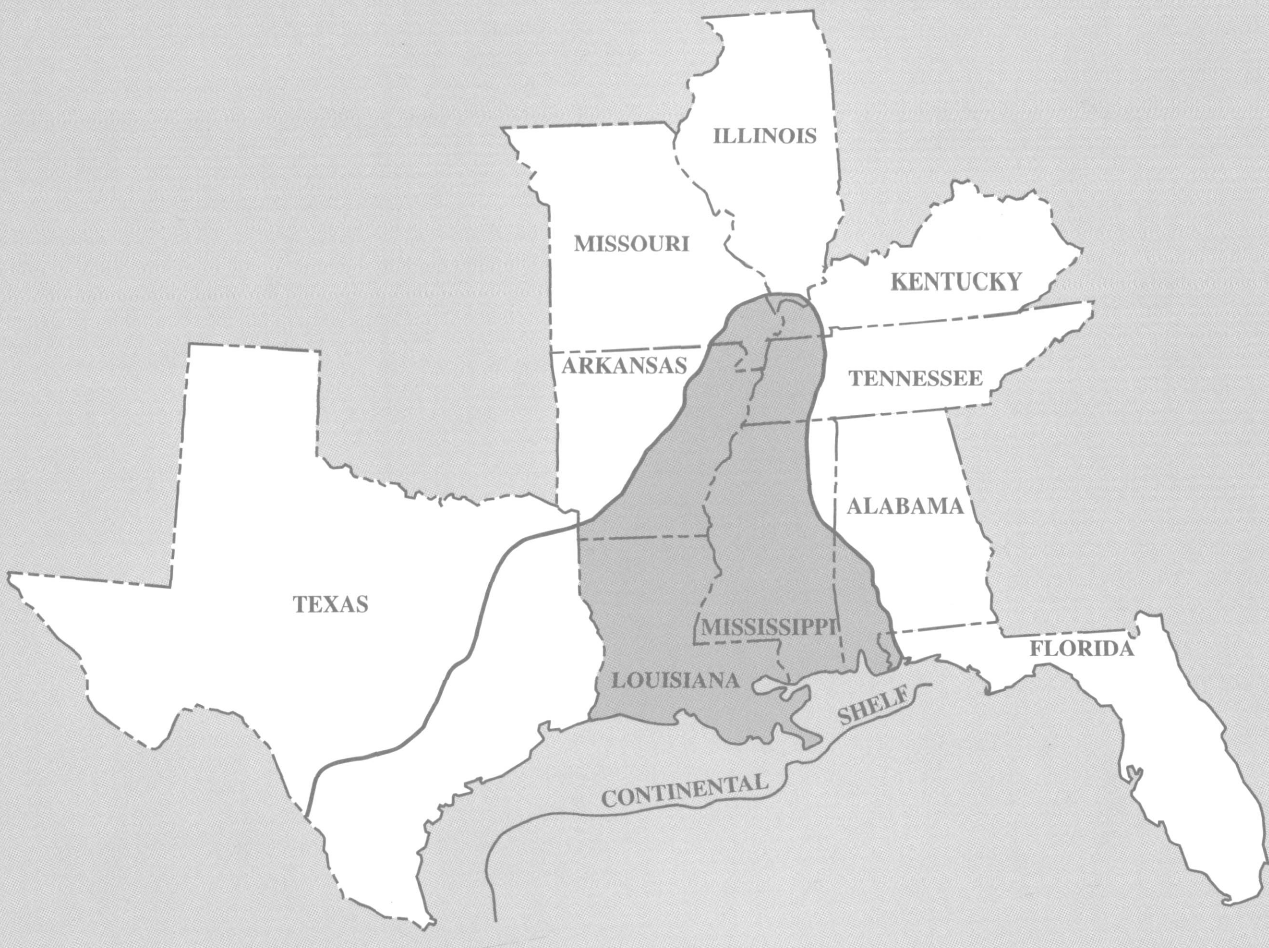
# GROUND-WATER FLOW ANALYSIS OF THE MISSISSIPPI EMBAYMENT AQUIFER SYSTEM, SOUTH-CENTRAL UNITED STATES

REGIONAL AQUIFER-SYSTEM ANALYSIS

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# Ground-Water Flow Analysis of the Mississippi Embayment Aquifer System, South-Central United States

*By* J. KERRY ARTHUR *and* RICHARD E. TAYLOR

REGIONAL AQUIFER-SYSTEM ANALYSIS—GULF COASTAL PLAIN

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# FOREWORD

## THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Thomas J. Casadevall

Thomas J. Casadevall
Acting Director

# CONTENTS



# ILLUSTRATIONS

[Plates are in pocket]

# TABLES



## CONVERSION FACTORS

| *Multiply* | *By* | *To obtain* |
|---|---|---|
| Foot (ft) | 0.3048 | Meter (m) |
| Foot per day (ft/d) | 0.3048 | Meter per day (m/d) |
| Foot per mile (ft/mi) | 0.1894 | Meter per kilometer (m/km) |
| Grams per liter (g/L) | 0.0142234 | Pounds per square inch (lb/in.$^2$) |
| Inch (in.) | 25.4 | Millimeter (mm) |
| Inch per year (in./yr) | 25.4 | Millimeter per year (mm/yr) |
| Mile (mi) | 1.609 | Kilometer (km) |
| Million cubic feet per day (Mft$^3$/d | 0.3278 | Cubic meter per second (m$^3$/s) |
| Square mile (mi$^2$) | 2.590 | Square kilometer (km$^2$) |
| Foot squared per day (ft$^2$/d) | 929.0 | Centimeter squared per day (cm$^2$/d) |

*Temperature* in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F= (1.8 ×°C)+32.

*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.

# GROUND-WATER FLOW ANALYSIS OF THE MISSISSIPPI EMBAYMENT AQUIFER SYSTEM, SOUTH-CENTRAL UNITED STATES

By J. KERRY ARTHUR and RICHARD E. TAYLOR

## ABSTRACT

The Mississippi embayment aquifer system is composed of six regional aquifers covering about 160,000 square miles in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. The flow analysis presented in this report as part of the Gulf Coast Regional Aquifer-System Analysis study pertains to five aquifers in sediments of the Wilcox and Claiborne Groups of Tertiary age. In descending order, the aquifers are (1) the upper Claiborne, (2) the middle Claiborne, (3) the lower Claiborne–upper Wilcox, (4) the middle Wilcox, and (5) the lower Wilcox. The flow analysis of the sixth aquifer in the aquifer system, the Mississippi River Valley alluvial aquifer in sediments of Holocene and Pleistocene age, is presented in chapter D of this Professional Paper.

In 1886, before ground-water development began, potentiometric surfaces of the Mississippi embayment aquifers sloped from the outcrop areas on the eastern and western sides of the embayment toward the embayment axis in the central and northern parts of the embayment and southward toward the Gulf of Mexico in the southern part of the embayment. The Sabine uplift in northwestern Louisiana interrupted this pattern, and water surfaces in the area of the uplift sloped away from the uplift flanks. In the Mississippi Alluvial Plain in northeastern Louisiana, predevelopment water levels in the upper Claiborne aquifer were 60 to 80 feet lower than water levels in adjacent areas in the upper Claiborne aquifer and the underlying middle Claiborne aquifer, indicating an area of upward flow and predevelopment system discharge.

Simulations indicate that the greatest amount of aquifer recharge under predevelopment conditions was to the middle Claiborne aquifer in northern Mississippi and southern Tennessee where recharge rates exceeded 1 inch per year. The greatest aquifer discharge under predevelopment conditions was to the Mississippi River Valley alluvial aquifer east of Crowleys Ridge and west of the Memphis, Tennessee, area where water moved upward from the subcropping Claiborne and Wilcox aquifers into the alluvial aquifer at a rate of 0.6 inch per year. Large aquifer transmissivity, high heads in outcrop areas, and short flow paths from recharge to discharge areas were factors contributing to the high rates of recharge and discharge in the northern area of the embayment. Total predevelopment discharge to the Mississippi River Valley alluvial aquifer was about 34 million cubic feet per day (254 million gallons per day). The northern area of the embayment (north of the 35th parallel) had the greatest predevelopment discharge to the alluvial aquifer, about 21 million cubic feet per day (157 million gallons per day). The northern area had the greatest predevelopment vertical flow between aquifers; about 11.5 million cubic feet per day (86.0 million gallons per day) flowed upward into the upper Claiborne aquifer from the middle Claiborne aquifer. Predevelopment horizontal flow in the aquifers generally was southward and westward. Total predevelopment horizontal flow southward across the 35th parallel from the northern area was about 0.9 million cubic feet per day (6.7 million gallons per day). Total predevelopment horizontal flow westward across the axis of the embayment south of the 35th parallel was about 2.6 million cubic feet per day (19.4 million gallons per day). Most of the southward predevelopment horizontal flow was in the middle Claiborne aquifer, about 0.5 million cubic feet per day (3.74 million gallons per day). Most of the westward predevelopment horizontal flow was in the upper Claiborne aquifer, about 1.4 million cubic feet per day (10.5 million gallons per day).

Significant ground-water development of the Mississippi embayment aquifer system began in 1886 at Memphis, Tennessee, with pumpage from the middle Claiborne aquifer. During 1985 total pumpage from the five aquifers was about 102.2 million cubic feet per day (764.5 million gallons per day), a decrease of 5 percent from 1980 totals. The greatest pumpage during 1985 was from the middle Claiborne aquifer; about 74.3 million cubic feet per day (556 million gallons per day) was withdrawn. The Memphis, Tennessee, area had the largest ground-water usage during 1985; about 25.5 million cubic feet per day (191 million gallons per day) was pumped from the middle Claiborne aquifer. The least used aquifer in the Mississippi embayment aquifer system is the middle Wilcox; total pumpage during 1985 was about 3.3 million cubic feet per day (24.7 million gallons per day).

Flow analysis simulation indicates that 1987 water levels in the middle Claiborne aquifer were 125 feet below predevelopment levels in the Memphis, Tennessee, area. Water-level declines in the middle Claiborne aquifer of more than 200 feet below predevelopment levels have resulted from heavy pumpage in the Pine Bluff–Stuttgart and El Dorado areas in Arkansas and in the Monroe area in Louisiana.

Recharge to the middle Claiborne aquifer in outcrop areas east and southeast of Memphis under 1987 conditions was more than 1.5 inches per year. In the northern area of the embayment, total recharge to the middle Claiborne aquifer was about 40 million cubic feet per day (299 million gallons per day) during 1987, an increase of about 67 percent over predevelopment rates. Total aquifer-system discharge to the Mississippi River Valley alluvial aquifer was about 1.8 million cubic feet per day (13.5 million gallons per day) by 1987, a decrease of about 95 percent from predevelopment rates. In the northern area, net vertical flow between the upper Claiborne and middle Claiborne aquifers was upward prior to development but changed to downward flow of about 9.2 million cubic feet per day (68.8 million gallons per day) into the heavily pumped middle Claiborne aquifer during 1987.

Ground-water development in the Memphis area changed the direction of net horizontal flow east of the Mississippi River near the 35th parallel from southward before development to a northward flow of about 0.6 million cubic feet per day (4.49 million gallons per day) during 1987. Heavy pumpage from the middle Claiborne aquifer in the Pine Bluff–Stuttgart area in Arkansas increased the net southward horizontal flow on the west side of the Mississippi River to about 2.4 million cubic feet per day (17.2 million gallons per day) during 1987.

Comparison of the predevelopment and 1987 ground-water flow budgets indicates that the current (1985) pumpage from the five regional aquifers is supplied mostly by (1) increased recharge in the outcrop areas of the upper and middle Claiborne aquifers and (2) reduction of discharge from those two aquifers to the Mississippi River alluvial aquifer. Loss of ground water from aquifer storage is very small.

On a regional scale the five aquifers in the Mississippi embayment aquifer system have potential for future ground-water development; the middle Claiborne aquifer has the greatest potential for providing large point sources of water. Simulation results indicate that, by the year 2000, an increase in total pumpage from the aquifer system of 20 percent relative to 1985 rates will produce significant declines in water levels. Declines of about 25 feet below 1987 levels are indicated at the end of the 13-year period in the middle Claiborne aquifer in the Memphis, Tennessee, area and about 30 feet in the middle Claiborne aquifer in the El Dorado, Arkansas, and Monroe, Louisiana, areas. In the Jackson, Mississippi, and Pine Bluff–Stuttgart, Arkansas, areas, simulation results indicate that water levels in this aquifer will be about 20 feet below 1987 levels after 13 years.

Simulated point increases in pumpage of 5.35 million cubic feet per day (40 million gallons per day) added to the 1985 pumpage from the middle Claiborne aquifer at Marianna, Arkansas, south of the lower Claiborne confining unit facies change, would lower water levels in the aquifer at Marianna about 90 feet below 1987 levels by the year 2000. If the simulated increases in pumpage were at Wynne, Arkansas, north of the lower Claiborne confining unit facies change, water levels in the aquifer would be lowered about 30 feet below 1987 levels after 13 years.

# INTRODUCTION

## BACKGROUND

The Gulf Coast Regional Aquifer-System Analysis project is part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) program that began in 1978 to study the regional aquifers that provide a significant part of the country's freshwater supply (fig. 1). A brief overview of each RASA project is provided by Ren Jen Sun (1986). The Gulf Coast RASA project, which began in November 1980, is a study of regional aquifers that underlie about 230,000 $mi^2$ (square miles) in all or parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and Texas. The objectives of the project are to define the geohydrologic framework in which the regional aquifers exist, to describe the chemical and physical characteristics of the ground water, and to analyze the flow patterns within the regional ground-water system.

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 (Grubb, 1984). The three systems were delineated on the basis of differences in geologic framework, regional ground-water flow patterns, and distribution of fine-grained sediments. Five subprojects were conducted to study in detail different parts of these aquifer systems. Two of the subprojects focused on the Texas coastal uplands aquifer system and the coastal lowlands aquifer system, and two subprojects focused on two regional aquifers, the Mississippi River Valley alluvial aquifer and the McNairy-Nacatoch aquifer. This report discusses five regional aquifers in the Mississippi embayment aquifer system.

The Mississippi River Valley alluvial aquifer is the uppermost aquifer of the Mississippi embayment aquifer system throughout 33,000 $mi^2$ in the central part of the Gulf Coast RASA study area (fig. 2). The alluvial aquifer was selected for detailed study because it provides large quantities of water for agriculture, it has been partially dewatered locally, and it has a substantial hydraulic connection with the numerous streams that cross the Mississippi Alluvial Plain. Ackerman (1989, 1996) described the Mississippi River Valley alluvial aquifer and presented an analysis of regional ground-water flow in the aquifer.

The Texas coastal uplands aquifer system has been described by Ryder (1988; Ryder and Ardis, in press) and is laterally equivalent to the Mississippi embayment aquifer system. Both aquifer systems decrease in thickness in the vicinity of the Texas-Louisiana State line.

The Mississippi embayment aquifer system is separated from the coastal lowlands aquifer system by the Vicksburg-Jackson confining unit, which crops out in a narrow band across central Louisiana and central Mississippi. The confining unit overlies the Mississippi embayment aquifer system downdip of its outcrop area. Martin and Whiteman (1989; in press) described the coastal lowlands aquifer system, except that part in Texas, and presented an analysis of regional ground-water flow.

The McNairy-Nacatoch aquifer underlies the Mississippi embayment aquifer system in an area of about 27,000 $mi^2$ in the northern part of the Mississippi embayment and was chosen for study to investigate flow between aquifers studied in the central midwest RASA and the Mississippi embayment aquifer system (fig. 1). Brahana and Mesko (1988) described the McNairy-Nacatoch aquifer and reported that throughout most of its areal extent it is hydraulically independent of the Mississippi embayment aquifer system.


**EXPLANATION**

| 10 | **REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM**—Numbering system for identification purposes only, not intended to imply priority |
|---|---|

1 Northern Great Plains
2 High Plains
3 Central Valley, California
4 Northern Midwest
5 Southwest alluvial basins
6 Floridan aquifer system
7 Northern Atlantic Coastal Plain
8 Southeastern Coastal Plain
9 Snake River Plain
10 Central Midwest
11 Gulf Coastal Plain
12 Great Basin
13 Northeast glacial aquifers
14 Upper Colorado River Basin
15 Oahu Island, Hawaii
16 Caribbean Islands
17 Columbia Plateau Basalt
18 Michigan Basin
19 San Juan Basin
20 Edwards-Trinity aquifer system
21 Ohio-Indiana carbonates and glacial deposits
22 Appalachian Valleys and Piedmont
23 Puget-Willamette Lowland
24 Southern California basins
25 Northern Rocky Mountains Intermontane basins

FIGURE 1.—Location of Regional Aquifer-System Analysis studies. Modified from Sun and Weeks (1991).

## PURPOSE AND SCOPE

The purpose of this report is to present the results of a detailed analysis of the ground-water flow system of five regional aquifers in sediments of the Wilcox and Claiborne Groups. These aquifers make up most of the Mississippi embayment aquifer system as defined by Grubb (1984). A sixth aquifer (the Mississippi River Valley alluvial aquifer), a surficial aquifer in part of the Mississippi embayment aquifer system, was not analyzed in detail as part of this report because it is the subject of a detailed study by Ackerman (1989, 1996). The McNairy-Nacatoch aquifer, composed of sands of Cretaceous age underlying the Wilcox Group, was included in the Mississippi embayment aquifer system by Grubb (1984), but work by Brahana and Mesko (1988) indicates that only a small quantity of water flows between the McNairy-Nacatoch aquifer and the overlying Mississippi embayment aquifer system. Therefore, the McNairy-Nacatoch aquifer has been excluded from the Mississippi embayment aquifer system (Grubb, 1987).

Flow simulation results for predevelopment conditions and for conditions representing current and potential aquifer development are included in this report. Some of the aquifers extend as far south as the Gulf of Mexico and contain water having dissolved-solids concentrations greater than 30,000 mg/L (milligrams per liter); however, this study was limited to that part of the flow system containing water that has dissolved-solids concentrations of 10,000 mg/L or less.

## APPROACH

The procedure used in this study was to analyze hydrologic information assembled in the initial phase of the study and to present the analysis of the ground-water flow system. Results from a multilayered, digital, finite-difference, ground-water flow model representing hydrogeologic conditions in the study area were extensively used to aid in understanding the flow system. A preliminary report of ground-water flow in the Mississippi embayment aquifer system (Arthur and Taylor, 1990) describes the hydrogeologic framework and the conceptual model of the flow system and documents the digital ground-water flow model.

Previous modeling efforts in the study area mostly represent only limited areal coverage of a particular aquifer and do not consider the regional interaction between the studied aquifer and related aquifers and aquifer systems. Reed (1972) considered the entire areal extent of the Sparta Sand, a water-bearing unit in the Mississippi embayment aquifer system, in a ground-water model flow analysis; however, he simulated only the aquifer under study, and no regional flow analysis of the entire Mississippi embayment aquifer system was presented.

The areal extent of the Mississippi embayment aquifer system and its relation to other aquifer systems and to the entire Gulf Coast RASA study area are shown in figure 2. A five-layered, 100-row by 88-column digital flow model (McDonald and Harbaugh, 1984) with a grid spacing of 5 miles was used to simulate ground-water flow in the five regional aquifers in the Mississippi embayment aquifer system (pl. 1). The model simulates the distribution of head and the components of the flow budget (inflow, outflow, and change in storage) based on estimated pumping conditions for the period 1886–1987. Comparisons were made between pumping and predevelopment conditions. Aquifer response to a projected 20 percent increase in pumpage for a period of 13 years also was simulated to evaluate the potential for continued ground-water development. An additional 40 million gallons per day (Mgal/d) pumpage was simulated at two locations, Marianna, and Wynne, Ark., to illustrate differences in aquifer system response resulting from different hydrogeologic conditions. 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 1980 conditions were presented previously (Arthur and Taylor, 1990). A short description of how the aquifer properties and model boundaries were simulated is provided below, and the reader is referred to Arthur and Taylor (1990) for detailed discussion of these topics.

Transmissivity was calculated by multiplying the aquifer sand-bed thickness times a uniform value of hydraulic conductivity within each of the three areas. The hydraulic conductivity ranged from 5 to 80 feet per day (ft/d) and area values were slightly modified near area boundaries to avoid abrupt changes at the boundaries. Sand-bed thickness was multiplied by a uniform value of specific storage ($1 \times 10^{-6}$) to obtain storage coefficients for each aquifer.

Vertical flow from the overlying coastal lowlands aquifer system was controlled by the thickness of the Vicksburg-Jackson confining unit (100–3,000 ft) and a model-derived vertical hydraulic conductivity of $1 \times 10^{-5}$ ft/d. Flow between the individual aquifers of the Mississippi embayment aquifer system where they are overlain by the Mississippi River Valley alluvial aquifer was controlled by the vertical hydraulic conductivities and thicknesses of the respective units. Model-derived vertical hydraulic conductivities of the aquifers of the Mississippi embayment aquifer system range from 0.0001 to 0.00001 ft/d (Arthur and Taylor, 1990). Flow through the underlying basal Midway confining unit is minimal (Brahana and Mesko, 1988) and was assumed to be zero for this analysis. No flow was assumed along the western and eastern boundaries. Recharge in the aquifer outcrop areas was simulated as a near-constant-head source-sink controlled by the water-table altitude.

Hydraulic heads from simulations of flow in the overlying Mississippi River Valley alluvial aquifer and the coastal lowlands aquifer system were used to calculate gradients relative

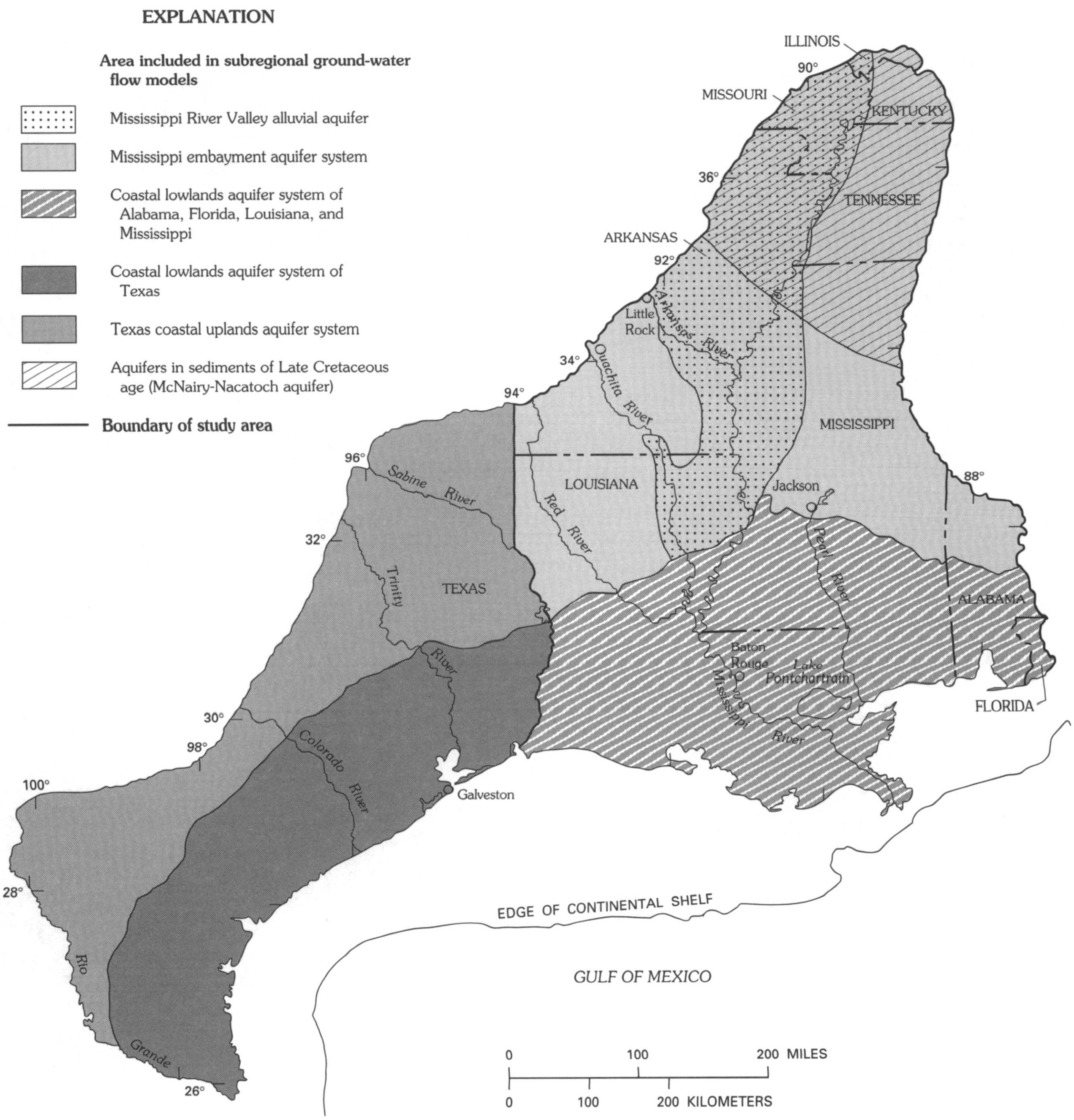



FIGURE 2.—Areal extent of subproject models in the Gulf Coast Regional Aquifer-System Analysis (RASA) study. Modified from Ryder (1988).

to the Mississippi embayment aquifer system for each pumping period.

## PHYSIOGRAPHY, CLIMATE, AND DRAINAGE

The Mississippi embayment aquifer-system study area includes about 160,000 mi$^2$ in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee (fig. 3). The area extends from the confluence of the Mississippi and Ohio Rivers southward to the Gulf of Mexico and from the Sabine River at the Louisiana-Texas State line eastward to the Mobile River in southwestern Alabama. The area is approximately bisected by the Mississippi River.

The study area is in the Gulf Coastal Plain physiographic province; a large part of it (about 35 percent) is in the Mississippi Alluvial Plain, the most extensive physiographic section in the region (pl. 1). The alluvial plain is flat to slightly

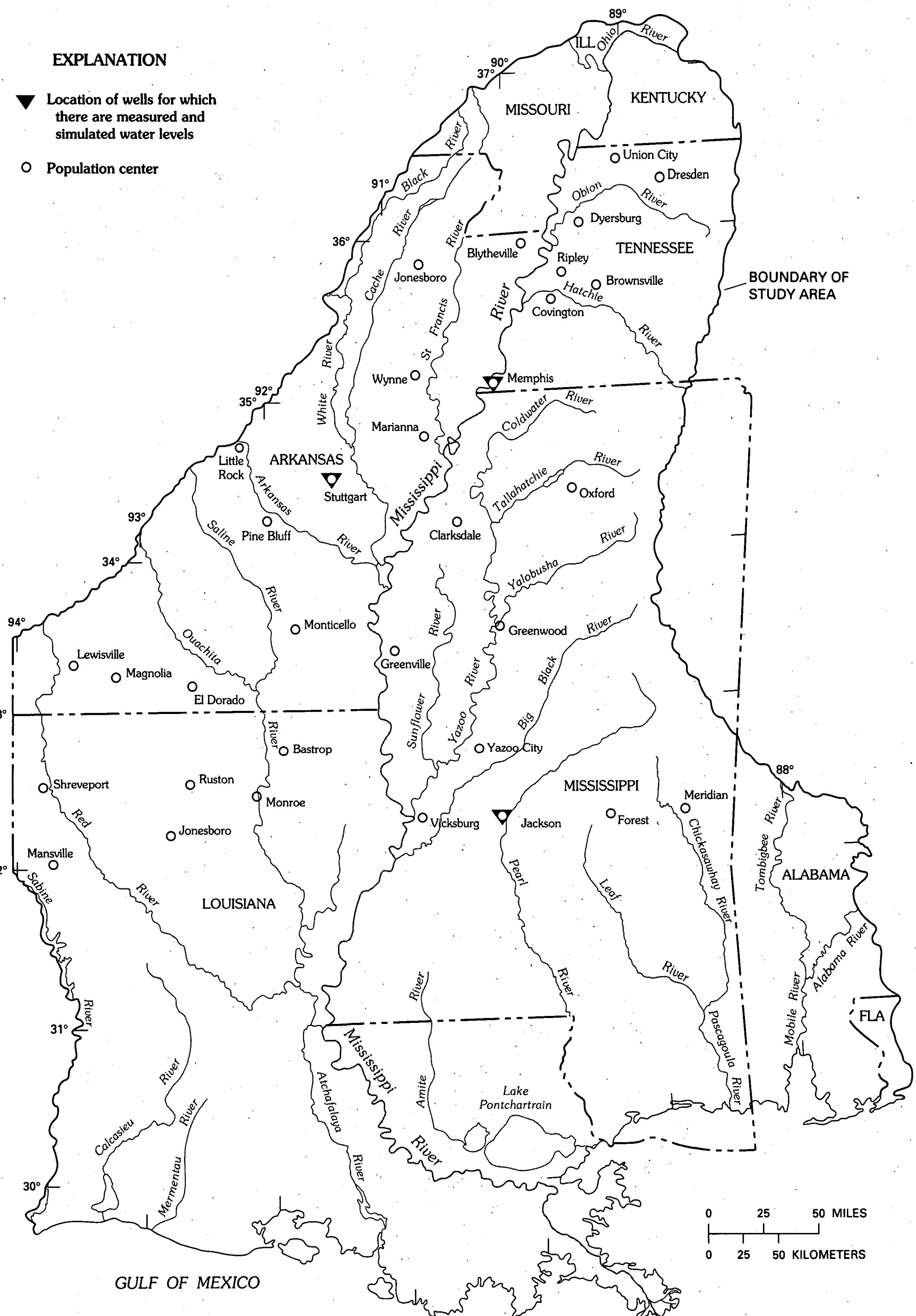

EXPLANATION
Location of wells for which there are measured and simulated water levels
Population center
BOUNDARY OF STUDY AREA
0 25 50 MILES
0 25 50 KILOMETERS
GULF OF MEXICO
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
33°
32°
31°
30°
88°
ILL
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
ALABAMA
LOUISIANA
FLA
Ohio River
Black River
Cache River
St Francis River
White River
Mississippi River
Obion River
Hatchie River
Coldwater River
Tallahatchie River
Yalobusha River
Arkansas River
Saline River
Ouachita River
Sunflower River
Yazoo River
Big Black River
Red River
Sabine River
Pearl River
Leaf River
Chickasawhay River
Tombigbee River
Alabama River
Mobile River
Pascagoula River
Amite River
Atchafalaya River
Calcasieu River
Mermentau River
Lake Pontchartrain
Union City
Dresden
Dyersburg
Blytheville
Ripley
Brownsville
Covington
Jonesboro
Wynne
Memphis
Marianna
Little Rock
Stuttgart
Pine Bluff
Clarksdale
Oxford
Monticello
Greenwood
Greenville
Lewisville
Magnolia
El Dorado
Bastrop
Yazoo City
Shreveport
Ruston
Monroe
Vicksburg
Jackson
Forest
Meridian
Jonesboro
Mansville

FIGURE 3 (facing page).—Location of Mississippi embayment aquifer-system study area, selected population centers, and wells for which there are measured and simulated water levels.

undulating and has an average gulfward slope of about 0.5 ft/mi. In the northern and southern thirds of the alluvial plain, the Mississippi River meanders along the eastern edge of the plain, whereas in the middle third the river lies approximately in the center of the plain. The width of the alluvial plain varies from about 40 to about 110 miles and is widest in the middle third of the study area.

A major topographic feature in the alluvial plain is Crowleys Ridge, a narrow segmented ridge about 200 miles long extending northward from the Mississippi River in extreme east-central Arkansas into southeastern Missouri. The ridge, an erosional remnant underlain by rocks ranging in age from Paleozoic to late Tertiary, is as much as 250 feet higher than the surrounding alluvial plain.

The Loess Hills form the eastern physiographic boundary of the alluvial plain and extend the length of the study area. The windblown material forming the Loess Hills belt rises several hundred feet above the plain and averages about 15 miles wide. The western boundary of the alluvial plain is the uplands of the Interior Highlands physiographic province.

In the extreme southern part of the study area (southern Louisiana, Mississippi, and southwestern Alabama), the terrain slopes gently gulfward and becomes almost flat. The topography of the northern three-fourths of the area outside of the alluvial plain is typical of the Gulf Coastal Plain uplands and is characterized by gently rolling terrain. The study area is trough shaped and generally aligned north-south with the Mississippi River and its alluvial plain at the axis of the trough. The highest land-surface altitudes in the study area are on the eastern and western flanks of the trough; the eastern side has substantially higher altitudes than the western side. Altitudes exceed 500 feet on the eastern side but generally are less than 350 feet on the western side.

The climate of the entire study area is humid subtropical. Precipitation usually is abundant and well distributed throughout the area. The average annual precipitation ranges from about 48 inches in the northern part of the study area to about 68 inches in the southeastern part (pl. 1). On a seasonal basis, precipitation maximums are during winter or spring in the northern sections and during summer in the southern section.

The Mississippi River is the major drainage outlet in the study area and extends from its confluence with the Ohio River southward to its mouth at the Gulf of Mexico. Drainage from about one-third of the study area flows into the Mississippi River from major tributaries such as the St. Francis River in Arkansas and Missouri, the White and Arkansas Rivers in Arkansas, and the Yazoo and Big Black Rivers in Mississippi. The remainder of the area is drained by rivers and streams in southern Louisiana, southern Mississippi, and southwestern Alabama directly into the Gulf of Mexico. The major rivers with direct drainage to the Gulf are the Mobile River in Alabama, the Calcasieu, Atchafalaya, Amite, and Mermentau Rivers in Louisiana, and the Pearl and Pascagoula Rivers in Mississippi (fig. 4). Average annual runoff in the area ranges from about 12 inches in southeastern Arkansas to about 32 inches in southeastern Mississippi (pl. 1).

# HYDROGEOLOGIC FRAMEWORK

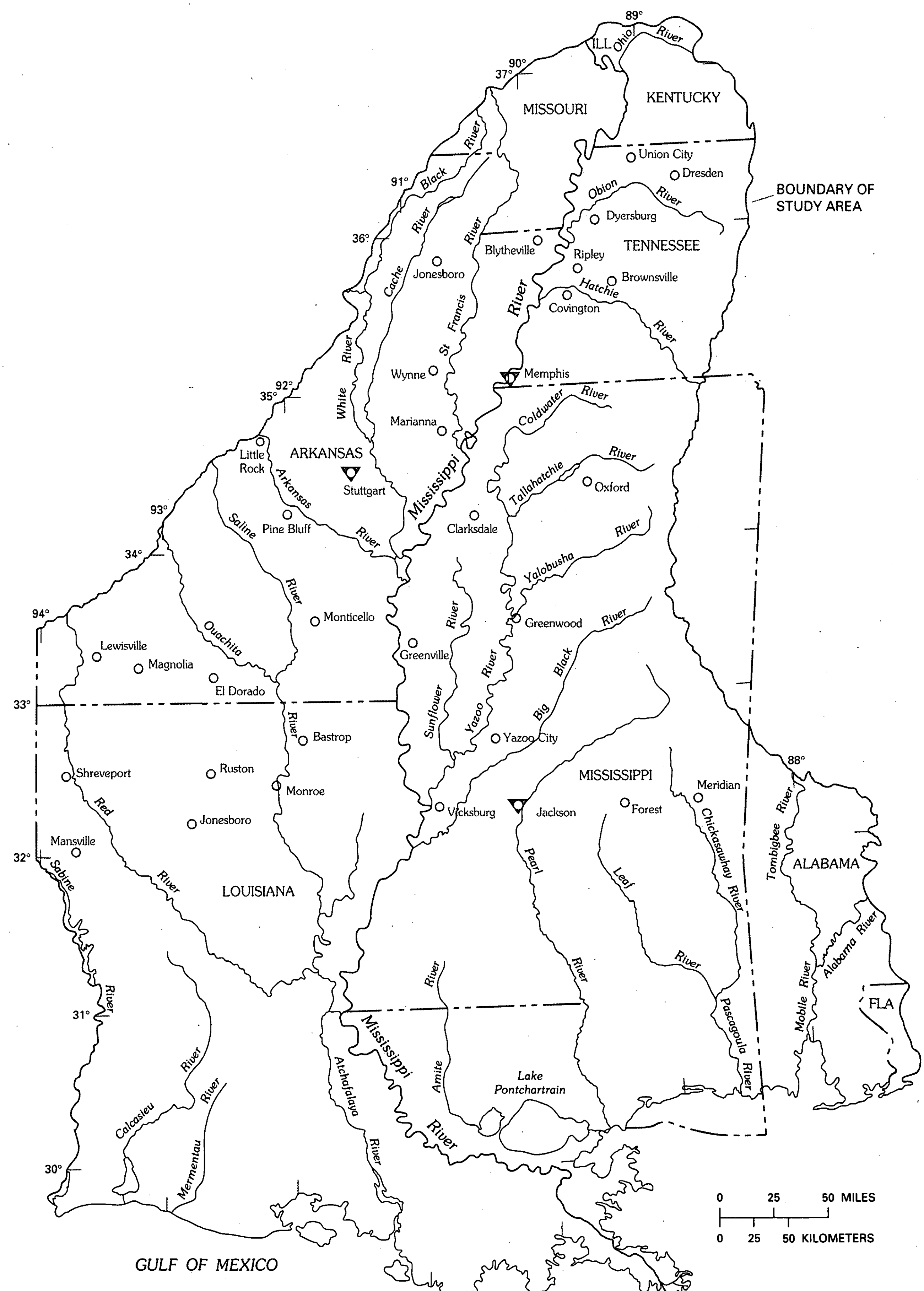
The sediments that comprise the geohydrologic units described in this report were deposited in the Mississippi embayment during the Paleocene and Eocene Epochs of the Tertiary Period. The five regional aquifers and associated confining units under study in the Mississippi embayment aquifer system consist of fluvial sand to clayey marine deposits and have a large range of thicknesses and hydraulic characteristics.

This report presents a generalized description of the geohydrologic framework of the Mississippi embayment aquifer system. Hosman and Weiss (1991), as part of an analysis of the entire Gulf Coast RASA study area, presented a detailed geohydrologic description of the aquifers and confining units in the Mississippi embayment aquifer system.

## GENERALIZED GEOLOGY

The Mississippi embayment area has experienced subsidence, as well as cyclic transgressions and regressions of the sea, since the end of the Paleozoic Era. The resulting structural trough, now called the Mississippi embayment, was filled with sediments. Subsidence accompanied by cyclic invasions of the sea continued through the Cretaceous and Tertiary Periods. Each invasion stopped successively farther to the south during the Tertiary Period. The troughlike shape of the embayment results in the older rock units cropping out in an arcuate pattern approximately parallel with the periphery of the embayment. The younger Miocene and Pliocene sediments in the southern part of the area exhibit less arcuate outcrop belts that generally parallel the axis of the Gulf Coast geosyncline (pl. 1).

Pleistocene glaciation caused a lowering of sea level and subsequent changes in drainage. Among these changes was the entrenchment of the Mississippi River valley into Cretaceous and Tertiary sediments. Melting glaciers produced tremendous volumes of water flowing southward to the Gulf of Mexico. The raging waters eroded the ancestral Mississippi River valley more than 100 feet deeper than the present-day surface of the Mississippi Alluvial Plain. As sea level rose following the melting of the glaciers, stream gradients decreased and the entrenched valley was filled with sediments to its present level, forming the Mississippi Alluvial Plain.


89°
90°
37°
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ILL
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
ALABAMA
LOUISIANA
FLA
BOUNDARY OF
STUDY AREA
Ohio River
Black River
Cache River
St Francis River
White River
Obion River
Hatchie River
Mississippi River
Coldwater River
Tallahatchie River
Arkansas River
Saline River
Yalobusha River
Sunflower River
Yazoo River
Big Black River
Ouachita River
Red River
Sabine River
Pearl River
Leaf River
Chickasawhay River
Pascagoula River
Tombigbee River
Mobile River
Alabama River
Amite River
Atchafalaya River
Calcasieu River
Mermentau River
Union City
Dresden
Dyersburg
Blytheville
Ripley
Brownsville
Covington
Jonesboro
Wynne
Memphis
Marianna
Little Rock
Stuttgart
Pine Bluff
Clarksdale
Oxford
Monticello
Greenwood
Greenville
Lewisville
Magnolia
El Dorado
Bastrop
Yazoo City
Shreveport
Ruston
Monroe
Vicksburg
Jackson
Forest
Meridian
Jonesboro
Mansville
Lake Pontchartrain
GULF OF MEXICO
0 25 50 MILES
0 25 50 KILOMETERS

FIGURE 4 (facing page).—Major drainages in study area.

Geologic units exposed in the study area are from Cretaceous to Holocene in age, with most of the surficial deposits of Quaternary age. In the northern part of the embayment, some Paleozoic-age and Cretaceous-age sediments subcrop the Quaternary deposits. In the remainder of the area, Tertiary-age sediments composed predominantly of unconsolidated to slightly consolidated beds of sand and clay and some interbedded gravel, silt, lignite, chalk, and limestone subcrop the surficial Quaternary deposits. In the western side of the northern one-third of the embayment, most surficial deposits are Mississippi River alluvial deposits of Quaternary age; few to no older deposits crop out. On the eastern side of the embayment from the Loess Hills eastward, older sedimentary rocks are exposed at the surface. In the northern part of the study area, strata dip toward the axis of the Mississippi embayment syncline, which generally is coincident with the present Mississippi River. In the central part of the area, the dip gradually changes toward the south as a result of the influence of the Gulf Coast geosyncline, and in southern Mississippi and Louisiana the dip generally is southward toward the axis of the geosyncline (pl. 1). Structural features such as the Monroe and Sabine uplifts, Jackson dome, Mobile graben, and Desha basin affect local and regional thicknesses and dip of geologic units.

In the southern one-third of the study area, surficial units consist of Miocene and younger deposits that overlie thick marine clays of the Jackson and Vicksburg Groups. The basal unit of the Mississippi embayment aquifer system is a thick marine clay unit that is part of the Midway Group of Paleocene age and underlies the entire study area.

## MAJOR AQUIFERS

The Mississippi embayment aquifer system is composed of six regional aquifers; the oldest five consist of sediments of Tertiary age and the youngest is the Mississippi River Valley alluvial aquifer in sediments of Pleistocene and Holocene age. The focus of this report is five regional aquifers in deposits of Tertiary age in the Wilcox and Claiborne Groups. The five aquifers are separated from underlying aquifers in deposits of Cretaceous age by thick marine clay of the Midway confining unit. The five aquifers of this study are hydraulically connected to the younger Mississippi River Valley alluvial aquifer where they subcrop the alluvial aquifer. In the southern one-third of the study area, where the coastal lowlands aquifer system overlies the Mississippi embayment aquifer system, the two systems are hydraulically separated by the thick sequence of marine clay in the Vicksburg-Jackson confining unit. Results of flow analysis of the Mississippi River Valley alluvial aquifer and of the coastal lowlands aquifer system are presented in chapters D and H of this Professional Paper.

Because equivalent aquifers and confining units may have different names in adjacent States, names of hydrologic units have been designated that apply throughout the Gulf Coast RASA study area (table 1). These names do not always reflect one stratigraphic unit but, depending on permeability, may represent parts of adjacent units. All aquifers and confining units discussed in this report will be referred to by their Gulf Coast RASA names.

The five major aquifers in sediments of Tertiary age investigated in this report are, in descending order, the (1) upper Claiborne aquifer, (2) middle Claiborne aquifer, (3) lower Claiborne–upper Wilcox aquifer, (4) middle Wilcox aquifer, (5) lower Wilcox aquifer. Within the Mississippi embayment aquifer system, two confining units, the middle Claiborne confining unit and the lower Claiborne confining unit, separate the upper three aquifers. The middle Wilcox aquifer, as identified by Hosman and Weiss (1991) and Williamson and others (1990), is separated from the lower Claiborne–upper Wilcox aquifer above, and the lower Wilcox aquifer below, by discontinuous clay beds in the Wilcox Group. The vertical sequence between the lower Claiborne–upper Wilcox aquifer and the lower Wilcox aquifer consists of interbedded coarse and fine-grained beds of varying lateral hydraulic connection and relatively low effective horizontal permeability. These sediments are considered collectively as one water-bearing unit because of the large overall thickness and areal expanse. Although the entire vertical sequence is recognized as a permeable zone, the clays within the middle Wilcox aquifer are the major restriction to vertical flow between overlying and underlying units.

An idealized hydrogeologic section from west to east (fig. 5) across the Mississippi embayment (approximately from the western boundary of Louisiana to the eastern boundary of Mississippi), just south of a line from Monroe, La., to Jackson, Miss., shows the generalized relation between the aquifers, confining units, topography, and general flow patterns. Land-surface altitudes on the eastern side of the embayment are considerably higher than those on the western side. Consequently, water levels in the aquifer outcrop areas on the eastern side of the embayment are substantially higher than corresponding water levels on the western side. In addition, the aquifer outcrop bands are wider on the eastern side of the embayment than on the western side where a large part of the area is covered by sediments of the Mississippi Alluvial Plain. The aquifers in sediments of Tertiary age underlie the alluvial plain in the central and northwestern part of the embayment, and, consequently, the water table is lower there than in the outcrop areas on the eastern side of the embayment (pl. 1). In response to this imbalance in potentiometric surface, water moves from the outcrop areas on the eastern side of the embayment westward through the aquifers, then upward through confining units in the central and western part of the embayment, and subsequently into the Mississippi River Valley alluvial aquifer (fig. 5). In the southern one-third of the study area, the general relation of aquifers, confining units, and topography is similar to that in

TABLE 1.—*Generalized correlation chart of hydrogeologic and geologic units of Tertiary age in the Mississippi embayment aquifer system.*
[--, not present; Fm, Formation; Gr, Group; Mt, Mountain]

| Hydrogeologic unit | Group | Missouri | Kentucky | Arkansas Southern | Arkansas Northeastern | Tennessee | Louisiana | Mississippi |
|---|---|---|---|---|---|---|---|---|
| Vicksburg-Jackson confining unit | Vicksburg | -- | -- | -- | -- | -- | Vicksburg Formation | Vicksburg Group undivided |
| | Jackson | Jackson Formation | Jackson Formation | Jackson Group undivided | Jackson Group undivided | Jackson Formation | Jackson Group undivided | Jackson Group undivided |
| Upper Claiborne aquifer | | Cockfield Formation | Cockfield Formation | Cockfield Formation | Cockfield Formation | Cockfield Formation | Cockfield Formation | Cockfield Formation |
| Middle Claiborne confining unit | | Cook Mt Formation | Cook Mt Formation | Cook Mt Formation | Cook Mt Formation | Cook Mt Formation | Cook Mt Formation | Cook Mt Formation |
| Middle Claiborne aquifer | Claiborne | | | Sparta Sand | | | Sparta Sand | Sparta Sand |
| Lower Claiborne confining unit | | Memphis Sand | Memphis Sand | Cane River Formation | Memphis Sand | Memphis Sand | Cane River Formation | Zilpha Clay |
| Lower Claiborne–upper Wilcox aquifer | | | | Carrizo Sand, upper sands in Wilcox Group | | | Carrizo Sand , upper sands in Wilcox Group | Winona Sand, sand in Tallahatta Formation, upper sand in Wilcox Group |
| Middle Wilcox aquifer | Wilcox | Middle sand in Wilcox Group | Middle sand in Wilcox Group | Middle sand in Wilcox Group | Middle sand in Wilcox Group | Middle sand in Wilcox Group | Middle sand in Wilcox Group | Middle sand in Wilcox Group |
| Lower Wilcox aquifer | | Lower sand in Wilcox Group , Fort Pillow Sands | Lower sand in Wilcox Group | Lower sand in Wilcox Group | Lower sand in Wilcox Group | Lower sand in Wilcox Group, Fort Pillow Sand | Lower sand in Wilcox Group | Lower sand in Wilcox Group |
| Midway confining unit | Midway | Midway Group undivided | Midway Group undivided | Midway Group undivided | Midway Group undivided | Midway Group undivided | Midway Group undivided | Midway Group undivided |

NOTE: See table 1, Hosman and Weiss, 1988, for detailed correlation chart.

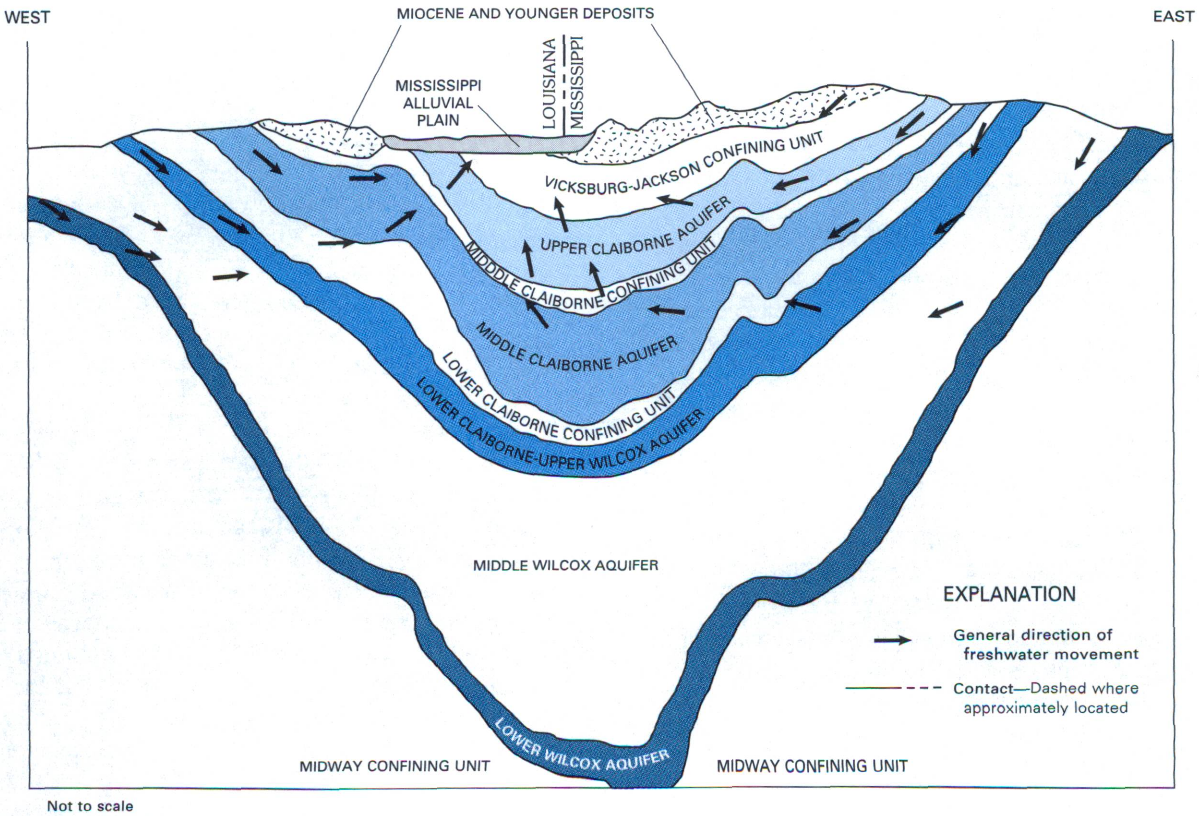



FIGURE 5.—Idealized hydrogeologic section, Louisiana, Mississippi, just south of a line from Monroe, La., to Jackson, Miss. Arrows indicate general direction of freshwater movement. Dashed line indicates contact is approximately located. Modified from Payne (1976, fig. 2).

other parts of the study area except that aquifer outcrops are more nearly parallel with the axis of the Gulf Coast geosyncline.

### UPPER CLAIBORNE AQUIFER

The upper Claiborne aquifer is the uppermost of the five aquifers in sediments of Eocene age in the study area (table 1). The upper Claiborne aquifer underlies the Vicksburg-Jackson confining unit that separates the Mississippi embayment aquifer system from the coastal lowlands aquifer system in the southern part of the study area. The aquifer is separated from the older, deeper middle Claiborne aquifer by the middle Claiborne confining unit.

The upper Claiborne aquifer predominantly consists of sand beds in the Cockfield Formation and all sand beds in the Cook Mountain Formation that are in direct contact with the Cockfield sand beds. The aquifer mainly consists of interbedded fine- to medium-grained quartz sand, silt, and carbonaceous clay and averages about 250 feet thick in the subsurface. The aquifer thins downdip toward the Gulf as sediments gradually change to a clay facies. In part of the aquifer that contains freshwater, the total sand bed thickness (the aggregate of sand beds thicker than 20 feet) is from less than 100 feet in the northern part of the area to more than 300 feet in the vicinity of Vicksburg, Miss. (pl. 3). The upper Claiborne aquifer crops out on both sides of the embayment, and the major outcrop areas are in central Mississippi, north-central Louisiana, and south-central Arkansas. The aquifer underlies the Loess Hills in western Tennessee and is the most extensive subcropping aquifer underlying the Mississippi River Valley alluvial aquifer. The aquifer subcrops about 43 percent of the alluvial plain from northeastern Louisiana northward to about the northern extent of the embayment.

### MIDDLE CLAIBORNE AQUIFER

The middle Claiborne aquifer, composed mostly of the Sparta Sand in the southern two-thirds of the study area and the Memphis Sand in the northern one-third (Tennessee, east-central Arkansas, southeastern Missouri, southwestern Kentucky, and northwestern Mississippi), is the most extensively developed of the five aquifers. The aquifer is composed of sand, clay, shale, and lignite. It underlies the entire central part of the study area and crops out on both sides of the embayment. It crops out in an arcuate band on the eastern side of the embayment from the northern end of the embayment in Kentucky, through Tennessee, and two-thirds the length of Mississippi. The outcrop band averages about 15 miles wide, with the widest and most extensive part of the band in north-central and northern Mississippi and western Tennessee. The middle Claiborne aquifer does not crop out in the northwestern one-third of the embayment: rather, the aquifer subcrops in a narrow band under the Mississippi River alluvial plain. The aquifer crops out on the western side of the embayment in southwestern Arkansas and northwestern Louisiana on the eastern flank of the Sabine uplift. The aquifer is the second most extensive subcropping aquifer; it underlies about 15 percent of the Mississippi River Valley alluvial aquifer, predominantly in northwestern Mississippi and northeastern Arkansas.

The middle Claiborne aquifer also includes sand beds of the Cook Mountain Formation where the sand beds are in direct contact with sand beds of the Sparta Sand. In some areas, the Cook Mountain Formation is composed of clay, and the top of the Sparta consists of clay. In these places the top of the aquifer is the top of the uppermost sand bed of the Sparta. The base of the middle Claiborne aquifer is the top of the underlying Zilpha Clay, or the Cane River Formation where that formation is clay. Where the basal Sparta consists of clay and overlies clay of the Zilpha or Cane River, the base of the aquifer is at the top of basal Sparta clay. Where the basal Sparta is sandy and the upper part of the underlying geologic unit is also sandy, the base of the aquifer is at the top of the first clay in the underlying unit.

In extreme northwestern Mississippi and east-central Arkansas near the 35th parallel, the underlying lower Claiborne confining unit undergoes a facies change. The predominantly marine clay of the confining unit south of the parallel changes to a massive sand and becomes part of the middle Claiborne aquifer north of the parallel. A hydrogeologic section illustrating this facies change is shown on plate 2. From the facies change northward, the middle Claiborne aquifer includes the stratigraphic interval that is occupied by the lower Claiborne confining unit and the lower Claiborne–upper Wilcox aquifer south of the facies change. In the area north of the facies change, the middle Claiborne aquifer is equivalent to the Memphis Sand. From the facies change southward, where the units exist, the lower Claiborne confining unit separates the middle Claiborne aquifer from the lower Claiborne–upper Wilcox aquifer, and the middle Claiborne confining unit separates the middle Claiborne aquifer from the upper Claiborne aquifer.

Aggregate sand thickness of the middle Claiborne aquifer is from about 100 to more than 700 feet; the aquifer is the thickest in the vicinity of the juncture of Arkansas, Tennessee, and Mississippi (pl. 3). In other areas aggregate sand thickness is commonly several hundred feet. The aquifer increases in thickness from its outcrop area to about 400 feet in the subsurface. Farther downdip the sand beds decrease in thickness until the aquifer pinches out near the Gulf of Mexico.

## LOWER CLAIBORNE–UPPER WILCOX AQUIFER

The lower Claiborne–upper Wilcox aquifer underlies the lower Claiborne confining unit and may include all or parts of several stratigraphic units. The aquifer is made up of discontinuous, hydraulically connected sand beds in different geologic units and varies considerably in thickness and lithology. The aquifer includes all sand beds below the clay beds of the lower Claiborne confining unit down to and including the sand beds of the upper part of the Wilcox Group. The aquifer includes the sand beds of the Winona-Tallahatta and Meridian–upper Wilcox in Mississippi, the Carrizo-Wilcox sand in Louisiana, and the Carrizo Sand in Arkansas (table 1). In northwestern Mississippi and east-central Arkansas, where the lower Claiborne confining unit has changed to a sand facies, the lower Claiborne–upper Wilcox sediments are considered to be part of the middle Claiborne aquifer. Aggregate sand thickness of the lower Claiborne–upper Wilcox aquifer is greater east of the Mississippi River; in some areas sand thicknesses are more than 400 feet, as compared to 100–300 feet west of the Mississippi River (pl. 3).

The lower Claiborne–upper Wilcox aquifer crops out on both sides of the embayment and subcrops the Mississippi River valley alluvial aquifer in a small area in east-central Arkansas. The largest outcrop area is on the eastern side of the embayment and extends southward from about the 35th parallel for a distance two-thirds the length of Mississippi and into southwestern Alabama in an arcuate band 10–20 miles wide. The outcrop on the western side of the embayment in southwestern Arkansas and northwestern Louisiana is considerably narrower and shorter.

## MIDDLE WILCOX AQUIFER

The middle Wilcox aquifer is the least significant aquifer in the Mississippi embayment aquifer system. The aquifer is composed predominantly of thin interbedded sand, silt, and clay and includes all sand beds of the Wilcox Group between the lower Claiborne–upper Wilcox aquifer and the lower Wilcox aquifer. The aquifer consists of sand beds hydraulically interconnected to varying degrees, and no dominant sand bed is traceable over a large area.

The middle Wilcox aquifer crops out on both sides of the embayment and subcrops the Mississippi River valley alluvial aquifer in northeastern Arkansas and southeastern Missouri. The outcrop area is less than 5 miles wide in the northern end of the embayment, about 10 miles wide in western Tennessee, and averages about 20 miles wide in Mississippi. The aquifer also crops out in southwestern Arkansas and is the uppermost unit overlying the Sabine uplift in northwestern Louisiana.

Aggregate sand thickness of the middle Wilcox aquifer ranges from less than 200 feet in the extreme northern and southern parts of the study area to more than 1,500 feet in central Louisiana (pl. 3). In most of the Mississippi embayment area the aquifer thickness is 200–500 feet.

#### LOWER WILCOX AQUIFER

The lower Wilcox aquifer underlies the middle Wilcox aquifer and is an extensively developed source of freshwater in Arkansas, Mississippi, and Tennessee. The lower Wilcox aquifer, consisting of sand in the basal part of the Wilcox Group, is equivalent to the Fort Pillow Sand in Tennessee, Arkansas, and Missouri and is informally called the "1400-foot" sand in the Memphis, Tenn., area.

Sand beds in the lower Wilcox aquifer generally are thicker and more continuous than the thin, interbedded sands of the main body of the Wilcox Group. Vertical flow of water between the lower Wilcox aquifer and the overlying middle Wilcox aquifer is restricted by numerous interbedded clays in the middle part of the middle Wilcox aquifer. Consequently, sand beds in the upper part of the middle Wilcox aquifer may have little hydraulic connection with the lower Wilcox aquifer, whereas sand beds in the lower part of the middle Wilcox aquifer may be, to a limited degree, hydraulically interactive with the lower Wilcox aquifer.

The lower Wilcox aquifer crops out on both sides of the embayment in a band generally less than 5 miles wide in southwestern Arkansas and in a band about 10 miles wide on the eastern side of the embayment in western Tennessee and east-central Mississippi. The outcrop altitudes of the lower Wilcox aquifer are the highest of any of the aquifers in this study and are 400–500 feet above sea level in Mississippi, Tennessee, and Kentucky. The outcrop altitudes on the western side of the embayment average about 200 feet lower. The aquifer subcrops the Mississippi River Valley alluvial aquifer in northeastern Arkansas and southeastern Missouri where the land surface is 200–250 feet above sea level.

Aggregate sand thickness of the lower Wilcox aquifer exceeds 300 feet in two areas in the north-central part of the embayment but is 200–300 feet in most of the northern part of the embayment in the confined part of the aquifer. Aggregate sand thickness of the aquifer increases substantially in the southern part of the embayment and is more than 600 feet in south-central Mississippi (pl. 3).

### MAJOR CONFINING UNITS

Four major confining units of regional scope influence the hydrology of the five major aquifers in sediments of Tertiary age in the Mississippi embayment aquifer system. The Vicksburg-Jackson confining unit is the upper confining unit and the Midway confining unit is the lower confining unit that separate the five aquifers of this study from permeable units above and below. Within the aquifer system, the middle Claiborne confining unit and the lower Claiborne confining unit separate adjacent aquifers.

The Vicksburg-Jackson confining unit is composed predominantly of marine clay, marl, and limestone of late Eocene and Oligocene age and separates the Mississippi embayment aquifer system from the younger coastal lowlands aquifer system in sediments of Miocene and Pliocene age in the southern one-third of the study area. The confining unit crops out in a band 10–40 miles wide in the southern one-third of the study area and generally parallels the present Gulf of Mexico coastline. The confining unit subcrops about 23 percent of the Mississippi River Valley alluvial aquifer in northeastern Louisiana and west-central Mississippi and in a discontinuous section in southeastern Arkansas. The primary confining bed is a calcareous, fossiliferous dark-gray to blue clay in the Jackson Group. In the subsurface this clay bed generally is about 300–500 feet thick.

The middle Claiborne confining unit, in sediments of Eocene age, hydraulically separates the upper Claiborne aquifer from the middle Claiborne aquifer. The confining unit predominantly consists of marine clay beds in the Cook Mountain Formation and clay beds in the underlying Sparta Sand that are continuous with the Cook Mountain Formation. The middle Claiborne confining unit crops out on both sides of the embayment in a band that is 10–20 miles wide in southwestern Arkansas and has a maximum width of about 30 miles in northwestern Louisiana. On the eastern side of the embayment the outcrop band is about 5–10 miles wide in Kentucky, Tennessee, and Mississippi. The middle Claiborne confining unit subcrops the Mississippi River Valley alluvial aquifer in a narrow band in northeastern Arkansas, southeastern Missouri, and northwestern Mississippi. In most areas, the confining unit is about 100–200 feet thick, but downdip in south-central Louisiana, where units that generally are sand in updip areas change to a marine clay facies, it is more than 700 feet thick.

The lower Claiborne confining unit in sediments of Eocene age consists mainly of marine clay, marl, and thin beds of fine sand of the Cane River Formation in south-central Arkansas and Louisiana and the Zilpha Clay in Mississippi. The confining unit hydraulically separates the middle Claiborne aquifer from the lower Claiborne–upper Wilcox aquifer. The confining unit also includes clay beds in the base of the Sparta Sand that are continuous with the clay beds of the Zilpha Clay and Cane River Formation. The lower Claiborne confining unit is not present in the northern part of the embayment north of approximately the 35th parallel where the unit changes to a sand facies. The lower

Claiborne confining unit crops out on both sides of the embayment in a narrow band about 1–10 miles wide and encircles the Sabine uplift. The lower Claiborne confining unit is the only unit in the study area that does not subcrop the Mississippi River Valley alluvial aquifer. The unit ranges in thickness from less than 100 feet updip near its outcrop to more than 800 feet in south-central Louisiana.

The Wilcox Group contains no confining unit traceable over a large area. It is composed predominantly of lenticular deposits of sand, silt, and clay. Discontinuous clay and silty-clay deposits hydraulically separate the middle Wilcox aquifer from both the lower Claiborne–upper Wilcox and the lower Wilcox aquifers.

The Midway confining unit is a regional flow boundary that hydraulically separates the five major aquifers in sediments of Tertiary age in the Mississippi embayment aquifer system from the underlying aquifers in Upper Cretaceous sediments. The Midway confining unit is composed almost entirely of dense marine clay and shale of the Midway Group. The continuous outcrop and (or) subcrop of the confining unit defines the updip limit of the study area. The confining unit generally is more than 1,000 feet thick in the southern part of the study area and less than 1,000 feet thick in the northern part of the area. The confining unit generally is at least several hundred feet thick throughout the area except where it crops out.

## AREAL SUBDIVISIONS

For purpose of analysis, the study area was subdivided into three parts, northern, eastern, and western areas, each having unique topographic or stratigraphic features (fig. 6). The subdivision was made to compare and contrast aquifer properties, development of ground-water pumpage, and response of the flow system to pumpage.

The northern area includes all the area from the facies change in the lower Claiborne confining unit northward to the updip extent of the study area. It encompasses about 18 percent of the study area and includes parts of northwestern Mississippi, northeastern Arkansas, western Tennessee, southeastern Missouri, western Kentucky, and southern Illinois.

The eastern area includes about 41 percent of the study area. The eastern boundary of this area is congruent with the eastern boundary of the study area; the present Mississippi River is the western boundary, and the southern boundary is the downdip extent of the aquifer system. The northern extent of the eastern area is in extreme northwestern Mississippi just south of the 35th parallel where the lower Claiborne confining unit changes from a clay to a sand facies. The eastern area includes most of Mississippi, a small part of southwestern Alabama, and all of Louisiana east of the Mississippi River.

The western area includes about 41 percent of the study area and includes all the area west of the Mississippi River and south of the facies change in the lower Claiborne confining unit (about the 35th parallel). The western boundary of this area is congruent with the western boundary of the study area, and the southern boundary is the downdip extent of the aquifer system. The western area includes all of Louisiana, except the small part of the State east of the Mississippi River, and all of southeastern Arkansas.

### NORTHERN AREA

The northern area is the smallest and narrowest (average width about 130 miles) of the three areas and extends throughout about 21,000 mi$^2$ in the northern end of the Mississippi embayment north of the facies change in the lower Claiborne confining unit (about 35th parallel). The two physiographic provinces that make up the northern area are the Mississippi Alluvial Plain and the east Gulf Coastal Plain uplands. Topography varies from the flat, gently gulfward sloping alluvial plain on the west to uplands of moderate to steep rolling hills on the east. Altitude in the alluvial plain ranges from about 190 feet above sea level in the Memphis, Tenn., area to about 300 feet above sea level near the northern extent of the study area. Altitude in the uplands area ranges from about 300 feet above sea level near the Mississippi River to more than 500 feet above sea level near the eastern border of the area.

The Mississippi Alluvial Plain has a farm-based land use with mostly row-crop agriculture, whereas the uplands area is mostly forested with some open-land agriculture. Memphis, Tenn., is the largest population center in the northern area and in the study area. The large population and industrial base of Memphis depends heavily on the water resources of the Mississippi embayment aquifer system. Other towns in the northern area dependent on these resources are Brownsville, Covington, Ripley, Union City, and Dresden, Tenn., and Blytheville, Wynne, and Jonesboro, Ark. (fig. 3).

The northern area has the smallest aquifer outcrop area in the study area. All the aquifers and confining units in the northern area crop out in the eastern part of the area, except for the small outcrop areas on Crowleys Ridge. The most extensive aquifer cropping out is the middle Claiborne aquifer (Memphis Sand). The area of outcrop of the upper Claiborne aquifer is also extensive, but a large part of the upper Claiborne outcrop is overlain by loess.

The major subcropping units of the Mississippi River Valley alluvial aquifer in the northern area are the middle Claiborne and upper Claiborne aquifers, which subcrop more than three-fourths of the alluvial aquifer. The remainder of


FIGURE 6.—Sketch of northern, eastern, and western areas of the Mississippi embayment aquifer system. Heavy lines indicate boundary of study area.

the subcrop area of the alluvial aquifer is evenly distributed between the lower Wilcox aquifer, middle Wilcox aquifer, and the middle Claiborne confining unit. The alluvial plain encompasses about one-half of the northern area.

The major physiographic characteristics of the northern area that influence the hydrogeology of the Mississippi embayment aquifer system are as follows:

- The embayment has an average width of about 130 miles.
- The Mississippi Alluvial Plain overlays about one-half of the area.
- The entire western half of the embayment is underlain by the Mississippi River Valley alluvial aquifer.
- Aquifers in sediments of Tertiary age crop out only in the eastern half of the embayment in the Coastal Plain uplands.
- Altitudes are the highest in the study area and are from 190 to 300 feet above sea level in the alluvial plain in the western half of the area and from 300 to more than 500 feet above sea level in the eastern half.
- The middle Claiborne and upper Claiborne aquifers subcrop the Mississippi River valley alluvial aquifer in about three-fourths of the area of its occurrence.

## EASTERN AREA

The eastern area includes most of the eastern half of the Mississippi embayment and includes almost all of Mississippi. Generally two physiographic provinces are represented in the area of flow analysis (area with ground water containing dissolved-solids concentrations of 10,000 mg/L or less). The lowlands of the Mississippi Alluvial Plain extend over about 7,000 mi$^2$ of the area, and the Gulf Coastal Plain uplands extend over the remaining 50,000 mi$^2$ of the area. The altitude of the flat alluvial plain ranges from about 100 feet above sea level at Vicksburg, Miss., to about 180 feet above sea level in the northwestern corner of Mississippi. Topography in the Gulf Coastal Plain uplands is characterized by rolling hills and moderate relief in the upper reaches of drainage basins. The altitude of the uplands ranges from about 200 feet to more than 500 feet above sea level, with the higher altitudes in the northeastern part of the area.

The entire eastern area has an agricultural-based economy. The alluvial plain is predominantly cleared farmland, whereas the coastal uplands are predominantly forest lands. The eastern area has the smallest total population of the three areas, but large population centers such as Jackson, Vicksburg, Yazoo City, Greenwood, Greenville, Clarksdale, Oxford, Forest, and Meridian (fig. 3) withdraw freshwater from the aquifers of the Mississippi embayment aquifer system in Mississippi.

The middle Claiborne aquifer has the largest outcrop area in the eastern area and the lower Wilcox aquifer the smallest. The most extensive subcropping aquifers in the eastern area are the middle Claiborne and the upper Claiborne aquifers, which subcrop about two-thirds of the Mississippi River Valley alluvial aquifer. The remainder of the alluvial aquifer is directly underlain by the Vicksburg-Jackson, the middle Claiborne, and the lower Claiborne confining units.

The major physiographic characteristics of the eastern area that influence the hydrogeology of the Mississippi embayment aquifer system are as follows:

- All aquifers crop out in a smooth arcuate pattern along the entire length of the eastern side of the area.
- Average land-surface and water-table altitudes in outcrop areas in the eastern area are higher than those in the adjacent western area.
- The Mississippi Alluvial Plain includes an area of about 7,000 mi$^2$, the smallest of the three areas.
- The middle Claiborne and the upper Claiborne aquifers are the only aquifers subcropping the Mississippi River Valley alluvial aquifer.

### WESTERN AREA

The western area represents the majority of the western half of the Mississippi embayment and includes most of Louisiana and southern Arkansas. The western area includes parts of two physiographic provinces in the area of flow analysis. These are the lowlands of the Mississippi Alluvial Plain, which include about 11,500 mi$^2$ of the area, and the Gulf Coastal Plain uplands, which make up the remaining 45,000 mi$^2$ of the area. The alluvial plain slopes toward the Gulf of Mexico and has little topographic relief. Altitudes in the alluvial plain range from about 50 feet above sea level in the southern part to about 150 feet above sea level in the northern part. The Gulf Coastal Plain uplands in southwestern Arkansas and western Louisiana has rolling hills with altitudes generally between 200 and 300 feet above sea level; in places, however, altitudes more than 300 feet above sea level are common. The average land-surface altitude in the uplands area is substantially less in the western area than in the eastern area.

The Mississippi Alluvial Plain has a mostly agricultural economy but has some industry in the larger towns. The uplands area has significant industrial development in the larger towns, but the rural areas generally are forested and have some row-crop and livestock farming. Major population and industrial centers that withdraw freshwater from the aquifers of the Mississippi embayment aquifer system are Bastrop, Jonesboro, Winnfield, Monroe, and Ruston, La., and El Dorado, Lewisville, Magnolia, Monticello, Pine Bluff, and Stuttgart, Ark. (fig. 3).

All of the aquifers studied crop out in the western area. The upper Claiborne aquifer, with a 6,000 mi$^2$ outcrop area, has by far the largest aquifer outcrop. The second most extensive outcrop area is that of the middle Wilcox. Another major outcropping unit is the middle Claiborne aquifer, which has an outcrop area of 3,200 mi$^2$. The Sabine uplift interrupts the normal arcuate outcrop pattern in the area. The upper Claiborne aquifer, middle Claiborne aquifer, and lower Claiborne–upper Wilcox aquifer crop out around the eastern and southern flanks of the uplift. The uplift exposes the middle Wilcox aquifer sediments over a large area in northwestern Louisiana along the western boundary of the study area.

The western area includes about 11,500 mi$^2$ of the Mississippi Alluvial Plain. The upper Claiborne aquifer is the major subcropping aquifer in the western area, underlying about one-half of the alluvial aquifer. The other four aquifers subcrop only a very small part of the alluvial aquifer. The Vicksburg-Jackson confining unit is the major subcropping confining unit of the Mississippi River Valley alluvial aquifer in the western area.

The major physiographic characteristics of the western area that influence the hydrogeology of the Mississippi embayment aquifer system are as follows:

- The western area contains the largest percentage of the total aquifer outcrop in the study area.
- The upper Claiborne, middle Wilcox, and middle Claiborne aquifers have the largest aquifer outcrop areas in the western area.
- On the western side of the area the Sabine uplift disrupts the normal arcuate aquifer outcrop pattern and distribution and has caused the middle Wilcox aquifer to crop out over a large area.
- Altitudes in aquifer outcrop areas in the western area are lower than altitudes in corresponding areas in the adjacent eastern area.
- The Mississippi Alluvial Plain occupies about 11,500 mi$^2$ in the western area.
- The upper Claiborne aquifer is the major subcropping aquifer and directly underlies about one-half of the Mississippi River Valley alluvial aquifer. No other aquifer has a substantial subcrop in the western area.

## HYDRAULIC PROPERTIES

The five aquifers under study in the Mississippi embayment aquifer system have a large range of hydraulic characteristics. Ranges of hydraulic property values from aquifer test results are tabulated in Arthur and Taylor (1990, table 2). For purposes of simulation, hydraulic properties were estimated between aquifer-test sites and are assumed to be constant throughout the 25-$mi^2$ area representing each model grid block. The hydraulic properties presented in this report do not consider localized variability but instead represent regional estimates generalized for the study area.

The ranges of transmissivity values determined from model calibration are shown on plate 4. The upper Claiborne aquifer has transmissivity values greater than 10,000 $ft^2/d$ in west-central Mississippi and northeastern Louisiana due to thick accumulation of sand (pl. 4). Total sand thickness in the aquifer decreases in all directions from these areas with a corresponding decrease in transmissivity values.

The middle Claiborne aquifer is the most heavily pumped and generally the most transmissive of the five aquifers under study. Massive sand beds in this aquifer in the northern area are partly a result of a facies change in the lower Claiborne confining unit to a sand unit. The increase in sand thickness, coupled with large hydraulic conductivity values for the sand, results in transmissivity values of 10,000–50,000 $ft^2/d$ for the middle Claiborne aquifer in the northern area (pl. 4). The transmissivity of the aquifer decreases somewhat in east-central Arkansas, south of the area of facies change. In most of the downdip zone of the aquifer in the eastern area the transmissivity of the middle Claiborne aquifer is between 5,000 and 10,000 $ft^2/d$, except in central and southeastern Mississippi where it generally is less than 5,000 $ft^2/d$.

The lower Claiborne–upper Wilcox aquifer in the northern area is considered part of the middle Claiborne aquifer as a result of the lower Claiborne confining unit changing to a sand facies and forming one vertically continuous massive sand (Memphis Sand). Transmissivity values for the lower Claiborne–upper Wilcox aquifer generally are less than 5,000 $ft^2/d$ throughout the western area (pl. 4). In central and northwestern Mississippi transmissivity values for the aquifer exceed 5,000 $ft^2/d$, but in the remainder of the eastern area values are less than 5,000 $ft^2/d$.

The middle Wilcox aquifer generally is the least transmissive of the five aquifers and consequently is the least developed aquifer in the Mississippi embayment aquifer system. Transmissivity values for the middle Wilcox aquifer are less than 5,000 $ft^2/d$ for the entire study area except for a small area in extreme west-central Louisiana where values generally are between 5,000 and 10,000 $ft^2/d$ (pl. 4).

Transmissivity values for the lower Wilcox aquifer are more than 5,000 $ft^2/d$ in most of the northern area (pl. 4); the highest values are in the central part of the northern area. In the eastern area in central Mississippi, the lower Wilcox aquifer has transmissivity values generally between 5,000 and 10,000 $ft^2/d$. The remainder of the area has values less than 5,000 $ft^2/d$. In all of the western area, transmissivity values for the lower Wilcox aquifer are less than 5,000 $ft^2/d$.

Confined conditions exist in the five aquifers downdip of their outcrop areas. Storage coefficients of most confined aquifers range from about $1 \times 10^{-5}$ to $1 \times 10^{-3}$ (Heath, 1983). Ranges of storage coefficient values for the aquifers under study were estimated using sand-bed thicknesses and assuming a uniform specific storage of $1 \times 10^{-6}$. Storage coefficients generally range between $2.5 \times 10^{-5}$ and $2.5 \times 10^{-4}$ in the freshwater zones of these five aquifers; the middle Claiborne aquifer has values of more than $2.5 \times 10^{-4}$ for most of its extent because of its large sand thickness.

Flow between aquifers and aquifer systems is determined mostly by the leakance values of the confining units separating the aquifers from one another and from adjacent aquifer systems. The leakance values used in the aquifer flow analysis vary areally with confining unit thickness and vertical hydraulic conductivity. Arthur and Taylor (1990, figs. 25–28) showed the variations in thickness of the clay confining units that influence the vertical flow between aquifers and aquifer systems in the Mississippi embayment aquifer system. Vertical hydraulic conductivity values of confining units used in the flow analysis range from $1 \times 10^{-5}$ ft/d for the thick marine clays of the Vicksburg-Jackson confining unit to $1 \times 10^{-3}$ ft/d for the clays in the middle Claiborne confining unit in the northern area. For the purpose of this analysis the basal confining unit, consisting of thick marine clays of the Midway Group, was assumed to be a no-flow boundary. Intersystem flow through the Midway confining unit (between the McNairy-Nacatoch and lower Wilcox aquifers) was investigated by Brahana and Mesko (1988) and is discussed in a later section of this report.

## PREDEVELOPMENT GROUND-WATER FLOW ANALYSIS

The first artesian well in the Memphis, Tenn., area was completed in the middle Claiborne aquifer (Memphis Sand) in 1886 (Criner and Parks, 1976). The first known pumpage from the middle Claiborne aquifer in the Pine Bluff, Ark., area was by the Pine Bluff Water and Light Company in 1898 (Klein and others, 1950). The first large-capacity well of record in Jackson, Miss., was drilled in 1896 (Harvey and others, 1964). These are three of the first reported large-capacity wells constructed by municipalities in the study area. It is probable that other major urban areas began developing significant ground-water supplies, mainly from the upper Claiborne and middle Claiborne aquifers, during this same time period. Because major ground-water development began during this period, the simulation of predevelopment flow represents conditions prior to 1886. For the predevelopment flow analysis, the ground-water flow system is assumed to be in a state of long-term dynamic equilibrium with recharge balanced by natural discharge to the Mississippi River Valley alluvial aquifer and to the river valleys that intercept the water table in outcrop areas. The flow simulations for 1987 and future development conditions, presented later in the report, represent transient conditions with pumpage varying with time. The ground-water model used in the flow simulation analysis of the five regional aquifers was described by Arthur and Taylor (1990).

## POTENTIOMETRIC SURFACES OF AQUIFERS

Analysis of simulated predevelopment heads indicates, as Payne (1968) discussed, that downdip where the aquifers become confined, potentiometric surfaces were higher in successively deeper aquifers. Water levels for a particular aquifer were higher and hydraulic gradients were steeper in outcrop areas (pl. 5).

Predevelopment water levels on the eastern flank of the embayment were substantially higher than water levels in the same aquifer on the western flank. This is most evident in the northern area where aquifers crop out only in the eastern half of the embayment. This condition produced disproportionately higher water levels in the eastern half of the northern area than in the western half of the northern area where the aquifers subcrop the Mississippi River Valley alluvial aquifer. This condition also existed, to a lesser degree, in the western and eastern areas. In the western area the aquifers crop out in the upland areas on the western flank of the embayment, but water levels for an individual aquifer generally were higher on the eastern flank of the embayment as compared to water levels in outcrop areas on the western flank.

Throughout the study area, model simulation results indicate that predevelopment hydraulic gradients were steeper in outcrop areas and were more uniform and flatter downdip in the confined zone. In the northern area, gradients sloped west-southwest near outcrop areas, westward in the center of the embayment, and southwestward on the western edge of the embayment. In the eastern area, hydraulic gradients generally were westward away from the outcrop areas in the northern and central reaches of the area and southwestward to southward as the eastern flank of the embayment approached a parallel alignment with the Gulf Coast geosyncline. In the western area, gradients were more complex, possibly because of the influence of the Sabine uplift and the absence of aquifer outcrop areas on the western side of the northern area. In the northwestern part of the western area, updip gradients were northeastward toward aquifer subcrops but southward near the axis of the embayment. In southwestern Arkansas, heads sloped east-southeast, but farther south in northern Louisiana the influence of the Sabine uplift caused gradients to slope in a northeasterly direction on the north flank of the uplift and in a southerly direction near the south flank of the uplift.

The general southward slope of potentiometric surfaces along the embayment axis was interrupted in the upper Claiborne and middle Claiborne aquifers in northeastern Louisiana and in the middle Claiborne aquifer in north-central Mississippi. In the area where the upper Claiborne aquifer subcrops the Mississippi River Valley alluvial aquifer in northeastern Louisiana, heads in the upper Claiborne aquifer were 60–80 feet lower than heads in adjacent areas (pl. 5). The middle Claiborne aquifer also had lower heads in this area, but the depression was shallower; heads were 40 feet lower than heads in adjacent areas in the middle Claiborne aquifer (pl. 5) and about 60–80 feet higher than those in the upper Claiborne aquifer. The other closed contour depression in the potentiometric surface of the middle Claiborne aquifer was in the subcrop area of the Mississippi River Valley alluvial aquifer in north-central Mississippi. That depression was not as deep or extensive as the one in northeastern Louisiana, but it produced a major interruption in the flow system due to its proximity to the aquifer outcrop area that is immediately adjacent to the alluvial plain. The most probable explanation for the two large head depressions in the subcropping aquifers is that they are regional predevelopment discharge areas.

The lower Claiborne–upper Wilcox, middle Wilcox, and lower Wilcox aquifers all had similar predevelopment potentiometric-surface configurations. In the northern half of the embayment, these aquifers had potentiometric surfaces that sloped westward and southwestward toward potentiometric lows near the western and southwestern edges of the Mississippi embayment. In the southern part of the eastern area and the extreme southern part of the western area, potentiometric surfaces sloped southward toward the Gulf of Mexico.

## RECHARGE AND DISCHARGE IN AQUIFER OUTCROP AND SUBCROP AREAS

Predevelopment recharge to aquifers was predominantly by direct infiltration of rainfall in the aquifer outcrop areas. Predevelopment discharge was by all naturally occurring flow from the aquifers to streams, springs, and seeps and by leakage to adjacent aquifers.

The majority of predevelopment recharge was surficial vertical flow from aquifer outcrop and subcrop areas and a small amount (about 0.3 $Mft^3/d$ (million cubic feet per day) or 2.2 Mgal/d (million gallons per day)) that was downward leakage from the overlying coastal lowlands aquifer system in the southern part of the study area. Rates of simulated predevelopment recharge and discharge to the Mississippi embayment aquifer system in outcrop and subcrop areas are shown in figure *7A*. The middle Claiborne aquifer outcrop area on the eastern side of the northern area of the embayment had the greatest predevelopment recharge, receiving more than 1 in./yr (inch per year) in some areas of northern Mississippi and southern Tennessee. As shown in figure 7*A*, most of the Mississippi Alluvial Plain is a predevelopment discharge area for the five studied aquifers. The zone that had the largest predevelopment discharge, also in the northern area, was in the Mississippi Alluvial Plain east of Crowleys Ridge where the upper Claiborne aquifer subcrops the Mississippi River Valley alluvial aquifer. For the majority of this area, discharge to the alluvial aquifer was more than 0.2 in./yr, and in a small area (about 100 $mi^2$) west of Memphis discharge from the upper Claiborne aquifer was more than 0.6 in./yr. Possible explanations for this large recharge and discharge in the northern area are (1) the middle Claiborne aquifer has large transmissivity, (2) the embayment is narrow and thus flow paths from recharge points to discharge points are shorter, and (3) high heads in the aquifer outcrop areas produce correspondingly higher heads in individual aquifers under the Mississippi Alluvial Plain, forcing flow upward into the upper Claiborne aquifer and thence into the Mississippi River Valley alluvial aquifer.

Before development, aquifer outcrop areas in the eastern and western areas had more than 0.2 in./yr recharge in the upland areas of central Mississippi, south-central Arkansas, and northwestern Louisiana, but most of the outcrop areas had less than 0.2 in./yr recharge (fig. 7*A*). Predevelopment discharge from the aquifer system in the eastern and western areas was predominantly to the Mississippi River Valley alluvial aquifer, but some discharge was to large rivers and valleys. The Mississippi River Valley alluvial aquifer, which underlies the Mississippi Alluvial Plain, received as much as 0.2 in./yr discharge from the subcropping aquifers over much of the Mississippi Alluvial Plain. The area with greatest simulated predevelopment discharge in the eastern and western areas was in south-central Arkansas and extreme northeastern Louisiana where the upper Claiborne aquifer subcrops the alluvial plain (Hosman and Weiss, 1991, pl. 10). In most of this area the system discharge was about 0.2 in./yr, but small areas in extreme south-central Arkansas and northeastern Louisiana had a discharge greater than 0.4 in./yr. The areas of least predevelopment regional discharge to the Mississippi River Valley alluvial aquifer are immediately north of the Arkansas-Louisiana border along the Mississippi River and in northeastern Louisiana just west of the Mississippi River. In these two areas, the Vicksburg-Jackson confining unit subcrops the alluvial aquifer, and the thick marine clays of the confining unit restrict vertical flow (Hosman and Weiss, 1991, pl. 10).

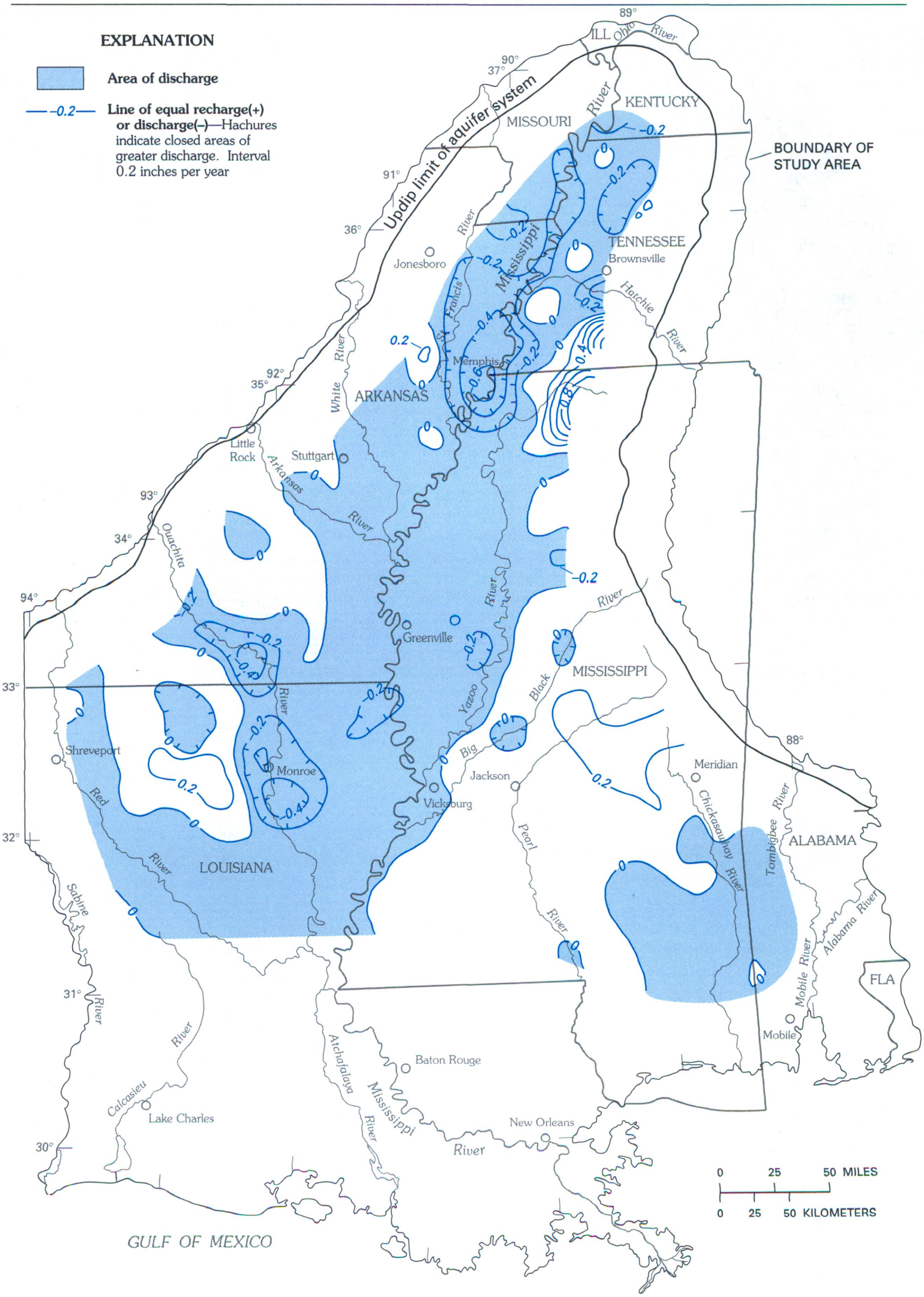
## LATERAL AND INTERAQUIFER FLOW

Most water entering the Mississippi embayment aquifer system in outcrop areas moves predominantly downward along a relatively short flow path and is discharged to nearby streams, seeps, and springs. The remainder of the flow moves laterally downdip to the confined area of the aquifer system. Downdip confined lateral flow in aquifers is characterized by (1) diminishing interconnection between surface water and ground water, (2) decreasing vertical hydraulic conductivity, and (3) increasing thickness of confining units in a downdip direction. Flow farther downdip near the saltwater interface is influenced by decreasing horizontal conductivity coupled with increasing dissolved-solid concentrations. Near the saltwater interface, flow is predominantly upward to overlying, more permeable freshwater zones and to regional discharge areas.

Predevelopment horizontal and vertical flow in the study area was greatest north of the facies change in the lower Claiborne confining unit (about 35th parallel) in the northern area. The combination of topographically high outcrops, short flow paths, and large transmissivity values facilitates both horizontal and vertical flow in the aquifers. These conditions are particularly characteristic of the middle and upper Claiborne aquifers in the northern area. Flow was predominantly from recharge areas on the eastern side of the embayment to the regional discharge area, the Mississippi River Valley alluvial aquifer. Net vertical flow in the aquifer system as a whole was upward. The area underlain by the Mississippi River Valley alluvial aquifer in the northern area had the greatest upward movement of water in the study area. The low altitude of the water table in the Mississippi River Valley alluvial aquifer, in combination with the high altitude of the potentiometric surfaces of the confined aquifers beneath the alluvial plain, produced an upward head gradient from the deepest aquifer to the alluvial aquifer. Under predevelopment conditions, about 0.5 $Mft^3/d$ (3.74 Mgal/d) of water moved upward from the lower and middle Wilcox aquifers into shallower aquifers in the northern area (fig. 8*A*). The greatest vertical flows were between the middle and upper Claiborne aquifers; however, flow between the upper Claiborne aquifer and the Mississippi River Valley alluvial aquifer was almost as great. In the northern area, a net vertical flow of about 11.5 $Mft^3/d$ (86.0 Mgal/d) moved from the middle Claiborne aquifer through the middle Claiborne confining unit into the upper Claiborne aquifer and about 10.5 $Mft^3/d$ (78.5 Mgal/d) moved upward from the upper Claiborne aquifer into the alluvial aquifer. Total simulated predevelopment flow to the alluvial aquifer in the northern area from the five aquifers was about 21 $Mft^3/d$ (157 Mgal/d).

The eastern and western areas had similar predevelopment flow patterns (figs. 9*A*, 10*A*). Horizontal flow moved from outcrop areas on the flanks of the embayment toward the

FIGURE 7 (overleaf).—Simulated rates of recharge to and discharge from the Mississippi embayment aquifer system for (*A*) predevelopment and (*B*) 1987 conditions.


EXPLANATION
Area of discharge
-0.2 Line of equal recharge(+) or discharge(-)—Hachures indicate closed areas of greater discharge. Interval 0.2 inches per year
BOUNDARY OF STUDY AREA
Updip limit of aquifer system
ILL
KENTUCKY
MISSOURI
TENNESSEE
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
FLA
Ohio River
Mississippi River
St. Francis River
White River
Arkansas River
Ouachita River
Hatchie River
Yazoo River
Big Black River
Pearl River
Red River
Sabine River
Calcasieu River
Atchafalaya River
Chickasawhay River
Tombigbee River
Mobile River
Alabama River
Jonesboro
Brownsville
Memphis
Little Rock
Stuttgart
Greenville
Shreveport
Monroe
Jackson
Vicksburg
Meridian
Mobile
Baton Rouge
Lake Charles
New Orleans
GULF OF MEXICO
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
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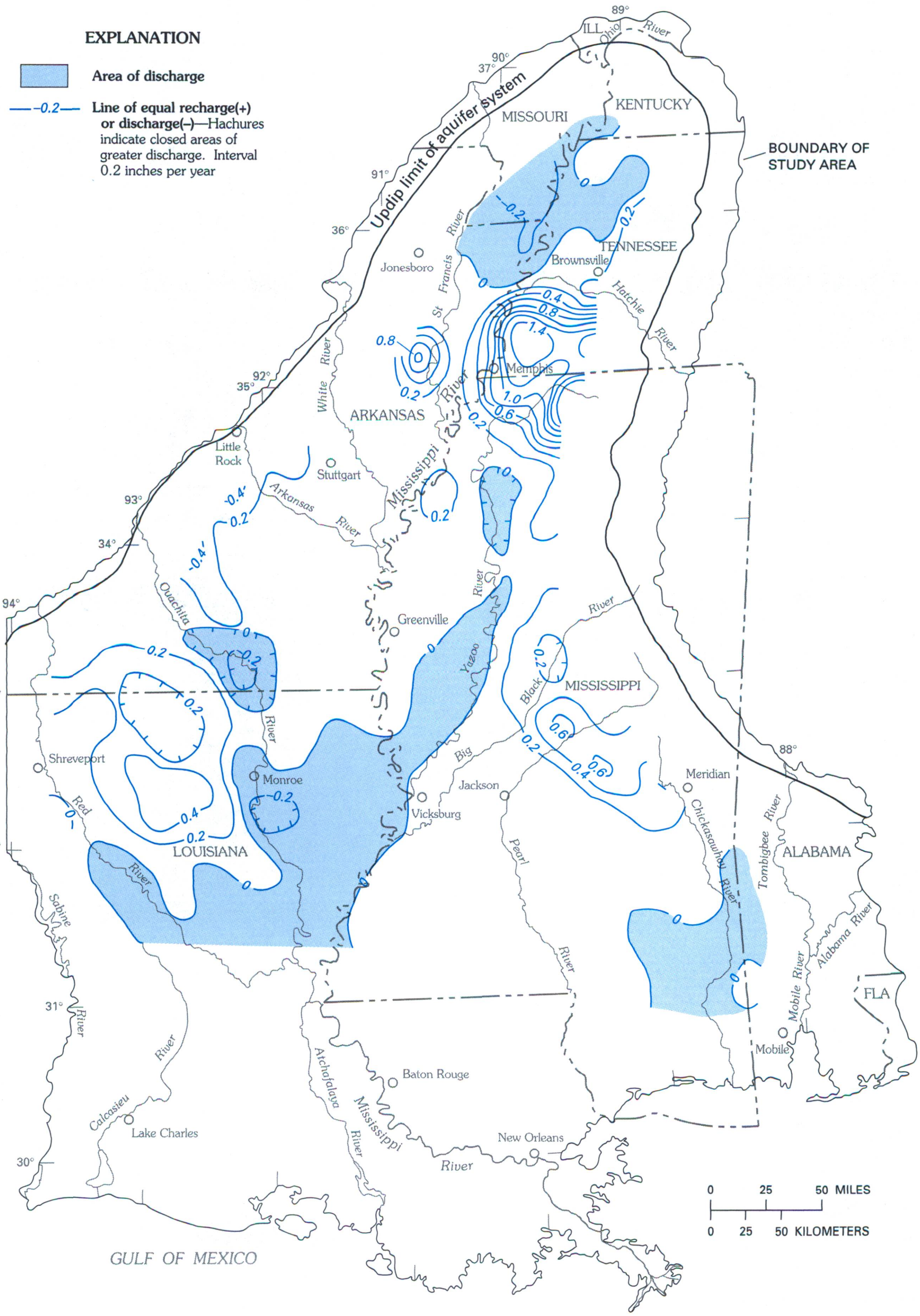
32°
31°
30°
88°
0 25 50 MILES
0 25 50 KILOMETERS


EXPLANATION
Area of discharge
-0.2 Line of equal recharge(+) or discharge(-)—Hachures indicate closed areas of greater discharge. Interval 0.2 inches per year
BOUNDARY OF STUDY AREA
Updip limit of aquifer system
ILL
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
FLA
Ohio River
St Francis River
White River
Hatchie River
Mississippi River
Arkansas River
Ouachita River
Yazoo River
Black River
Big Black River
Red River
Pearl River
Chickasawhay River
Tombigbee River
Mobile River
Alabama River
Sabine River
Calcasieu River
Atchafalaya River
Jonesboro
Brownsville
Memphis
Little Rock
Stuttgart
Greenville
Shreveport
Monroe
Vicksburg
Jackson
Meridian
Mobile
Baton Rouge
Lake Charles
New Orleans
GULF OF MEXICO
89°
90°
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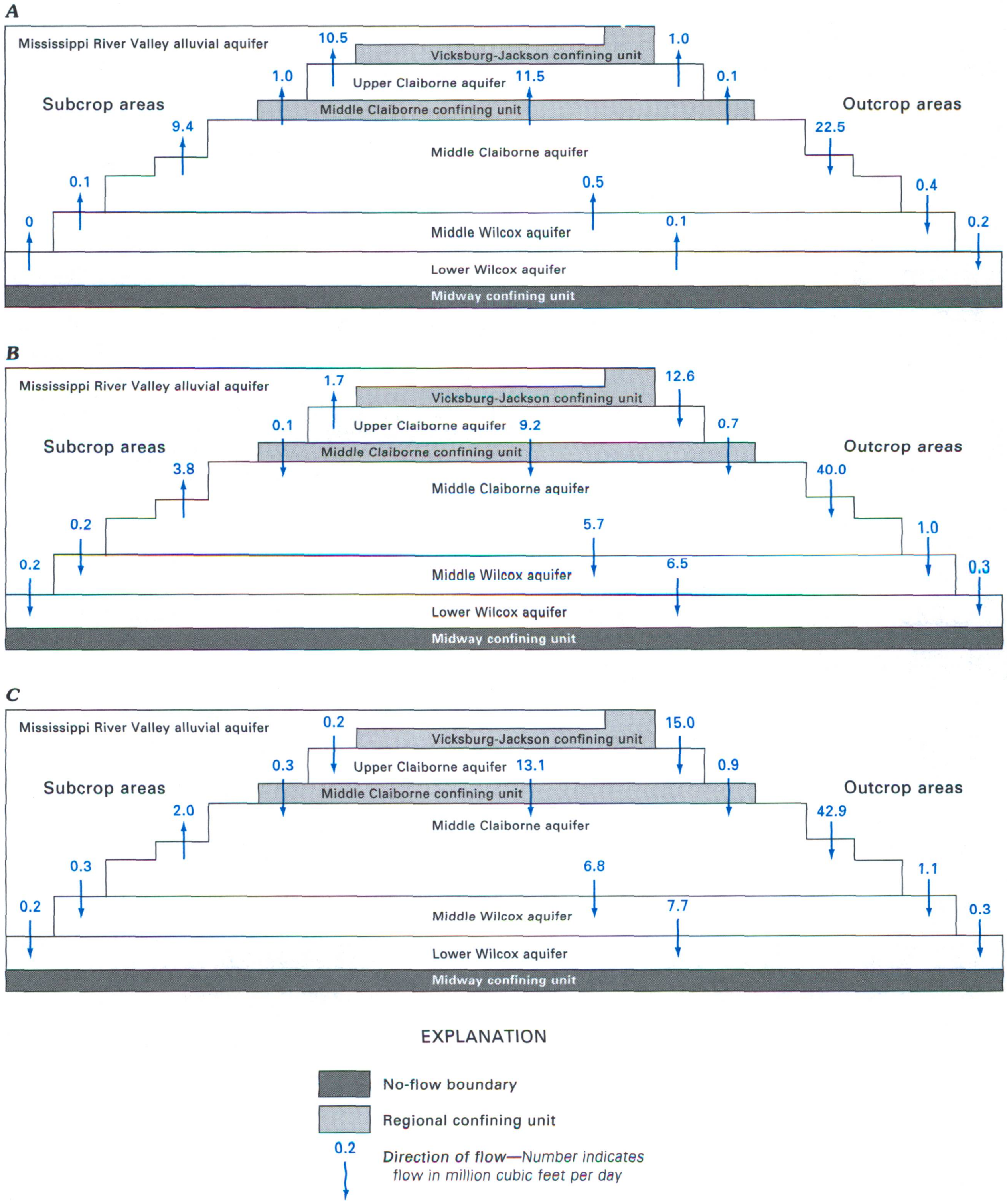



FIGURE 8.—Simulated rates of vertical flow in northern area for (*A*) predevelopment (1986), (*B*) 1987, and (*C*) 2000 conditions (20 percent pumpage increase from 1987 conditions).

axis of the embayment. The vertical flow component was upward in the center one-third of the embayment toward the eventual discharge area, the Mississippi River Valley alluvial aquifer. The system outflow was less in the eastern and western areas than in the northern area. Smaller transmissivity values and longer flow paths combine to reduce the potential for upward vertical flow. Most of the vertical flow was in the large subcrop area where the upper and middle Claiborne aquifers are in contact with the Mississippi River Valley alluvial aquifer. Total simulated

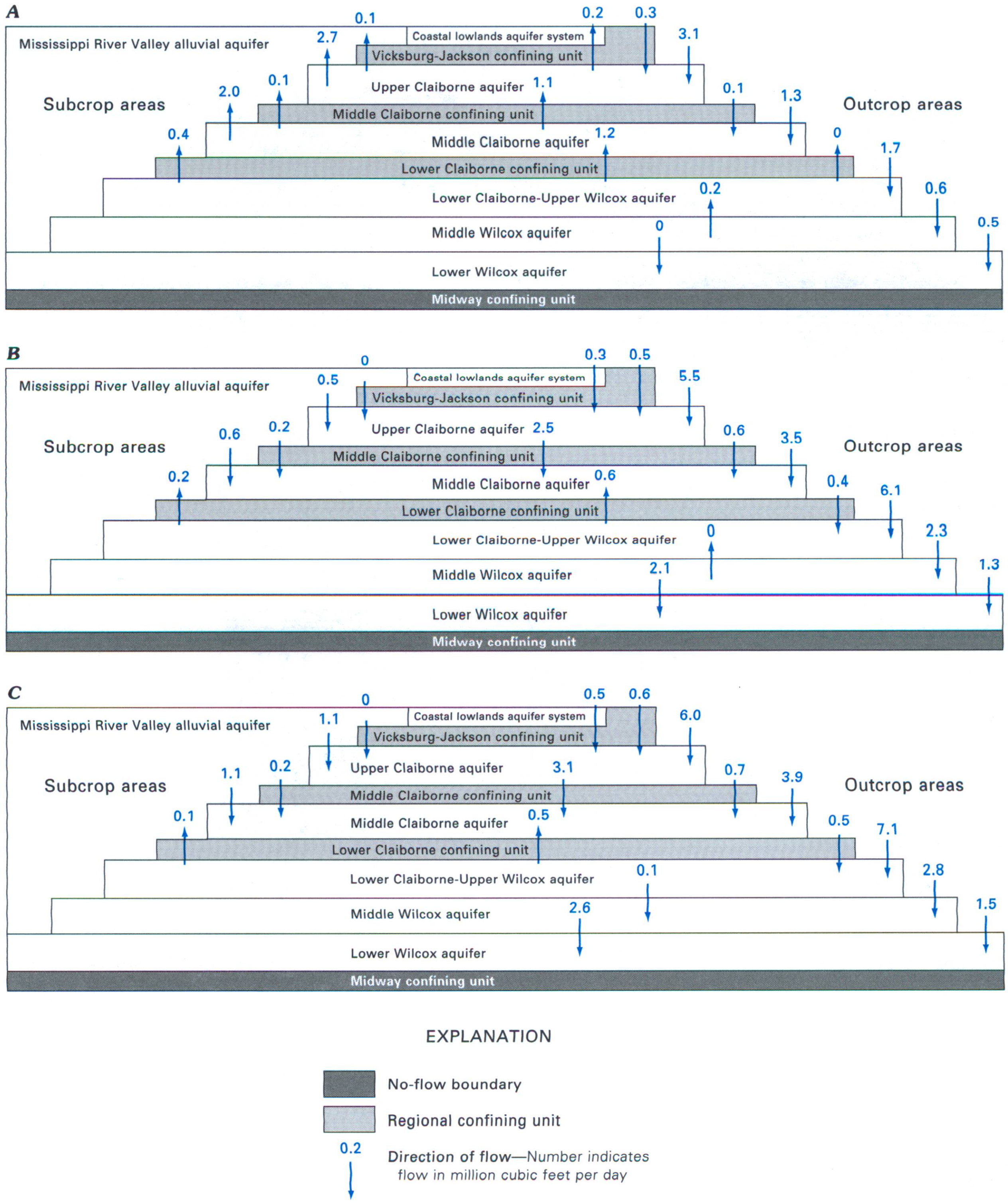



FIGURE 9.—Simulated rates of vertical flow in eastern area for (*A*) predevelopment (1986), (*B*) 1987, and (*C*) 2000 conditions (20 percent pumpage increase from 1987 conditions).

predevelopment upward flow to the alluvial aquifer from the five aquifers was about 5.3 Mft$^3$/d (39.6 Mgal/d) in the eastern area and about 7.7 Mft$^3$/d (57.6 Mgal/d) in the western area. In both areas most of the upward flow was from the upper Claiborne aquifer.

## FLOW TO ADJACENT AREAS AND AQUIFER SYSTEMS

Simulated predevelopment net flow between areas generally is in accordance with the regional aquifer system

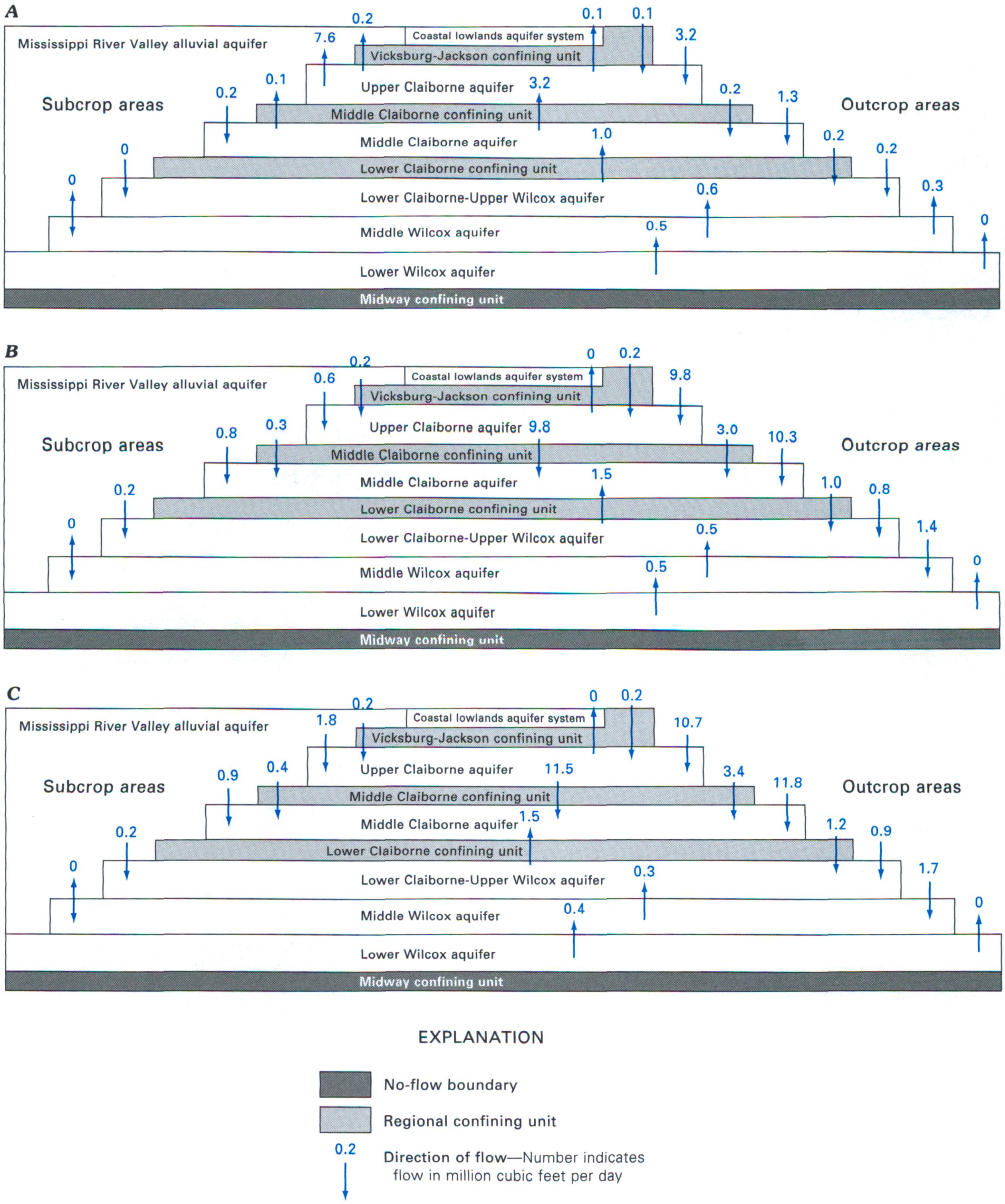



FIGURE 10.—Simulated rates of vertical flow in western area for (*A*) predevelopment (1986), (*B*) 1987, and (*C*) 2000 conditions (20 percent pumpage increase from 1987 conditions).

pattern of southward and westward flow. Simulation results indicate that net system predevelopment flow from the northern area southward into the eastern and western areas was about 0.5 and 0.4 $Mft^3/d$ (3.74 and 2.99 Mgal/d), respectively (fig. 11). Net system flow from the eastern area to the western area was about 2.6 $Mft^3/d$ (19.4 Mgal/d). The middle Claiborne aquifer in the northern area had the greatest predevelopment southward flow of about 0.4 $Mft^3/d$ (2.99

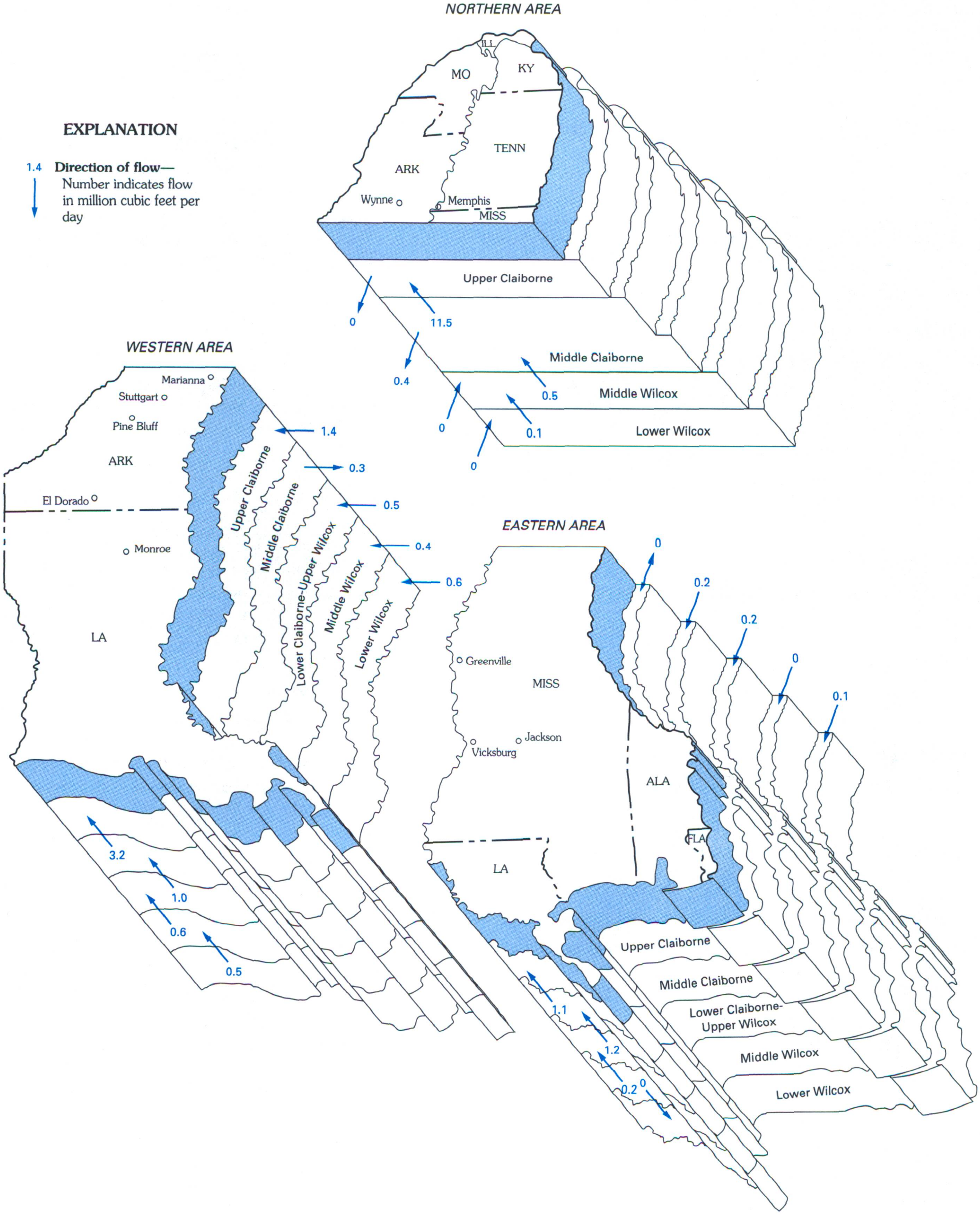



FIGURE 11.—Simulated predevelopment horizontal flow between areas and vertical flow between aquifers.

Mgal/d), moving into both the eastern and western areas toward potentiometric lows in the Mississippi River Valley alluvial aquifer in Mississippi and northeastern Louisiana. The upper Claiborne aquifer provided the greatest westward flow of about 1.4 Mft$^3$/d (10.5 Mgal/d), moving laterally from the eastern area into the western area in northeastern Louisiana toward one of the major discharge areas of the aquifer system.

The flow direction between areas was similar to the regional flow direction in all but two locations. One exception was between the western and northern areas in the middle and lower Wilcox aquifers, where the horizontal flows [combined flows less than 0.1 Mft$^3$/d (0.748 Mgal/d)] were to the northeast from upland outcrop areas in south-central Arkansas toward subcrop areas in east-central Arkansas. The other exception was between the eastern and western areas in the middle Claiborne aquifer, where net lateral flow was eastward. Even though flow was westward in the middle Claiborne aquifer in the southern one-half of the eastern area, a greater flow from the western area moved southeast toward potentiometric lows in the Mississippi River Valley alluvial aquifer in Mississippi and northeastern Louisiana. The large southeastward flow toward the Mississippi Alluvial Plain resulted in a net eastward flow of about 0.3 Mft$^3$/d (2.24 Mgal/d) in the middle Claiborne aquifer.

Predevelopment flow from the five aquifers to other aquifer systems defined in the Gulf Coast RASA study was not substantial, but flow to the Mississippi River Valley alluvial aquifer within the Mississippi embayment aquifer system was significant. Total net predevelopment discharge to the Mississippi River Valley alluvial aquifer was 34 Mft$^3$/d (254 Mgal/d). Most of the discharge [about 21 Mft$^3$/d, (157 Mgal/d)] occurred in the northern area and was centered along the embayment axis. The simulated predevelopment flow budget for each aquifer in the study area is shown in figure 12.

In most of the study area, thick marine clay of the Midway confining unit prevented any substantial predevelopment vertical flow between the deeper aquifers of the Mississippi embayment aquifer system and aquifers in sediments of Cretaceous age. Brahana and Mesko (1988) reported that for most of the study area, simulated predevelopment flow from the McNairy-Nacatoch aquifer into the lower Wilcox aquifer was less than about 0.5 Mft$^3$/d (3.74 Mgal/d), but in the extreme northwestern part of the embayment in Missouri, about 4.5 Mft$^3$/d (33.7 Mgal/d) flowed into the lower Wilcox aquifer. Potential for lateral flow to or from aquifer systems outside the study area was very limited. Lateral flow interchange with the Texas coastal uplands aquifer system to the west is limited by the effect of the Sabine uplift. Flow between the two aquifer systems was restricted to the middle and lower Wilcox aquifers, but, considering the effects of the uplift and small transmissivity values of the two aquifers, the intersystem flow was assumed negligible in relation to the total flow in the aquifer system. No substantial lateral flow occurred between aquifer systems on the eastern edge of the study area due to the combined hydrogeologic effects of Mobile Bay, the Mobile River, the Mobile graben, and a facies change in the aquifers. The coastal lowlands aquifer system overlies the southern one-third of the eastern and western areas. Flow to or from this system is severely restricted by the thick marine clays and limestones of the Vicksburg-Jackson confining unit, and total simulated predevelopment discharge from the Mississippi embayment aquifer system to the coastal lowlands aquifer system was about 0.3 Mft$^3$/d (2.24 Mgal/d).

## GROUND-WATER FLOW ANALYSIS—1886–1987

Flow analysis of the five aquifers studied in the Mississippi embayment aquifer system under developed (stressed) conditions was simulated by dividing the time between predevelopment (prior to 1886) and 1987 conditions into 12 pumping periods. Pumpage rates for each of the 12 simulation periods are mid-period rates and were assumed to remain constant throughout the period. Flow characteristics were evaluated and graphically represented at the end of each simulation period, and a special effort was made to analyze the changes in regional flow patterns from predevelopment to 1987 conditions. The following sections present results from the analysis of the regional flow patterns of the five aquifers under study.

### GROUND-WATER WITHDRAWAL TRENDS

The first large development of ground water from the studied aquifers in the Mississippi embayment aquifer system began in 1886 with pumpage from the middle Claiborne aquifer in Memphis, Tenn., in the northern area. Pumpage in the Memphis area increased about 0.43 Mft$^3$/d (3.2 Mgal/d) per year from 1886 to 1894 (fig. 13). The rate of increase lessened to about 0.03 Mft$^3$/d (0.2 Mgal/d) per year from 1895 to 1920, with about 4.4 Mft$^3$/d (32.9 Mgal/d) being withdrawn during 1920. The average annual rate of increase in withdrawals from 1920 to 1974 was about 0.39 Mft$^3$/d (2.92 Mgal/d) per year, and the pumpage rate in 1974 was about 25.4 Mft$^3$/d (190 Mgal/d) (Criner and Parks, 1976). Since 1974 pumpage in the Memphis area has stabilized, and during 1985 pumpage from the middle Claiborne aquifer was about 25.5 Mft$^3$/d (191 Mgal/d).

In other parts of the study area significant pumping began about 1920. Even though these areas, such as Pine Bluff, Stuttgart, El Dorado, and Magnolia, Ark., Monroe, La., and Jackson, Miss., have less individual pumpage than the Memphis area, the development patterns since 1920 are similar to the pattern at Memphis. Pumpage rates have stabilized since the late 1970's and even decreased 5 percent from 1982 to

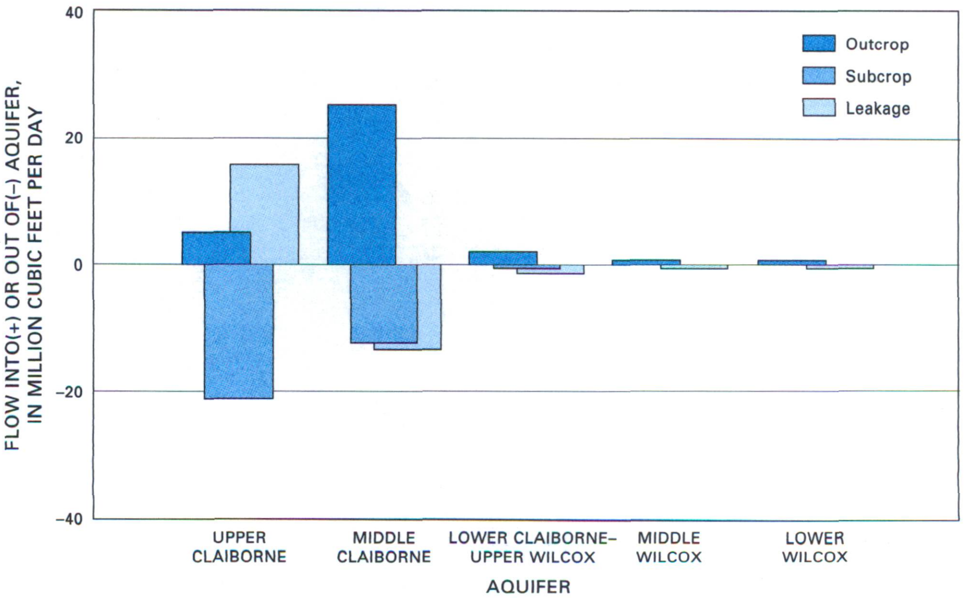



FIGURE 12.—Simulated predevelopment flow budget for aquifers in the study area.

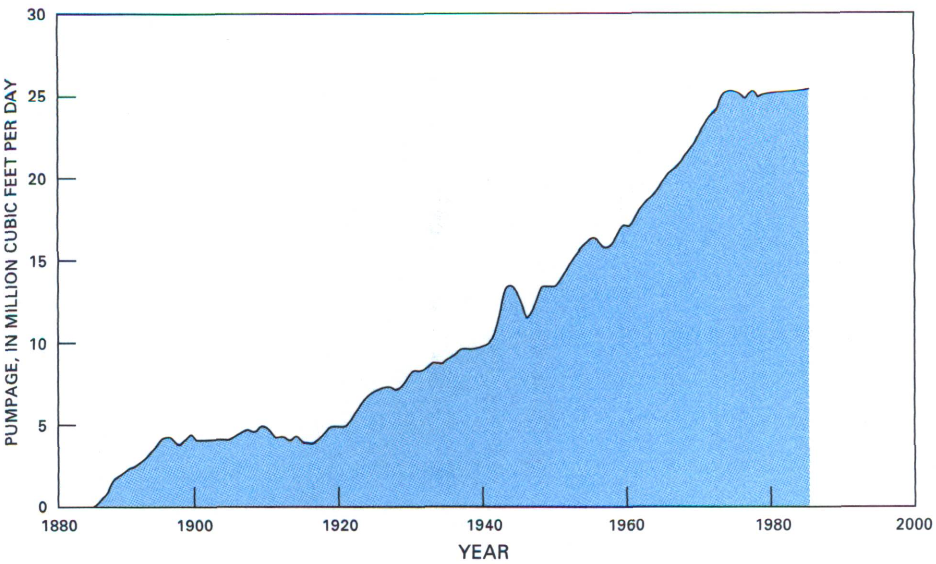



FIGURE 13.—Pumpage (1886–1985) from the middle Claiborne aquifer in the Memphis (Shelby County), Tennessee, area. Modified from Criner and Parks (1976).

1987 (fig. 14). Recently, increased concern for water resource conservation, the economic environment, and other factors have contributed to the stabilization of ground-water withdrawals.

Total pumpage from the five aquifers in the study area during 1985 (pumpage for simulated stress period 1982–1987) was about 102.2 $Mft^3/d$ (764.5 Mgal/d). The middle Claiborne was the most heavily pumped aquifer with about 74.3 $Mft^3/d$ (556 Mgal/d) withdrawn during 1985 or about 72.7 percent of the total pumpage from the study area (fig. 15). The northern area had the largest total pumpage during 1985 (about 48.1 $Mft^3/d$, 360 Mgal/d) (fig. 16). Much of this pumpage (about 39.1 $Mft^3/d$, 292 Mgal/d) was from the middle Claiborne aquifer. The lower Wilcox aquifer had the second largest pumpage during 1985, about 10.7 $Mft^3/d$ (80.0 Mgal/d) or about 10 percent of the total pumpage from the study area. The northern area had the largest pumpage from the lower Wilcox aquifer during 1985, about 7.0 $Mft^3/d$ (52.4 Mgal/d) or about 65 percent of total withdrawal from the aquifer. The middle Wilcox aquifer had the smallest withdrawal of any aquifer. During 1985, about 3.3 $Mft^3/d$ (24.7 Mgal/d) was pumped from the middle Wilcox aquifer of which about 2.2 $Mft^3/d$ (16.5 Mgal/d) was from the western area.

The eastern area had the least total pumpage (about 21 percent of the 1985 total) in the study area, but it had the most evenly distributed pumpage among the aquifers (fig. 14*B*). Most of the pumpage in the western and northern areas (85 and 81 percent, respectively) was from the middle Claiborne aquifer.

With the stabilization of pumpage rates since the late 1970's, water levels in heavily pumped areas also stabilized.

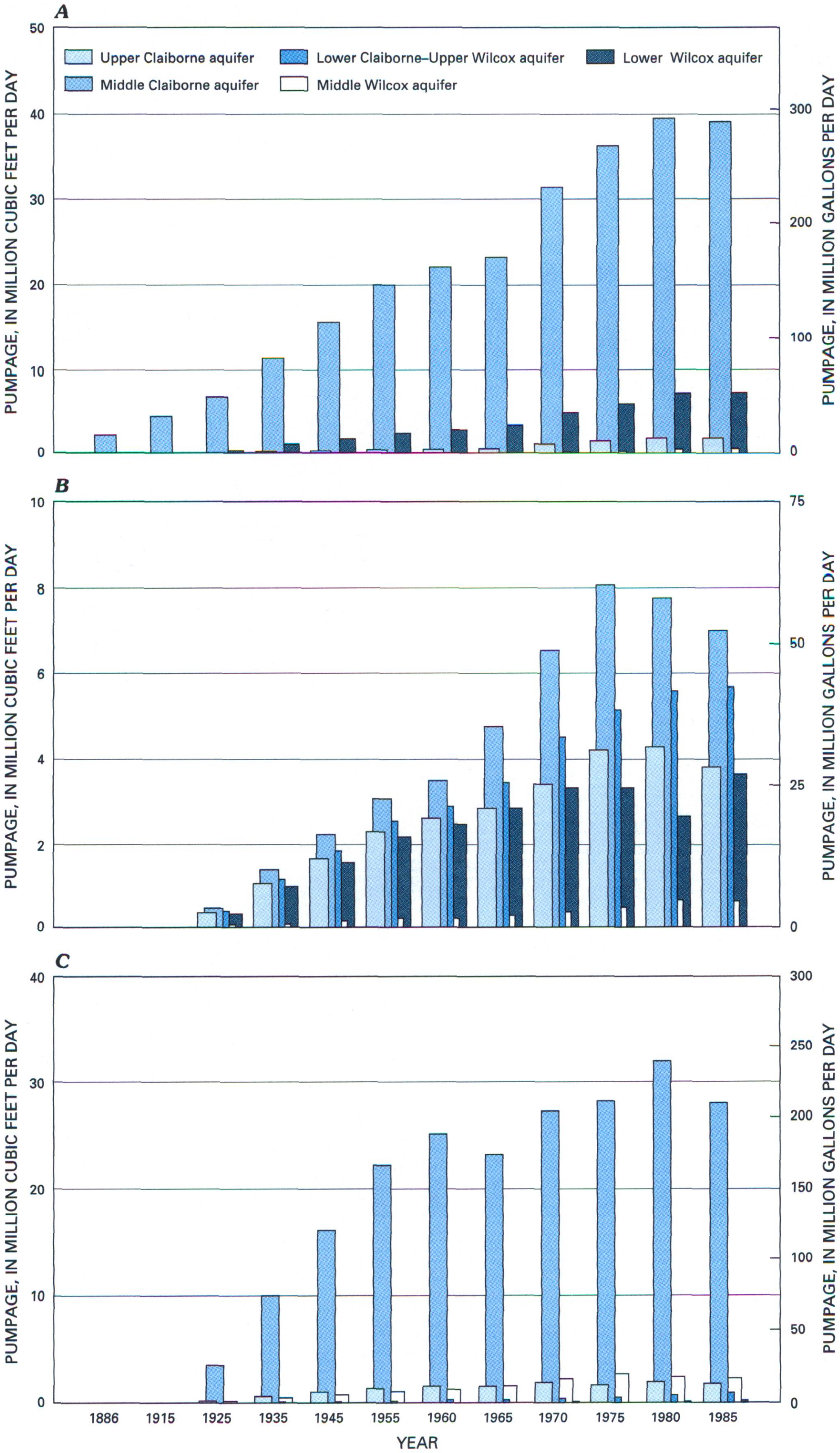



FIGURE 14.—Pumpage from aquifers in (*A*) northern, (*B*) eastern, and (*C*) western areas of the study area.

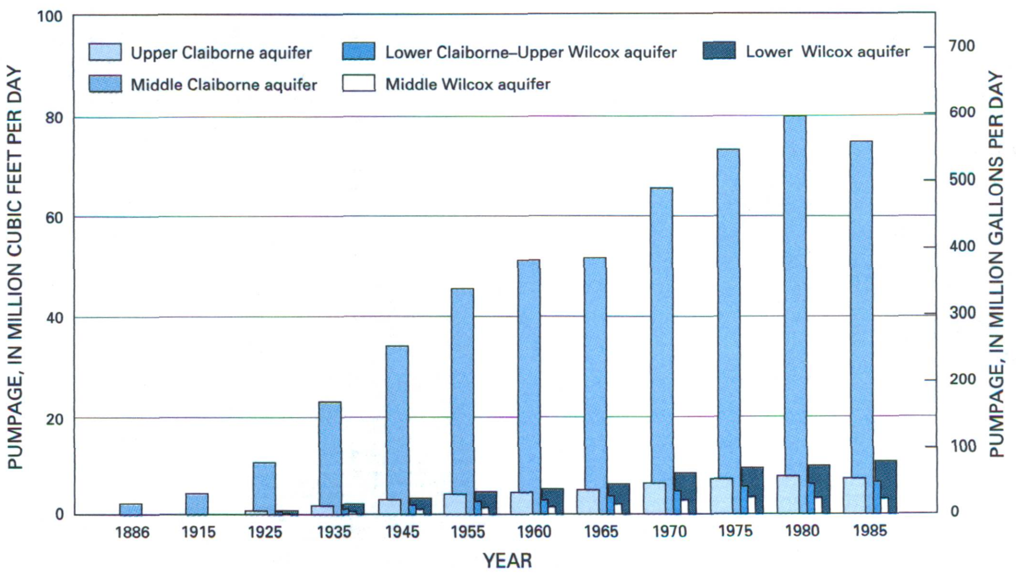



FIGURE 15.—Total pumpage from aquifers in study area.

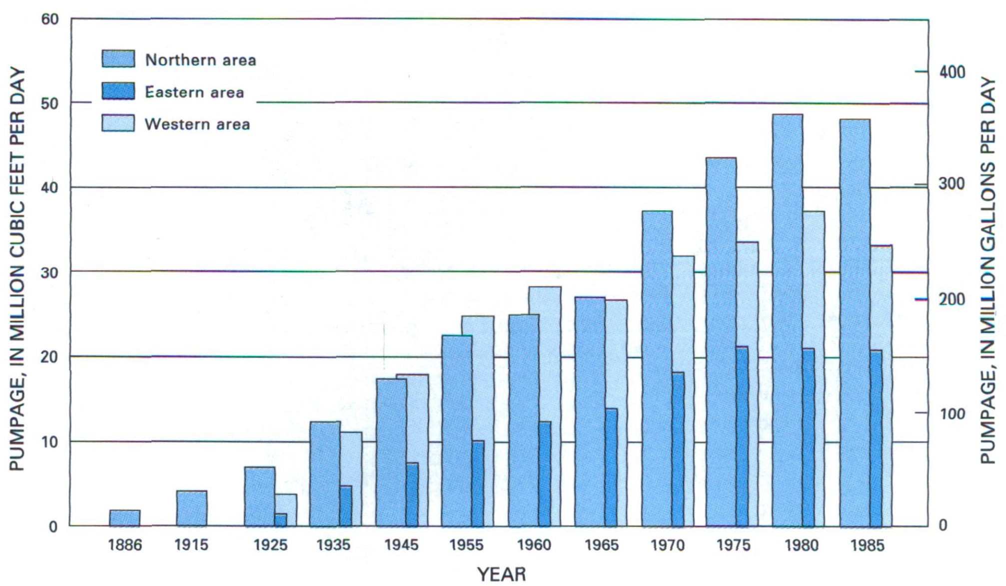



FIGURE 16.—Total pumpage in northern, eastern, and western areas of the study area.

Figure 17 shows measured and simulated water levels in selected wells completed in the upper and middle Claiborne aquifers in the Memphis, Tenn., Stuttgart, Ark., and Jackson, Miss., areas. The stabilizing of water levels since 1980, shown by the hydrographs for these heavily pumped areas, indicates the probability of little change in water levels in areas with less pumpage.

## POTENTIOMETRIC SURFACES OF AQUIFERS

In response to pumping, potentiometric surfaces in the confined parts of the five aquifers have declined from predevelopment levels. Rates and magnitudes of declines are directly related to the rate of increase and magnitude of pumpage and to the hydraulic properties of the aquifers. The greatest water-level declines from predevelopment levels have been in the heavily pumped middle Claiborne aquifer, and the least declines have been in the lightly pumped middle Wilcox aquifer. Because pumpage has stabilized since the late 1970's, the 1987 potentiometric surfaces of the aquifers probably would have a similar configuration as the surfaces determined from 1980 water-level measurements (pl. 6). Because water-level measurements were not available throughout the entire study area, the areal extent of the mapped potentiometric surfaces was limited. The potentiometric surfaces shown generally represent areas with greatest withdrawal. Simulated 1987 potentiometric surfaces for the five aquifers under study are shown on plate 7. These surfaces are thought to represent reasonably well the actual

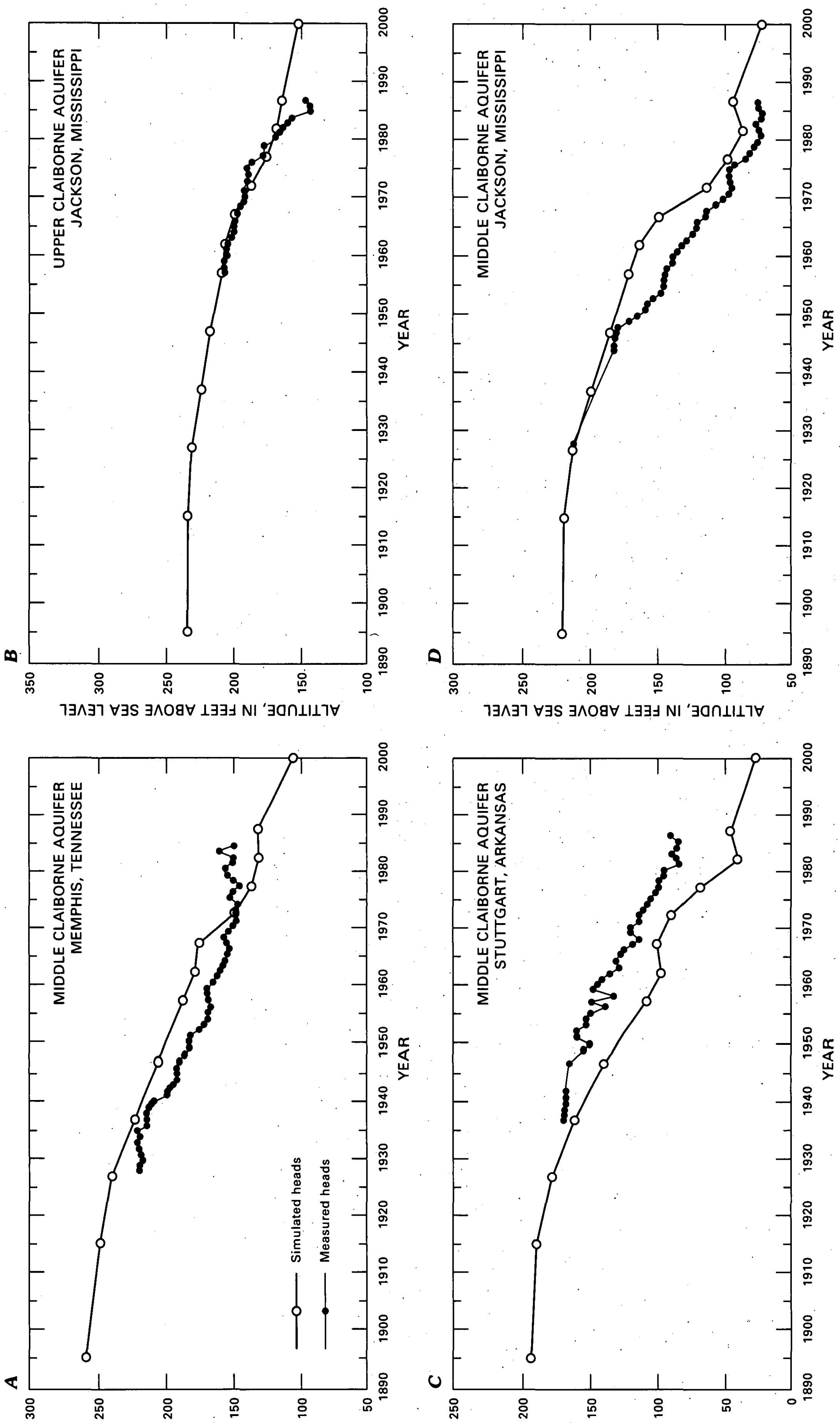



FIGURE 17.—Measured and simulated water levels for selected wells. See figure 3 for well locations.

water-level conditions for that year, given the regional extent of the analysis and the coarse discretization of aquifer hydraulic properties. Table 2 shows the root-mean-square error between the simulated 1987 and measured 1980 potentiometric surfaces for those areas with enough water-level data to define the potentiometric surface.

The effects of pumping from a particular aquifer or from vertically adjacent aquifers can be seen on the simulated potentiometric surfaces of each of the aquifers. The simulated 1987 potentiometric surface of the upper Claiborne aquifer had two areas of substantial drawdown from predevelopment heads. Both were in the eastern area, one near Jackson, Miss., where drawdown was as much as 75 feet, and the other around Greenville, Miss., where drawdown was as much as 100 feet (pl. 8). In the Memphis, Tenn., area, where water-table conditions exist in the upper Claiborne aquifer, local water levels were drawn down as much as 75 feet because of heavy pumping from the underlying middle Claiborne aquifer.

The middle Claiborne aquifer, the most heavily pumped aquifer in the study area, has the greatest water-level declines from predevelopment levels (pl. 8). Four major pumping centers, two in the western area and one each in the eastern and northern areas, have drawdowns that have significantly altered the potentiometric surfaces of the middle Claiborne aquifer. Simulated 1987 water levels in the heavily pumped Memphis area are at least 125 feet below predevelopment water levels. Even though this area is the most heavily pumped of the four major pumping centers in the middle Claiborne aquifer, water-level declines are smaller than those in areas with less pumpage. A thick sand aquifer having high permeability and short flow paths from recharge areas to pumping centers are the main factors contributing to the smaller water-level declines in the Memphis area. The two areas of greatest decline from predevelopment water levels are in the western area: one in east-central Arkansas extends across the Mississippi River into Mississippi, and the second is a large area in extreme southern Arkansas and north-central Louisiana (pl. 8). These areas have the second largest pumpage from the middle Claiborne aquifer and the largest drawdowns. Water levels in the middle Claiborne aquifer in the east-central Arkansas area have declined more than 125 feet throughout about a 1,200-$mi^2$ area. In north-central Louisiana and in a small area in extreme southern Arkansas declines were just as large but less areally extensive. Local drawdowns of more than 150 feet occurred in large pumping centers at Pine Bluff, Stuttgart, and El Dorado, Ark., and at Monroe and Jonesboro, La. The smallest water-level declines in the middle Claiborne aquifer were in the eastern area, where only west-central Mississippi has significant declines. Here declines of 75 feet from predevelopment levels occurred throughout a 2,300-$mi^2$ area, and declines as great as 125 feet occurred in localized areas around Jackson.

The simulated 1987 potentiometric surface of the lower Claiborne–upper Wilcox aquifer shows two areas of significant drawdown in the eastern area (pl. 8). One of the areas is in west-central Mississippi where water levels are 100 feet lower than predevelopment levels, and the other is a small area in east-central Mississippi where levels are as much as 100 feet lower.

TABLE 2.—*Root-mean-square error between 1980 measured water levels and simulated 1987 water levels.*

| Aquifer | Root-mean-square error (in feet) |
|---|---|
| Upper Claiborne | 27 |
| Middle Claiborne | 38 |
| Lower Claiborne–Upper Wilcox | 20 |
| Middle Wilcox | 46 |
| Lower Wilcox | 34 |

The middle Wilcox aquifer, which has few large-capacity wells, is the least-developed aquifer in the study area. Accordingly, the potentiometric surface of the middle Wilcox aquifer shows no area of large water-level declines caused by pumpage from the aquifer itself. The large area of water-level decline centered around Memphis, Tenn. (pl. 8), closely matches, however, the decline in the potentiometric surface of the lower Wilcox in the Memphis area (pl. 8). The middle Wilcox, which is not a productive aquifer in the Memphis area, had water-level declines of 100 feet below predevelopment levels that resulted from pumping from the underlying lower Wilcox aquifer.

The shape of the 1987 simulated potentiometric surface of the lower Wilcox aquifer is very similar to the simulated middle Wilcox aquifer potentiometric surface (pl. 7). Because the lower Wilcox aquifer has much greater pumpage, the shape of the middle Wilcox aquifer potentiometric surface is affected by the stresses in the lower Wilcox aquifer. The similarities in configuration of the potentiometric surfaces of these two aquifers suggests that good hydraulic connection exists between the middle and lower Wilcox aquifers throughout most of the study area.

The potentiometric surface of the lower Wilcox aquifer declined the most from predevelopment to simulated 1987 conditions in the Memphis, Tenn., area (pl. 8). The lower Wilcox aquifer, the second most heavily pumped aquifer in the study area, is widely used in the Memphis area and has water-level declines of more than 125 feet below predevelopment levels. The large, oval-shaped area of drawdown, oriented north-south, extends from the Missouri border to northern Mississippi. The only other significant drawdown in the lower Wilcox aquifer is in a small area in east-central Mississippi where simulated 1987 water levels are more than 75 feet below predevelopment levels.

## RECHARGE AND DISCHARGE IN AQUIFER OUTCROP AND SUBCROP AREAS

Recharge to all the aquifers in all three areas has increased from predevelopment rates in places where they crop out (fig. 18). The increase is a direct result of the gradual development of the ground-water resources in the study area. Pumping has induced more recharge to the aquifers and probably decreased the amount of local discharge to springs, seeps, and streams in outcrop areas.

Net discharge to the Mississippi River Valley alluvial aquifer from the subcropping aquifers has decreased from predevelopment amounts in all three areas (fig. 19). As shown in figure 7*B*, the regional discharge to the Mississippi River Valley alluvial aquifer has been substantially reduced since development of the five aquifers. Pumping has lowered potentiometric surfaces and captured much of the natural discharge to the alluvial aquifer. The lowering of the potentiometric surfaces in the subcropping aquifers resulted in smaller head differences or a reversal of vertical gradients between the subcropping aquifer and the alluvial aquifer. Consequently, net discharge from subcropping aquifers to the alluvial aquifer decreased. In areas where flow directions have been reversed, water is being recharged to the subcropping aquifers from the alluvial aquifer.

As shown in figure 18, the northern area had the greatest predevelopment recharge in outcrop areas and also had the greatest increase in recharge in outcrop areas. Of the five aquifers, the middle Claiborne aquifer in the northern area had the greatest recharge in outcrop areas and the largest increase in recharge since predevelopment. The large pumpage in the Memphis, Tenn., area increased recharge to the middle Claiborne aquifer in the northern area from a predevelopment rate of about 24 $Mft^3/d$ (180 Mgal/d) to more than 40 $Mft^3/d$ (299 Mgal/d) during 1987. The outcrop area east and southeast of Memphis had the greatest amount of recharge with more than 1.4 in./yr entering the middle Claiborne aquifer (fig. 7). Correspondingly, discharge to the Mississippi River Valley alluvial aquifer from the subcropping upper Claiborne aquifer has been reduced in the northern area from about 10.5 $Mft^3/d$ (78.5 Mgal/d) prior to development to 1.5 $Mft^3/d$ (11.2 Mgal/d) during 1987 (fig. 19).

The eastern and western areas exhibit similar characteristics of increased simulated recharge in aquifer outcrop areas with increased aquifer development. In the western area, recharge to the middle Claiborne aquifer in outcrop areas increased from predevelopment rates of about 1.5 $Mft^3/d$ (11.2 Mgal/d) to more than 13 $Mft^3/d$ (97.2 Mgal/d) during 1987 (fig. 18). In the eastern area, recharge increased from predevelopment amounts of about 1.5 $Mft^3/d$ (11.2 Mgal/d) to about 4.1 $Mft^3/d$ (30.7 Mgal/d) during 1987 (fig. 18). Recharge to the outcrop areas for all aquifers in the eastern area also was more evenly distributed among the aquifers. This is because of less pumpage and because the pumpage was more evenly distributed among the aquifers. Some small upland outcrop areas in central Mississippi, south-central Arkansas, and northwestern Louisiana had more than 0.5 in./yr recharge during 1987, but most areas had less than 0.4 in./yr (fig. 7).

The northern area had the greatest simulated discharge to the Mississippi River Valley alluvial aquifer before development; the upper Claiborne and middle Claiborne aquifers each discharged more than 10 $Mft^3/d$ (74.8 Mgal/d) to the alluvial aquifer (fig. 19). During 1987, the northern area was the only area with a net discharge to the alluvial aquifer. Before development, the upper Claiborne aquifer, the most extensively subcropping aquifer in the western area, discharged about 7.7 $Mft^3/d$ (57.6 Mgal/d) to the Mississippi River Valley alluvial aquifer. Most of the discharge was in northeastern Louisiana and southeastern Arkansas. After development began, the upper Claiborne aquifer subcrop in the western area changed from a net discharge area to a net recharge area. During 1987, net recharge to the aquifer was about 0.7 $Mft^3/d$ (5.24 Mgal/d), even though local areas in northeastern Louisiana and southeastern Arkansas continued to discharge as much as 0.2 in./yr to the Mississippi River Valley alluvial aquifer. Subcrops of the upper and middle Claiborne aquifers in the eastern area exhibit similar characteristics but have less net discharge and recharge (fig. 19). Before development the upper Claiborne and middle Claiborne aquifers discharged about 2.8 and 2.1 $Mft^3/d$ (20.9 and 15.7 Mgal/d), respectively, to the alluvial aquifer in the eastern area, and during 1987 these aquifers received about 0.5 and 0.8 $Mft^3/d$ (3.74 and 5.98 Mgal/d), respectively, from the alluvial aquifer.

## LATERAL AND INTERAQUIFER FLOW

Predevelopment flow characteristics in individual aquifers and between vertically adjacent aquifers differ from simulated 1987 flow characteristics. Large withdrawals, mainly from the middle Claiborne aquifer, have produced increased vertical flow from sources above and below the pumped aquifer, as well as changes in hydraulic gradients and horizontal flow patterns. Before development, regional vertical flow in the confined parts of the aquifers was upward from the deepest aquifers into successively shallower aquifers and finally to the regional discharge area, the Mississippi River Valley alluvial aquifer. Before development, the northern area had the most upward flow between the middle and upper Claiborne aquifers (fig. 20). As development progressed, flow between the upper and middle Claiborne aquifers changed to a net downward movement of water from the upper Claiborne aquifer into the middle Claiborne aquifer (fig. 20). The net downward movement occurred in all areas; the western and northern areas had the greatest downward flows with about 9.8 and 9.2 $Mft^3/d$ (73.3 and 68.8 Mgal/d), respectively, during 1987 (figs. 10, 8). In the western area, about 1.5 $Mft^3/d$ (11.2 Mgal/d) moved upward

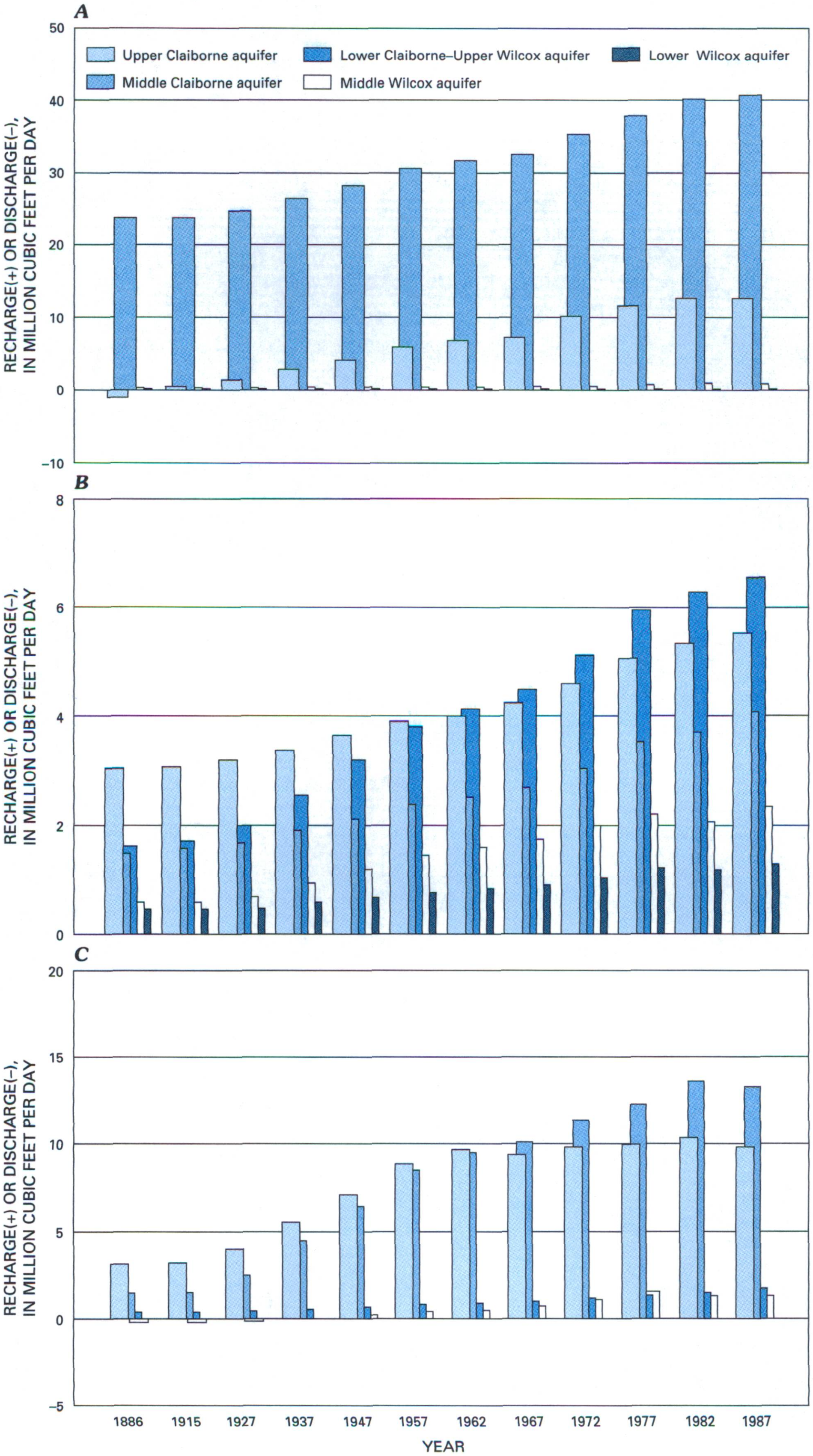



FIGURE 18.—Net recharge and discharge in aquifer outcrops in the (*A*) northern, (*B*) eastern, and (*C*) western areas.

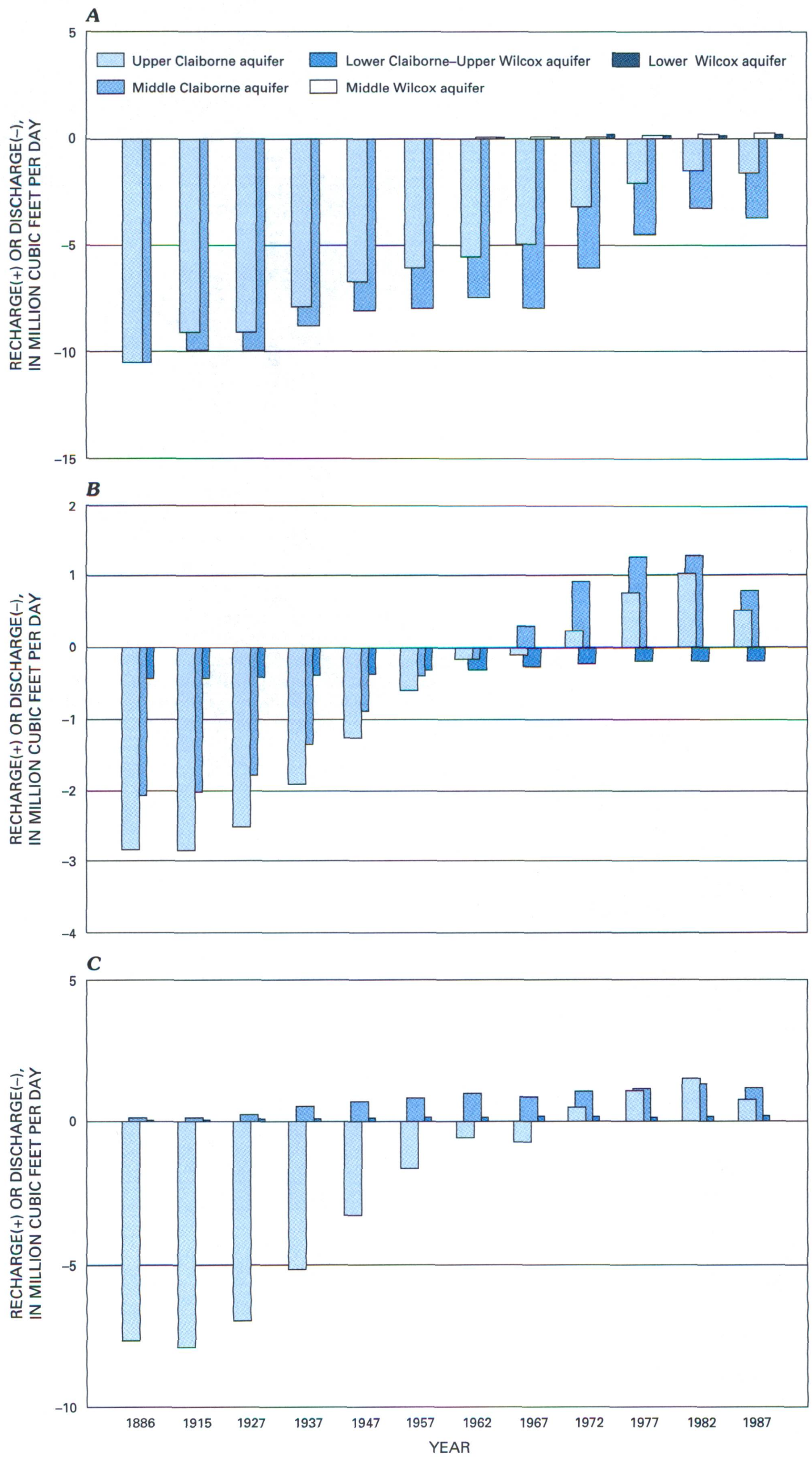



FIGURE 19.—Net recharge and discharge in aquifer subcrops of the Mississippi River Valley alluvial aquifer in (*A*) northern, (*B*) eastern, and (*C*) western areas.

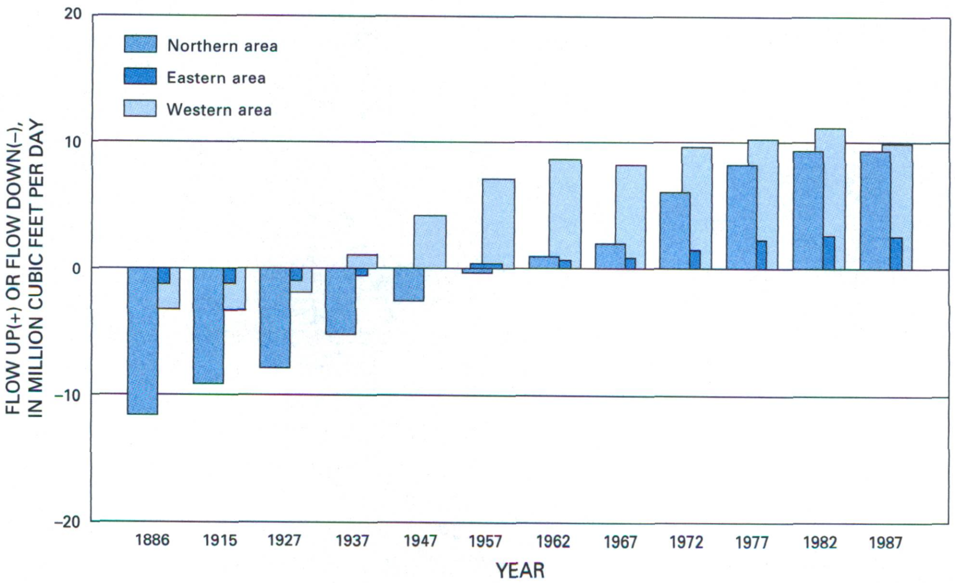



FIGURE 20.—Vertical flow between the upper Claiborne and middle Claiborne aquifers.

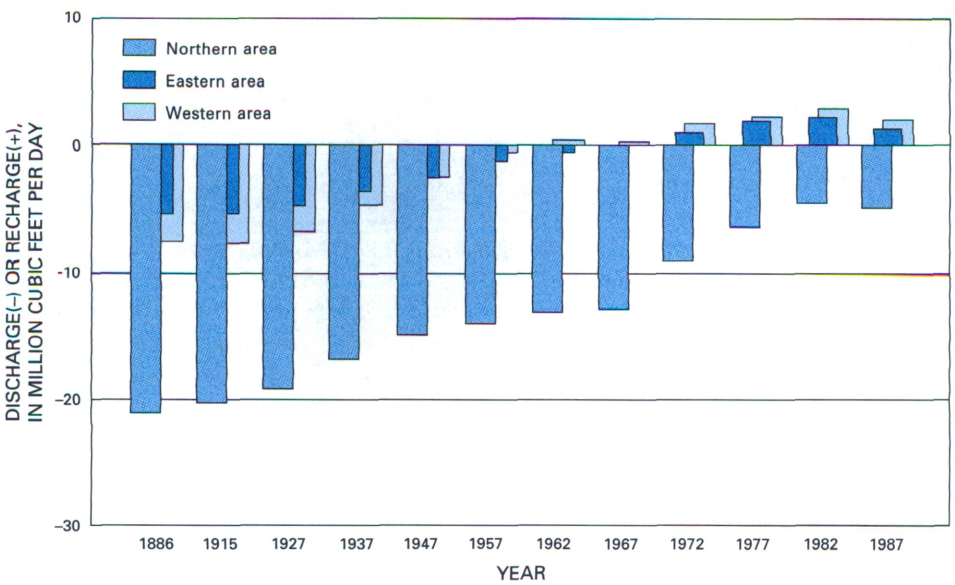



FIGURE 21.—Net discharge from the Mississippi embayment aquifer system to the Mississippi River Valley alluvial aquifer in the northern, eastern, and western areas.

from deeper aquifers through the lower Claiborne confining unit into the middle Claiborne aquifer during 1987. The northern area had a net vertical flow of about 5.7 $Mft^3/d$ (42.6 Mgal/d) moving downward during 1987 from the middle Claiborne aquifer into the middle Wilcox and about 6.5 $Mft^3/d$ (48.6 Mgal/d) from the middle Wilcox into the lower Wilcox aquifer. In the heavily pumped Memphis, Tenn., area, however, net vertical flow was upward from the lower and middle Wilcox aquifers into the middle Claiborne aquifer. Pumpage during 1987 was less in the eastern area, and less downward flow was induced between aquifers (fig. 9). Downward flow from the upper Claiborne aquifer into the middle Claiborne aquifer in the eastern area during 1987 was about 2.5 $Mft^3/d$ (18.7 Mgal/d). Flow into the middle Claiborne aquifer from underlying aquifers was about 0.6 $Mft^3/d$ (4.49 Mgal/d).

The simulated flow from the five aquifers to the Mississippi River Valley alluvial aquifer has decreased since development began (fig. 21). The northern area, which had a discharge of about 21.0 $Mft^3/d$ (157 Mgal/d) to the alluvial aquifer before development, had the greatest decrease in discharge and was the only area with a net discharge to the alluvial aquifer in 1987. The amount of this discharge was about 5.0 $Mft^3/d$ (37.4 Mgal/d). Even though the aquifers in the northern area continued to have a net discharge to the alluvial aquifer during 1987, the alluvial aquifer immediately west of the Memphis, Tenn., area provided more than 0.5 in./yr recharge to the subcropping upper Claiborne aquifer. This condition was caused by the lowering of the potentiometric surface in the upper Claiborne aquifer as a result of heavy pumping from the middle Claiborne aquifer in the Memphis area. Because the eastern and western areas had significantly less flow to the alluvial aquifer before development (about 5.4 and 7.6 $Mft^3/d$, 40.4 and 56.8 Mgal/d, respectively) than did the northern area, aquifer development had a more pronounced effect on the vertical flow regime in the subcropping aquifers. During 1987, the direction of net vertical flow between the subcropping aquifers and the alluvial aquifer in the eastern and western areas was reversed from the direction of flow before development. During 1987, flow from the alluvial aquifer to the subcropping aquifers was about 1.2 $Mft^3/d$ (8.98 Mgal/d) in the eastern area and about 2.0 $Mft^3/d$ (15.0 Mgal/d) in the western area.

### FLOW TO ADJACENT AREAS AND AQUIFER SYSTEMS

Increased pumpage, mainly from the middle Claiborne aquifer, has changed the regional lateral flow pattern in the aquifers and the amount of horizontal flow between areas (fig. 22). The most radical change in flow direction from predevelopment conditions was between the eastern and northern areas. Simulation indicates that heavy pumpage from the middle Claiborne and lower Wilcox aquifers in the Memphis, Tenn., area has caused reversal of the regional lateral flow direction between the eastern and northern areas. Before development net flow was southward, whereas during 1987 net flow was northward. All aquifers except the upper Claiborne had a net northward lateral flow between the eastern and northern areas during 1987. The middle Claiborne and lower Claiborne–upper Wilcox aquifers, which merge in the northern area, had the greatest northward flow, about 0.3 $Mft^3/d$ (2.25 Mgal/d) each during 1987. Flow northward in the middle and lower Wilcox aquifers was less than about 0.1 $Mft^3/d$ (0.75 Mgal/d) during the same time period. Total net northward flow from the eastern area to the northern area during 1987 was about 0.6 $Mft^3/d$ (4.49 Mgal/d).

In all the aquifers the lateral flow directions between the western and northern areas were the same in 1987 as before development. Net movement was from the northern area into the western area. The magnitude of flow was similar in all aquifers except the middle Claiborne. Simulation suggests that the heavy pumpage from the middle Claiborne aquifer in the Pine Bluff and Stuttgart, Ark., areas increased the southward flow in that aquifer from about 0.4 $Mft^3/d$ (2.99 Mgal/d) before development to about 2.2 $Mft^3/d$ (16.6 Mgal/d) during 1987. Total net flow from the northern area into the western area during 1987 was about 2.3 $Mft^3/d$ (17.2 Mgal/d).

Lateral flow between the eastern and western areas during 1987 was westward in all aquifers. Pumpage from the upper Claiborne aquifer in the eastern area reduced the westward flow in the aquifer to about 0.7 $Mft^3/d$ (5.24 Mgal/d) during 1987, a reduction of 50 percent from predevelopment rates. The large pumpage (about 28.2 $Mft^3/d$, 211 Mgal/d) from the middle Claiborne aquifer in the western area caused the net lateral flow in the middle Claiborne aquifer to change from a net eastward flow of about 0.3 $Mft^3/d$ (2.24 Mgal/d) before development to a westward flow of about 0.9 $Mft^3/d$ (6.73 Mgal/d) during 1987. Westward flow in the lower Claiborne–upper Wilcox aquifer was reduced from about 0.5 $Mft^3/d$ (3.74 Mgal/d) before development to about 0.1 $Mft^3/d$ (0.75 Mgal/d) during 1987. In 1987 lateral flows in the middle and lower Wilcox aquifers were westward, and net flows were similar to those before development. Total net westward flow during 1987 from the eastern area to the western area was about 2.4 $Mft^3/d$ (18.0 Mgal/d), about 0.2 $Mft^3/d$ (1.50 Mgal/d) less than before development.

Pumpage not only induces more recharge to the aquifer system but also captures water that would normally be discharged from the aquifers to the Mississippi River Valley alluvial aquifer and the coastal lowlands aquifer system. Pumpage has reduced the net discharge to the alluvial aquifer in the study area to about 1.8 $Mft^3/d$ (13.5 Mgal/d) and has completely eliminated the small upward net predevelopment discharge (about 0.3 $Mft^3/d$, 2.24 Mgal/d) to the coastal lowlands aquifer system. The water released from confined storage varied from slightly more than 1 percent of the volume pumped in 1915 to a high of about 6 percent of the volume pumped in 1970. Simulation indicates that under 1987 conditions, 2.3 $Mft^3/d$ (17.2 Mgal/d) was released from confined storage from the five aquifers. The flow budget for each aquifer in the study under 1987 conditions is shown in figure 23. Net flow from the McNairy-Nacatoch aquifer into the lower Wilcox aquifer has been reduced from about 5 $Mft^3/d$ (37.4 Mgal/d) before development to about 4 $Mft^3/d$ (29.9 Mgal/d) under 1987 conditions (Brahana and Mesko, 1988).

## POTENTIAL FOR GROUND-WATER RESOURCE DEVELOPMENT

A brief evaluation of the potential for future ground-water development was made simulating two approaches of applying additional pumping stress to the aquifer system. The first approach assumes a 20 percent regional increase over 1985 pumping rates in all aquifers for the entire study area for an additional 13-year period (1987–2000). The second approach consists of two scenarios, each applying an additional, hypothetical local increase in pumpage of 5.35 $Mft^3/d$ (40.0 Mgal/d), uniformly distributed throughout a 100-$mi^2$ area, from the middle Claiborne aquifer. In one scenario, the pumpage is centered at Marianna, Ark., in the western area (south of the lower Claiborne confining unit facies change); in the other, the center of pumpage is at Wynne, Ark., in the northern area (north of the lower Claiborne confining unit facies change). In the second approach, the areal pumpage

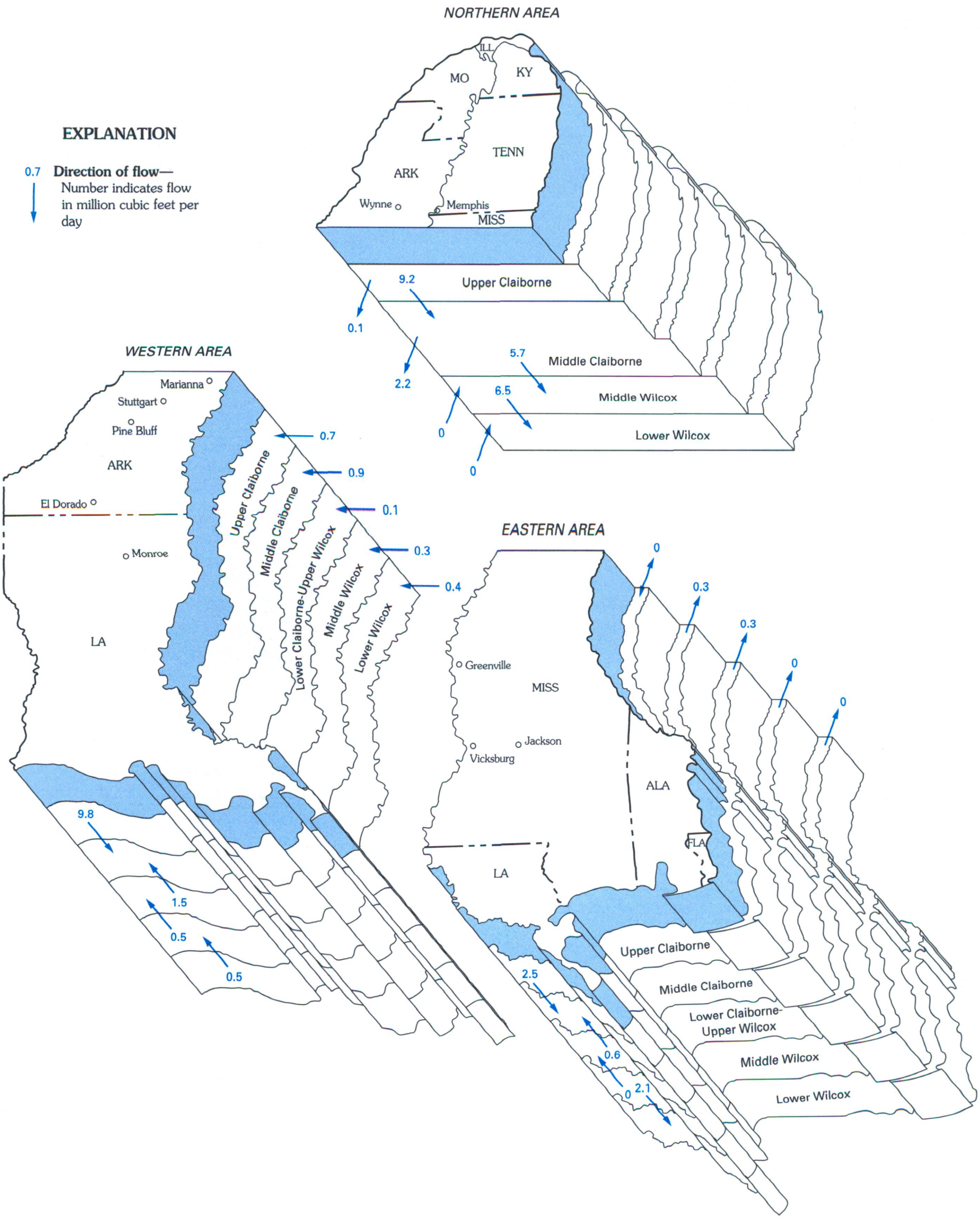



FIGURE 22.—Simulated horizontal flow between areas and vertical flow between aquifers, 1987.

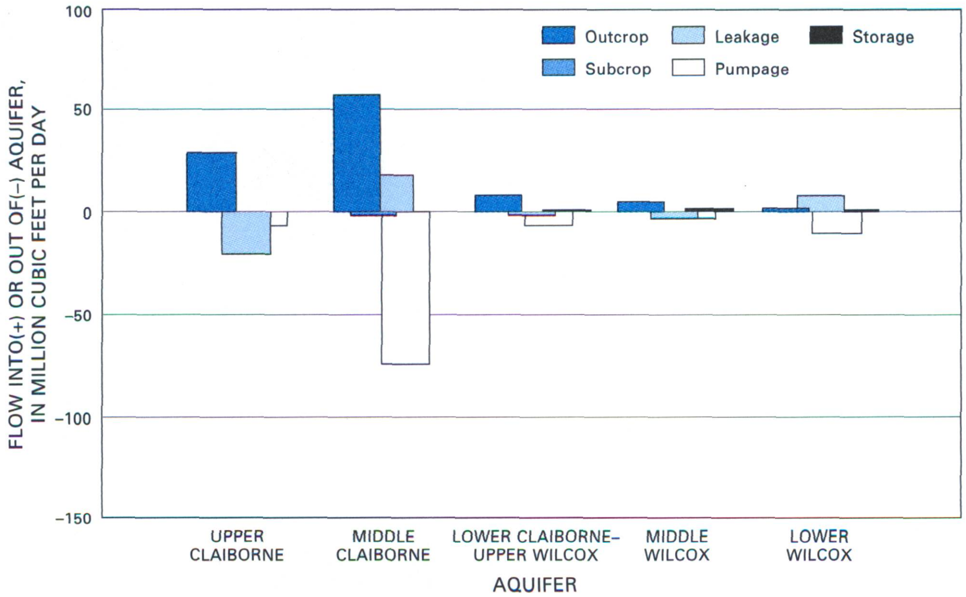



FIGURE 23.—Simulated 1987 flow budget for aquifers in study area.

from all the other aquifers is at the 1985 rate during the projected 13-year period.

## REGIONAL PUMPAGE INCREASE

Although total pumpage from the aquifer system declined in the study area from about 106.9 $Mft^3/d$ (799.6 Mgal/d) during 1980 to about 102.21 $Mft^3/d$ (764.5 Mgal/d) during 1985, future development is expected to place added demands on the aquifer system. Based on an assumed uniform 20 percent increase in pumpage over 1985 rates, the average total withdrawal from all the aquifers during the projected 13-year period (1987–2000) is about 122.6 $Mft^3/d$ (917.0 Mgal/d).

Using this same 20 percent increase in withdrawal, simulation results indicate that after 13 years water levels in the upper Claiborne aquifer will be more than 10 feet below 1987 levels in the Jackson and Greenville, Miss., areas and the Memphis, Tenn., area (pl. 9). In the remainder of the study area, simulated water levels in the upper Claiborne aquifer will be about 5 feet below 1987 levels.

Simulated results indicate that the heavily pumped middle Claiborne aquifer would experience the most widespread water-level declines if a uniform 20 percent pumping rate increase is applied for a 13-year period (pl. 9). The El Dorado, Ark., and Monroe, La., areas are estimated to have water-level declines of about 30 feet below 1987 levels. Water levels in the center of the heavily pumped Memphis, Tenn., area are estimated to decline about 25 feet below 1987 levels. Water levels in the Jackson, Miss., area and the Pine Bluff–Stuttgart, Ark., area are estimated to decline about 20 feet below 1987 levels. Away from these pumping centers, the water-level decline in the middle Claiborne aquifer generally is estimated to be 5–10 feet below 1987 levels.

If the regional 20 percent increase in pumpage is assumed, simulation results indicate that the area of the greatest projected water-level declines from 1987 levels for the lower Claiborne–upper Wilcox aquifer would be in Mississippi (pl. 9). The greatest simulated declines would be the Forest and Greenwood, Miss., areas, with water levels about 30 and 20 feet, respectively, below 1987 levels. Most of the remaining area would have estimated declines of 10–15 feet. Estimated water-level declines in the lower Claiborne–upper Wilcox aquifer throughout a large area in Louisiana and Arkansas would be 5–10 feet below 1987 levels.

The middle Wilcox aquifer is not a highly productive aquifer in the study area. This aquifer has the least pumpage and, consequently, is projected to have the least increase in pumpage. If pumpage is increased by a uniform 20 percent, the estimated water-level declines from 1987 levels would be greatest in the eastern area, with most declines 10–15 feet (pl. 9). In the Memphis, Tenn., area, the middle Wilcox is not considered a productive aquifer, but water levels in the middle Wilcox aquifer would be about 20 feet below 1987 levels as a result of increased pumpage from the middle Claiborne and lower Wilcox aquifers. The remainder of the study area is estimated to have declines about 5–10 feet below 1987 levels in the middle Wilcox aquifer.

Based on a regional uniform 20 percent increase in pumpage, simulation results indicate that the lower Wilcox aquifer water levels would decline about 20 feet in the Memphis, Tenn., area and about 20–25 feet in the Meridian, Miss., area after 13 years (pl. 9). Average regional declines in the remainder of the eastern and northern areas are estimated to be about 10 feet below 1987 levels. Average water-level declines in the lower Wilcox aquifer in the western area are estimated to be less than 10 feet below 1987 levels.

Simulated horizontal flow between areas and vertical flow between aquifers after the 13-year period of increased

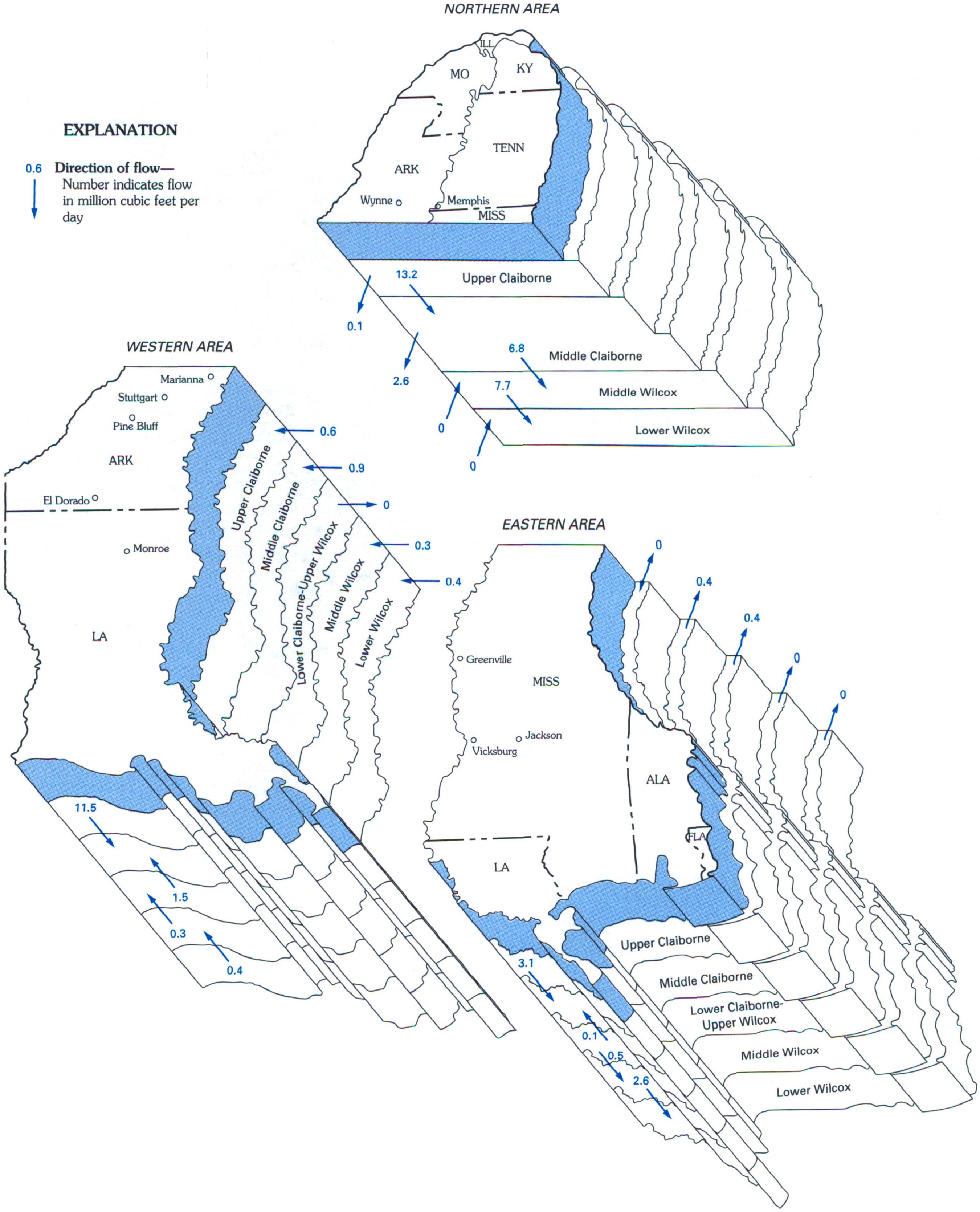



FIGURE 24.—Simulated horizontal flow between areas and vertical flow between aquifers, year 2000, assuming a uniform 20 percent increase in pumpage over 1985 rates.

withdrawal would have patterns and flow rates similar to 1987 (fig. 24). The magnitude of flow components is greater due to the projected 20 percent increase in pumpage. The increased pumpage is expected to induce more recharge in aquifer outcrop and subcrop areas. Also, more water is released from aquifer storage. Simulation results indicate that 4.5 Mft$^3$/d (33.7 Mgal/d) is released from confined aquifer storage from the five aquifers. The flow budget for each aquifer, assuming a regional 20 percent increase in withdrawals for a 13-year period, is shown in figure 25.

### LOCAL PUMPAGE INCREASE

The middle Claiborne aquifer will probably continue to provide large point sources of water in the future. Two areas, one at Marianna, Ark., south of the lower Claiborne confining unit facies change (about the 35th parallel) in the western area and the other at Wynne, Ark., north of the facies change in the northern area, were selected as sites for hypothetical large increases in local pumpage (5.35 Mft$^3$/d, 40.0 Mgal/d) to assess the effects of pumpage increases from the middle Claiborne aquifer. In both areas the middle Claiborne aquifer has large transmissivity values (greater than 10,000 ft$^2$/d). In the Wynne area the lower Claiborne confining unit consists mostly of sand, thus the aquifer is thicker.

With pumpage held constant at 1985 rates in all aquifers except for an additional hypothetical pumpage of 5.35 Mft$^3$/d (40.0 Mgal/d) from the middle Claiborne aquifer applied uniformly throughout a 100-mi$^2$ area around Marianna, Ark., simulated water levels in the middle Claiborne aquifer would be about 90 feet below 1987 levels at Marianna after 13 years (fig. 26*A*). The increased pumpage at Marianna would produce water-level declines of about 10 feet or more below 1987 levels as far as 35 miles to the south and west, 25 miles to the north, and about 28 miles to the east. In the Memphis, Tenn., and Stuttgart, Ark., areas, water levels would be 5–10 feet below 1987 levels after 13 years. The hypothetical pumpage at Marianna from the middle Claiborne aquifer also is expected to affect water levels in aquifers above and below the pumped aquifer. Water levels in the overlying upper Claiborne aquifer and the underlying lower Claiborne–upper Wilcox aquifer are estimated to be between 10–20 feet lower than 1987 levels by the year 2000. The increased pumpage is expected to also result in an increase in lateral flow from the northern area into the western area in the middle Claiborne aquifer, from about 2.2 Mft$^3$/d (16.5 Mgal/d) in 1987 to about 4.1 Mft$^3$/d (30.7 Mgal/d) after 13 years. Lateral flow from the eastern area into the western area is expected to increase from about 0.9 Mft$^3$/d (6.73 Mgal/d) to 1.5 Mft$^3$/d (11.2 Mgal/d) after 13 years with additional pumpage.

If, instead, the hypothetical 5.35 Mft$^3$/d (40.0 Mgal/d) increase in pumpage is applied uniformly to a 100-mi$^2$ area centered at Wynne, Ark., in the northern area (north of the transition zone), simulation results indicate there would be substantially less drawdown in water levels in the middle Claiborne aquifer after 13 years (fig. 26*B*). The resulting water levels in the middle Claiborne aquifer after 13 years (year 2000) would be about 30 feet below 1987 levels at Wynne, as compared to the estimated maximum decline of 90 feet if the pumpage were centered at Marianna (fig. 26*A*). Drawdowns of as much as 10 feet below 1987 levels would extend 15 miles from Wynne and would be about 5 feet below 1987 levels in the Memphis, Tenn., area. The declines would probably extend only a short distance into the western area, and little or no effect is likely to be evident in the heavily pumped Stuttgart, Ark., area. Water levels in the upper Claiborne aquifer in the vicinity of Wynne would be about 10 feet below 1987 levels as a result of the increased pumpage from the middle Claiborne aquifer after 13 years of additional pumpage. Lateral flow southward in the middle Claiborne aquifer from the northern area into the western area would be reduced from about 2.2 Mft$^3$/d (16.5 Mgal/d) in 1987 to about 1.8 Mft$^3$/d (13.5 Mgal/d) in the year 2000 after 13 years with the additional pumpage at Wynne.

On a regional scale, the five aquifers in the Mississippi embayment aquifer system have potential for increased ground-water development. Simulation results indicate that a regional 20 percent increase in pumpage over 1985 pumpage rates from the aquifer system will not produce major regional water-level declines by the year 2000. Simulating large pumpage increases in localized areas where large drawdowns already exist, such as in the middle Claiborne aquifer in Monroe, La., and Pine Bluff–Stuttgart, Ark., may produce problems such as aquifer dewatering, saline water moving into parts of the aquifer previously containing freshwater, and other problems associated with aquifer overdevelopment. The middle Claiborne aquifer has potential for increased development of large ground-water supplies away from areas already being heavily pumped in the northern area (north of the transition zone in the lower Claiborne confining unit). South of the transition zone, potential for development of large ground-water supplies in the middle Claiborne aquifer also exists, but drawdowns would probably be two to three times greater than those north of the transition zone for similar withdrawal rates.

## SUMMARY

The Mississippi embayment aquifer system is composed of six major regional aquifers extending throughout 160,000 mi$^2$ in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. This report presents the results of the flow analysis of five aquifers in sediments of the Wilcox and Claiborne Groups of Tertiary age that make up the Mississippi embayment aquifer system. In descending order these aquifers are (1)

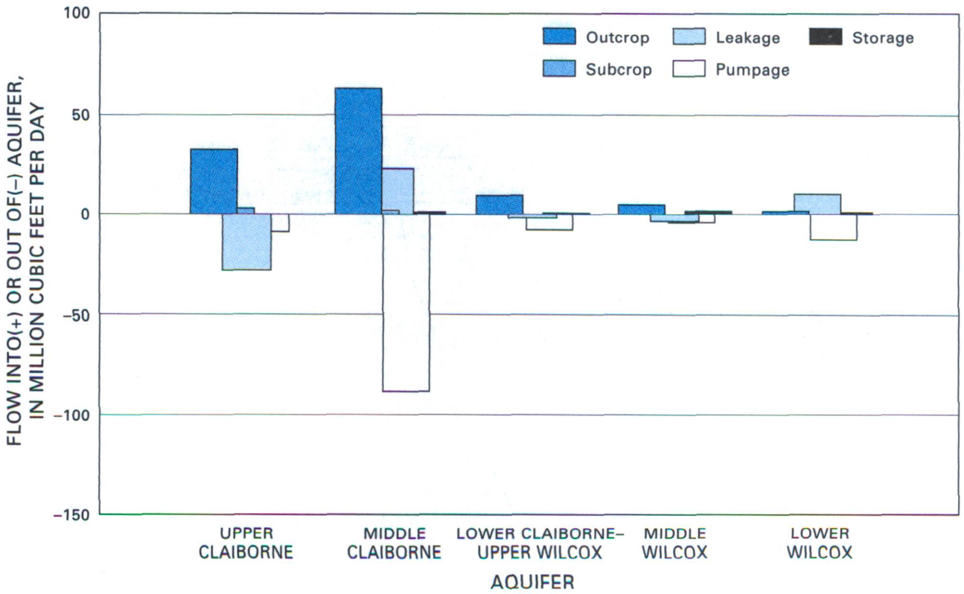



FIGURE 25.—Simulated year 2000 flow budget for aquifers in study area, assuming a uniform 20 percent increase in pumpage over 1985 rates.

the upper Claiborne, (2) the middle Claiborne, (3) the lower Claiborne–upper Wilcox, (4) the middle Wilcox, and (5) the lower Wilcox. The flow analysis of the sixth aquifer in the aquifer system, the Mississippi River Valley alluvial aquifer in sediments of Holocene and Pleistocene age, is described in chapter D of this Professional Paper.

The formation of the Mississippi embayment was the result of subsidence accompanied by cyclic transgression and regression of the sea. With the lowering of sea level that accompanied Pleistocene glaciation, the Mississippi River entrenched into the Tertiary and Cretaceous sediments that filled the embayment. As sea level began to rise, stream gradients decreased and the entrenched valley was filled with sediment forming the Mississippi Alluvial Plain. The troughlike shape of the embayment resulted in Tertiary-age sediments cropping out in a series of arcuate bands approximately parallel with the periphery of the Mississippi embayment. Outcrops in the upland areas on the eastern edge of the embayment are at altitudes significantly higher than outcrops on the western edge of the embayment. Outcrops of Tertiary sediments are absent in the northwestern part of the embayment where they are covered by the Mississippi River Valley alluvial aquifer that extends to the northwestern edge of the study area. In this area, aquifers and confining units subcrop the alluvial plain.

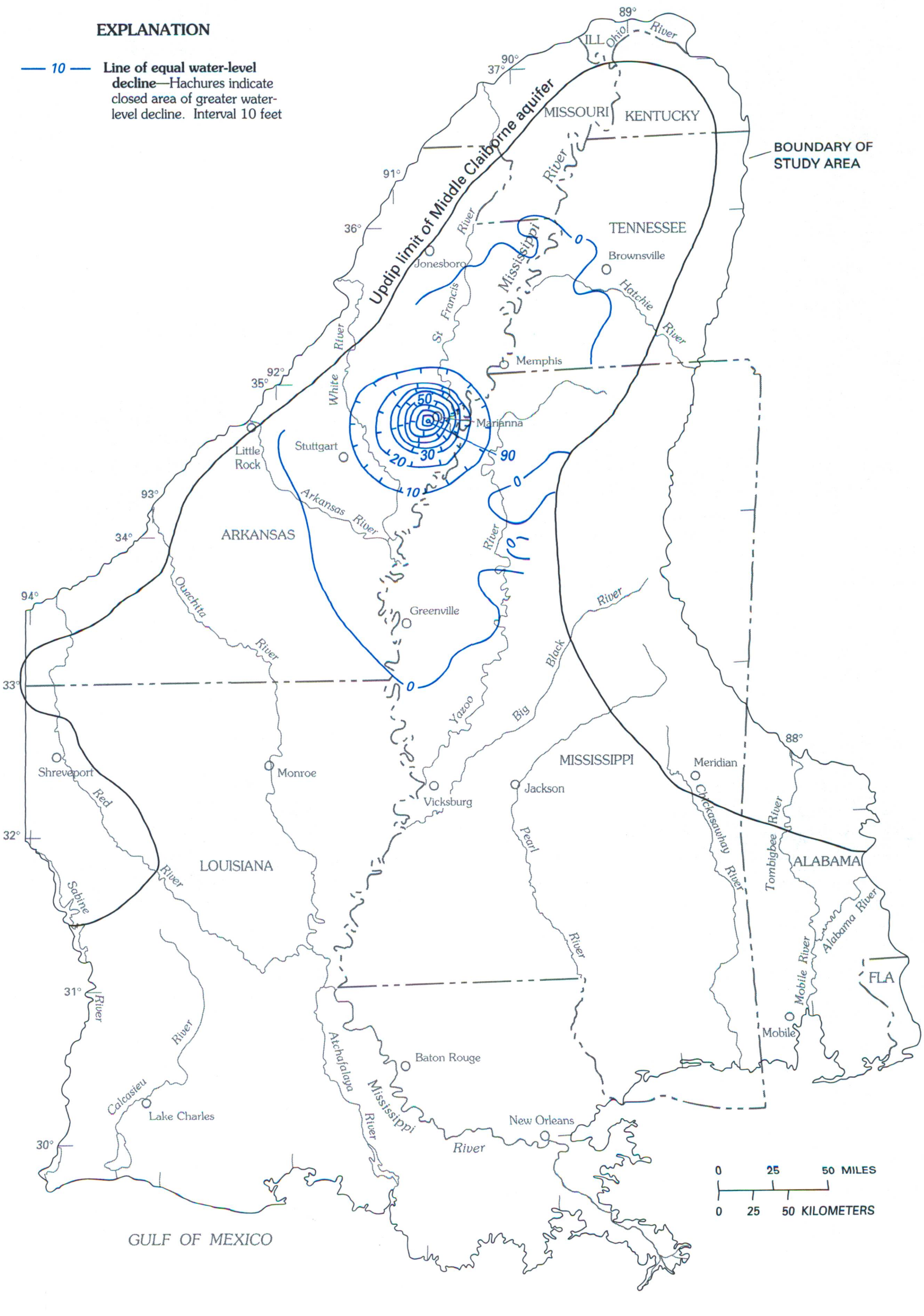
The upper Claiborne aquifer is the youngest and uppermost of the five aquifers studied and is composed predominantly of the Cockfield Formation. The upper Claiborne aquifer averages about 250 feet in thickness in the subsurface and is the most extensive subcropping aquifer in that it directly underlies about 43 percent of the alluvial plain from northeastern Louisiana to the northern edge of the embayment.

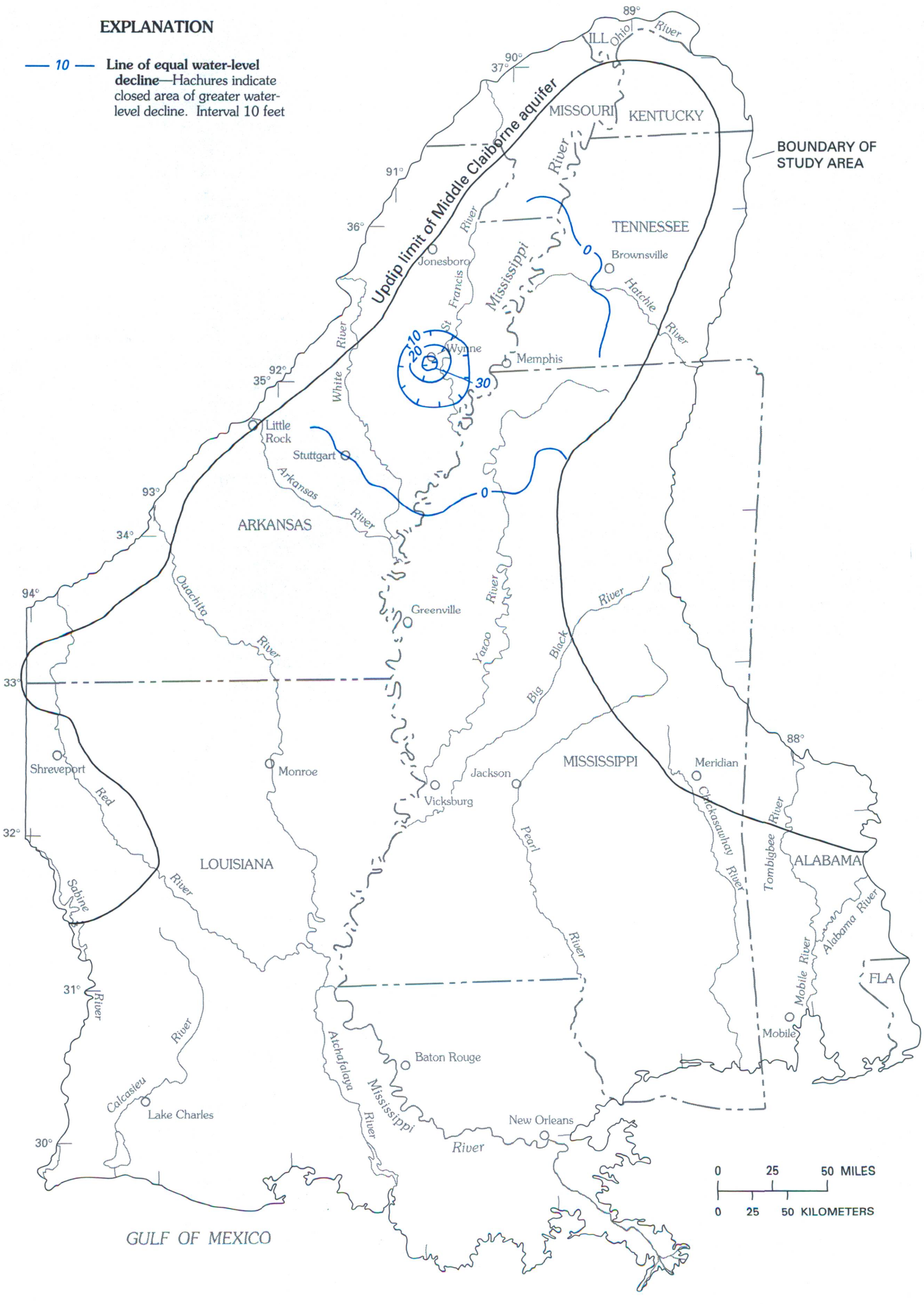
The middle Claiborne aquifer, composed mostly of the Sparta Sand in the southern two-thirds of the study area and the Memphis Sand in Tennessee, east-central Arkansas, southeastern Missouri, southwestern Kentucky, and northwestern Mississippi, is the most extensively developed of the five aquifers. In the northern area, it consists of massive sand beds (more than 700 feet thick) as a result of clay of the underlying lower Claiborne confining unit changing to sand and becoming part of the middle Claiborne aquifer. The middle Claiborne aquifer crops out on both sides of the embayment, and its outcrop band is widest in the northeastern part of the embayment. The middle Claiborne aquifer is the second most extensive subcropping aquifer and directly underlies about 15 percent of the Mississippi River Valley alluvial aquifer.

The lower Claiborne–upper Wilcox aquifer is equivalent to the Winona-Tallahatta and Meridian–upper Wilcox aquifers in Mississippi, the Carrizo-Wilcox sand in Louisiana, and the Carrizo Sand in Arkansas. This aquifer is considered the lower part of the middle Claiborne aquifer in the northern area of the embayment. The lower Claiborne–upper Wilcox aquifer crops out on both sides of the embayment and is 100–500 feet thick in the subsurface.

The middle Wilcox is the least developed aquifer in the Mississippi embayment aquifer system. It is composed predominantly of interbedded sand, silt, and clay of the Wilcox Group between the lower Claiborne–upper Wilcox aquifer and the lower Wilcox aquifer. The middle Wilcox aquifer crops out on both sides of the embayment and is the surficial unit over the Sabine uplift. Total sand thickness of the aquifer ranges from less than 200 feet in the northern and southern parts of the study area to more than 1,500 feet in central Louisiana.

FIGURE 26 (overleaf).—Water level declines in the middle Claiborne aquifer from 1987 to year 2000, with pumpage increase of 5.35 million cubic feet per day at (left view) Marianna, and (right view) Wynne, Ark.


EXPLANATION
10 Line of equal water-level decline—Hachures indicate closed area of greater water-level decline. Interval 10 feet
BOUNDARY OF STUDY AREA
Updip limit of Middle Claiborne aquifer
ILL
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
ALABAMA
LOUISIANA
FLA
Ohio River
Mississippi River
St Francis River
White River
Arkansas River
Hatchie River
Ouachita River
Red River
Sabine River
Yazoo River
Big Black River
Pearl River
Chickasawhay River
Tombigbee River
Alabama River
Mobile River
Calcasieu River
Atchafalaya River
Jonesboro
Brownsville
Memphis
Marianna
Stuttgart
Little Rock
Greenville
Shreveport
Monroe
Vicksburg
Jackson
Meridian
Mobile
Baton Rouge
New Orleans
Lake Charles
GULF OF MEXICO
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
33°
32°
31°
30°
88°
0
10
20
30
50
90
0 25 50 MILES
0 25 50 KILOMETERS


EXPLANATION
— 10 — Line of equal water-level decline—Hachures indicate closed area of greater water-level decline. Interval 10 feet
Updip limit of Middle Claiborne aquifer
BOUNDARY OF STUDY AREA
ILL
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
FLA
GULF OF MEXICO
Ohio River
Mississippi River
St Francis River
White River
Arkansas River
Hatchie River
Ouachita River
Yazoo River
Big Black River
Red River
Sabine River
Pearl River
Chickasawhay River
Tombigbee River
Mobile River
Alabama River
Atchafalaya River
Calcasieu River
Jonesboro
Brownsville
Wynne
Memphis
Little Rock
Stuttgart
Greenville
Shreveport
Monroe
Jackson
Vicksburg
Meridian
Mobile
Baton Rouge
Lake Charles
New Orleans
0
10
20
30
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
33°
32°
31°
30°
88°
0 25 50 MILES
0 25 50 KILOMETERS

The lower Wilcox aquifer is the basal aquifer in the Wilcox Group and is equivalent to the Fort Pillow Sand in Tennessee, Arkansas, and Missouri. The aquifer is an extensively developed source of freshwater, second only to the middle Claiborne aquifer. Aggregate sand thickness is 200–300 feet in most of the area.

Four confining units of regional scope influence the hydrology of the five major aquifers in sediments of Tertiary age in the Mississippi embayment aquifer system. The middle Claiborne confining unit and the lower Claiborne confining unit separate the upper Claiborne, middle Claiborne, and lower Claiborne–upper Wilcox aquifers. The Vicksburg-Jackson confining unit and the Midway confining unit separate the Mississippi embayment aquifer system from overlying and underlying aquifer systems.

The study area was divided into three areas, each having unique topographic or stratigraphic features. The northern area represents all the area north of the facies change in the lower Claiborne confining unit, north of about the 35th parallel. The eastern area is all the area east of the Mississippi River and south of the facies change in the lower Claiborne confining unit, and the western area is all the area west of the Mississippi River and south of the facies change. The northern area is the smallest and narrowest of the three areas. Here aquifer outcrop areas are only on the eastern side of the embayment and are at their highest altitudes in the study area. The Mississippi Alluvial Plain occupies the western half of the northern area. The studied aquifers subcrop the Mississippi River Valley alluvial aquifer, and the upper Claiborne and the middle Claiborne aquifers are the most extensive subcropping units in the northern area. The eastern area is characterized by a large percentage of the total aquifer outcrop, high altitudes in outcrop areas, and only a small part of its area in the Mississippi Alluvial Plain province. The western area has the lowest outcrop altitudes and the largest part of its area in the Mississippi Alluvial Plain; it contains the Sabine uplift, a structurally high area that disrupts the normal embayment outcrop pattern.

The middle Claiborne aquifer has large transmissivity values over a wider areal extent than any other aquifer in the study area. Transmissivity values of 10,000–50,000 $ft^2/d$ are in the middle Claiborne aquifer throughout the northern area, in east-central Arkansas in the western area, and around Clarksdale, Miss., in the eastern area. The middle Wilcox aquifer has the smallest transmissivity values of the five aquifers; transmissivity values are less than 5,000 $ft^2/d$ in most of the study area. Storage coefficient values for the aquifers generally are between $2.5\times10^{-5}$ and $2.5\times10^{-4}$ in the freshwater zones. Vertical hydraulic conductivity values of confining units range from $1\times10^{-5}$ ft/d for the marine clays of the Vicksburg-Jackson confining unit to $1\times10^{-3}$ ft/d for clays in the middle Claiborne confining unit.

Pumping from the aquifers in the Mississippi embayment aquifer system began in 1886. Predevelopment water levels were higher on the eastern flank of the embayment than for corresponding levels on the western flank. Predevelopment head gradients were steepest in outcrop areas and more uniform and flatter downdip in the confined zone. Head gradients sloped generally toward the axis of the embayment in the northern two-thirds of the embayment and sloped southward toward the Gulf of Mexico in the southern one-third. Interruptions of this flow pattern are caused by the Sabine uplift and by regional discharge zones in the Mississippi River Valley alluvial aquifer.

Simulated predevelopment recharge to aquifers was predominantly by direct infiltration of rainfall in aquifer outcrop areas and secondarily by leakage from other aquifer systems. Predevelopment aquifer discharge was to streams, springs, seeps, and by leakage to adjacent aquifers. The middle Claiborne aquifer outcrop area on the eastern side of the northern area of the embayment had the greatest recharge prior to development, receiving more than 1 in./yr in some areas of northern Mississippi and southern Tennessee. Aquifer outcrop areas in the eastern and western areas had more than 0.2 in./yr recharge in central Mississippi, south-central Arkansas, and northwestern Louisiana, but most of the outcrop areas had recharge of less than 0.2 in./yr. Maximum predevelopment discharge, more than 0.6 in./yr, was to the Mississippi River Valley alluvial aquifer west of Memphis, Tenn. Prior to development, the major discharge zones in the eastern and western areas were in south-central Arkansas and extreme northeastern Louisiana, where about 0.2 in./yr discharged upward into the alluvial aquifer.

Simulated predevelopment horizontal and vertical flow was greatest north of the facies change in the lower Claiborne confining unit. Under predevelopment conditions, about 0.5 $Mft^3/d$ (3.74 Mgal/d) moved upward from the lower and middle Wilcox aquifers into shallower aquifers in the northern area. About 11.5 $Mft^3/d$ (86.0 Mgal/d) moved upward from the middle Claiborne aquifer into the upper Claiborne aquifer, and about 10.5 $Mft^3/d$ (78.5 Mgal/d) moved upward from the upper Claiborne aquifer into the Mississippi River Valley alluvial aquifer in the northern area. Total predevelopment flow from the five aquifers to the alluvial aquifer in the northern area was about 21 $Mft^3/d$ (157 Mgal/d). Total predevelopment flow from the five aquifers to the alluvial aquifer was about 5.3 $Mft^3/d$ (39.6 Mgal/d) in the eastern area and about 7.6 $Mft^3/d$ (56.8 Mgal/d) in the western area.

Simulated predevelopment net flows between areas generally followed the regional flow direction of southward and westward flow. Net system predevelopment flow from the northern area southward into the eastern and western areas was about 0.5 and 0.4 $Mft^3/d$ (3.74 and 2.99 Mgal/d), respectively. Net system flow from the eastern area to the western area was about 2.6 $Mft^3/d$ (19.4 Mgal/d). The middle

Claiborne aquifer had the greatest southward flow, about 0.4 Mft$^3$/d (2.99 Mgal/d). The upper Claiborne aquifer had the greatest westward flow, about 1.4 Mft$^3$/d (10.5 Mgal/d). Total net predevelopment discharge to the Mississippi River Valley alluvial aquifer in the study area was about 34 Mft$^3$/d (254 Mgal/d). Total net predevelopment discharge to the coastal lowlands aquifer system was about 0.3 Mft$^3$/d (2.24 Mgal/d). Total net predevelopment flow to the lower Wilcox from the McNairy-Nacatoch aquifer was about 5 Mft$^3$/d (37.5 Mgal/d).

The first large development of ground water from the five regional aquifers began in 1886 with pumpage from the middle Claiborne aquifer in Memphis, Tenn. Pumpage increased in the Memphis area until 1974, when total withdrawal was about 25.4 Mft$^3$/d (190 Mgal/d). Since 1974, rates have stabilized, and pumpage from the middle Claiborne aquifer was about 25.5 Mft$^3$/d (191 Mgal/d) during 1985. Pumping in other parts of the study area began about 1920 with Pine Bluff, Stuttgart, El Dorado, and Magnolia, Ark.; Monroe, La.; and Jackson, Miss., the main pumping centers.

Total pumpage from the five aquifers in the study area during 1985 was about 102.2 Mft$^3$/d (764.5 Mgal/d). The middle Claiborne aquifer was the most heavily pumped aquifer, yielding about 74.3 Mft$^3$/d (556 Mgal/d) during 1985. The middle Wilcox aquifer had the smallest pumpage, yielding about 3.3 Mft$^3$/d (24.7 Mgal/d) during 1985. The northern area had the largest total pumpage, about 48.1 Mft$^3$/d (360 Mgal/d) during 1985. The eastern area had the least total pumpage, about 21 percent of the 1985 total withdrawal. Total pumpage in the study area decreased about 5 percent from 1980 to 1985.

Water-level declines from predevelopment to 1987 were greatest in the middle Claiborne aquifer and least in the middle Wilcox aquifer. Simulated 1987 water levels in the middle Claiborne aquifer in the Memphis, Tenn., area were as much as 125 feet below predevelopment levels. In east-central Arkansas and in extreme southern Arkansas and north-central Louisiana, simulated 1987 water levels were more than 125 feet below predevelopment levels in the middle Claiborne aquifer throughout a 1,000-mi$^2$ area. Declines of more than 200 feet have occurred in the middle Claiborne aquifer around large pumping centers in the Pine Bluff–Stuttgart and El Dorado areas in Arkansas and in the Monroe area in Louisiana. In west-central Mississippi, simulated 1987 water levels were more than 75 feet below predevelopment levels in the middle Claiborne aquifer and as much as 125 feet in localized areas around Jackson, Miss. The lower Wilcox aquifer, the second most heavily pumped aquifer, had simulated 1987 water levels more than 125 feet below predevelopment levels in the Memphis area. The lower Claiborne–upper Wilcox aquifer had simulated 1987 water levels 100 feet lower than predevelopment levels in west-central Mississippi. The simulated 1987 potentiometric surface in the upper Claiborne aquifer was as much as 70 feet below predevelopment levels in the Jackson, Miss., area and as much as 100 feet below predevelopment levels in the Greenville, Miss., area. Simulated water levels in the middle Wilcox aquifer were 100 feet below predevelopment water levels in the Memphis area as a result of pumping from the underlying lower Wilcox aquifer.

In all areas, simulated recharge to all the aquifers has increased in their outcrop areas as pumpage has increased. Pumping in the Memphis, Tenn., area increased recharge to the middle Claiborne aquifer in the northern area from about 24 Mft$^3$/d (180 Mgal/d) before development to more than 40 Mft$^3$/d (299 Mgal/d) during 1987. Pumping reduced the discharge to the Mississippi River Valley alluvial aquifer from the subcropping upper Claiborne aquifer in the northern area from predevelopment rates of about 10.5 Mft$^3$/d (78.5 Mgal/d) to about 1.5 Mft$^3$/d (11.2 Mgal/d) during 1987. In the western area, recharge to the middle Claiborne aquifer in outcrop areas increased from predevelopment rates of about 1.5 Mft$^3$/d (11.2 Mgal/d) to more than 13 Mft$^3$/d (97.2 Mgal/d) during 1987. In the eastern area, recharge to the middle Claiborne aquifer in outcrop areas increased from about 1.5 Mft$^3$/d (11.2 Mgal/d) before development to about 4.1 Mft$^3$/d (30.7 Mgal/d) during 1987. In the western area the upper Claiborne aquifer discharged to the alluvial aquifer at a rate of about 7.7 Mft$^3$/d (57.6 Mgal/d) before development, but by 1987 the upper Claiborne aquifer was receiving recharge from the alluvial aquifer at a rate of about 0.7 Mft$^3$/d (5.24 Mgal/d). In the eastern area, the upper Claiborne and middle Claiborne aquifers discharged about 2.8 and 2.1 Mft$^3$/d (20.9 and 15.7 Mgal/d), respectively, to the alluvial aquifer before development but received about 0.5 and 0.8 Mft$^3$/d (3.74 and 5.98 Mgal/d), respectively, from the alluvial aquifer during 1987.

As development progressed, the simulated predevelopment condition of upward flow from the middle Claiborne aquifer to the upper Claiborne aquifer changed to a net downward flow from the upper Claiborne aquifer into the middle Claiborne aquifer. The western and northern areas had the greatest downward flow from the upper Claiborne aquifer to the middle Claiborne aquifer; about 9.8 and 9.2 Mft$^3$/d (73.3 and 68.8 Mgal/d), respectively, during 1987. Downward flow from the upper Claiborne aquifer to the middle Claiborne aquifer in the eastern area was about 2.5 Mft$^3$/d (18.7 Mgal/d) during 1987. The northern area, with about 21.0 Mft$^3$/d (157 Mgal/d) discharge to the Mississippi River Valley alluvial aquifer before development, had the greatest decrease in discharge to the alluvial aquifer and was the only area with a net discharge to the alluvial aquifer (about 5.0 Mft$^3$/d (37.4 Mgal/d)) during 1987. Immediately west of the heavily pumped Memphis, Tenn., area, more than 0.5 in./yr of recharge was supplied by the alluvial aquifer to the subcropping upper Claiborne aquifer during 1987. Net vertical flow in the eastern and western areas between the alluvial aquifer and the subcropping aquifers has reversed from predevelopment conditions, and about 1.2 and 2.0 $Mft^3/d$ (8.98 and 15.0 Mgal/d), respectively, flowed from the alluvial aquifer into the subcropping aquifers during 1987.

Simulated regional lateral flow patterns between the three areas have been altered by increased pumpage, mainly from the middle Claiborne aquifer. Heavy pumping from the middle Claiborne and lower Wilcox aquifers in the Memphis, Tenn., area has caused reversal of the lateral flow between the eastern and northern areas. Before development net flow was southward; during 1987 net flow was northward and was about 0.6 $Mft^3/d$ (4.49 Mgal/d). The lateral flow direction in all the aquifers across the interface between the western and northern areas has not changed since development; however, the magnitude of the southward flow in the middle Claiborne aquifer increased from predevelopment rates of about 0.4 $Mft^3/d$ (2.99 Mgal/d) to about 2.2 $Mft^3/d$ (16.6 Mgal/d) during 1987 due to heavy pumping in the Pine Bluff–Stuttgart area of Arkansas. Total net flow from the northern area into the western area during 1987 was about 2.3 $Mft^3/d$ (17.2 Mgal/d). Lateral flow between the eastern and western areas during 1987 was westward in all aquifers, and the total net westward flow was about 2.4 $Mft^3/d$ (18.0 Mgal/d).

Pumping from the Mississippi embayment aquifer system has reduced the simulated net discharge to the Mississippi River Valley alluvial aquifer to about 1.8 $Mft^3/d$ (13.5 Mgal/d) and has eliminated the upward net predevelopment discharge of about 0.3 $Mft^3/d$ (2.24 Mgal/d) to the coastal lowlands aquifer system. Net flow from the aquifers in Upper Cretaceous sediments into the lower Wilcox aquifer decreased from about 5 $Mft^3/d$ (37.4 Mgal/d) before development to about 4 $Mft^3/d$ (29.9 Mgal/d) during 1987.

Comparison of the simulated predevelopment and 1987 ground-water budgets indicates that the current (1985) pumpage is supplied primarily by (1) increased recharge in the outcrop areas of the upper and middle Claiborne aquifers and (2) reduction of discharge from these two aquifers to the Mississippi River Valley alluvial aquifer. Loss of ground water from storage is very small.

On a regional scale, the five studied aquifers in the Mississippi embayment aquifer system have potential for future ground-water development. To study the effect of increased pumpage, a uniformly distributed 20 percent increase in pumping over 1985 rates was simulated for the period 1987–2000. Simulation results indicate that water levels would decline about 30 feet below 1987 levels in the middle Claiborne aquifer in the El Dorado, Ark., and Monroe, La., areas. The Memphis area would experience water-level declines of 25 feet below 1987 levels in the middle Claiborne aquifer; declines in the Jackson, Miss., and the Pine Bluff–Stuttgart, Ark., areas would be about 20 feet.

Because the middle Claiborne aquifer furnishes about 64 percent of the total ground water withdrawn from the five studied aquifers, it will probably be the source of large quantities of water for future development. A hypothetical future increase in pumpage of 5.35 $Mft^3/d$ (40 Mgal/d) from the middle Claiborne aquifer at Marianna, Ark., south of the facies change in the lower Claiborne confining unit, was simulated to assess the effects of such withdrawals. Simulation results indicate that by the year 2000, water levels in the aquifer at Marianna would decline about 90 feet from 1987 levels. Simulation of a similar hypothetical increase in pumpage from the middle Claiborne aquifer at Wynne, Ark., north of the facies change, indicates that water levels in the aquifer would decline about 30 feet from 1987 levels.

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