HYDROLOGY OF THE MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER, SOUTH-CENTRAL UNITED STATES

U.S. GEOLOGICAL SURVEY

Open-File Report 90-358

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By D.J. Ackerman

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U.S. GEOLOGICAL SURVEY

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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.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallon per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
acre-foot per year	0.001233	cubic hectometer per year (hm^3/yr)

Degrees Fahrenheit (°F) are converted to degrees Celsius (°C) by using the following formula:

$$°C = 5(°F-32)/9$$

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."

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ABSTRACT

A quantitative analysis of the regional ground-water flow in the Mississippi River Valley alluvial aquifer was made using observations of changes in water levels and simulation (computer modeling) of aquifer response between 1906 and 1987. The analysis includes an evaluation of the effects of additional ground-water development on the flow system. The boundary of the computer model and of the study area correspond to the physical limits of the Mississippi River Valley alluvial aquifer except that the southern limit is designated where the alluvial aquifer crosses the subcrop of the top of the Vicksburg-Jackson confining unit.

The Mississippi River Valley alluvial aquifer underlies a vast low, flat plain that extends from the apex of the Mississippi embayment southward to the Gulf of Mexico and is the upper aquifer of the Mississippi embayment aquifer system. The aquifer consists of 60 to 140 feet of Quaternary sand and gravel that grades from gravel at the bottom to fine sand near the top, and underlies 32,000 square miles in parts of Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. The alluvial aquifer is in hydraulic connection with many rivers and drains. Hydraulic conductivity of the aquifer is about 200 feet per day and storage coefficients vary from 0.0001 to 0.30 for confined and unconfined conditions, respectively. 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. It is underlain by the less permeable aquifers and confining units of the Mississippi embayment aquifer system, the McNairy-Nacatoch aquifer, and undifferentiated Paleozoic rocks.

Predevelopment flow (prior to large pumpage) in the Mississippi River Valley alluvial aquifer consisted of inflow through the overlying Mississippi River Valley confining unit, inflow from underlying aquifers, and outflow to rivers. Most inflow, about 74 percent, was through the confining unit at an average net rate of 0.8 inch per year. Individual areas differed in the relative contribution from underlying units. The simulated predevelopment potentiometric surface shows movement down the Mississippi River Valley and following the slope of land surface toward major rivers near the axes of the St. Francis, White, Arkansas, Yazoo, and Boeuf basins.

Development of the Mississippi River Valley alluvial aquifer started in the early 1900's in central Arkansas and water use has been primarily for agriculture, particularly the irrigation of rice. Large withdrawals in other areas generally began about 1950. The largest increases in withdrawals occurred in all areas between 1973 and 1982. Maximum withdrawals before the present (1988) are estimated at 7,800 cubic feet per second (5,000 million gallons per day).

Pumpage from the alluvial aquifer has caused a decrease in outflow to rivers, an increase of inflow from rivers, and an increase of inflow through the overlying Mississippi River Valley confining unit. In some areas the

decrease in outflow to rivers and increase in inflow have not been sufficient to meet the demands of pumpage. The long-term excess of pumpage over net-inflow has resulted in regional declines in water levels, reduction in water in storage, and decreases in well yields for some parts of the aquifer. The response of water levels in the alluvial aquifer to pumpage has followed the temporal and areal trend of development. Water levels in the Mississippi River Valley alluvial aquifer have shown long-term drawdown of as much as 90 feet.

Only parts of the aquifer north of the Arkansas River and west of Crowleys Ridge show appreciable decreases in saturated thickness. Decreases in saturated thickness through 1982 generally were 20 to 60 feet. Only the area between the Arkansas and White Rivers, where saturated thickness has decreased to less than 50 feet, may be considered in danger of being depleted for the purpose of rice irrigation. Parts of the aquifer north of the Arkansas River and west of Crowleys Ridge, where saturated thickness has decreased to less than 75 feet throughout large areas, may be considered as not currently in danger but trending toward depletion. One percent or less of all other areas underlain by the aquifer has a decrease in saturated thickness to less than 75 feet.

In some areas the direction of flow has changed compared to the predevelopment flow system. Two areas north of the Arkansas River and west of Crowleys Ridge have large depressions in the potentiometric surface and pronounced changes in the direction of flow. Pumpage has not resulted in large-scale regional changes in direction of flow in other areas underlain by the aquifer. Most of the aquifer has only a general lowering of 5 to 15 feet in the potentiometric surface. The contours of the potentiometric head have shifted upgradient (usually north) resulting in only minor or local changes in direction of flow.

Regional flow in the Mississippi River Valley alluvial aquifer has steadily changed since large-scale pumpage began in the early 1900's. By the mid-1970's rivers became a source of more than 30 percent of total flow rather than the sink of net outflow as they were during predevelopment. Inflow through the Mississippi River Valley confining unit increased from a rate of 0.8 inches per year for predevelopment to 1.3 inches per year by 1982. Net inflow from underlying aquifers has varied slightly in amount but has decreased as a proportion of total flow. The alluvial aquifer has had continuous net losses of storage representing approximately 10 to 25 percent of pumpage. Current rates of loss of water from storage range from 1 to 8 inches per year in the Grand Prairie area, from 5 to 14 inches per year in parts of the Cache area, and are generally less than 1 inch per year elsewhere.

To assess response of the regional flow system to continued development and to evaluate the potential of the aquifer to support additional development, two flow-model simulations were made to the year 2022. The effect of continued or increased development and the ability to support development were evaluated by the change in head in the aquifer and decreases in saturated thickness. Simulation results after 40 years of pumping at 1985 rates, indicated a moderate effect (a decrease to less than 75 feet of saturated thickness) in the area north of the Arkansas River and west of Crowleys Ridge. Some parts of this area were unable to sustain current development (a decrease to less than 25 feet of saturated thickness). Simulation of additional pumpage over all the aquifer at the rate of 1.2 million gallons per day per 25-square-mile area above 1985 rates for 35 years resulted in a severe effect (less than 50 feet of remaining saturated thickness) for most of the area between the Arkansas and White Rivers and a large part of the area immediately west of Crowleys Ridge. Drawdowns from 1982 conditions were greater than 10 feet in small scattered locations throughout the rest of the area. None of these small areas coincided with decreases in saturated thickness to less than 70 feet for an area greater than 25 square miles.

The areas with greatest potential for development of additional pumpage are in the central part of the delta (northwestern Mississippi), the northern part of the area east of Crowleys Ridge (southeast Missouri), and small parts of the area south of the Arkansas River. These areas coincide with thick parts of the aquifer except where drawdown in excess of 10 feet is indicated. In general, areas with more than 100 feet of saturated thickness have the greatest potential for further development of ground water. However, other areas where additional inflow can be induced probably will be able to support additional pumpage with less saturated thickness. Sustained yields from the Mississippi River Valley alluvial aquifer are historically greatest where inflow is induced from larger rivers and, to a limited extent, through the Mississippi River Valley confining unit. Therefore, locations where rivers are near and in good hydraulic connection with the alluvial aquifer or locations where the Mississippi River Valley confining unit is thin, sandy, or absent would have the greatest potential for further development. Conversely, locations distant from areas where inflow could be induced have less potential for development even if saturated thickness is great. Predevelopment saturated thickness was more than 100 feet in the area west of Crowleys Ridge and less than 75 feet in the center of the area between the Arkansas and White Rivers. The additional saturated thickness in the area west of Crowleys Ridge is apparently only delaying an inevitable decrease in yield and reduction in use.

INTRODUCTION

The Gulf Coast regional aquifer-system analysis began in 1980 and includes aquifer systems in Cenozoic deposits underlying the Coastal Plain in the south-central United States. In the northern part of the study area an aquifer system in upper Cretaceous sediments also is included. This study is one of about 30 similar projects in the Regional Aquifer-System Analysis (RASA) program conducted by the U.S. Geological Survey in support of Federal and State needs for information to support better ground-water management (Sun, 1986, p. 4). The total Gulf Coast RASA study area is about 290,000 mi^2 and consists of all or parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and Texas (fig. 1). About 60,000 mi^2 of offshore area is included in the total. The major objectives of the Gulf Coast RASA are to define the geohydrologic framework in which the aquifers exist, describe the chemistry of the ground water, and analyze the regional ground water flow patterns in the flow system (Grubb, 1984, p. 6).

Three regional aquifer systems are delineated in the Gulf Coast RASA study area: the Mississippi embayment aquifer system, the Texas coastal uplands aquifer system, and the coastal lowlands aquifer system (fig. 2). The three systems were delineated based on differences in geologic framework, regional ground water flow patterns, and distribution of fine-grained sediments.

The definition of the conceptual geohydrologic framework (Grubb, 1986) allowed the division of most detailed work on the ground water flow system into five subregional studies (fig. 1).

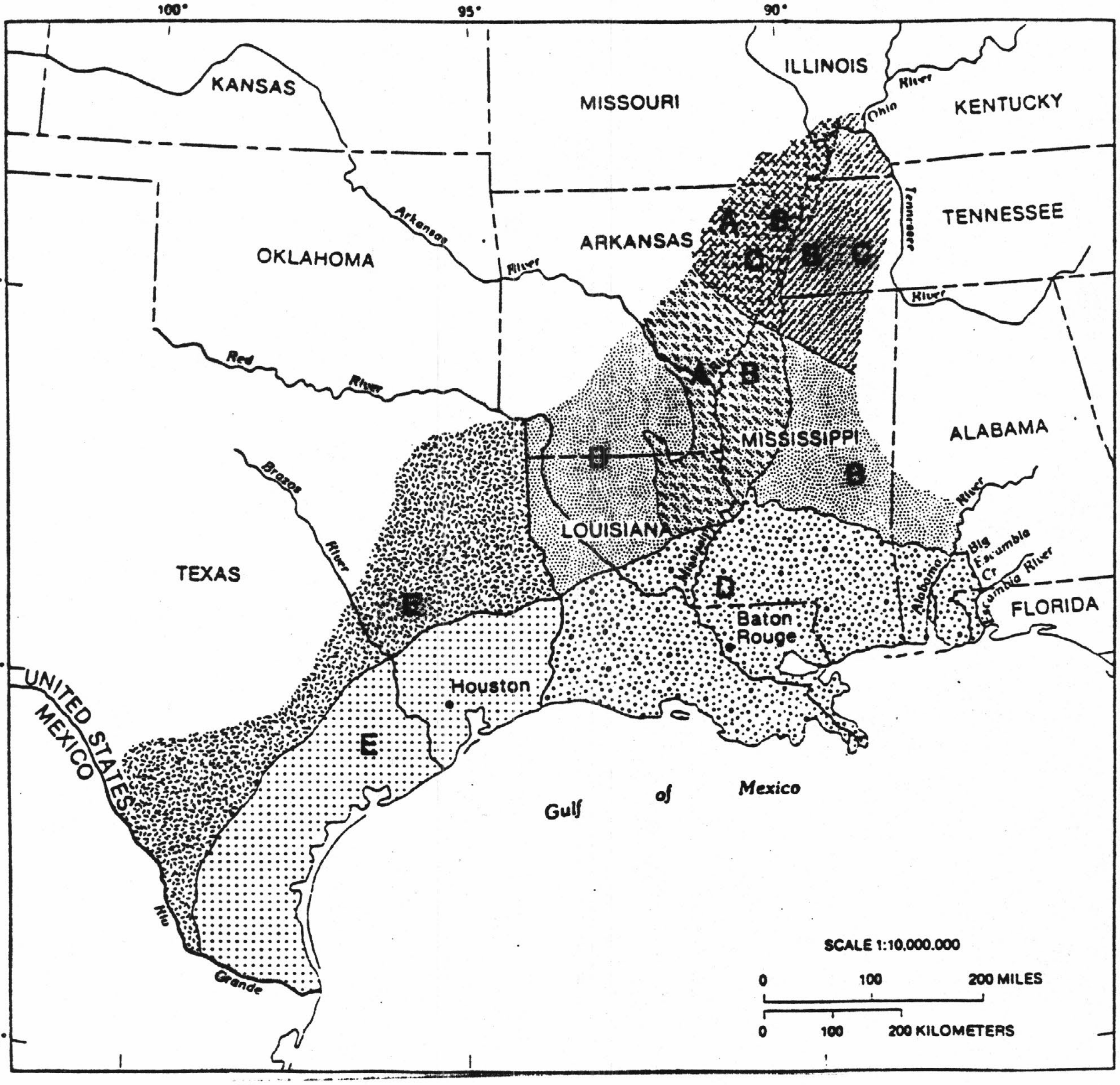
The five subregional studies include two regional aquifers, the Mississippi River Valley alluvial aquifer (this study) and the McNairy-Nacatoch aquifer, and the three regional aquifer systems noted above. Preliminary results of the regional study and the subregional studies have been published in numerous reports (Weeks and Sun, 1987, p. 49; Williamson and others, 1989). Final reports, of both regional and subregional scope, that describe the geohydrologic framework, ground-water flow, or geochemistry, are released in Professional Paper 1416 as companion chapters of this report as the interpretive results of the studies become available.

This study analyzes regional flow in the Mississippi River Valley alluvial aquifer, which is the uppermost aquifer of the Mississippi embayment aquifer system in the central part of the Gulf Coast RASA study area (fig. 1). The study area of the aquifer covers about 32,000 mi^2 in parts of Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. The alluvial aquifer was selected for a detailed study because it provides large quantities of water for agriculture, it has been partially dewatered locally, and it is hydraulically connected with the numerous streams that cross the Mississippi Alluvial Plain.

The alluvial aquifer is laterally equivalent to the upper part of the coastal lowlands aquifer system in east-central Louisiana (Hosman and Weiss, in press). Along the northwestern margin of the study area the alluvial aquifer directly overlies the McNairy-Nacatoch aquifer. In this narrow band of a few miles in width the McNairy-Nacatoch aquifer extends beyond Tertiary age rocks that compose the bulk of the Mississippi embayment aquifer system.

Purpose and Scope

The objectives of this study are to analyze the regional ground water flow patterns in the Mississippi River Valley alluvial aquifer and to provide a framework of background information that can be used for regional assessment of ground-water resources in support of more detailed studies. This report presents a quantitative analysis of regional ground-water flow in the Mississippi River Valley alluvial aquifer. Specifically the predevelopment flow system, historical changes in the flow system, and the potential for future development are discussed in terms of flow components; stress on the aquifer due to development of large-scale pumpage for agricultural water use; direction, distribution, and quantity of flow; and changes in saturated thickness. Flow simulation (computer modeling) is used to analyze ground-water flow patterns and to provide a method to evaluate the effects of development on ground-water resources. The geohydrologic framework of the Mississippi River Valley alluvial aquifer, the conceptual model, and the digital model of regional flow in the aquifer are detailed in a previous report of this study (Ackerman, 1989a). The study boundary (fig. 2) is the extent of the Mississippi River Valley alluvial aquifer north of the subcrop of Miocene and younger rocks and the southern limit of the subcrop of the Vicksburg-Jackson confining unit. The Vicksburg-Jackson confining unit (table 1) separates the Mississippi embayment aquifer system (to the north) from the coastal lowlands aquifer system (to the south). The data compiled and analyzed for the study were collected from about 1900 through 1985.



EXPLANATION

SUBREGIONAL STUDY AREAS--The studies of the Texas Coastal Uplands aquifer system and the Mississippi embayment aquifer system extend for a short distance beyond the landward extent of the Coastal Lowlands aquifer system. The studies of the Coastal Lowlands aquifer systems extend for a short distance beyond the shore of the Gulf of Mexico

A — Missisippi River Valley alluvial aquifer

B — Mississippi embayment aquifer system

D — Coastal Lowlands aquifer system of Alabama, Florida, Louisiana, and Mississippi

E — Coastal Lowlands aquifer system of Texas

E — Texas Coastal Uplands aquifer system

C — McNairy-Nacatoch aquifer

Figure 1.--Location of subregional study areas [from Grubb, 1986, figure 94].

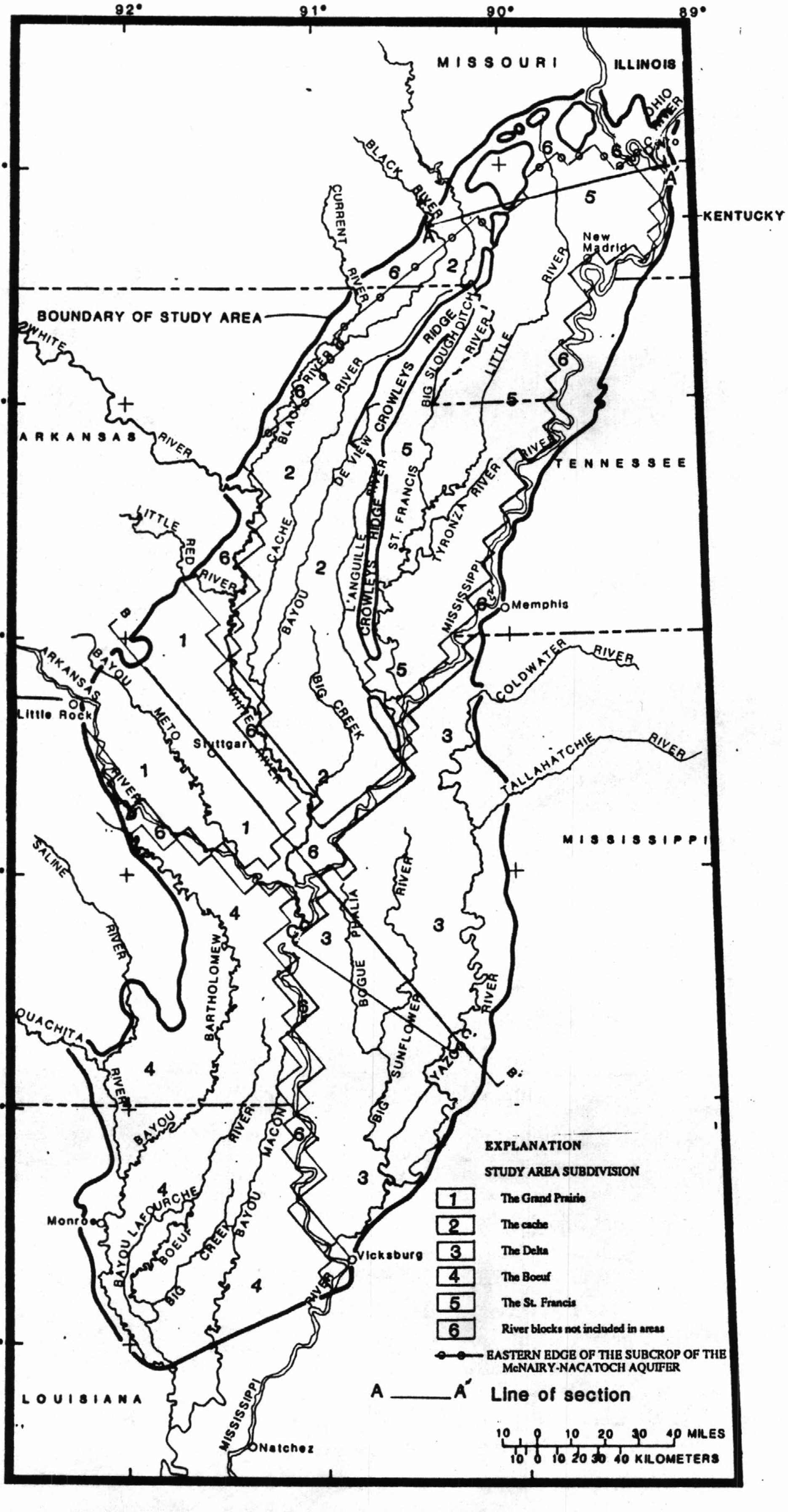


FIGURE 2.—Location of study area, areal subdivisions, and lines of section.

Part 1 of 2

Figure 2.--Location of study area, subareas, and lines of section. County outlines, names, and seats to be included on final copy. Part 2 of 2

Table 1.--Hydrogeologic nomenclature

[Numbers in parentheses are part of the Gulf Coast RASA system of numbering hydrostratigraphic units and are for cross reference or labeling of hydrogeologic unit map 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 embayment aquifer system: Mississippi River Valley confining unit (11a)
		Pleistocene									Mississippi embayment aquifer system: Mississippi River Valley alluvial aquifer (11)
	Tertiary	Oligocene	X	X	X	X	Vicksburg Formation	X	X	X	Vicksburg-Jackson confining unit (15)
		Eocene	X	Jackson Group: Undifferentiated	X	X	Jackson Group: Undifferentiated	Jackson Group: Undifferentiated	X	X	
			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)
			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)
			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)
				Claiborne Group: Cane River Formation	X	Claiborne Group: Tallahata Formation	X	Claiborne Group: Zilpha Clay		X	Lower Claiborne confining unit (13)
				Claiborne Group: Carrizo Sand	X		X	X		X	Lower Claiborne-upper Wilcox aquifer (4)
			Wilcox Group: Flour Island Formation	Wilcox Group: Undifferentiated	Wilcox Formation	Wilcox Formation	X	X	Wilcox Group: Flour Island Formation	X	Middle Wilcox aquifer (3)
		Paleocene	Wilcox Group: Fort Pillow Sand		X	X	X	X	Wilcox Group: Fort Pillow Sand	X	Lower Wilcox aquifer (2)
			Wilcox Group: Old Breastworks Formation		X	X	X	X	Wilcox Group: Old Breastworks Formation	X	Midway confining unit (12)
			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 Group: Clayton Formation	Midway Group: Clayton Formation	Midway Group: Clayton Formation	Midway Group: Clayton Formation	X	X	Clayton Formation	X	
Mesozoic	Cretaceous	Upper Cretaceous	Arkadelphia Marl	X	McNairy Sand	McNairy Sand	X	X	Owl Creek Formation	X	
			Nacatoch Sand	X			X	X	McNairy Sand	X	McNairy-Nacatoch aquifer (1)
Paleozoic	X	X	Paleozoic rocks undifferentiated	X	X	X	X	X	Paleozoic rocks undifferentiated	X	Unnamed units (0)

Geography

The Mississippi River Valley alluvial aquifer occupies a vast low, flat alluvial plain with one significant interruption, Crowleys Ridge (fig. 2). The land surface slopes generally southward from an altitude of about 330 ft above sea level in the northern end of the study area to about 50 ft above sea level near Vicksburg, Mississippi at the southern end. 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 bisecting the northern half of the alluvial plain. The southern half of the ridge averages about 3 mi wide and the land surface is 100 to 150 ft above the plain. In the northern half the ridge averages about 10 mi wide and the maximum land surface altitude is about 250 ft above the plain.

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

The climate of the study area is mild and humid. Mean annual air temperature ranges from 14 °C in the north to about 19 °C near Vicksburg. Annual precipitation ranges from about 47 inches in the north to 52 inches near Vicksburg. Rainfall is not evenly distributed throughout the year, and the least rainfall occurs during late summer and early fall. Agriculture is a vital part of the economy and uses most of the ground water withdrawn in the study area. Crops grown in the region that require continuous or intermittent irrigation include rice, soybeans, cotton, and some others to a smaller degree. Aquaculture also requires large withdrawals of ground water.

Previous Investigations

The first regional studies of ground water in the study area (Crider and Johnson, 1906; Glenn, 1906; Veatch, 1906; and Shepard, 1907) gave the first evaluations of the ground-water resources of the Mississippi River Valley alluvial aquifer. However, most early studies neglected or dismissed the alluvial aquifer as an important source of water for water quality or sanitary reasons. Purdue (1904, p. 325) said that the water was so charged with iron and other minerals to be of little value. Crider and Johnson (1906, p. 5) described the waters as unwholesome. Glenn (1906, p. 105) said that wells in the alluvium give poor water. Veatch (1906, p. 87) described the water as mineral in character and like Glenn (1906) and others of their time, concentrated on deeper artesian aquifers, which were believed to be less susceptible to pollution. Veatch (1906, p. 89-91) compiled several examples of dramatic reductions in sickness when shallow wells were abandoned in favor of deeper wells. Parts of the Mississippi River Valley alluvial aquifer were described in a more detailed inventory of ground-water resources of northeastern Arkansas by Stephenson and Crider (1916) and of northwestern Mississippi by Stephenson and others (1928).

The first report covering the whole study area, which made a comprehensive contribution to the understanding of the hydrogeologic framework of the alluvial aquifer, was that of Fisk (1944). Krinitzsky and Wire (1964), in the first report with a comprehensive treatment of ground-water conditions throughout the study area as the major purpose, expanded on the hydrogeologic work of Fisk. Boswell and others (1968) named the Mississippi River Valley alluvial aquifer and presented an overview of the alluvial aquifer in the context of ground-water availability from all aquifers in the Mississippi embayment. These two reports (Krinitzsky and Wire, 1964; Boswell and others, 1968) contain references to many of the reports describing local ground-water conditions in the study area.

More-recent investigations of the Mississippi River Valley alluvial aquifer have described the results of simulating ground-water flow to predict the response of the head in the aquifer to development. Reed and Broom (1979) modeled the part of the alluvial aquifer in Arkansas south of the Arkansas River for the period 1953-70. Broom and Lyford (1981) modeled the alluvial aquifer in Arkansas northeast of the White River and generally west of Crowleys Ridge for the period 1911-78 with projections through the year 2000. Sumner and Wasson (1984) modeled the alluvial aquifer in Mississippi for the period April 1981 through September 1983 with projections through 2003. Peralta and others (1985) modeled a portion of the alluvial aquifer in Arkansas approximately between the White River and Bayou Meto for the period 1972-82 with projections to 1993. Due to limitations in scope, these models contained boundary assumptions that are not necessary in the large model used in this study (table 2). When natural boundaries are too far from the modeled area to be included, the common practice is to place assumed boundaries far enough from the area of interest so that errors in assumed boundary conditions will not be significant (Wang and Anderson, 1982, p. 108). All previous models considered the bottom of the Mississippi River Valley alluvial aquifer as a no-flow boundary.

The alluvial aquifer extends beyond the modeled area in all of the studies noted above. The aquifer extends beyond the lateral boundary of the model along 4 percent of the boundary length in this study and along 72 to 100 percent of the boundary length of previous studies. In some cases 57 to 83 percent of the boundary blocks, representing a continuation of the aquifer, contained rivers. In only two of the models was the boundary of the active modeled area coincident with the physical boundary of the aquifer for more than 25 percent of the model perimeter.

The model boundaries (table 2) also differ in the degree to which they constrain the simulated flow system. The most specific and most constraining boundaries are those specifying constant head or constant flux. These include the boundaries listed on table 2 as constant head, variable specified head, constant flux, and no-flow. The constant head and variable specified head boundaries sometimes cause modeled aquifer systems to become insensitive to changes in hydraulic conductivity (Franke and Reilly, 1987, p. 8). The use of constant flux to simulate inflow (recharge) to the top of the aquifer in transient models of a ground-water system undergoing extensive development is also too constraining. Bredehoeft and Young (1970) indicated that major ground-water development may significantly change recharge-discharge relations with time. Freeze (1971) gave an example of how a ground-water system may show increases in the rate of recharge with time as a response to increased withdrawals. A head-dependent flux boundary, a combination or mixed condition boundary, can be used to describe flux to an active block described as a function of the head gradient between the active area and the area outside the modeled area and of the conductance of the material outside the active area. The description of head dependent boundaries used in this study may be found in Ackerman (1989a, fig. 20).

Table 2.--Nature of boundary treatments used in models of the Mississippi River Valley alluvial aquifer

[CH = constant head; HDF = head-dependent flux; CF = constant flux; VF = variable flux; VSH = variable specified head (time variable constant head)]

	Reed and Broom (1979)	Broom and Lyford (1981)	Sumner and Wasson (1984)	Peralta and others (1985)	Ackerman (1989a)
Approximate model area, in square miles	3,200	9,000 (5,300)[1]	7,000	1,900	38,400
Block size, in square miles	1.778	9.000	6.180	9.000	25.000
Boundary condition treatments					
Bottom	no-flow	no-flow	no-flow	no-flow	HDF
Top (recharge)	VF[2]	CF	CF	no-flow	HDF
Rivers	VSH, HDF	CH	HDF, VSH	none	HDF
Adjacent aquifer beyond active model area	HDF	no-flow	VSH	CH	HDF
Adjacent non-aquifer material	no-flow	no-flow	none	none	HDF
Lateral boundary, in percent					
Adjacent aquifer					
no flow		14			
CH				100	
VSH			43		
HDF	14				4
Adjacent aquifer under river					
CH		83			
VSH	45		57		
HDF	13				
Adjacent non-aquifer material					
no flow	28	4			
HDF					96

[1]Actual area simulated with pumpage less than total model area

[2]A function of precipitation and pan evaporation

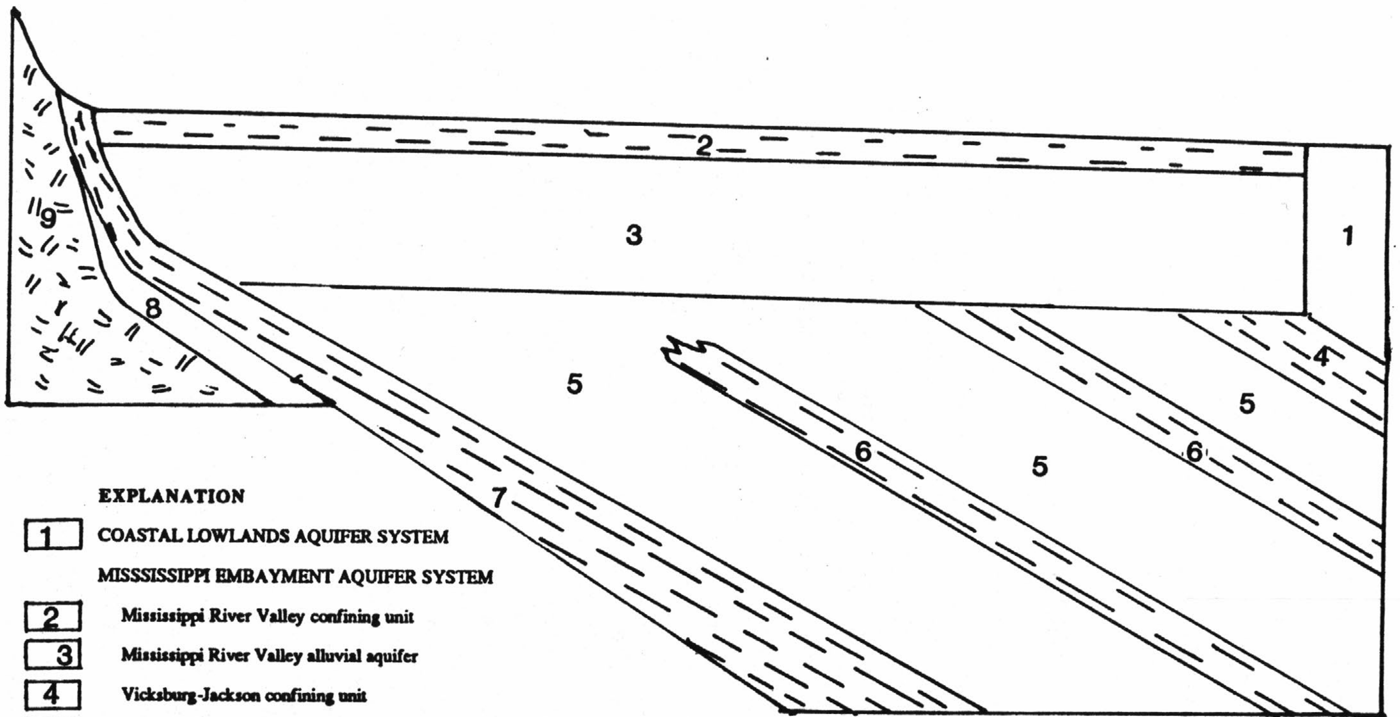
The use of the less constraining head-dependent flux boundaries and the location of the model boundary at the aquifer boundary should make the model analysis described in this report useful for evaluating boundaries used in previous models and for selecting boundary conditions in future studies. The quantitative description of the development of the ground water flow system contained in this report should increase the understanding of the regional flow and aid more detailed local studies. An analysis of the components of the flow budget and changes in head as a result of simulated development may show some more constrained choices of boundary conditions to be reasonable compromises for certain models.

HYDROGEOLOGIC SETTING

The Mississippi River Valley alluvial aquifer (Boswell and others, 1968), as shown on figures 2 and 3, is a part of the Mississippi embayment aquifer system (Grubb, 1984). The regional hydrogeologic framework and nomenclature of the Mississippi embayment aquifer system as used in this study is described in Professional Paper 1416-B (Hosman and Weiss, in press).

The study area of the alluvial aquifer was divided into five areas (fig. 2). The primary basis for the division was the existence of lateral boundaries that controlled regional flow patterns. Those boundaries are Crowleys Ridge, the Mississippi River, the Arkansas River, and the White and Little Red Rivers. Large simulated flux through the alluvial aquifer between underlying units and rivers in the subcrop of Cretaceous and older rocks tended to obscure interpretations in the remainder of the study area (Ackerman, 1989a, p. 56). Therefore the edge of the subcrop of the McNairy-Nacatoch aquifer (updip limit of the subcrop of Midway confining unit) also was used as an area boundary. The names of each area were derived from local physiographic names or from the name of a river near the axis of the area. The area descriptions are as follows:

Area	Description
Grand Prairie	The area north and east of the Arkansas River and south and west of the White and Little Red Rivers. This area is named for an informal physiographic name in common use. The boundaries of the Grand Prairie are rarely consistent between authors (Engler and others, 1945, fig. 1; Krinitzsky and Wire, 1964, fig. 2), but all lie within this area.
Cache	The area west of Crowleys Ridge, north and east of the White River, and south and east of the subcrop of the McNairy-Nacatoch aquifer.
Delta	The area east of the Mississippi River in the State of Mississippi. This area corresponds to the drainage of the Yazoo River and is locally called "the Delta" (Sumner and Wasson, 1984, p. 2).



EXPLANATION

- [1] COASTAL LOWLANDS AQUIFER SYSTEM
- MISSSISSIPPI EMBAYMENT AQUIFER SYSTEM
  - [2] Mississippi River Valley confining unit
  - [3] Mississippi River Valley alluvial aquifer
  - [4] Vicksburg-Jackson confining unit
  - [5] Aquifers in Eocene rocks
  - [6] Confining units in Eocene rocks
- [7] MIDWAY CONFINING UNIT
- [8] McNAIRY-NACATOCH AQUIFER
- [9] PALEOZOIC ROCKS, UNDIFFERENTIATED

FIGURE 3–Relation of hydrogeologic units. [Modified from Grubb 1986, figure 93].

Boeuf	The area south of the Arkansas River and west of the Mississippi River.
St. Francis	The area west of the Mississippi River, east of Crowleys Ridge, and south and east of the subcrop of the McNairy-Nacatoch aquifer.

Most of the following description of the hydrogeologic setting of the aquifer is derived from a preliminary report of this study (Ackerman, 1989a). In turn, much of the preliminary report is a synthesis of the regional and local studies of the Mississippi River Valley alluvial aquifer since about 1900. Reference to many of the local studies also can be found in Ackerman (1989a). In this report the Mississippi River Valley alluvial aquifer is often referred to as the alluvial aquifer or simply the aquifer.

Framework and Hydraulic Properties of the Alluvial Aquifer

The hydrogeology of the alluvial aquifer is relatively simple when considered at a regional scale. The Quaternary alluvium overlies and is laterally adjacent to aquifers and confining beds in older rock units. 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.

The base of the alluvial aquifer is a sub-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.

Three components of contrasting hydraulic conductivity comprise the Mississippi River Valley alluvial aquifer system (fig. 3). 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 overlying unit confine the alluvial aquifer in most places. Some of the underlying or adjacent strata are considered as confining units that provide varying degrees of hydraulic connection with underlying deeper aquifers over much of the area. Even where aquifers directly underlie the alluvial aquifer, the contrast between the higher hydraulic conductivity of the coarse lower part of the alluvial aquifer and the lower hydraulic conductivity of underlying aquifers is sufficient to differentiate the aquifers.

The Mississippi River Valley alluvial aquifer consists of an extensive deposit of unconsolidated sand and gravel in alluvium and terrace deposits. The alluvium has long been recognized as containing two distinct lithologies (Fisk, 1944, p. 17; Boswell and others, 1968, p. 4). The formal differentiation of the aquifer from its overlying confining unit was first proposed (Ackerman, 1989a, p. 14) as a part of this study. Descriptions of the alluvial aquifer in this report may be somewhat more specific or limited in terms of thickness than some previous reports that considered the total thickness of alluvium.

The areal distribution of the underlying and adjacent hydrogeologic units is shown in figure 4. Section A-A' (fig. 5) crosses Crowleys Ridge and shows the relation of overlying and underlying units in the north. Section B-B' (fig. 6) crosses the midsection of the study area and the subcrop of most of the hydrogeologic units.

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, p. 21). The lower part of the aquifer generally is a coarse sand matrix with 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 occur at many places in the aquifer.

Although the alluvial aquifer extends from the apex of the Mississippi embayment near the confluence of the Mississippi and Ohio Rivers southward under the Mississippi Alluvial Plain to the Gulf of Mexico, this study concentrates on the part of the aquifer north of the southern limit of the subcrop of the Jackson Group and Vicksburg Formation (fig. 4), 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 at 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 erosional remnant of Tertiary strata. In some places the lateral contact of the alluvial aquifer with older strata is masked by a thin covering of older terrace deposits. The lateral boundaries shown on figure 4 are modified from a map in Hosman and Weiss (in press) 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 (fig. 6b). Local extremes of thickness for the alluvial aquifer occur where the Mississippi River Valley confining unit is absent or very thick. Except in areas where cones of depression have developed, the potentiometric surface of the alluvial aquifer is above or near the top of the aquifer. Therefore, saturated thickness is usually equal to the thickness of aquifer materials.

Hydraulic conductivity values for 51 aquifer tests in the alluvial aquifer generally ranged from 120 to 330 ft/d and had a geometric mean of 205 ft/d (A.K. Williamson, U.S. Geological Survey, written commun., 1985). This is in agreement with 38 hydraulic conductivity values given by Krinitzsky and Wire (1964, table 2). Their reported values generally were between 120 and 390 ft/d and had a geometric mean of 210 ft/d. Newcome (1971) reported an average hydraulic conductivity of 200 ft/d and a range of 90 to 400 ft/d for the alluvial aquifer in Mississippi.

Storage coefficients of the alluvial aquifer generally are between values of specific yield, indicating unconfined conditions, and values of about 0.0001, representing confined conditions. Of 75 storage-coefficient observations, mostly from Arkansas, 16 were between 0.02 and 0.15; 34 between 0.001 and 0.01; and 25 between 0.0001 and 0.0009 (A.K. Williamson, U.S. Geological Survey, written commun., 1985). Specific yield from laboratory tests on repacked samples from Arkansas County, Arkansas ranged from 0.27 to 0.38 (Johnson and others, 1966, p. 23). Values of 0.31 to 0.38 were determined for samples from the bottom of the aquifer and a value of 0.27 was

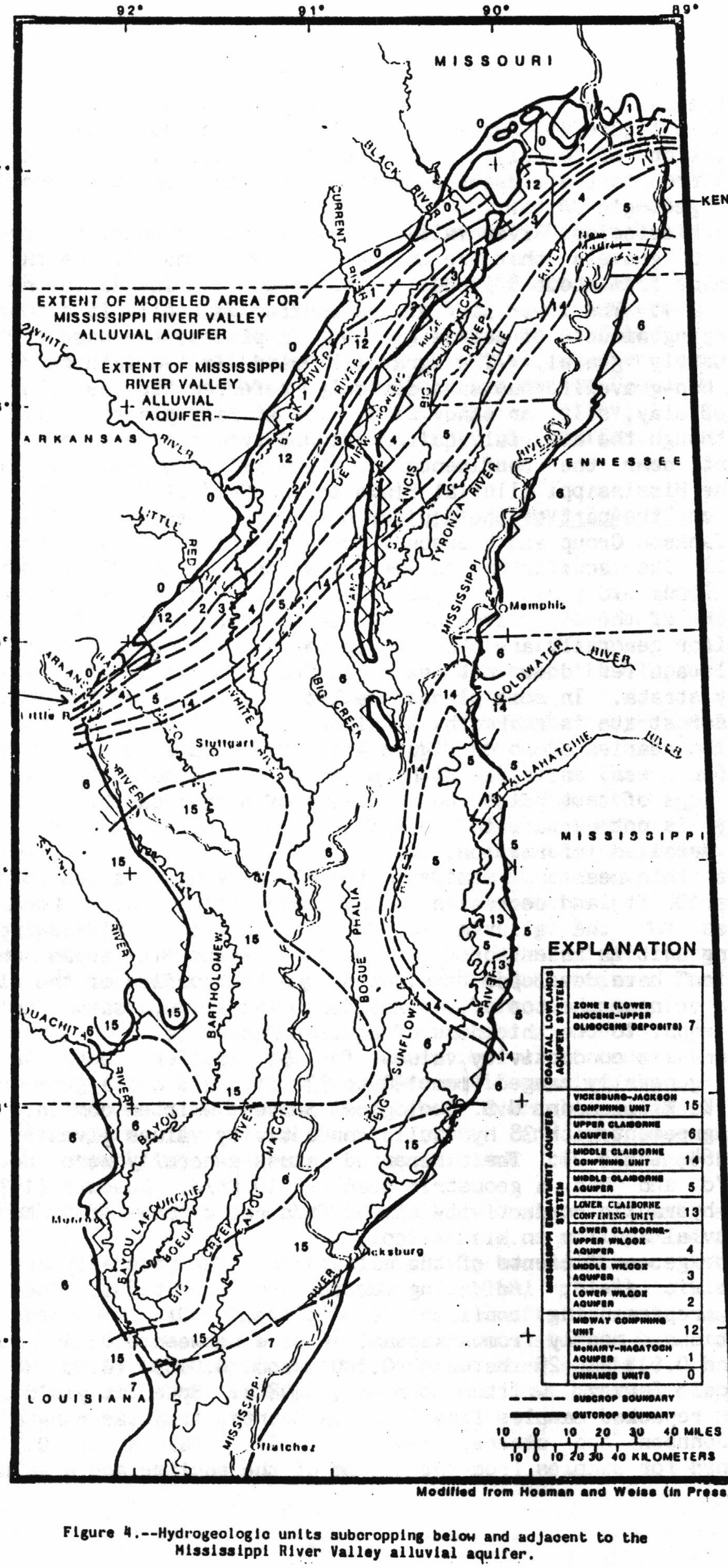


Figure 4.--Hydrogeologic units subcropping below and adjacent to the Mississippi River Valley alluvial aquifer.

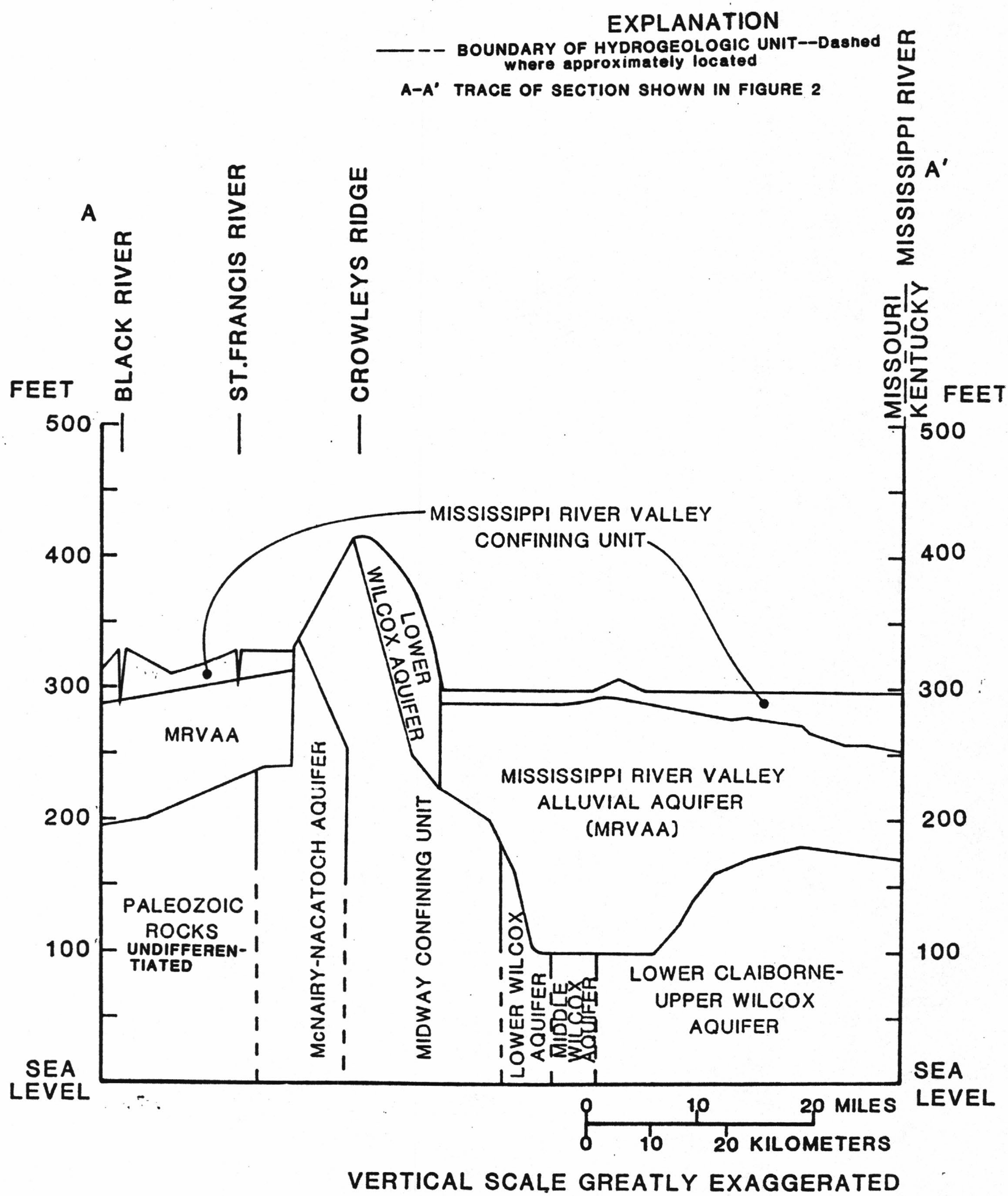


Figure 5.--Hydrogeologic section A-A' [from Ackerman, 1988, figure 16].

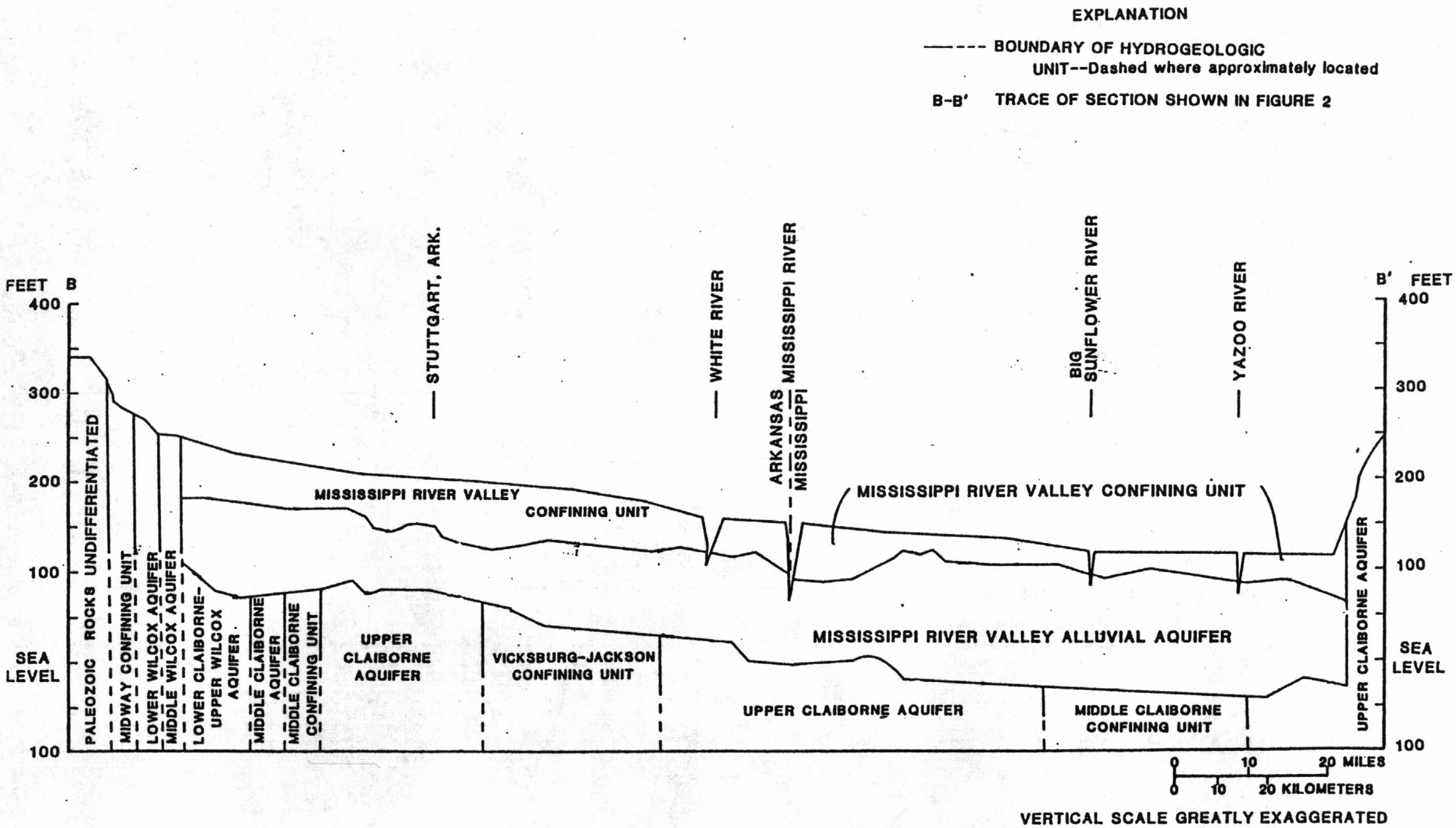


Figure 6.--Hydrogeologic section B-B' [from Ackerman, 1988, figure 17].

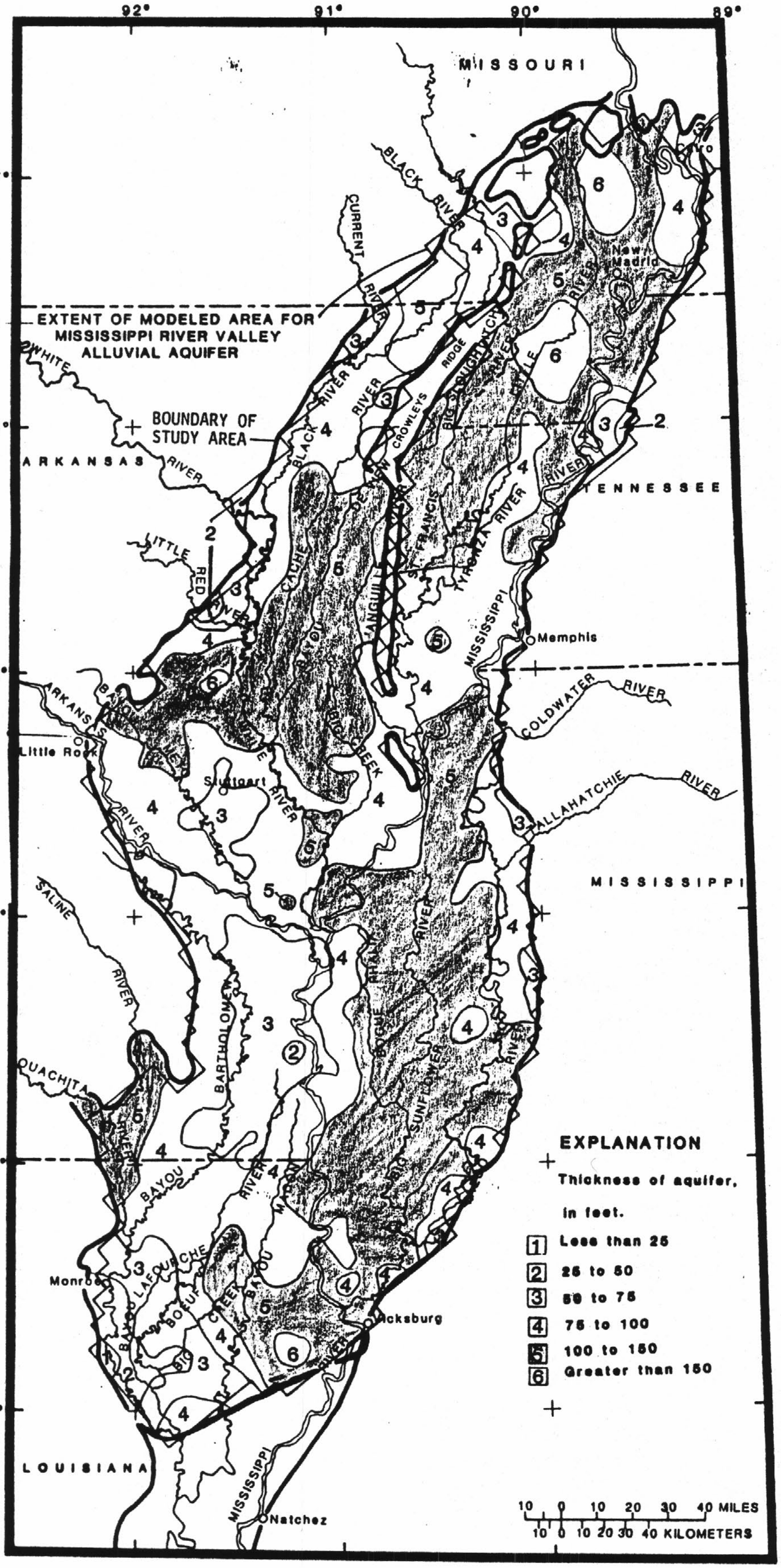


Figure 6b.--Thickness of Mississippi River Valley alluvial aquifer.

estimated for material near the top. Results of long-term aquifer tests at the same site indicated a storage coefficient of 0.28 after 4 days of pumping (Sniegocki and others, 1965, p. 5). A storage coefficient of 0.30 was reached after 9 days of recharge tests at the same location (Sniegocki and others, 1965, p. 8). Data for hydraulic conductivity and storage coefficient were insufficient to describe the areal distribution of these aquifer properties.

Relation of the Alluvial Aquifer to Adjacent Units

The Mississippi River Valley alluvial aquifer is bounded on the top by the Mississippi River Valley confining unit and on the bottom and sides by other units in the Mississippi embayment aquifer system, the McNairy-Nacatoch aquifer, and by undifferentiated Paleozoic rocks (figs. 3-7). The adjacent units have lower hydraulic conductivities and different lithologic characteristics sufficient to distinguish them from the alluvial aquifer. The only exception is a short segment of the southern boundary in Louisiana where the alluvial aquifer continues to the south.

The southern boundary (subcrop of the Vicksburg-Jackson confining unit) is approximately perpendicular to the contours of the alluvial aquifer potentiometric surface as shown by Whitfield (1975, fig. 2). Although the southern boundary does not represent a hydraulic conductivity contrast, it is a definable hydrologic boundary which can be considered no-flow so long as there are no pumping wells near the boundary.

Mississippi River Valley Confining Unit

Throughout most of the study area clays, silts, and fine-grained sands overlie and confine the Mississippi River Valley alluvial aquifer and impede inflow (Krinitzsky and Wire, 1964, p. 90). The overlying beds of fine-grained material were named the Mississippi River Valley confining unit by Ackerman (1989a, p. 14). 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, it generally ranges from 10 ft to 50 ft in thickness and averages 30 ft. Locally it can be as much as 150 ft in thickness (fig. 7). The confining unit is thinnest in the north and near the margins of the aquifer (Fisk, 1944, 1947). Although confining unit thickness is highly variable, thickness increases from north to south (Ackerman, 1989a, fig. 9). The confining unit is thickest beneath the Grand Prairie near Stuttgart, Arkansas, where it is consistently greater than 50 ft.

In the study area three major types of depositional environments can be described for the 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).

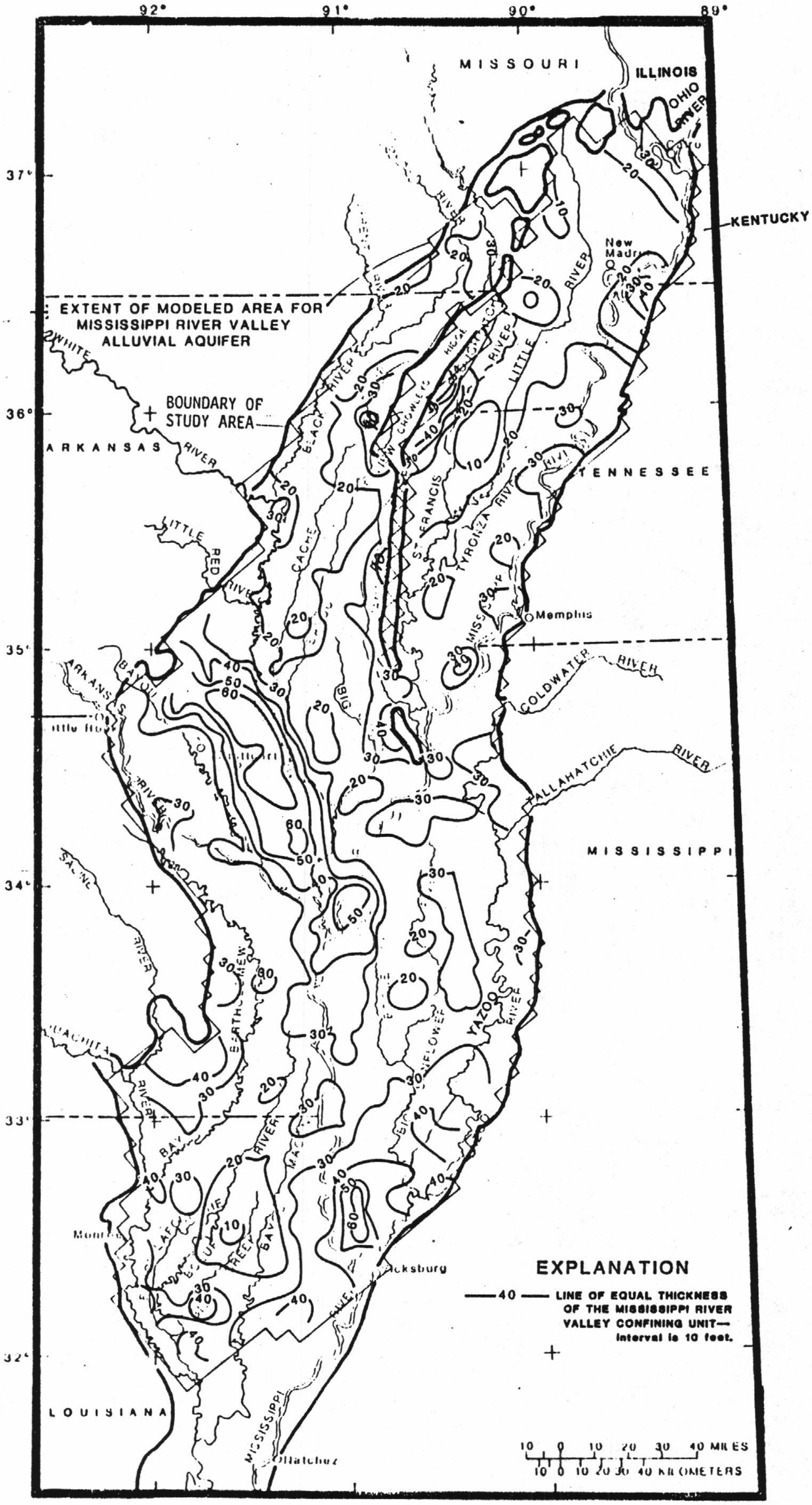


Figure 7.--Thickness of the Mississippi River Valley confining unit [From Ackerman, 1988, figure 11].

Laboratory determinations of hydraulic conductivity for samples of the confining unit in the clay to silty sand textures ranged from 0.0001 to 0.5 ft/d (M.S. Bedinger, U.S. Geological Survey, written commun., 1960). These values are reasonable for the grain sizes of the samples (Freeze and Cherry, 1979, p. 29).

Underlying Units

Nomenclature for aquifers and confining units subcropping the Mississippi River Valley alluvial aquifer is shown in table 1 and the subcrop patterns are shown in figure 4. Paleozoic units are the oldest strata underlying the alluvial aquifer (table 1). The Paleozoic rocks consist of shales, limestones, dolomites, and quartzites of uncertain but probably very low hydraulic conductivity (Brahana and Mesko, 1988, p. 4). The remaining subcropping aquifers and confining units, which correspond to hydrologic units of the Mississippi embayment aquifer system and the McNairy-Nacatoch aquifer, 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 are regional aquifers. Horizontal hydraulic conductivities of these underlying aquifers generally range from 10 to 172 ft/d (Brahana and Mesko, 1988, p. 21; Arthur and Taylor, 1989, table 2).

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). Data are not available on the hydraulic conductivity of these materials, but similar materials would range from 10^{-7} to 10^{-3} ft/d (Freeze and Cherry, 1979, p. 29).

For a more complete discussion of the hydrogeologic framework of aquifer systems underlying the alluvial aquifer the reader is referred to Boswell and others (1965), Hosman and others (1968), Brahana and Mesko (1988), and Arthur and Taylor (1989). These aquifers and confining units also are discussed in other chapters of Professional Paper 1416.

Lateral Units

The lateral boundary of the Mississippi River Valley alluvial aquifer is the contact with the same hydrogeologic units as those underlying the aquifer. Much of the boundary is a contact with Paleozoic rocks and various confining units of very low hydraulic conductivity. The remainder of the boundary consists of the contact with other aquifers of the Mississippi embayment aquifer system that generally have a distinctly lower hydraulic conductivity than the alluvial aquifer. In the study area, Crowleys Ridge forms an interruption to the continuity of lithology and ground-water flow of the aquifer. The rocks of the ridge have a lower hydraulic conductivity (Hines and others, 1972, sheet 2) and, consequently, restrict flow. The effects of the restriction are seen in the steep potentiometric gradients and drawdowns in the alluvial aquifer at the west edge of the ridge. Wells constructed in the Ridge have water levels higher than those in the surrounding alluvium. At the least, Crowleys ridge would be the site of a drainage divide and, therefore, a barrier for the alluvial flow system.

The concept of Crowleys Ridge as a barrier or restriction to flow in the alluvial aquifer conflicts with the treatment used by Broom and Lyford (1981, p. 35). They treat Crowleys Ridge as a continuation of the alluvial aquifer but with a lower hydraulic conductivity. The treatment of this boundary will be discusssed further in the section on the predevelopment potentiometric surface.

Relation of the Alluvial Aquifer to Rivers

The Mississippi River Valley alluvial aquifer is penetrated by numerous rivers. The rivers received most of the outflow from the aquifer before modern development of the aquifer and have become the source of much inflow since development of the aquifer (Ackerman, 1989a). The rivers may or may not be in good hydraulic connection with the alluvial aquifer depending on the nature of riverbed materials and the depth to which the rivers penetrate the confining unit and the aquifer. The effect and degree of hydraulic connection between the alluvial aquifer and rivers can be seen in the hydrographs of four rivers and nearby wells (fig. 8). These hydrographs of shallow wells (all within 500 ft of the river stage gage) show differing degrees of correlation with river stage hydrographs. Hydrographs A and B show good connection between the aquifer and the rivers. Sites C and D show little or no correlation. Sites A, B, and C are classified as perennial streams with a 7-day, 10-year low flow of about 6,000, 16, and 7 ft^3/s, respectively (Hunrichs, 1983). For site D the recurrence interval of 7-day zero flow is 3 years (Hunrichs, 1983). Site D is a location where the top of the aquifer is below the bottom of the river. Site C is a location where the potentiometric surface has declined below the riverbed.

In some areas the potentiometric surface in the alluvial aquifer has declined sufficiently to remain below the streambed of rivers. Examples are some reaches of: the Big Sunflower River (Sumner and Wasson, 1984, p. 10); the Cache River (fig. 8C); and Bayou Meto, currently not a perennial stream for most of its length (Hunrichs, 1983).

This analysis of the exchange of water between rivers and the alluvial aquifer only considers net regional flow over time spans of years, and does not consider seasonal or local changes in flow. The flow between the aquifer and a river varies, and may be either inflow or outflow at different times during the year, depending on fluctuations in the direction of the head gradient. Fluctuations in river stage generally are greater than aquifer water-level changes. As the rivers change in stage, water moves in and out of aquifer storage near the river. The most striking example of this relation is found near the Mississippi River. The stage range on the Mississippi River is much greater than other rivers in the study area (Ackerman, 1989a, fig. 13). Water stored in the aquifer within a few miles of the river during a spring high stage is released to the river during lower stage in the late summer (fig. 9). Even during this release to the river in late summer, water in the aquifer continues to move toward a low on the potentiometric surface near the Big Sunflower River. A large part of the water moving away from the Mississippi River is inflow to the aquifer from the river (Sumner and Wasson, 1984, p. 47). Most of the ground water being discharged to the river is probably bank storage.

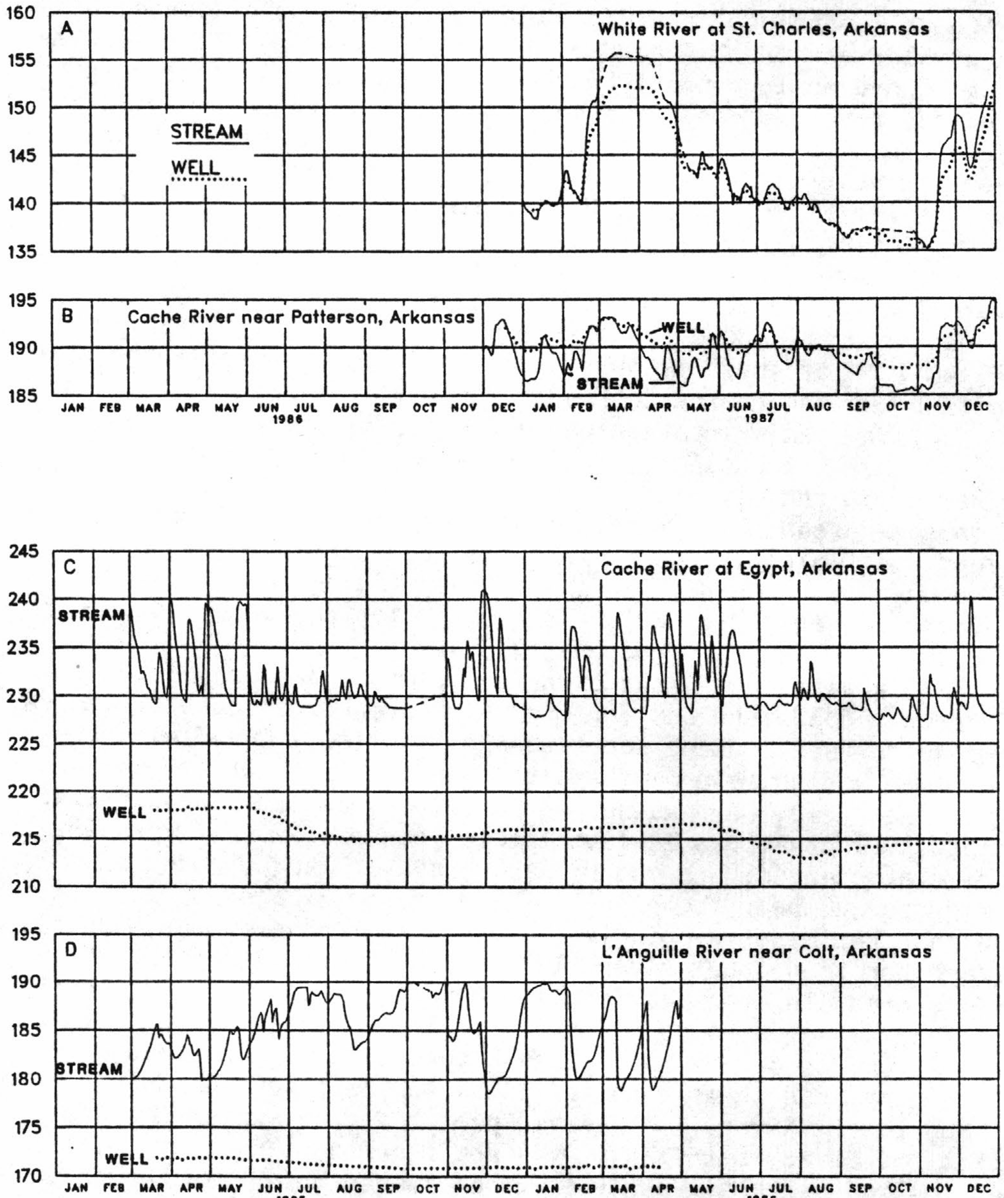


FIGURE 8.— Water levels for selected wells and nearby rivers. Water levels dashed where data are missing.

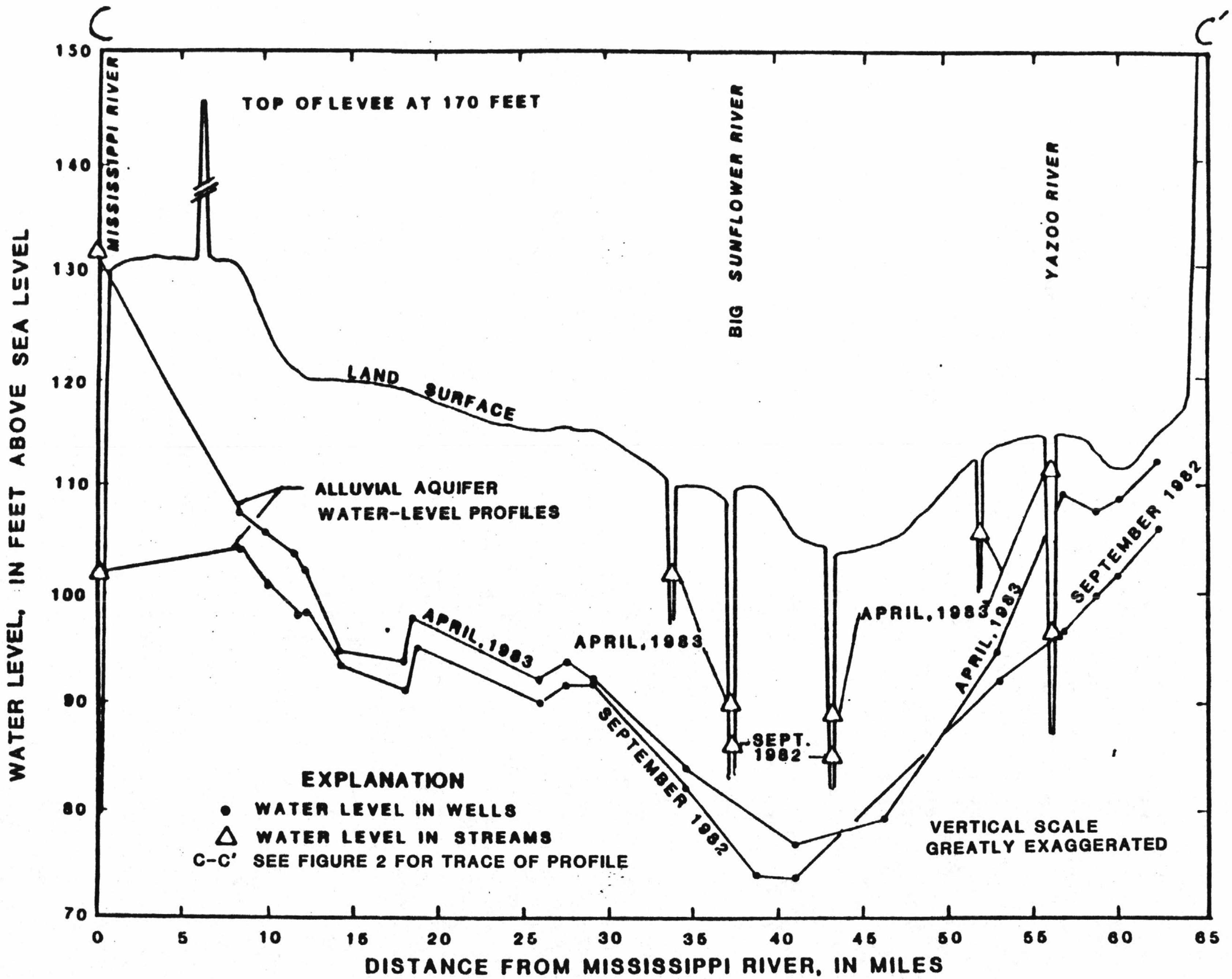


Figure 9.--Water-level profiles in the Mississippi River Valley alluvial aquifer across northwestern Mississippi (modified from Sumner and Wason, 1984, figure 7).

The Mississippi River is the widest, deepest, and largest river in the study area and has the largest sustained flow. The average discharge at Memphis is 485,000 ft^3/s and the 7-day, 10-year low flow is 119,000 ft^3/s (Hunrichs, 1983). During most of the year the river is a drain to the alluvial aquifer (Ryling, 1960, p. 26; Plebuch, 1961, p. 37; Luckey, 1985, p. 24). The Mississippi River is a hydrologic flow boundary in the alluvial aquifer because it commonly cuts through the entire thickness of the aquifer (Whitfield, 1975, p. 6; Ackerman, 1989a, fig. 10) and its stage controls ground-water flow on both sides of the river. The areas where water levels are most affected by the Mississippi River are relatively small west of the river as compared to areas affected by other rivers and drains that are of lower altitude (Luckey, 1985, p. 24; Ackerman, 1989a).

The White and Arkansas Rivers penetrate the alluvial aquifer and have large perennial discharges. They are effective hydrologic boundaries in the alluvial aquifer. These rivers border areas where large withdrawals have increased head gradients in the alluvial aquifer. The steep head gradients approach but do not extend beyond these rivers. There is no evidence of long-term decline in potentiometric head in the vicinity of the rivers, only short-term changes correlated with river stage.

Quality of Water in the Alluvial Aquifer

Water from the Mississippi River Valley alluvial aquifer is suitable for most uses, and is used extensively for irrigation and industry. It is used for public supply, usually with treatment, only where an adequate supply of water of better quality is not available from deeper aquifers (Boswell and others, 1968, p. 13). The two water characteristics cited most frequently that limit the usefulness of water for public supply from the alluvial aquifer are excessive hardness and high concentrations of iron and manganese. Median concentrations for hardness as calcium carbonate and iron given by Jeffery (Boswell and others, 1968, p. 12) were approximately 250 and 5 mg/L (milligrams per liter), respectively. Most analyses of water from the alluvial aquifer indicate either a calcium bicarbonate or calcium-magnesium bicarbonate type water with less than 250 mg/L total dissolved solids.

In isolated areas the alluvial aquifer contains water with more than 250 mg/L of chloride. Areas of the aquifer ranging from 25 to 75 mi^2 yielding water with more than 250 mg/L of chloride have been described by Whitfield (1975, p. 12), Fitzpatrick (1985), and Morris and Bush (1986). A source of saline water below the alluvial aquifer is suspected, but no avenue of movement of saline water to the aquifer has been proven conclusively.

Because water in the alluvial aquifer generally is of such uniform and dilute chemistry (Pettijohn and others, 1988), little knowledge of regional flow can be determined from the geochemistry of water using available data. Because of the low total dissolved solids, density of the water as a function of salinity is not a consideration in the regional flow in the alluvial aquifer.

REGIONAL FLOW SYSTEM

Regional ground-water flow in the Mississippi River Valley alluvial aquifer was analyzed by model simulations from predevelopment (prior to aquifer withdrawals) to modern-day conditions. A finite-difference digital ground-water model (McDonald and Harbaugh, 1984) was used to simulate two-dimensional confined or unconfined steady-state and transient regional flow. The description of the regional flow system, the changes in flow system, and the evaluation of the potential for further ground-water development are the result of the analysis of pumpage, hydraulic head data, and simulation output. The transient model simulates the distribution of head and the components of the flow budget (inflow, outflow, and change in storage) from estimated pumping conditions for the period 1906-87. Comparisons were made between pumping and predevelopment conditions. Aquifer response to projected continuance or increased pumpage for periods of 10 and 20 years also were simulated to evaluate the potential for continued ground-water development. A complete discussion of the conceptual model of the flow system, the hydrogeologic framework, the input data for the model, and the preliminary calibration procedure for a model of steady-state flow for predevelopment and 1972 conditions are in a previous report (Ackerman, 1989a). A discussion of model adaptation for transient analysis and of the final calibration values are in the appendix at the end of this report. A short description of how the aquifer properties and boundaries were modeled is provided below and the reader is referred to Ackerman (1989a) and the appendix section of this report for detailed discussions of these topics.

Transmissivity was calculated from the saturated aquifer thickness (fig. 6b) multiplied by a uniform value of hydraulic conductivity within each of the five areas shown in figure 2. The hydraulic conductivity varied from 200 to 450 ft/d and is given in the appendix (table 8). Uniform values of specific yield (0.28) and confined storage coefficient (0.0001) were used for the entire aquifer. Vertical flow from an overlying source head at the altitude of land surface shown in figure 9aa (Ackerman, 1989a, p. 38) was controlled by the thickness of the Mississippi River Valley alluvial confining unit (fig. 7) and a model-derived vertical hydraulic conductivity of 0.00035 ft/d for all areas except for the Boeuf area where the value was 0.00044 ft/d (see Appendix, table 8). Flow between underlying aquifers and the alluvial aquifer, and between adjacent aquifers and the alluvial aquifer was controlled by the vertical or horizontal hydraulic conductivities and thicknkesses of the respective units as shown diagrammatically in fig. 9a (Ackerman, 1989a, fig. 20). Vertical hydraulic conductivities of the underlying aquifers of the Mississippi embayment aqufier system were reported by Arthur and Taylor (1989) and range from 0.0001 to 0.00001 ft/d. Vertical hydraulic conductivities of the underlying McNairy-Nacatoch and Ozark-St. Francois aquifers were reported by Brahana and Mesko (1988) and range from 0.0000043 to 0.000000173 ft/d. Flow between rivers and the aquifer was controlled by using previously tabulated river widths (Ackerman, 1989a, table 3) and lengths with a uniform value (0.16 per day) of the ratio of vertical stream bed hydraulic conductivity to stream bed thickness.

Hydraulic heads from simulations of flow in the underlying aquifers of the Mississippi embayment aquifer system and the McNairy-Nacatoch aquifer were used to calculate gradients relative to the alluvial aquifer for each pumping period. Mean annual stage at stream gaging stations was used to estimate the hydraulic head in rivers as discussed in detail by Ackerman (1989a, p. 38).

The following conventions are used for labeling the components of flow and in describing the hydrologic budget. Net flow to the aquifer from rivers, underlying confining units, adjacent units, the Mississippi River Valley confining unit, and other forms of recharge is inflow. Net flow from the aquifer to rivers, underlying confining units, wells, the Mississippi River Valley confining unit, the adjacent part of the aquifer to the south, and

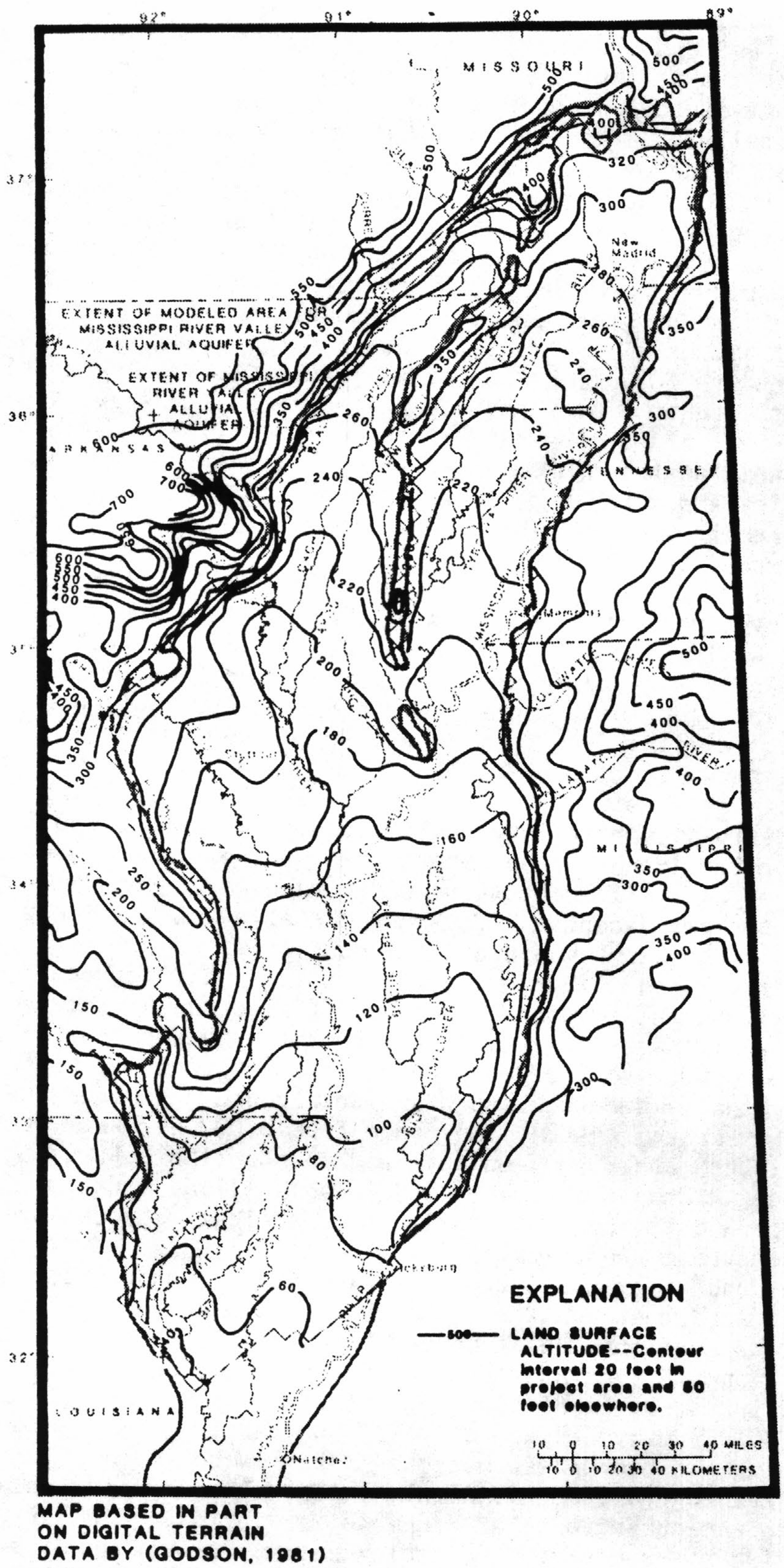


Figure 9aa.--Topography in and near the study area.

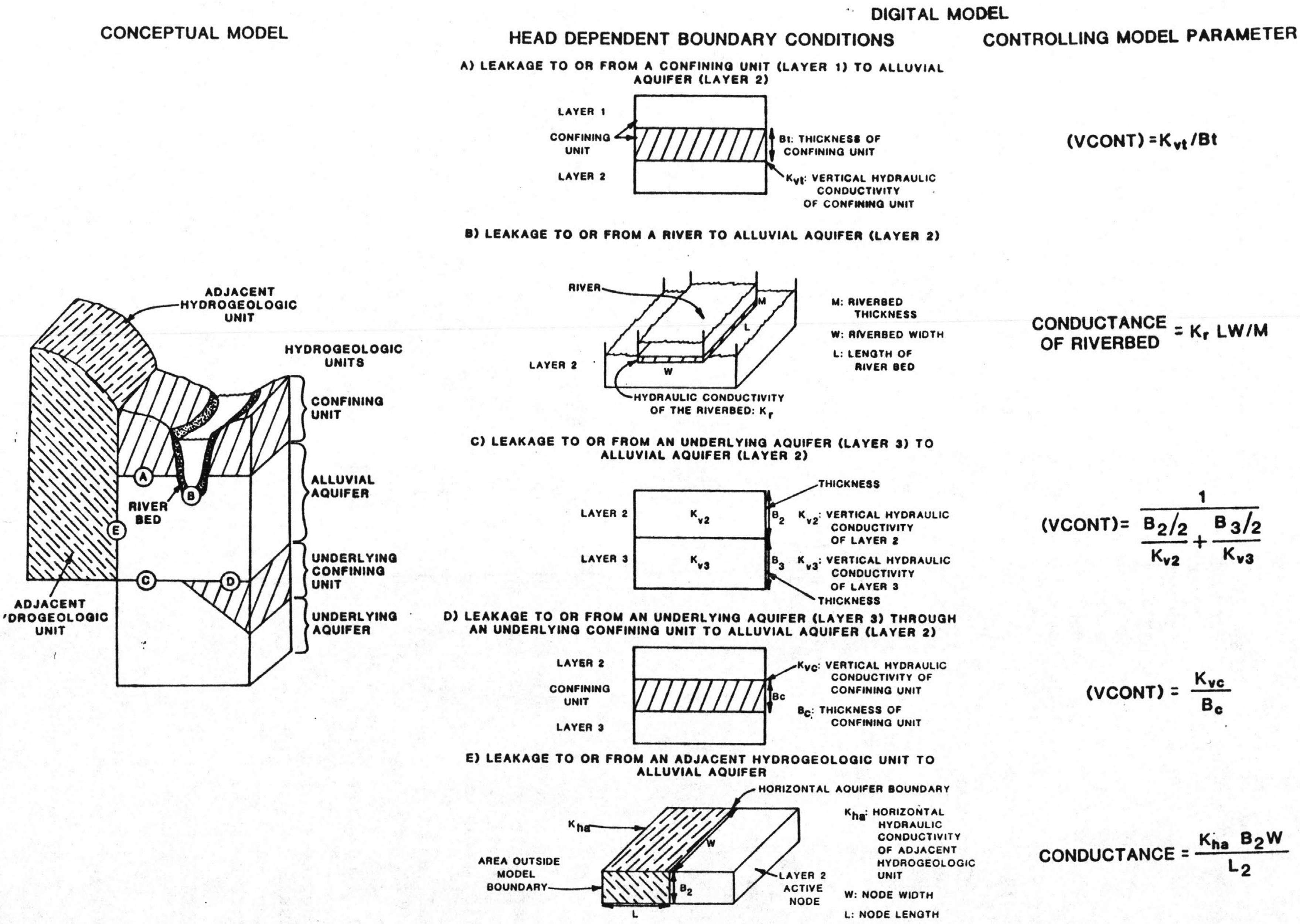


Figure 9a.--Conceptual and digital model of head-dependent boundaries.

other forms of discharge is outflow. Because the dominant trend since predevelopment has been a decrease in water stored in the aquifer, it is convenient to discuss components of flow as percent of total outflow. The inflow plus the net change in storage (decrease of water in storage) is equal to the outflow. In some parts of the aquifer and for the entire aquifer after the mid-1970's, proportions of total flow (outflow) may be considered as proportions of pumpage--the only net outflow.

Rates of water as presented in the hydrologic budgets, tables 3-4e and 6 are given in millions of gallons per day. These units are consistent with water-use data for the project (Mesko and others, 1990). Comparisons of rates within and between areas are given as rates normalized for area. The smallest unit of area used in this analysis was the surface of a model block, 25 mi^2. The comparisons of rates within and between areas are expressed as inches per year which are equivalent to 1.190 Mgal/d per 25 mi^2.

Predevelopment Steady-State Flow in the Alluvial Aquifer

Prior to agricultural development of the Mississippi River Valley alluvial plain, much of the land was often flooded or wet, especially parts of the St. Francis area (Crider, 1906, p. 56). Wetlands drainage, flood control, navigation improvements, and agricultural land use have significantly reduced the amount of wetlands. For the purposes of this study the predevelopment flow system is that which would result if pumping from wells were discontinued but drainage, flood control, and river navigation infrastructures were maintained.

Hydrologic Budget

A hydrologic budget was developed for simulated predevelopment regional ground-water flow in the Mississippi River Valley alluvial aquifer (fig. 10 and table 3). Inflow to the aquifer was down through the Mississippi River Valley confining unit and up from underlying units. Outflow from the aquifer was to rivers. Lateral inflow from adjacent hydrogeologic units was a very small (about 1 percent) part of total flow. The flow to and from the alluvial aquifer was separated in two categories based on the aquifers that underlie the study area. The first is a large area of about 30,000 mi^2 (94 percent of the study area) where the more extensive aquifers and confining units of the Mississippi embayment aquifer system subcrop the alluvium (corresponds to the subregional study of Arthur and Taylor, 1989). The second is a small area of about 2,000 mi^2 along the northwestern boundary where the Paleocene Midway Group and older rocks subcrop the alluvium (corresponds to the McNairy-Nacatoch subregional study described by Brahana and Mesko, 1988). The Cache and St. Francis areas extend beyond the limits of aquifers in the Mississippi embayment aquifer system and include the very slight flow through the Midway confining unit.

The amount of flow from the subcrop area of aquifers in Cretaceous and older rocks is large and is confined to a small discharge area near the rivers along the northwestern boundary of the study area (Ackerman, 1989a) and will not be discussed in detail. Interflow between the areas represented about 3 percent of inflow to the area underlain by the Mississippi embayment aquifer system. The total flow for the area underlain by the Mississippi embayment aquifer system sediments may be considered as most representative of the study

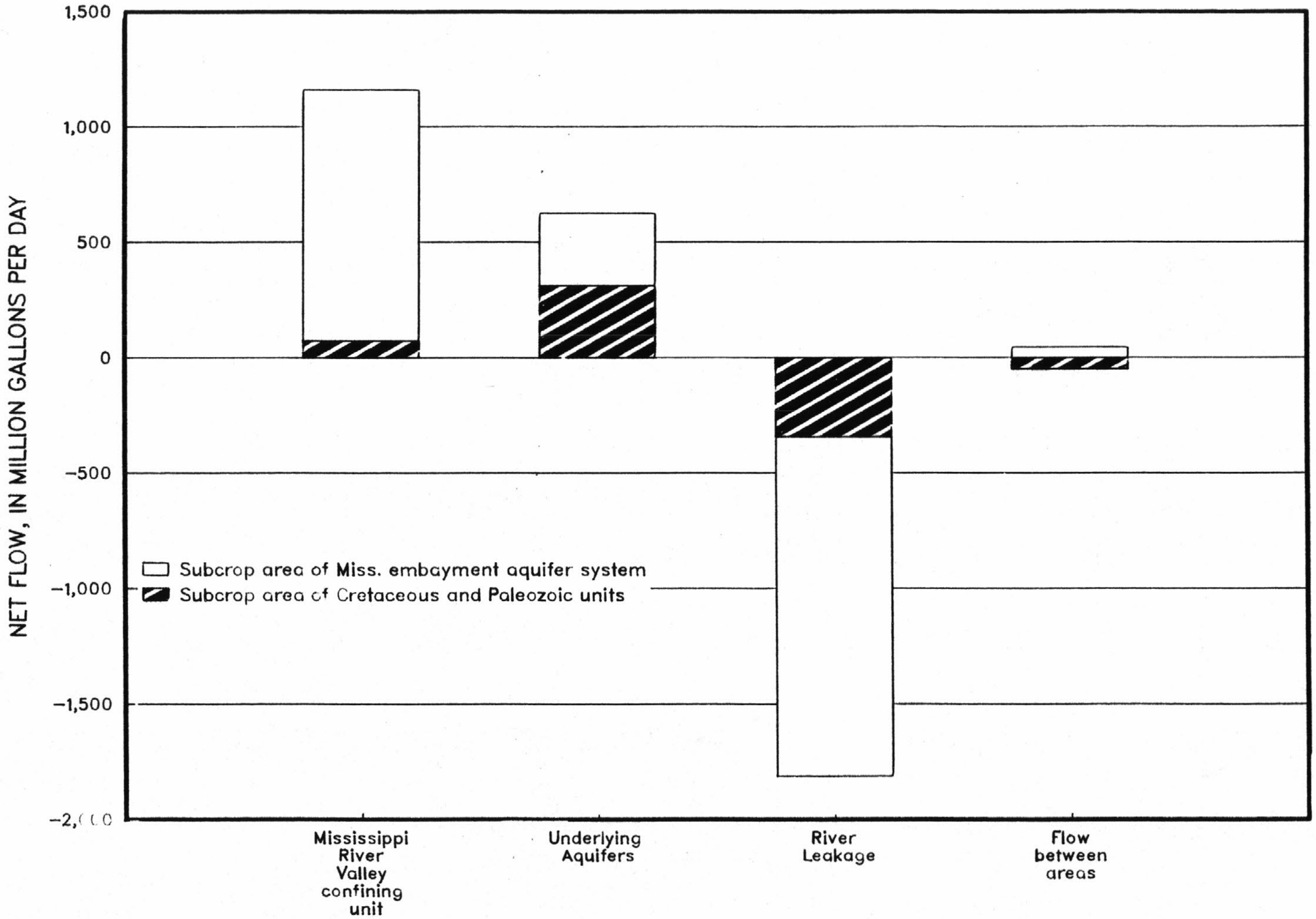


FIGURE 10.—Budget for simulated predevelopment regional flow in the Mississippi River Valley alluvial aquifer. Negative values are flow out of the aquifer.

Table 3.--Hydrologic budget for predevelopment regional flow in the Mississippi River Valley alluvial aquifer

[Net flow in million gallons per day; negative values are flow out of the aquifer; CP = subcrop of Cretaceous and Paleozoic units; MEB = subcrop of Mississippi embayment aquifer system; sums show slight variations due to rounding]

Model subcrop subareas	Mississippi River Valley confining unit	Underlying units	Adjacent units	All rivers	Interchange between outcrop areas
CP	75	314	<1	-341	-48
MEB	1,088	315	14	-1,466	+48
Total	1,163	629	15	-1,807	--

area as a whole, and will be used in subsequent tables, illustrations, and discussions. Most inflow (about 74 percent) was through the Mississippi River Valley confining unit. This corresponds to an inflow rate of 0.8 in/yr (1 Mgal/d/block). Flow from underlying aquifers represented 22 percent of inflow and corresponds to a rate of 0.2 in/yr. All outflow was to rivers. A small amount of water, 3 Mgal/d (less than 0.2 percent of the total regional flow), leaves the study area as lateral flow down the Mississippi River Valley in the alluvial aquifer to the coastal lowlands aquifer system.

In the Grand Prairie, predevelopment flow (table 4a) was dominated by vertical flow through the Mississippi River Valley confining unit to the alluvial aquifer and then lateral flow to rivers. The relative contribution from underlying aquifers (about 4 percent) was smaller than any other area. The inflow rate was about 0.7 in/yr (0.8 Mgal/d/block) through the Mississippi River Valley confining unit and 0.05 in/yr (0.06 Mgal/d/block) from underlying aquifers.

The Cache, Delta, and Boeuf areas were similar in the relative proportions of sources of inflow. In these areas most inflow was vertically through the Mississippi River Valley confining unit but a significant part of the total inflow (10 to 20 percent) to the alluvial aquifer was from underlying aquifers (tables 4b, 4c, and 4d). In the Cache area a small proportion of the outflow (less than 1 percent) left the area as lateral flow to adjacent parts of the alluvial aquifer. The inflow rates through the Mississippi River Valley confining unit were 0.8, 1.0, and 0.5 in/yr (1, 1.2, and 0.6 Mgal/d/block) in the Cache, Delta, and Boeuf areas, respectively. Inflow rates from underlying aquifers were 0.3, 0.1, and 0.2 in/yr (0.4, 0.1, and 0.2 Mgal/d/block), respectively.

The St. Francis area had a slightly larger (16 percent) contribution through the Mississippi River Valley confining unit than from underlying aquifers (table 4e). Lateral flow from adjacent areas of the alluvial aquifer amounted to about 9 percent of inflow. The inflow rate was 0.6 in/yr (0.7 Mgal/d/block) through the Mississippi River Valley confining unit and 0.4 in/yr (0.5 Mgal/d/block) from underlying aquifers.

Predevelopment Potentiometric Surface

The simulated predevelopment potentiometric surface (fig. 11) indicates movement down the Mississippi River Valley following the land surface slope toward major rivers near the axes of the St. Francis, White, Arkansas, Yazoo, and Boeuf basins. Few data are available to verify the simulated potentiometric surface. Other than the preliminary version of figure 11 (Ackerman, 1989a, fig. 31), only one other predevelopment potentiometric surface has been presented for any large area of the alluvial aquifer. That map (Broom and Lyford, 1981, plate 10) was made using model simulation results, and shows the location of several control points. The potentiometric surface (fig. 11) is in agreement with that map except near Crowleys Ridge in southern Craighead and Poinsett Counties. In that area Broom and Lyford (1981, p. 35) simulated a hydraulic connection through Crowleys Ridge. As a result, their map shows similar heads on either side of Crowleys Ridge in that area. This study simulated the contact between Crowleys Ridge and the aquifer as a head dependent flux from Ridge sediments with a distinctly smaller horizontal conductivity (Ackerman, 1989a, p. 36). The head shown on the west side of Crowleys Ridge is 20 to 30 ft greater than on the east side. This is in agreement with Hines and others (1972, sheet 1) who stated "Natural water levels in the alluvium were 25-30 ft higher west of Crowleys Ridge than east of the ridge."

Table 4a.--Hydrologic budget for regional flow in the Mississippi River Valley alluvial aquifer: Grand Prairie area

[Net flow in million gallons per day; negative values are flow out of the aquifer; data are from the end of the last time step in selected pumpage periods; sums may show variations due to rounding]

Pumpage period	Year	Mississippi River Valley confining unit	Underlying units	Adjacent units	Storage	Arkansas River	White and Little Red Rivers	Bayou Meto	All rivers	Wells
Predevelopment		83	3	0	--	-14	-49	-23	-86	--
3	1933	136	37	0	37	0	8	17	25	-236
5	1942	149	28	0	10	1	8	17	33	-220
7	1952	192	-77	0	222	15	42	36	93	-432
8	1957	207	-19	<1	233	17	48	45	116	-537
9	1962	213	-4	0	13	26	34	45	105	-327
10	1967	215	17	0	45	24	34	41	98	-376
11	1972	218	-56	<1	100	27	32	45	104	-367
12	1977	228	-37	<1	198	39	41	49	129	-519
13	1982	233	-5	<1	388	54	53	52	160	-777
14	1987	233	37	<1	268	56	59	52	167	-706

Table 4b.--Hydrologic budget for regional flow in the Mississippi River Valley alluvial aquifer: Cache area

[Net flow in million gallons per day; negative values are flow out of the aquifer; data are from the end of the last time step in selected pumpage periods; sums may show variations due to rounding]

Pumpage period	Year	Mississippi River Valley confining unit	Underlying units	Adjacent units	Adjacent alluvium	Storage	Cache River	All rivers	Wells
Predevelopment		175	61	3	-2	--	-123	-237	--
3	1933	200	83	4	-2	2	-111	-213	-74
5	1942	215	70	4	<-1	17	-97	-184	-122
7	1952	256	-86	4	1	230	-25	-70	-335
8	1957	262	-8	4	3	173	-8	-29	-405
9	1962	270	-16	5	5	198	9	16	-377
10	1967	275	-1	5	6	161	26	54	-500
11	1972	275	57	5	7	112	10	41	-496
12	1977	292	16	5	15	414	137	259	-1,000
13	1982	313	83	5	25	743	238	538	-1,704
14	1987	313	157	6	35	553	246	571	-1,635

Table 4c.--Hydrologic budget for regional flow in the Mississippi River Valley alluvial aquifer: Delta area

[Net flow in million gallons per day; negative values are flow out of the aquifer; data are from the end of the last time step in selected pumpage periods; sums may show variations due to rounding]

Pumpage period	Year	Mississippi River Valley confining unit	Underlying units	Adjacent units	Storage	Mississippi River	All rivers	Wells
Predevelopment		332	39	5	--	-34	-377	--
3	1933	334	34	5	0	-33	-372	0
5	1942	337	17	5	2	-31	-360	0
7	1952	340	5	5	2	-29	-351	0
8	1957	372	11	5	14	-6	-226	-176
9	1962	383	9	5	15	2	-185	-224
10	1967	376	<-1	5	4	-3	-207	-176
11	1972	381	-8	5	5	4	-178	-204
12	1977	450	-11	5	59	50	143	-646
13	1982	492	-10	5	127	83	416	-1,028
14	1987	500	-8	5	78	87	440	-1,014

Table 4d.--Hydrologic budget for regional flow in the Mississippi River Valley alluvial aquifer: Boeuf area

[Net flow in million gallons per day; negative values are flow out of the aquifer; data are from the end of the last time step in selected pumpage periods; sums may show variations due to rounding]

Pumpage period	Year	Mississippi River Valley confining unit	Underlying units	Adjacent units	Adjacent alluvium	Storage	Arkansas River	Mississippi River	All rivers	Wells
Predevelopment		227	54	1	-3	--	-5	9	-279	--
3	1933	228	50	1	-3	1	-5	9	-275	-2
5	1942	230	32	1	-3	8	-5	10	-260	-10
7	1952	249	24	1	-3	25	12	17	-174	-124
8	1957	266	25	1	-3	43	30	26	-90	-241
9	1962	261	24	1	-2	7	17	24	-120	-171
10	1967	270	19	1	-2	17	21	26	-87	-219
11	1972	274	16	1	-2	11	18	27	-72	-229
12	1977	302	39	1	-2	45	32	35	65	-450
13	1982	311	22	1	-2	73	39	47	167	-571
14	1987	313	19	2	-1	33	37	50	164	-530

Table 4e.--Hydrologic budget for regional flow in the Mississippi River Valley alluvial aquifer: St. Francis area

[Net flow in million gallons per day; negative values are flow out of the aquifer; data are from the end of the last time step in selected pumpage periods; sums may show variations due to rounding]

Pumpage period	Year	Mississippi River Valley confining unit	Underlying units	Adjacent units	Adjacent alluvium	Storage	All rivers	Wells
Predevelopment		147	103	3	26	--	-281	--
3	1933	149	97	3	26	0	-276	0
5	1942	154	83	3	26	1	-259	-8
7	1952	162	58	3	26	2	-225	-26
8	1957	165	58	3	25	3	-211	-43
9	1962	170	66	3	26	4	-194	-75
10	1967	182	57	3	25	7	-157	-118
11	1972	189	51	3	26	8	-138	-140
12	1977	206	35	4	25	23	-72	-220
13	1982	231	45	4	25	33	58	-396
14	1987	240	47	4	25	46	87	-448

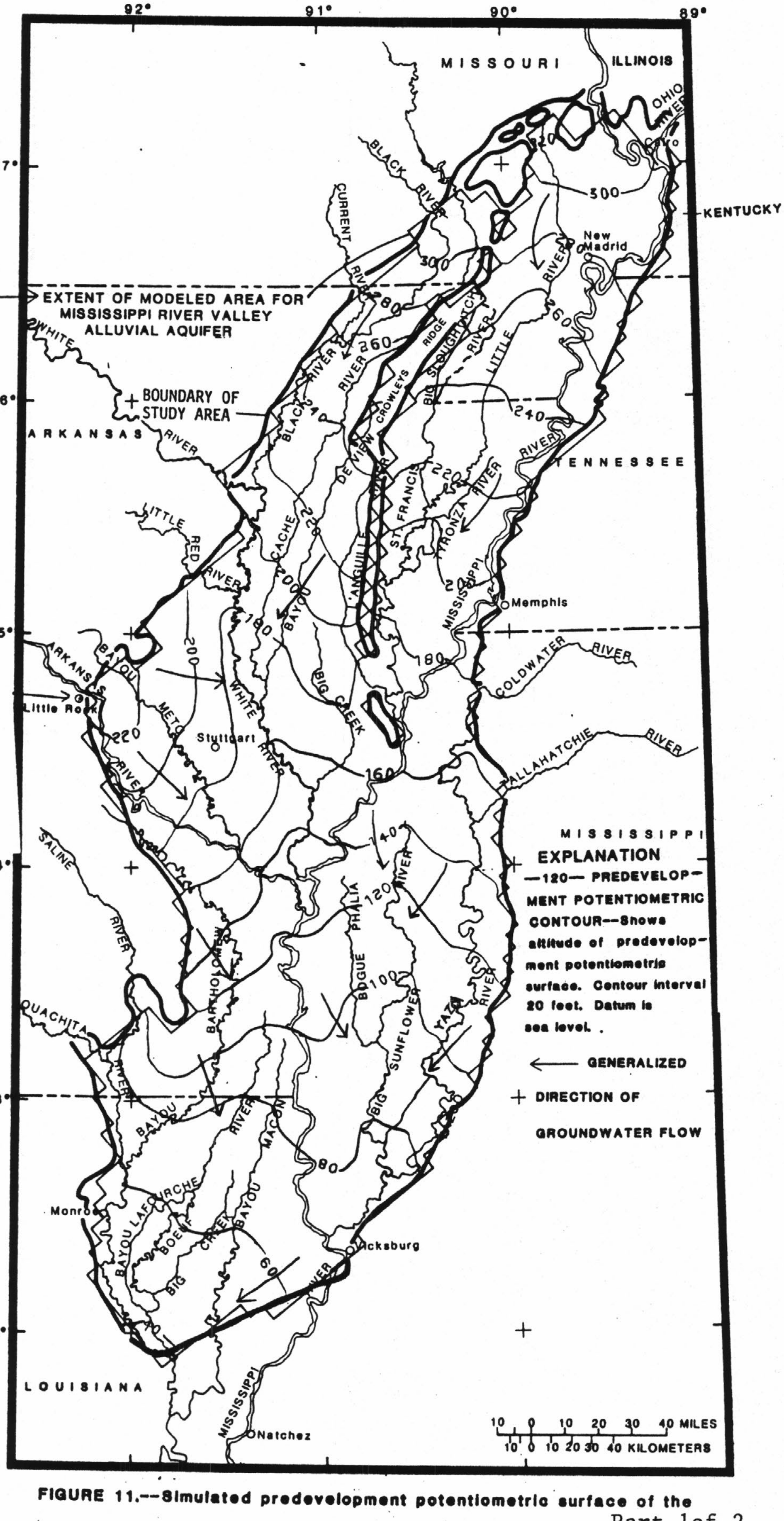


FIGURE 11.--Simulated predevelopment potentiometric surface of the Mississippi River Valley alluvial aquifer.

Part 1of 2

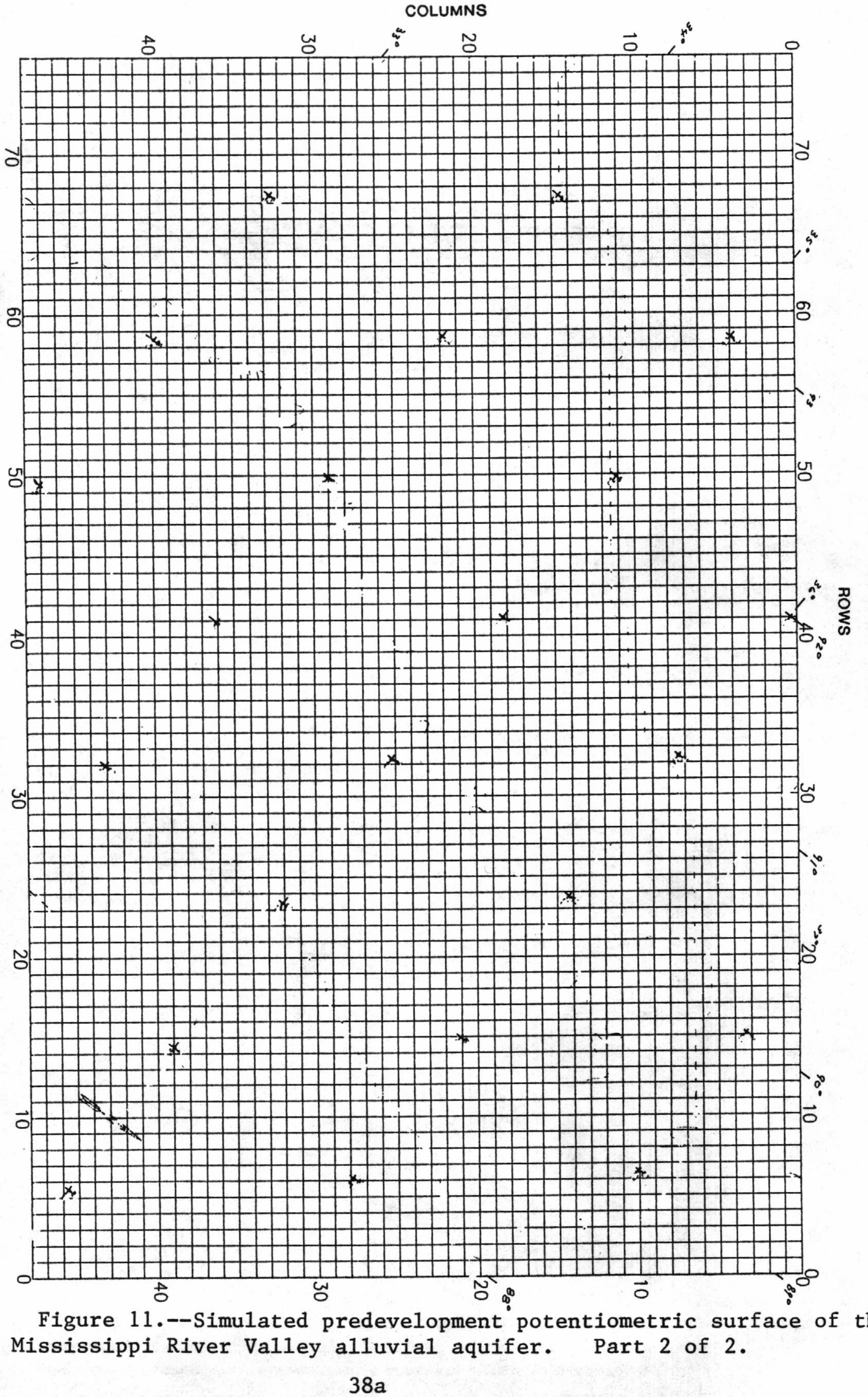


Figure 11.--Simulated predevelopment potentiometric surface of the Mississippi River Valley alluvial aquifer. Part 2 of 2.

Except for an area of western Drew and Ashley Counties in Arkansas, most simulated predevelopment heads were less than 20 ft below land surface. This is in agreement with Broom and Lyford (1981, p. 28). Hines and others (1972, sheet 1) stated that predevelopment heads in western Poinsett and Craighead Counties, Arkansas were about 5 to 15 ft below land surface. In this area simulated heads shown in figure 11 generally were 4 to 12 ft below land surface. Simulated heads generally were within 5 ft of several heads given by Engler and others (1945, p. 29) in or near the edge of the Grand Prairie that may represent predevelopment conditions.

Distribution of Flow Components

Predevelopment inflow to the Mississippi River Valley alluvial aquifer is evenly distributed over the aquifer whereas outflow is concentrated at rivers. Areal distribution of predevelopment inflow and outflow across the top of the alluvial aquifer through the Mississippi River Valley confining unit and from rivers is shown in figure 12a. Inflow to the top of the aquifer, as shown in the cumulative distribution (fig. 12b), is fairly even; most of the area receives less than 0.8 in/yr (1 Mgal/d/block) and 90 percent of the area receives less than 2 in/yr (2 Mgal/d/block). Outflow from rivers generally is less than 3 in/yr (4 Mgal/d/block). About 90 percent of river reaches were gaining water from the aquifer. Predevelopment inflow to the top of the aquifer does not show any discernable areal pattern. A small amount of simulated outflow to the Mississippi River Valley confining unit in Missouri and Louisiana may be due to input errors in land surface elevations and for the aquifer framework caused by sparse data.

Areal distribution of simulated predevelopment inflow and outflow to the bottom of the alluvial aquifer is shown in figures 13a and 13b. Inflow to the alluvial aquifer from underlying aquifers is greatest north of 35° N. latitude and along the margins of the alluvial aquifer. The area north of 35° N. corresponds to the subcrop of the middle and upper Claiborne aquifers (fig. 4). The other areas of larger inflow also correspond to subcrops of aquifers. The flow is largest in these areas because the leakance is large and gradients are steep. Leakance is large due to the larger vertical hydraulic conductivity of aquifer materials. Gradients are steepest in the area of transition between higher heads for underlying aquifers in the topographically higher outcrop areas and lower heads under the alluvial aquifer in the lowlands of the Mississippi River Valley. The highest average rate of inflow to the alluvial aquifer from underlying aquifers was in the St. Francis area. The subregional study of the Mississippi embayment aquifer system has shown that the steeper gradient in the St. Francis area is due to a topographically higher recharge area to the east and to a shorter flow path (J.K. Arthur, U.S. Geological Survey, written commun., 1988). Flow paths are longer and topographic differences between outcrop recharge areas and subcrop discharge areas (below the alluvial aquifer) are less for aquifers subcropping in the Delta and Boeuf areas. The Grand Prairie and Cache areas on the west side of the study area are farther from the outcrop areas for the underlying aquifers and have less inflow from underlying units. Outflow to underlying aquifers from the alluvial aquifer is small, and occurs mostly in the western part of the Grand Prairie and Cache areas.

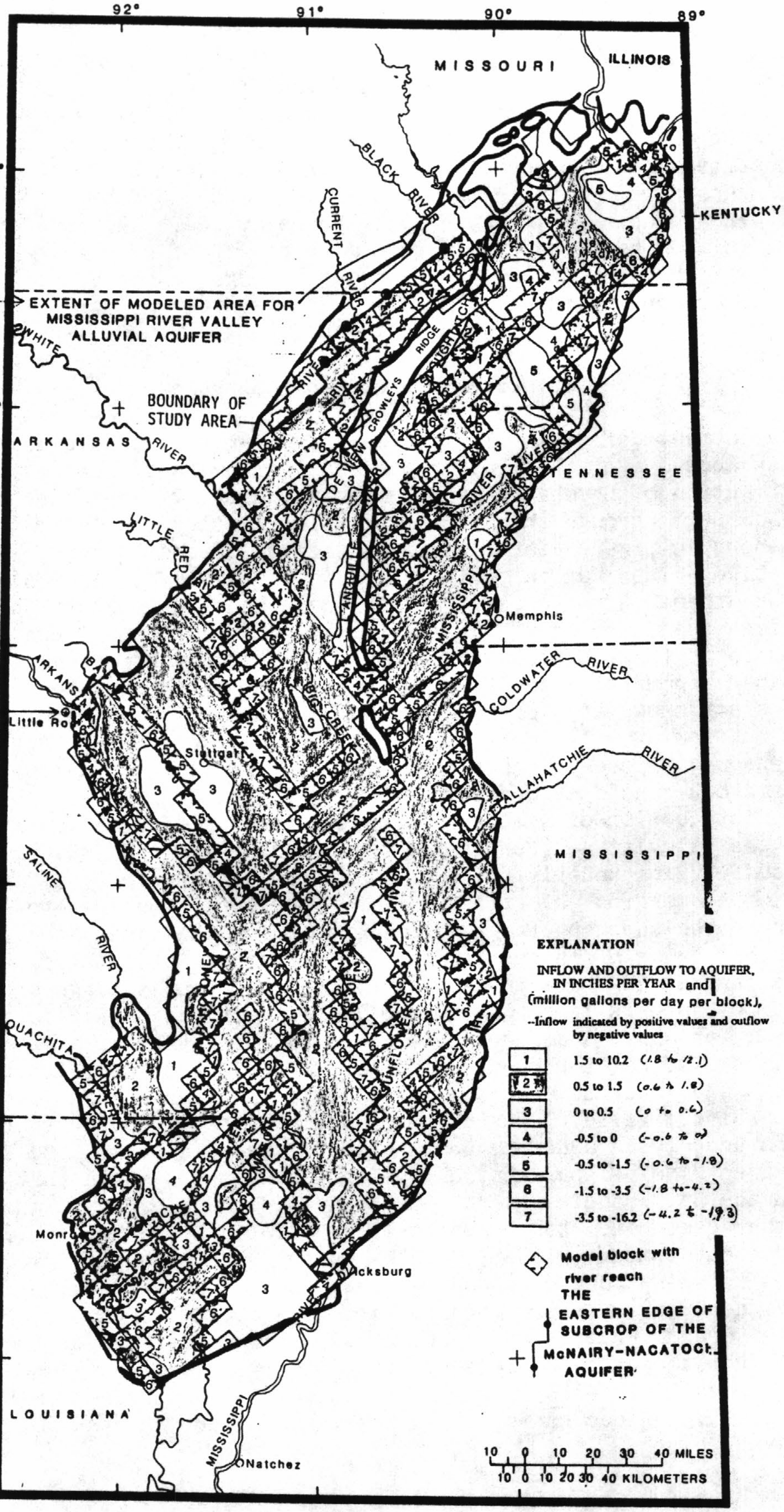


Figure 12a.--Simulated predevelopment inflow and outflow to the top of the Mississippi River Valley alluvial aquifer and to rivers.

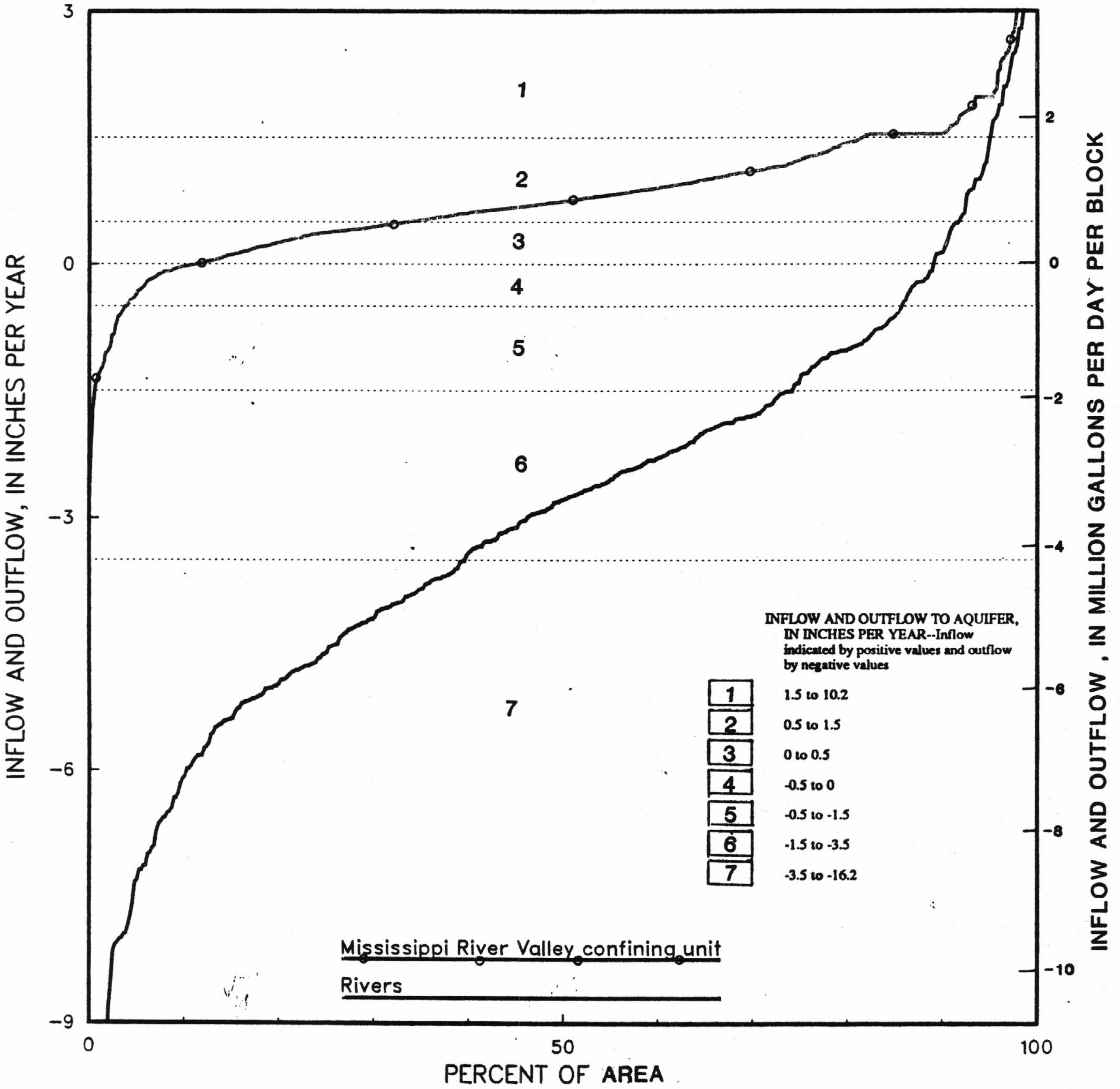


FIGURE 12b.--Simulated predevelopment inflow and outflow to the top of the Mississippi River Valley alluvial aquifer and to rivers.

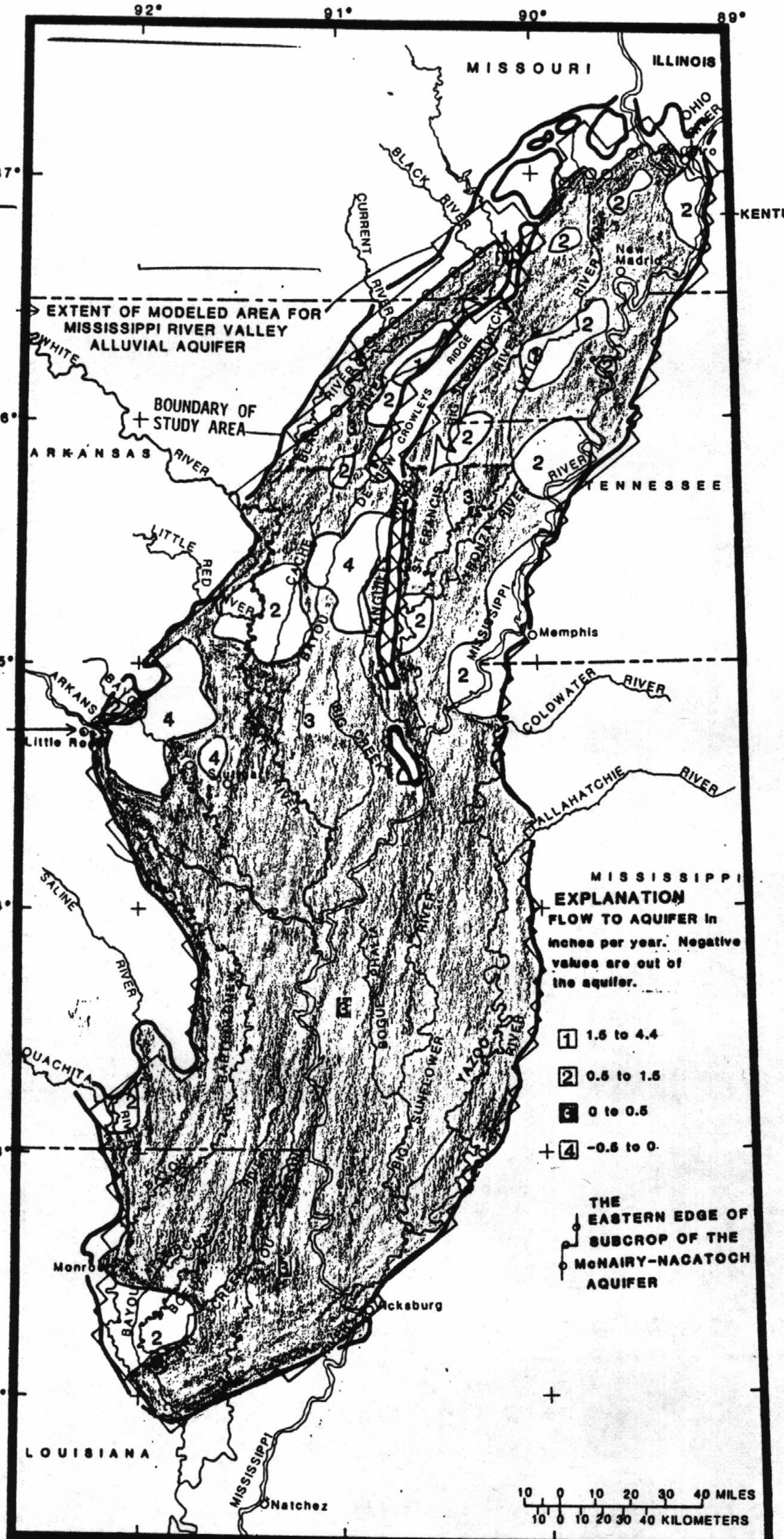


Figure 13a.--Simulated predevelopment inflow and outflow to the bottom of the Mississippi River Valley alluvial aquifer.

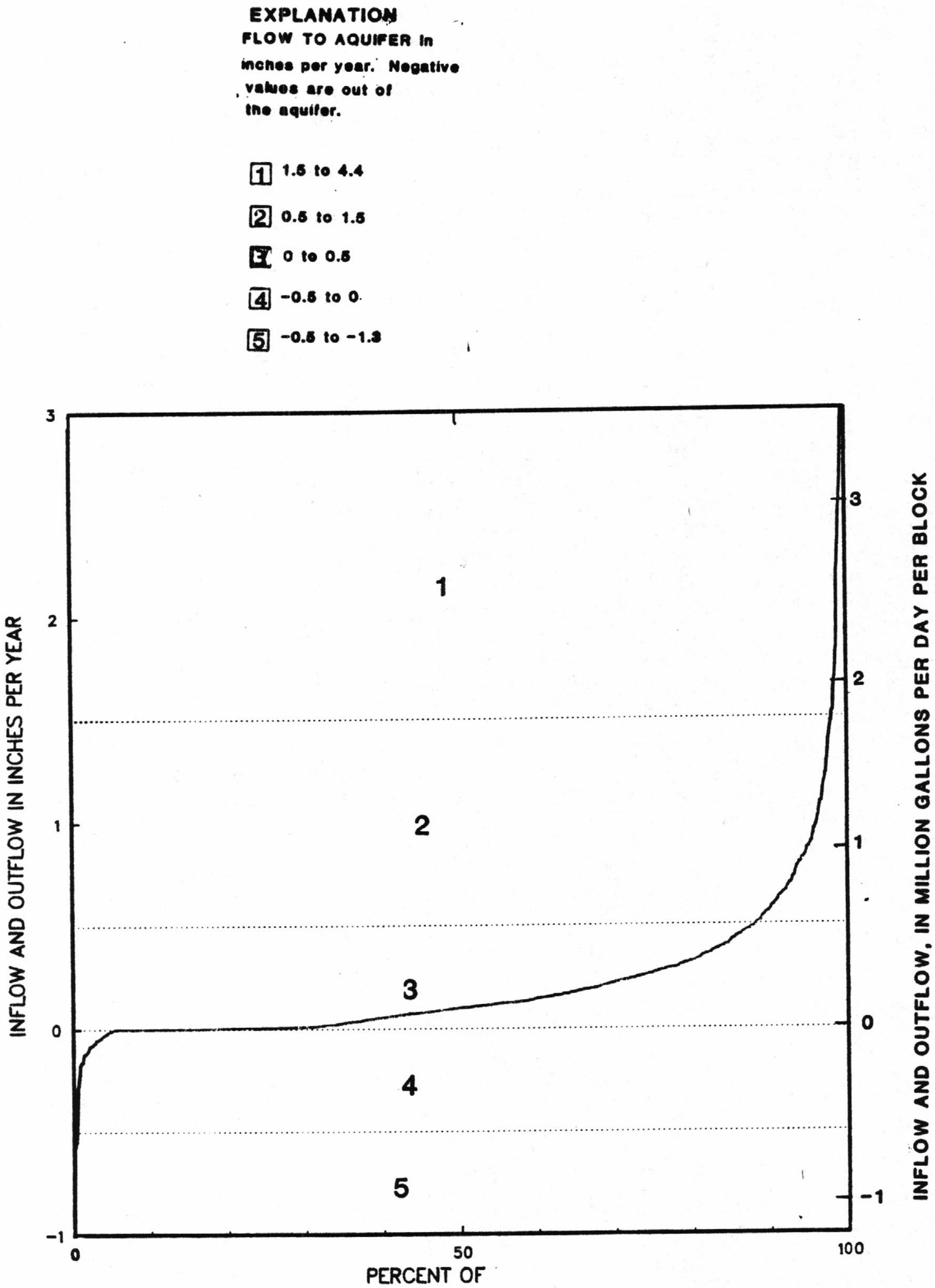


FIGURE 13b.--Simulated predevelopment inflow and outflow to the bottom of the Mississippi River Valley alluvial aquifer.

Ground-Water Development and Changes in Water Levels in the Alluvial Aquifer

Pumpage from wells tapping the Mississippi River Valley alluvial aquifer has been primarily for agricultural use. Withdrawals of large quantities of water, especially for rice irrigation, began in the Grand Prairie in the early 1900's. By the late 1950's large quantities of water were being pumped from the alluvial aquifer in all parts of the study area. Large seasonal withdrawals remained constant or increased nearly every year until about 1983. The withdrawals resulted in water-level declines in some areas to the extent that they are considered water problem areas.

History of the Development of the Alluvial Aquifer

In the early 1900's ground water was a primary water source for domestic, farm, municipal, manufacturing, and railroad use in the Mississippi Alluvial Plain. The alluvial aquifer was not the preferred source of potable water due to water-quality problems, but was commonly the only source used due to the expense of drilling deeper wells. At the turn of the century, scientific interest, as expressed by the nature of early reports, concerned deep flowing wells. Few data were available for wells in the shallow alluvium. Prior to 1903 a variety of uses of water from the alluvial aquifer were cataloged (Purdue, 1904, p. 377), including one well yielding 100 gal/min at Stuttgart, Arkansas.

The impetus for the extensive development of the Mississippi River Valley alluvial aquifer was the realization that water from shallow wells could be used for commercial rice production. The history of the development of the alluvial aquifer parallels the history of rice culture. Stephenson and Crider (1916, p. 144-145) give an account of the early attempts from 1897-1903 to raise rice in Arkansas. Commercial success was realized in 1904 when 80 acres were planted. After this initial success near Lonoke on the Grand Prairie, rice culture expanded rapidly at first in Arkansas, and later in adjoining states as shown in the following table which is abbreviated from Engler and others (1963, table 2):

Acreage of rice in the Grand Prairie region of Arkansas

Year	Total area irrigated (acres)	Year	Total area irrigated (acres)
1905	460	1930	141,000
1910	48,000	1935	105,000
1915	80,000	1940	126,000
1920	149,000	1945	158,000
1925	143,000	1950	169,000
		1955	185,000

Rice culture uses large quantities of water to maintain 4 to 6 inches of water in the leveed fields for most of the growing season (May or June through July or August). The history of the increase in rice acreage, and therefore the most significant part of the history of water use from the alluvial aquifer, is shown in figure 14.

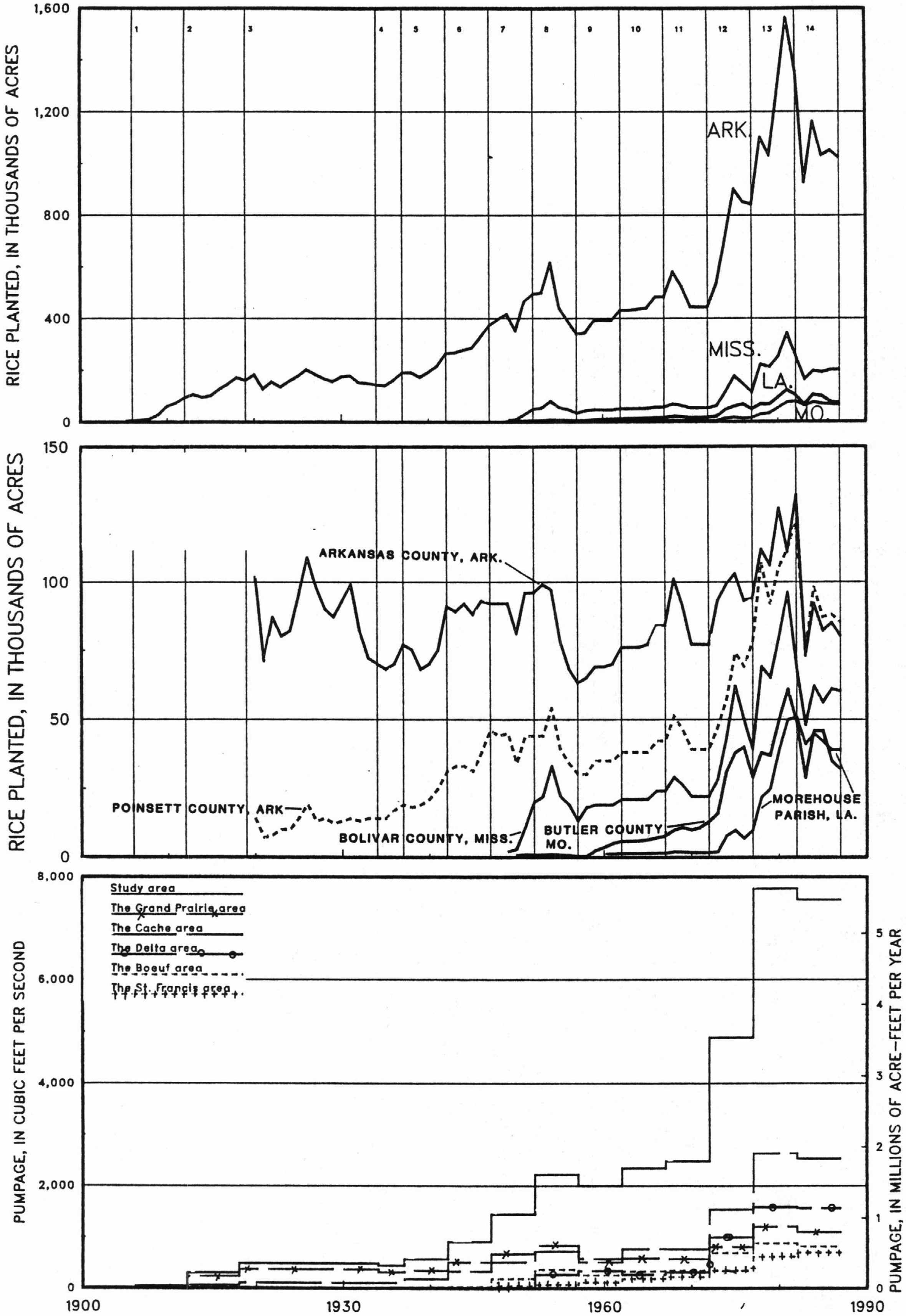


FIGURE 14.--Acreage of rice planted for select states and counties in the study area and trends in pumpage for the Mississippi River Valley alluvial aquifer. Numbers along upper time axis are model pumpage periods.

Within 10 years after rice culture started in the Grand Prairie, it began in the Cache area with approximately 20,000 acres planted in 1915 and 33,000 acres by 1925. Rice acreage in the Arkansas part of the Boeuf area was about 7,000 acres in 1945 and 31,000 acres by 1950. In the Delta, 7,000 acres of rice were planted in 1950 and 53,000 acres in 1955. Rice acreage in the St. Francis area probably exceeded 5,000 acres in 1952 and probably did not exceed 8,000 acres in all of Missouri until 1974.

From 1955 to 1973 rice acreage was relatively constant. From 1974 to 1981 or 1982 there were large increases in rice acreages. In 1983 acreage decreased sharply in response to changes in national farm policy. Since 1983 the rice acreage has been relatively large but less than the peak of 1981 or 1982. Data describing the county distributions of water use, from reports such as Holland and Ludwig (1981), Walter (1982), and Callahan (1983) were compiled and distributed by model blocks for 1960-85 as a part of this project (Mesko and others, 1990).

Estimates of water use for the period 1905-57 in Arkansas were based on the work of Engler and others (1963, table 2) for the Grand Prairie and on rice acreages published by the Arkansas Agricultural Statistics Service for the rest of the area. Estimates of water use for irrigation are based on application rates for rice production. Application rates range from 22 to more than 60 inches of water, and depend on the area, source of water, and amount of rainfall during the growing season. Because substantial acreage is irrigated with surface water, water-use estimates were adjusted for the percentage of land irrigated with ground water. In parts of the Grand Prairie a significant part (as much as 18 percent in 1980) of the ground water pumped for rice irrigation is from the middle Claiborne aquifer.

Irrigation of crops probably accounts for about 90 percent of the current water use from the alluvial aquifer. Approximately 80 percent of the water withdrawn from the alluvial aquifer currently (1988) is used for rice irrigation. A large quantity of water withdrawn from the alluvial aquifer is used for flood and sprinkler irrigation of other crops (principally soybeans, cotton, and corn). Use of water from the alluvial aquifer for irrigation of these crops is less due to lower application rates (2 to 15 inches of water) and fewer irrigated acres.

The third major water use of ground water from the alluvial aquifer is aquaculture, mostly catfish farming. Aquaculture is concentrated in the southeastern part of the Delta and the northwestern part of the Grand Prairie. About 3 to 9 ft of water is estimated to be added to large leveed ponds throughout the year. Substantial pumpage for aquaculture probably started in the 1960's and has continued to increase through the 1980's. The combined pumpage for irrigation and aquaculture currently accounts for more than 95 percent of water use from the alluvial aquifer.

Water withdrawn from the alluvial aquifer also is used for domestic supply, farm supply, small municipalities, rural water systems, industrial supplies, and thermoelectric power generation. Individual users withdrawing 5 to 11 Mgal/d during 1980 were three thermoelectric power generation facilities at Clarksdale, Greenwood, and Yazoo City, Mississippi; paper mills near Pine Bluff in Jefferson County, Arkansas; and Crossett, in Ashely County, Arkansas; and the city of Vicksburg, Mississippi.

The pumpage from the Mississippi River Valley alluvial aquifer was estimated for 14 pumpage periods beginning in 1906 (table 5). The overall trend for pumpage from the Mississippi River Valley alluvial aquifer (fig. 14) has been for an increase in water use to about 1982 followed by a slight decrease. Largest increases were in the early 1950's and from about 1973 to 1982.

Table 5.--Pumpage periods used for the analysis of transient regional flow in the Mississippi River Valley alluvial aquifer

[a pumpage period is equivalent to stress period in McDonald and Harbaugh (1984)]

Pumpage period	Time period represented	Length, years	Time steps
1	1906-11	6	10
2	1912-18	7	10
3	1919-33	15	15
4	1934-37	4	10
5	1938-42	5	10
6	1943-47	5	10
7	1948-52	5	10
8	1953-57	5	10
9	1958-62	5	10
10	1963-67	5	10
11	1968-72	5	10
12	1973-77	5	10
13	1978-82	5	10
14	1983-87	5	10
15[1]	1988-92[2]	5	10
16[1]	1993-2002[2]	10	10
17[1]	2003-2022[2]	20	10

[1]Pumpage periods 15-17 were used for projected response only

[2]Time periods beyond 1987 were projected based on conditions similar to those of 1987 with similar or increased pumpage.

Maximum pumpage was about 5,000 Mgal/d. The expansion in the areas of pumpage and increase of withdrawal rates with time can be seen by comparing figures 15a-17b. During 1940 most pumpage was in the Grand Prairie and Cache areas. By 1960 pumpage occurred throughout the project area. During 1980 pumpage continued to increase in all areas except parts of the Grand Prairie. Parts of Arkansas and Prairie Counties, Arkansas in the Grand Prairie have had nearly stable water levels (fig. 18) since about the late 1950's which indicates fairly uniform withdrawals. In this area some water users have drilled new wells for additional supply in the middle Claiborne aquifer. For this study, it was assumed that usage from the alluvial aquifer was steady at a rate of about 5 Mgal/d/block (4 in/yr) from 1958 to 1987.

Water Level Change Due to Development

Water-level fluctuations of 2 to 20 ft on a scale of months or years are common in the Mississippi River Valley alluvial aquifer (fig. 18). Most wells show a seasonal cycle of water levels. Lowest water levels occur in the late summer or early fall corresponding to the end of the growing and irrigation seasons, low river stages, and less rainfall. Highest water levels generally occur in the spring and correspond to higher river stages and periods of greater precipitation, less evapotranspiration, and little or no irrigation. Fluctuations due to changes in natural inflow and outflow such as river stage change (fig. 8), seasonal wet and dry periods, and drought periods of a few years in duration tend to average out over a few years time. These natural fluctuations cause no long-term change in storage and, therefore, no long-term change in water levels.

Withdrawals from the alluvial aquifer have caused seasonal and long-term fluctuations in water levels. The pumpage from individual irrigation wells is large, commonly 400 to 1,400 gal/min. Areal application rates of 22 to 60 inches of water per year, adjusted to the length of the growing season, are equivalent to withdrawal rates of more than 80 inches of water per year. This is higher than most rates of recharge or other inflow. Short-term excess of outflow over inflow is supplied from aquifer storage. Effects of pumpage from the alluvial aquifer range from short-term water-level declines in individual wells to long-term water-level declines extending throughout large areas of several hundred square miles. Declines in water levels are important for several reasons:

1. Pumpage costs increase as water levels decrease (lift increase),
2. Yields of wells decrease as water levels decrease (if saturated thickness decreases)
3. Pump settings and sometimes screens must be lowered as pumping levels decrease
4. Continually decreasing water levels are indicative of overdraft of the aquifer (pumpage exceeds inflow)

The recognition of long-term water-level declines due to pumpage exceeding inflow is difficult for three reasons. First, original (pre-pumping) water levels commonly are not available. Second, early changes in water levels due to pumpage may be masked by natural water-level fluctuations. Third, water-level changes are strongly influenced by areal differences in the aquifer storage coefficient. In some places the water level is above the top of the aquifer (confined conditions) all or part of the year. In these areas pronounced water-level declines usually have equivalent recovery. In other areas where the water level is below the top of the aquifer (unconfined conditions), declines are less pronounced.

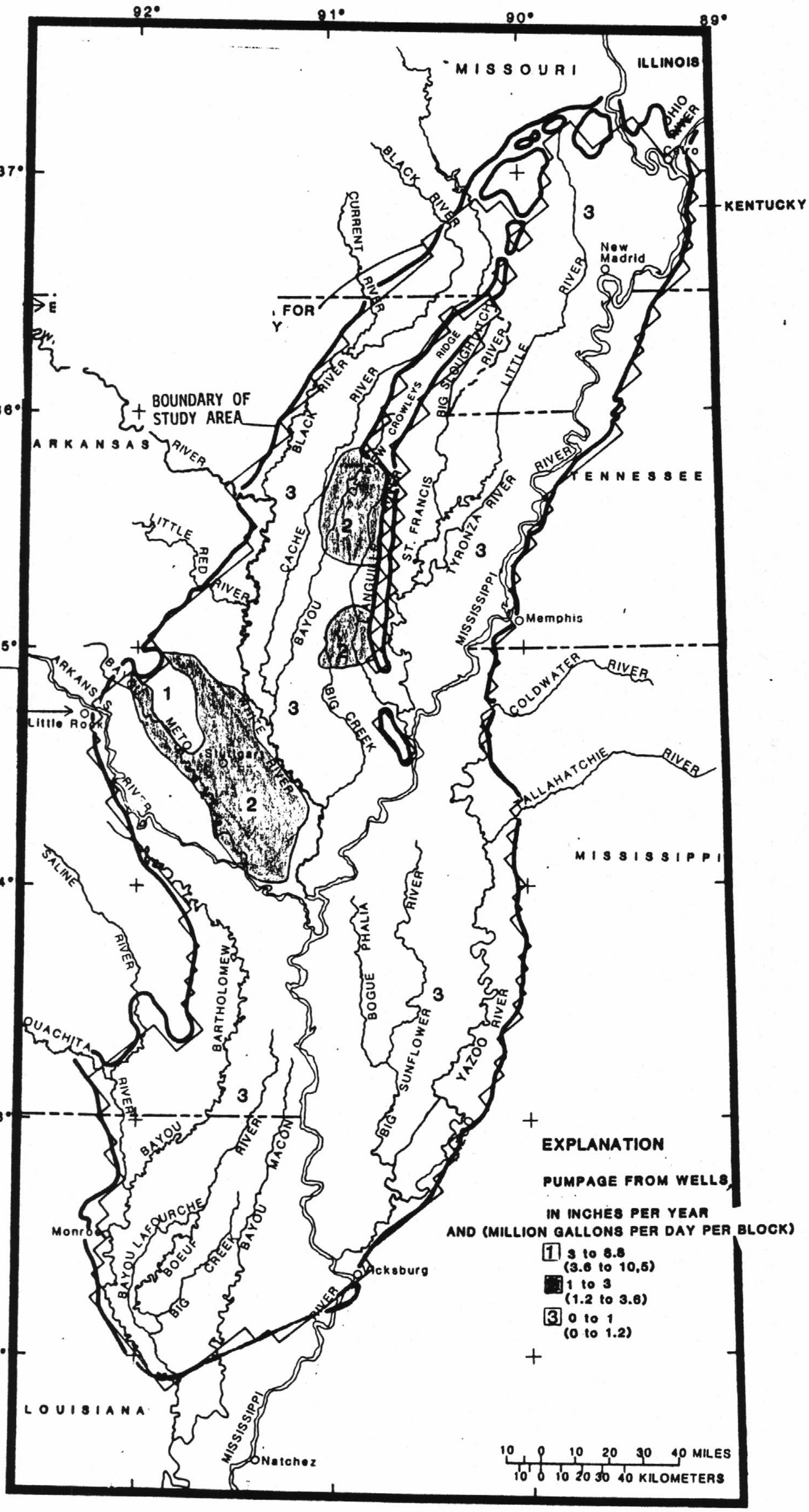


Figure 15a.--Distribution of pumpage in the Mississippi River Valley alluvial aquifer, 1940.

EXPLANATION

PUMPAGE FROM WELLS,

IN INCHES PER YEAR
AND (MILLION GALLONS PER DAY PER BLOCK)

- 1 3 to 8.8 (3.6 to 10.5)
- 2 1 to 3 (1.2 to 3.6)
- 3 0 to 1 (0 to 1.2)

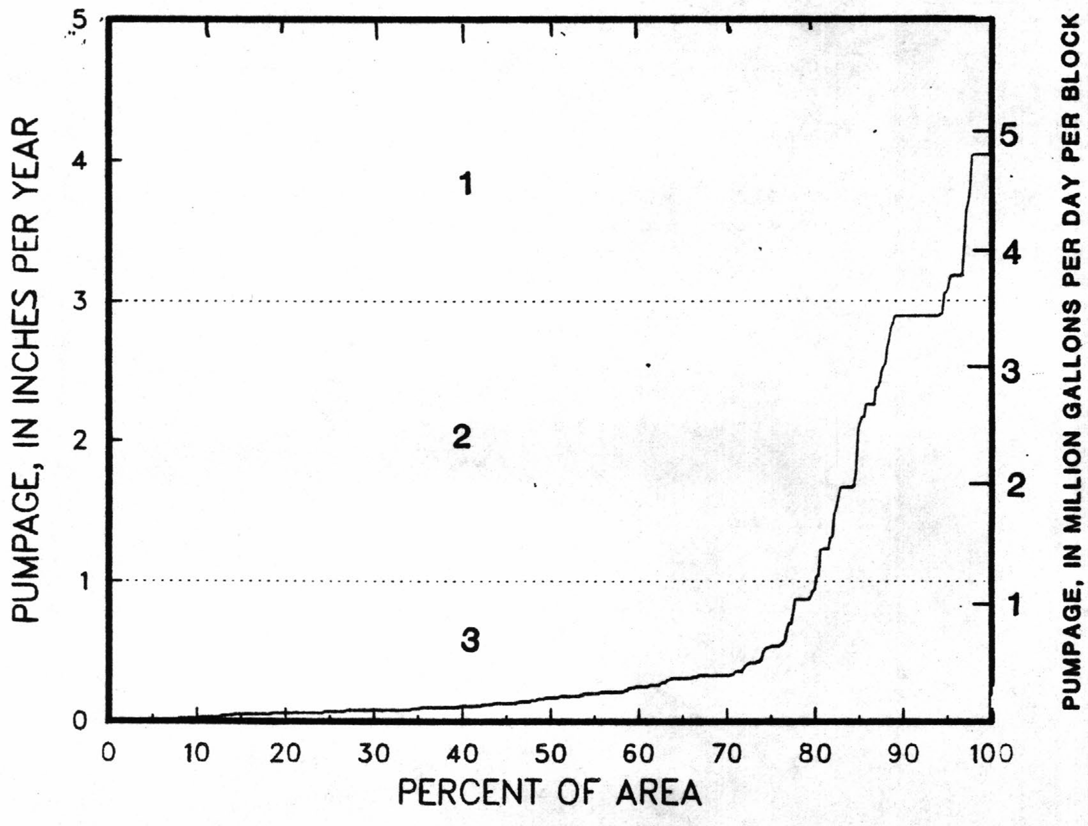


FIGURE 15b.--Distribution of pumpage in the Mississippi River Valley alluvial aquifer, 1940.

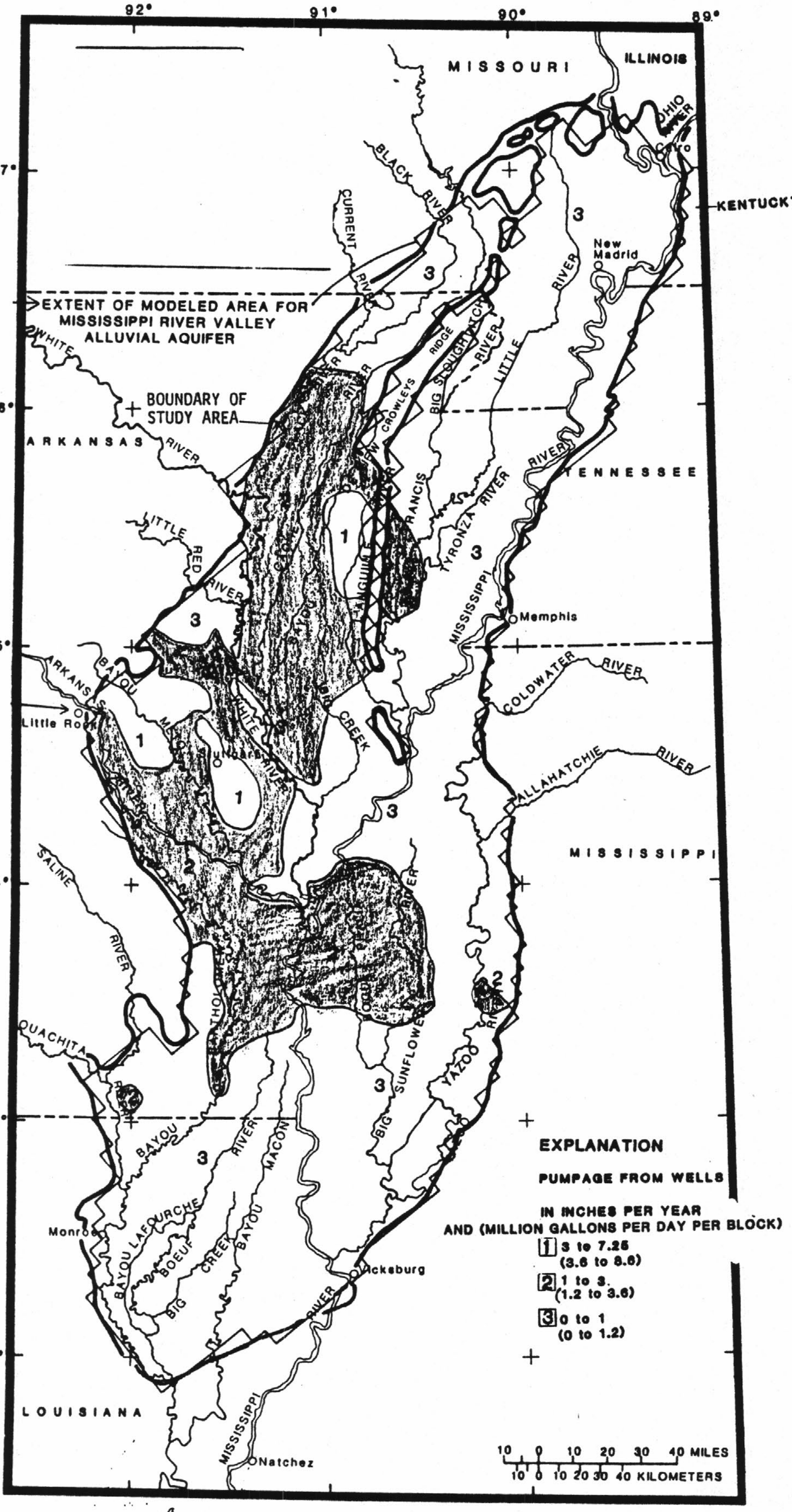


Figure 16.--Distribution of pumpage in the Mississippi River Valley alluvial aquifer, 1960.

EXPLANATION

PUMPAGE FROM WELLS

IN INCHES PER YEAR

[1] 3 to 7.25

[2] 1 to 3

[3] 0 to 1

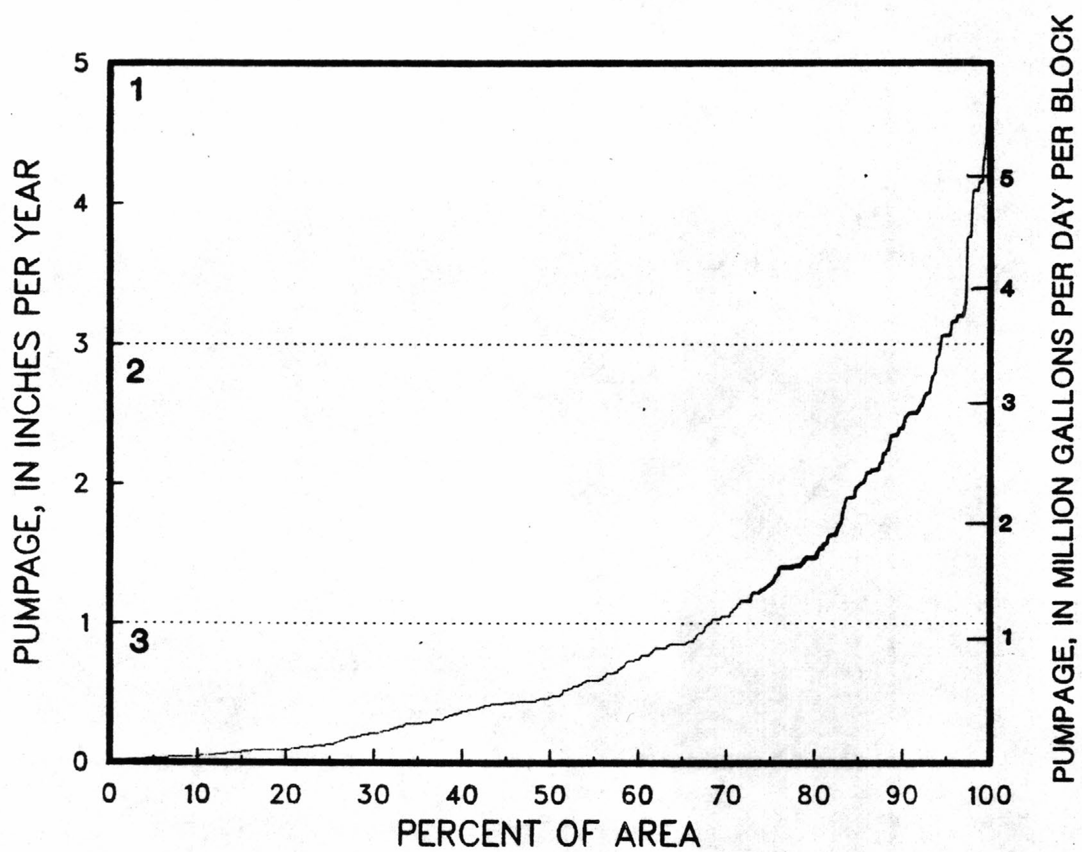


FIGURE 16b.--Distribution of pumpage in the Mississippi River Valley alluvial aquifer, 1960.

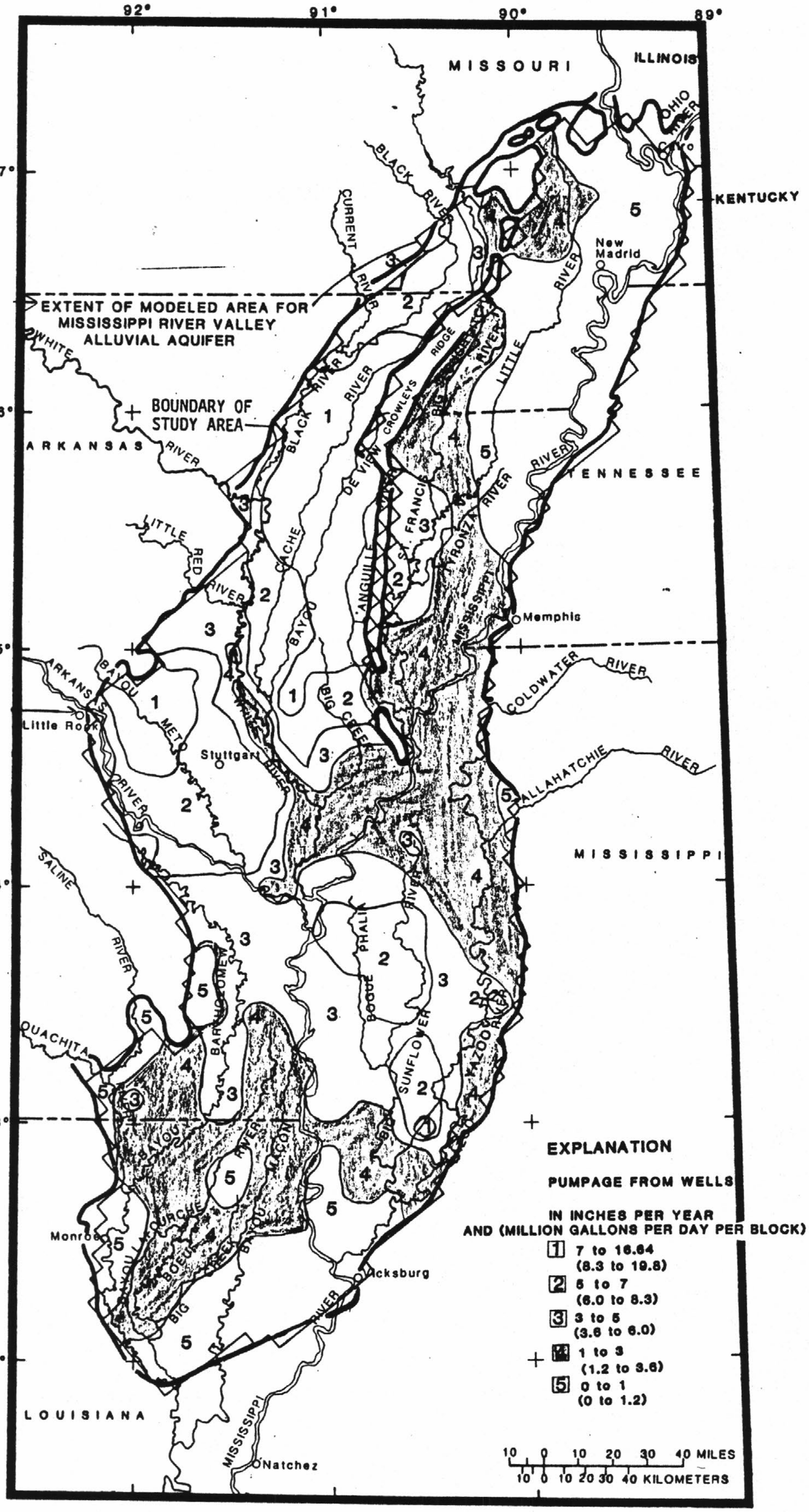


Figure 17a.--Distribution of pumpage in the Mississippi River Valley alluvial aquifer, 1980.

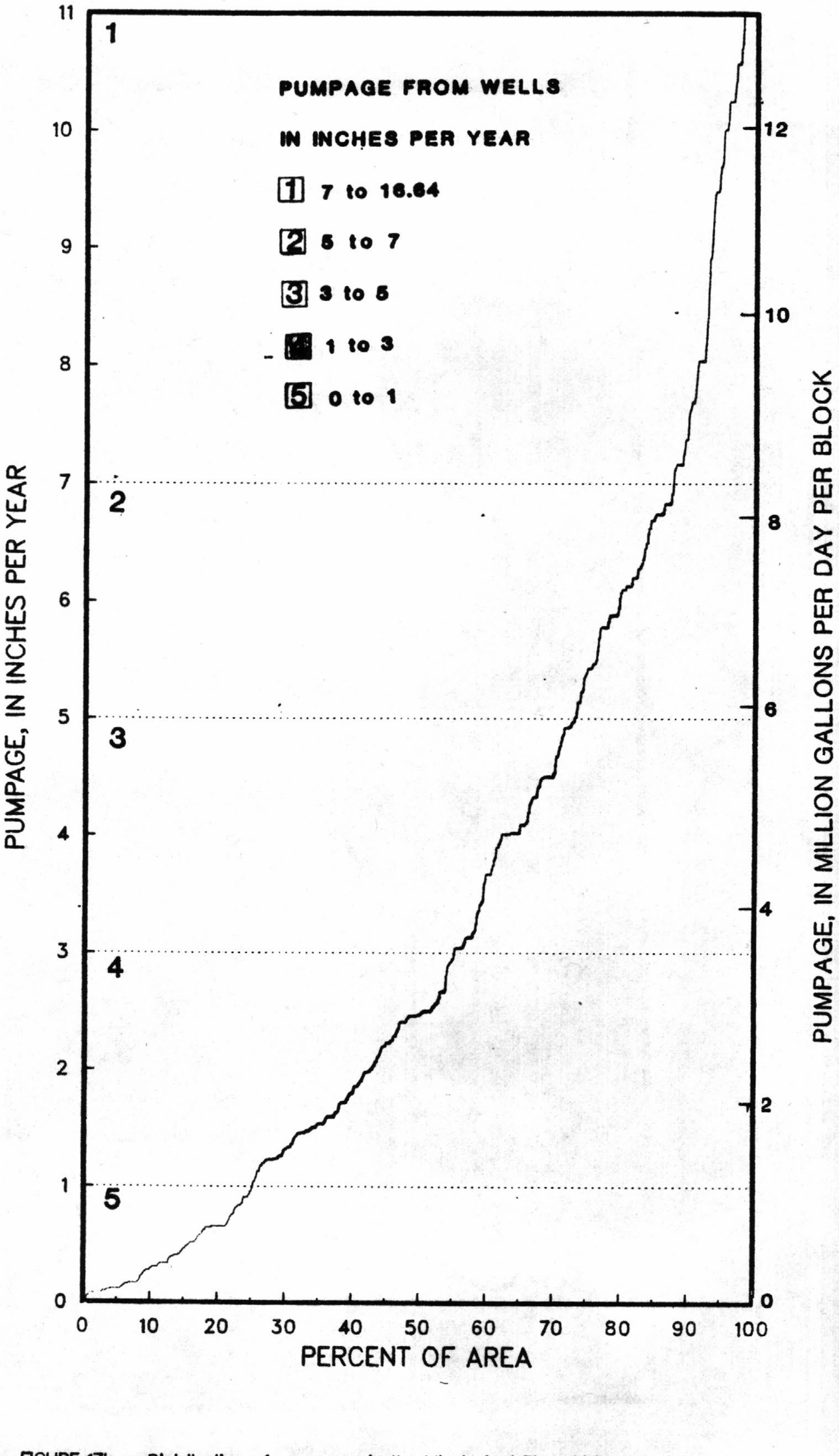


FIGURE 17b.--Distribution of pumpage in the Mississippi River Valley alluvial aquifer, 1980.

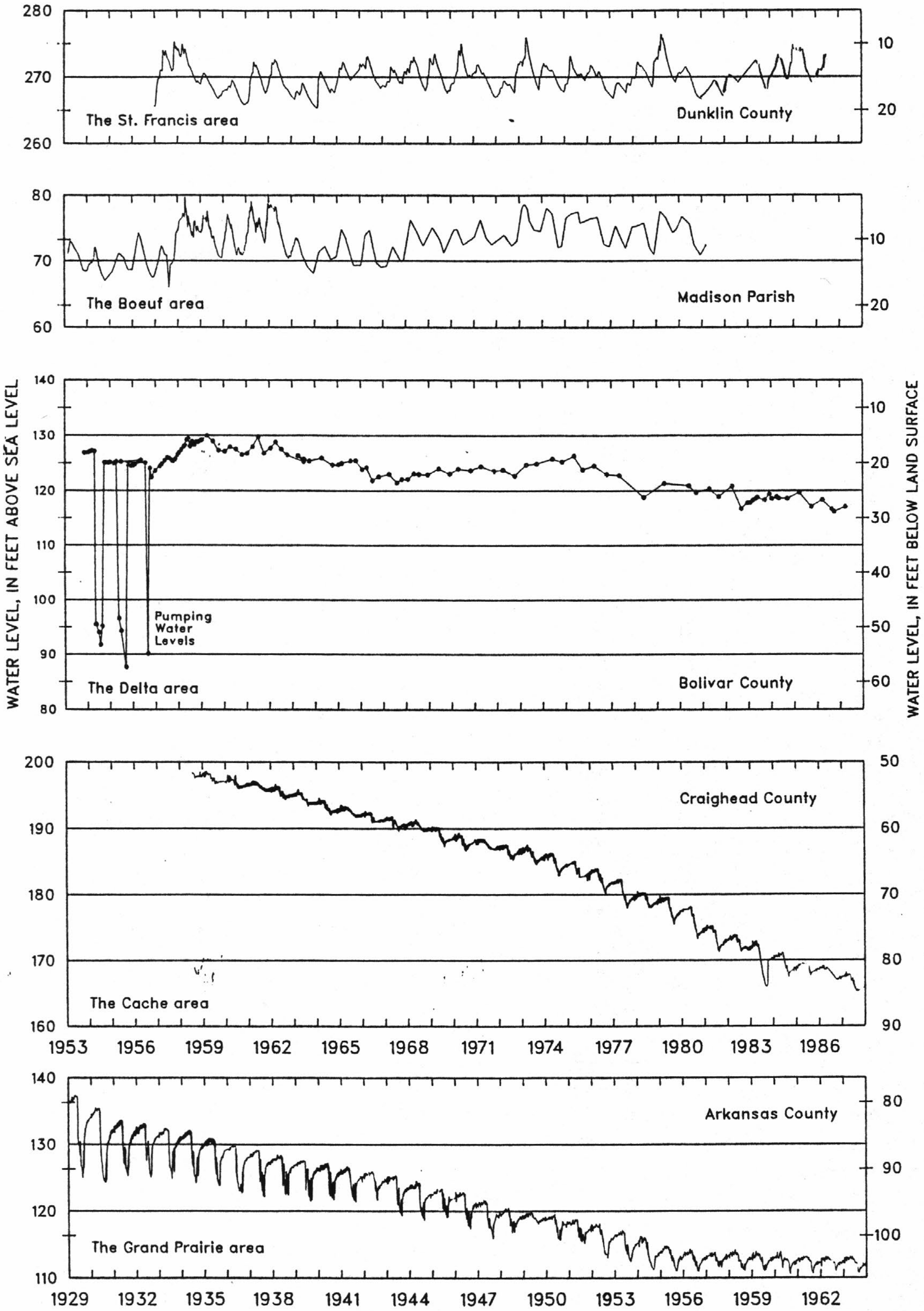


FIGURE 18.--Water levels of selected wells in the Mississippi River Valley alluvial aquifer. Data for Bolivar County plotted from periodic measurements.

Simulated heads and drawdowns from the calibrated model of predevelopment and transient flow were used to aid in the understanding of regional flow systems in the alluvial aquifer. The simulated potentiometric surface and hydrographs were in good agreement with available observed data. The simulated drawdowns for pumpage periods 8 through 13 were very good representations of estimated drawdowns constructed from available water-level data for 5-year intervals from 1957-82 and the simulated predevelopment heads. The estimated drawdowns for 1972 (Ackerman, 1989a, fig. 40) and the method of constructing estimated drawdowns were given in Ackerman (1989a, p. 37). The saturated thickness and change in saturated thickness calculated from observed head also compare well with simulated values.

Areas with Long-Term Regional Declines in Water Levels

The impact of water-level declines in the Mississippi River Valley alluvial aquifer on irrigated agriculture was first realized in about 1927 for the Grand Prairie (Engler and others, 1963, p. 21). The first potentiometric map for the area was included in a press release by D.G. Thompson of the U.S. Geological Survey (see Engler and others, 1963, p. 21 and plate 4). This map of the 1929 potentiometric surface showed an elliptical area of depression 50 miles long and 20 miles wide. Thompson estimated that pumpage was exceeding inflow (about 156 Mgal/d) for part of the Grand Prairie as early as 1916 and concluded that the supply of irrigation water would need to be increased or pumpage reduced (see Engler and others, 1963, p. 22). Engler and others (1945, p. 46) repeated Thompson's conclusion, but estimated inflow to that part of the Grand Prairie to be 121 Mgal/d. The first map showing quantitative water-level declines was prepared by Counts and Engler (1954, fig. 3) for the period 1938-53. They described the extent of water-level declines in the Grand Prairie and Cache areas and recognized that a depression in the potentiometric surface probably existed in 1938 for an area just west of Crowleys Ridge in the Cache area (Counts and Engler, 1954, p. 3 and 8).

The water-level decline in the Cache area was either not recognized or not considered significant by Boswell and others in 1965 (1968, p. 7). Hines and others (1972) estimated that pumpage exceeded inflow by one-third in 1966 and concluded that, while there was no immediate shortage, continued pumpage in excess of inflow would cause serious depletion in the next few decades.

General lowering of water levels such as occurred in the Cache area (figs. 19 and 21) are not as immediately recognizable as the development of a large trough such as occurred in the Grand Prairie. The lowering of water levels are most apparent by observing water-level changes.

The expansion of the areas of water-level decline shown in figures 19-21 follows the trends in pumpage as shown in figures 15-17. In 1942 the most significant decline was in the central part of the Grand Prairie. In 1962 the drawdown trough in the Grand Prairie had expanded and a cone was evident in the Cache area. By 1982 drawdown had increased most in the northwestern part of the Grand Prairie and near Crowleys Ridge in the Cache area. Maximum drawdown was nearly 90 ft in the Grand Prairie and about 70 ft in the Cache area. Water levels generally declined throughout both areas except near large rivers. The Cache area did not show as rapid initial water-level declines as the Grand Prairie. This is probably because of the larger thickness of the Mississippi River Valley confining unit (fig. 7) that overlies the aquifer in the Grand Prairie. Initial water-level declines to the top of the aquifer in the Grand Prairie represented decreases in confined storage. A decline in water level from an altitude near land surface to the top of the aquifer is a

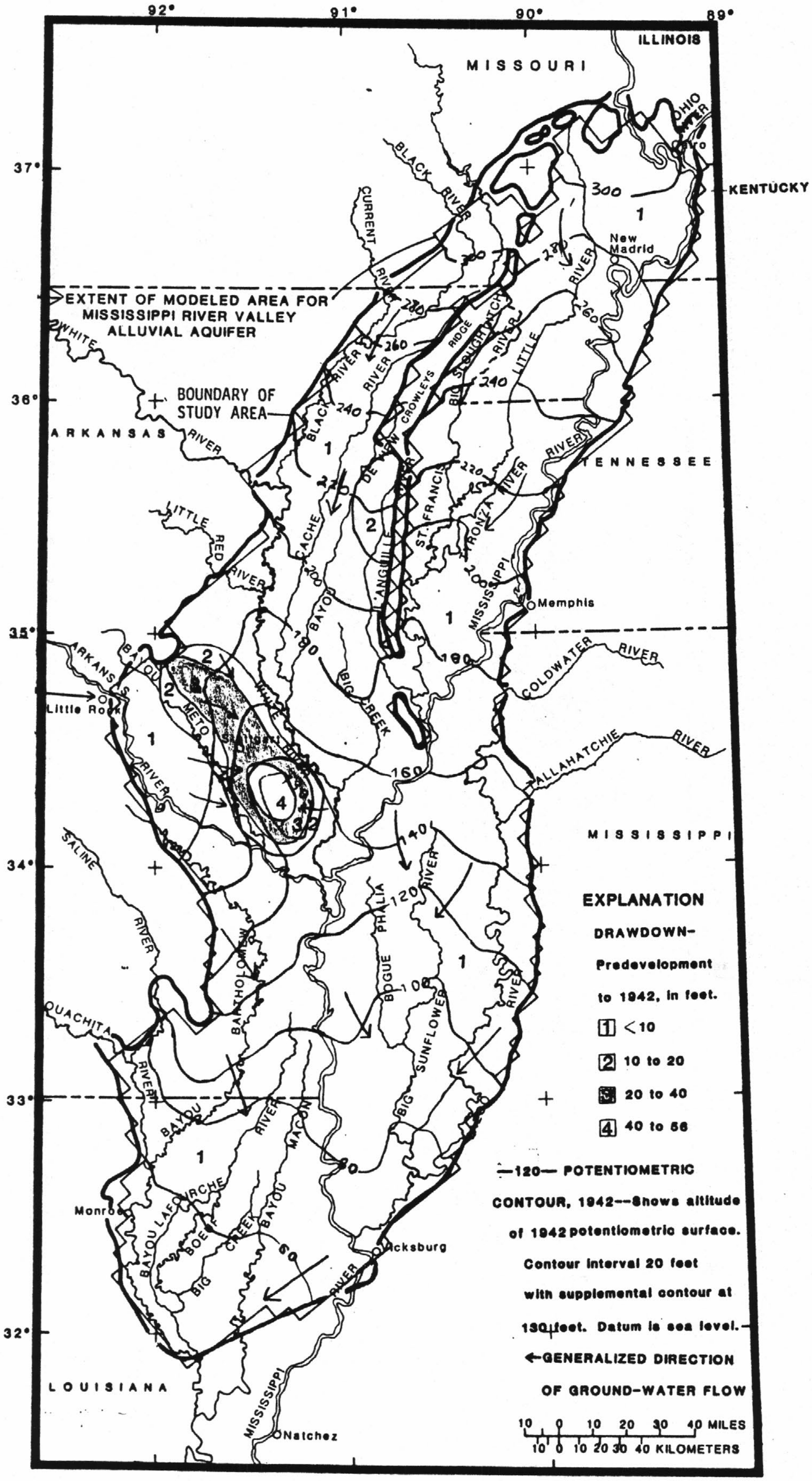


Figure 19.--Simulated potentiometric surface and drawdown from predevelopment conditions for the Mississippi River Valley alluvial aquifer, 1942

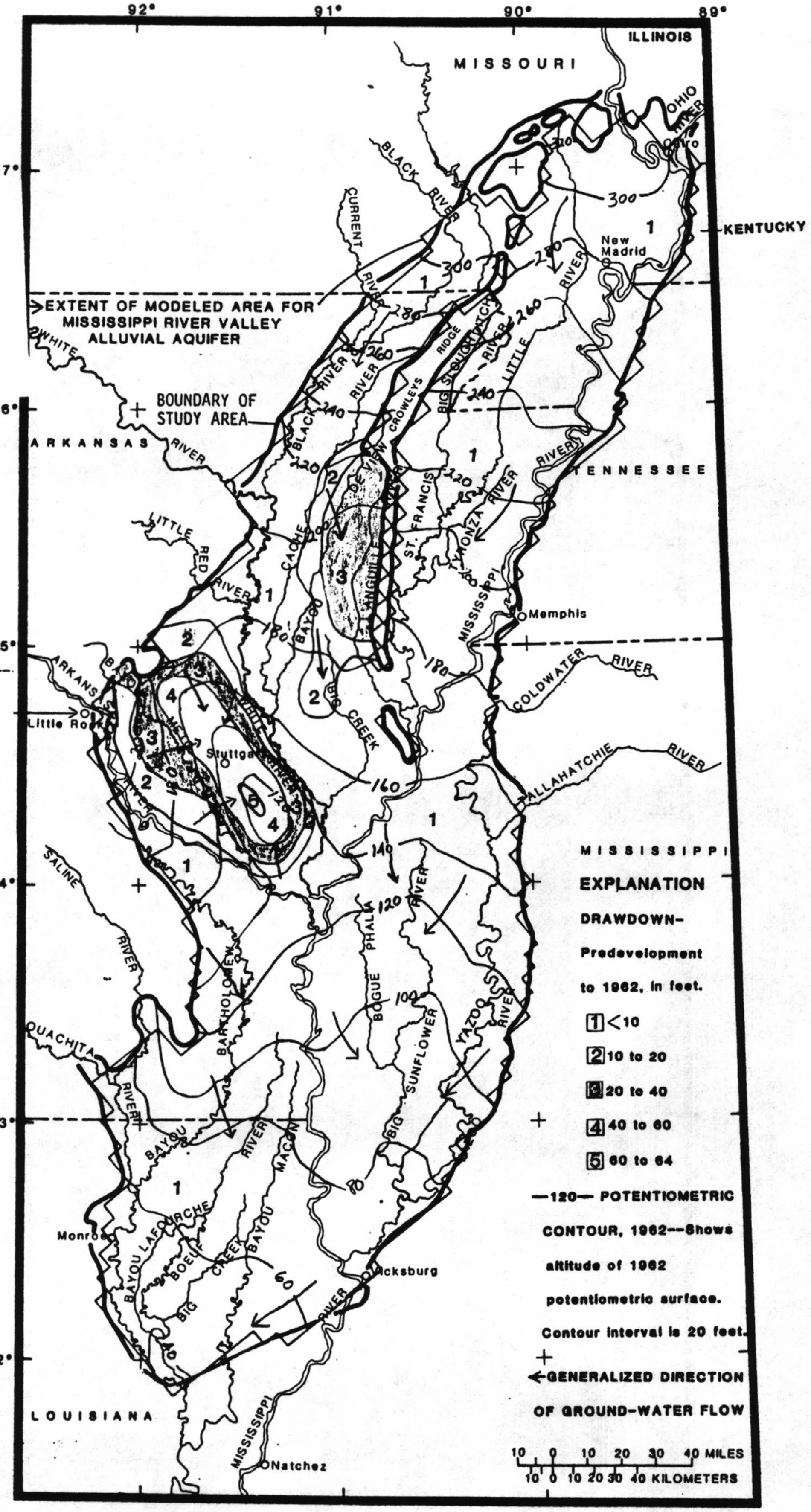


Figure 20.--Simulated potentiometric surface and drawdown from predevelopment conditions for the Mississippi River Valley alluvial aquifer, 1962.

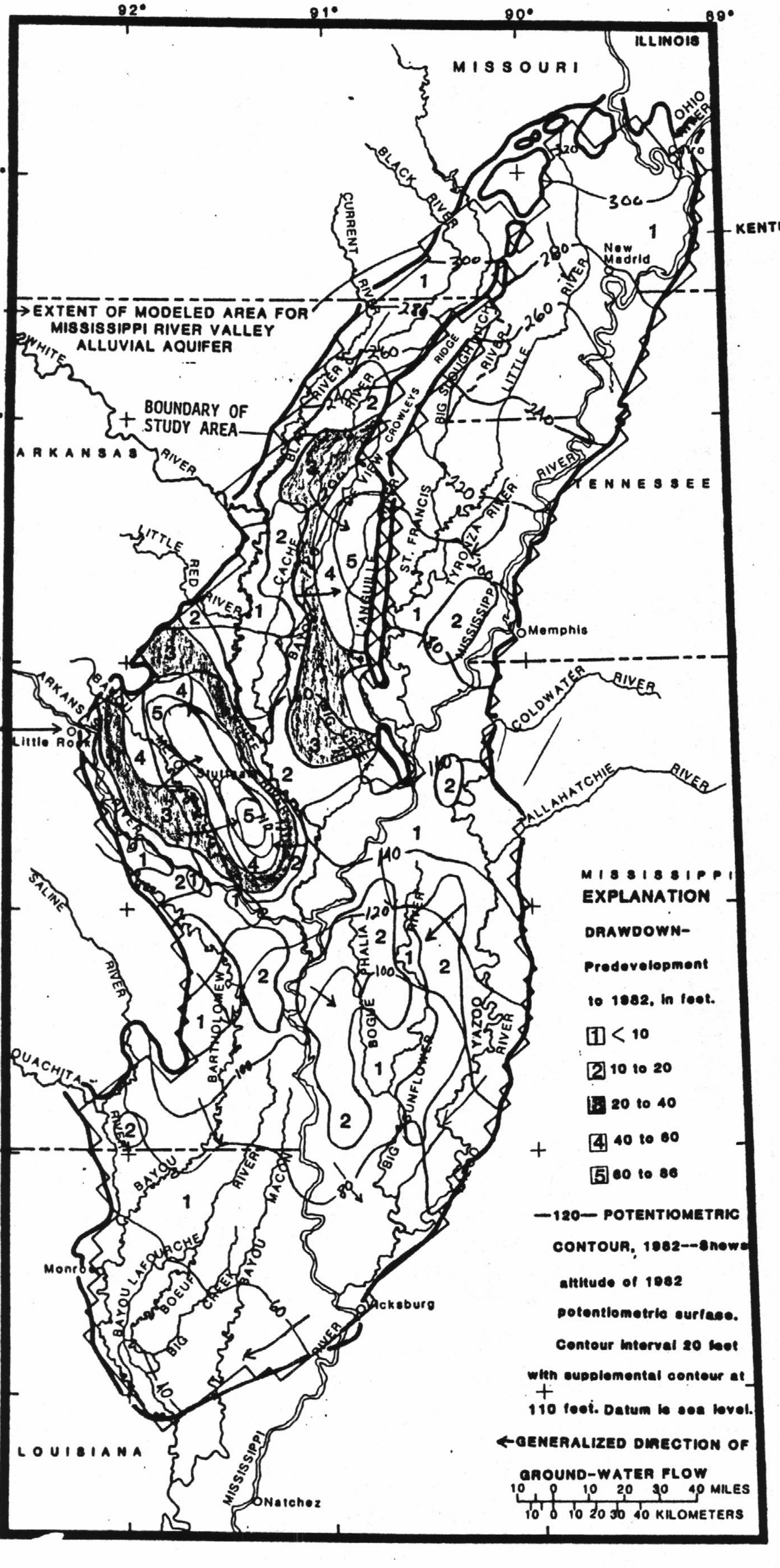


Figure 21.--Simulated potentiometric surface and drawdown from predevelopment conditions for the Mississippi River Valley alluvial aquifer, 1982, from simulated heads.

decline of 40 to 60 ft for the Grand Prairie as opposed to a drop of 20 to 40 ft for the Cache area. Rates of decline in water levels for the Cache area, especially after 1962, seem to be greater than at any time for the Grand Prairie (fig. 18).

Areas with Limited Regional Declines in Water Levels

Long-term declines are smaller and cover less area in the Delta, Boeuf, and St. Francis areas than those of the Grand Prairie and Cache areas. These declines are indicated in model results and generally are confirmed by short-term hydrographs and maps illustrating short-term change in potentiometric surfaces.

Several areas with long-term water-level declines (fig. 21) are scattered throughout parts of the Delta, Boeuf, and St. Francis areas in Mississippi and Arkansas. For the most part, these local declines in water levels correspond to locations of slightly more intense pumpage between streams. All areas with 10 ft or more of decline in water level by 1982 (fig. 21) are shown as areas of short term (1 to 5 years) water-level declines in map reports by Edds and Fitzpatrick (1984), Plafcan and Edds (1986), Plafcan and Fugitt (1987), Plafcan and Remsing (1989), Darden (1982a 1982b, 1983), and Sumner (1984a; 1984b). Only in the Delta area are water-level declines greater than 10 ft over large parts of the area.

The largest and most persistent declines are between Bogue Phalia and the Big Sunflower River and between the Big Sunflower and Yazoo Rivers in the central part of the Delta. Most long-term hydrographs in the Delta do not show long-term changes but some short-term hydrographs show declines since 1980 (Sumner and Wasson 1984, p. 10). Sumner (1984a) describes the central part of the Delta as having gradually declining water levels with slight seasonal recoveries.

In the Boeuf area between Bayou Bartholomew, the Arkansas River, and the Mississippi River in Desha and Lincoln Counties, Arkansas, water-levels have declined 10 to 20 ft. These declines occurred mostly since about 1973. Onellion (1956, p. 19) noted no declines before 1956. A small area near Crossett in western Ashley County, Arkansas, (an area with pumpage for the wood and paper industry) has shown water-level declines at least since the 1930's (Hewitt and others, 1949, p. 28).

In the St. Francis area between the Tyronza and Mississippi Rivers in Crittenden County, Arkansas, simulated water-level declines in 1982 were about 15 ft. The declines in this area from model simulations are less reliable due to lack of supporting data. The few hydrographs available for this area do not show as much drawdown as is indicated by the model results or by comparison of 1982 water levels with simulated predevelopment heads. It may be that the model has a resolution near 10 ft of drawdown in this area. The lack of resolution for drawdown may be due to underestimates of predevelopment head, overestimates of 1982 head, or both.

Areas With No Regional Declines in Water Levels

Examination of model results, comparison of measured water level with simulated predevelopment heads, and examination of available long-term hydrographs indicates that water-level declines for most of the Boeuf and St. Francis areas are very limited in extent and magnitude. Water-level declines in these areas are generally localized or seasonal.

Most of the Boeuf and St. Francis areas and locations near major rivers show no long-term water-level declines. Whitfield (1975, p. 9) concluded that declines in the Mississippi River Valley alluvial aquifer in Louisiana may be as much as 40 ft, but are only seasonal. Plebuch (1962) reported a small net rise in the Arkansas part of the St. Francis area between 1955 and 1962. Broom and Lyford (1981, plate 7) described that area as having little or no water-level declines until 1978. Luckey (1985, p. 26) states that no significant changes had taken place in the potentiometric surface of the alluvial aquifer in Missouri between 1956 and 1976.

Changes in Saturated Thickness Due to Development

Long-term decreases in saturated thickness are the most important indication that the excess of outflow over inflow has affected the use of the Mississippi River Valley alluvial aquifer. A decrease in saturated thickness represents not only an increase in pumping lift, but also a reduction in the ability of an aquifer to sustain current withdrawal rates because of reduced transmissivity. Continued decreases in saturated thickness indicate that the aquifer did not compensate for withdrawals by increased vertical inflow due to increased vertical head gradients or by the movement of distant inflow due to increased horizontal gradients. The demand imposed by withdrawals also was not met by the reduction in natural outflow. Because most of the alluvial aquifer contained water under confined conditions before development, a reduction in saturated thickness is an indication of a significant effect of development. Continuing decreases in saturated thickness are indicative that the aquifer does not have the capacity to compensate for development, and that current development may not be sustained. A reduction in saturated thickness may proceed to a point where most wells in an area do not have the capacity to sustain their design yields throughout an irrigation season. The aquifer framework, first defined regionally as part of this study, and simulated heads were used to analyze the change, or lack of change, in saturated thickness in the alluvial aquifer.

Simulated aquifer response showed no decrease in saturated thickness from predevelopment greater than 6 ft before 1942 in any place other than parts of the Grand Prairie and one small part of the Boeuf area (in western Ashley County, Arkansas). Thompson (Engler and others, 1963, plate 4) showed some unquantified reduction in saturated thickness along the axes of depression in the 1929 potentiometric surface. The largest area in Thompson's 1929 map with a reduction in saturated thickness corresponded to the only area where any adjacent blocks had more than 7 ft of simulated decrease in saturated thickness. By 1962 parts of the Grand Prairie and Cache areas had decreases in saturated thickness of more than 10 ft (fig. 22). In parts of Lonoke and Prairie Counties in the Grand Prairie, scattered blocks had decreases in saturated thickness of 20 to 45 ft. Decreases of 20 to 36 ft were noted just west of Crowleys Ridge in Poinsett and Cross Counties, Arkansas. No other area had more than 7 ft of decrease in saturated thickness except the small area in Ashley County, Arkansas.

After the large increases in pumpage in the 1970's and early 1980's the saturated thickness decreased three times as much from 1962 to 1982 as it had from predevelopment to 1962. Large parts of the Grand Prairie and Cache areas show reductions in saturated thickness of more than 20 ft (fig. 23) by 1982.

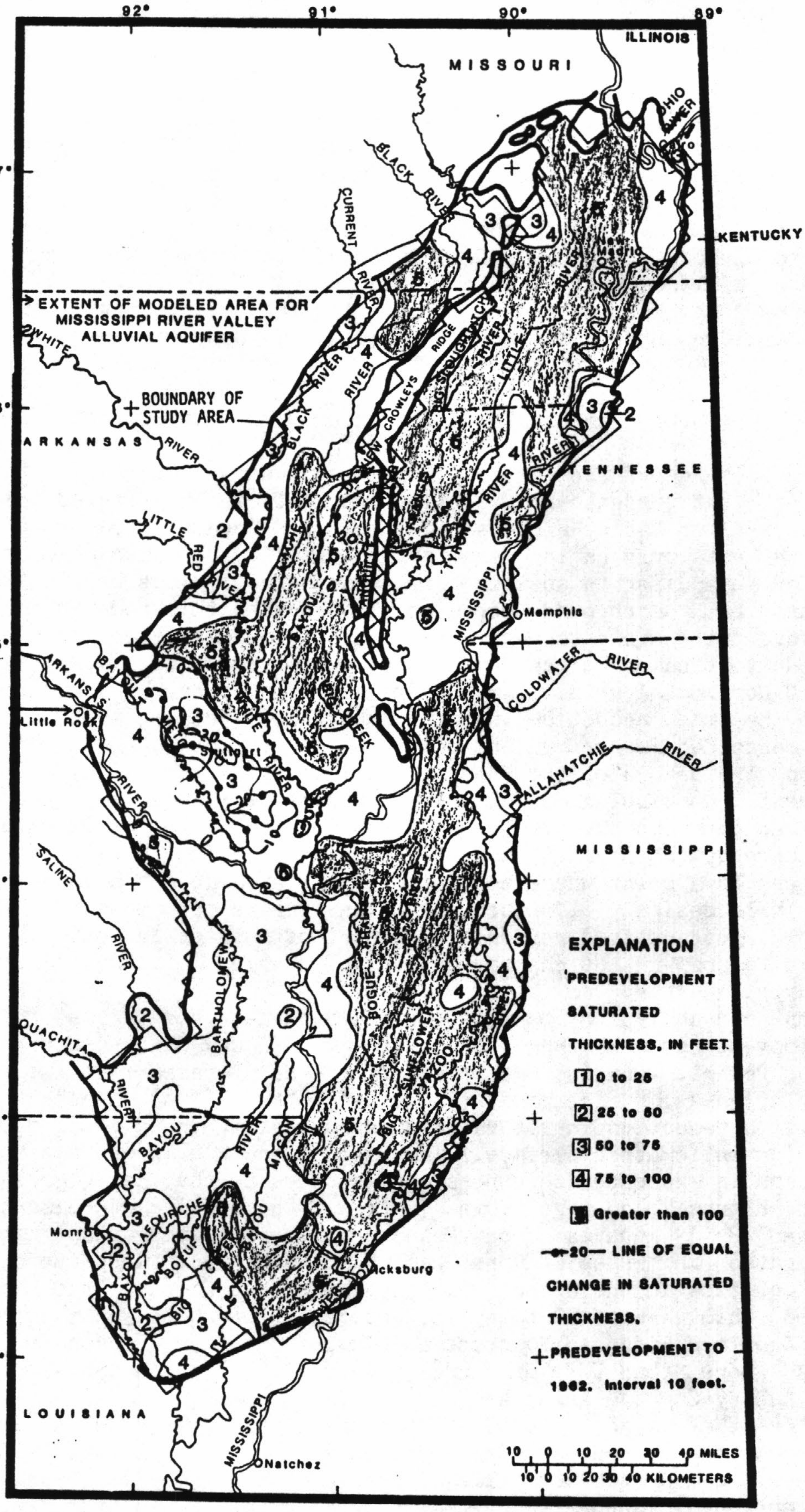


Figure 22.--Estimated predevelopment saturated thickness of the Mississippi River Valley alluvial aquifer, and change in saturated thickness, predevelopment to 1962, from simulated heads.

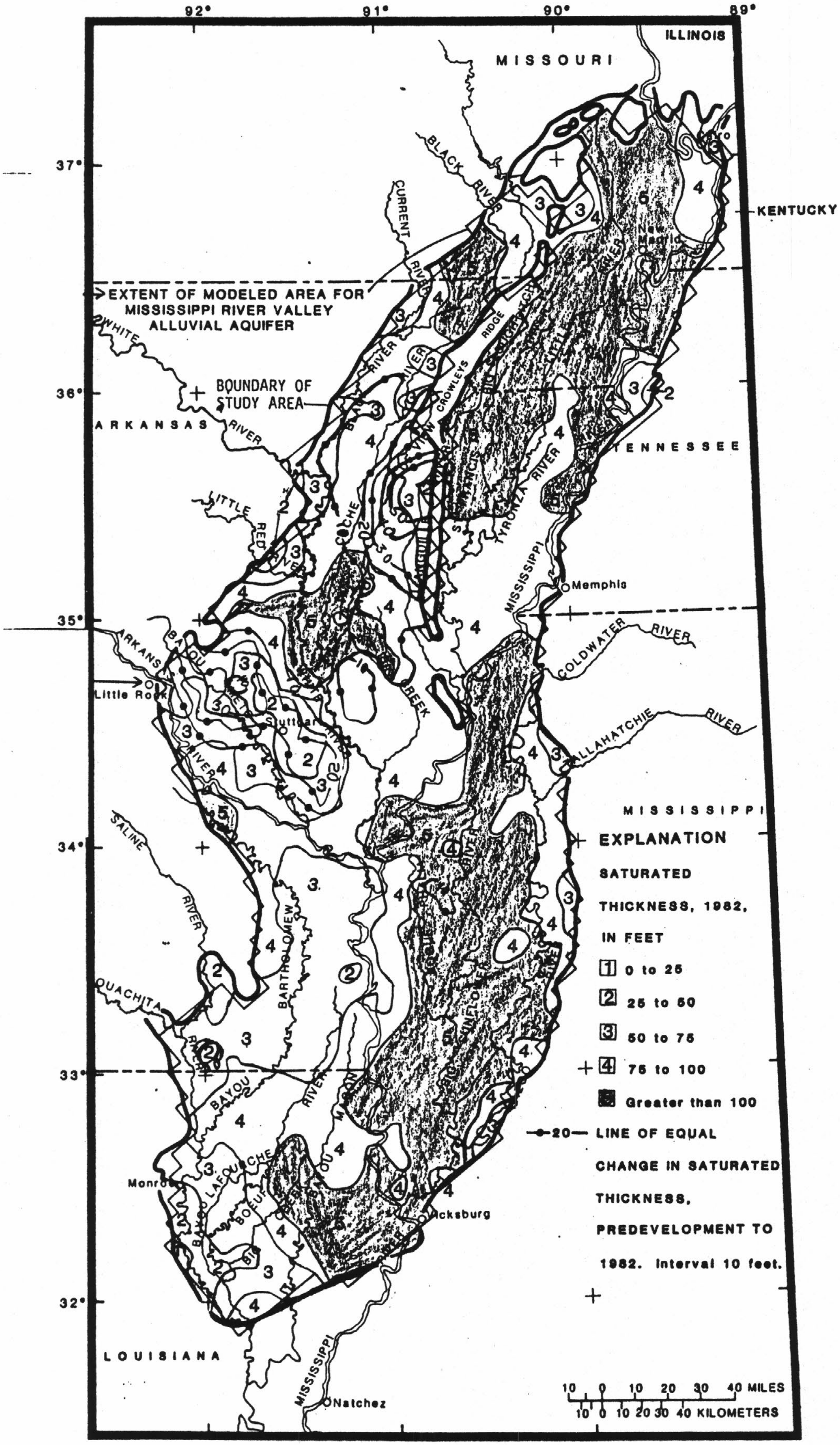


Figure 23.--Estimated saturated thickness of the Mississippi River Valley alluvial aquifer, 1982, and change in saturated thickness, predevelopment to 1982.

Decreases in saturated thickness through 1982 in the central Grand Prairie generally were 20 to 40 ft and as much as 50 to 60 ft. The largest change from 1962 to 1982 occurred in the northwestern end of the Grand Prairie in Lonoke County, Arkansas where decreases were as much as 26 ft.

In the Cache area decreases in saturated thickness through 1982 generally were from 30 to 60 ft in the area between the Cache River and Crowleys Ridge. The decrease in saturated thickness between 1962 and 1982 generally was between 25 and 35 ft and as much as 38 ft.

The mean thickness calculated from simulated values for the total aquifer area and for individual areas (fig. 2) are shown in figure 23b. Also shown are the confidence intervals about the mean at the 50 and 90 percent probability levels for the total area and the Grand Prairie and Cache areas. Confidence limits were calculated according to methods given in Snedecor and Cochran (1967) from the formula

$$CI_x = Z_c \, s_x$$

where

CI_x is the confidence limit of the sample mean;

n is the sample size;

Z_c is the confidence at n-1 for degrees of freedom for the given probability level, c; and

s_x is the standard error of the sample mean.

The confidence interval, CI_x is then given by

$$CI_x = x \pm CI_x$$

where x is the sample mean. Only the Grand Prairie and Cache areas had decreases of more than 10 ft of mean saturated thickness for the period 1905-82. The Grand Prairie had a decrease by 1942 and has continuously decreased since then. Saturated thickness for the Grand Prairie has shown the largest decrease since predevelopment. The Cache area has shown a decrease only since 1942 and has shown the greatest rate of decrease for any area since 1962.

A small area of the central part of the Delta had a decrease in saturated of 5 to 18 ft. The western part of the Boeuf area in Arkansas had a decrease of 5 to 14 ft. Over most of the Delta and Boeuf and all of the St. Francis area decreases in saturated thickness were less than 11 ft and generally less than 5 ft.

About 75 percent of the alluvial aquifer had more than 75 ft of saturated thickness in 1982 (fig. 23) as compared with 80 percent before development (fig. 22). The areas where saturated thickness decreased to less than 75 ft were nearly all in the Grand Prairie and Cache areas. About 20 percent of the Cache area had less than 75 ft of saturated thickness in 1982, a change of almost 15 percent from predevelopment. Nearly all of the decreases in saturated thickness to less than 75 ft have taken place since 1962. More than one-half of the Grand Prairie had less than 75 ft of saturated thickness in 1982, a change of more than 20 percent from predevelopment. About 15 percent of the Grand Prairie decreased to less than 50 ft of saturated thickness by 1982. Equal increases in area with saturated thickness less than 50 ft took place from 1942-62 and from 1962-82.

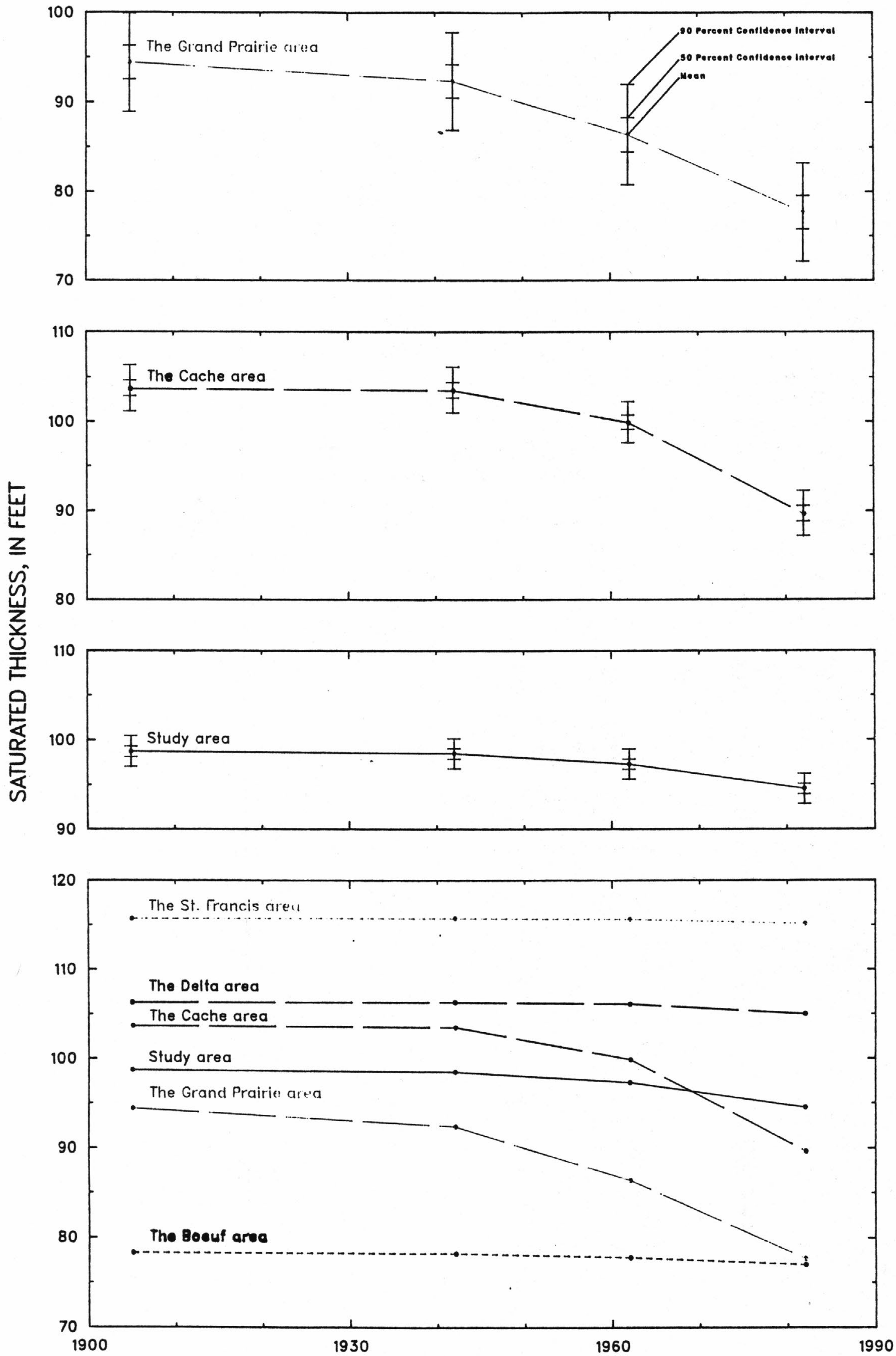


FIGURE 23B.—Change in saturated thickness of the Mississippi River Valley alluvial aquifer, predevelopment to 1982 from simulated heads.

Sniegocki (1964, p. 32) stated that well yields range from 250 to 700 gal/min in areas that have 25 to 40 ft of saturated thickness and that any area where saturated thickness is less than 25 ft may be considered seriously depleted. Sniegocki (1964, p. 32) also stated that a well yield of 300 gal/min is a lower limit for economical rice irrigation. Peralta and others (1985, p. 19-27) used 25 ft as the minimum desirable saturated thickness in the Grand Prairie for efficient and reliable ground-water sources used for rice and soybean production. Their determination of desirable aquifer saturated thickness was based on irrigating 50 acres of rice with a 500 gal/min well during typical and drought years.

Annual water-level changes reflecting changes in saturated thickness (Plafcan and Remsing, 1989; Sumner, 1984a; Sumner 1984b) generally are 2 ft or less averaged over periods of 3 or 5 years. If saturated thickness is 50 to 75 ft then continuous declines on the order of 2 ft per year would result in a serious depletion (less than 25 ft saturated thickness) in the near future.

If areas where the saturated thickness has decreased to less than 50 ft are in danger of being depleted in the near future, only the Grand Prairie had any appreciable area near serious depletion in 1982. If areas where saturated thickness has decreased to less than 75 ft are not currently in danger of but trending toward depletion, then only the Grand Prairie and Cache areas have any areas trending toward depletion in the near future. In all other areas less than 1 percent of the area had a decrease to less than 75 ft of saturated thickness and less than 2 percent of the area had a decrease to less than 100 ft of saturated thickness in 1982.

Changes in Regional Flow Due to Development

Changes in the regional flow system of the Mississippi River Valley alluvial aquifer were analyzed at various intervals from predevelopment to 1987. During this period the alluvial aquifer has been developed extensively as a source of water for agricultural use--the major stress on the system. Pumpage has had a major effect on the flow system throughout most of the aquifer as shown by an analysis of the hydrologic budget. As a result of this stress outflow to rivers has decreased, inflow from rivers has increased, and inflow through the overlying Mississippi River Valley confining unit has increased. In some areas the decrease in outflow to rivers and increase in inflow have not been sufficient to meet the demands of pumpage. As a consequence water has been removed from storage resulting in large scale regional declines in water levels, reduction in saturated aquifer thickness and decreases in well yields for some parts of the aquifer. However, throughout most of the aquifer large scale regional effects evidenced by changes in potentiometric head have not occurred. In some areas the direction of flow has been changed from that of the predevelopment flow system. Two areas have large depressions in the potentiometric surface and pronounced changes in the direction of flow. Most of the aquifer has no pronounced change in direction of flow, only a general lowering of 5 to 15 ft in the potentiometric surface.

Hydrologic Budget

The hydrologic budget for regional flow in the Mississippi River Valley alluvial aquifer (fig. 24) shows a steady change in the distribution of inflow, outflow, and storage with time (table 6). The change in flow consisted of increased inflow and a general decrease in water in storage that has balanced the increase in outflow to wells. For the aquifer as a whole, pumpage from wells became the only outflow (100 percent of total flow) by the mid-1970's and corresponded to a rate of 4 Mgal/d/block (3 in/yr) in 1985. At the same time rivers became a source of more than 30 percent of total flow rather than the recipient of net outflow. Inflow through the Mississippi River Valley confining unit increased from 0.8 in/yr (1 Mgal/d/block) for predevelopment to 1.3 in/yr (1.5 Mgal/d/block) by 1982. Inflow from underlying aquifers and confining beds has varied slightly in amount but has decreased as a proportion of the total flow. The alluvial aquifer has had continuous net losses of storage representing approximately 10 to 25 percent of total flow. Storage in the aquifer decreased at rates generally between (0.2 and 1 Mgal/d/block (0.2 and 0.9 in/yr). Inflow from areas outside the aquifer is less than 1 percent of total flow at any time for all areas.

Pumpage from wells in the Grand Prairie has caused the largest effect on the flow system as seen by large changes in the amount and distribution of flow and by changes in water levels. The hydrologic budget for the Grand Prairie (table 4a and fig. 25) shows that inflow through the confining unit increased until about the 1950's and remained steady or increased only slightly through 1987. Inflow rates increased from 0.7 in/yr (0.8 Mgal/d/block) in predevelopment to about 1.9 in/yr (2.2 Mgal/d/block) in the 1980's. This value is probably near the maximum value for downward leakage because the head in the alluvial aquifer is below the top of the aquifer throughout the area. Inflow from rivers increased from 1906 to 1987 accounting for more than 20 percent of total flow after the mid-1970's. Nearly all river reaches in the area were losing water to the aquifer by the early 1950's. By 1987 approximately equal proportions of inflow were coming from the Arkansas River, Bayou Meto, and the White and Little Red Rivers. For much of the length of Bayou Meto, the potentiometric surface is 15 to 46 ft below the riverbed. Leakage from Bayou Meto has probably been near the maximum value since the mid-1950's. Movement of water from or to underlying aquifers in the area was less than 3 percent of total flow. Water removed from aquifer storage has supplied 20 to 50 percent of the total flow since the early 1970's. This corresponds to a loss of 1 to 4 Mgal/d/block (1 to 3 in/yr) from storage. Pumpage from wells generally has been between 4 and 5 Mgal/d/block (3 and 4 in/yr) from 1950 through 1970 and 5 to 7 Mgal/d/block (4 to 6 in/yr) since 1970. The aquifer has not attained an equilibrium between pumpage and inflow since development started.

Changes in flow for the Cache area (table 4b and fig. 26) are similar to those for the Grand Prairie: increases in pumpage from wells resulted in loss of water from storage and increases in inflow. Inflow through the Mississippi River Valley confining unit has increased only slightly since the 1950's. For most of the area the potentiometric surface is below the bottom of the confining unit (top of the alluvial aquifer) resulting in maximum inflow. Inflow through the confining unit increased from 0.8 in/yr (1 Mgal/d/block) in predevelopment to 1.4 in/yr (1.7 Mgal/d/block) in the 1980's. Rivers that formerly received outflow from the aquifer during early development became sources of inflow in the 1960's. By the 1980's inflow from rivers accounted

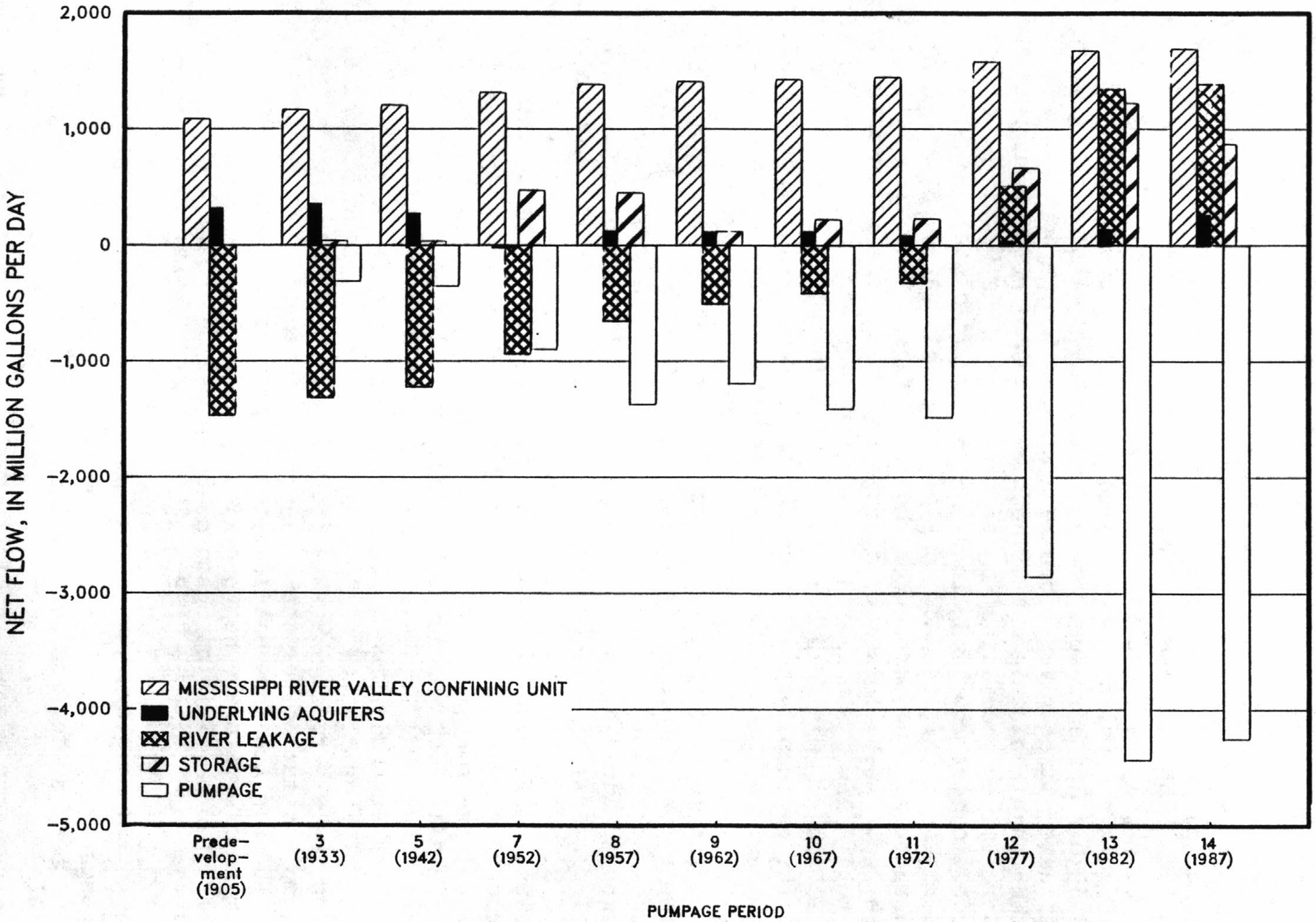


FIGURE 24.--Budget for simulated regional flow, in the Mississippi River Valley alluvial aquifer. Negative values are flow out of the aquifer.

Table 6.--Hydrologic budget for regional flow in the Mississippi River Valley alluvial aquifer

[Net flow in million gallons per day; negative values are flow out of the aquifer; data are from the end of the last time step in selected pumpage periods; sums may show variations due to rounding]

Pumpage period	Year	Mississippi River Valley confining unit	Underlying units	Adjacent units	Adjacent alluvium	Storage	All rivers	Wells
Predevelopment		1,088	315	17	-3	--	-1,466	--
3	1933	1,168	352	17	-3	41	-1,313	-312
5	1942	1,207	270	17	-3	36	-1,222	-355
7	1952	1,319	-24	17	-3	474	-938	-878
8	1957	1,390	120	17	-3	453	-654	-1,372
9	1962	1,412	109	18	-2	119	-508	-1,192
10	1967	1,432	112	18	-2	223	-414	-1,410
11	1972	1,450	79	18	-2	228	-328	-1,484
12	1977	1,583	36	19	-2	668	511	-2,855
13	1982	1,678	133	19	-2	1,228	1,348	-4,433
14	1987	1,694	255	21	-1	874	1,391	-4,250

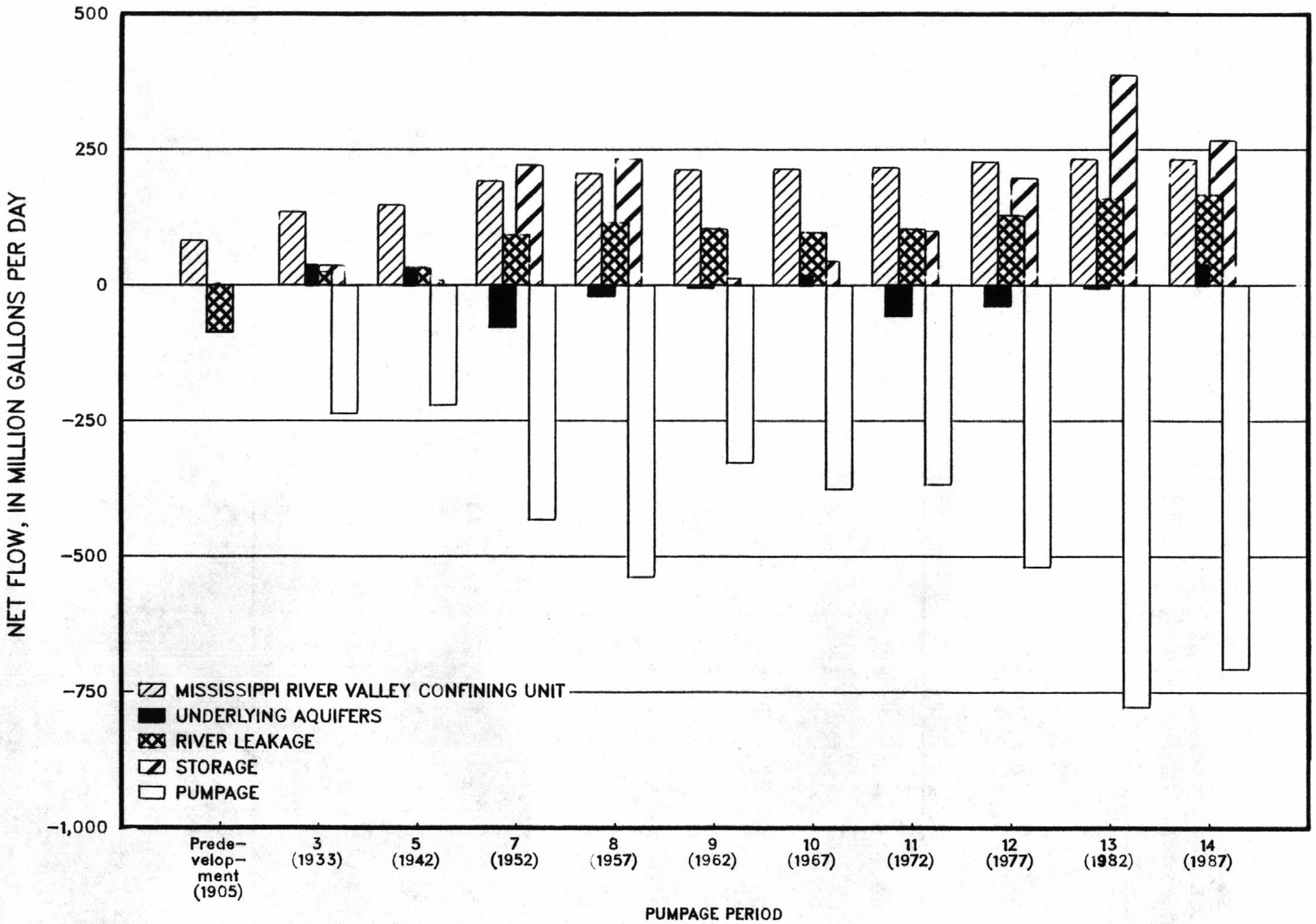


FIGURE 25.––Budget for simulated regional flow in the Mississippi River Valley alluvial aquifer: Grand Prairie area. Negative values are flow out of the aquifer.

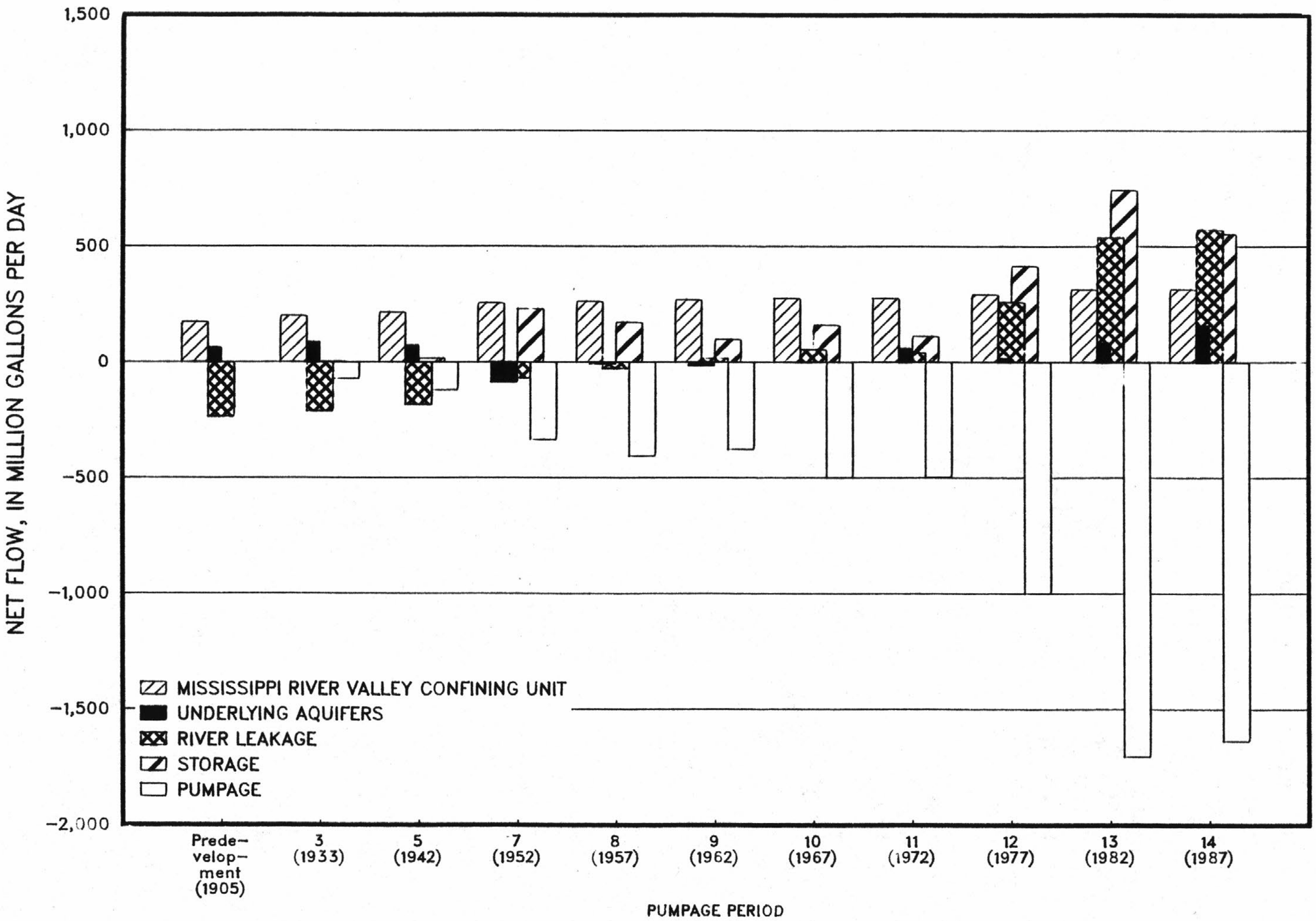


FIGURE 26.--Budget for simulated regional flow in the Mississippi River Valley alluvial aquifer: Cache area. Negative values are flow out of the aquifer.

for more than 30 percent of the total inflow. The Cache River is the largest source of inflow from rivers but most recent increases have been from the White and Black Rivers.

For part of the length of the Cache River the potentiometric surface of the alluvial aquifer is below the riverbed resulting in the maximum available inflow from reaches near areas of heaviest pumpage. Site C of figure 8 is in this area. In the area where the Cache River crosses Jackson County and southwestern Craighead County, Arkansas, the potentiometric surface is 4 to 21 ft below the riverbed. As inflow from the Cache River reached a maximum, more of the increase in inflow has been induced from reaches of the White and Black Rivers west of the area of greatest increase in pumpage. Nearly all reaches of all rivers were losing water to the alluvial aquifer by the mid-1970's. Inflow from or outflow to underlying aquifers generally has been a small part of total aquifer flow. In the 1970's and 1980's the alluvial aquifer received less than 11 percent, and generally about 7 percent, of total flow from underlying aquifers.

The increase in average pumpage from 1.8 Mgal/d/block (1.5 in/yr) in the 1950's to more than 5 Mgal/d/block (4 in/yr) in the mid-1970's and to 9 Mgal/d/block (8 in/yr) in the 1980's, has exceeded increases in inflow causing losses in storage in the Cache area. Net loss of storage was 0.6 Mgal/d/block (0.5 in/yr) to 1.2 Mgal/d/block (1 in/yr) from the early 1950's to mid-1970's and 2 to 4 Mgal/d/block (2 to 3 in/yr) since the mid-1970's. Water removed from storage has represented 22 to 43 percent of total flow since the late 1950's.

The changes in flow for the Delta since predevelopment have mostly been the decrease in outflow to rivers and increase in inflow from rivers in response to increasing pumpage (table 4c and fig. 27). Inflow from rivers exceeded outflow to rivers in the mid-1970's and represented more than 40 percent of total flow in the 1980's. Nearly all reaches of all rivers in the area were losing water to the alluvial aquifer by the early 1980's. Inflow through the confining unit has increased from 1 Mgal/d/block (1 in/yr) in predevelopment to 1.8 Mgal/d/block (1.5 in/yr) during the late 1970's and 1980's. Average pumpage in the Delta was about 0.6 Mgal/d/block (0.5 in/yr) prior to the mid-1970's and 2 to 4 Mgal/d/block (2 to 3 in/yr) since the mid-1980's.

Change in storage has supplied a noticeable part (about 8 to 12 percent) of total flow only since the mid-1970's. Loss of storage has been 0.2 to 0.5 Mgal/d/block (0.2 to 0.4 in/yr). The potential for increased induced inflow apparently exists for a large part of the Delta because the potentiometric surface is above the bottom of riverbeds and generally above the top of the aquifer. Outflow to underlying units has been a very small part of the total flow (less than 2 percent) since the early 1970's.

The changes in flow for the Boeuf area (table 4d fig. 28) are similar to those of the Delta. Most changes in flow have been in sources of inflow in response to increasing pumpage. Inflow through the confining unit increased from 0.7 in/yr (0.8 Mgal/d/block) in predevelopment to 1 in/yr (1 Mgal/d/block) after the mid-1970's. Outflow to rivers decreased and inflow from rivers increased until the late 1970's when the rivers became net sources of inflow. Unlike the Grand Prairie, Cache, and Delta areas, part of total (but not net) flow still was flow to rivers in the 1980's indicating that not all outflow had been captured by pumpage. Average pumpage was 0.5 to 1 Mgal/d/block (0.4 to 0.8 in/yr) from 1950 to the mid-1970's. After the mid-1970's it was 1.7 to 2.1 Mgal/d/block (1.4 to 1.8 in/yr).

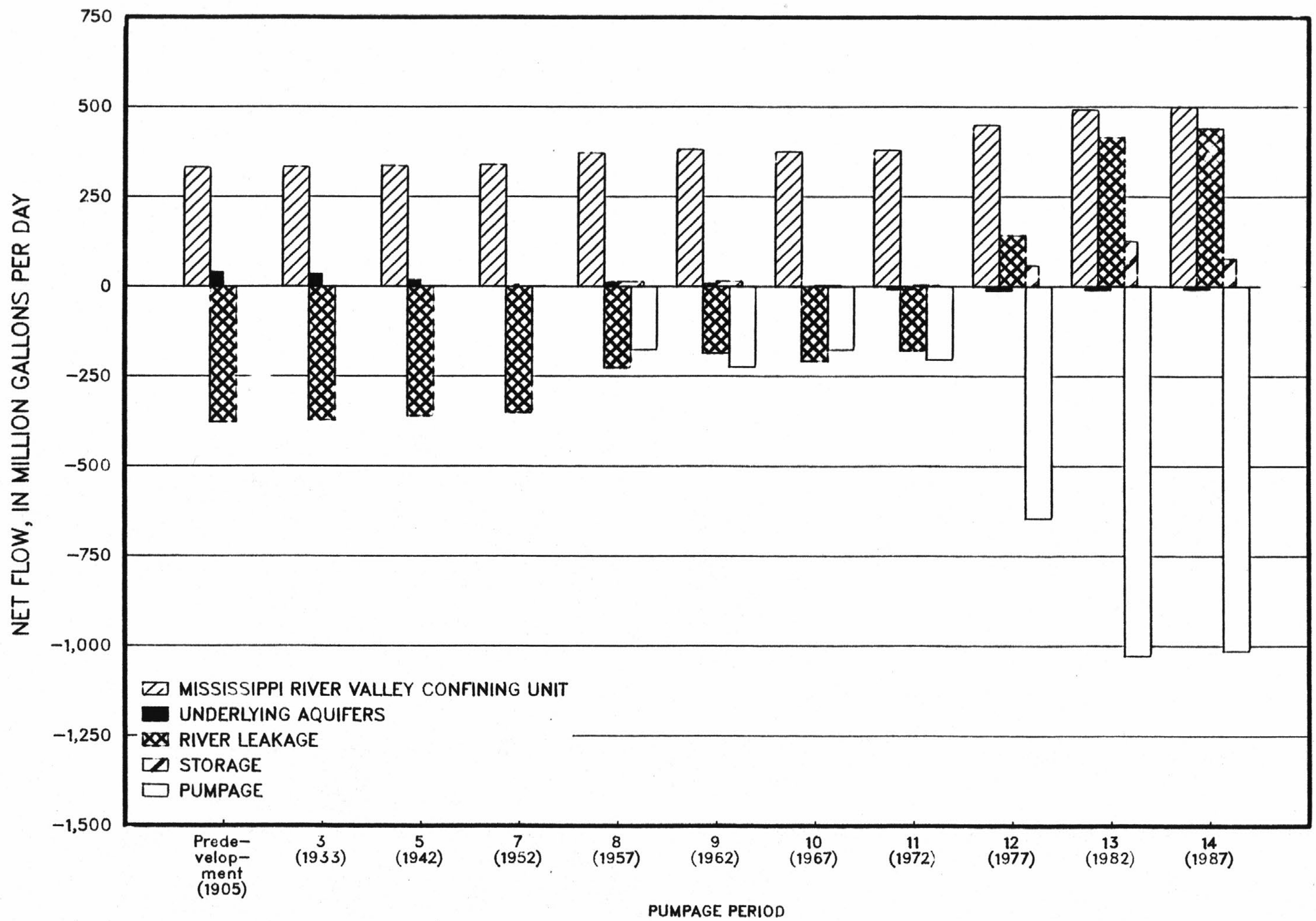


FIGURE 27.––Budget for simulated regional flow in the Mississippi River Valley alluvial aquifer: Delta area. Negative values are flow out of the aquifer.

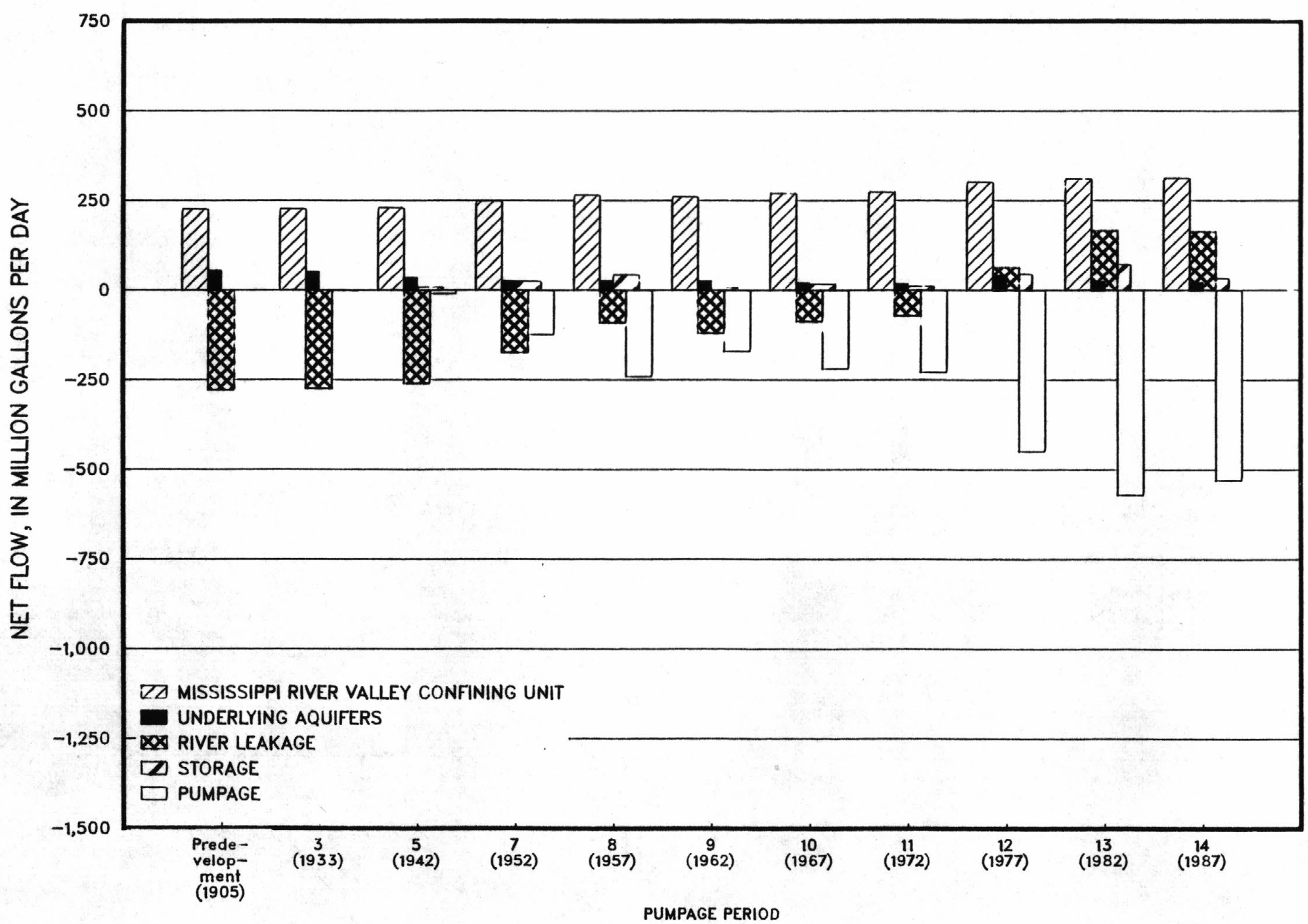


FIGURE 28.--Budget for simulated regional flow in the Mississippi River Valley alluvial aquifer: Boeuf area. Negative values are flow out of the aquifer.

Although loss of water from storage in the Boeuf area was relatively small (0.1 to 0.2 Mgal/d/block) compared to other areas, it generally has been a noticeable part (3 to 12 percent) of total flow. This may be due to slight but persistent water-level declines along the western border in southern Arkansas. Flow to the alluvial aquifer from underlying units has decreased slightly since predevelopment, and represented less than 4 percent of total flow in the 1980's.

The changes in flow for the St. Francis area are similar to those of the Delta and Boeuf areas and may be thought of as progressing in the same direction but not as far. Increases in pumpage have been mostly satisfied by changes in sources and amounts of inflow (table 4e and fig. 29). Inflow through the confining unit increased from 0.6 in/yr (0.7 Mgal/d/block) in predevelopment to 0.9 in/yr (1.1 Mgal/d/block) in the 1980's. Outflow to rivers decreased steadily from predevelopment. Inflow from rivers increased until rivers became a minor source of net regional inflow in 1982. There was nearly a balance between river outflow and inflow because about as many river reaches were gaining as were losing. This was expected because many rivers and streams in the St. Francis area were engineered to act as drains.

Average pumpage increased steadily from 0.2 Mgal/d/block (0.2 in/yr) in the mid-1950's to 1.1 Mgal/d/block (0.9 in/yr) in the late 1970's. In the 1980's pumpage was about 2 Mgal/d/block (1.7 in/yr). Loss of water from storage has been small, about 0.1 to 0.2 Mgal/d/block (0.1 to 0.2 in/yr) in the 1980's, but represented 10 percent of total flow. Inflow from underlying aquifers 0.4 in/yr (0.5 Mgal/d/block) was a major part (37 percent) of predevelopment flow but was progressively less important (0.2 in/yr, 10 percent) by the 1980's.

Distribution of Flow Components

The driving force for change in the distribution of inflow and outflow is pumpage from the Mississippi River Valley alluvial aquifer. This can best be seen by noting the evolution of pumpage distribution (figs. 15-17). The most striking change in distribution of inflow and outflow is the change from predevelopment to 1982 of most river reaches from outflow toward inflow (fig. 30b). The largest increases in flux were along the middle part of the Cache River in the Cache area (fig. 30). The smallest increase was along the Little River, a gaining river, in the St. Francis area. Most of the aquifer had increases in inflow through the Mississippi River Valley confining unit. The area with the largest gain in inflow from the confining unit was southwest of Bayou Meto in the Grand Prairie. Areas of least gain in inflow were in the Boeuf and St. Francis areas.

Another large change in the areal distribution of the components of flow is the loss of water from storage. This can be visualized by observing the decline in saturated thickness. A decrease in saturated thickness of 10 ft is a loss of about 34 inches of water, assuming the specific yield is 0.28, or a loss of 0.5 Mgal/d/block (0.4 in/yr) of water each year for the 77 years from 1906 to 1982. Current rates of loss of water from storage (fig. 31) are in the range of 1 to 10 Mgal/d/block (1 to 8 in/yr) in the Grand Prairie; 5 to 14 Mgal/d/block (4 to 12 in/yr) in the parts of the Cache area just west of Crowleys Ridge, and 4 Mgal/d/block (3 in/yr) or less, generally less than 1 Mgal/d/block (1 in/yr), elsewhere.

Changes in the distribution of inflow or outflow to the underlying aquifers (fig. 32a) were small. About 86 percent of the area changed ± 0.6 Mgal/d/block (±0.5 in/yr) or less (fig. 32b).

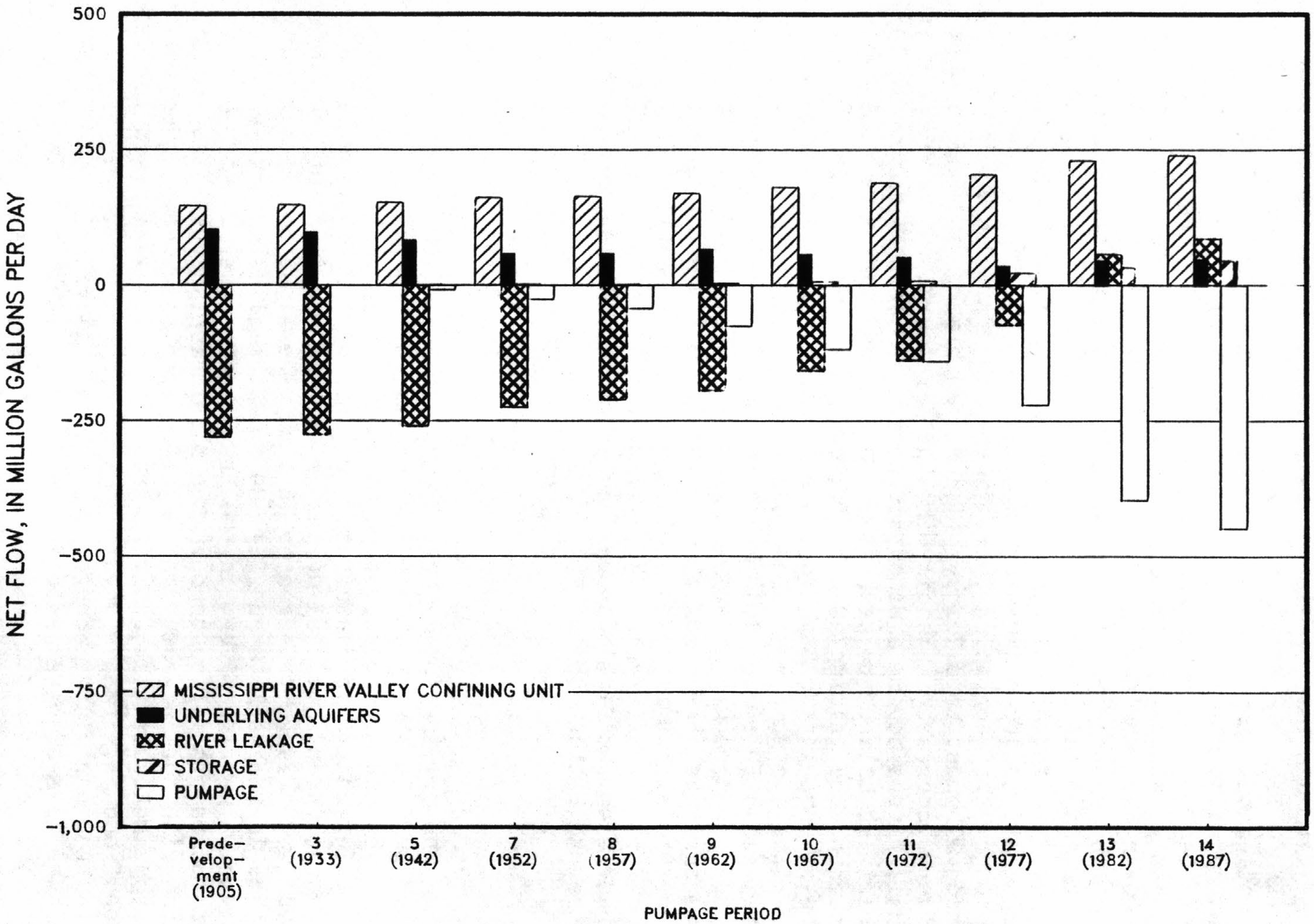


FIGURE 29.--Budget for simulated regional flow in the Mississippi River Valley alluvial aquifer: St. Francis area. Negative values are flow out of the aquifer.

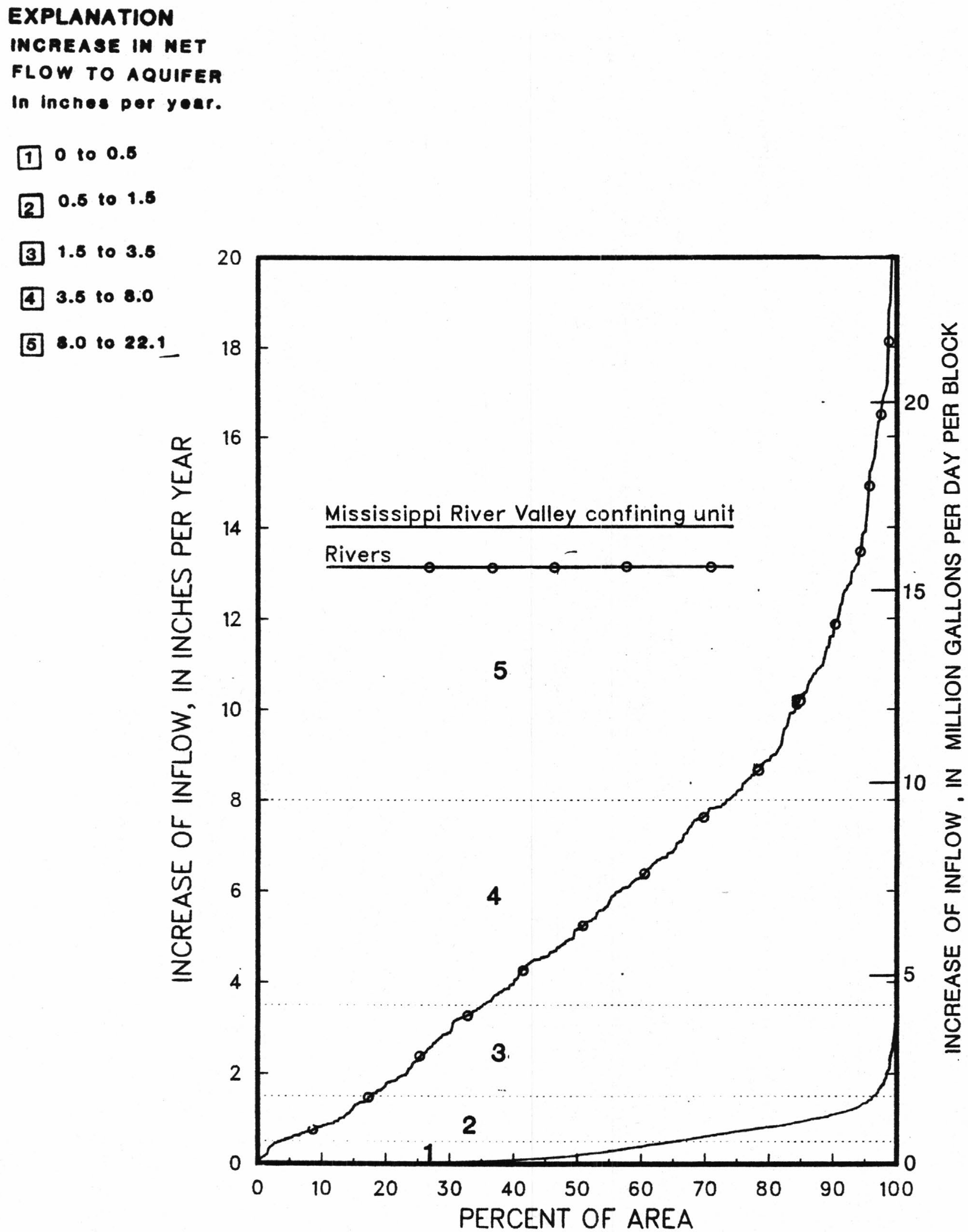


Figure 30b.--Net change in simulated inflow to the top of the Mississippi River Valley alluvial aquifer and to rivers, predevelopment to 1982.

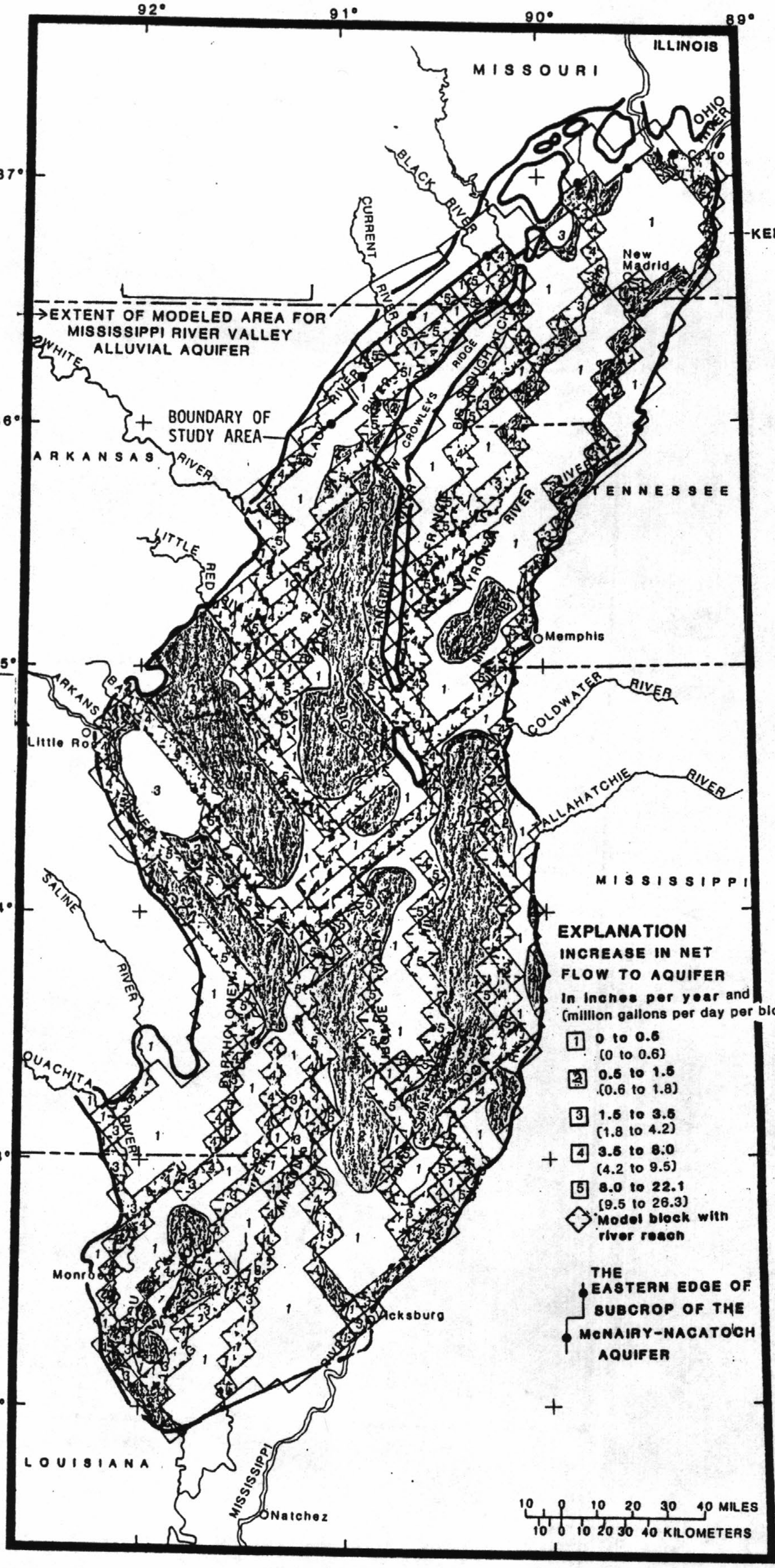


Figure 30.--Net change in simulated inflow and outflow to the top of Mississippi River Valley alluvial aquifer and to rivers, predevelopment to 1982.

EXPLANATION

LOSS OF STORAGE–In inches per year.

- [1] Less than 1
- [2] 1 to 3
- [3] 3 to 6
- [4] 6 to 9
- [5] 9 to 11.9

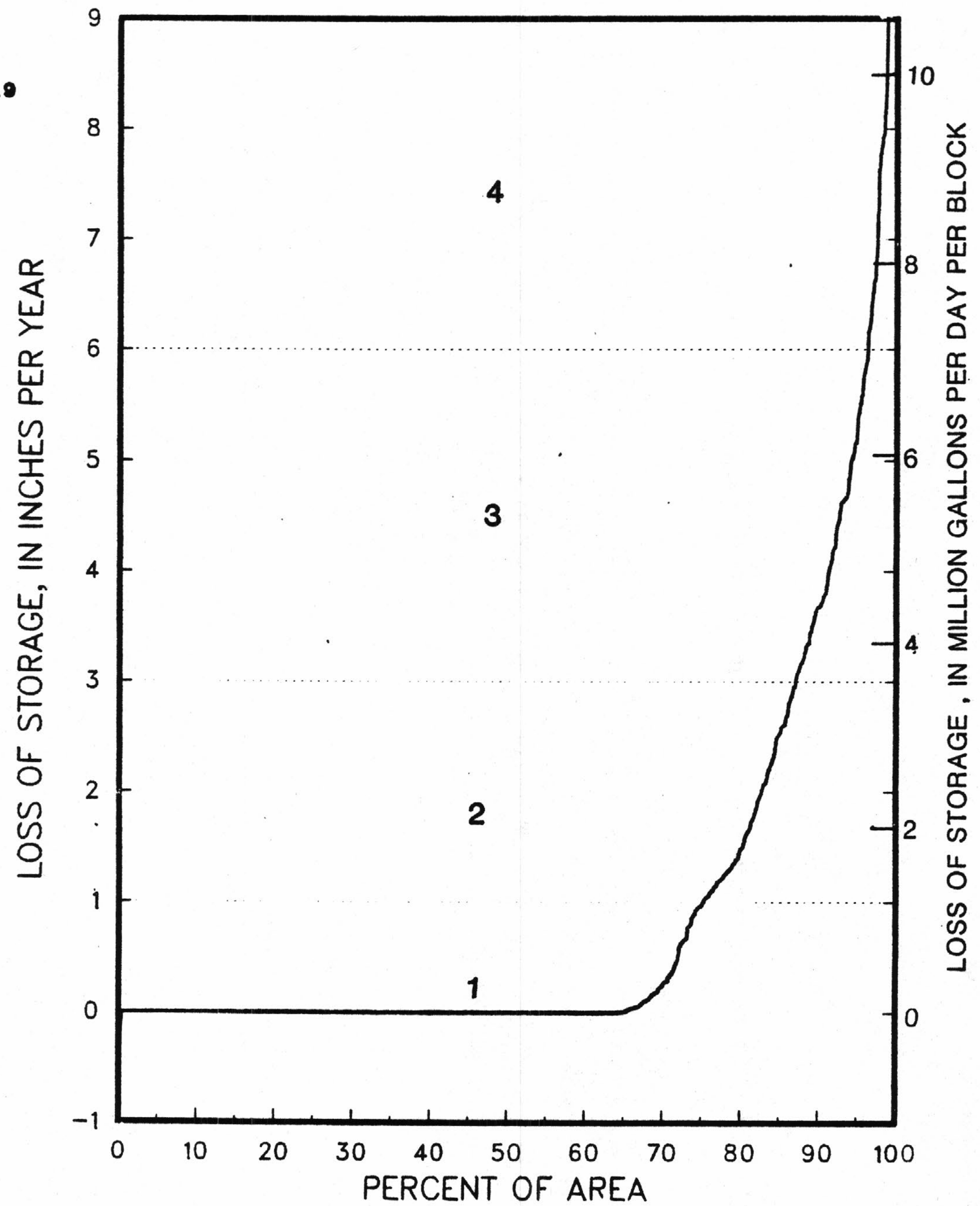


Figure 31b.--Rate of loss in storage from the Mississippi River Valley alluvial aquifer, 1982.

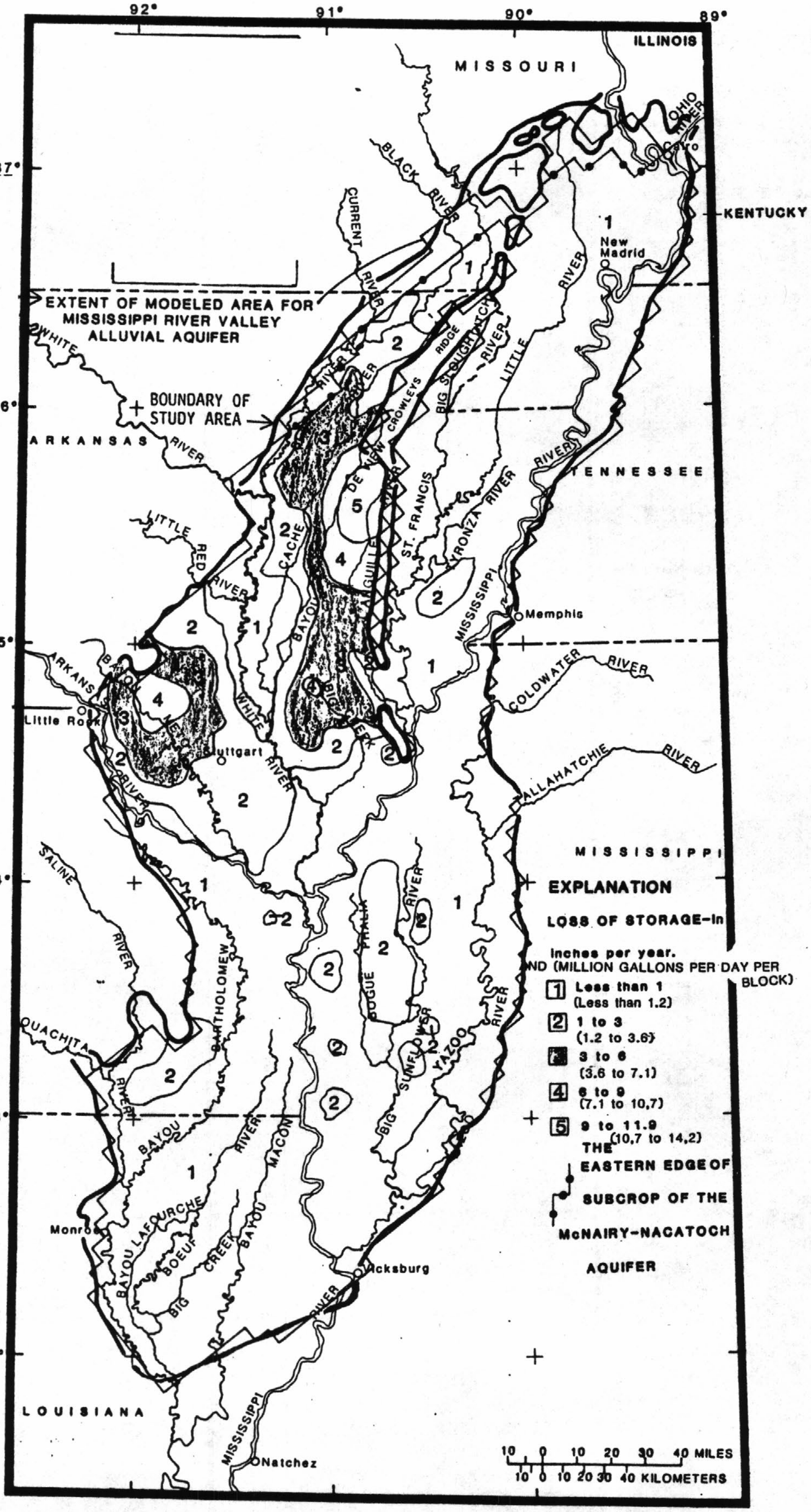


Figure 31.--Rate of loss in storage from the Mississippi River Valley alluvial aquifer in 1982.

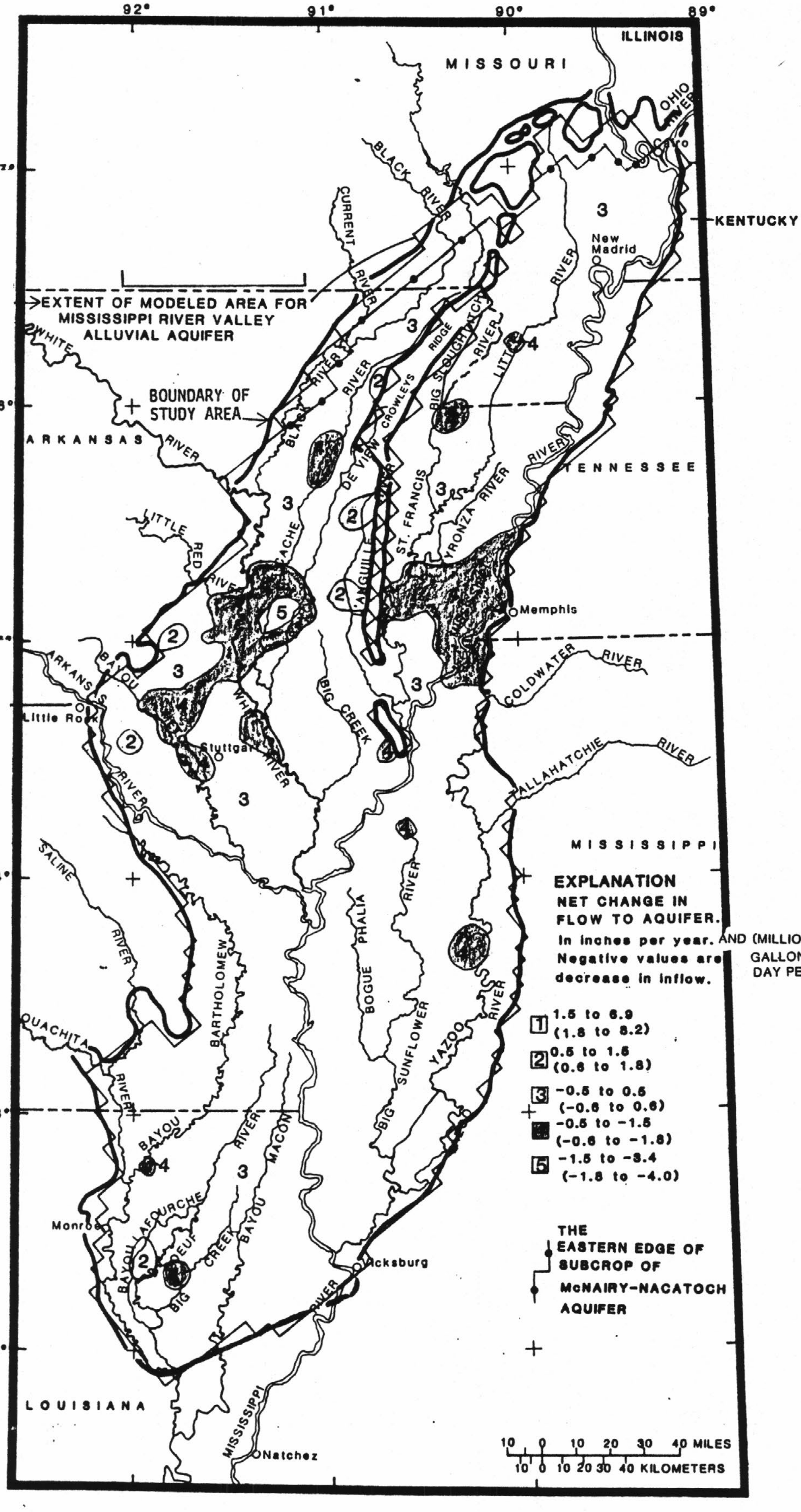


Figure 32.--Net change in simulated inflow and outflow to the bottom of the Mississippi River Valley alluvial aquifer, predevelopment to 1982.

EXPLANATION

NET CHANGE IN FLOW TO AQUIFER. In inches per year. Negative values are decrease in inflow.

1 1.5 to 6.9

2 0.5 to 1.5

3 -0.5 to 0.5

4 -0.5 to -1.5

5 -1.5 to -3.4

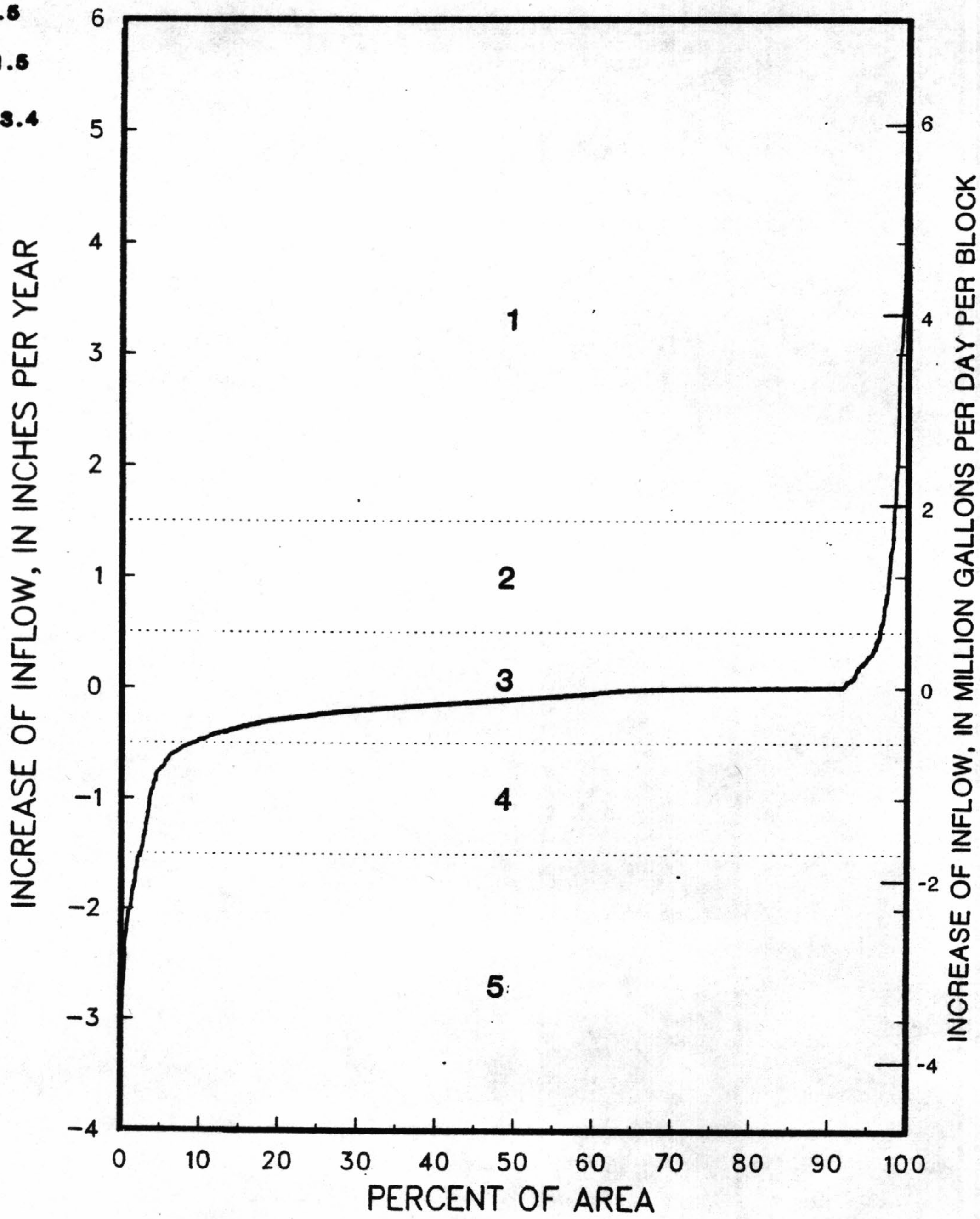


Figure 32 b.--Net change in simulated inflow and outflow to the bottom of the Mississippi River Valley alluvial aquifer.

Direction of Flow

The development of the Mississippi River Valley alluvial aquifer has caused a change in directions of flow in the Grand Prairie and Cache areas. The changes in the Grand Prairie, as evidenced by the closed contours on the potentiometric surfaces and by areas of prominent drawdown, are more pronounced than those of the Cache area (fig. 19-21). The changes in direction of flow in the Cache area are more recent but were more rapid than those in the Grand Prairie.

Predevelopment regional flow directions (fig. 11) in the Grand Prairie generally were southeastward, toward the White River, but locally toward the Arkansas River. By 1942 the potentiometric surface (fig. 19) indicated that flow was diverted toward an elongate northwest-southeast trough which plunges southeast and contains a closed circular depression centered 20 miles southeast of Stuttgart. The trough coincides with the thickest part of the Mississippi River Valley confining unit (fig. 7), more intense pumpage (fig. 15), and is between sources of inflow from rivers. Flow was diverted away from the downstream reaches of the White and Arkansas Rivers but remained toward the rivers near the upstream reaches. Between 1942 and 1962 the trough in the potentiometric surface deepened and expanded. The trough area expanded to the northwest and became an ellipse. In 1962 nearly all flow in the Grand Prairie (fig. 20) was toward the axis of the trough. Flow in the vicinity of the Arkansas and White Rivers was away from the rivers toward the trough. The 1982 potentiometric surface (fig. 21) indicates a continuation of the expansion of the elliptical cone of depression. Hydraulic gradients did not change in direction but did change in magnitude, especially on the flanks and the northwest end of the trough.

In the Cache area, predevelopment flow directions generally were southwestward and toward the White River. Locally, flow in the vicinity of the smaller Cache and Black Rivers was toward the rivers. No large scale change in flow direction for the Cache area could be discerned from the 1942 potentiometric map (fig. 19). Slight changes in the potentiometric surface may have caused local or small changes in flow direction. The first significant drawdown was in 1962. The potentiometric surface (fig. 20) indicated a trough had developed between Crowleys Ridge and the Cache River, between 35° N. and 36° N. latitude. Flow directions shifted southeastward toward the most intense pumpage (fig. 16).

The 1982 potentiometric surface (fig. 21) showed a recognizable trough between the Cache River and Crowleys Ridge. The trough plunges southward paralleling Crowleys Ridge. The eastern extent of the trough is truncated by Crowleys Ridge. On larger scale maps with smaller contour intervals, parts of the trough show as closed contours in the potentiometric surface as early as 1972 (Ackerman, 1989b). Nearly all rivers in the area were losing flow to the alluvial aquifer in 1982 (fig. 21 and 30). Some flow from the White and Black Rivers and from areas between those rivers and the Cache River was moving under the Cache toward the major pumping area (fig. 21 and 17). This observation was based on both modeled and mapped potentiometric gradients and is supported by hydrographs of wells (fig. 8) and by analysis of flow components mentioned previously that indicated the potentiometric surface was below the bottom of the riverbed in some areas.

In recent years the greatest drawdown of the potentiometric surface and, consequently, the greatest changes in the flow system are in the part of the Cache area just west of Crowleys Ridge. The reasons for the changes in this area are several:

1. The most intense pumpage has been in this area (fig. 17). Poinsett County has the greatest rice acreage and pumpage from the alluvial aquifer of any county in the project area since 1975 (Halberg, 1977; Holland and Ludwig, 1981; and Holland, 1987).
2. Inflow through the Mississippi River Valley confining unit is low. The area is underlain by an above average thickness of the confining unit (fig. 7).
3. The eastern side of the area is a hydrologic boundary between the alluvial aquifer and aquifers or confining beds having lower hydraulic conductivity. The simulated value of water crossing this boundary was not greater than 0.4 in/yr (0.5 Mgal/d/block) even though it was greater along this boundary than any other segment of the aquifers lateral boundary in the study area.
4. The rivers and streams in the area are smaller and probably do not penetrate to the aquifer. Most of the area is isolated from larger streams.

In the central part of the Delta and in parts of the Boeuf and St. Francis areas, drawdowns have been less than 20 ft (fig. 21). Most changes to the potentiometric surface since predevelopment have only shifted the contours upgradient (usually north) and have resulted in only minor or local changes in direction.

GROUND WATER DEVELOPMENT POTENTIAL

Continued use and further development of the Mississippi River Valley alluvial aquifer as an integral part of the water supply of the study area are assumed to a varied degree in all water use or water management studies. Specific studies that project increased demand are U.S. Department of Agriculture (1983) and Sumner and Wasson (1984).

The effect of development has been greatest in Arkansas. The alluvial aquifer became so depleted in parts of the Grand Prairie that users were forced to reduce pumpage or turn to deeper aquifers for irrigation supplies. Various alternatives for water-supply management have been investigated including: no action, conservation, surface-water diversion, and conjunctive use-sustained yield pumping strategies (U.S. Army Corps of Engineers, 1985). To assess the response of the regional flow system to continued use and further development and to evaluate the potential of the aquifer to support additional development, two simulations were made to represent ground-water flow from 1982 to 2022. This report will first discuss aquifer response to pumpage in terms of possible effects and then discuss the indicated potential for additional development in areas without projected effects.

The effect of continued or increased development and the ability of the system to support development were evaluated based on the change in head of the aquifer and decreases in saturated thickness. A decrease in head (drawdown) is an incomplete indication of the response of the system. A decrease in head generally is not economically significant unless accompanied by a serious decrease in saturated thickness and, consequently, a decrease in yield. Peralta and others (1985, p. 32) noted that increasing pumping costs due to declining ground-water levels probably are not and will not be prohibitive. As previously noted, 25 ft of saturated thickness is a lower limit for economical rice irrigation. When drawdown of head results in saturated thickness less than 25 ft, the aquifer is assumed to be unable to support pumping at the simulated rate. A decrease in saturated thickness of

25 to 50 ft is probably indicative that the aquifer has been severely affected and is not likely to support current development. When saturated thickness decreases to 50 to 75 ft, the effect of development is probably moderate.

Some areas have always had a small saturated thickness (figs. 22 and 23). Yields in these areas would probably always be less than yields in that part of the alluvial aquifer with larger saturated thickness. If drawdowns from pre-existing conditions are less than 10 ft after more than 20 years of sustained pumpage, effects are probably not significant.

The converse of measuring severity of effects by decrease in saturated thickness is to measure potential for further pumpage by lack of decrease in saturated thickness. Areas with less than 10 ft of drawdown and more than 100 ft of saturated thickness could be optimal locations for continued pumpage with the least foreseeable effect.

In the following discussion of projected regional aquifer response and potential for additional pumpage no consideration was given to possible changes in water quality. In some isolated areas the potential for continued use or additional pumpage may be limited by the presence of saline water in the alluvial aquifer. Additional use of the aquifer may also induce the movement of poor-quality water from adjacent areas or aquifers. Areas of the alluvial aquifer where water quality has degraded are small and probably the result of local conditions.

Projected Aquifer Response to Current and Additional Development

Based on simulation, the response of the Mississippi River Valley alluvial aquifer in the year 2002 to 20 years of pumpage at 1985 rates would be most pronounced in the Grand Prairie and Cache areas. The areas where saturated thickness would decrease as a result of sustaining current pumpage can be seen by comparing the simulated saturated thickness in 1982 (fig. 23) to that in 2022 (figs. 33 and 34). A decrease in saturated thickness to the extent that a severe effect or an inability of the aquifer to maintain current pumpage rates would be indicated only in parts of the Grand Prairie and Cache areas. In some areas saturated thickness would decline to less than 25 ft. In some areas where drawdown since 1982 would have exceeded 15 ft, saturated thickness would decline to less than 50 ft. After 40 years of pumpage at 1985 rates the Grand Prairie and Cache areas would be the only areas in the year 2022 with more than moderate effects (fig. 34). The areas of severe effects would decrease slightly. Areas unable to sustain development would increase from the year 2002 to 2022. Other than a small area of possible moderate effect in the St. Francis area, all the areas except the Grand Prairie and parts of the Cache areas seem to have the ability to sustain current levels of pumpage with only minimal effects.

A second simulation was made in order to assess the effect of increased pumpage and to determine areas that have a potential for increased pumpage. Beginning in 1987 an increased pumpage of 1.2 Mgal/d/block (1 in/yr) above 1985 rates was applied to all the study area for 35 years. The aquifer response projected by the two preceding development scenarios is not intended to predict future response. It is highly unlikely that increased pumpage would occur uniformly throughout the study area as simulated. The purpose of this work is to indicate regions in the aquifer likely to show a similar response. After 15 years of pumping at the additional rate (2002) most of the aquifer would not be even moderately affected (fig. 35). Effects on the

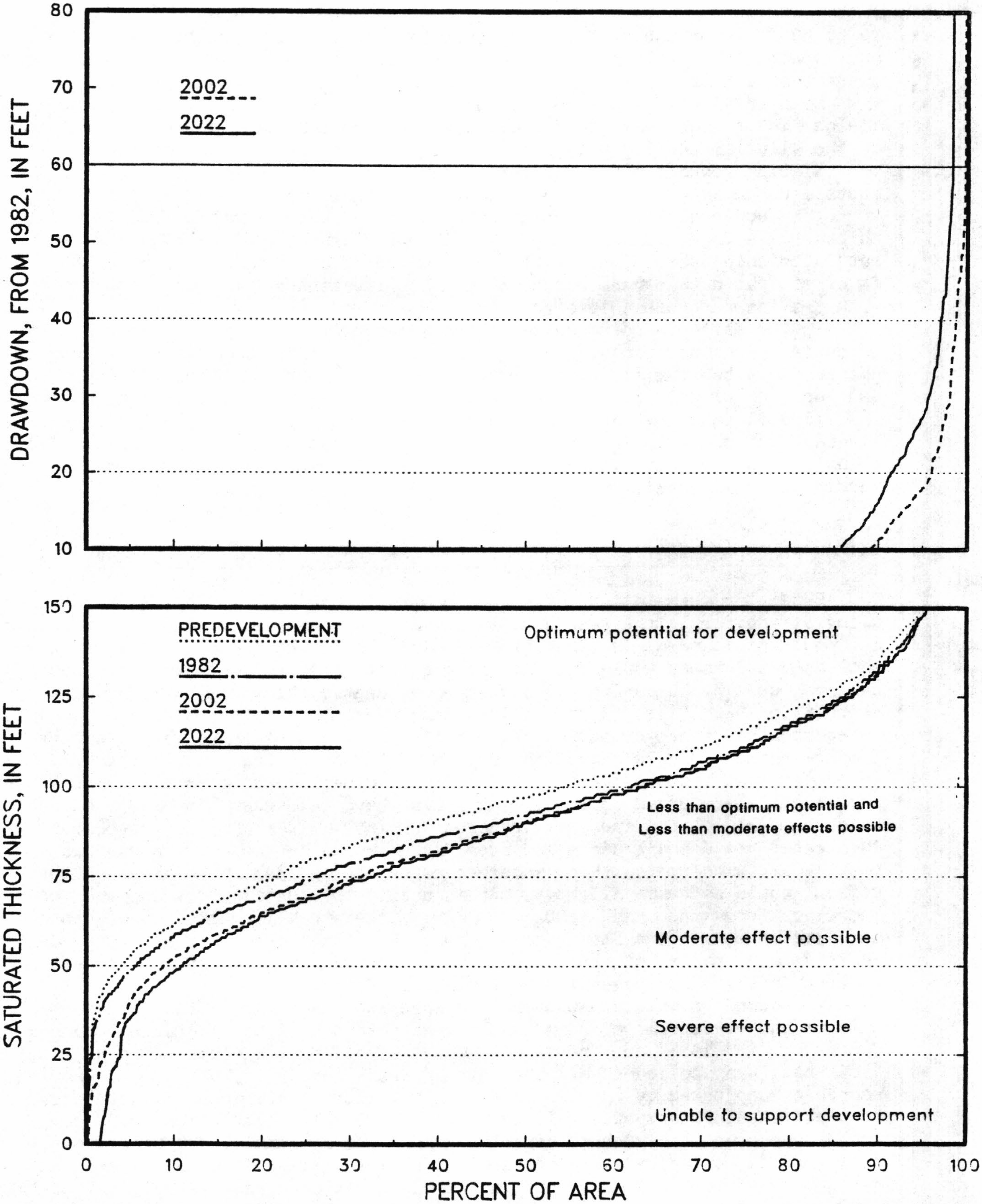


FIGURE 33.--Potential for sustaining current development of the Mississippi River Valley alluvial aquifer.

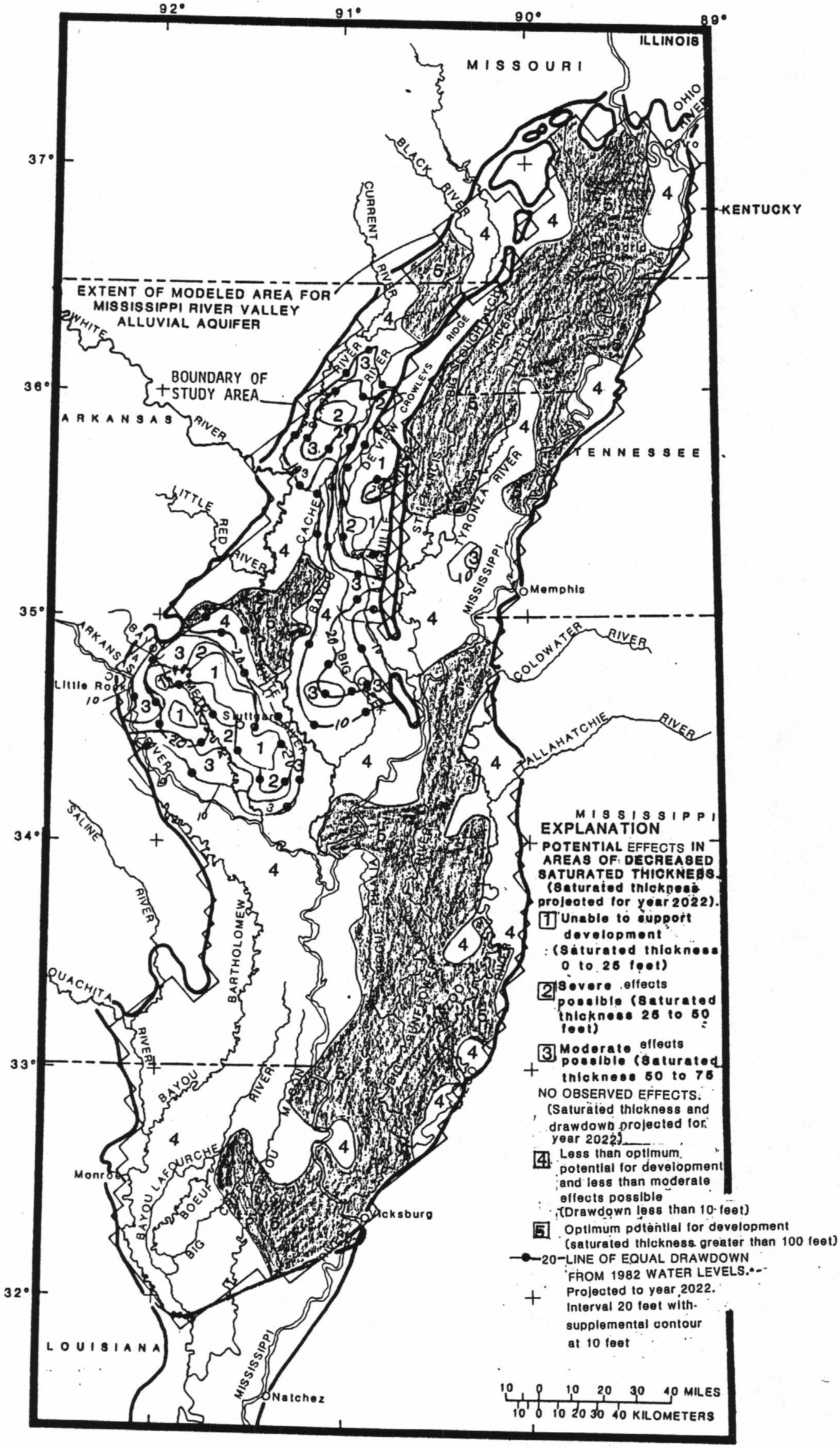


Figure 34.--Potential for sustaining current development of the Mississippi River Valley alluvial aquifer.

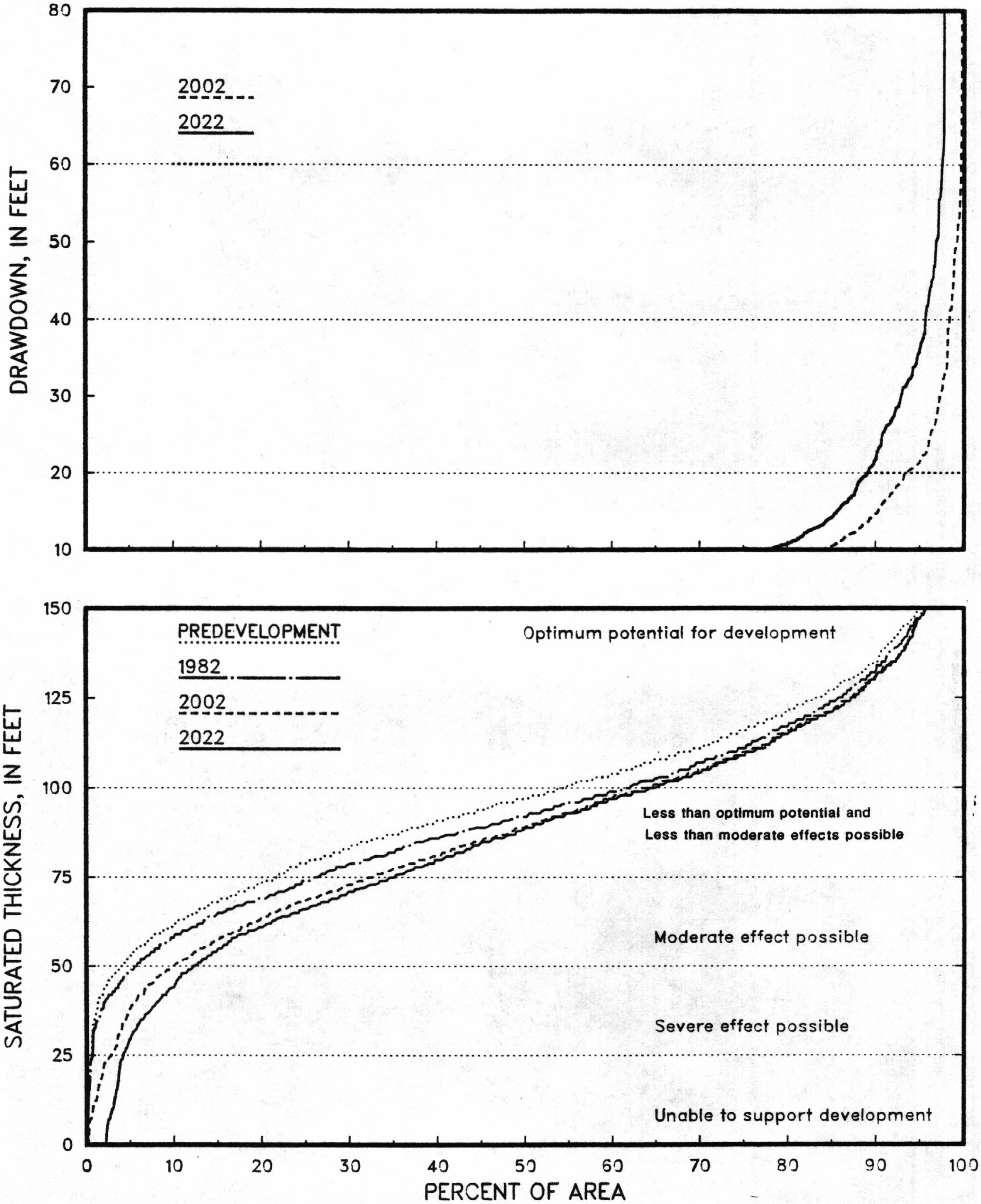


FIGURE 35.--Potential for additional development of the Mississippi River Valley alluvial aquifer.

aquifer would be moderate or greater in large parts of the Grand Prairie and Cache areas (fig. 36), but only slightly more than that resulting from sustaining current pumpage (fig. 34). In these areas additional pumpage of 1.2 Mgal/d/block for 15 years would not be proportionately a large increase. The most noticeable effects of increased pumpage would occur after 35 years. A severe effect of additional pumpage would occur for most of the Grand Prairie and a large part of the Cache area. Possible effects would occur for small areas in the Boeuf and St. Francis areas. The part of the Boeuf area that would have moderate to severe effects is at the edge of the alluvial aquifer where it consists of thin terrace deposits. The part of the St. Francis area where moderate effects would occur lies between the Tyronza and Mississippi Rivers in Crittenden County, Arkansas. This moderate effect area was mentioned in the section on water-level changes due to development as showing declines in water levels that were unsupported by observations. Results may be less sure due to the lack of supporting data. Drawdowns from 1982 conditions of more than 10 ft would occur in small scattered locations throughout the Delta, and in the remainder of the Boeuf and St. Francis areas. None of these small areas would coincide with decreases in saturated thickness of less than 70 ft for an area of more than 25 mi^2.

The areas modeled as being unable to support development were allowed to be pumped beyond the likely limit of use. As mentioned by Peralta and others (1985, p. 32) reduction of well yields is probably such a strong signal that water users will reduce withdrawals, abandon shallow wells, seek alternate supplies, improve efficiency, or switch to crops that demand less water. Various combinations of reduced water use or, at the least, reduced increase in water use have probably been affecting ground-water demand in the Grand Prairie for many years. The trends in rice acreage for Arkansas County, Arkansas and in pumpage (fig. 14) for the Grand Prairie do not show a significant increase subsequent to 1940 as compared to other areas. Use of water from the underlying middle Claiborne aquifer for irrigation and aquaculture, has increased steadily from about 1940 to 1980 in the Grand Prairie (D.J. Fitzpatrick, U.S. Geological Survey, written commun., 1987). The middle Claiborne aquifer was probably the primary alternative source of water in the Grand Prairie for those users who were experiencing problems with declining yields from the alluvial aquifer. In 1962 the saturated thickness in the central part of the Grand Prairie was about 40 to 70 ft. In 1982 the saturated thickness was about 30 to 60 ft in the same area. As other areas, especially part of the St. Francis area, approach limits of sustained yield as indicated by a saturated thickness of 40 to 60 ft, the pumping rates from the aquifer will stabilize or decrease.

Potential for Additional Development

Simulation of aquifer response to a uniform additional pumpage of 1.2 Mgal/d/block (1 in/yr) above 1985 rates was used to delineate areas with potential for supporting increased pumpage. By using the criteria of more than 100 ft of saturated thickness and less than 10 ft of drawdown following 35 years of additional development, several large areas of Mississippi River Valley alluvial aquifer show potential for continued pumpage at rates greater than 1985 pumpage. The largest area covers the central part of the Delta and small parts of the Boeuf area (fig. 36). The area coincides with thick saturated sections of the aquifer except for several small areas where drawdown in excess of 10 ft would be indicated. Pumpage in this area for the simulation generally was 2.3 to 7 Mgal/d/block.

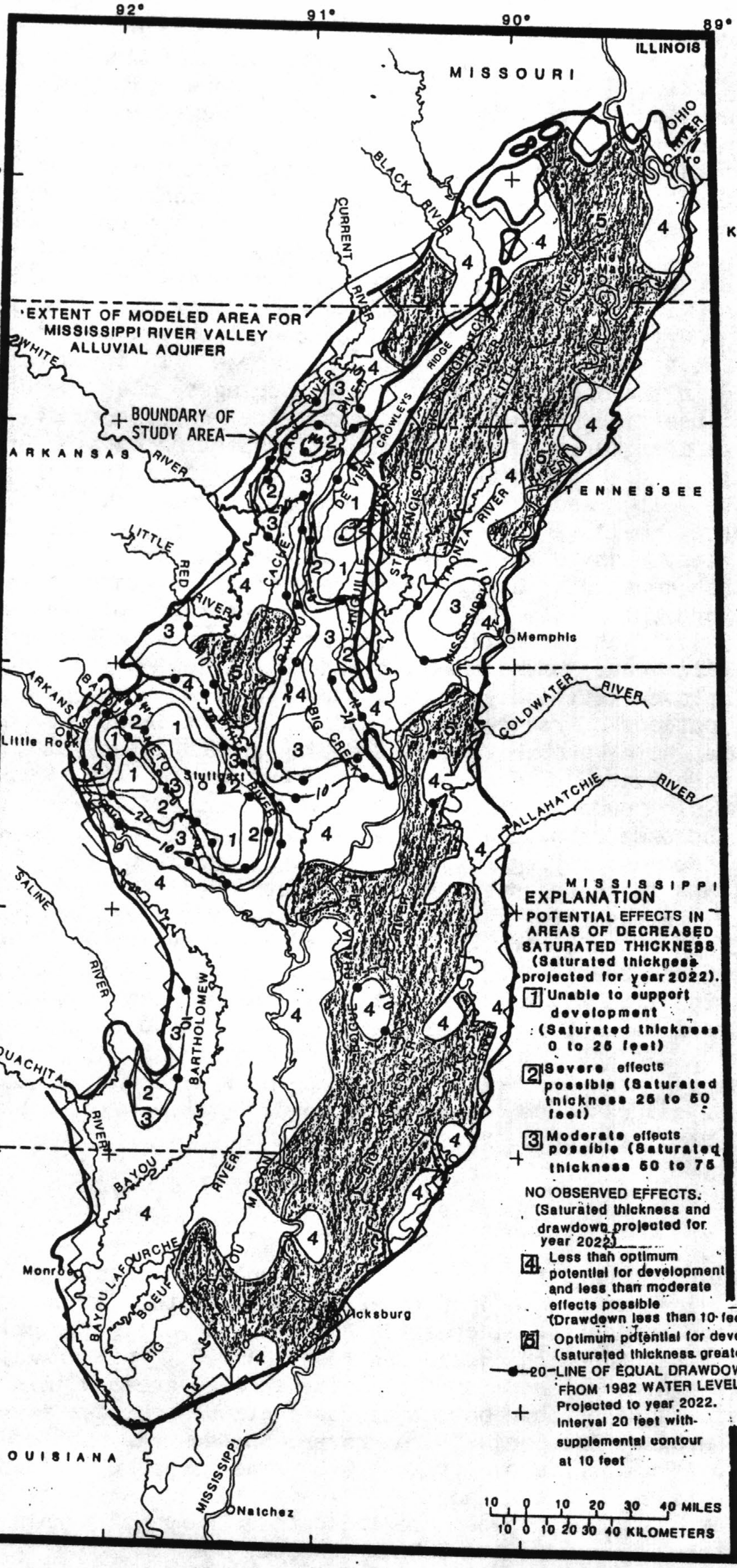


Figure 36.--Potential for additional development of the Mississippi River Valley alluvial aquifer.

A second large area where projected aquifer response indicates potential for increased development is the northern part of the St. Francis area. Simulated pumpage was 1 to 7 Mgal/d/block but generally 1 to 3.6 Mgal/d/block.

Three small areas, mostly in the Cache area, are indicated as having potential for additional development. One site is on the Arkansas Missouri border, another is at the confluence of the White and Cache Rivers and the third is at the confluence of the White and Mississippi Rivers. Simulated pumpage in these areas generally was 3.6 to 9.5 Mgal/d/block.

In reality, the potential for additional development is not limited to areas with more than 100 ft of saturated thickness nor is the greatest potential for further development directly proportional to saturated thickness. Other areas exist that probably would be able to support additional development with less saturated thickness. Historically, the best potential for inducing inflow to the alluvial aquifer is near large rivers, and to a limited extent, through the Mississippi River Valley confining unit. Therefore, locations where major rivers are in good hydraulic connection with the alluvial aquifer, or locations where the confining unit is thin, sandy, or absent, would have the greatest potential for further development. Conversely, areas far from potential induced recharge may have reduced potential for increased development even where saturated thickness is great. Predevelopment saturated thickness was more than 100 ft in the heavily stressed part of the Cache area near Crowleys Ridge and less than 75 ft in the central part of the Grand Prairie. The additional saturated thickness in the Cache area is apparently only delaying the inevitable decrease in yield and reduction in use.

SUMMARY

The Mississippi River Valley alluvial aquifer underlies a vast low, flat plain that extends from the apex of the Mississippi embayment south to the Gulf of Mexico. This report is limited to the area of occurrence north of the southern limit of the subcrop of the Vicksburg-Jackson confining unit (an area of about 32,000 mi^2). The alluvial aquifer is part of the Mississippi embayment aquifer system and is comprised of unconsolidated alluvium and terrace deposits of Quaternary age. The aquifer consists predominately of sand and gravel. The aquifer grades from gravel or gravely sand at the bottom to fine-grained sand at the top. Lenses of clay, silt, or sandy silt occur at many places in the aquifer. The upper part of the Quaternary deposits are the silt, clays, and sands of the Mississippi River Valley confining unit.

Aquifer thickness generally ranges from 60 to 140 ft, and extremes occur where the Mississippi River Valley confining unit is absent or thick. Saturated thickness generally is equal to aquifer thickness except in areas where drawdown extends below the top of the aquifer. Based on aquifer tests the hydraulic conductivity is about 200 ft/d and storage coefficients vary from 0.0001 where water in the aquifer is confined to 0.30 where it is unconfined.

The overlying Mississippi River Valley confining unit averages 30 ft in thickness, but is highly variable--generally ranging from 10 to 50 ft. The confining unit is thinnest in the north and near the margins of the aquifer and is thickest between Bayou Meto and the White River near Stuttgart, Arkansas, where it is consistently more than 50 ft thick.

The alluvial aquifer is underlain by alternating sands and clays of the McNairy-Nacatoch aquifer and the Mississippi embayment aquifer system and also, in a small area, undifferentiated Paleozoic rocks. Most of the geohydrologic units of the Mississippi embayment aquifer system that underlie the alluvial aquifer are regional aquifers. They have distinctly smaller hydraulic conductivities, and consist of alternating beds of sand and clay with some interbedded silt, lignite, and limestone. The Paleozoic rocks consist of shales, limestones, dolomites, and quartzites of minimal hydraulic conductivity.

The lateral boundary of the alluvial aquifer, including the contact with Crowleys Ridge, consists of the same hydrologic units that underlie the aquifer. Much of the boundary is a contact with the Paleozoic rocks and with the confining units of the Mississippi embayment aquifer system units of minimal hydraulic conductivity. The remainder of the boundary consists of the contact with aquifers of the Mississippi embayment aquifer system, which generally have distinctly smaller hydraulic conductivities than the alluvial aquifer.

The alluvial aquifer is in hydraulic connection with many rivers and drains. The degree of connection is greatest for large rivers that fully penetrate the confining unit and the aquifer and is least, or not directly connected, for rivers not fully penetrating the confining unit. The Mississippi River is the largest of the rivers and commonly penetrates the aquifer but does not affect the water levels for as much of the area of the aquifer as do other rivers and drains. A large area to the east of the Mississippi River receives recharge from the river. This occurs even though the net flow is to the Mississippi River for most of the year. A large gradient to the east exists year round a few miles from the Mississippi River. The Mississippi, White, and Arkansas Rivers are hydrologic boundaries for flow in the alluvial aquifer.

For the purpose of discussion the study area was divided into five areal subdivisions bounded by three major rivers, Crowleys Ridge, and the eastern limit of the subcrop of the McNairy-Nacatoch aquifer. The five areas respond slightly differently and somewhat independently to pumpage. The area west of the McNairy-Nacatoch aquifer subcrop is excluded because simulated budget terms in that area would obscure analysis for the remainder of the area.

Simulation (computer modeling) of aquifer response between 1906 and 1987 was used to analyze ground-water flow patterns and to evaluate the effects of development on the flow system. The boundary of the computer model and of the study correspond to the physical limits of the Mississippi River Valley alluvial aquifer except that the southern limit is where the alluvial aquifer crosses the subcrop of the top of the Vicksburg-Jackson confining unit. The inclusion of all of the aquifer in the study area and the representation of all physical boundaries of the model as head dependent flux boundaries in the computer model required less boundary assumptions and less constraint of the simulation of the flow system.

Predevelopment flow in the Mississippi River Valley alluvial aquifer consisted of inflow through the Mississippi River Valley confining unit, inflow from underlying and adjacent aquifers, and outflow to rivers. Most inflow, about 74 percent, was through the confining unit at a net rate of 0.8 in/yr. Average rates for the five areas varied between 0.5 and 1.0 in/yr. Flow from underlying aquifers represented 22 percent of inflow and corresponds to a rate of 0.2 in/yr. Individual areas differed in the relative contribution from underlying units the smallest being in the Grand Prairie and the largest in the St. Francis area. The simulated predevelopment potentiometric surface shows movement down the Mississippi River Valley and following the slope of land surface toward major rivers near the axes of the St. Francis, White, Arkansas, Yazoo, and Boeuf basins. Most predevelopment heads were within 20 ft of land surface.

The development of ground water from the alluvial aquifer has been primarily for agricultural use, particularly the irrigation of rice. The withdrawal of large quantities of water for rice irrigation started in the early 1900's in the Grand Prairie and was followed within about 10 years by similar development in the Cache area. Large withdrawals in other areas generally began about 1950. The largest increases in withdrawals occurred in all areas between 1973 and 1982. Maximum withdrawals for the study area before the present (1988) are estimated at 7,800 ft^3/s (5,000 Mgal/d).

The water-level response to pumpage of the alluvial aquifer has followed the trend of development in time and areally. Water levels in the alluvial aquifer have shown long-term drawdowns of nearly 90 ft. The greatest drawdown of water levels occurred in the Grand Prairie. The drawdown in the Grand Prairie was first documented in about 1927 and has been continuous since. Drawdown in the Cache area probably began in the 1940's but was indicated only as a closed depression on the potentiometric surface in the early 1960's. Water level decline has continued since then and the Cache area has the largest rate of decline in recent years of any area. The Delta has shown a limited regional drawdown of 10 to 20 ft only recently. The Boeuf area has only limited areas of drawdown of more than 10 ft since about 1973. The St. Francis area has one area where drawdown of 10 ft or more may have occurred.

Change in saturated thickness is a more important measure of aquifer response to increased development than drawdown. Decreases in saturated thickness represent not only increases in pumping lift, but also decreases in potential yield and reduction in the ability of an aquifer to sustain current yield. Continuing decreases in saturated thickness indicate that the aquifer has not compensated for withdrawals by increased local inflow or by the movement of distant inflow.

Only the Grand Prairie and Cache areas have appreciable decreases in saturated thickness. The Grand Prairie had decreases by 1942 and continuous decrease since 1942. The Cache area has had decreases only since 1942, and has had the greatest rate of decrease since 1962. Decreases in saturated thickness through 1982 in the central Grand Prairie generally were 20 to 40 ft, and isolated decreases were 50 to 60 ft. Decreases in saturated thickness in the Cache area through 1982 generally were from 30 to 60 ft. A small area in the central part of the Delta had a decrease in saturated thickness of 5 to 18 ft. Decreases in saturated thickness in most of the Delta and Boeuf areas and in all of the St. Francis area were less than 11 ft and generally less than 5 ft.

About 75 percent of the Mississippi River Valley alluvial aquifer had more than 75 ft of saturated thickness in 1982 as compared with 80 percent before development. The areas where saturated thickness decreased below 75 ft were nearly all in the Grand Prairie and Cache areas. More than one-half of the Grand Prairie had less than 75 ft of saturated thickness in 1982, a decrease of more than 20 percent from predevelopment. About 15 percent of the Grand Prairie decreased to less than 50 ft of saturated thickness by 1982. About 20 percent of the Cache area had less than 75 ft of saturated thickness in 1982, a decrease of almost 15 percent from predevelopment.

If areas where saturated thickness has decreased to less than 50 ft may be considered to be in danger of being depleted for rice irrigation in the near future (10 to 25 years), only the Grand Prairie had any appreciable area near serious depletion in 1982. If areas where saturated thickness has decreased to less than 75 ft may be considered to be not currently in danger of depletion but trending toward depletion, then only the Grand Prairie and Cache areas have any large area trending toward depletion in the near future. No other areas have decreases of more than 1 percent of the area to less than 75 ft of saturated thickness, or 2 percent of the area to less than 100 ft of saturated thickness.

For most of the aquifer the demand imposed by pumpage has had a major effect on the hydrologic budget. Outflow to rivers has decreased, inflow from rivers has increased, and inflow through the overlying confining unit has increased. In some areas the decrease in outflow to rivers and increase in inflow have not been sufficient to meet the demands of pumpage. The excess of outflow over inflow has resulted in the removal of water from storage, large scale regional water-level declines, reduction in saturated aquifer thickness, and decreases in well yields for some parts of the aquifer. However, large scale regional changes in head are not common for most of the aquifer. In some areas the flow directions have been changed from that of predevelopment flow system. Parts of the Grand Prairie and Cache areas have large depressions in the potentiometric surface and pronounced changes in the direction of flow. Most of the aquifer has no pronounced change in direction of flow, only a general decline of less than 15 ft in the potentiometric surface.

Regional flow in the Mississippi River Valley alluvial aquifer shows a steady change toward increased inflow and a general decrease in water in storage to offset the increase in outflow to wells. Outflow to wells became the only net outflow by the mid-1970's and corresponded to a rate of 3 in/yr in 1985. At the same time rivers became a source of more than 30 percent of total inflow rather than the recipient of net aquifer outflow as they were in predevelopment. Recharge through the Mississippi River Valley confining unit increased from an inflow rate of 0.8 in/yr for predevelopment to 1.3 in/yr by 1982. Inflow from underlying aquifers and confining beds has varied only slightly but has decreased as a proportion of the total budget. The alluvial aquifer has had continuous net losses of storage representing approximately 10 to 25 percent of total flow. Storage for the entire aquifer generally decreased at rates between 0.2 and 0.9 in/yr.

Inflow through the Mississippi River Valley confining unit in the Grand Prairie increased until about the 1950's and remained steady or increased only slightly through 1987. Inflow from rivers continued to increase from 1906 to 1987 accounting for more than 20 percent of total flow after the mid-1970's. The amount of water removed from storage has supplied 20 to 50 percent of total aquifer flow since the early 1970's.

The changes in flow for the Cache area are similar to those for the Grand Prairie. Increases in pumpage from wells resulted in loss of water from storage and increases in inflow. Inflow through the confining unit has increased only slightly since the 1950's. Rivers changed from the net outflow for the area in predevelopment to net inflow in the 1960's. By the 1980's inflow from rivers accounted for more than 30 percent of the total flow through the aquifer.

The changes in flow of the Delta since predevelopment mostly have been a decrease in outflow to rivers in response to increasing pumpage. Inflow from rivers exceeded outflow to rivers in the mid-1970's and represented more than 40 percent of total flow in the 1980's. Decrease in storage has supplied from about 8 to 12 percent of total flow since the mid-1970's. The potential for increased induced inflow apparently exists for a large part of the Delta because the potentiometric surface is above the bottom of river beds and generally above the top of the aquifer which indicates confined conditions.

The changes in flow for the Boeuf area are similar to those of the Delta. Most changes in flow have been shifts in sources of inflow in response to increasing pumpage. Outflow to rivers decreased and inflow from rivers increased until the late 1970's when the rivers became net sources of inflow. Unlike the Grand Prairie, Cache, and Delta areas a large component of total flow still was flow to rivers in the 1980's indicating that not all outflow had been captured by pumpage. Loss of water from storage was relatively small compared to other areas.

The changes in flow for the St. Francis area are similar to those of the Delta and Boeuf areas and may be thought of as progressing in the same direction but not as far. Increases in pumpage have been mostly satisfied by changes in source and amounts of inflow. Outflow to rivers decreased steadily from predevelopment and inflow increased until rivers became a minor source of net regional inflow in 1982. Loss of water from storage has been small but it represented 10 percent of total flow. Inflow from underlying aquifers was a major part, 37 percent, of the predevelopment budget but was progressively less, 10 percent, by the 1980's.

The development of the Mississippi River Valley alluvial aquifer has caused a change in flow directions in the Grand Prairie and Cache areas. Most changes to the potentiometric surface since predevelopment in the St. Francis, Boeuf, and Delta areas have resulted in the contours being shifted upgradient (usually north). Only minor or local changes in direction have resulted. The changes in the Grand Prairie, as evidenced by the closed contours on the potentiometric surfaces and by areas of prominent drawdown, are more pronounced than those of the Cache. The changes in flow direction in the Cache area have occurred later but were more rapid than those in the Grand Prairie.

Flow in the Grand Prairie has been diverted toward an elliptical trough with a closed circular depression centered 20 miles southeast of Stuttgart, Arkansas. The trough roughly corresponds to the occurrence of the thickest part of the Mississippi River Valley confining unit, the area of largest pumpage, and is between sources of inflow from rivers.

The greatest recent drawdown of the potentiometric surface and, consequently, the greatest recent changes in the flow system are in the Cache area. Flow has been diverted toward a trough developed between Crowleys Ridge and the Cache River (between 35° N. and 36° N. latitude). The reasons for the changes in this area are as follows:

1. The largest pumpage has been in this area.
2. Inflow through the Mississippi River Valley confining unit is low. The area is underlain by a greater than average thickness of the confining unit.
3. The eastern side of the area is a hydrologic boundary between the alluvial aquifer and aquifers or confining beds having lower hydraulic conductivities.
4. Most of the area is isolated from larger streams. The rivers and streams in the area are small and probably do not penetrate the aquifer.

To assess response of the regional flow system to continued pumpage and to evaluate the potential of the aquifer to support additional ground-water development, two simulations were made to the year 2022. The effect of continued or additional pumpage and the ability to support development were based on simulated changes in head of the aquifer and decreases in saturated thickness. Drawdown is a fair indication of the response of the system but generally is not economically significant unless accompanied by a large decrease in saturated thickness and, consequently, a decrease in yield. When saturated thickness decreases to less than 25 ft, the aquifer is assumed to be unable to support pumpage at the simulated rate. A decrease in saturated thickness to 25 to 50 ft is probably indicative that the aquifer has been severely affected and probably cannot support current pumpage in the near future. When saturated thickness decreases to 50 to 75 ft the effect of pumpage is probably moderate. The converse of measuring severity of effects by decrease in saturated thickness is to measure potential for further ground-water development by lack of decrease in saturated thickness. Areas with less than 10 ft of drawdown and more than 100 ft of saturated thickness may be optimal locations for continued use or development with the least foreseeable effects.

The response of the Mississippi River Valley alluvial aquifer by the year 2002 to 20 years of pumpage at 1985 rates was most pronounced in the Grand Prairie and Cache areas. Saturated thickness would decrease to less than 25 ft in small areas. In some areas where drawdown would exceed 15 ft, saturated thickness would decrease to less than 50 ft. Saturated thickness would decrease to the extent that a severe effect or an inability of the aquifer to maintain development was indicated only in the Grand Prairie and Cache areas. After 40 years of pumping at 1985 rates the Grand Prairie and Cache areas would be the only areas with more than moderate effects by the year 2022. Almost all of the Delta, Boeuf, and St. Francis and parts of the Cache areas would be able to sustain current levels of development with minimal effects.

In order to assess the effects of increased development and to determine areas with potential for increased development a second simulation beyond 1987 was made with uniform additional pumpage of 1.2 Mgal/d/block (1 in/yr) above 1985 rates. After 15 years of pumping most of the aquifer did not show even moderate effects by the year 2002. Effects on the aquifer would be moderate to severe in large parts of the Grand Prairie and Cache areas, but would be only slightly greater than that shown as a result of sustaining current development. After 35 years, the year 2022, severe effects because of additional development would be indicated for most of the Grand Prairie and a large part of the Cache area. Drawdowns from 1982 conditions would be greater than 10 ft in small scattered locations throughout the Delta, Boeuf, and St. Francis areas. None of the small areas would coincide with decreases in saturated thickness to less than 70 ft for an area larger than 25 mi^2.

Projection of aquifer response to additional development was used to delineate areas with potential for supporting increased pumpage. Several areas of the Mississippi River Valley alluvial aquifer show potential for continued development at rates greater than 1985 pumpage. The largest areas are in the central part of the Delta and small parts of the Boeuf area. The areas coincide with thick sections of the aquifer except several small areas where drawdown in excess of 10 ft is indicated. A second large area where simulation indicates potential for additional development is the northern part of the St. Francis area. The potential for further development is not limited to areas with more than 100 ft of saturated thickness nor is the greatest potential for further development directly proportional to saturated thickness. There are other areas that probably would be able to support much further development with less saturated thickness. These areas are in locations where additional recharge could be induced. Historically, the best potential for inducing inflow to the alluvial aquifer is near large rivers, and to a limited extent, through the Mississippi River Valley confining unit.

Therefore, locations where rivers are near and in good hydraulic connection with the alluvial aquifer or locations where the Mississippi River Valley confining unit is thin, sandy, or absent would have the greatest potential for further development.

Conversely, locations distant from areas where recharge may be induced would have less potential for increased development even where saturated thickness is great. Predevelopment saturated thickness was more than 100 ft in the heavily-stressed part of the Cache area near Crowleys Ridge and less than 75 ft in the central part of the Grand Prairie. The additional saturated thickness in the Cache area is apparently delaying the inevitable decrease in yield and reduction in use.

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APPENDIX--DIGITAL MODEL ANALYSIS OF POST-DEVELOPMENT REGIONAL FLOW

This appendix documents differences between the transient-flow model used to analyze post-development regional flow in the Mississippi River Valley alluvial aquifer and the steady-state flow model used for preliminary analysis (Ackerman, 1989a). The appendix also provides additional information on model sensitivity not applicable to the steady-state model. The information provided in the appendix is intended to accomodate evaluation of the transient model.

Changes to Preliminary Model

The digital model used for simulating post-development regional flow in the Mississippi River Valley alluvial aquifer is nearly the same as that reported previously (Ackerman, 1989a). The following input data or boundary conditions were changed or added for transient modeling:

1. pumpage was added for all pumpage (stress) periods,
2. revised heads in underlying aquifers were added for all pumpage periods,
3. predevelopment heads from steady-state simulation were used for initial conditions,
4. storage terms were added, and
5. values for hydrogeologic parameters were changed by area as a result of calibration of the transient model.

In addition to the above changes and additions, head data from the period 1956 to 1983 were used in the calibration process.

This model shares the 5-year discretization used by other projects in the RASA study for pumping simulations from 1958 through 1987. The time period from 1905 to 1957 was subdivided into pumping periods so as to give reasonable approximations of the pumpage stress on the aquifer (fig. 14, table 5). The pumpage used for the entire study area for pumpage periods 9-14 (1958-87) was compiled at 5-year intervals by Mesko and others (in press) from water-use reports. Pumpage for the period 1906 to 1957 was based on the work of Engler and others (1963, table 2) and on rice acreages published by the Arkansas Agricultural Statistics Service.

Water use for irrigation of rice in Arkansas prior to 1975 was based on application rates given by Halberg (1977, p. 18). Based on an analysis of the amount (fig. 14) and distribution of rice acreage in Mississippi, pumpage in stress periods 8 and 10 were the same in the Delta. Pumpage prior to 1957 in Louisiana (part of the Boeuf area) and in Missouri (parts of the Cache and St. Francis area) was assumed to be zero.

Based on the work of T.W. Holland (U.S. Geological Survey, written commun., 1988), water use for aquaculture in Arkansas was revised for the period 1963-87. The revision was based on revised estimates of acreage and resulted in reductions in pumpage of 30 to 56 percent for aquaculture.

Revised heads in underlying aquifers of the Mississippi embayment aquifer system for predevelopment and each pumpage period were from the Mississippi embayment subregional model (J.K. Arthur, U.S. Geological Survey, written commun., 1988). The model code (McDonald and Harbaugh, 1984) was modified to allow the head in underlying aquifers to vary linearly with time during pumping periods (Stan Leake, U.S. Geological Survey, written commun., 1987). Heads in underlying aquifers of Cretaceous age and older were from the Cretaceous and Paleozoic subregional model (Brahana and Mesko, 1988).

Initial conditions were provided by simulation of steady-state conditions with no pumpage and predevelopment heads in underlying aquifers. The results reported in this report reflect changes to the calibration provided by transient simulation and are very similar to those reported by Ackerman (1989a).

Two values of storage coefficient were used for simulation of the alluvial aquifer--one each for the confined and unconfined equations of flow. Because no data concerning the areal distribution of storage coefficient were available, the model used uniform values of confined storage coefficient or specific yield depending upon the flow condition being simulated. Aquifer test data compiled for the project showed a range of storage coefficients from 0.0001 to 0.15 for 75 locations, and most values were between 0.0001 and 0.01 (A.K. Williamson, U.S. Geological Survey, written commun., 1985). Previous model simulations of the Mississippi River Valley alluvial aquifer were concerned mainly with predicting effects of long-term dewatering of the aquifer, and were calibrated using specific yield. These models generally were calibrated with a value of 0.3 for specific yield (Broom and Lyford, 1981, p. 35; Peralta and others, 1985, p. 3; and Sumner and Wasson, 1984, p. 46). Specific yield from laboratory tests on repacked samples from near Stuttgart in the Grand Prairie ranged from 0.27 to 0.38 (Johnson and others, 1966, p. 23). Values of 0.31 to 0.38 were determined using samples from the bottom of the aquifer. A value of 0.27 was determined from material near the top of the aquifer. Results of long-term aquifer tests at the same site indicated a storage coefficient of 0.28 after 4 days of pumping (Sniegocki and others, 1965, p. 5). A storage coefficient of 0.30 was reached after 9 days of recharge tests at the same location (Sneigocki and others, 1965, p. 8). Only Sumner and Wasson have simulated confined conditions for the alluvial aquifer. They report using 0.001 for the storage coefficient and state that the value, although high, is relatively unimportant due to the lack of model sensitivity to storage coefficient (Sumner and Wasson, 1984, p. 46).

Calibration

Calibration of the transient model was accomplished by adjusting the hydrogeologic parameters within plausible or observed bounds until a best fit of observed head with simulated head was achieved. The procedure for calibration was the same as that used for preliminary calibration except that (1) model performance was judged for six pumping periods, (2) model performance also was judged separately for each area, and (3) both root mean squared error and mean error were used. The hydraulic head data (A.K. Williamson, U.S. Geological Survey, written commun., 1987) are at 5-year intervals and represent averages of all values from 1/2 year before to 1/2 year after a given year. Thus, calibration for pumpage period 13 that ends in 1982 (table 5) was a comparison of simulated heads at the end of pumpage period 13 with the average of observed heads between July 1981 and June 1983. The results of calibration of the model are shown in figure 37. The areal distribution of the error in simulated head for pumping period 13 is shown in figure 38. The percentile distribution of the difference between observed and simulated head for pumpage periods 8-13 is given in figure 39. Data generally were well distributed (table 7) except that few observations were available for Missouri. Excellent coverage was available for pumping period 12 (1977) in Missouri. For that pumpage period, nearly all of Missouri had a difference of less than ±5 ft. Less than 2 percent, of 540 observations in Missouri,

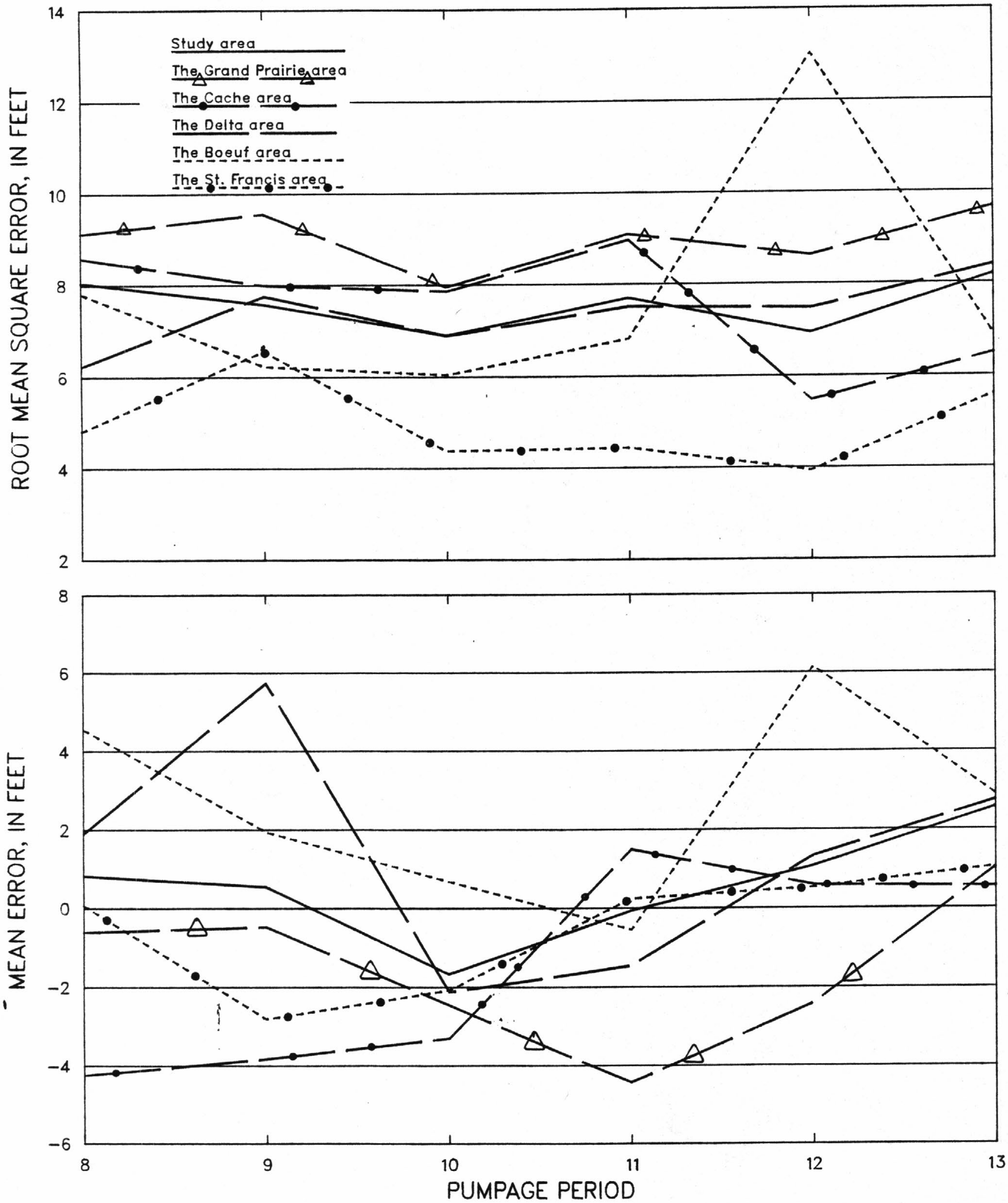

Figure 37.--Calibration results for model of transient flow in the Mississippi River Valley alluvial aquifer.

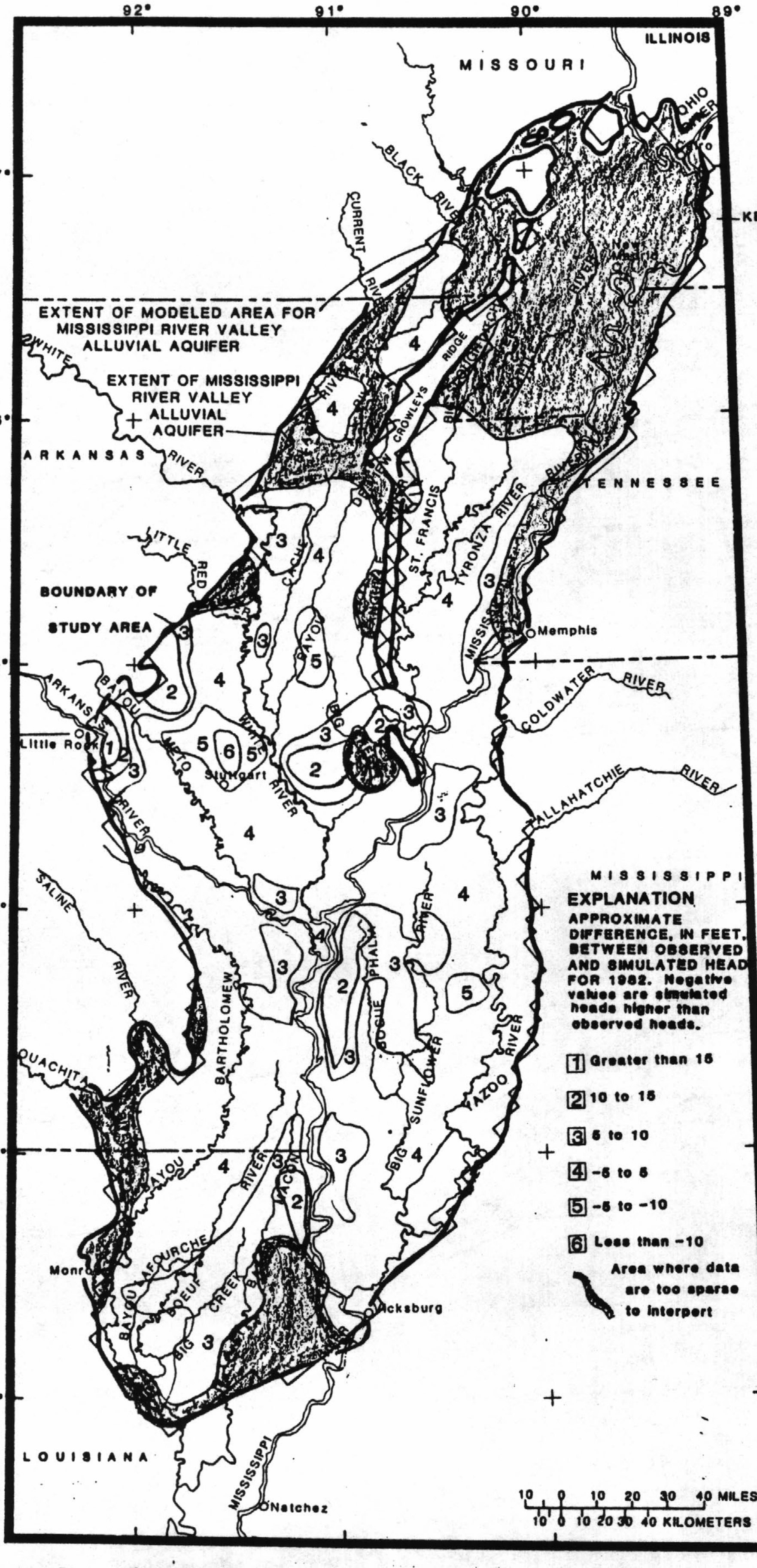

Figure 38.--Difference between observed and simulated 1982 hydraulic head for the Mississippi River Valley alluvial aquifer.

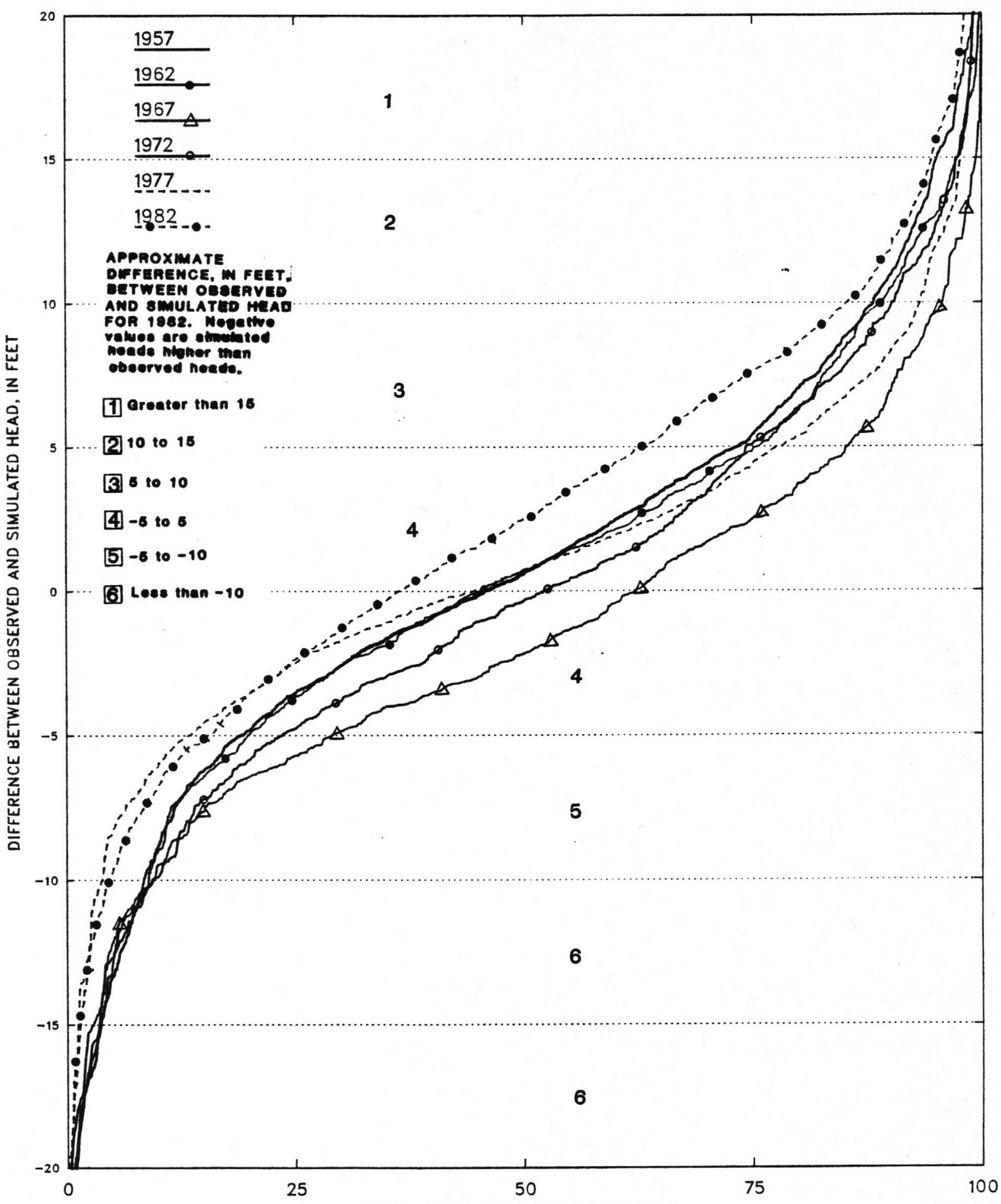

FIGURE 39.--Percentiles of difference between observed and simulated hydraulic head for transient model of Mississippi River Valley alluvial aquifer.

Table 7.--Numbers of hydraulic head observations used for calibration of transient flow in the Mississippi River Valley alluvial aquifer

[PP = pumpage period]

Model area	Model pumpage period and year represented					
	PP 8 1957	PP 9 1962	PP 10 1967	PP 11 1972	PP 12 1977	PP 13 1982
Grand Prairie	681	681	170	93	93	88
Cache	71	82	118	149	123	102
Delta	73	157	42	58	306	1,011
Boeuf	293	264	190	257	127	95
St. Francis	252	16	64	40	462	40
Total model area	1,501	1,114	669	690	1,246	1,403

showed a difference of more than ±10 ft. Simulated head closely agrees with observed head for most of the study area (fig. 38). Hydrographs of wells in areas of long-term drawdown (fig. 40) show agreement between observed head and head in the center of the nearest model block.

The calibrated model has reproduced the potentiometric surface of the Mississippi River Valley alluvial aquifer with errors generally less than 9 ft for all periods where data were available. The major features of potentiometric surface maps from the map dated 1929 by Thompson (Engler and others, 1963, plate 4) through the most recent (Plafcan and Remsing, 1989; Lukey, 1985, fig. 15; Sumner, 1984b; Whitfield, 1975, fig. 2) are all shown in model output except those which are seasonal or ephemeral. Seasonal or ephemeral features such as mounds on the potentiometric surface near the Mississippi River (Ryling, 1960, p. 26; Sumner and Wasson, 1984, p. 10) were not reproducible with the discretization of time and space used for this model.

The potentiometric surface in the two major areas of drawdown (fig. 21) is adequately modeled (fig. 38). Values of hydrogeologic parameters (table 8) were changed only slightly from those chosen for calibration of 1972 flow as steady state (Ackerman, 1989a).

The calibration of the transient model was more difficult than the steady-state model because five more pumpage periods, and one additional criterion (mean error) were evaluated for each of the five areas. The values of calibration criteria were not constant with time or between areas due to differences in the distribution of observed head, response of the aquifer, and assumptions in the conceptual model (fig. 37). The values of hydrogeologic parameters were adjusted by area as a last step in calibration. Formal parameter estimation to areas smaller than the areas of this study was probably not warranted by the discretization of the model, distribution and quality of the observations, or purpose of the study.

Sensitivity of the transient model was tested by observing the results of each sensitivity analysis run after changing each hydrogeologic parameter individually from calibrated values (table 9). The sensitivity of the calibration process for the transient model to changes in values of calibration parameters and pumpage was similar to that of the preliminary steady-state model. Sensitivity of the calibration parameters for pumpage stress period 11 (1972) is compared with similar values from Ackerman (1989a, fig. 29 and 30) for 1972 as steady state in figure 41. The values of the hydrogeologic parameters used for sensitivity analysis are given in table 9. The most sensitive parameters were about the same as those in Ackerman (1989a) with the order now being, most sensitive to least sensitive, pumpage > vertical hydraulic conductivity of Mississippi River Valley confining unit > specific yield > hydraulic conductivity of the alluvial aquifer. On the basis of the ability of the model to reproduce the observed heads over the period 1929 to 1986 without severe bias in any area and the similarity of calibration values to those of a previous calibration and other models, the calibration was considered sufficient for the purposes of this study.

As a further test of the sensitivity of an interpretation to changes in hydrogeologic parameters, the cumulative flux from various sources was examined for each sensitivity analysis model run. As can be seen in figure 42, the conclusion that rivers changed from sources of net discharge to sources of net recharge in the 1970's, was true for all values of hydrogeologic parameters tested. The total amount of flux from rivers was most sensitive to the changes in values of vertical hydraulic conductance of the materials in overlying and underlying units and least sensitive to

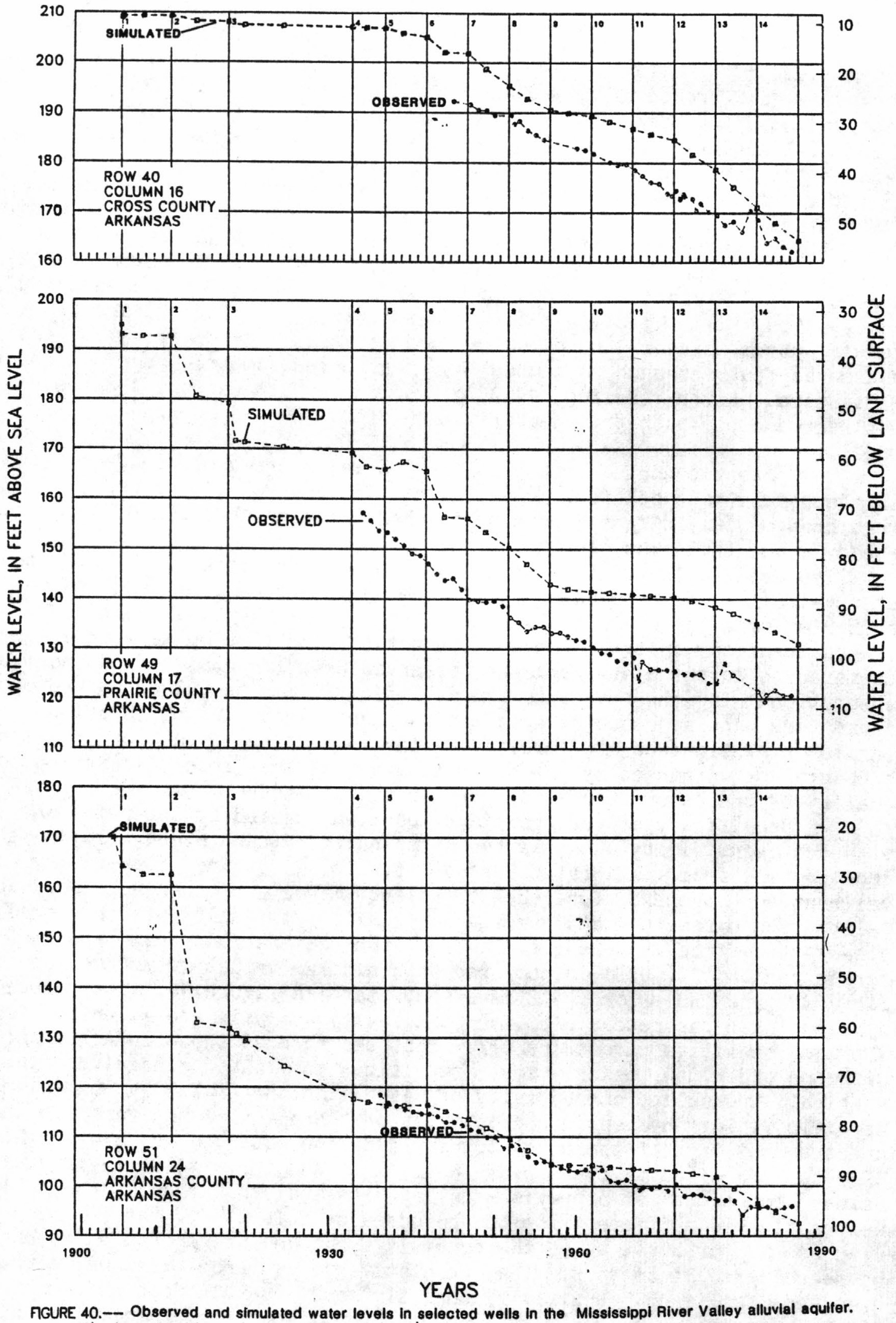

FIGURE 40.— Observed and simulated water levels in selected wells in the Mississippi River Valley alluvial aquifer. Numbers along time axis are model pumpage periods. Water levels in feet below land surface for observed data only.

Table 8.--Calibration values for individual areas of the Mississippi River Valley alluvial aquifer

[ft/d, feet per day]

	Preliminary calibration	Transient calibration				
		Area				
		Grand Prairie	Cache	Delta	Boeuf	St. Francis
Hydraulic conductivity of the Mississippi River Valley alluvial aquifer, ft/d	300	200	300	300	450	450
Vertical hydraulic conductivity of the Mississippi River Valley confining unit, ft/d	.0003	.00035	.00035	.00044	.00035	.00035
Ratio of vertical hydraulic conductivity to bed thickness for riverbed materials, day^{-1}	.05	.16	.16	.16	.16	.16
Multiple of vertical hydraulic conductivity of underlying units[1]	3	1	1	1	1	1
Storage coefficient (specific yield) for unconfined conditions	--	.28	.28	.28	.28	.28
Storage coefficient for confined conditions	--	.0001	.0001	.0001	.0001	.0001

[1]The vertical hydraulic conductivity of underlying units is the same as that used in the simulations of Mississippi embayment aquifers (Arthur and Taylor, 1989) and Cretaceous and Paleozoic aquifers (Brahana and Mesko, 1988).

Table 9.--Sensitivity values for individual areas of the Mississippi River Valley alluvial aquifer

[ft/d, feet per day]

	Multipliers for sensitivity analysis	Range of values Area Grand Prairie	Cache	Delta	Boeuf	St. Francis
Hydraulic conductivity of the Mississippi River Valley alluvial aquifer, ft/d	0.67-1.5	133-300	200-450	200-450	300-675	300-675
Vertical hydraulic conductivity of the Mississippi River Valley confining unit, ft/d	.71-1.28	.00025-.00045	.00025-.00045	.00035-.00058	.00025-.00045	.00025-.00045
Ratio of vertical hydraulic conductivity to bed thickness for river bed materials, day^{-1}	.12-3.12	.015-.5	.015-.5	.015-.5	.015-.5	.015-.5
Multiple of vertical hydraulic conductivity of underlying units	.5-2.0	.5-2	.5-2	.5-2	.5-2	.5-2
Specific yield	.86-1.33	.24-.32	.24-.32	.24-.32	.24-.32	.24-.32

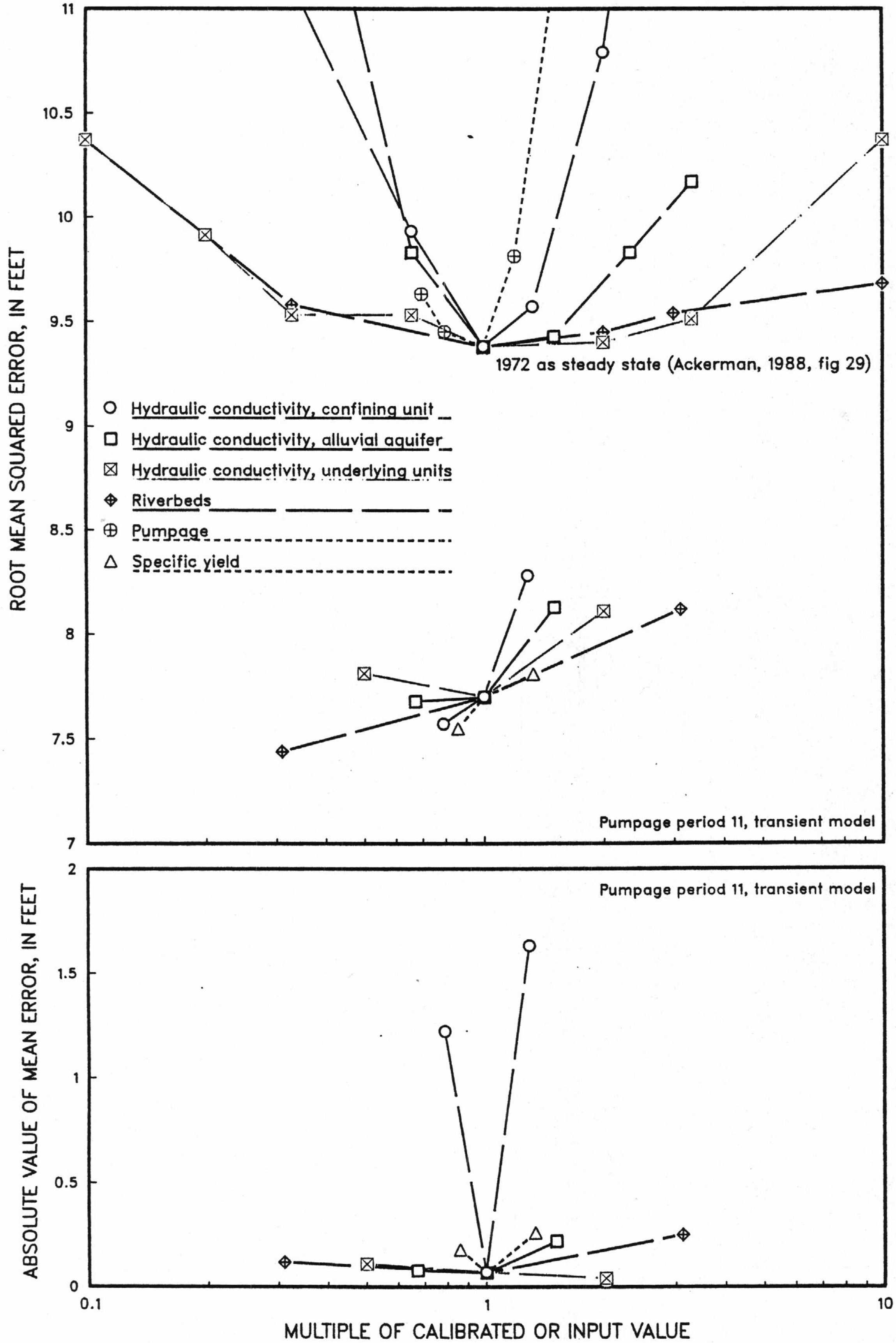

FIGURE 41--Sensitivity of regional models to changes in calibration values.

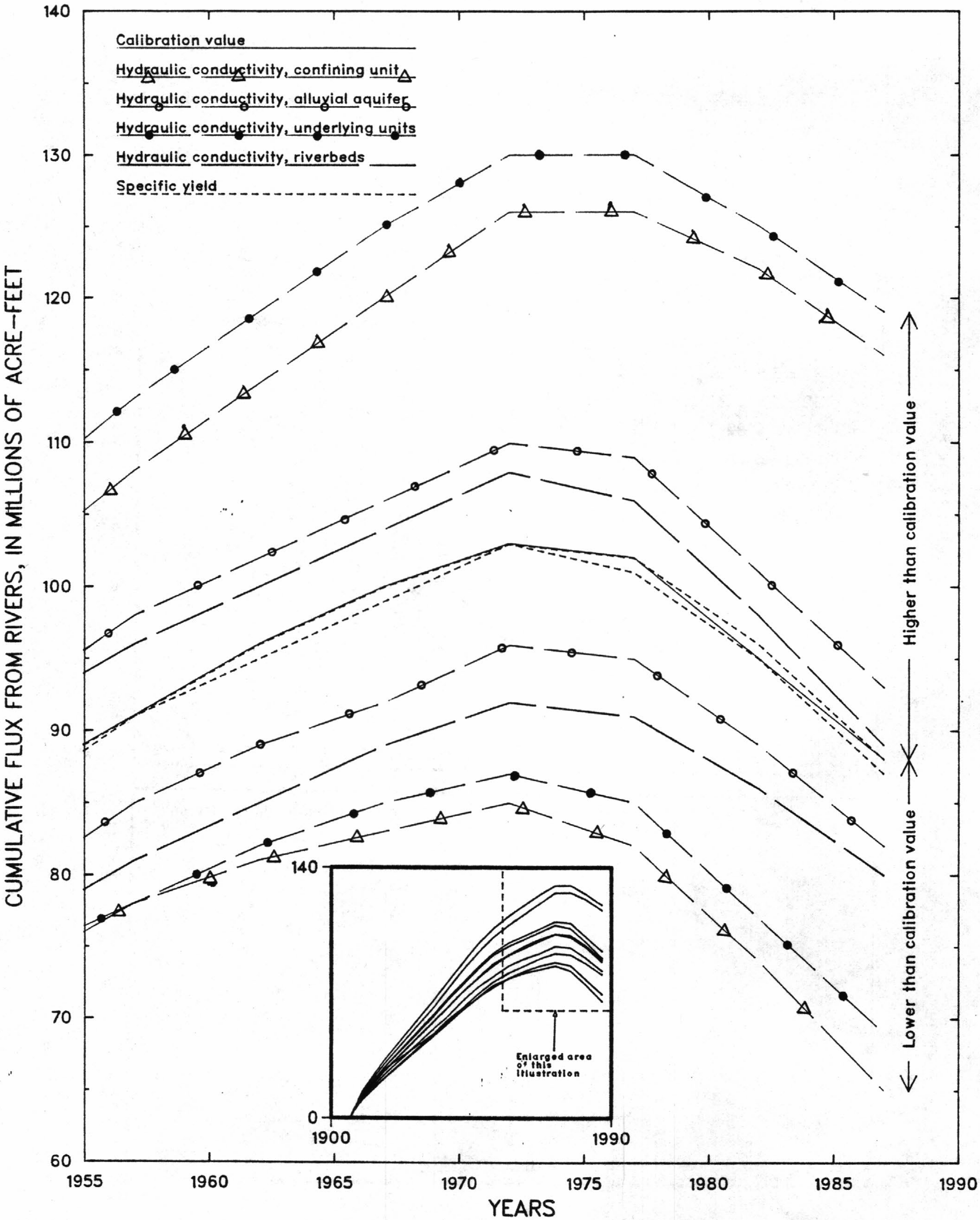

FIGURE 42.--Sensitivity of cumulative flux from rivers to changes in calibration values. A positive slope indicates net flux is to rivers (1906–72). A negative slope indicates net flux is from rivers to the aquifer (1972–87).

specific yield. The total flux from rivers might have been much larger or smaller and the calibration less accurate, but the conclusion regarding change in flow from rivers would have been the same. As in the preliminary model (Ackerman, 1989a) the major assumptions were not sensitive to the changes in hydrologic parameters used in sensitivity analysis.