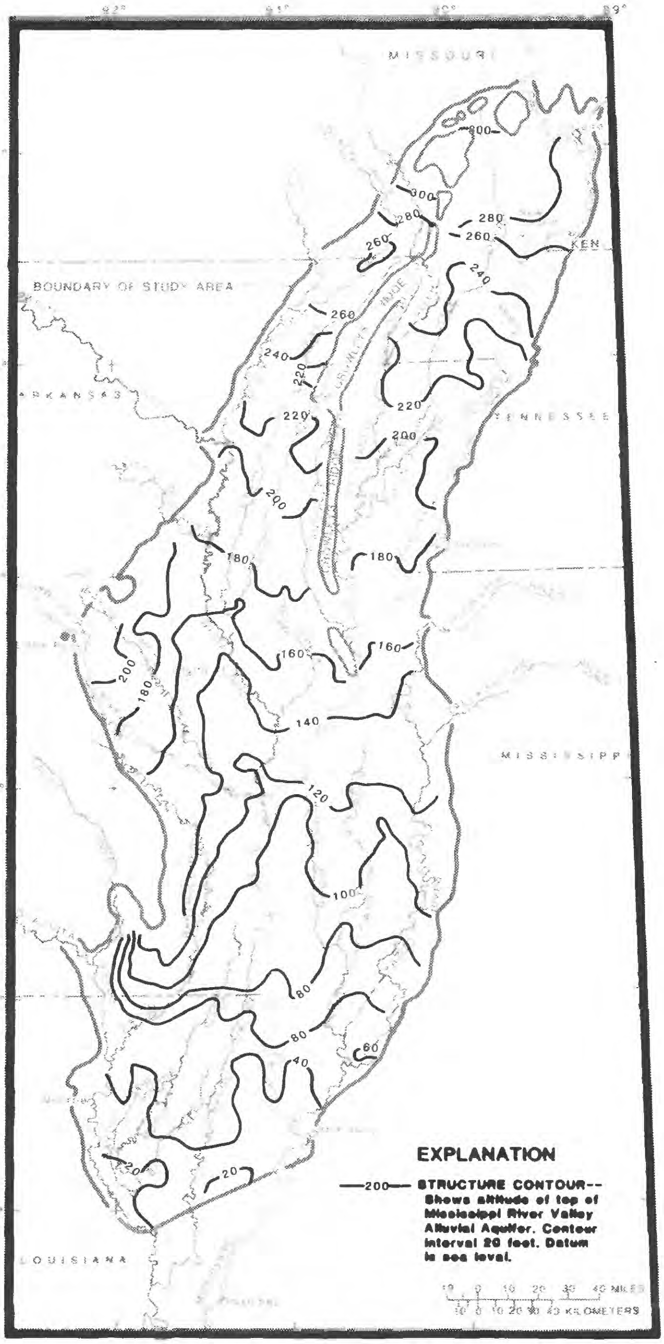


Figure 23.--Altitude of the top of the Mississippi River Valley alluvial aquifer.

Head in hydrologic unit adjacent to the horizontal limit of the model was derived from a linear relation between water-table elevation and land-surface altitude (A.K. Williamson, U.S. Geological Survey, written commun., 1986).

The hydraulic conductivity of the alluvial aquifer was assumed to be uniform. Although grain size is known to decrease to the south there was no readily discernible pattern to the hydraulic conductivity data shown on figure 8. Transmissivity was calculated in the model by multiplying saturated thickness times hydraulic conductivity.

The pumpage for the 1972 simulation (fig. 24) was based on 1970 ground-water pumpage data from the States and counties and on a distribution of county pumpage to individual nodes for 1980 (D.J. Ackerman and A.K. Williamson, U.S. Geological Survey, written commun., 1985). The municipal and industrial use was allocated to the node in which it occurred. Agricultural use (mainly irrigation and fish farming) was distributed to nodes according to the percentage of the node in the county and underlain by the aquifer. In some instances where the agricultural use is known to be unevenly distributed within the county certain nodes were weighted more heavily than others. The 1980 distribution of pumpage should suffice since most differences in water-use patterns probably occurred between counties rather than within counties.

The leakage from constant-head nodes in layer 1 (representing an imaginary layer containing the head in the confining unit and illustrated in fig. 20) was controlled by the internal model parameter "Vcont" (McDonald and Harbaugh, 1984, p. 138). Vcont for leakage from layer 1 was calculated by dividing the vertical hydraulic conductivity of the confining unit by the confining unit thickness. The relative magnitude of vertical hydraulic conductivity of the confining unit was distributed according to taxonomic classifications of soils shown on general soil maps of the States provided by USDA, SCS. The vertical hydraulic conductivities of soil materials were grouped into high and low areas (fig. 25) with higher areas assumed to be twice as permeable as the lower (Larry Ward, USDA, SCS, written commun., 1985). Maximum flux from layer 1 to layer 2 is constrained by the choice of the flow equations for layer 2 (confined and unconfined) and by the method of simulating layer 1 leakage to a value dependent upon the vertical hydraulic conductivity of the confining unit.

Vcont for leakage from constant-head nodes in layer 3 (illustrated in fig. 20) was taken from the values used by the Mississippi Embayment aquifer system and the Cretaceous and Paleozoic subregional models (J.K. Arthur and J.V. Brahana, U.S. Geological Survey, written commun., 1986). The value of Vcont ranged from 2×10^{-4} to 5×10^{-4} day^{-1} for aquifers underlying the alluvial aquifer. The value of Vcont ranged from 1×10^{-7} to 1×10^{-4} day^{-1} for confining beds underlying the alluvial aquifer. These values of Vcont include thickness of confining units from the geophysical log data base (locations on fig. 18).

The leakage from head-dependent boundaries representing units adjacent to the model area is controlled by the model parameter hydraulic conductance (McDonald and Harbaugh, 1984, p. 344). The hydraulic conductance of the material outside the model area is represented on figure 20 and can be reduced to a single unknown variable, the product of hydraulic conductivity and the interface thickness along the model boundary, all other terms being constant for this grid size. Hydraulic conductivities of laterally adjacent hydrologic

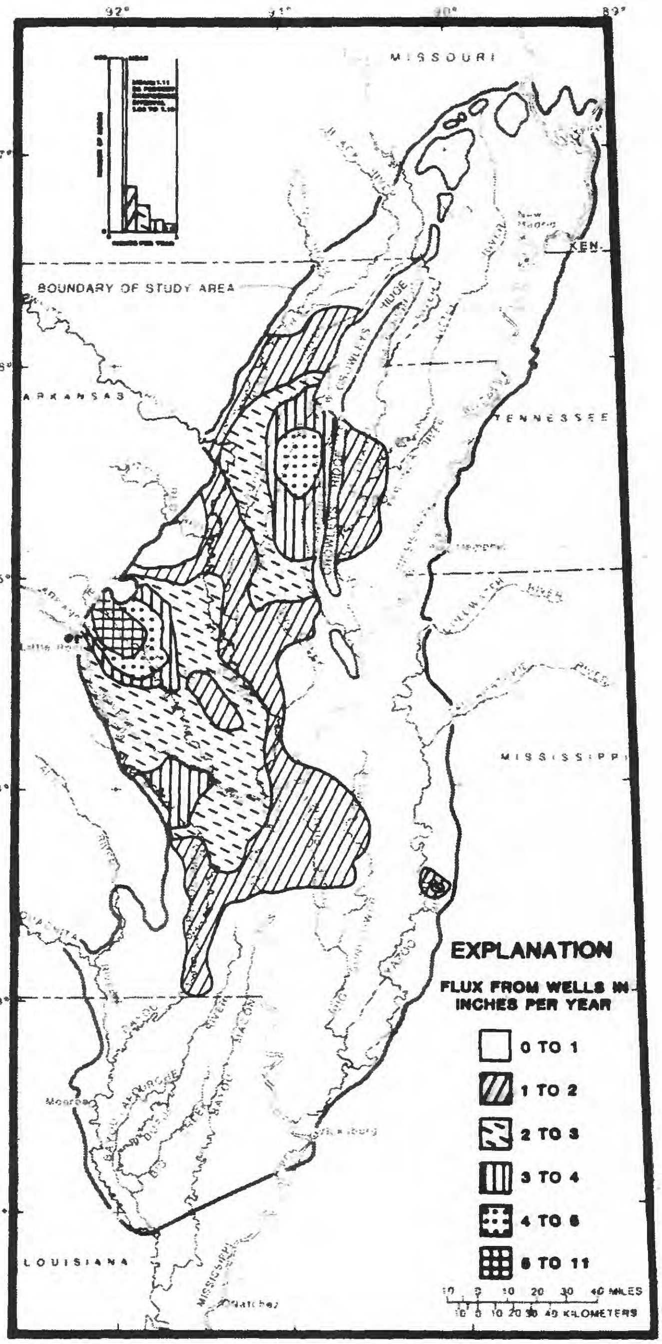


Figure 24.--Distribution of discharge from wells in the Mississippi River Valley alluvial aquifer for 1970.

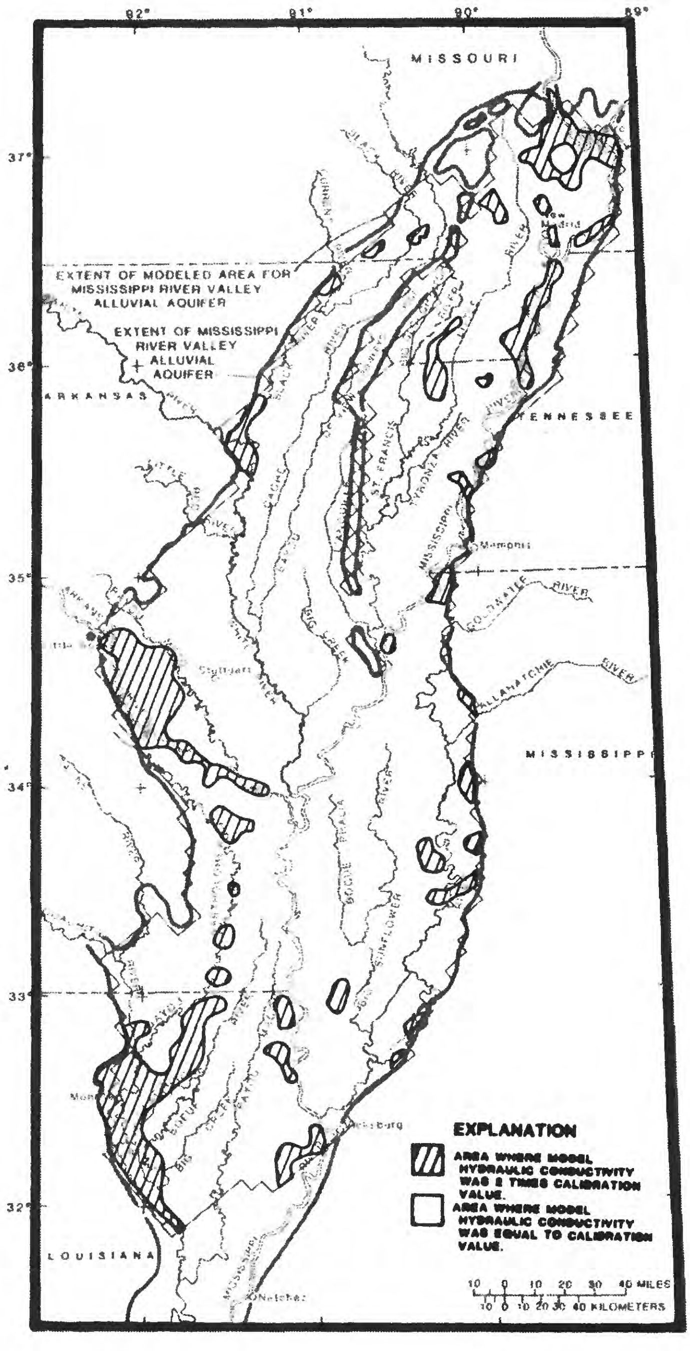


Figure 25.--Areal distribution of vertical hydraulic conductivity of the Mississippi River Valley confining unit.

units were assumed to be in a ratio of 300:10:0.001, respectively, for the alluvial aquifer, adjacent aquifers, and adjacent confining units or Paleozoic rocks.

The hydrogeologic parameter controlling leakage to the aquifer from head-dependent boundaries representing river reaches is represented by the model parameter hydraulic conductance (McDonald and Harbaugh, 1984, p. 214). The hydraulic conductance of a reach of a riverbed is represented on figure 20 and can be reduced to a single unknown variable, the ratio of hydraulic conductivity to thickness for riverbed materials. Lengths of individual river reaches were measured from a map with the model grid superimposed. These lengths are unique to this model discretization. Widths of river reaches (table 3) were derived from measurement notes for discharge measurements at gaging stations or from 7.5 minute topographic maps.

The diagram in figure 26 shows the model simulation along row 50 (geologic and hydrogeologic section D-D', figs. 7 and 17). All boundary conditions are present along row 50.

Calibration

Preliminary model calibration was accomplished by adjusting the hydrogeologic parameters within plausible (observed) bounds until a best fit of observed head was found for the 1972 simulation. Additionally, some boundary conditions and input data were varied as the study progressed and as additional data became available. After satisfactory performance for the current set of input data was obtained, several hydrogeologic parameters were varied systematically within the plausible bounds to document model sensitivity. During the course of this study input data and boundary conditions will continue to be changed as differences between subregional models are resolved. In addition, calibration will also include transient modeling in the next phase of this work.

It is acknowledged that most hydrogeologic parameters vary spatially within the aquifer system. Data available for estimating some of these parameters indicate a variability but the data are not adequate to describe the variation as a discernible pattern for all variables. The approach used for this report was to calibrate using values of hydrogeologic parameters within the estimated uncertainty for the parameter and by using only the available information on areal variation.

Procedure

Model performance was evaluated both objectively and subjectively. A root-mean-square error (RMSE) analysis of the distribution of head was used for objective analysis. The RMSE was calculated for observed and simulated water levels by

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (h_i^o - h_i^s)^2}{n}}$$

Table 3.--Values of river width used in simulation of rivers

Basin and river	Reach	Width (feet)
Mississippi River mainstem and Ohio River		
Mississippi River	Cape Girardeau, Mo. to Caruthersville, Mo.	3,050
Mississippi River	Caruthersville, Mo. to Memphis, Tenn.	3,200
Mississippi River	Memphis, Tenn. to Mellwood, Ark.	2,550
Mississippi River	Mellwood, Ark. to Vicksburg, Miss.	2,250
Ohio River	Cairo, Ill. to mouth	2,000
Arkansas River Basin		
Arkansas River	Little Rock, Ark. to mouth	1,200
Bayou Meto	To mouth	90
Yazoo River Basin		
Coldwater River	Prichard, Miss. to mouth	150
Tallahatchie River	Lambert, Miss. to mouth	200
Yazoo River	Greenwood, Miss. to mouth of the Sunflower River	300
Yazoo River	Mouth of Sunflower River to mouth	900
Yazoo Cutoff	Silver City, Miss. to mouth of Sunflower River	300
Sunflower River	Clarksdale, Miss. to Sunflower, Miss.	200
Sunflower River	Sunflower, Miss. to Callao Landing, Miss.	300
Sunflower River	Callao Landing, Miss. to mouth	400
Bogue Phalia	West of Cleveland, Miss. to mouth	200
St. Francis River Basin		
St. Francis River	Fisk, Mo. to Tulot, Ark.	170
St. Francis River	Tulot, Ark. to mouth	250
Big Slough Ditch	To mouth	100
Little River	Morehouse, Mo. to Lilbourn, Mo.	100
Little River	Lilbourn, Mo. to south of Lilbourn, Mo.	150
Little River	South of Lilbourn, Mo. to Hornersville, Mo.	200
Little River	Hornersville, Mo. to mouth	300
Tyronza River	To mouth	100
St. Francis Floodway	To mouth	100
L'Anguille River	Palestine, Ark. to mouth	100
White River Basin		
White River	Batesville, Ark. to mouth	500
Black River	Poplar Bluff, Mo. to east of Pocohantas, Ark.	100
Black River	East of Pocohantas, Ark. to mouth	200
Current River	Arkansas-Missouri State line to mouth	100
Little Red River	Searcy, Ark. to mouth	100
Cache River	Knob, Ark. to Patterson, Ark.	50
Cache River	Patterson, Ark. to mouth	100
Bayou Deview	Morton, Ark. to mouth	200
Big Creek	Popular Grove, Ark. to mouth	80
Ouachita-Tensas Basin		
Bayou Macon	Chicot, Ark. to Oak Grove, La.	100
Bayou Macon	Oak Grove, La. to above Epps, La.	150
Bayou Macon	Epps, La. to mouth	300
Boeuf River	Lake Village, Ark. to Eudora, Ark.	100
Boeuf River	Eudora, Ark. to Oak Ridge, La.	200
Boeuf River	Oak Ridge, La. to Fort Necessity, La.	300
Bayou Lafourche	Oak Ridge, La. to Fort Necessity, La.	300
Big Creek	Holly Ridge, La. to mouth	250
Ouachita River	U.S. Highway 82 to Sterlington, La.	400
Ouachita River	Sterlington, La. to Columbia, La.	550
Saline River	Southeast of Warren, Ark. to mouth	210
Bayou Bartholomew	Star City, Ark. to mouth	150

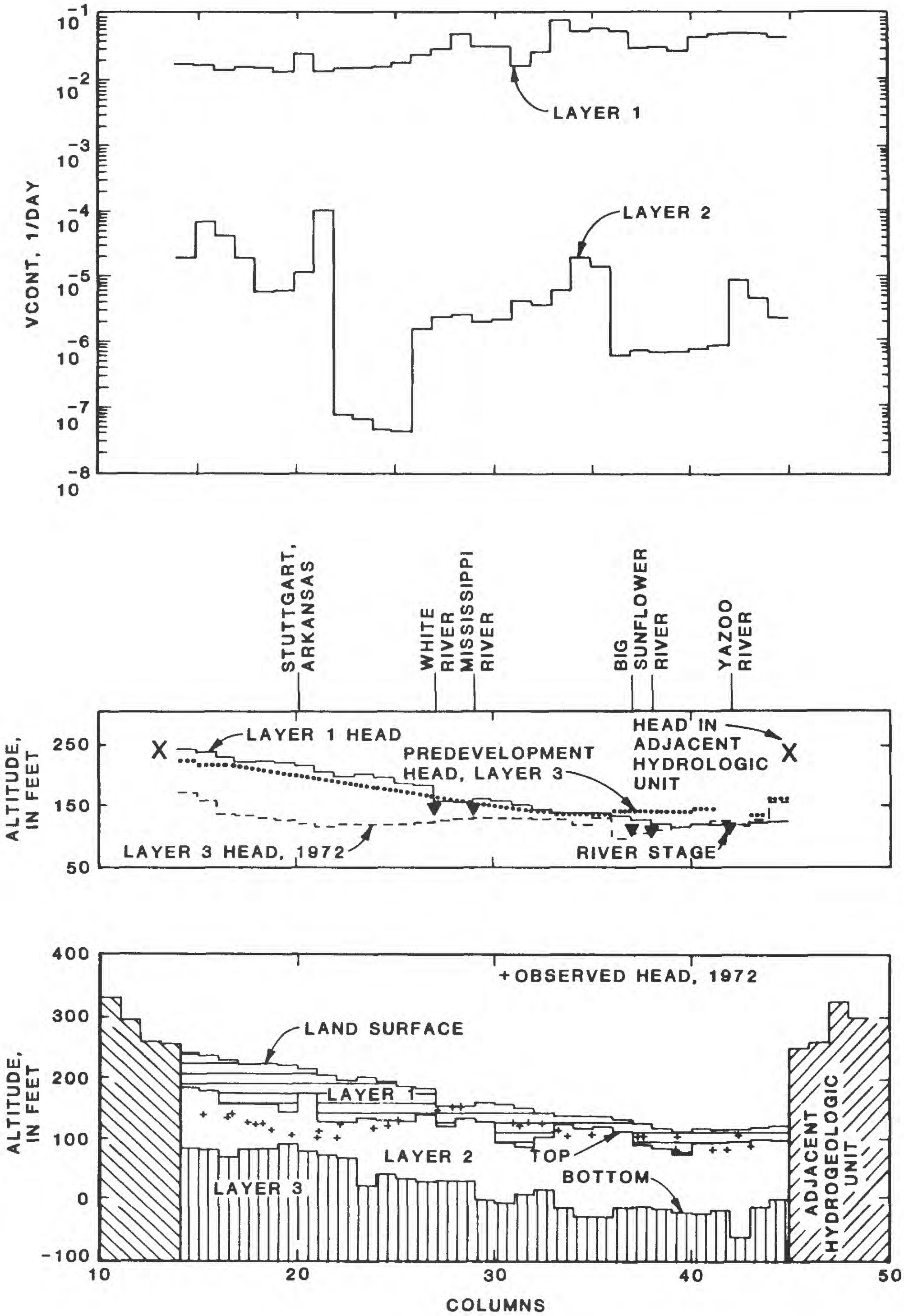


Figure 26.--Digital model simulation along row 50. Observed potentiometric data are for layer 2 and were used for calibration. Most observed heads were within 2.5 miles of center of row 50.

where n is the number of observations,

h_i^o is the observed water level, in feet, and

h_i^s is the simulated water level, in feet (adjusted to the observed location.

Inspection of the distribution of errors of head, flux distribution, and flux quantity were used to subjectively analyze model performance.

The head data (fig. 27) were assembled from records of measurement of water levels in wells that were found in the WATSTORE ground-water file (A.K. Williamson, U.S. Geological Survey, written commun., 1987). The values are the averages of all heads between July 1971 and June 1973.

Although flux distribution within a particular source (rivers, underlying aquifers, or from the confining unit) was evaluated during calibration, this subjective criterion was mainly used to spot discretization errors or gross input errors. The quantity of flux from rivers was used only as a qualitative check on the plausibility of results.

Results

The results of the preliminary calibration reported here can be described in terms of the head distribution, flux distribution, and choices for hydrogeologic parameters. The distribution of difference between observed and simulated head is illustrated by figure 28. The budget for the simulation is given in table 4. Choices for hydrogeologic parameters are as follows:

1. hydraulic conductivity of the Mississippi River Valley alluvial aquifer, 300 ft/d,
2. vertical hydraulic conductivity of the Mississippi River Valley confining unit, 0.0003 ft/d,
3. ratio of vertical hydraulic conductivity to bed thickness for riverbed materials, 0.05 day^{-1}, and
4. vertical hydraulic conductivity of underlying units three times that used by the Mississippi Embayment and Cretaceous and Paleozoic subregional models.

The value chosen to represent the hydraulic conductivity of the alluvial aquifer is nearly the same as that chosen by Broom and Lyford (1981), and by Peralta and others (1985), (270 ft/d) and by Griffis (1972), (267 ft/d). This value is somewhat less than that used by Sumner and Wasson (1984), (400 ft/d), especially considering the lognormal nature of the distribution. The vertical hydraulic conductivity of layer 1 is within the range given previously for these materials. The ratio of vertical hydraulic conductivity to thickness for confining units between layers 2 and 3 is also reasonable for representative thickness and hydraulic conductivity values assuming a vertical to horizontal anisotropy of 1:100 or 1:1000 for both layers. The ratio of hydraulic conductivity to riverbed thickness is less than one order of magnitude greater than the value of 0.008 day^{-1} reported by Sumner and Wasson (1984, p. 46).

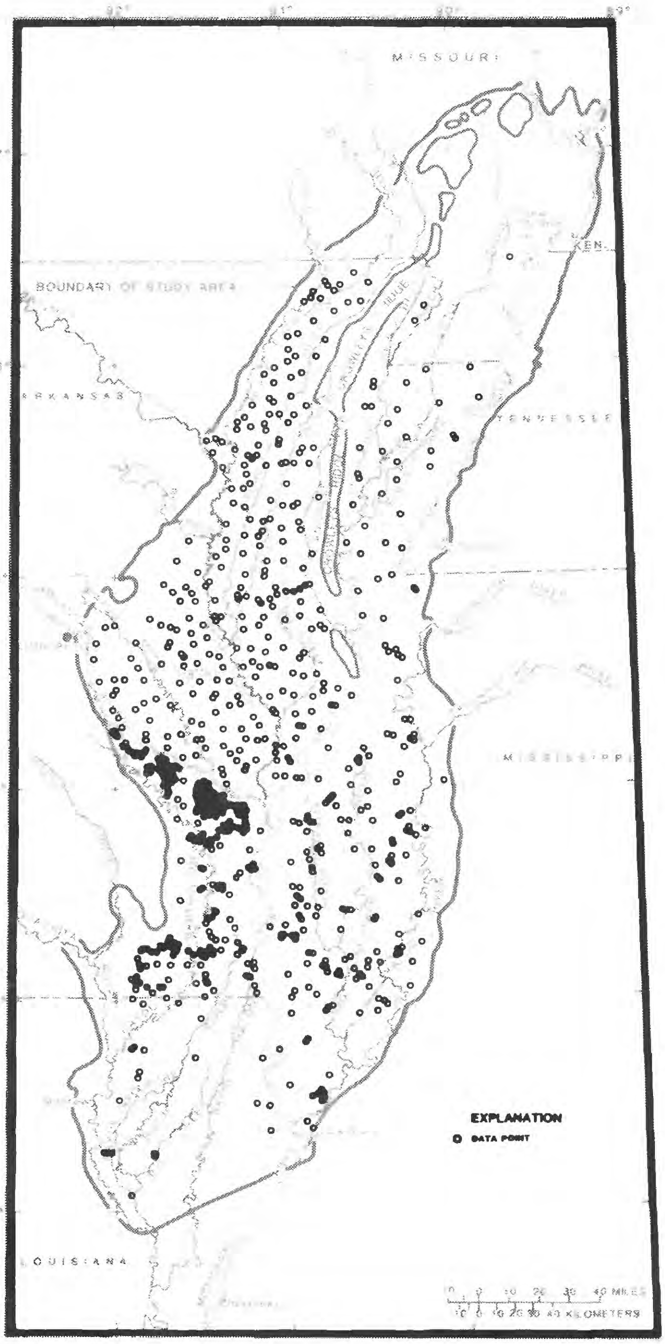


Figure 27.--Distribution of observed hydraulic head data used in calibration of steady-state model.

Table 4.--Hydrologic budgets for preliminary simulation of steady-state regional flow in the Mississippi River Valley alluvial aquifer

[Flow in cubic feet per second; CP = Cretaceous and Paleozoic subarea; MEB = Mississippi embayment subarea; Sums may show slight variations due to rounding]

Source of flow to or from the alluvial aquifer		Predevelopment In	Predevelopment Out	Predevelopment Net	1972 In	1972 Out	1972 Net	Change from predevelopment to 1972 Net
Layer 1								
	CP	97	-51	+46	119	-50	+69	+23
	MEB	1,264	-132	+1,132	1,871	-90	+1,781	+649
	Subtotal	1,361	-183	+1,178	1,990	-140	+1,850	+672
Rivers								
	CP	23	-790	-768	32	-824	-792	-24
	MEB	58	-2,556	-2,499	739	-1,049	-310	+2,189
	Subtotal	81	-3,346	-3,266	771	-1,873	-1,102	+2,165
Adjacent units								
	CP	1	0	+1	1	0	+1	0
	MEB	26	-2	+24	29	-1	+28	+4
	Subtotal	27	-2	+25	30	-1	29	+4
Wells								
	CP	0	0	0	0	-169	-169	-169
	MEB	0	0	0	0	-2,312	-2,312	-2,312
	Subtotal	0	0	0	0	-2,481	-2,481	-2,481
Layer 3								
	CP	776	-11	+766	937	-9	+928	+162
	MEB	1,380	-82	+1,299	1,096	-320	+776	-523
	Subtotal	2,156	-93	+2,065	2,033	-329	+1,704	-361
Total		3,625	-3,625	0	4,824	-4,824	0	

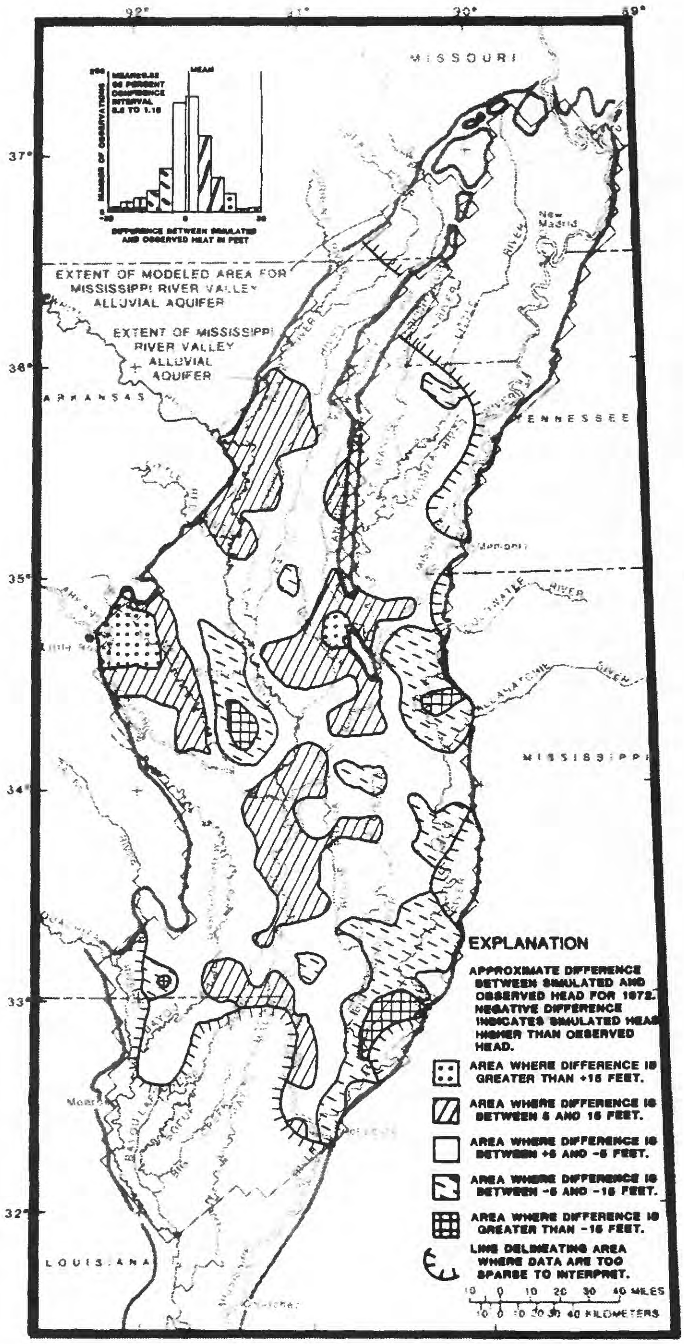


Figure 28.--Distribution of difference between observed and simulated 1972 hydraulic head for the Mississippi River Valley alluvial aquifer.

The performance of the model for this calibration can be judged by testing the magnitude and distribution of difference in head between observed and simulated head. Simulated heads for layer 2 were within 10 ft of the observed 1972 head for 76 percent of all (812) observations. The mean difference was 0.8 ft (simulated heads lower than observed heads) with a 95 percent confidence interval of 0.2 to 1.5 ft. The root-mean-squared error was 9.4 ft.

Two areas with consistently high positive or negative differences between observed and simulated head can be seen on figure 28. These areas roughly correspond to the location of the Grand Prairie as shown on figures 19 and 2. Toward the southeastern end of the Grand Prairie, southeast of Stuttgart, simulated heads were greater than observed heads. This is probably due to errors in the distribution of pumpage from the alluvial aquifer in the county. Recent refinement of the location of irrigation pumpage from an underlying aquifer and a study of land-use maps (D.J. Fitzpatrick, U.S. Geological Survey, oral commun., 1986) indicate that additional pumpage from the alluvial aquifer should be modeled. At the northwestern end of the Grand Prairie, east of Little Rock, simulated heads were lower than observed heads. As this is an area of increasing pumpage (fig. 15), and declining water levels (fig. 14), the steady-state assumption is probably invalid and may bias results. The heads from the model simulation would represent the result of sustained pumpage at 1970 rates.

Simulated regional ground-water discharge from the alluvial aquifer to rivers (table 5) generally was more than one order of magnitude less than the estimated discharge gain of corresponding rivers (table 2) for one part of the year. The model did not compute discharge to rivers for either simulation that was larger than the discharges given in table 2. Due to the local flow or bank storage component of flux and due to the large uncertainty in measuring discharge gain and losses on these large complex river systems, it is doubtful that regional flow modeling of the alluvial aquifer can use a model river budget as an independent check on model accuracy other than to show that fluxes are reasonable to an approximation. The discharge to rivers simulated by the model (table 5) represents only regional ground-water discharge. A large portion of ground-water discharge to rivers may be part of local flow in the alluvial aquifer that can not be simulated with the large (5 mi x 5 mi) grid of this model.

Table 5.--Simulated regional aquifer flow to and from rivers for steady-state conditions

[Flux in cubic feet per second; Sums may show slight variations due to rounding]

Drainage basin	Predevelopment simulation			1972 simulation		
	To aquifer (+)	From aquifer (-)	Net	To aquifer (+)	From aquifer (-)	Net
Mississippi River	+24	-546	-522	+136	-279	-143
Arkansas River	+11	-147	-136	+163	-14	+149
White River	+26	-1,250	-1,226	+319	-843	-523
St. Francis River	+16	-480	-464	+56	-249	-193
Yazoo River	+7	-487	-481	+22	-234	-212
Boeuf-Tensas River	+37	-517	-480	+119	-298	-179
Total	+119	-3,429	-3,310	+815	-1,917	-1,102

Sensitivity Analysis

A limited sensitivity analysis was performed on the preliminary calibrated model to determine the response of the model to changes in hydraulic conductivity and pumpage. The hydraulic conductivity of each layer and of the riverbeds was varied uniformly by multiples of the calibration values throughout the model area. Pumpage also was varied in a similar manner. Figure 29 shows changes in RMSE resulting from each of the tests in which conductivity or pumpage was varied separately.

The model results, as judged by RMSE, were most sensitive to pumpage, particularly increased pumpage. The model also was sensitive to the hydraulic conductivity of layers 1 and 2, particularly higher values for layer 1 and lower values for layer 2. The model was least sensitive to the hydraulic conductivity of layer 3 and the riverbeds.

In addition to the above mentioned hydrologic parameters, the following boundary conditions were tested:

1. Head in layer 1 was reduced uniformly by 5 ft,
2. Stage in rivers was reduced by 5 ft,
3. Stage in rivers was changed to spring 1972 conditions (average increase of almost 2 ft), and
4. Conductances for hydrologic units outside the model boundary were increased and decreased by a factor of 10.

In all cases the model was relatively insensitive to these boundary changes. The calibration values of the other hydrogeologic parameters would have changed only slightly (if at all), and all preliminary interpretations in the next section were unchanged as a result of these boundary changes.

The calibration and sensitivity analysis could have used criteria other than RMSE. Figure 30 shows the sensitivity analysis results of several calibration criteria for the hydrologic conductivity of the confining unit (layer 1). All criteria on figure 30 are based on the statistics of the difference between observed and simulated heads. RMSE was originally chosen due to ease of use and because it showed maximum definition of calibration values for all parameters.

The sensitivity of fluxes to or from the aquifer and the sensitivity of interpretations regarding the flow system based on the results of preliminary calibration were not rigorously tested nor are they reported here.

Application

The preliminary model is a fair approximation of regional steady-state flow. Replication of the 1972 potentiometric surface was good but the model budget can not be judged by flux to rivers because the grid size does not simulate discharge of local ground-water flow to rivers. The model will suffice as the basis for further calibration with refined input data and will be used to develop a model of transient regional flow. Additional data needed for transient simulation will be:

1. a discretization scheme for time,
2. storage coefficients,

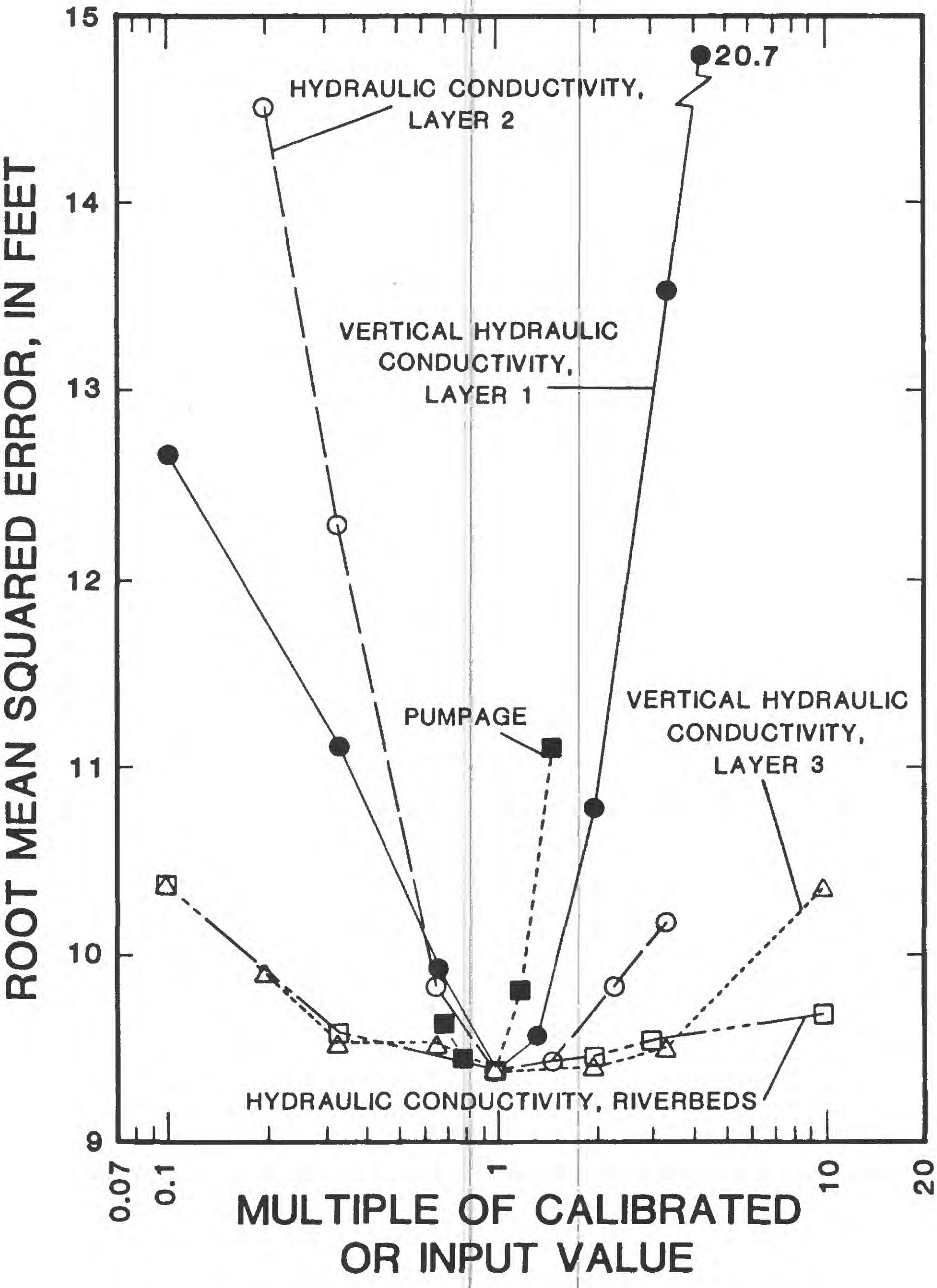


Figure 29.--Sensitivity of model to changes in calibration parameters and pumpage.

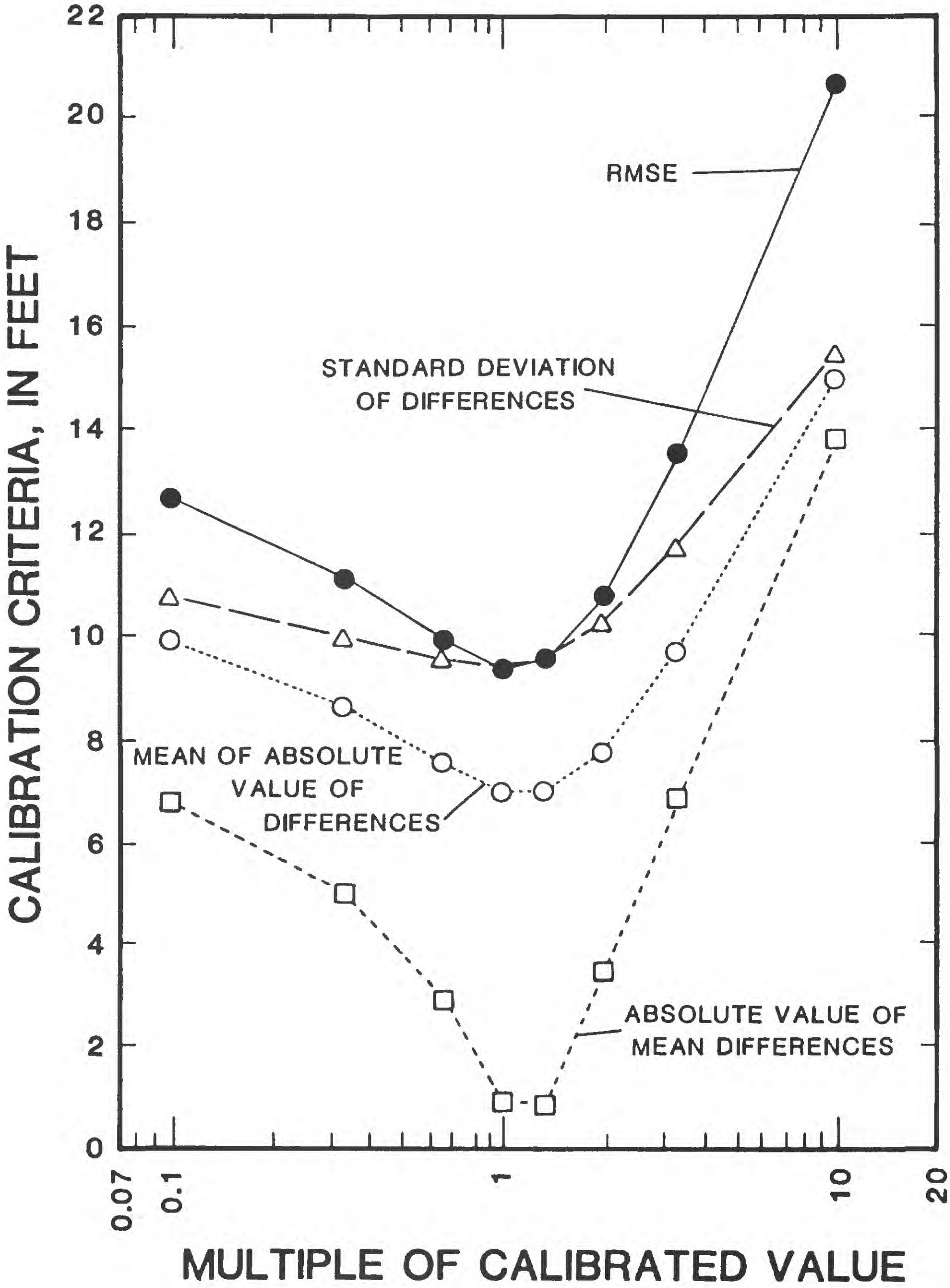


Figure 30.--Comparison of calibration criteria for model of 1972 as steady state.

3. pumping stress as a function of time, and
4. heads in underlying aquifers as a function of time.

Since this model uses a more rigorous head-dependent treatment of leakage from the confining unit rather than a specified flux (areas recharge) as previous models have, it is anticipated that with the ability to vary recharge both areally and with time, further simulation will be more accurate. The amount and distribution of drawdown for 1972 could not be simulated with uniform areal recharge nor with no areal recharge.

The sensitivity of the model (fig. 29) and the distribution of differences between simulated and observed head (fig. 28) indicate that pumpage quantity and distribution are critical to model analysis.

PRELIMINARY ANALYSIS OF REGIONAL FLOW

The preliminary calibration of the model was followed by a simulation of predevelopment conditions. The pumpage values for the 1972 simulation were removed for the steady-state development simulation. The two following sections will describe and contrast the preliminary results and conclusions describing regional ground-water flow.

Predevelopment

The flow system as described by the predevelopment simulation is illustrated by figures 31 through 35 and tables 4 and 5. Recharge to the Mississippi River Valley alluvial aquifer was from underlying aquifers and from the Mississippi River Valley confining unit. Nearly all regional discharge was to rivers. The distribution of flux to or from underlying aquifers and the confining unit is not shown for a subarea corresponding to the Cretaceous and Paleozoic (CP) subregional study. The CP subarea is that part of the modeled area north and west of the Mississippi Embayment aquifer system subarea (MEB) as shown on figure 19. Most flux from Cretaceous and Paleozoic rocks moves through the alluvium and is discharged to rivers within one or two model blocks of the western model boundary. Net flux to rivers in the CP subarea is approximately balanced by the net flux from the underlying rocks and represents more than 80 percent of the budget for that subarea. Budget terms describing flux from underlying aquifers in the CP subarea are approximately the same as those in the CP subregional model (J.V. Brahana, U.S. Geological Survey, written commun., 1987). However, the model of the alluvial aquifer is very insensitive to changes in this flux due to the proximity of rivers to the potential discharge area of the Cretaceous and Paleozoic rocks.

The net flux across the top of the alluvial aquifer, that may be thought of as regional recharge from the confining unit, averaged 0.3 and 0.5 inch/year for the CP and MEB subareas, respectively, and 0.5 inch/year for the whole model area. Net flux from underlying aquifers averaged 4.3 and 0.6 inch/year for the CP and MEB subareas, respectively, and 0.9 inch/year for the whole model area. The upper Claiborne aquifer (table 1) accounted for about 60 percent of the flow from underlying aquifers in the MEB subarea.

Figures 33 and 34 show that most recharge rates to the aquifer were not greater than 3 inches/year nor were rates for any large areas uniformly greater than about 1 inch/year.

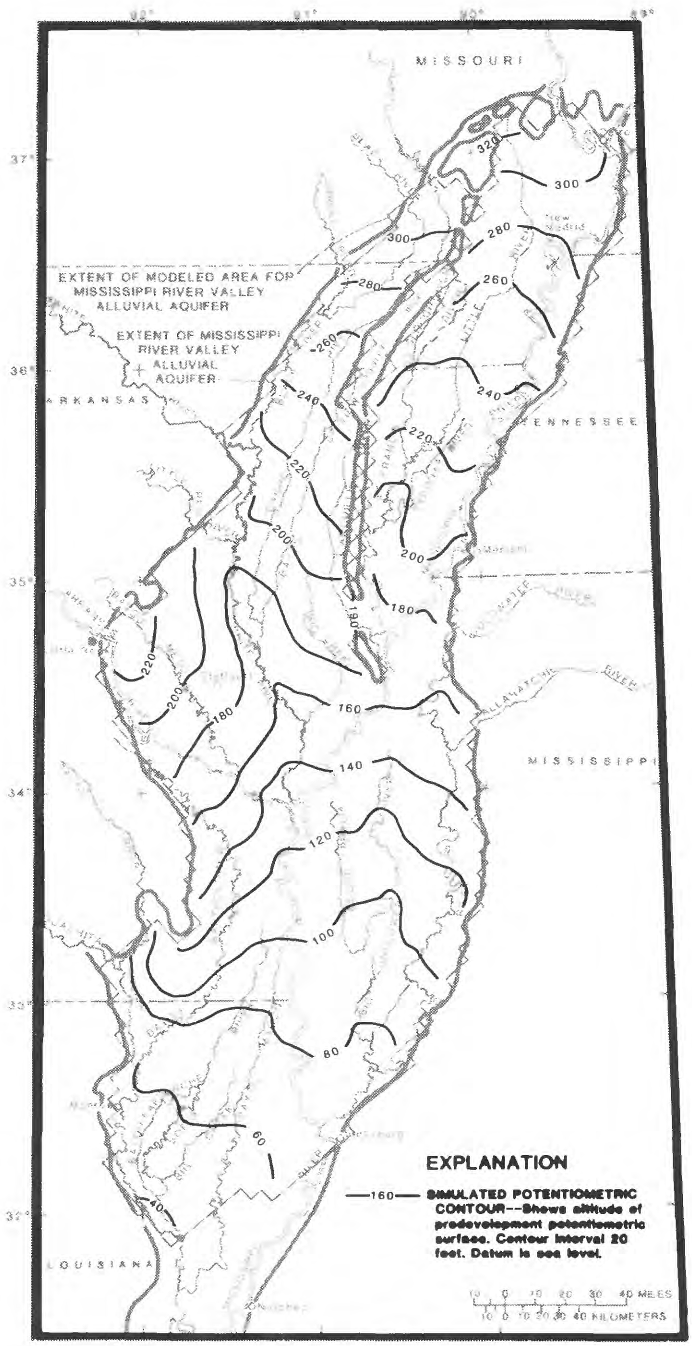


Figure 31.--Simulated predevelopment potentiometric surface of the Mississippi River Valley alluvial aquifer.

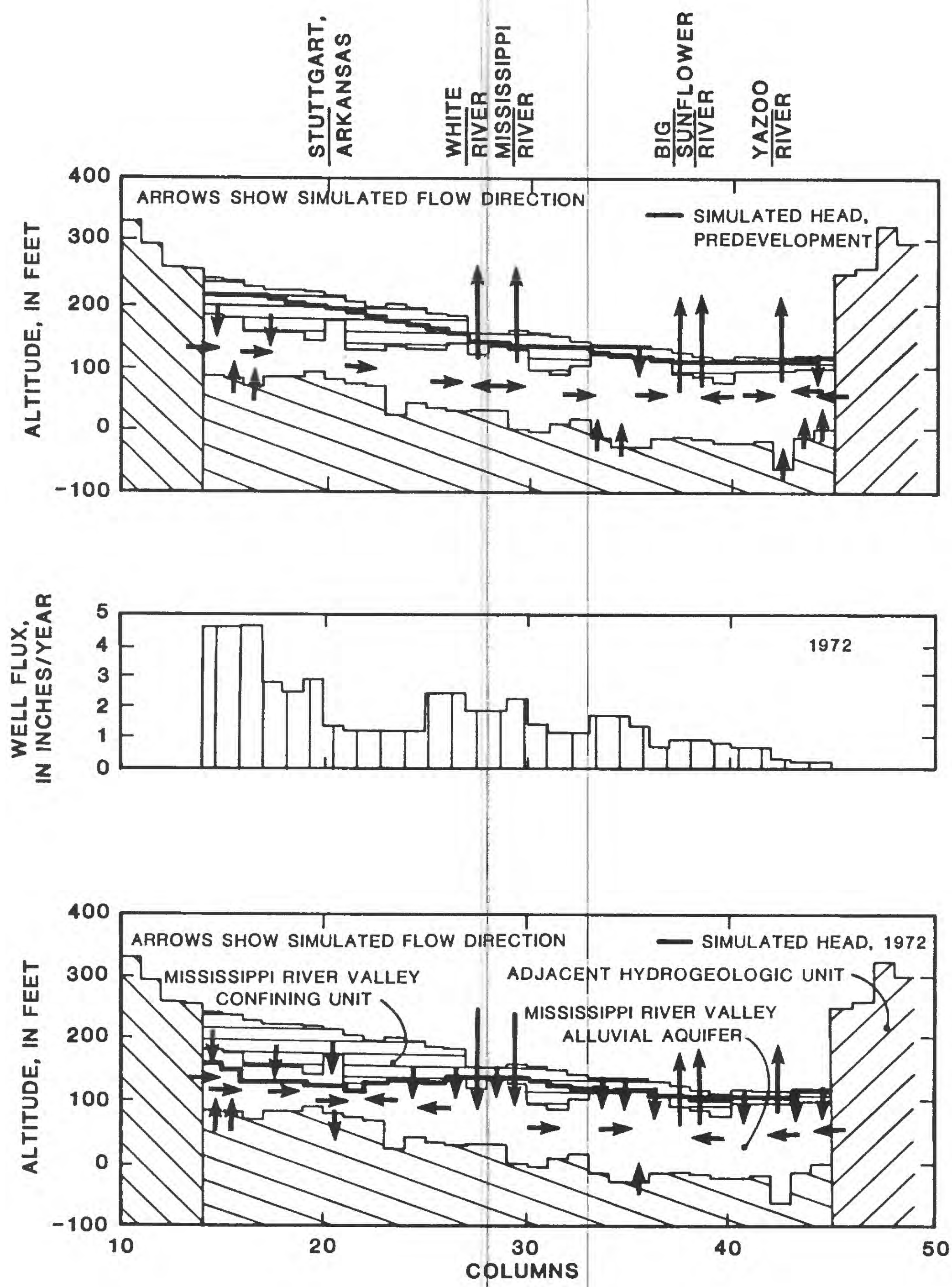


Figure 32.--Simulated predevelopment and 1972 steady-state ground-water flow along row 50.

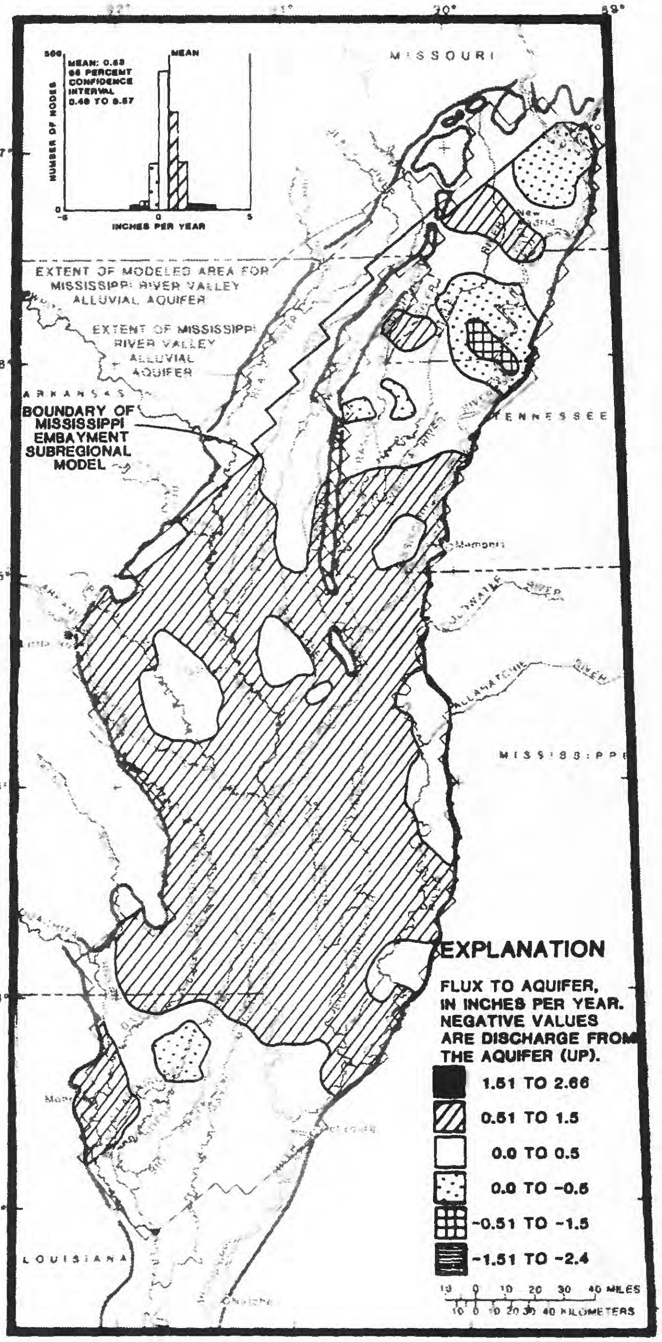


Figure 33.--Simulated predevelopment distribution of recharge and discharge at the top of the Mississippi River alluvial aquifer excluding that from rivers.

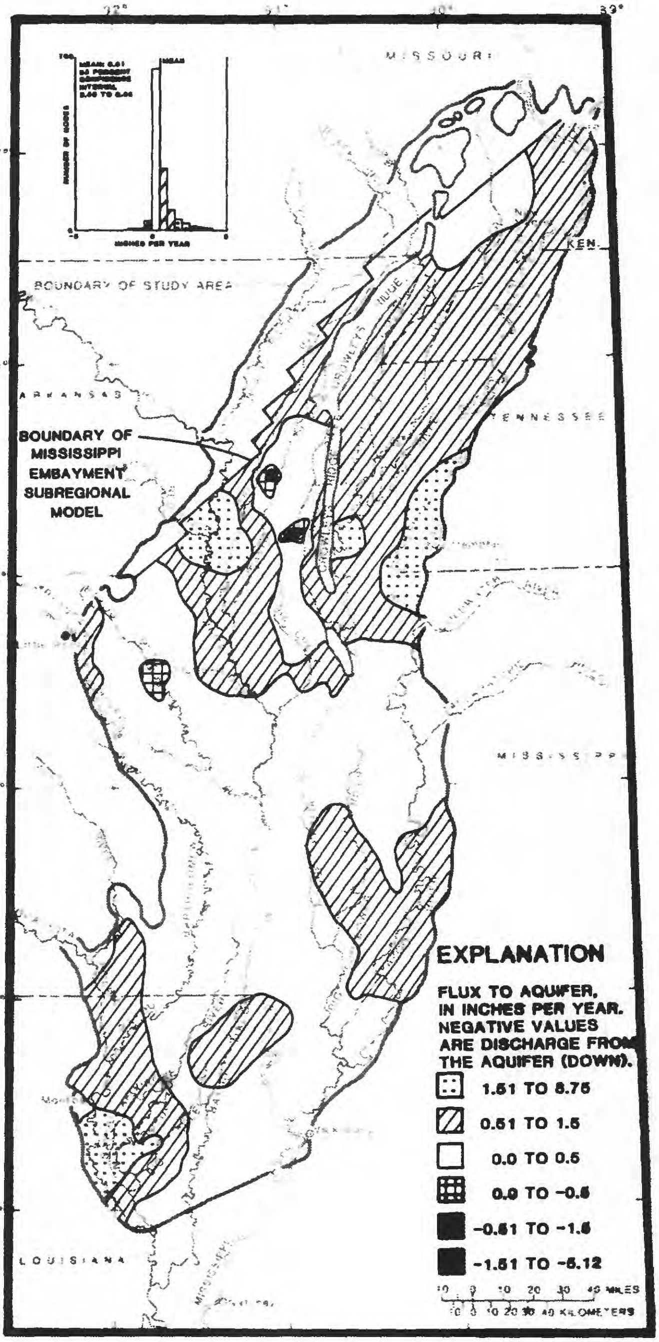


Figure 34.--Simulated predevelopment distribution of recharge and discharge at the bottom of the Mississippi River Valley alluvial aquifer.

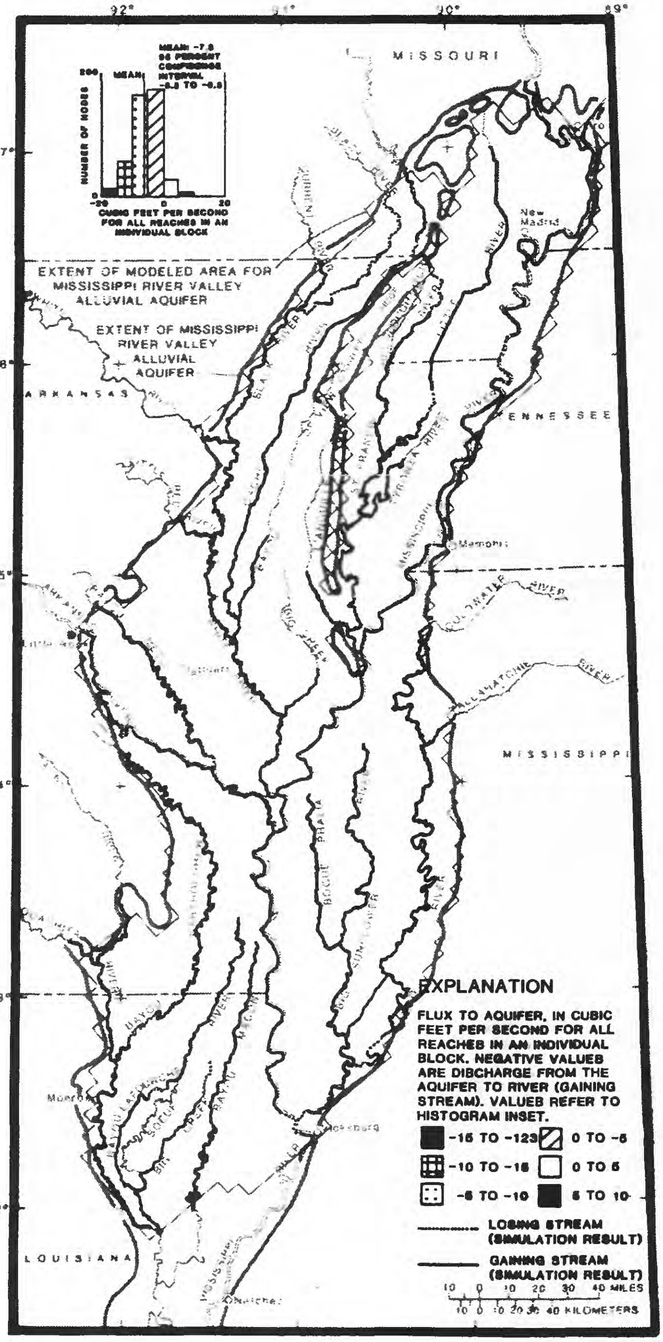


Figure 35.--Simulated predevelopment distribution of recharge and discharge from rivers to the Mississippi River Valley alluvial aquifer.

Almost all river reaches (fig. 35) were gaining, averaged 7 ft^3/s per model block, and few gained more than 15 ft^3/s per block. Flux from the river to the aquifer was the exception.

1972

The flow system as described by the 1972 simulation is illustrated by figures 24, 32, and 36 through 40 and tables 4 and 5. Pumpage from wells changed the flow system enormously. Net recharge to the Mississippi River Valley alluvial aquifer from the Mississippi River Valley confining unit was 0.4 and 0.8 inch/year in the CP and MEB subareas, respectively, 0.8 inch/year over the whole model area. Net flux from underlying aquifers was 5.3 and 0.4 inch/year in the CP and MEB subareas, respectively, and 0.7 inch/year over the model area as a whole. The upper Claiborne aquifer contributed about 35 percent of the flux from underlying aquifers in the MEB subarea. The reduction in leakage to the upper Claiborne aquifer represents nearly all the change in flux to aquifers in the MEB subarea. Net discharge to rivers averaged about 2.5 ft^3/s per model block with river reaches. Discharge from wells averaged about 1.1 inch/year (2 ft^3/s) per model block.

Pumpage from wells (fig. 24) is highest between Little Rock and Stuttgart, Arkansas. The surrounding area north to Missouri and southeast to the central part of northwestern Mississippi also is more heavily stressed than the remainder of the model area. Areas of highest leakage from the confining unit (fig. 37) correspond to the area of highest pumpage. A large part of the area shows uniform flux of about 1.3 inch/year. In these areas leakage from the confining unit was at the conceptual maximum reached when head in the alluvial aquifer dropped below the top of the alluvial aquifer. Flux from the underlying aquifers (fig. 38) also is highest just southeast of Little Rock near the areas of largest withdrawals but a few areas show loss from the alluvium to underlying aquifers. The heads in some underlying aquifers also have decreased in these areas in response to pumpage. Model results indicate that four large rivers, the Arkansas, and the lower parts of the White, Cache, and Mississippi Rivers are nearly everywhere losing water to the alluvial aquifer (fig. 39). Most reaches of other rivers are gaining flow from the alluvial aquifer.

The simulated flow in the alluvial aquifer and flow into and out of it along row 50 of the model in the plane of the section are illustrated in figure 32. The sources of recharge, the movement of water, and location of discharge are typical of the relations for the aquifer in the heavily developed and most heavily used parts of the study area.

A map of estimated drawdown from predevelopment in 1972 was constructed (fig. 40) based on the difference between the simulated predevelopment heads (fig. 31) and the observed 1972 heads (fig. 27). The largest drawdowns were more than 80 ft in the Grand Prairie region near Stuttgart, Arkansas. The drawdown is probably greatest for several reasons:

1. The long history of sustained intense irrigation for rice farming has caused the greatest withdrawals of water from the alluvial aquifer.

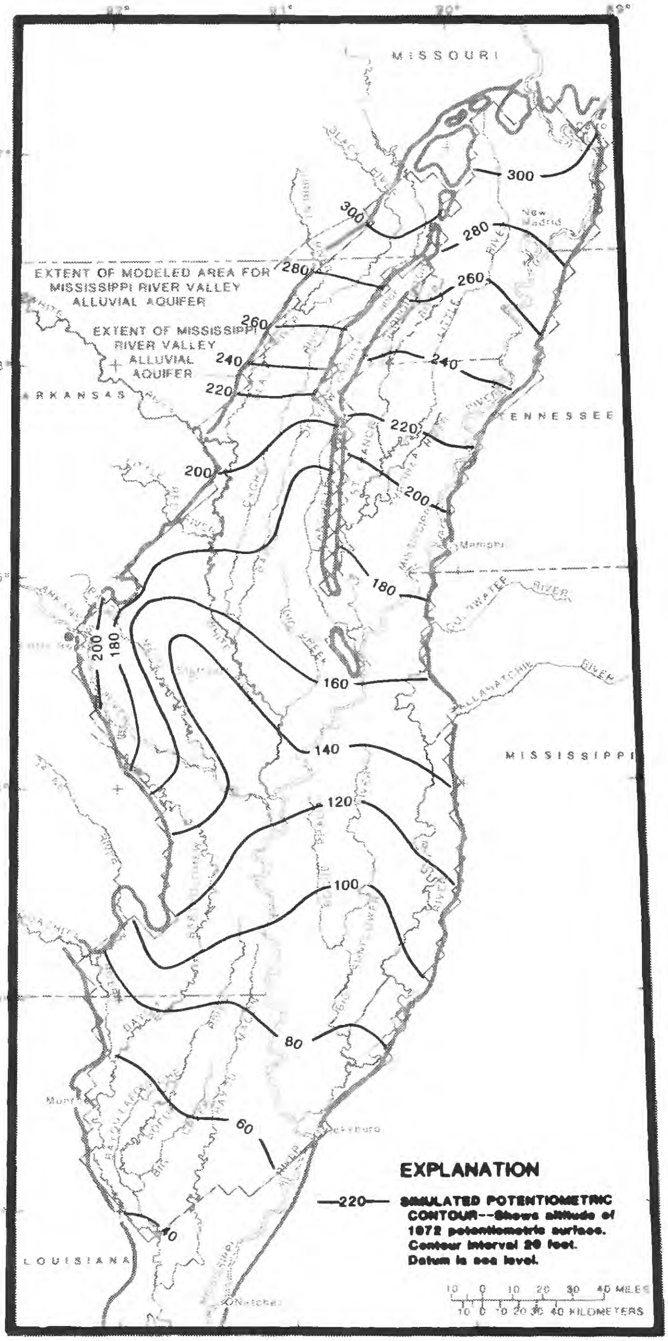


Figure 36.--Simulated 1972 potentiometric map for the Mississippi River Valley alluvial aquifer.

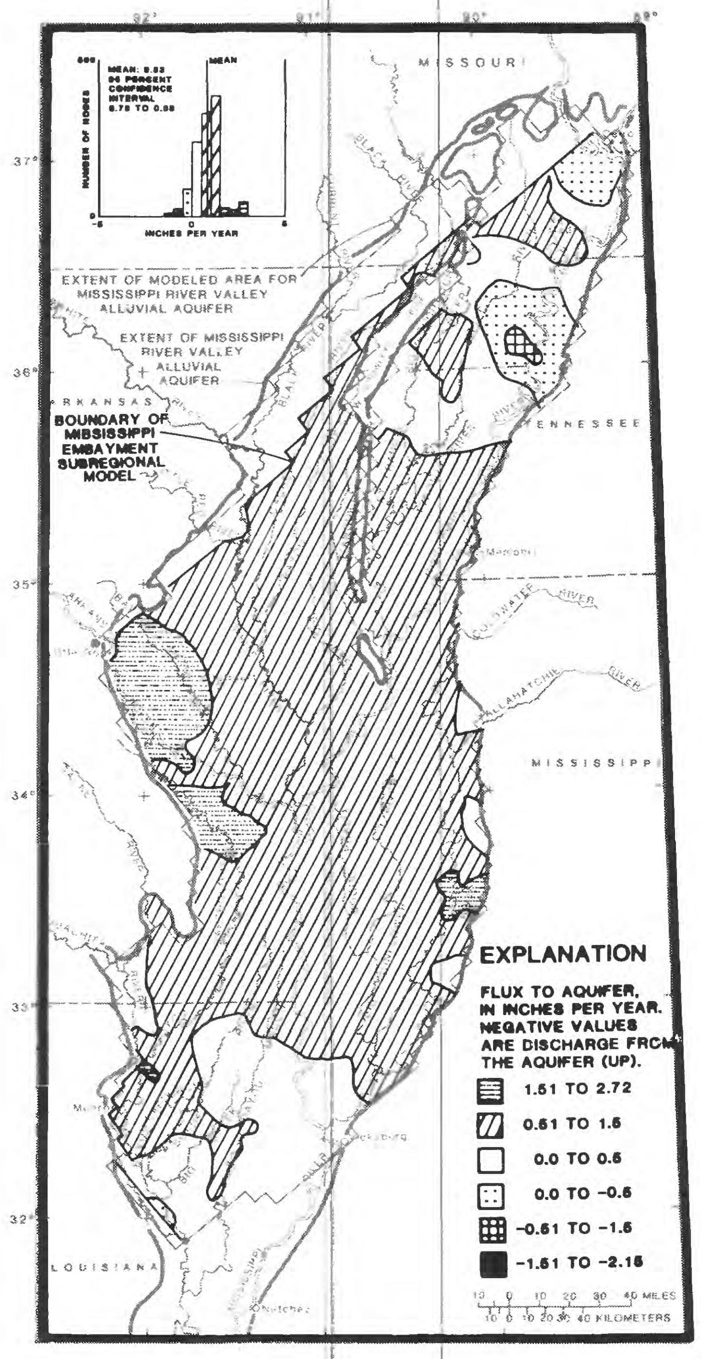


Figure 37.--Simulated 1972 distribution of recharge and discharge at the top of the Mississippi River Valley alluvial aquifer excluding that from rivers.

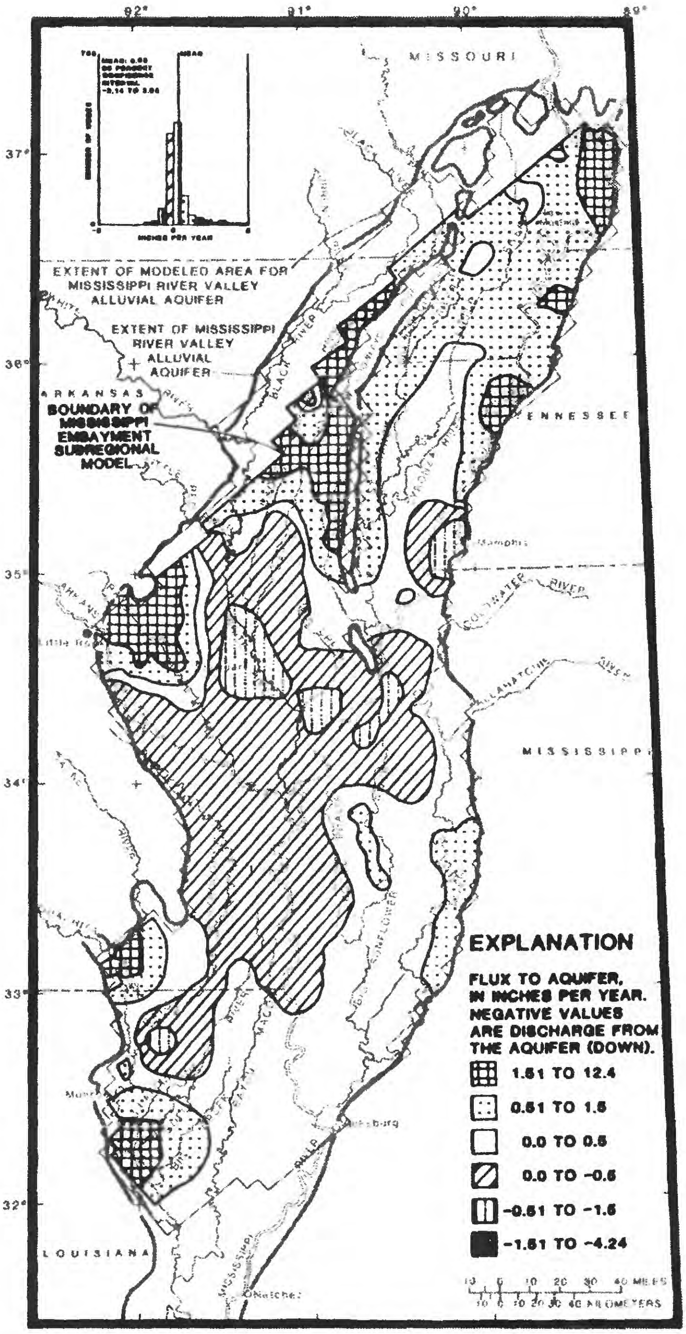


Figure 38.--Simulated 1972 distribution of recharge and discharge at the bottom of the Mississippi River Valley alluvial aquifer.

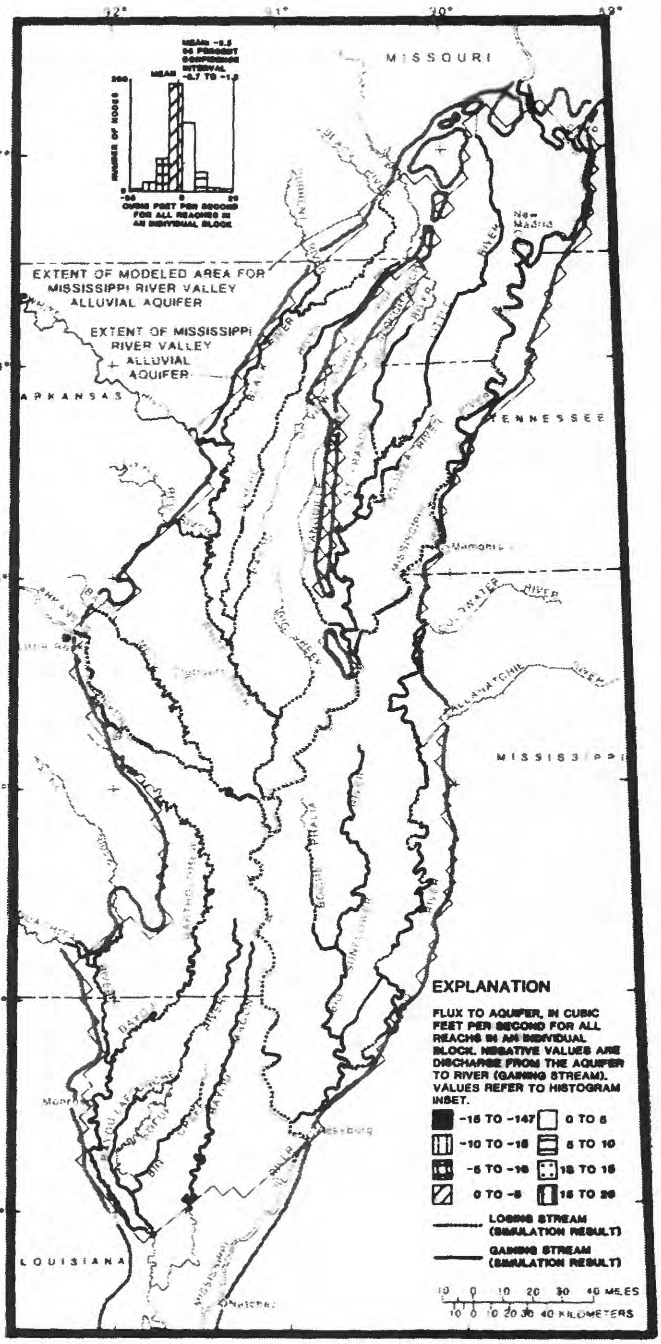


Figure 39.--Simulated 1972 distribution of recharge and discharge from rivers to the Mississippi River Valley alluvial aquifer.

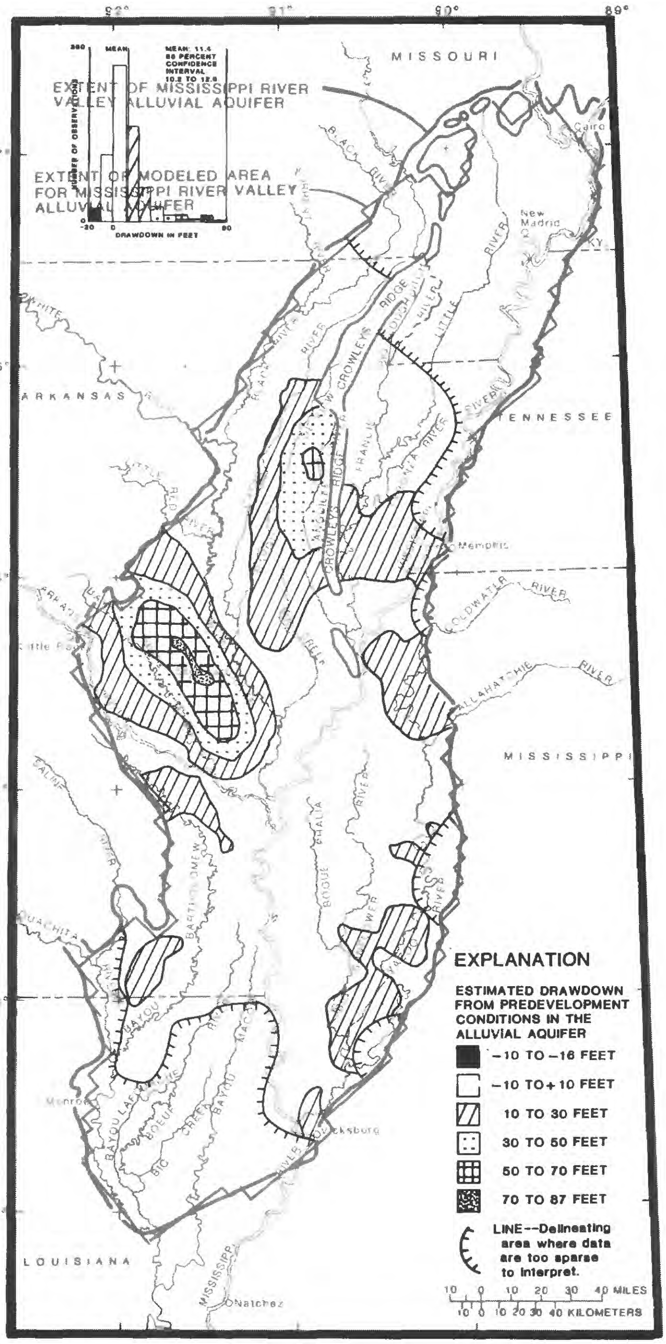


Figure 40.--Net drawdown between simulated predevelopment potentiometric surface and observed 1972 potentiometric surface for the Mississippi River Valley alluvial aquifer.

2. Leakage through the confining unit is restricted by the thicker less permeable confining unit. It can not reach its theoretical maximum until the head in the aquifer drops below the top of the aquifer (bottom of the confining unit).
3. Large rivers were a longer distance from intense pumpage. As a result much higher gradients within the alluvial aquifer had to be developed to move large quantities of water through the aquifer from the river.
4. Since the confined storage coefficient is much smaller than the unconfined storage coefficient, only relatively small amounts of water could be supplied to the aquifer from storage (per foot of head decline) until the head in the aquifer dropped below the top of the aquifer. In the Grand Prairie region the confining unit is the thickest (fig. 10), therefore, the top of the aquifer (the level at which unconfined storage becomes important) is the deepest.

A second area in Arkansas (just west of Crowleys Ridge) is another site of large drawdown (fig. 40). Most of the hydrologic conditions (large long-term pumpage, thick confining unit, and greater than average distance from rivers) are similar to those of the Grand Prairie region. Additionally, the proximity of the pumpage to the edge of the aquifer increases the drawdown. The distinctly lower permeability of the adjacent units probably exerts a boundary effect on the aquifer response in this area.

The combination of heavy pumpage and hydrologic conditions that limits the ability of the aquifer to adjust to that stress by increasing recharge has resulted in long-term lowering of the potentiometric surface in these two areas in Arkansas. In only one small area outside of Arkansas is the estimated drawdown indicated to be greater than 20 ft. Although most areas in Missouri and Louisiana have insufficient observations of head in 1972 to calculate drawdown, reports for those areas (Whitfield, 1975; Luckey, 1985) report no long-term drawdown. Apparently smaller pumpage and more favorable conditions for inducing recharge have prevented more than seasonal or limited long-term water-level declines outside of the two areas in Arkansas.

The changes in the budget of the flow system between predevelopment and 1972 are given in table 4. The largest single net change was an increase in pumpage of 2,481 ft^3/s (1,601 million gallons per day). Other large changes in the budget and their proportion expressed as a percentage of pumpage are as follows: (1) decrease in discharge to rivers (60 percent), (2) increase in recharge from rivers (30 percent), (3) increase in recharge from the confining unit (25 percent), (4) increase in discharge to underlying aquifers (10 percent), and (5) decrease in recharge from underlying aquifers (10 percent).

The model results indicate the importance of leakage from both rivers and the Mississippi River Valley confining unit to providing recharge to sustain the large amounts of pumpage in the Mississippi River Valley alluvial aquifer. Recharge as leakage from the confining unit, that was about 0.8 inch/year for 1972 for the whole model area and at a maximum of 1.3 inch/year for parts of the alluvial aquifer, is slightly higher than previously published estimates of 0.4 inch/year (Broom and Lyford, 1981) and 0.5 inch/year (Sumner and Wasson, 1984). Other model studies (Griffis, 1972; Peralta and others, 1985) assumed no flow or connection with the confining unit.

SUMMARY

Pumpage from the Mississippi River Valley alluvial aquifer, that totaled 7,600 ft^3/s (1,600 million gallons per day) in 1985, for agricultural and other uses has caused long-term declines of about 20 to 80 ft in parts of Arkansas and as much as 20 ft in parts of Mississippi. The pumpage is primarily for the irrigation of rice and accounts for nearly 60 percent of the pumpage in the Gulf Coast Regional Aquifer System.

The Mississippi River Valley alluvial aquifer underlies the Mississippi Alluvial Plain from Cairo, Illinois, to the Gulf of Mexico. In this study, which covers the area north of the subcrop of the Vicksburg-Jackson confining unit, the aquifer occurs over about 32,000 mi^2. Aquifer materials are the sand and gravel portion of a sequence of gravel, coarse to fine sand, silts, and clays that become finer upward in alluvium of Quaternary age. The silts and clays at the top of the Quaternary alluvium, the Mississippi River Valley confining unit, nearly everywhere overlies the Mississippi River Valley alluvial aquifer and confines the aquifer in most places. Underlying the alluvial aquifer are bedrock units of Paleozoic to Eocene age. The underlying units are mostly aquifers and confining units of the Mississippi Embayment aquifer system that consists of alternating beds of sand and clay with some interbedded silt, lignite, and limestone.

The thickness of the Mississippi River Valley alluvial aquifer generally ranges from 60 to 140 ft and averages 100 ft. Saturated thickness generally is equal to thickness of aquifer materials, except in areas where drawdown cones have developed. The hydraulic conductivity of the alluvial aquifer averages about 200 ft/d according to aquifer tests.

The thickness of the Mississippi River Valley confining unit is highly variable but averages 30 ft. The confining unit is locally absent but is generally 10 to 50 ft thick. In one area, the Grand Prairie region of Arkansas, the confining unit generally is greater than 50 ft thick.

Flow to the Mississippi River Valley alluvial aquifer originates as recharge from rainfall or as leakage from the confining unit, rivers, underlying aquifers, and adjacent hydrologic units. The alluvial aquifer discharges water to wells and by leakage to the confining unit, rivers, underlying aquifers, or adjacent hydrologic units. Other than discharge to wells, no item of the hydrologic budget has been measured. Previous estimates of recharge to the top of the alluvial aquifer have varied between zero and almost 2 inches/year.

Pumpage from the Mississippi River Valley alluvial aquifer for irrigation has changed regional flow directions substantially in some areas. Regional flow generally follows the slope of land surface (southward and toward the rivers along the axes of the river basins) except where flow is toward depressions in the potentiometric surface caused by large irrigation pumpage. Two areas of long-term depressions in the potentiometric surface are the Grand Prairie region and the area west of Crowleys Ridge in Arkansas.

The available data and the concepts of flow in the Mississippi River Valley alluvial aquifer were used to construct a digital model of steady-state

regional flow. The three-layer finite-difference model was constructed and calibrated to simulate two-dimensional confined or unconfined flow. The grid used for the model was 76 rows by 48 columns and consisted of 1,256 active blocks 5 mi on a side. Discretization was identical with other project models. Measurements of head for 1972 and pumpage from wells for 1970 were chosen to represent steady-state conditions. Recharge and discharge to the alluvial aquifer were represented by head-dependent flux or by constant flux in the case of pumpage. Recharge and discharge across the top and bottom of the alluvial aquifer (layer 2) were modeled as flow to or from constant-head sources in adjacent layers (1 and 3, respectively). Flow to or from rivers and adjacent hydrogeologic units were modeled with the river and general head boundary packages, respectively. Boundary-head values were chosen from observations of stage, assumed head (layer 1 and adjacent hydrogeologic units), and results from preliminary calibration of other models (layer 3).

The framework of the Mississippi River Valley alluvial aquifer was synthesized and interpreted from a variety of data sources. The thickness of the Mississippi River Valley confining unit is shown to be highly variable but can be described regionally. The vertical hydraulic conductivity of the confining unit was distributed spatially as high and low values at a ratio of 1:2 according to soil classification. All other hydraulic conductivities were assumed uniform for the hydrogeologic unit represented. The ratio of vertical hydraulic conductivity to thickness for underlying aquifers was the same as used by other subregional models. The length and width of river reaches were derived from topographic maps and from discharge measurement notes.

Calibration was achieved by adjusting hydraulic conductivities of each of the three layers and of the riverbed materials to minimize the root-mean-squared error of observed head and simulated head. Choices for hydrogeologic parameters are as follows:

1. hydraulic conductivity of the Mississippi River Valley alluvial aquifer, 300 ft/d,
2. vertical hydraulic conductivity of the Mississippi River Valley confining unit, 0.0003 ft/d,
3. ratio of vertical hydraulic conductivity to bed thickness for riverbed materials, 0.05 day^{-1}, and
4. ratio of vertical hydraulic conductivity to bed thickness for underlying units three times that used by the Mississippi Embayment and the Cretaceous and Paleozoic subregional models.

Model performance generally was good with a mean difference between simulated and observed heads of 0.8 ft, and 76 percent of 812 observations within 10 ft. The two areas of greatest difference between observed and simulated values are probably the result of errors in pumpage distribution and bias from the steady-state assumption. Greatest model sensitivity was indicated for increased pumpage, higher values of confining unit hydraulic conductivity, and lower values of alluvial aquifer hydraulic conductivity. The model calibration and preliminary interpretation were not sensitive to plausible changes of confining unit head, river stage, or hydraulic conductance for hydrologic units outside the mode boundary. The model will be the basis for further simulation and analysis of transient regional flow.

After calibration of the model of steady-state flow for 1972, pumpage was removed from the alluvial aquifer and predevelopment flow was simulated. The amount and distribution of flux to and from the aquifer was examined and contrasted. Due to the proximity of the subcrop of the Cretaceous and Paleozoic rock units to rivers the model results were insensitive to flux from underlying units in the Cretaceous and Paleozoic subcrop.

Preliminary analysis indicates that recharge was from underlying aquifers and the Mississippi River Valley confining unit for predevelopment flow. Net flux from underlying aquifers in the area underlain by the Mississippi Embayment aquifer system and net flux from the confining unit were about equal. About 60 percent of flux from underlying aquifers represented leakage from the upper Claiborne aquifer. Nearly all river reaches were gaining flow from the alluvial aquifer and accounted for almost all discharge before pumpage was initiated.

Well pumpage in 1972 and changes in underlying aquifer heads gave rise to a quite different flow system from the predevelopment simulation. Recharge from the Mississippi River Valley confining unit increased and recharge from the underlying aquifers was decreased. Discharge to underlying aquifers increased.

In the area underlain by the Mississippi Embayment aquifer system net flux from the confining unit was double that from underlying aquifers. About 35 percent of flux from underlying aquifers represented leakage from the upper Claiborne aquifer. Recharge from the confining unit averaged about 0.8 inch/year for the whole model area but was at a maximum of 1.3 inch/year for large parts of the alluvial aquifer. Large sections of the Arkansas, lower White, lower Cache, and lower Mississippi Rivers and smaller sections of other rivers were losing streams in 1972.

The changes in the budget of the flow system expressed as a percentage of 1972 pumpage are as follows: (1) decrease in discharge to rivers (60 percent), (2) increase in recharge from rivers (30 percent), (3) increase in recharge from the confining unit (25 percent), (4) increase in discharge to underlying aquifers (10 percent), and (5) decrease in recharge from underlying aquifers (10 percent).

Long-term drawdown in the Mississippi River Valley alluvial aquifer was estimated by comparing observed 1972 head data and simulated predevelopment data. Nearly all drawdown greater than 20 feet was found at two locations in Arkansas, the Grand Prairie region and the area west of Crowleys Ridge. In these areas the combination of heavy pumpage and limited ability of the aquifer to adjust to pumpage by increasing recharge have resulted in long-term declines in water levels. The model results indicate the importance of leakage from both rivers and the Mississippi River Valley confining unit to providing recharge to sustain the large amounts of pumpage from the Mississippi River Valley alluvial aquifer.

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