No. 143, Original

IN THE
Supreme Court of the United States

STATE OF MISSISSIPPI,
Plaintiff,

v.

STATE OF TENNESSEE, CITY OF MEMPHIS, TENNESSEE,
AND MEMPHIS LIGHT, GAS & WATER DIVISION,
Defendants.

On Bill of Complaint
Before the Special Master, Hon. Eugene E. Siler, Jr.

EXHIBITS TO PLAINTIFF'S RESPONSE TO DEFENDANTS' MOTION FOR SUMMARY JUDGMENT

JIM HOOD
Attorney General
State of Mississippi
DONALD L. KILGORE
GEORGE W. NEVILLE
MISSISSIPPI ATTORNEY GENERAL'S OFFICE
Walter Sillers State Office Building, Suite 1200
550 High Street
Jackson, MS 39201
(601) 359-3680
dkilg@ago.state.ms.us
gnevi@ago.state.ms.us

C. MICHAEL ELLINGBURG
Counsel of Record
DANIEL COKER HORTON & BELL, P.A.
4400 Old Canton Road, Suite 400
(39211)
P. O. Box 1084
Jackson, MS 39214-1084
mellingburg@danielcoker.com

JOHN W. (DON) BARRETT
DAVID M. MCMULLAN, JR.
BARRETT LAW GROUP, P.A.
404 Court Square North
Post Office Box 927
Lexington, MS 39095
(662) 834-2488
dbarrett@barrettlawgroup.com
donbarrettpa@gmail.com
dmcmullan@barrettlawgroup.com

LARRY D. MOFFETT
DANIEL COKER HORTON & BELL, P.A.
265 North Lamar Blvd., Suite R
P. O. Box 1396
Oxford, MS 38655
(662) 232-8979
lmoffett@danielcoker.com

GEORGE B. READY
GEORGE B. READY ATTORNEYS
Post Office Box 127
Hernando, MS 38632
(662) 429-7088
gbready@georgebreadyattorneys.com

ELIZABETH TIPPING
CHARLES BARRETT
WILLIAM J. HARBISON, II
NEAL & HARWELL, PLC
1201 Demonbreun Street, Suite 1000
Nashville, TN 37203
(615) 244-1713
etipping@nealharwell.com
cbarrett@nealharwell.com
jharbison@nealharwell.com

Counsel for the State of Mississippi

TABLE OF EXHIBITS

Exhibit	Description
1	David Wiley Expert Report, June 30, 2017
2	J.H. Criner, P-C. P. Sun, and D. J. Nyman, *Hydrology of Aquifer Systems in the Memphis Area, Tennessee*, Geological Survey Water-Supply Paper 1779-O ("1964 USGS Report ")
3	G. K. Moore, Geology and Hydrology of the Claiborne Group in Western Tennessee, Geological Survey Water-Supply Paper 1809-F ("1965 USGS Report")
4	Deposition of Richard Spruill, September 28, 2017 (Excerpts)
5	Deposition of Brian Waldron, September 27, 2017 (Excerpts)
6	Richard K. Spruill Expert Report, Addendum #1, July 31, 2017
7	B. Waldron, D. Larson, et al, *Mississippi Embayment Regional Ground Water Study*, EPA 600/R-10/130, January 2011 (Excerpts)
8	Richard K. Spruill Expert Report, June 30, 2017
9	J. Kerry Arthur and Richard E. Taylor, *Ground-Water Flow Analysis of the Mississippi Embayment Aquifer System, South-Central United States*, USGS 1416-J
10	B.R. Clark & R.M. Hart, *The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water availability in the Mississippi Embayment*, USGS Scientific Investigations Report 2009-5172
11	R.L. Hosman, A.T. Long, T.W.Lambert, H.G. Jeffery, *Water Resources of the Mississippi Embayment: Tertiary Aquifers in the Mississippi Embayment*, USGS Professional Paper 448-D
12	W.M. Alley, T.E. Reilly, O.L. Franke, *Sustainability of Ground-Water Resource*s, USGS Circular 1186 (Excerpts)
13	Deposition of John Van Brahana, November 5, 2007 (Excerpts)
14	David Wiley Rebuttal Expert Report, Addendum #1, July 31, 2017
15	C. J. Taylor, W.M. Alley, *Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data*, USGS Circular 1217 (2001) (Excerpts)
16	Deposition of Randy Gentry, August 7, 2006 (Excerpts)
17	J. V. Brahana and R.E. Broshears, *Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee*, USGS 89-4131

18	J.V. Brahana, *Digital Ground-Water Model of the Memphis Sand and Equivalent Units*, *Tennessee-Arkansas-Memphis*
19	James H. Criner and William S. Parks, *Historic Water-Level Changes and Pumpage from the Principal Aquifers of the Memphis Area, Tennessee:* 1886-1975, USGS WRI 76-67
20	David Feldman and Julia O. Elmendorf, *Final Report: Water Supply Challenges Facing Tennessee: Case Study Analyses and the Need for Long-Term Planning* (Excerpts)

CERTIFICATE OF SERVICE

Pursuant to Paragraph 3 of the Case Management Plan (Dkt. No. 57), I hereby certify that all parties on the Special Master's approved service list have been served by electronic mail, this the 6th day of July, 2018.

/s/ C. Michael Ellingburg
C. Michael Ellingburg

EXHIBIT 1

David Wiley Expert Report
June 30, 2017

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

Prepared For:

Jim Hood, Attorney General of the State of Mississippi

June 30, 2017

Prepared By:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Groundwater and Environmental Engineering Consultants
10014 North Dale Mabry Highway, Suite 205
Tampa, FL 33618

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

This report was prepared at the request of the Attorney General of the State of Mississippi. It updates and confirms previous work performed for the Attorney General to determine the effect of Memphis Light, Gas & Water's (MLGW's) consistent, significant expansion of the commercial water well pumping operations between 1965 and our last report on Mississippi's natural groundwater flow and storage. This report incorporates updated pumpage information from MLGW and the Mississippi DEQ.

This report presents the results of our evaluation of the effects of MLGW's long term groundwater pumpage on the natural groundwater flow and storage within the confined Sparta Sand within northwest Mississippi. The area of study for the report is shown in **Figure 1**. The tasks performed for this update report by LBG to support our opinions include: confirming existing information regarding the natural pre-development direction of groundwater movement in the Sparta Sand within Mississippi; collecting additional data on the Sparta Sand formation, and updated groundwater modeling to show the change in direction of groundwater movement beneath Mississippi caused by changes in the natural hydraulic gradients caused directly by MLGW pumping; and, performance of calculations to determine the volume of groundwater pumped into the Shelby County, Tennessee, area by MLGW out of Mississippi's natural groundwater flow and storage in the Sparta Sand. These calculations were performed using an existing groundwater flow model developed by the USGS. It is our opinion that the results obtained are within the expected range, and consistent with information developed and conclusions presented by other reliable scientific evaluations. Those analyses, and ours, clearly demonstrate that MLGW pumping has withdrawn billions of gallons of Mississippi groundwater from storage in the Mississippi Sparta Sand, permanently taking it out of Mississippi into Tennessee for sale and use in Tennessee.

BACKGROUND

The primary source of fresh water supply for most of northwest Mississippi and the Memphis, Tennessee areas is the deep confined Sparta Sand formation, referred to as the Memphis Sand in Tennessee within the Claiborne Geological Group. The confined Sparta Sand formation beneath northwest Mississippi and southwest Tennessee is a discrete geological formation which has existed for thousands of years. Since its formation, a significant but not unlimited quantity of high quality groundwater was collected and was stored under hydrostatic pressure from rainwater falling on outcrops within each state's current borders. Because it allows the transmission and storage of groundwater in usable quantities and is overlaid by a confining layer, the Sparta Sand is classified as a confined aquifer. But the fact that the geological formation underlies both states does not mean that any meaningful quantity of the groundwater stored and flowing over time within either state has ever been naturally shared between the states.

Substantially all of the groundwater naturally flowing, collected and stored within the Sparta Sand in each state originated, and was stored inside that state's borders over thousands of years. As a confined aquifer, the natural groundwater flow and storage in each state has resided in the current borders of that state because it naturally seeped from the outcrops in the state and moved exceedingly slowly in a predominantly east to west/southwest direction in Mississippi and an east to west/northwest direction in Tennessee.

The water supply in Shelby County, Tennessee, is primarily provided by groundwater, and most of the groundwater pumped in the county is pumped by MLGW, a public utility owned by the City of Memphis. Since its creation in 1939, MLGW has relied exclusively on groundwater from what was originally called the "500-foot Sand" or Memphis Sand. In the mid-1960's Tennessee learned that the upper part of the "500-Foot Sand" was correlated with the Sparta Sand (Moore, 1965). Based on available records since 1965, MLGW has consistently, annually increased its groundwater pumping for governmental use and sale in Shelby County and surrounding areas over the next several decades. Between 1965 and 2000, MLGW developed one of the largest artesian water pumping operations in the world, with over 170 commercial water wells located in 10 well fields. Three of these well fields are within 2 to 3 miles of the

Mississippi State line just above DeSoto County, Mississippi. **Figure 1** shows the location of MLGW's ten well fields pumping from the Sparta Sand and the approximate quantities pumped in 2016.

Using their very large artesian groundwater pumping and distribution system, between 1965 and 1985 MLGW pumping increased from approximately 72 million gallons per day (MGD) to 132 MGD. As of 1985 (Brahana & Broshears, 2001), Shelby County, Tennessee, groundwater pumping had increased to a rate of approximately 200 MGD. This rate of MLGW pumping continued to increase after 1985 until 2000, and the Sparta Sand in Tennessee has been continuously pumped at a higher rate than it can be naturally recharged based on its geology. As a result, the natural static head pressure within the aquifer has been drawn down by MLGW's pumping in the form of a funnel which reaches into Mississippi as far as south DeSoto County, Mississippi. This area in which the MLGW wells have reduced the pressure and changed the hydraulic gradients can be described as the area of influence of the MLGW wells and is further described in groundwater movement terms as a "cone of depression". This "cone of depression" is centered in and drawing groundwater into MLGW wells and expands outward from there into northwest Mississippi, pulling groundwater into Tennessee which would never have resided within Tennessee under natural conditions. **Figure 2** shows generalized hydrogeological cross sections and has been prepared to distinguish the natural pressure (pre-pumping conditions) in the aquifer from the current pumping conditions. The non-pumping groundwater pressure will raise the water to the level shown as the horizontal dashed blue line labeled pre-development or pre-pumping potentiometric surface. Potentiometric surface is defined in the literature: For a well penetrating a confined aquifer the potentiometric surface is the elevation to which the water rises due to the natural pressure within the aquifer. The upper figure shows several wells pumping with each of their respective potentiometric surface (groundwater level) drawdown cones. This drawdown of the groundwater level around the well forms a cone of depression as shown in the figure. This cone of depression is actually in the shape of a cone or funnel as would be seen three dimensionally and draws the water toward the low point.

While all wells create a cone of depression, the shape and extent, or size, of the cone depends on the rate and duration of the pumping, and the hydraulic properties of the aquifer (groundwater system). If pumping exceeds the rate of recharge, the depth to which a pump is lowered will have to be increased, and the area drained by the cone of depression will continue to grow. The upper part of **Figure 2** with only a few wells pumping shows that the cones of depression for each well do not overlap by exceeding the pre-pumping potentiometric surface causing a regional cone of depression. The lower part of **Figure 2** shows a greater number of wells closer together and their respective cones of depression. In this figure the cones of depression for these wells overlap and stay below the pre-pumping potentiometric surface causing a regional cone of depression. Historically recorded observations show that potentiometric surface (water levels) for the Sparta Sand have declined (dropped) by as much as 100 feet under Memphis since 1886 as a result of MLGW pumping, forming a large cone of depression extending into substantially all of DeSoto County, Mississippi. As a result, recorded water levels in the Sparta Sand under north DeSoto County, Mississippi have been estimated from a USGS model (Arthur and Taylor, 1990) to have declined by up to 90 feet. In a deposition on March 27, 2007 of Charles H. Pickel, a retired MLGW water manager, he confirmed that the cone of depression created by MLGW pumpage extended into northern Mississippi. This current large cone of depression only exists because of the continuous, cumulative increases in groundwater pumping in Shelby County, Tennessee, primarily in MLGW's 170+ commercial wells. Essentially, the ten significant MLGW well field cones of depression overlap forming one, large oval-shaped cone of depression centered in Memphis from which MLGW draws groundwater. **Figure 1** illustrates the area of the larger and somewhat oval-shaped cone of depression that occurs from the cumulative MLGW well field pumping. The Davis, Palmer and Lichterman well fields, which are located near the Mississippi state line, more readily withdraw groundwater out of the Sparta Sand in Mississippi.

Figure 3 is a three-dimensional illustration showing the approximate total area from which the MLGW cone of depression withdraws groundwater. The Arthur and Taylor model shows that Mississippi groundwater has been pulled out of storage and from its natural west/southwest direction of seep and drawn north into Tennessee by the MLGW cone of depression. These conditions were recognized by David Feldman from the University of Tennessee, prompting the publishing of a report titled "Water Supply

Challenges Facing Tennessee: Case Study Analyses and the Need for Long-Term Planning (June 2000), David Lewis Feldman, Ph.D., and Julia O. Elmendorf, J.D.” In this report the author states that, at a groundwater pumping rate of approximately 145 MGD from the MLGW cone of depression, 20-40 MGD is taken from beneath DeSoto County, Mississippi. The MLGW cone of depression can also be seen in potentiometric surface contour maps presented by Moore, 1960; Criner and Parks, 1976; and Parks, 1990. Copies of these maps were presented previously in the LBG, April 2014, Update Report On Diversion And Withdrawal Of Groundwater From Northern Mississippi Into The State Of Mississippi.

HYDROGEOLOGY OF SPARTA SAND

There are a number of aquifers and confining units in the northwestern Mississippi and southwestern Tennessee area. The major aquifers are the Sparta/Memphis Sand and the Fort Pillow Sand. The Sparta Sand is a distinct geological formation and primary source of groundwater in northwest Mississippi and Shelby County, Tennessee. **Figure 4** is a generalized hydrogeologic cross section showing the Sparta Sand and lower Fort Pillow confined aquifers.

The Sparta Sand is a thick, variable sand and sandstone formation made up of fine to very coarse sand with lenses of clay and silt (Graham and Parks, 1986). In north Mississippi, the Sparta Sand occurs at a depth of 0 to 600 feet, and varies in thickness between 200 to 900 feet. The formation is thinnest at outcrops at or near the surface in the eastern Shelby County and northwestern Fayette County, Tennessee, and in north Mississippi beginning in east Marshall County. The outcrops continue in a north and south strike along the edge of the Mississippi Embayment in both states. An outcrop is defined as the location where a laterally extensive dipping subsurface rock formation is exposed at or near land surface. **Figure 5** shows the outcrop area of the Sparta Sand. The formation descends from the outcrops. Getting progressively thicker, and is thickest near the Mississippi River in Shelby County, Tennessee, and in DeSoto County, Mississippi. Within north Mississippi and along the common border with Tennessee, the Sparta Sand formation has a dominant, gentle dip from eastern outcrops to the west/southwest across north Mississippi and Tennessee to the Mississippi River.

The Sparta Sand is confined above by the Jackson Formation and the upper part of the Claiborne Group which consist primarily of clay, silt and fine sand. This serves as a confining bed retarding vertical groundwater flow between the unconfined Surficial aquifer above and the Sparta Sand. Except in areas where the upper confining bed is breached, it protects the high quality of the stored water from surface pollution. The thickness of this confining bed is variable in the Tennessee and northwestern Mississippi areas, ranging from 0 to 360 feet (Graham and Parks, 1986). The Flour Island Formation is a confining bed consisting primarily of silty clay and sandy silt that underlies the Sparta Sand and separates it from the deeper Fort Pillow Sand. The Fort Pillow Sand is comprised of fine to medium-grained sand in the subsurface throughout the Memphis area and is the second most used aquifer by MLGW. The Sparta Sand formation has allowed the transmission and accumulation of high quality water stored under hydrostatic pressure over a long period time within each states border.

The Sparta Sand is one of the principal and most productive aquifers in Shelby County, Tennessee, and northwestern Mississippi. It is reported that the aquifer provides about 95 percent of the water used for all municipal and industrial water supplies in the Memphis area. Aquifer is defined as: A subsurface geologic formation capable of storing and transmitting usable amounts of water. This sandstone formation is saturated and stores groundwater collected over thousands of years, and very slowly transmits usable amounts of water within the formation, classifying it as an aquifer. The primary source of any new groundwater for collection and storage in the Sparta Sand is the recharge that occurs from rainfall. This groundwater recharge generally occurs east of Shelby County, Tennessee, east of Memphis, and in east Marshall County, Mississippi at the outcrop areas as shown on **Figure 5**. Within this outcrop belt, recharge occurs by infiltration of rainfall directly into the Sparta formation or by downward seepage of water from the overlying Surficial aquifer. **Figure 6** is a 3-dimensional diagram showing a cross-section of the hydrogeologic formations in the Memphis and northwestern Mississippi area. This diagram shows that the formations are dipping generally from east to west and the Sparta outcrop occurs in the eastern portion of the area. As rain falls on the outcrop area of the Sparta it slowly percolates downward and then under gravity and the weight of the water accumulated above it in the formation slowly provides recharge as it seeps through the tiny pore spaces of the sandstone down gradient following the dip of the formation in a slightly west to southwesterly direction under natural conditions. The groundwater recharge is exceedingly slow under natural conditions seeping through the sandstone at a rate of about 1 inch per day. At this rate, groundwater naturally collected resides in the Sparta Sand for thousands of years as it gradually moves down gradient towards the Mississippi River. **Figure 7** is an idealized hydrogeologic section from east to west across the Mississippi Embayment that shows the general relationship between the aquifers, confining units, topography and general flow patterns (Arthur & Taylor, 1998). Water levels in the aquifer outcrop areas on the eastern side of the embayment are higher than on the western side of the embayment due to higher land surface altitudes. The Middle Claiborne aquifer, where the Sparta Sand occurs underlies the Mississippi Alluvial Plain near the Mississippi River, where the water level is lower than the outcrop areas as shown on **Figures 7 and 8** (Arthur& Taylor, USGS,1990). As a result of these water-level differences in the potentiometric surface, water naturally moves from the outcrop areas on the eastern side of the embayment westward through the aquifer, then eventually upward through the confining units into the Mississippi River Alluvial aquifer. The eastern boundary of Mississippi Alluvial Plain aquifer in western Mississippi which overlies the Middle Claiborne aquifer runs north-south in northwest Mississippi as shown on **Figure 8** (Arthur& Taylor, USGS, 1990) and receives discharge from the Middle Claiborne aquifer. This causes potentiometric surface levels to equilibrate in a north-south direction through northwest Mississippi forcing groundwater to flow east to west from the recharge area on the east side of Mississippi Embayment in northwestern Mississippi under pre-development conditions. As a result, structural geology in northwest Mississippi influences the shape of potentiometric surface contours and direction of groundwater flow, which is westward.

Figure 9 shows the pre-development potentiometric surface under natural conditions generated from groundwater modeling and shows this generally east to west/southwest groundwater directional movement perpendicular to the contours in northwest Mississippi consistent with information presented by Arthur & Taylor of the USGS. As shown on **Figure 9** in blue, all but a very small portion of groundwater flow in northern Mississippi stays in Mississippi under pre-development conditions until its natural discharge at the Mississippi River Alluvial aquifer system near the river. Only a very small area in northeastern DeSoto County has groundwater flow entering Tennessee under pre-development conditions as shown in green in **Figure 9**.

HYDROLOGIC EVALUATIONS

Background Conditions

Groundwater conditions can be affected by a number of things that include climatic conditions, hydrogeologic characteristics and pumping from wells. For the purposes of this evaluation, pumpage from Shelby County, Tennessee wells, primarily in MLGW's well fields, has the greatest impact on Mississippi groundwater conditions. This is shown by an evaluation of available hydrologic data.

As discussed in the **BACKGROUND** section of this report, Memphis began using the Sparta Sand as its municipal water supply in 1886. There is no data to suggest that the initial usage had any impact on Mississippi groundwater. However, by the 1970s, available data shows that MLGW pumpage began increasing significantly from year to year, and by the late 1990s total Shelby County pumpage had increased to a rate of approximately 200 MGD (Brahana & Broshears, 2001). Approximately 75% of the pumpage was from MLGW wells. The continual increase in groundwater withdrawals in the Memphis area has drawn out groundwater faster than recharge is possible, lowering the potentiometric surface of the aquifer and pressure within the formation, and changing the groundwater flow direction and hydraulic gradients which are represented by the cone of depression. This has resulted in a long-term decline in groundwater levels in the Sparta Sand. This groundwater level condition is observed in hydrographs from observation wells monitored by the Tennessee USGS. Hydrographs were developed from actual water-level measurements collected in the field by USGS personnel and presented in the LBG, May 2007 Report On Diversion Of Ground Water From Northern Mississippi Due To Memphis Area Well Fields. These hydrographs show that water levels have declined from approximately 20 to 50 feet in these area observation wells since 1958. **Figure 10** included in this report contains two hydrographs representative of those presented previously in the LBG May 2007 report.

The USGS has also prepared groundwater elevation maps of the potentiometric surface for the Sparta Sand that shows the declining water-level conditions across the southwest Tennessee and northwest Mississippi. The potentiometric surface is the groundwater level that water in an aquifer will rise to in a tightly cased well.

Potentiometric surface maps illustrate the groundwater hydraulic gradient across a given area. Potentiometric surface maps were prepared for the following years; 1960, 1970, 1980, 1988, 1990, 1995, 2000 and 2005 and are presented in the May 2007 LBG report. **Figure 11** shows the potentiometric surface for year 2000, which has a similar and representative pattern as the potentiometric surface for the other seven years. As with the hydrographs, the potentiometric surface maps are based on actual water-level measurements. Water levels in the Sparta Sand in Shelby County, Tennessee, have declined by approximately 100 feet since 1886 forming a large cone of depression. Water levels in the Sparta Sand under northern DeSoto County, Mississippi have been estimated from a USGS model developed by Arthur and Taylor, 1990, to have declined by up to 90 feet.

These potentiometric surface maps provide information regarding groundwater hydraulic gradient showing the flow direction which is always perpendicular to contours. While the natural movement of the groundwater in the Sparta Sand is east to slightly southwest, the recent potentiometric maps all show that the groundwater flow in northwest Mississippi is now drawn radially to the north toward the center of Memphis where the lowest water levels are observed in the aquifer. This large cone of depression seen on **Figure 11** has been created by the cumulative groundwater pumping (hundreds of wells) in Tennessee, primarily from the MLGW well fields.

Groundwater Modeling Simulations

The Brahana and Broshears (2001) model has been for this for these diversion evaluations because it includes both the Sparta Sand and contributing aquifers in Shelby County including the Fort Pillow aquifer. A detailed description of the groundwater flow model prepared by the USGS;

> ***Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee, Water-Resources Investigations Report 89-4131 by J.V. Brahana and R.E. Broshears. U.S. Geological Survey. 2001.***

was presented previously in the May 2007 and April 2014 LBG reports. Following is a brief summary description of the model.

This is a regional groundwater model constructed by Brahana and Broshears to determine changes in regional flow from pre-development time to 1980 due to changes in pumpage in Sparta/Memphis Sand and Fort Pillow aquifers. The report includes the hydrogeology of the Sparta Sand and the Fort Pillow aquifers in the Memphis, Tennessee and northwestern Mississippi area. The model grid consists of three-layers, which are, from top to bottom: a) Fluvial Deposits; b) Sparta Sand Aquifer; and c) Fort Pillow Aquifer. The model is a transient groundwater model with hydrologic data from 1886 to 1980. The model was developed using the USGS finite difference groundwater flow code, MODFLOW (McDonald and Harbaugh, 1988). For our analysis, water-level conditions of the Sparta Sand were of primary interest.

Pre-development simulation was conducted by turning off the well package of MODFLOW. **Figure 12** included in this report**,** shows the model-computed potentiometric surface of the Sparta/Memphis Sand aquifer prior to 1886, which is considered to represent pre-development or pre-pumping conditions. This figure shows that the pre-development groundwater flow direction for the Sparta Sand was generally from east to west/southwest toward the Mississippi River in Mississippi. This pre-development potentiometric surface map was presented by Brahana, 2001 and has been published by others who have performed hydrologic analyses in the region. Post-development modeling scenarios were initially conducted from 1924 to 1980. The post-development includes changes in hydraulic stress due to pumpage in the Sparta Sand and Fort Pillow aquifers. **Figure 13** contained in this report, shows the potentiometric surface at the end of the 1980 stress period in the Sparta/Memphis Sand aquifer. During the post-development stage, i.e., in the year 1980, the potentiometric surface in the Memphis area was significantly altered due to pumpage in the Sparta/Memphis Sand aquifer as evidenced by the shapes of the contours on the figure. The "bull's-eye" areas in the figure are indicative of significant drawdown or cones of depression. The bending of the potentiometric contours in northwest Mississippi (DeSoto County) indicates that groundwater pumpage occurring in the Memphis area is affecting groundwater flow conditions in DeSoto County. This same effect on groundwater levels in northwest

Mississippi can be seen from work performed by others including Arthur and Taylor, 1990; Kinley, 1993; and Outlaw, 1994. Information on these groundwater levels and flow conditions was presented previously in the May 1007 and April 2014 LBG reports. All of the information contained in these sequential reports confirms a cone of depression originating under MLGW well fields and extending south into northwest Mississippi. A comparison of **Figure 12**, pre-development potentiometric surface vs **Figure 13,** 1980 potentiometric surface, the cone of depression shows that the groundwater flow direction has been altered and groundwater is continues to be diverted from its natural path in Mississippi northward into Tennessee due to the Memphis pumpage.

Since the original Brahana and Broshears model was developed only through 1980 it was determined to update the model in order to evaluate more current conditions. These updates were accomplished in both the May 2007 and April 2014 LBG reports. For this report, it was decided to further update the model. In order to further update the model, pumpage data was obtained from MLGW and the Mississippi DEQ. **Table 1** lists the historical pumpage from the MLGW well fields from 1965 through 2016. **Table 2** lists the historical pumpage for both MLGW and Desoto County, Mississippi. The model was then further updated through 2016 by including several additional stress periods. Drawdown and potentiometric surface maps for 2013 through 2016 are shown respectively, on **Figures 14 – 21** using the updated model. These maps are similar to potentiometric surface maps presented previously, which are based on actual water-level data collected by the USGS. These comparisons provide additional confidence in the updated model.

Groundwater drawdown at the end of each modeled stress period was determined by subtracting the groundwater heads after each stress period from the pre-development groundwater heads. There is a slight decrease in drawdown from 2013 through 2016 as shown in **Figures 14-17**. The shapes of the drawdown contours in these maps are similar to the shapes presented in the two previous LBG report in May 2007 and April 2014. In the Memphis area, drawdown in some places was as much as 100 feet in the Sparta Sand. These drawdown figures show the extent of the cone of depression formed in the Sparta Sand as a result of the groundwater pumpage which continues to be mostly by MLGW. The drawdown contours in the Sparta Sand tend to be longitudinally oriented, between the Mississippi River and the aquifer outcrop in the east. Due to the higher heads of the Mississippi River (simulated in the model as a constant head in layer -1), an effective hydrologic boundary is created that prevents the drawdown cone of depression from moving past the river into Arkansas. The Sparta Sand outcrops to the east in Tennessee and Mississippi, and in many places it gets direct recharge from precipitation, keeping the cone of depression from moving further out in the east. The cone of depression on all of these drawdown maps shows that the natural groundwater flow has been diverted from Mississippi to the Memphis area of Tennessee due to Memphis pumpage.

Potentiometric surface maps for 2013 through 2106 using the updated model are shown on **Figures 18 – 21**. The shapes of the potentiometric surface contours in these maps are similar to the shapes presented in the two previous LBG report in May 2007 and April 2014. A comparison of **Figure 12**, pre-development potentiometric surface vs **Figures 18 - 21,** shows that the groundwater flow direction continues to be altered and groundwater is being, and will continue to be, diverted northward from Mississippi into Tennessee due to the Tennessee pumpage.

Groundwater Budget Analysis

A groundwater budget analysis was conducted using the updated Brahana and Broshears model which includes the time period from 2013 through 2016. The groundwater budget represents the components of inflows, outflows and changes in storage to the aquifer. Groundwater budget analysis for the Memphis area was conducted using the same U.S. Geological Survey MODFLOW model (Brahana and Broshears, 2001). Once the model simulations were completed the cell-by-cell flow data for each of the zones was calculated for a specified time interval, which provides the amount of inflow and outflow such as pumping wells, constant heads, and storage out and into the county. The groundwater budget also provides amount of net flow being contributed by one county to another county due to stress in the system such as pumping wells. The net flow indicates the difference of flow from the developmental conditions to pre-development conditions (i.e., prior to any pumpage).

The focus of the budget analysis was to determine the net groundwater flow to the Shelby County, Tennessee area, from DeSoto and Marshall Counties, Mississippi.

Figure 22 included in this report shows a plot of net flow of groundwater to the Shelby County area under the influence of MLGW pumpage. The contribution or diversion of groundwater to Shelby County, Tennessee, from DeSoto and Marshall Counties has steadily increased with time as MLGW pumpage increased. From both **Figure 22 and Table 3**, in 1965 the diversion from DeSoto and Marshall Counties was 12.9 MGD, whereas in 1988 the diversion was 27.2 MGD. This increased flow from DeSoto and Marshall Counties to Shelby County is attributed to an increase in pumpage from the MLGW wells. The high pumpage creates a cone of depression that stretches as far south as DeSoto County with pronounced drawdown near the political boundary between Shelby County and DeSoto County. Some of the largest well fields of Shelby County, such as Davis and Lichterman well fields operated by MLGW are very close to the state boundary between Tennessee and Mississippi, causing significant drawdown and groundwater flow from DeSoto County to Shelby County, Tennessee. Moore in 1960 also presented a groundwater budget for the Memphis area. His analysis, which was based on 1960 data, shows that 25 MGD of groundwater is derived as underflow through the Sparta Sand from Mississippi. The results depicted in **Figure 22** are in the same range of values reported by Moore in 1965, Criner in 1964, Feldman in 2000, Gentry in 2000 and Arthur in 2006.

After 1988 to the current (2016), the contribution from DeSoto and Marshall Counties to Shelby County decreased to 13.5 MGD. This decrease can be observed on **Figure 22 and Table 3**. Even though pumpage in Shelby County increased during most of this period from approximately 143 MGD to a high of approximately 162 MGD as shown in **Table 1**, the decrease in contribution from DeSoto and Marshall Counties likely resulted from increases in pumpage from DeSoto County, which reduces the amount of groundwater available to flow into Shelby County. Upon further review of **Table 2**, MLGW pumpage has been on a decreasing trend from approximately 150 MGD in 2006 to approximately 124 MGD in 2016. **Table 2** also shows a steady increase in pumpage from DeSoto County. The decrease in pumpage from MLGW and increases in pumpage from DeSoto County explain the shape of the plot in **Figure 22**. However, with these pumpage changes, groundwater is still being diverted from the Mississippi flow path into Shelby County, Tennessee from MLGW pumpage. In fact, the total volume of groundwater taken from Mississippi due to MLGW pumpage since 1965 is calculated to be approximately 411.9 billion gallons.

It is our opinion that based on our hydrologic evaluation and from the review of technical reports, groundwater pumpage from the MLGW has created a large cone of depression that has altered natural groundwater flow paths in the Sparta Sand in northwest Mississippi, and as a result is diverting, and will continue to divert, and take groundwater from Mississippi that only naturally occurs within the state of Mississippi. The Mississippi groundwater gradient in the Sparta Sand has been altered from its natural generally east to west/southwest flow direction to a northerly direction. **Figures 23 and 24** are potentiometric surface maps for pre-development and 2016, respectively. Each of these maps also shows groundwater flow direction. The pre-development flow direction shown in **Figure 23** in northwestern Mississippi is generally from east to west/southwest in Mississippi with a very small flow component into Tennessee. The 2016 flow direction in **Figure 24** shows that the natural flow has been significantly changed and diverted towards Tennessee as a result of MLGW pumpage.

CONCLUSIONS

The primary purpose of our investigation as presented in this report is the evaluation of the effects on natural groundwater flows and availability in northwestern Mississippi caused by the unregulated groundwater pumpage in Shelby County, Tennessee, primarily by MLGW, which has been taking groundwater from Mississippi for decades without permission. This update evaluation included the review of existing technical reports and hydrologic data from the USGS, University of Memphis GWI, MLGW and the MDEQ and the performance of calculations to determine the volume of groundwater that is diverted from its natural flow in Mississippi by pumping in the Memphis, Tennessee area, focusing on MLGW through 2016. These calculations were performed using the existing groundwater flow model developed by the USGS and updated previously by LBG in May 2007 and April 2014.

It is clear from our review of a number of technical reports described previously that a large cone of depression of the potentiometric surface for the Sparta/Memphis Sand aquifer has been created by the groundwater pumpage in the Memphis, Tennessee area. Most of this pumpage that is diverting Mississippi's groundwater is attributable to MLGW. This cone of depression extends into northern Mississippi and has altered the groundwater gradient. The groundwater gradient of the Sparta Sand has been altered from its natural east to west/southwest flow direction and diverted to a northerly direction by this continued pumping. This finding is also confirmed from our review of water-level data associated with potentiometric surface maps prepared by the USGS and from groundwater flow modeling. Observations have shown that water levels in the Sparta/Memphis Sand aquifer have declined (dropped) by as much as 100 feet since 1886 forming the center of this large man made cone of depression. This cone of depression had dropped water levels under northern DeSoto County, Mississippi, as estimated by a USGS model (Arthur and Taylor, 1990), by up to 90 feet. In a deposition on March 27, 2007 of Charles H. Pickel, a retired MLGW water manager, he indicated that the cone of depression created by MLGW pumpage extended into northern Mississippi**.** These conditions were recognized by David Feldman from the University of Tennessee prompting the publishing of a report titled **"**Water Supply Challenges Facing Tennessee: Case Study Analyses and the Need for Long-Term Planning (June 2000), David Lewis

Feldman, Ph.D., and Julia O. Elmendorf, J.D." In this report the author states that, at a groundwater pumping rate of approximately 145 million gallons per day (MGD) from the Memphis area a cone of depression is formed and 20-40 MGD is derived from beneath DeSoto County which is located in northwestern Mississippi. The cone of depression of the Sparta Sand can also be seen in potentiometric surface contour maps presented by Moore, 1960; Criner and Parks, 1976; and Parks, 1990.

Groundwater flow modeling was performed for calculating groundwater flow contribution or diversion from Mississippi as a result of Memphis area pumpage. The modeling exercises were performed utilizing the USGS model prepared by Brahana and Broshears (2001). **Table 3** in this report list the diversion volumes calculated from the updated modeling for 1965 through 2016 as a result of the MLGW pumpage that has averaged approximately 21.7 MGD. These quantities are in the same range of values reported by Moore in 1965, Criner in 1964, Feldman in 2000, Gentry in 2000 and Arthur in 2006. From the review of **Table 2** contained in this report, which shows the pumpage amounts from MLGW and DeSoto County, an increase in pumpage from DeSoto County can be observed over time, while a decrease in MLGW pumpage occurred. This corresponds with a decrease in the flow diversion from DeSoto County to Shelby County calculated from the model. As a result, the increased pumpage in DeSoto County and decrease in MLGW pumpage is reducing the amount of groundwater being diverted from the northern Mississippi area.

Based upon the original Brahana Model, potentiometric surface mapping, updated groundwater modeling by LBG, and our review of studies by other reputable scientists and water policy analysts (as discussed herein), it is our opinion that Memphis area pumpage, primarily by MLGW, has altered the natural flow path and created a cone of depression in the Sparta Sand, resulting in the diversion of Mississippi's groundwater. The total volume of groundwater taken from Mississippi due to MLGW pumpage since 1965 is calculated to be approximately 411.9 billion gallons.

REFRENCES

Arthur, J.K. and Taylor, R.E. 1990. Definition of the geohydrologic framework and preliminary simulation of ground-water flow in the Mississippi Embayment aquifer system, Gulf Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 86-4364, 97 p.

Arthur, J.K. and Taylor, R.E. Taylor1998 Ground –Water Flow Analysis of the Mississippi Embayment Aquifer System, South-Central United States, Regional Aquifer-System Analysis-Gulf Coastal Plan, USGS Professional Paper 14

Brahana, J.V. 1981. Ground Water Supply, Chapter 3 – Final Report Metropolitan Area Urban Water Resources Study: U.S. Geological Survey.

Brahana, J.V. 1982a. Digital Ground Water Model of the Memphis Sand and Equivalent Units, Tennessee, Arkansas, Mississippi: U.S. Geological Survey Open-File Report 82-99, 55 p.

Brahana, J.V., and Broshears, R.E., 2001. Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee, Water-Resources Investigations Report 89-4131, 56 p.

Criner, J.H., Sun, P-C.P., and Nyman, D.J. 1964. Hydrology of the aquifer systems in the Memphis Area, Tennessee: U.S. Geological Survey Professional Paper 1779-O, 54 p.

Criner, J.H., and Parks, William S., 1976. Historical Water-Level Changes and Pumpage From the Principal Aquifers of the Memphis Area: U.S. Geological Survey Water Resources Investigations 76-67

C.W. Fetter, Applied Hydrogeology, 1988.

E.M. Gushing, E.H. Boswell, and R.L. Hosman, General Geology of the Mississippi Embayment, Water Resources of the Mississippi Embayment, (1964) Department of the Interior, Geological Survey Professional Paper 448-B

Environmental Simulations Incorporated (ESI), 2006. Groundwater Vistas a pre-and post-processors.

Feldman, D. L., Ph.D., and Elmendorf, J. O., J.D., Final Report – Water Supply Challenges Facing Tennessee: Case Study Analyses and the Need for Long-Term Planning (June 2000).

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

Graham, D.D., and Parks, W.S., 1986. Potential for leakage among principal aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 85-4295, 46 p.

Hosman, R.L., Long, A.T., and Lambert, T.W., and others. 1968. Tertiary aquifers in the Mississippi embayment, *with discussions* of Quality of the water by H.G. Jeffrey: U.S. Geological Survey Professional Paper 448-D, 29 p.

Ivey, S.S., 1999. Ground Water Institute analysis of the proposed south wellfield area, September 16.

LBG, May 2007 Report On Diversion Of Ground Water From Northern Mississippi Due To Memphis Area Well Fields.

LBG, April 2014, Update Report On Diversion And Withdrawal Of Groundwater From Northern Mississippi Into The State Of Mississippi.

McDonald, M.G. and Harbaugh, A.W. 1988. A modular three-dimensional finite difference ground-water flow model, USGS Techniques of Water-Resources Investigations, Book 6.

Mississippi Embayment Regional Ground Water Study, EPA 600R/-10/130, 1 January 2011

Moore, 1965. Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geological Survey Water-Supply Paper 1809-F, 44 p.

Outlaw, J.E., 1994. A ground water flow analysis of the Memphis sand aquifer in the Memphis, Tennessee Area.

Parks, W.S., and Carmichael, J.K. 1989a. Geology and ground-water resources of the Memphis Sand in western Tennessee: U.S. Geological Survey Water Resources Investigations Report 88-4182. 30 p.

T.P. Schrader, Potentiometric Surface in the Sparta-Memphis Aquifer of The Mississippi Embayment, Spring 2007, Scientific Investigations Map 3014, 2008

Wells, F.G., 1933. Ground-water resources of western Tennessee, *With a discussion of* Chemical character of the water by F.G. Wells and M.D. Foster: U.S. Geological Survey Water-Supply Paper 656, 319 p.

W. S. Parks and J. K. Carmichael, Altitude of Potentiometric Surface, FUN 1985, and Historic Water-Level Changes in the Memphis Aquifer in Western Tennessee, U.S. Geological Survey Water-Resources Investigations Report 88-4180 (1990a).

TABLES

Table 1

MEMPHIS LIGHT, GAS AND WATER DIVISION
CITY OF MEMPHIS
Water Pumpage By Stations
Gallons Per Day
1965-2012

	Sheahan	Mallory	Allen	Lichterman	McCord	Davis	Palmer	Morton	LNG	Shaw	TOTAL	Starting Bates #	Ending Bates #	Monthly or Yearly	Comments (If not raw pumpage data)
Row	41	41	45	44	33	50	48	33	26	33					
Column	25	17	21	29	25	17	24	18	26	32					
1965	17,773,000	13,268,000	22,519,000	4,220,000	14,181,000						71,961,000	MLGW 66416		Yearly	Net Pumpage
1966	16,991,000	12,618,000	22,969,000	9,697,000	13,472,000						75,747,000	MLGW 66417		Yearly	Net Pumpage
1967	15,870,000	12,364,000	22,592,000	13,277,000	13,599,000						77,702,000	MLGW 66417		Yearly	Net Pumpage
1968	15,961,000	12,582,000	23,430,000	14,621,000	14,487,000						81,081,000	MLGW 66417		Yearly	Net Pumpage
1969	15,063,000	11,961,000	23,934,000	16,192,000	15,495,000						82,645,000	MLGW 66418		Yearly	Net Pumpage
1970	15,556,000	11,231,000	27,167,000	16,775,000	16,211,000	3,258,000			101,000		90,299,000	MLGW 66418		Yearly	Net Pumpage
1971	18,332,000	12,953,000	25,420,000	15,585,000	15,930,000	7,487,000			151,000		95,858,000	MLGW 66418		Yearly	Net Pumpage
1972	15,927,000	15,973,000	22,024,000	16,373,000	15,491,000	10,204,000	2,801,000		249,000		99,042,000	MLGW 66419		Yearly	Net Pumpage
1973	17,167,583	18,880,000	21,578,667	18,084,333	17,281,583	10,867,333	2,776,333	1,660,000	174,166		108,469,998	MLGW 67682	MLGW 67741	Monthly	
1974	17,579,833	20,101,500	22,193,750	18,142,667	15,353,667	10,617,083	2,944,833	2,354,083	255,750		109,543,166	MLGW 67622	MLGW 67681	Monthly	
1975	18,130,916	19,148,583	21,276,750	17,378,916	19,111,750	11,688,416	3,047,666	160,500	243,833		110,187,330	MLGW 67562	MLGW 67621	Monthly	
1976	19,007,000	20,641,000	19,947,000	18,148,000	18,721,000	11,370,000	3,158,000	3,000	260,000		111,255,000	MLGW 66420		Yearly	Net Pumpage
1977	18,564,000	22,114,000	21,680,000	18,809,000	19,986,000	13,226,000	3,360,000	5,000	268,000		118,012,000	MLGW 66420		Yearly	Net Pumpage
1978	16,055,000	20,785,000	21,316,000	20,517,000	21,086,000	13,779,000	3,545,000	34,000	361,000		117,478,000	MLGW 67562	MLGW 67848	Monthly	
1979	17,419,000	20,294,000	19,867,000	22,645,000	22,164,000	14,125,000	2,869,000	4,000	327,000		119,714,000	MLGW 67831	MLGW 67835	Monthly	
1980	20,744,000	20,953,000	21,591,000	23,151,000	20,700,000	13,262,000	3,186,000	53,000	343,000		123,983,000	MLGW 67818	MLGW 67882	Monthly	
1981	21,229,000	20,375,000	19,305,000	21,633,000	21,556,000	11,526,000	3,425,000	20,000	339,000		119,408,000	MLGW 67805	MLGW 67809	Monthly	
1982	21,465,000	17,526,000	20,508,000	22,524,000	19,124,000	11,591,000	2,850,000	5,618,000	421,000		121,627,000	MLGW 67791	MLGW 67795	Monthly	
1983	22,914,000	17,338,000	20,947,000	22,163,000	17,269,000	12,705,000	179,000	10,874,000	465,000		124,855,983	MLGW 67778	MLGW 67782	Monthly	
1984	20,743,000	18,693,000	21,102,000	21,850,000	20,772,000	12,244,000	724,000	11,091,000	460,000		127,680,984	MLGW 67765	MLGW 67769	Monthly	
1985	20,499,000	21,784,000	23,607,000	21,550,000	20,764,000	11,294,000	255,000	11,402,000	500,274	-	131,655,274	MLGW 0003		Yearly	Net Pumpage
1986	20,310,411	20,834,795	24,906,027	24,151,781	20,575,068	12,620,548	138,904	12,447,671	554,247	-	136,539,452	GWI 013666	GWI 013684	Monthly	
1987	18,876,438	20,218,082	24,590,411	24,483,562	20,714,795	12,785,753	293,425	12,953,425	530,411	-	135,446,301	GWI 013685	GWI 013722	Monthly	
1988	21,445,479	21,059,178	24,733,973	25,466,575	20,743,562	12,714,521	1,681,096	14,218,082	526,849	-	142,589,315	GWI 012946	GWI 013051	Monthly	
1989	19,761,096	19,727,397	21,925,753	24,121,370	20,559,726	11,349,589	3,776,712	13,705,753	397,260	-	135,324,658	GWI 013082	GWI 013208	Monthly	Some Net pumpage used for Nov - MLGW 00005
1990	21,005,205	19,690,959	24,137,260	23,247,945	19,839,178	10,447,671	4,101,644	12,236,712	434,247	5,867,397	141,008,219	GWI 01321	GWI 013384	Monthly	Net pumpage used for Jan - MLGW 00005
1991	20,998,082	20,714,795	21,012,603	21,771,507	18,516,438	10,135,890	5,079,178	10,465,753	393,151	10,983,562	140,070,959	GWI 012341	GWI 012487	Monthly	
1992	20,023,836	20,626,849	20,444,110	21,130,685	19,223,562	9,701,918	5,337,534	10,458,904	423,014	11,872,603	139,243,014	GWI 012490	GWI 012636	Monthly	
1993	19,548,219	20,222,192	21,248,767	21,801,644	18,483,836	9,960,000	4,808,767	12,719,726	497,534	10,325,479	139,616,164	GWI 012639	GWI 012785	Monthly	
1994	20,627,397	15,901,370	21,576,712	21,936,438	17,695,890	11,866,027	4,938,356	14,360,548	477,260	12,982,466	142,362,466	GWI 012787	GWI 012943	Monthly	
1995	20,570,137	16,029,315	22,800,548	21,915,342	17,398,082	12,569,863	4,903,562	17,106,301	529,589	14,177,260	148,000,000	GWI 011938	GWI 012085	Monthly	
1996	20,170,137	17,329,589	22,532,055	21,929,041	17,373,425	14,135,616	4,668,767	18,168,767	515,342	13,058,630	149,881,370	GWI 012087	GWI 012235	Monthly	
1997	19,556,438	15,529,315	22,114,521	21,377,534	15,968,493	14,602,466	4,284,658	16,915,068	444,384	14,880,000	145,672,877	GWI 012239	GWI 012337	Monthly	Net pumpage used for Sept-Dec - MLGW 00009
1998	21,355,068	17,229,863	22,910,137	23,288,767	15,794,795	15,442,466	4,090,411	17,976,986	419,726	17,894,795	156,403,014	GWI 011534	GWI 011631	Monthly	Net pumpage used for Jan-Apr - MLGW 00009
1999	21,441,370	18,560,548	25,246,575	23,447,397	16,404,932	12,718,356	5,067,945	18,886,027	493,425	19,609,863	161,876,438	GWI 011632	GWI 011767	Monthly	Some Net pumpage used - MLGW 00010
2000	21,641,370	17,321,096	24,287,123	22,502,466	17,129,589	13,992,603	4,998,082	19,012,329	369,315	20,854,521	162,108,493	GWI 011773	GWI 011911	Monthly	Net pumpage used for May - MLGW 00010
2001	19,443,014	17,588,767	19,972,329	19,626,575	16,318,904	17,500,548	4,785,205	17,477,260	446,301	20,248,493	153,407,397	MLGW 00011		Yearly	Net Pumpage
2002	18,140,000	17,300,000	22,000,000	18,550,000	15,550,000	19,000,000	4,525,000	18,000,000	475,000	20,983,333	154,523,333	MLGW2 03771 **CD**		Monthly	
2003	15,616,666	15,708,333	22,383,333	18,133,333	16,066,667	19,508,333	5,108,333	18,941,667	334,167	20,100,000	151,900,832	MLGW2 03771 **CD**		Monthly	
2004	15,775,000	16,075,000	21,858,333	17,700,000	16,341,667	19,641,667	5,150,000	18,741,667	400,000	22,666,667	154,350,001	MLGW2 03771 **CD**		Monthly	
2005	15,266,667	17,141,667	21,675,000	19,158,333	17,700,000	20,225,000	3,383,333	18,783,333	558,333	23,000,000	156,891,666	MLGW2 03771 **CD**		Monthly	
2006	16,658,333	16,575,000	21,358,333	19,550,000	17,458,333	20,566,667	4,166,667	18,341,667	358,333	21,200,000	156,233,333	MLGW2 03771 **CD**		Monthly	

Table 2 - Pumpage Amounts From MLGW and DeSoto County

Year	Shelby County (MGD)	DeSoto County (MGD)
1965	72.1	0.90
1966	75.9	0.90
1967	77.8	0.90
1968	81.2	0.90
1969	82.8	0.90
1970	90.5	1.23
1971	96.0	1.23
1972	99.2	1.23
1973	108.7	1.23
1974	109.7	1.23
1975	110.4	4.18
1976	111.4	4.18
1977	118.2	4.18
1978	117.7	4.18
1979	119.9	4.18
1980	124.2	4.18
1981	119.6	4.18
1982	121.8	4.18
1983	125.1	3.60
1984	127.9	3.60
1985	131.9	3.60
1986	136.8	3.60
1987	135.7	3.60
1988	142.8	3.60
1989	135.6	3.60
1990	141.3	3.60

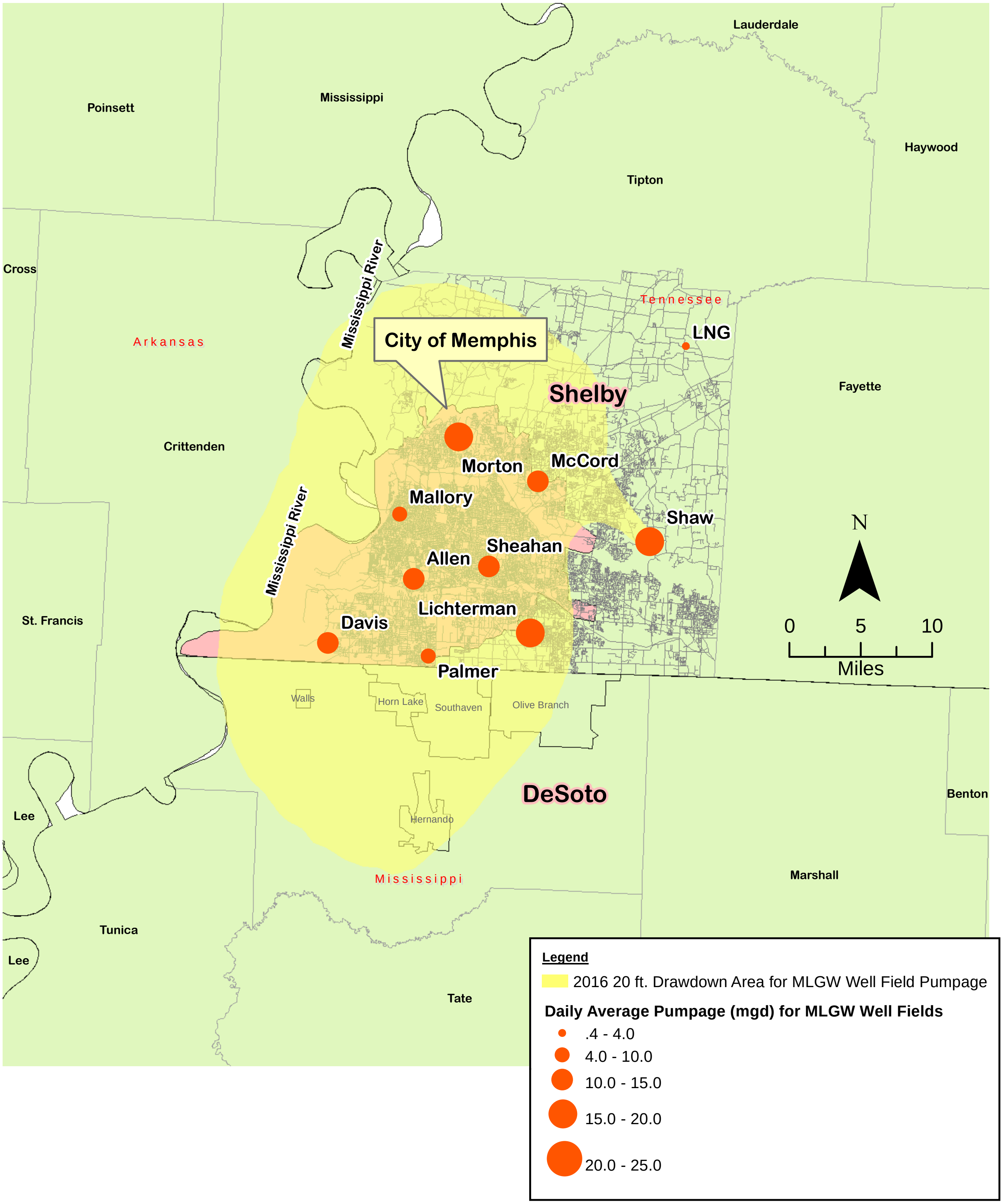
Year	Shelby County (MGD)	DeSoto County (MGD)
1991	140.3	3.60
1992	139.5	3.60
1993	139.9	3.60
1994	142.6	3.60
1995	148.3	13.04
1996	150.1	13.04
1997	145.9	13.04
1998	156.7	13.04
1999	162.2	13.04
2000	162.4	13.43
2001	153.7	13.43
2002	154.8	13.43
2003	152.2	13.43
2004	154.6	13.43
2005	157.2	13.97
2006	149.8	14.47
2007	151.9	11.09
2008	142.6	10.68
2009	135.9	12.44
2010	147.6	14.44
2011	147.6	13.37
2012	140.7	15.31
2013	132.4	18.27
2014	132.3	17.35
2015	125.6	19.83
2016	123.9	19.83

Table 3 - Volume of Groundwater Taken
From Mississippi Due to MLGW Pumpage

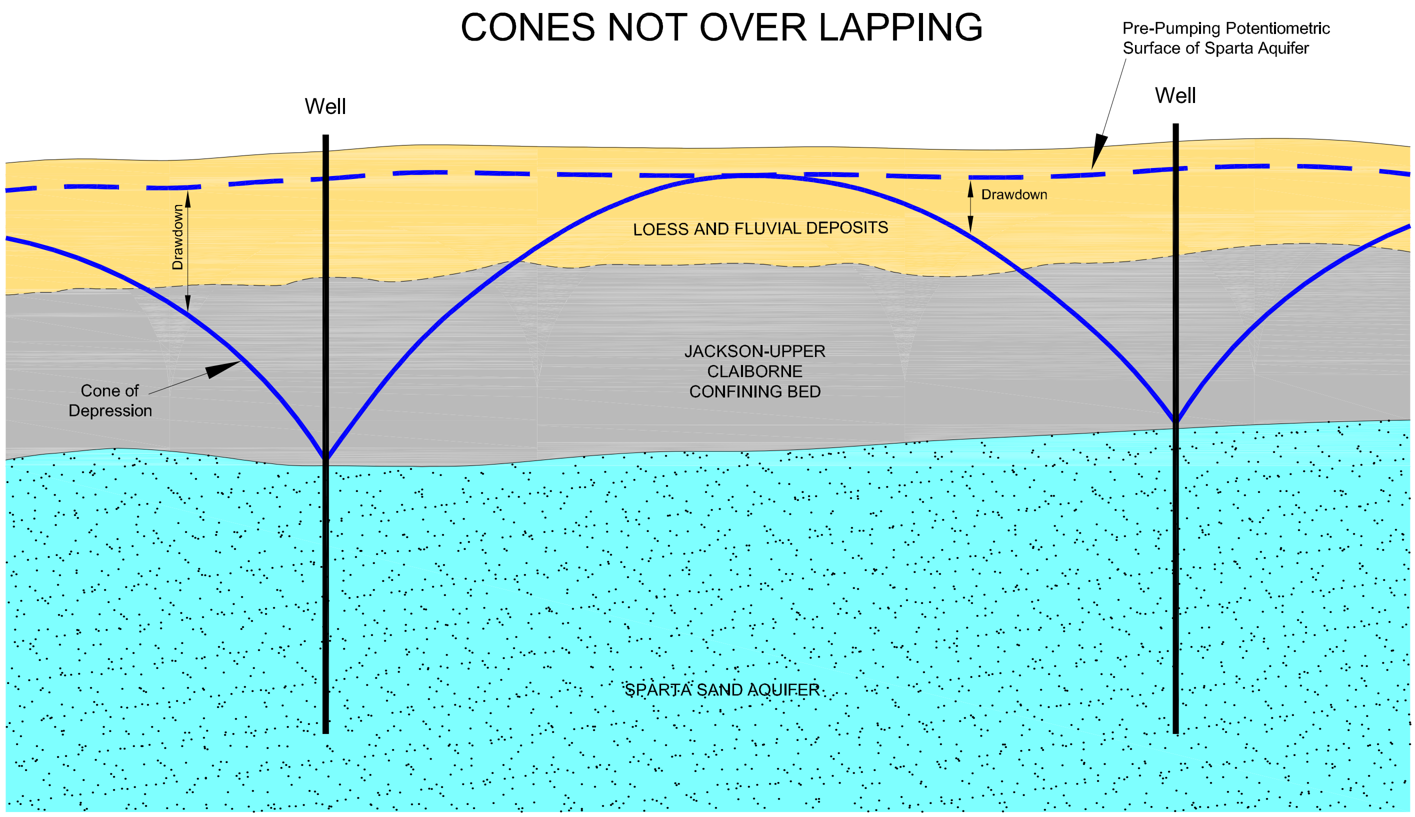
Year	MGD
1965	12.9
1966	14.5
1967	15.3
1968	16.0
1969	16.5
1970	18.6
1971	19.8
1972	21.1
1973	22.5
1974	22.9
1975	21.8
1976	21.9
1977	23.5
1978	23.6
1979	24.0
1980	25.1
1981	23.6
1982	23.8
1983	23.9
1984	23.9
1985	24.3
1986	25.8
1987	25.6
1988	27.2
1989	25.8
1990	26.1

Year	MGD
1991	25.1
1992	24.5
1993	24.8
1994	25.3
1995	23.1
1996	23.5
1997	22.7
1998	24.3
1999	24.8
2000	24.4
2001	22.9
2002	23.2
2003	23.0
2004	22.9
2005	22.7
2006	21.6
2007	22.3
2008	20.5
2009	18.6
2010	19.8
2011	20.2
2012	18.6
2013	15.7
2014	16.2
2015	14.1
2016	13.5

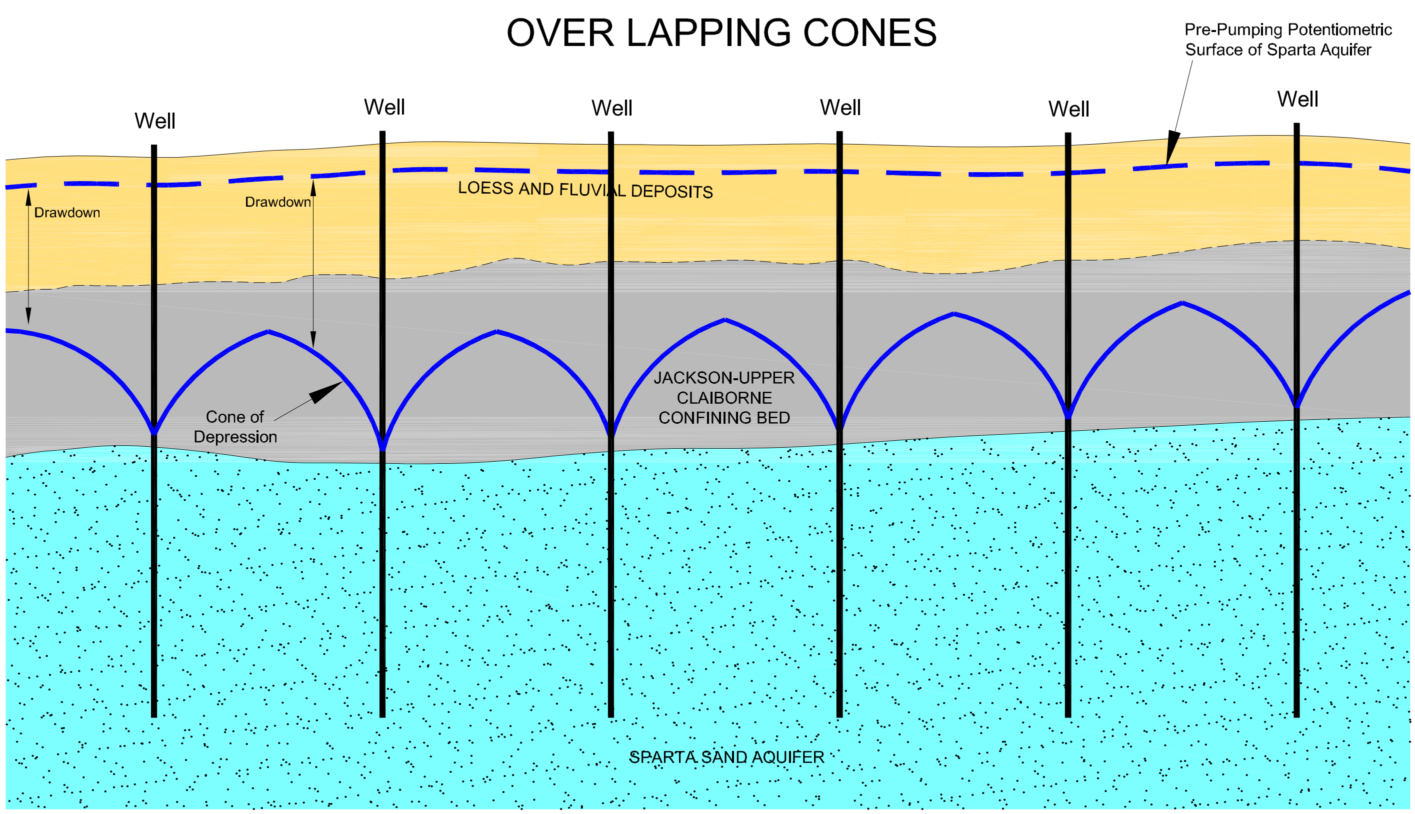
FIGURES



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE PROJECT AREA	PREPARED BY: LEGGETTE, BRASHEARS & GRAHAM, INC. Professional Ground-Water and Environmental Engineering Services Cypress Point Office Park 10014 North Dale Mabry Highway, Suite 205 Tampa, FLorida 33618 (813) 968-5882	Acad ☑ GIS Corel	DRAWN BY: TDH CHECKED BY: DAW DATE: June 2017 FILE NAME: Figure01.MXD FIGURE NO.: 1



Not to Scale & Vertically Exaggerated



Not to Scale & Vertically Exaggerated

DATE	REVISED

FILE NAME: FIGURE02.DWG

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

HYDROGEOLOGIC CROSS SECTION SHOWING AN EXAMPLE OF CONES OF DEPRESSION

PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway - Suite 205
Tampa, FL 33618
(813) 968-5882

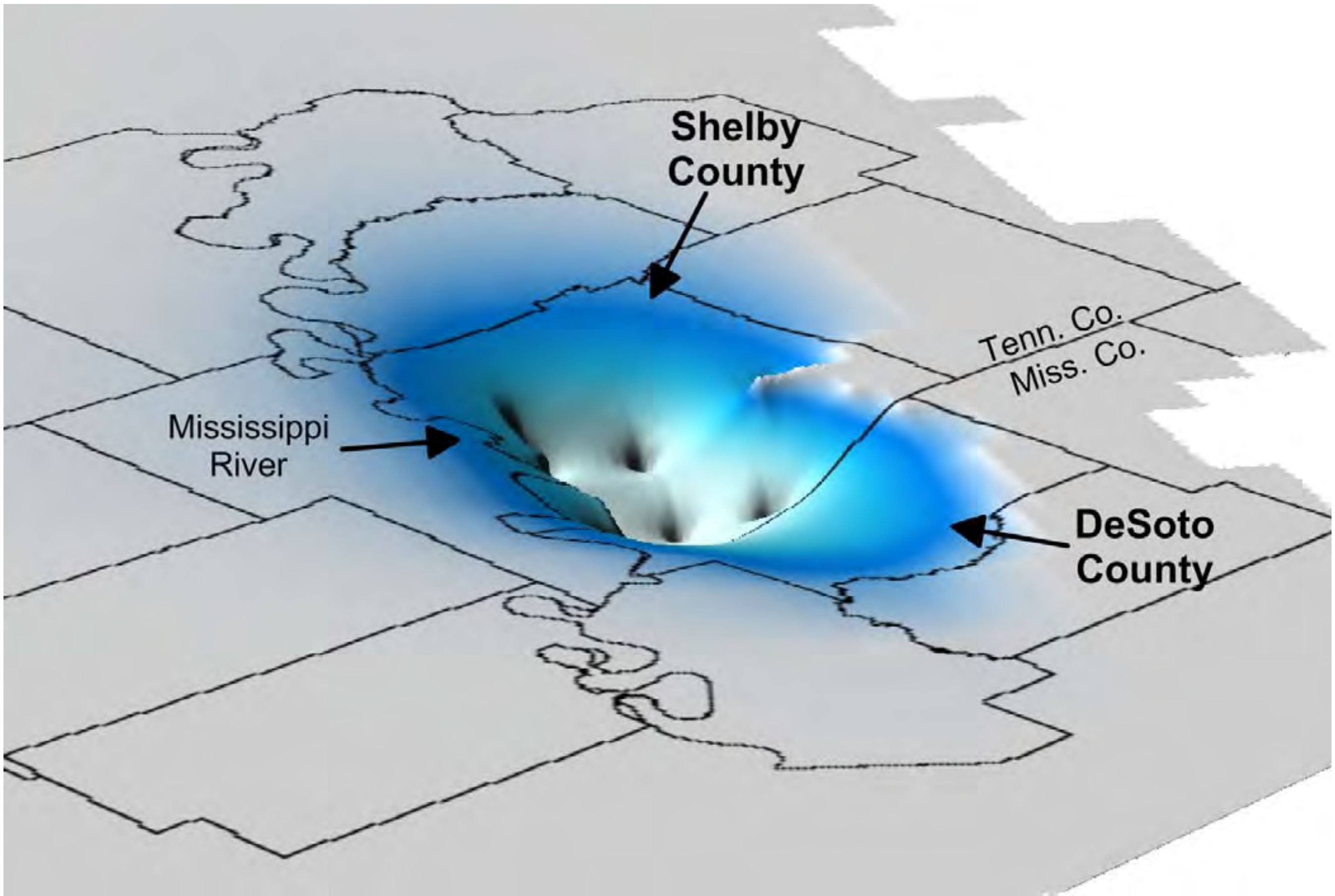
DRAWN: TDH

CHECKED: DAW

DATE: Jun. 2017

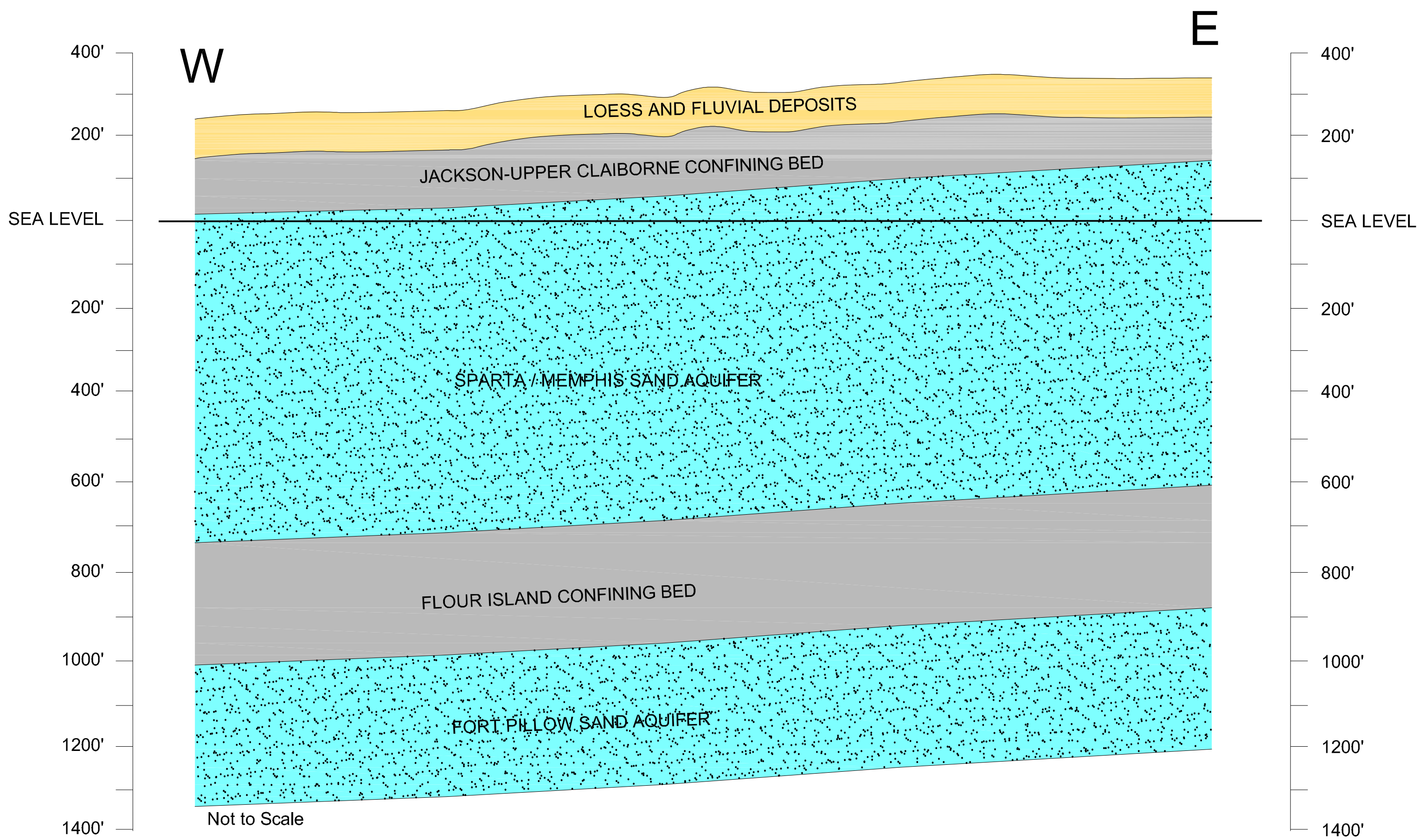
FIGURE: 2

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure02a.dwg, 6/28/2017 11:46:58 AM, Adobe PDF



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE THREE-DIMENSIONAL ILLUSTRATION SHOWING CONE OF DEPRESSION	PREPARED BY:	LEGGETTE, BRASHEARS & GRAHAM, INC. Professional Ground-Water and Environmental Engineering Services Cypress Point Office Park 10014 North Dale Mabry Highway, Suite 205 Tampa, FLorida 33618 (813) 968-5882	☐ Acad ☑ GIS ☐ Corel	DRAWN BY: TDH CHECKED BY: DAW DATE: Jun. 2017 FILE NAME: Figure03.MXD FIGURE NO.: 3

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure03.mxd



DATE	REVISED

FILE NAME: FIGURE04.DWG

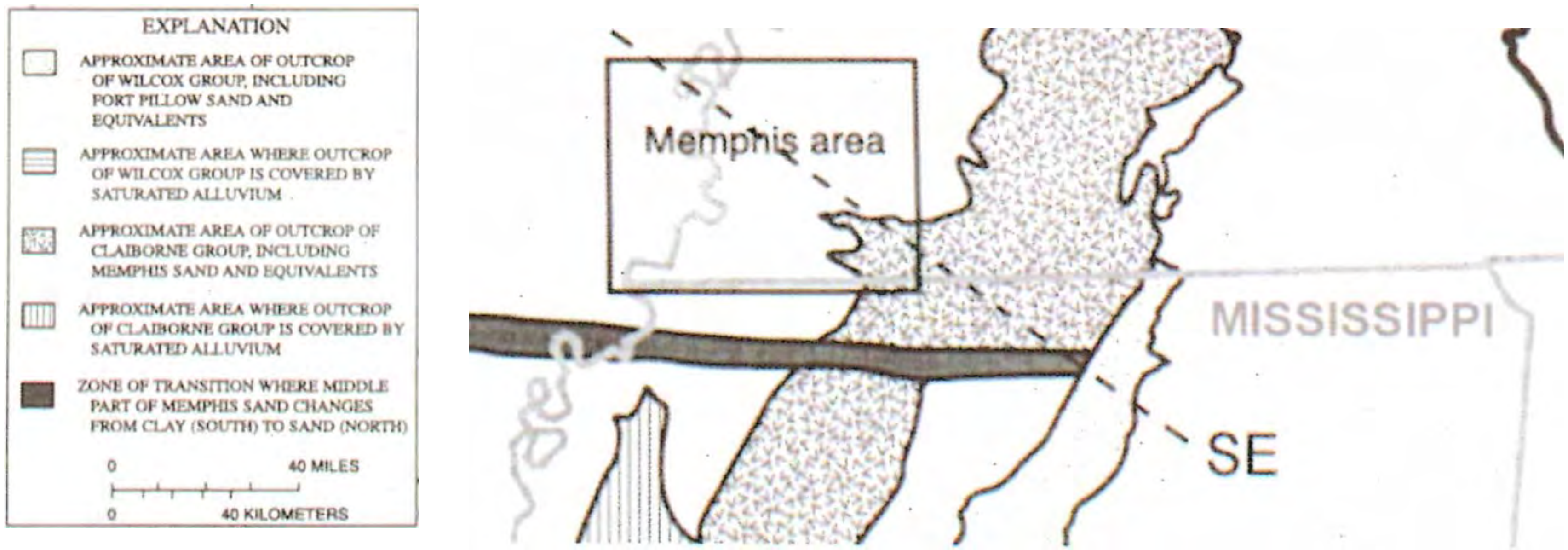
UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

HYDROGEOLOGIC CROSS SECTION SHOWING THE PRINCIPAL AQUIFERS AND CONFINING BEDS IN THE STUDY AREA

PREPARED BY:
LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway - Suite 205
Tampa, FL 33618
(813) 968-5882

DRAWN:	TDH
CHECKED:	DAW
DATE:	Jun. 2017
FIGURE:	4

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure04.dwg, 6/28/2017 11:53:45 AM, Adobe PDF



Map of the northern Mississippi Embayment (NME) showing approximate distribution of outcrop and subcrop of the Wilcox and Claiborne group sediments (From Brahana and Broshears, 2001). Dashed line shows trace of cross-section shown in Figure 3.

DATE	REVISED

☐ Acad ☑ GIS ☐ Corel

FILE NAME: FIGURE05.MXD

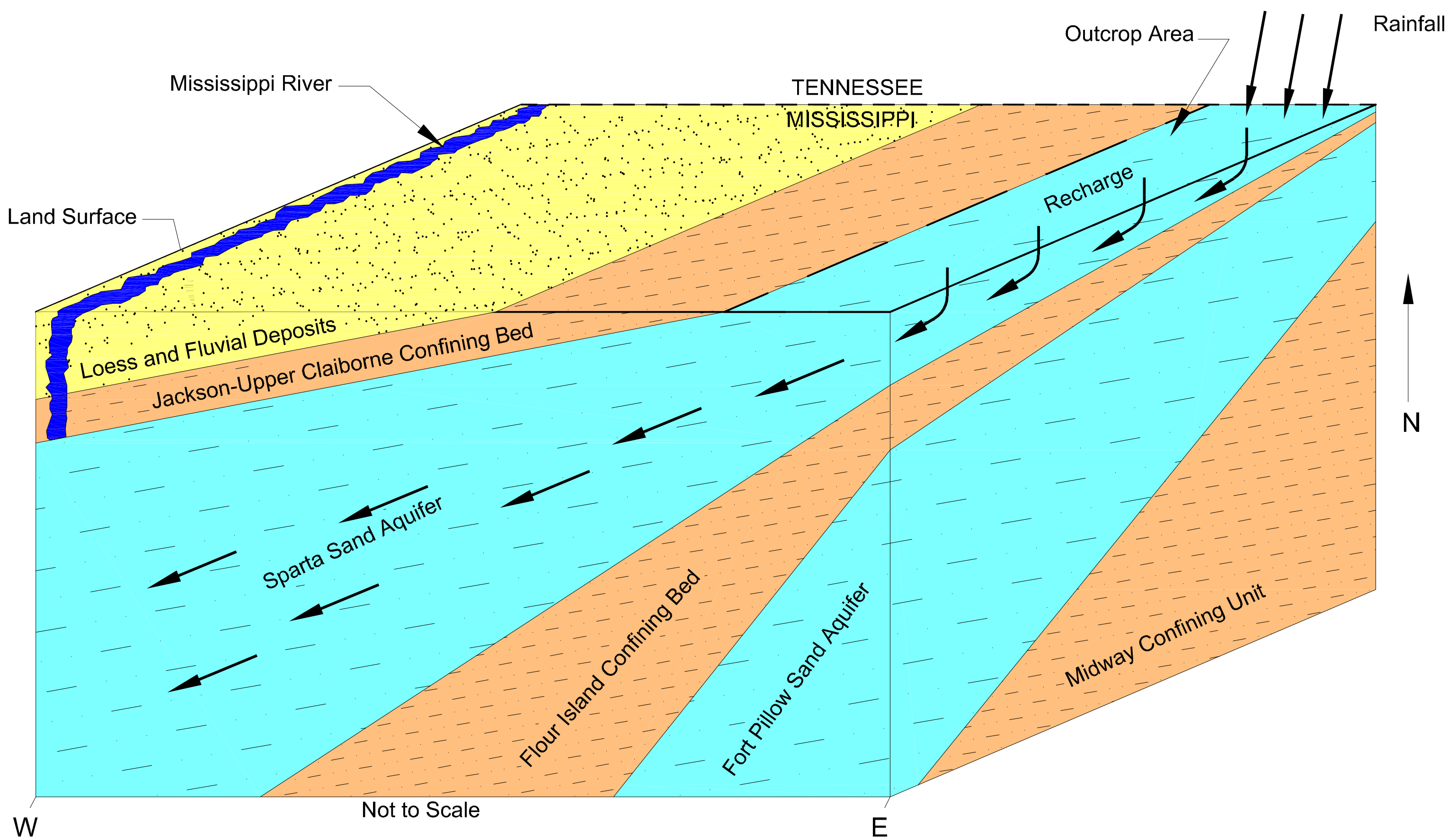
UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

MAP FROM THE NORTHERN MISSISSIPPI EMBAYMENT

PREPARED BY:
LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Groundwater and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

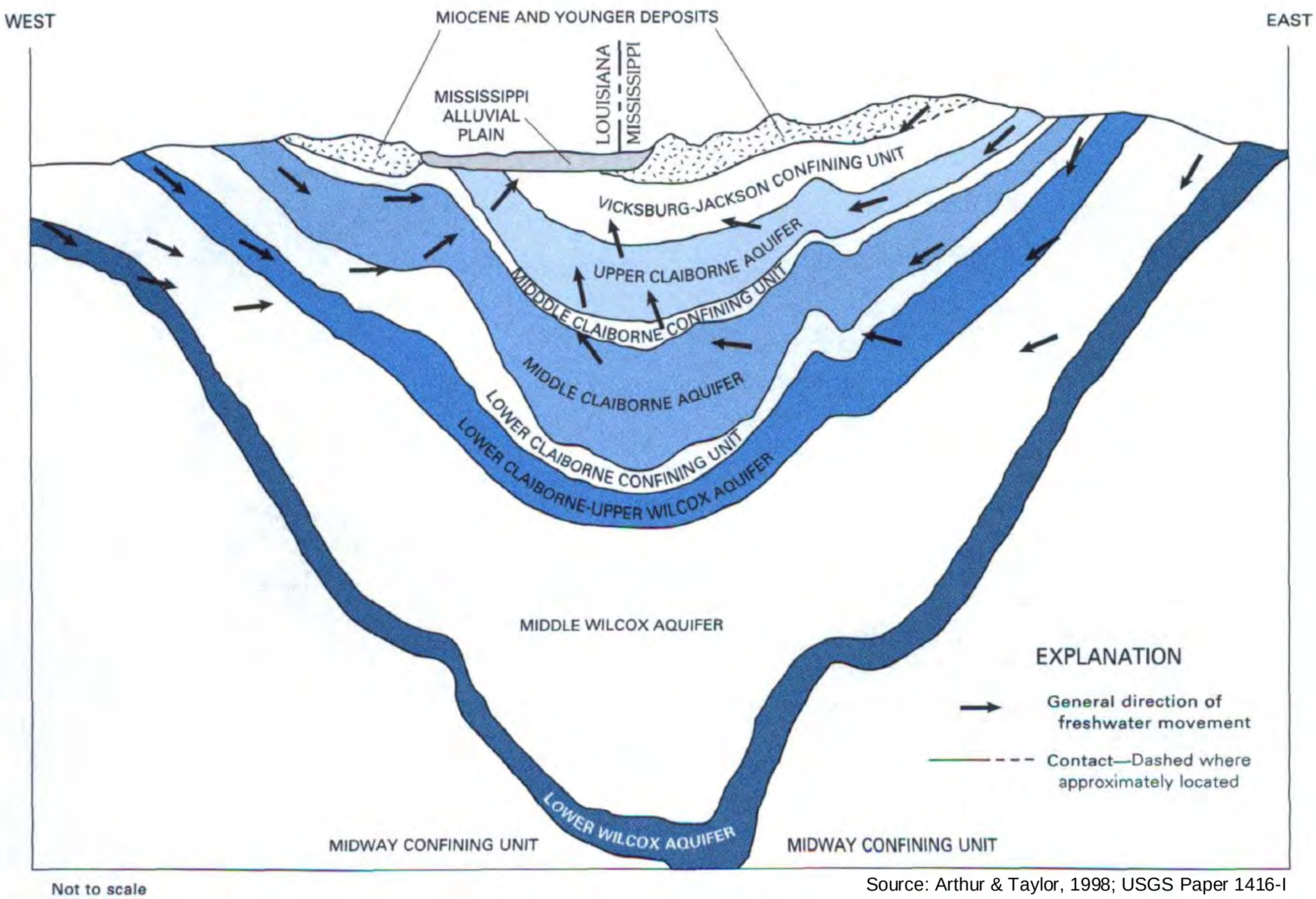
DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	Jun. 2017
FIGURE NO.:	5

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure05.mxd



DATE	REVISED	UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE	PREPARED BY:	DRAWN: TDH
		HYDROGEOLOGIC CROSS SECTION ILLUSTRATING RECHARGE AT OUTCROP AND GROUNDWATER FLOW	LEGGETTE, BRASHEARS & GRAHAM, INC. Professional Ground-Water and Environmental Engineering Services Cypress Point Office Park 10014 North Dale Mabry Highway - Suite 205 Tampa, FL 33618 (813) 968-5882	CHECKED: DAW
				DATE: Jun. 2017
FILE NAME: FIGURE06.DWG				FIGURE: 6

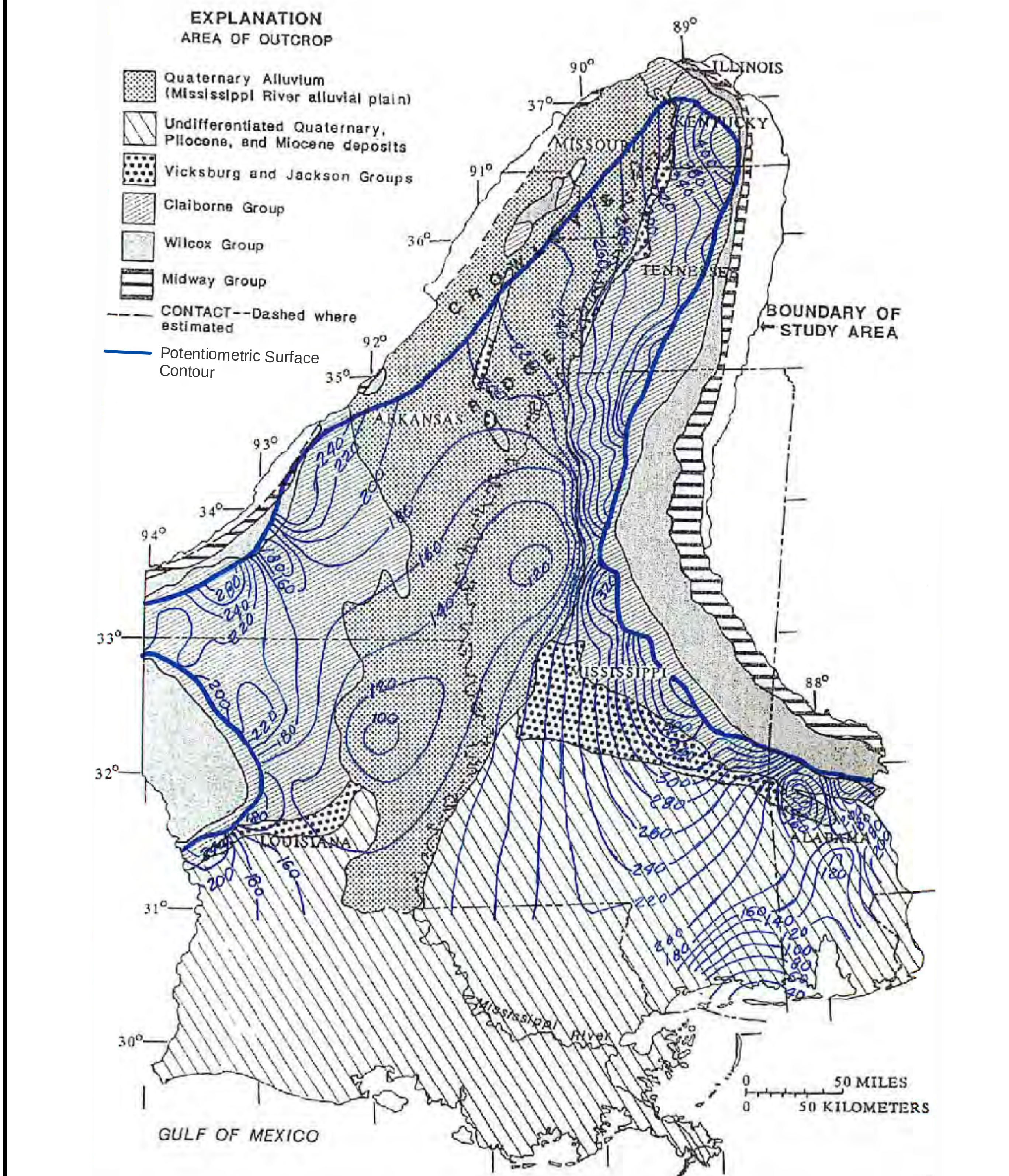
C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure06.dwg, 6/28/2017 12:10:09 PM, Adobe PDF



Source: Arthur & Taylor, 1998; USGS Paper 1416-I

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE HYDROGEOLOGIC SECTION OF PRINCIPAL AQUIFERS AND CONFINING UNITS EAST TO WEST THROUGH THE MISSISSIPPI EMBAYMENT WITH GROUNDWATER FLOW DIRECTION	*PREPARED BY:*	**LEGGETTE, BRASHEARS & GRAHAM, INC.** Professional Ground-Water and Environmental Engineering Services Cypress Point Office Park 10014 North Dale Mabry Highway, Suite 205 Tampa, FLorida 33618 (813) 968-5882	☐ Acad ☑ GIS ☐ Corel	*DRAWN BY:* TDH *CHECKED BY:* DAW *DATE:* Jun. 2017 *FILE NAME:* Figure07.MXD *FIGURE NO.:* 7

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure07.mxd



Source: Arthur & Taylor, 1990

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

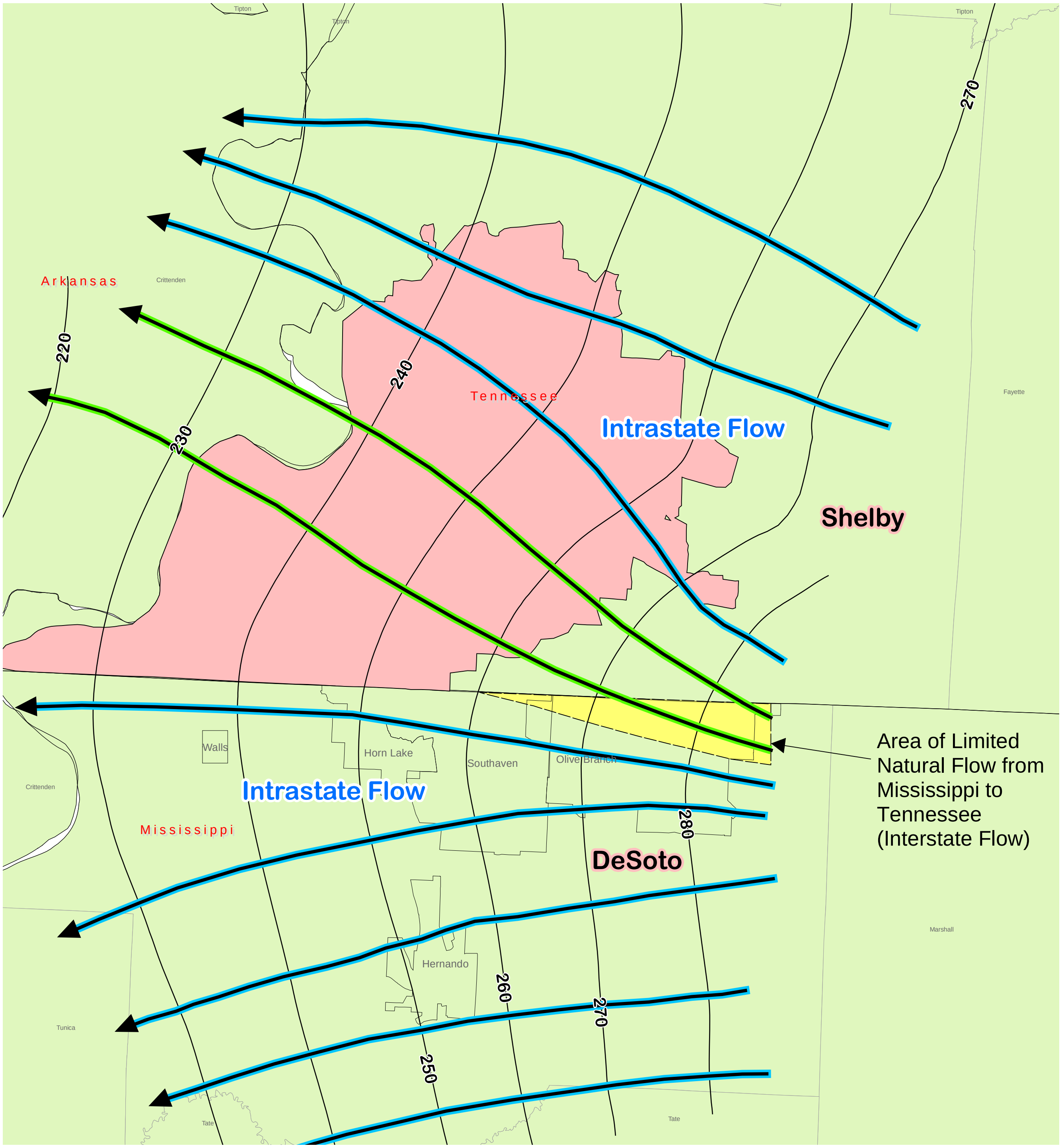
GENERALIZED GEOLOGY OF ENBAYMENT AND PRE-DEVELOPMENT POTENTIOMETRIC SURFACE OF MIDDLE CLAIBORNE AQUIFER

PREPARED BY:

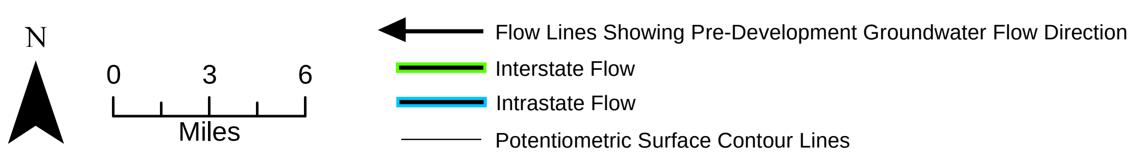
LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	Jun. 2017
FILE NAME:	Figure08.MXD
FIGURE NO.:	8

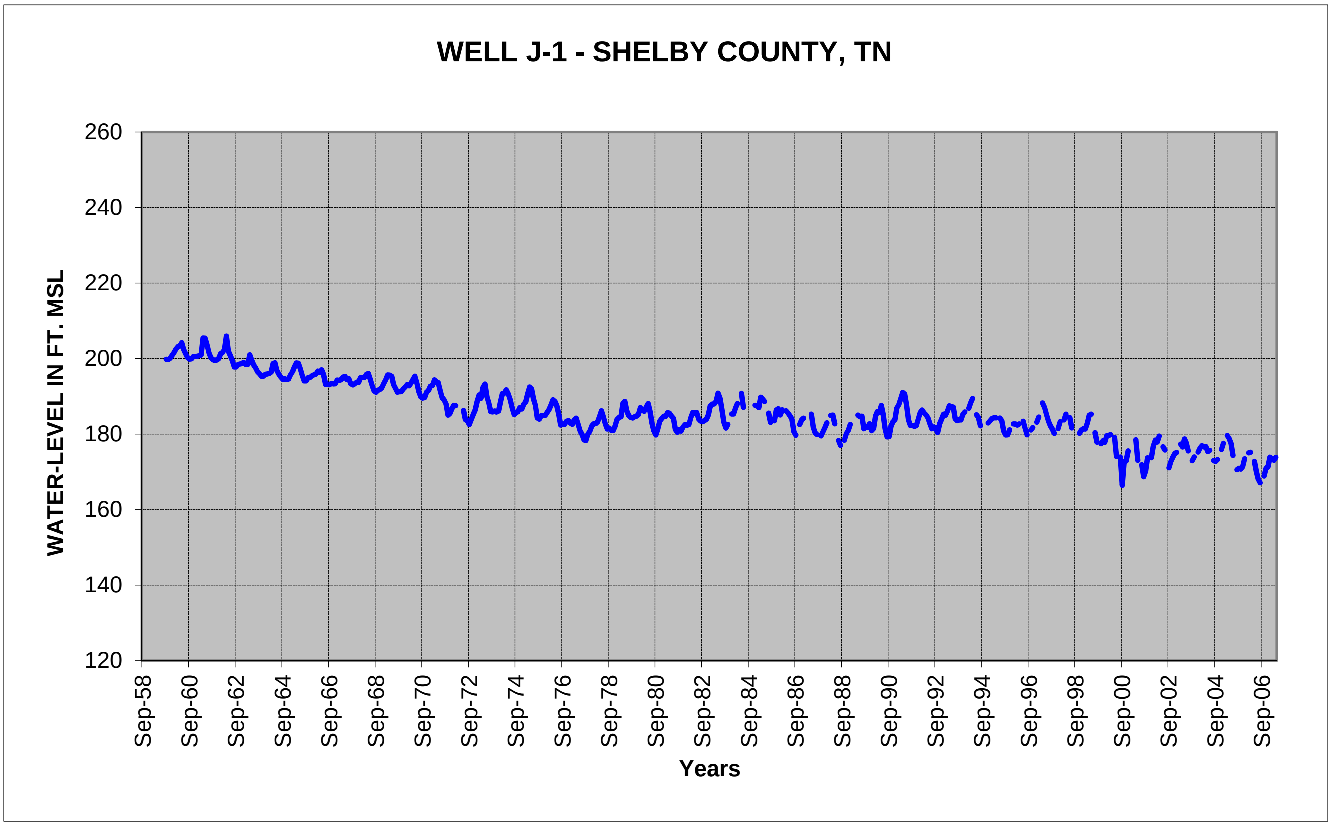


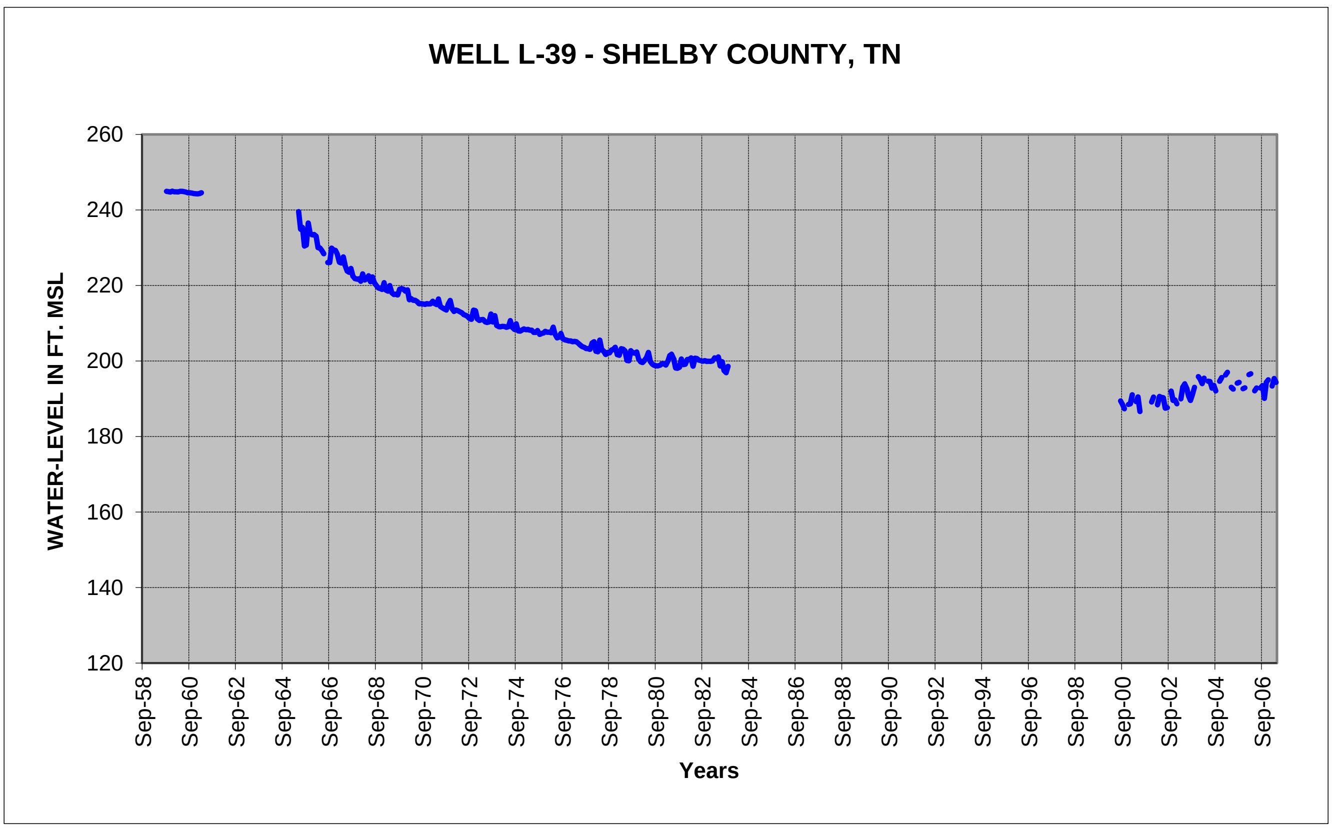
SOURCE: BRAHANA WRI 89-4131



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE 1886 ESTIMATED POTENTIOMETRIC SURFACE MAP FOR PREDEVELOPMENT CONDITIONS	*PREPARED BY:* **LEGGETTE, BRASHEARS & GRAHAM, INC.** Professional Ground-Water and Environmental Engineering Services Cypress Point Office Park 10014 North Dale Mabry Highway, Suite 205 Tampa, FLorida 33618 (813) 968-5882	Acad GIS Corel	*DRAWN BY:* TDH *CHECKED BY:* DAW *DATE:* Feb. 2017 *FILE NAME:* Figure09.MXD *FIGURE NO.:* 9

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure09.mxd





UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

SPARTA / MEMPHIS SAND AQUIFER HYDROGRAPHS

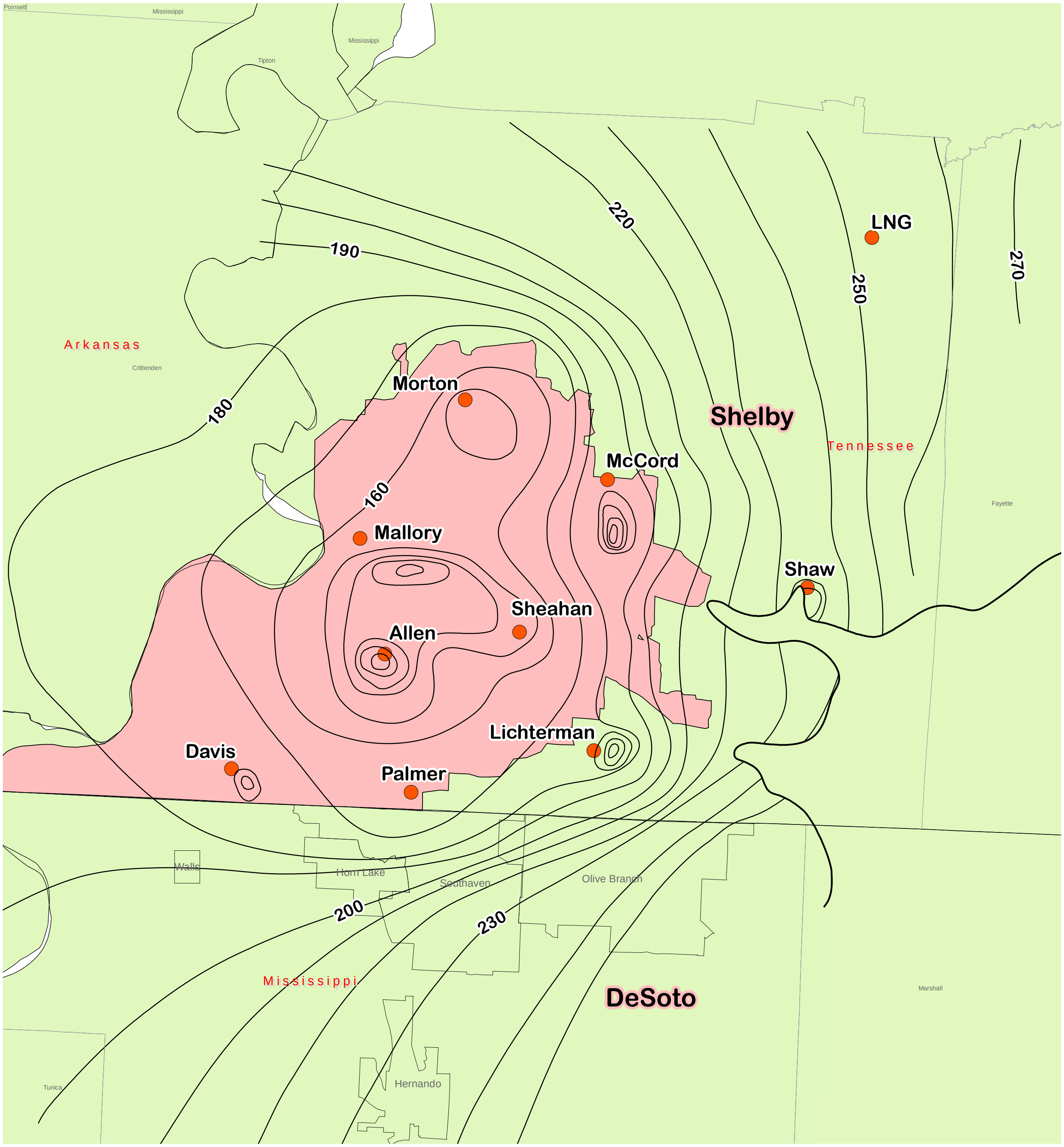
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	Jun. 2017
FILE NAME:	Figure10.xls
FIGURE NO.:	10

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure10.xlsx



Source: Tenn., USGS

N

0 3 6
Miles

Legend

Potentiometric Surface Contour Lines

MLGW Well Fields

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

USGS 2000 POTENTIOMETRIC SURFACE MAP

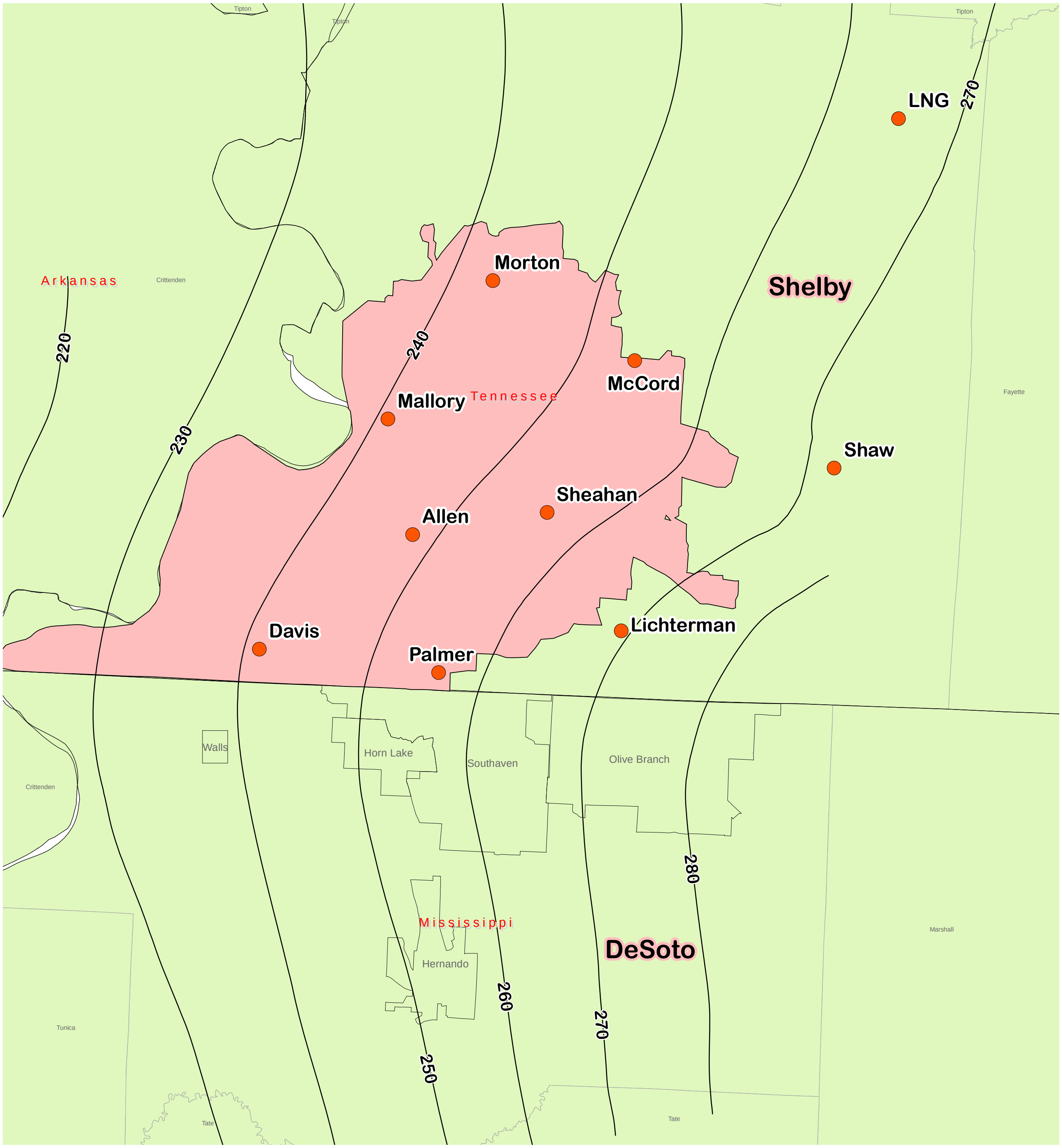
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

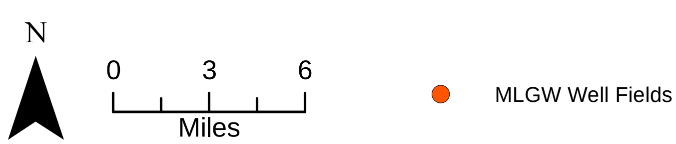
Acad
GIS
Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	Jun. 2017
FILE NAME:	Figure11.MXD
FIGURE NO.:	11

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure11.mxd



SOURCE: BRAHANA WRI 89-4131



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

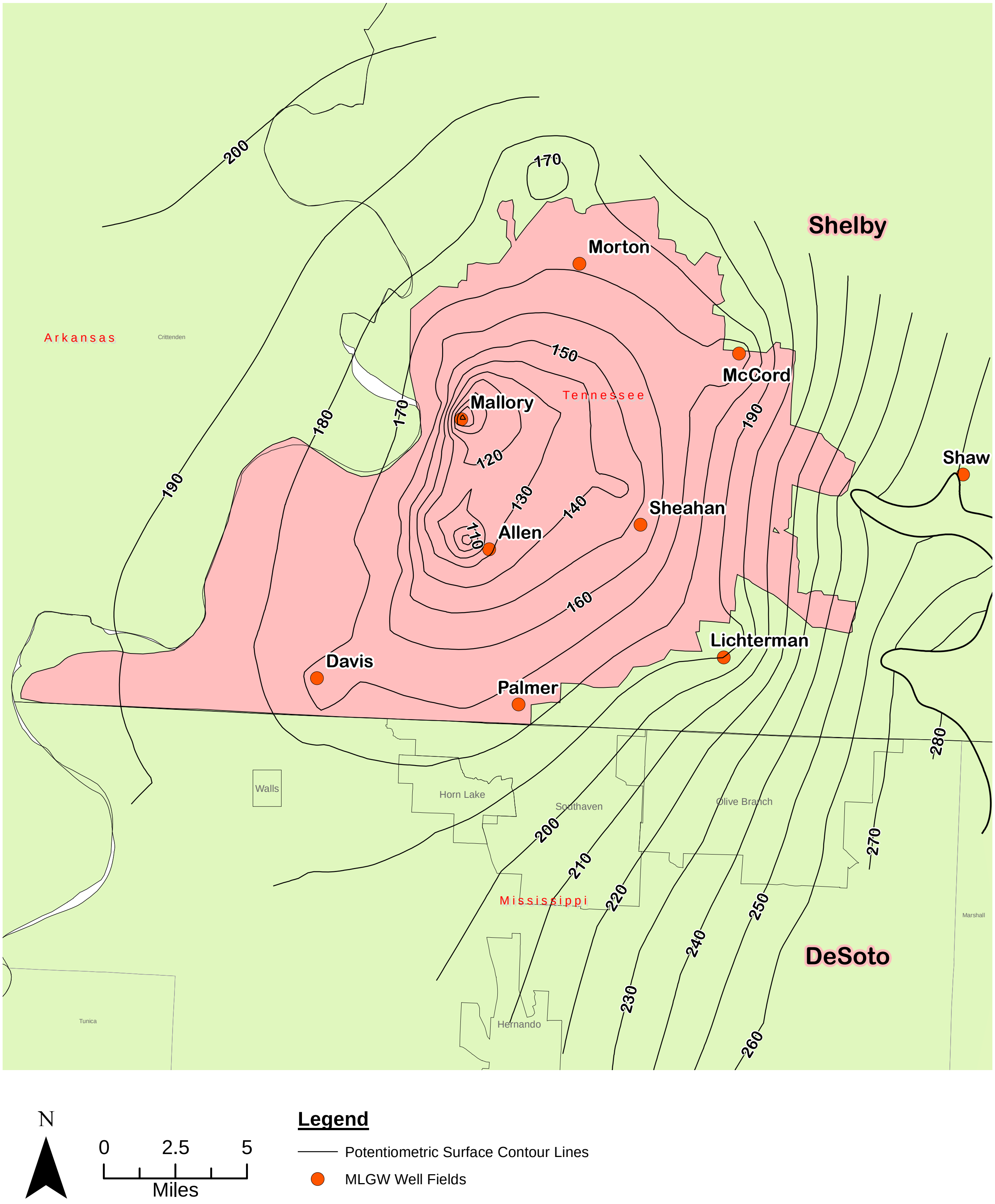
1886 ESTIMATED POTENTIOMETRIC SURFACE MAP FOR PREDEVELOPMENT CONDITIONS

PREPARED BY: **LEGGETTE, BRASHEARS & GRAHAM, INC.**
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*Apr. 2014*
FILE NAME:	*Figure12.MXD*
FIGURE NO.:	*12*

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure12.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

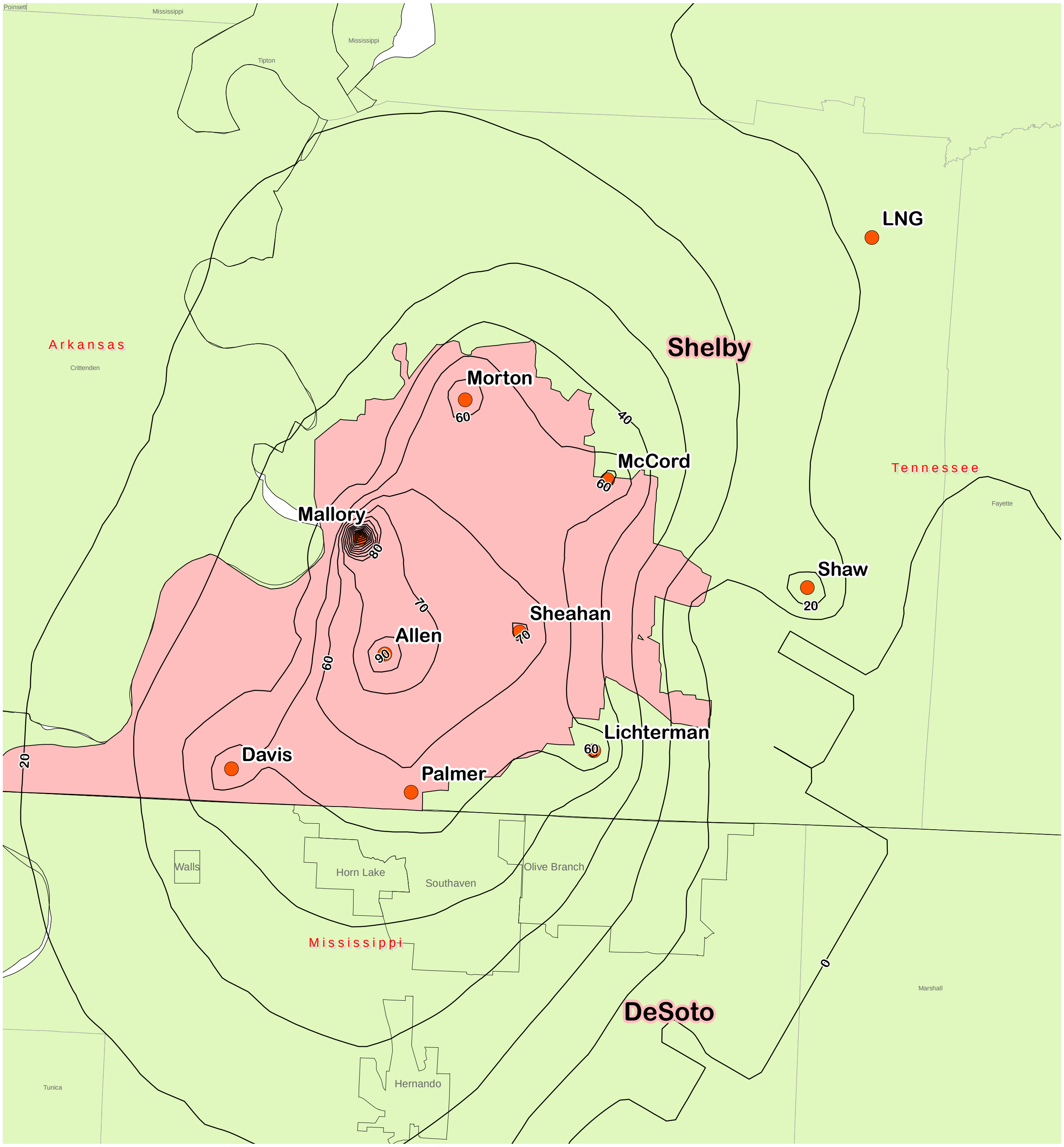
1980 POTENTIOMETRIC SURFACE MAP DEVELOPED FROM GROUNDWATER MODEL

PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	Jun. 2017
FILE NAME:	Figure13.MXD
FIGURE NO.:	13



Source: Tenn., USGS

N

0 3 6

Miles

Legend

Drawdown Contours

MLGW Well Fields

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2013 DRAWDOWN CONTOUR MAP
DEVELOPED FROM GROUNDWATER MODEL

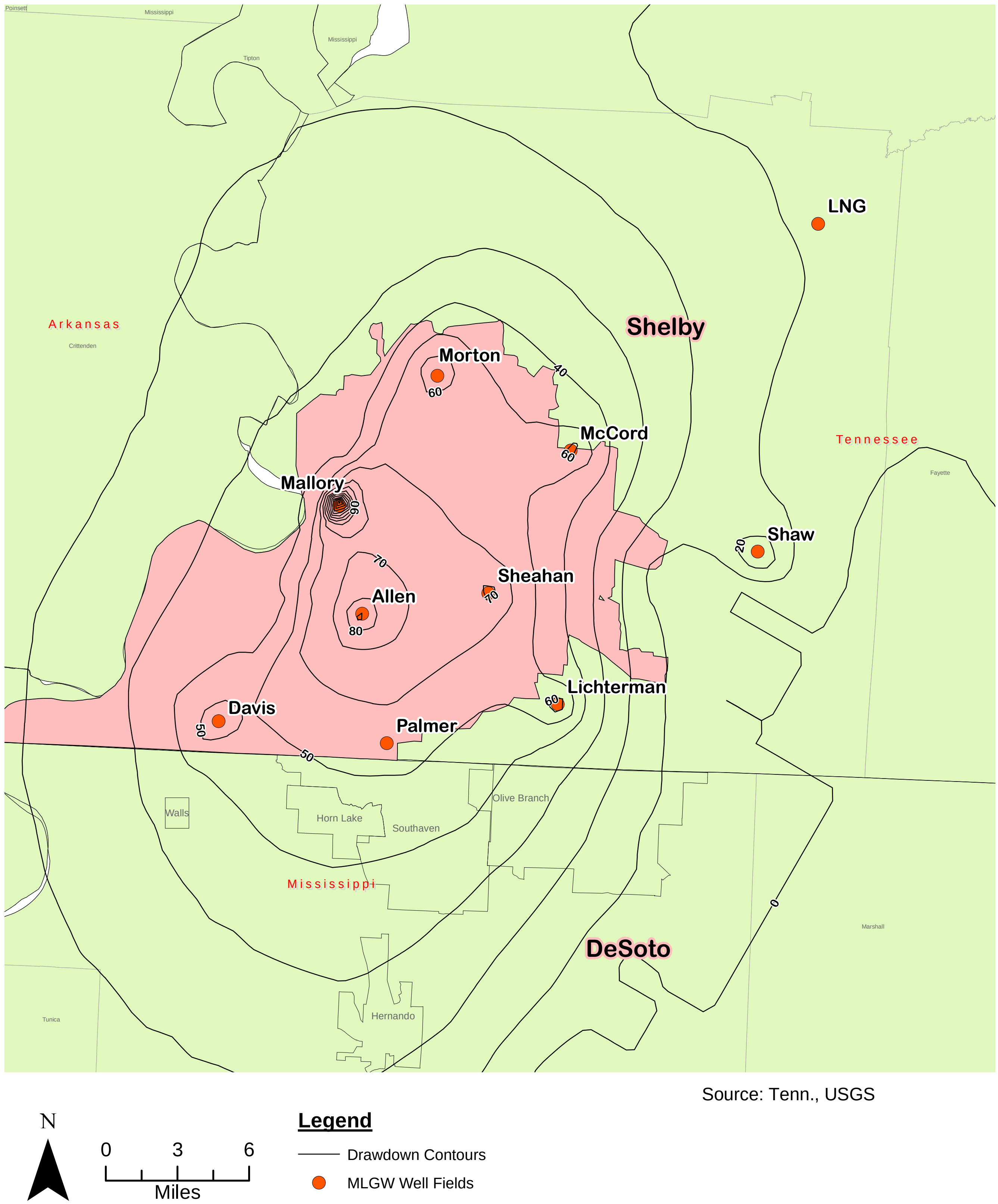
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*June 2017*
FILE NAME:	*Figure14.MXD*
FIGURE NO.:	*14*

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure14.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2014 DRAWDOWN CONTOUR MAP DEVELOPED FROM GROUNDWATER MODEL

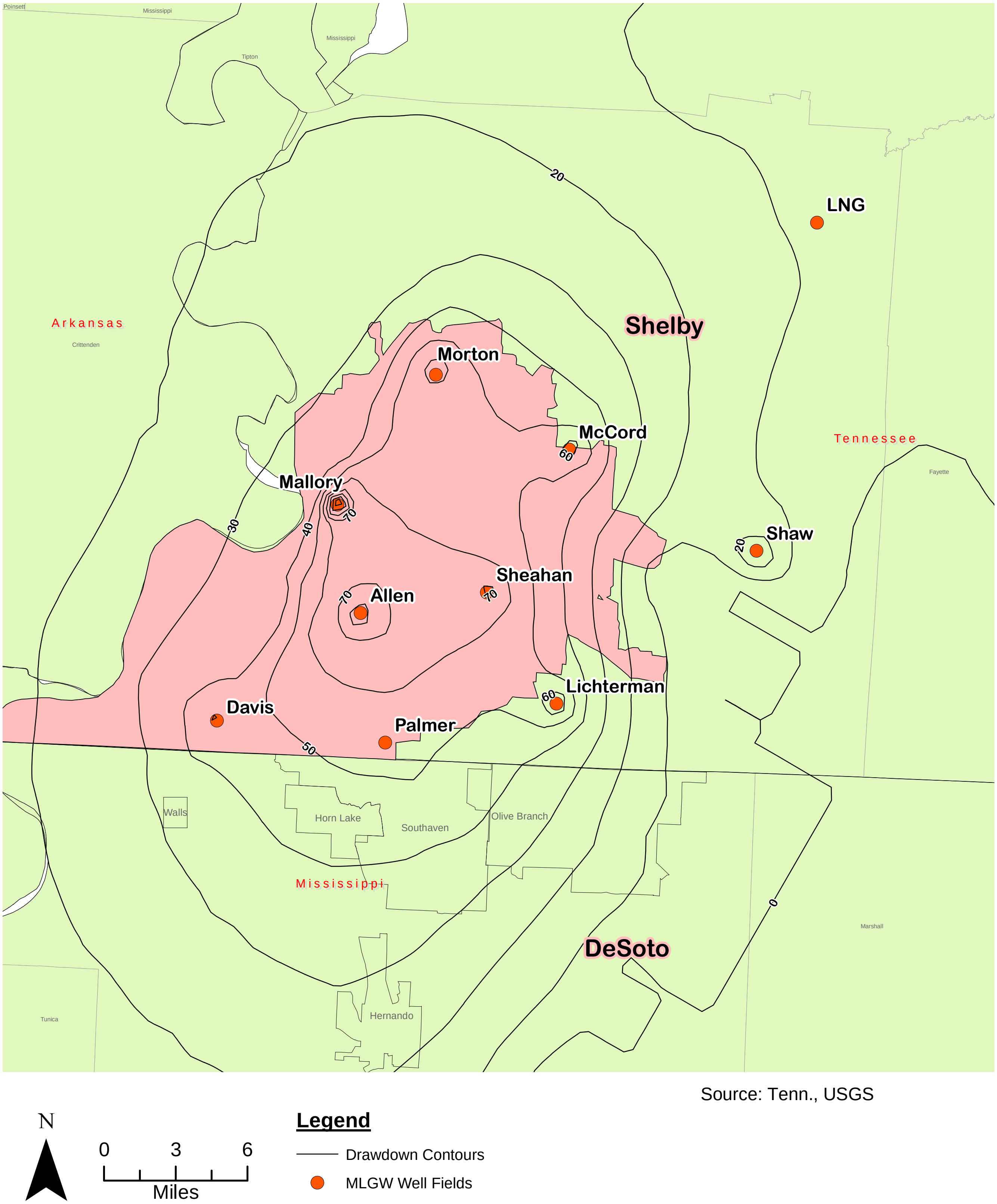
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

☐ Acad
☑ GIS
☐ Corel

DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*June 2017*
FILE NAME:	*Figure15.MXD*
FIGURE NO.:	*15*

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure15.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

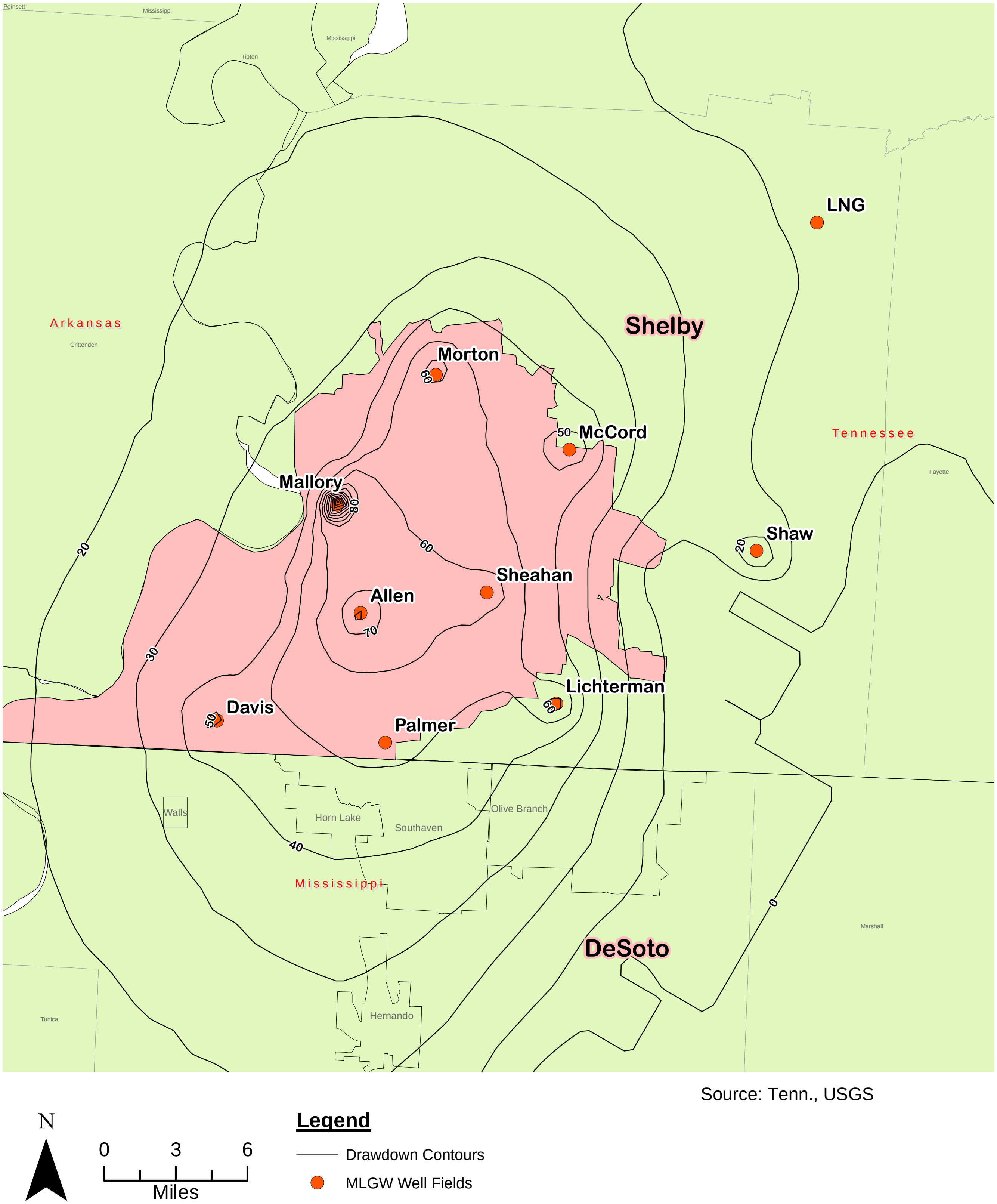
2015 DRAWDOWN CONTOUR MAP DEVELOPED FROM GROUNDWATER MODEL

PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

☐ Acad	DRAWN BY: TDH
☑ GIS	CHECKED BY: DAW
☐ Corel	DATE: June 2017
	FILE NAME: Figure16.MXD
	FIGURE NO.: 16

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure16.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2016 DRAWDOWN CONTOUR MAP DEVELOPED FROM GROUNDWATER MODEL

PREPARED BY:

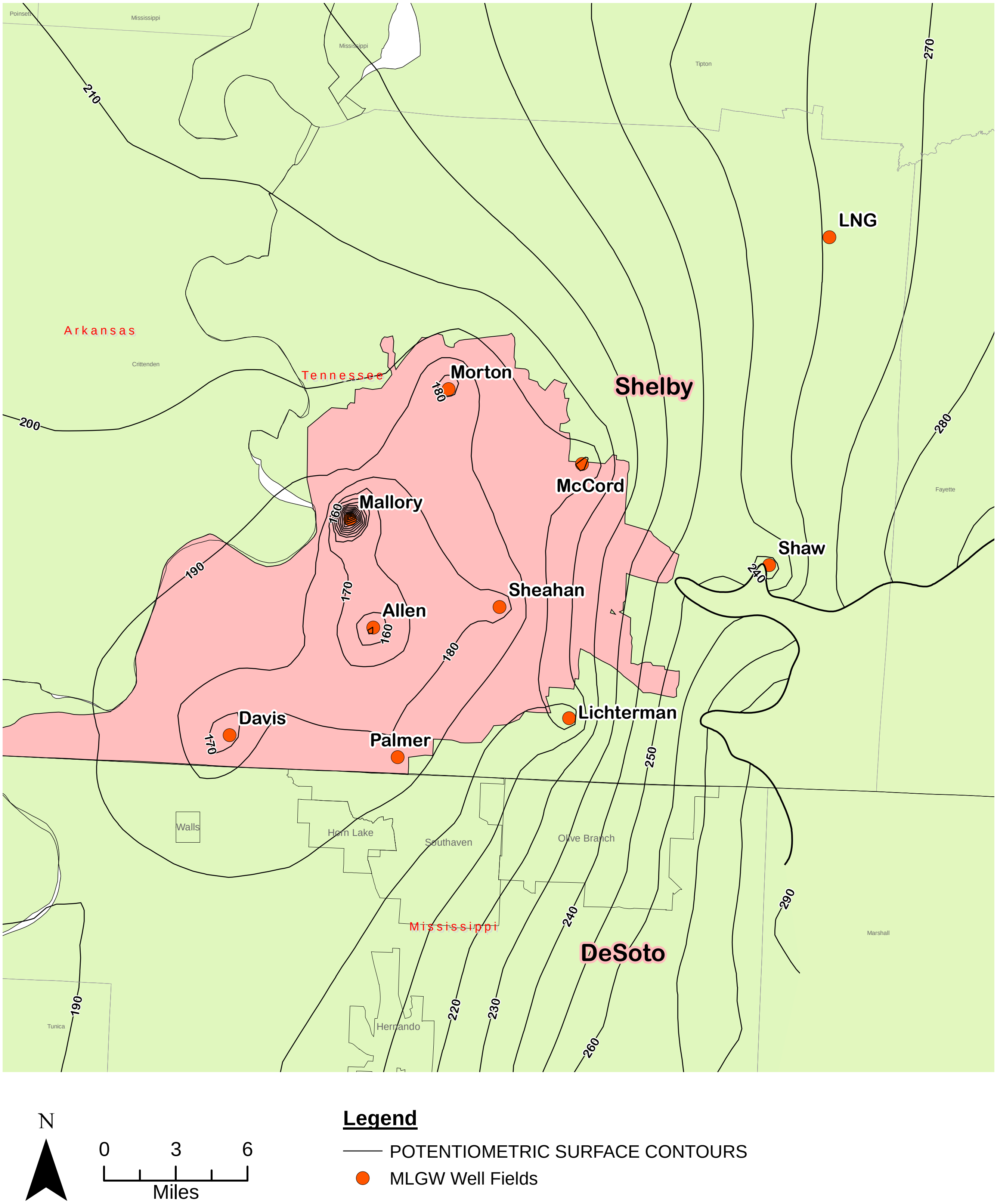
LEGGETTE, BRASHEARS & GRAHAM, INC.

Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

☐ Acad
☑ GIS
☐ Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	June 2017
FILE NAME:	Figure17.MXD
FIGURE NO.:	17

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure17.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2013 POTENTIOMETRIC SURFACE MAP
DEVELOPED FROM GROUNDWATER MODEL

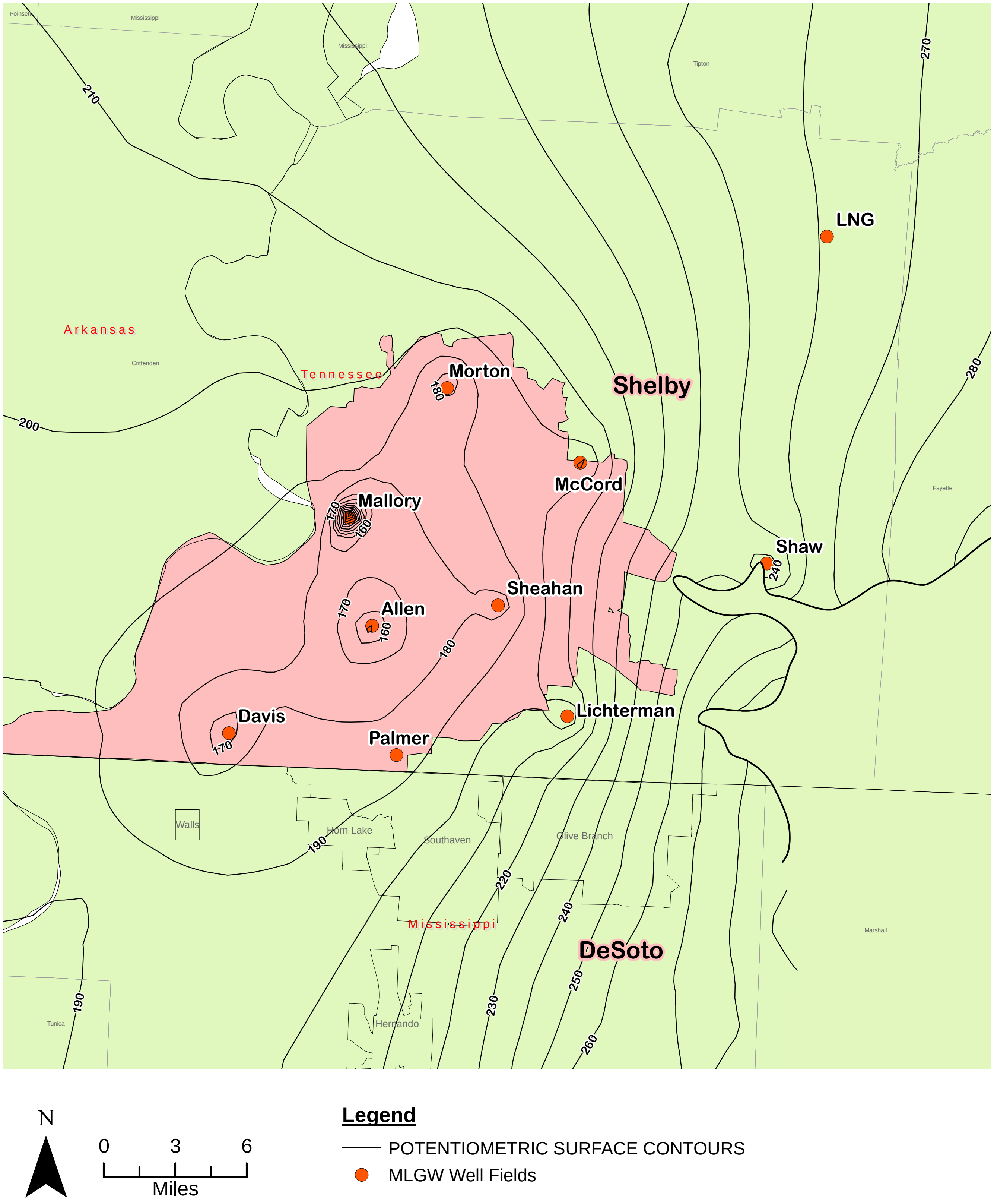
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

☐ Acad
☑ GIS
☐ Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	June 2017
FILE NAME:	Figure18.MXD
FIGURE NO.:	18

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure18.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2014 POTENTIOMETRIC SURFACE MAP DEVELOPED FROM GROUNDWATER MODEL

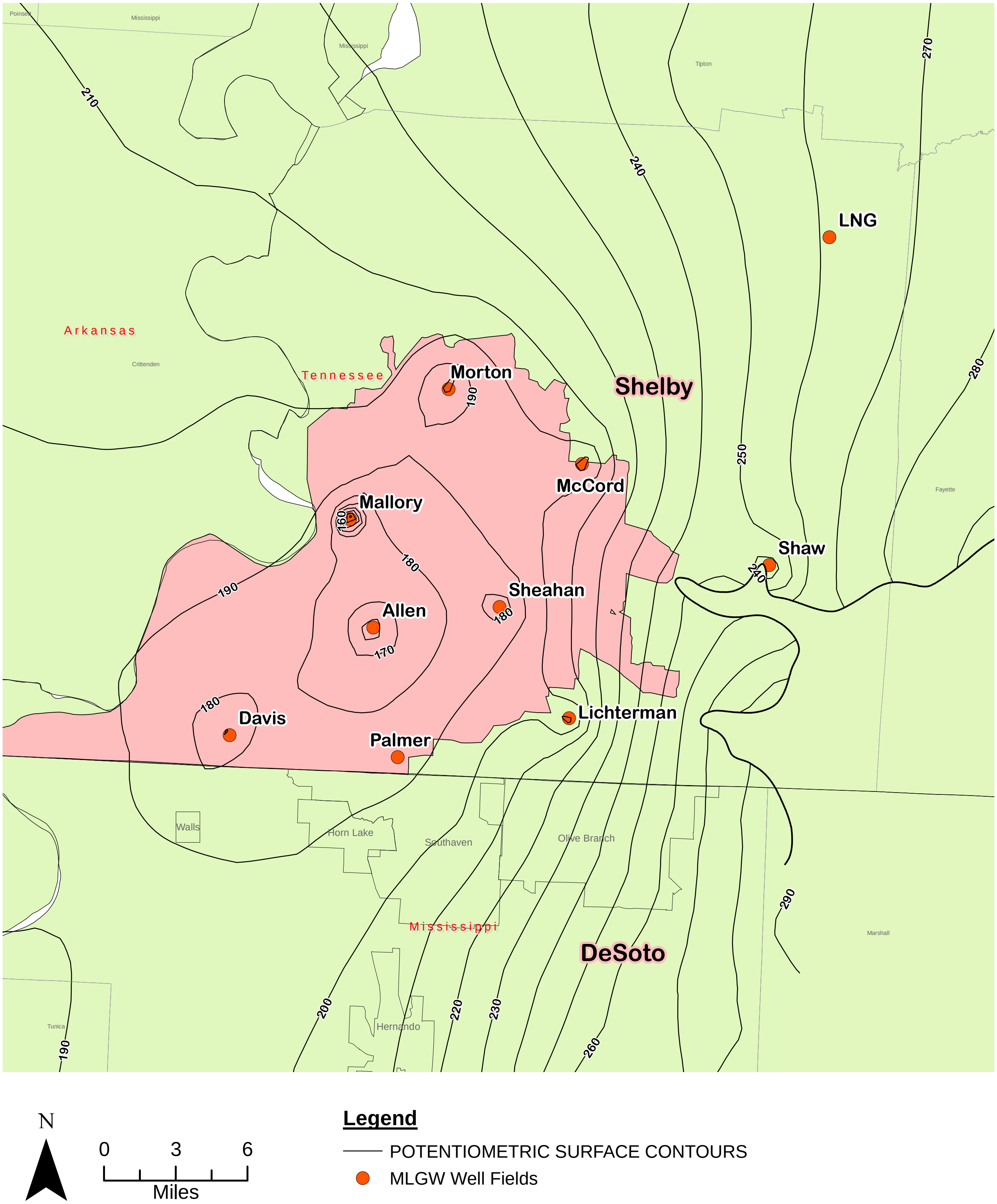
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	June 2017
FILE NAME:	Figure19.MXD
FIGURE NO.:	19

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure19.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2015 POTENTIOMETRIC SURFACE MAP
DEVELOPED FROM GROUNDWATER MODEL

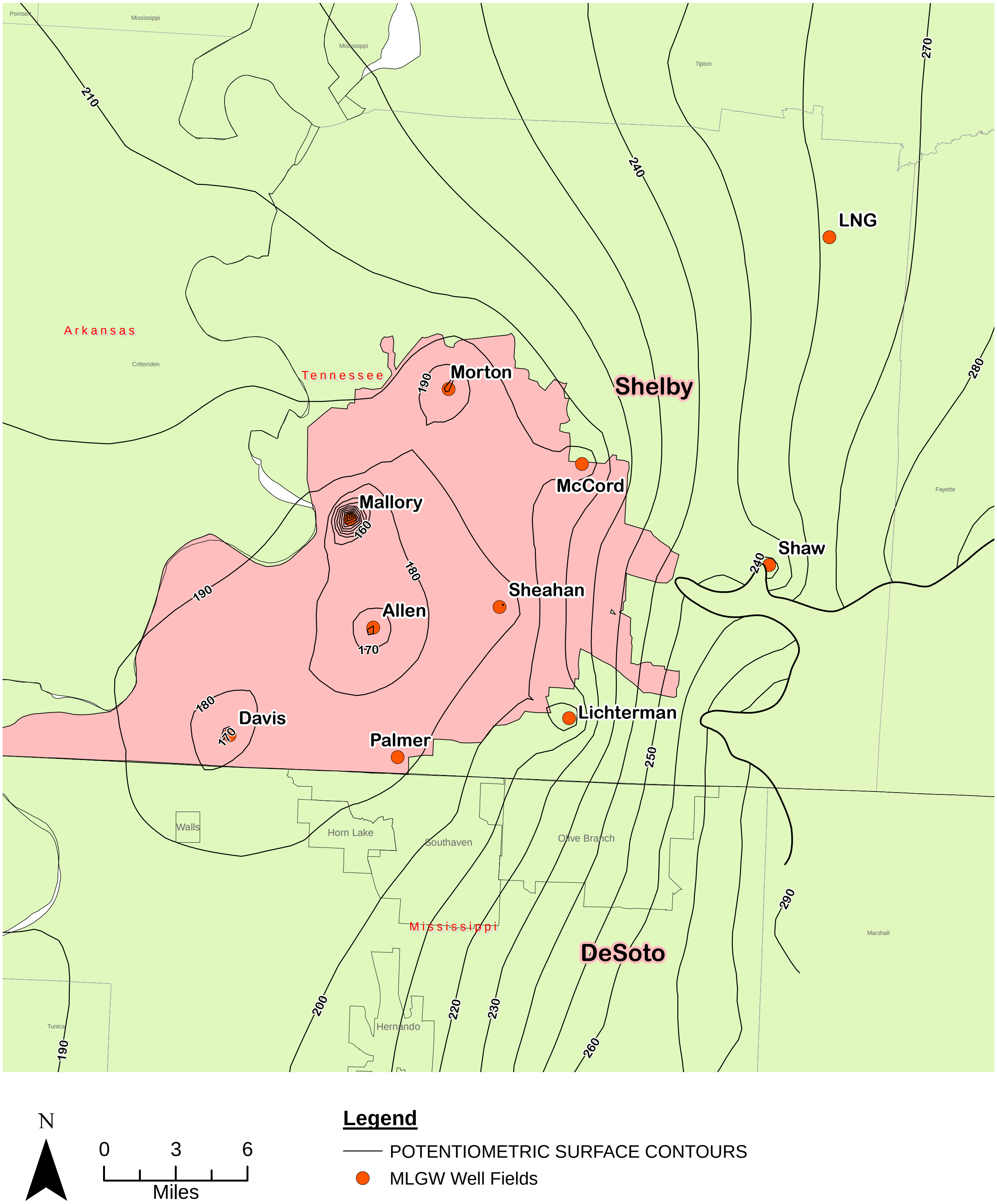
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and
Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*June 2017*
FILE NAME:	*Figure20.MXD*
FIGURE NO.:	20

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure20.mxd



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2016 POTENTIOMETRIC SURFACE MAP
DEVELOPED FROM GROUNDWATER MODEL

PREPARED BY:

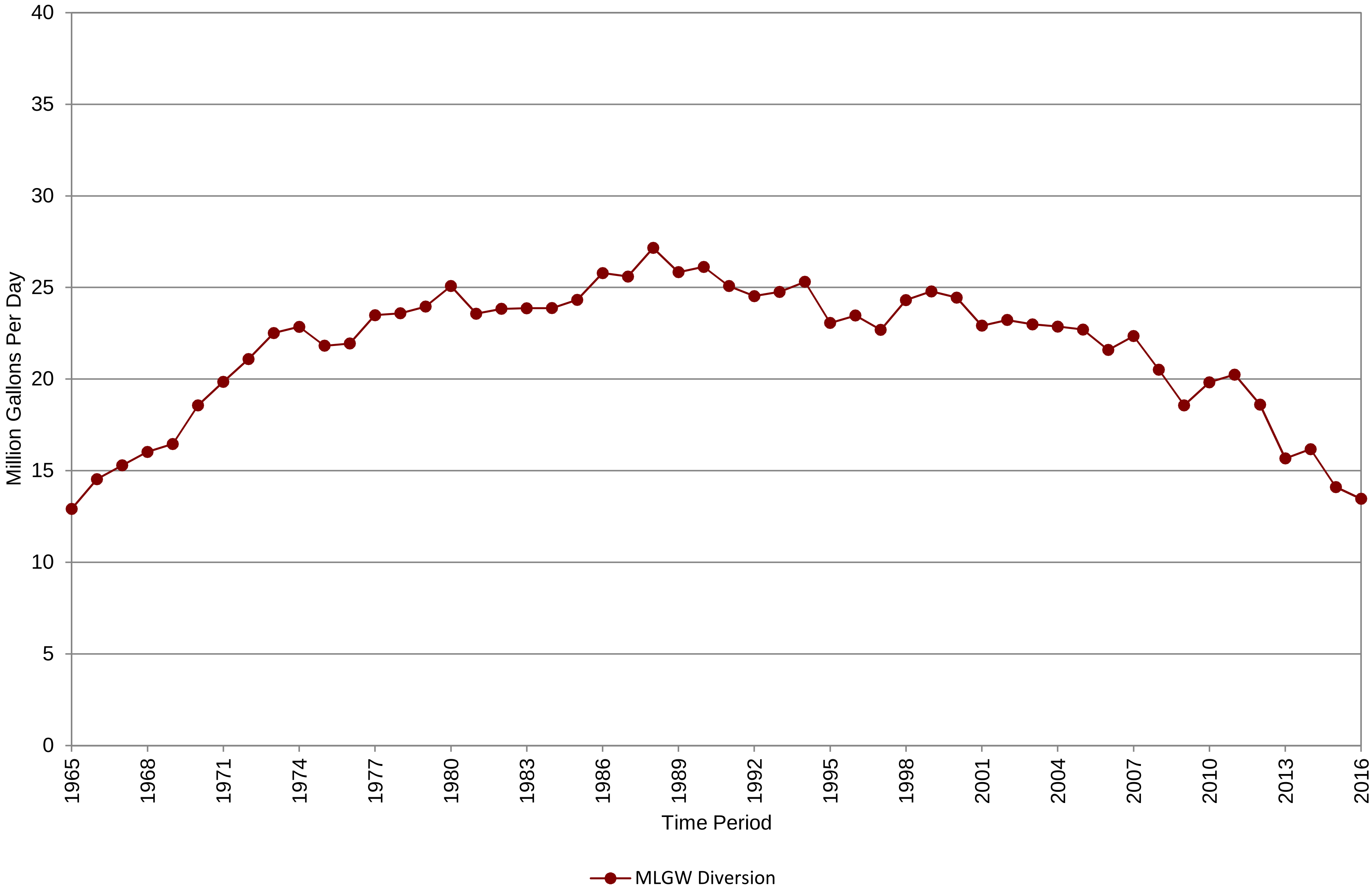
LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

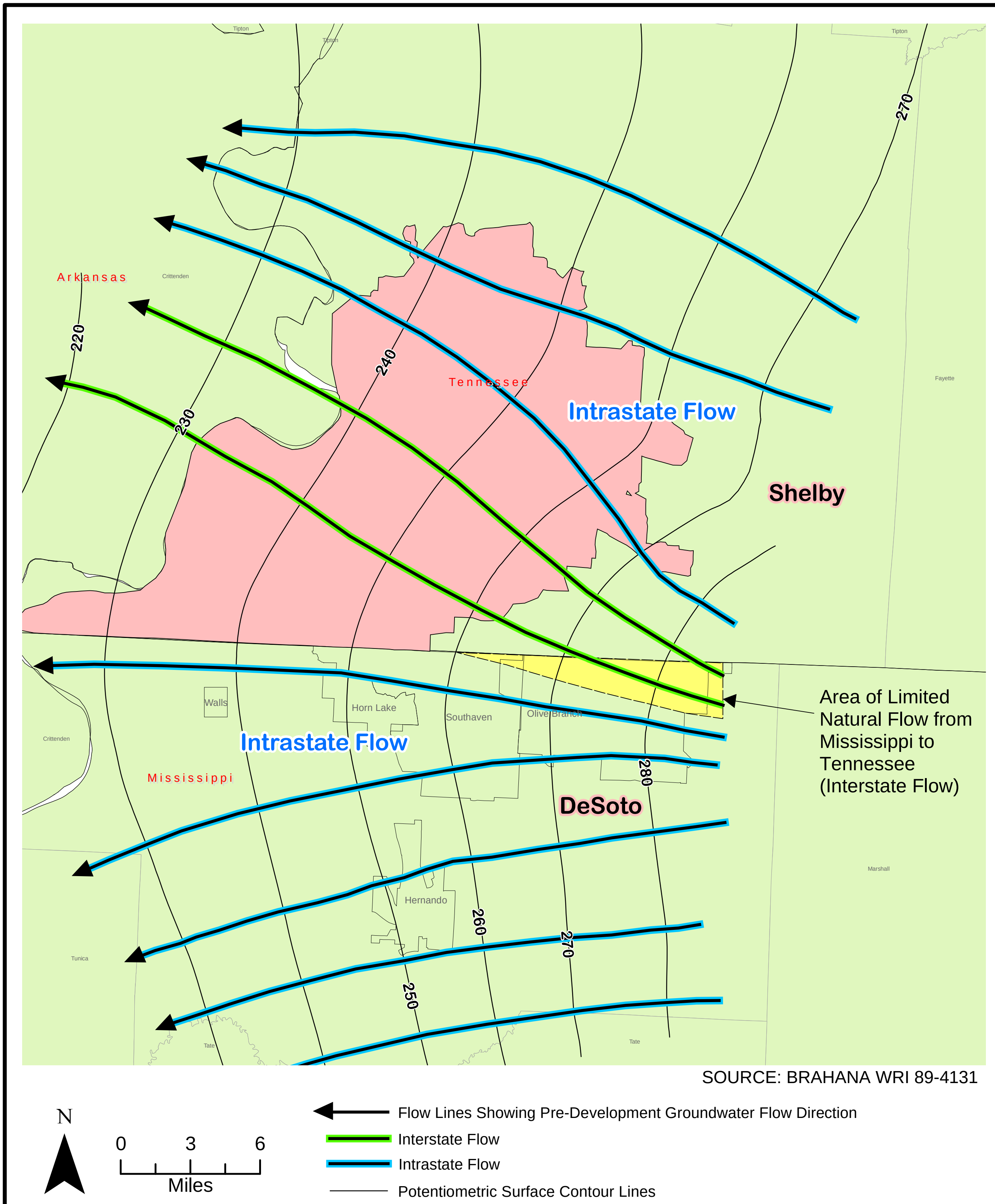
Acad
GIS
Corel

DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*June 2017*
FILE NAME:	*Figure21.MXD*
FIGURE NO.:	*21*

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure21.mxd

Figure 22
Volume of Groundwater Contributed to Shelby County, TN. From DeSoto & Marshall Counties
Mississippi Due to MLGW Pumpage (1965-2016)





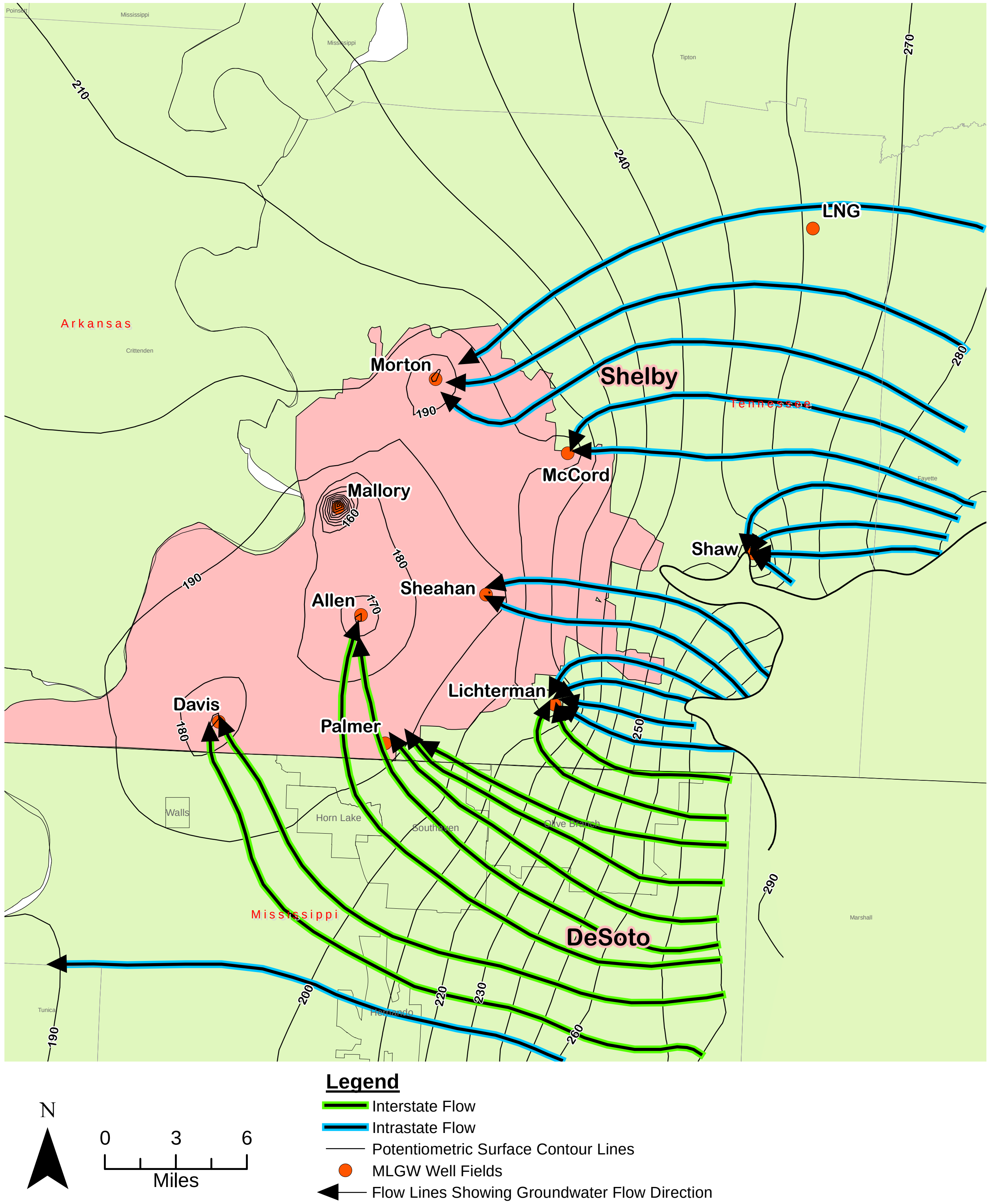
UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

1886 ESTIMATED POTENTIOMETRIC SURFACE MAP FOR PREDEVELOPMENT CONDITIONS

PREPARED BY: **LEGGETTE, BRASHEARS & GRAHAM, INC.**
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

☐ Acad
☑ GIS
☐ Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	Feb. 2017
FILE NAME:	Figure23.MXD
FIGURE NO.:	23



UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

2016 POTENTIOMETRIC SURFACE MAP DEVELOPED FROM GROUNDWATER MODEL

PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	June 2017
FILE NAME:	Figure24.MXD
FIGURE NO.:	24

C:\Graphics\GISDATA\0215.MISMEM\June 2017 Update Report\Figure24.mxd

EXHIBIT 2

J.H. Criner, P-C. P. Sun, and D. J. Nyman, *Hydrology of Aquifer Systems in the Memphis Area, Tennessee*, Geological Survey Water-Supply Paper 1779-O (“1964 USGS Report “)

Hydrology of Aquifer Systems in the Memphis Area, Tennessee

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1779-O

Prepared in cooperation with the city of Memphis, Memphis Light, Gas, and Water Division

Hydrology of Aquifer Systems in the Memphis Area, Tennessee

By J. H. CRINER, P-C. P. SUN, *and* D. J. NYMAN

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1779-O

Prepared in cooperation with the city of Memphis, Memphis Light, Gas, and Water Division

A hydrogeologic delineation, analysis, and evaluation of the principal water-bearing formations in the Memphis area, Tennessee

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1964

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

HYDROLOGY OF AQUIFER SYSTEMS IN THE MEMPHIS AREA, TENNESSEE

By J. H. Criner, P–C. P. Sun, and D. J. Nyman

ABSTRACT

The Memphis area as described in this report comprises about 1,300 square miles of the Mississippi embayment part of the Gulf Coastal Plain. The area is underlain by as much as 3,000 feet of sediments ranging in age from Cretaceous through Quaternary.

In 1960, 150 mgd (million gallons per day) of water was pumped from the principal aquifers. Municipal pumpage accounted for almost half of this amount, and industrial pumpage a little more than half. About 90 percent of the water used in the area is derived from the "500-foot" sand, and most of the remainder is from the "1,400-foot" sand; both sands are of Eocene age. A small amount of water for domestic use is pumped from the terrace deposits of Pliocene and Pleistocene age.

Both the "500-foot" and the "1,400-foot" sands are artesian aquifers except in the southeastern part of the area; there the water level in wells in the "500-foot" sand is now below the overlying confining clay. Water levels in both aquifers have declined almost continuously since pumping began, but the rate of decline has increased rapidly since 1940. Water-level decline in the "1,400-foot" sand has been less pronounced since 1956.

The cones of depression in both aquifers have expanded and deepened as a result of the annual increases in pumping, and an increase in hydraulic gradients has induced a greater flow of water into the area. Approximately 135 mgd entered the Memphis area through the "500-foot" sand aquifer in 1960, and, of this amount, 60 mgd originated as inflow from the east and about 75 mgd was derived from leakage from the terrace deposits, from the north, south, and west and from other sources. Of the water entering the "1,400-foot" sand, about 5 mgd was inflow from the east, and about half that amount was from each of the north, south, and west directions. The average rate of movement of water outside the area of heavy withdrawals is about 70 feet per year in the "500-foot" sand and about 40 feet per year in the "1,400-foot" sand. The average rate of depletion of storage in each aquifer since pumping began is about 1 mgd.

Most of the recharge to the "500-foot" and "1,400-foot" sands occurs in outcrop areas about 30–80 miles east of Memphis. Also, water leaks from the terrace deposits to the "500-foot" sand in some places, and there may be some leakage from streams where the confining clay is thin or is breached by faults or streams.

The quality of water from both the principal aquifers is very good. Iron, carbon dioxide, and hydrogen sulfide are the only constituents found in undesirable quantities. Water from the terrace deposits is hard but generally contains less iron and carbon dioxide than water from either of the principal aquifers.

The hydraulic characteristics of both aquifers were determined by pumping tests and by applying the knowledge of the geology of the area; these characteristics indicate that the aquifers are capable of producing more water than is currently being pumped from them. The "500-foot" sand will produce more water per unit decline of water level than will the "1,400 -foot" sand. There appears to be no reason why the development of water supplies from both aquifers should not continue, but well spacing will remain a factor which could affect future development. Greater well spacing will tend to prolong the useful life of a well and the aquifers.

INTRODUCTION

In 1960, industrial and municipal supply wells in the Memphis area pumped about 150 million gallons of water a day. Pumping has increased continuously since 1898, the earliest date for which records are available, and the rate of this increase has accelerated greatly since 1940. Decline of water levels has accompanied increases in the pumpage, and in 1928 the city of Memphis began a program of periodic water-level measurements to determine ways to reduce the rate of decline. The U.S. Geological Survey was requested to assist in this study, and a continuing cooperative program of investigations was begun in 1940. Early investigations showed the need for proper spacing of wells, which has been practiced to the present time.

PURPOSE AND SCOPE OF INVESTIGATION

The present investigation was started in 1958 as a quantitative study of the two principal aquifers that supply water to the Memphis area. The objectives were to delineate these aquifers, evaluate their hydraulic characteristics, show the relation between pumpage and water-level change, and determine the factors affecting the economical development and use of ground water. The study was based partly on the premise that the questions posed by Kazmann (1944, p. 17–18) must be answered as completely as possible to provide for orderly development and management of the ground-water resources. These questions are repeated and discussed in the concluding section of this report.

Work consisted of (1) delineation of the "500-foot" and "1,400-foot" sands by a series of subsurface contour maps based on drillers' logs and geophysical logs of wells, (2) collection of water-level records from a network of about 150 observation wells, 55 of which were equipped with automatic recorders, (3) preparation of contour maps showing water levels and the amount of water-level decline in the "500-foot" sand, (4) analyses of pumping tests of wells in both aquifers, (5) calculation of the amount of ground water moving into the area through each aquifer before development began and during 1960, (6) preparation of a ground-water budget for the "500-foot" sand, based on 1960 records, and (7) inventory of ground-water withdrawal and study of its relation to water-level decline.

LOCATION AND GENERAL FEATURES OF THE AREA

The Memphis area (fig. 1), about 1,300 square miles in this report, includes all Shelby County and parts of Fayette and Tipton Counties, Tenn., and contiguous parts of Arkansas and Mississippi. The area is near the center of the upper half of the Mississippi embayment in the Gulf Coastal Plain.

The climate of the Memphis area is warm and humid, having hot summers, mild winters, and a frost-free period of about 230 days between late March and early November. The average annual temperature is 61.9°F; the hottest month is July, which has an average temperature of 81.1°F; and the coldest month is January, which has an average temperature of 41.5°F.

The average annual rainfall Memphis (fig. 2), based on an 89-year period of record (1872–1960), is 48.48 inches. The maximum annual rainfall recorded was 76.85 inches in 1957, and the minimum was 30.54

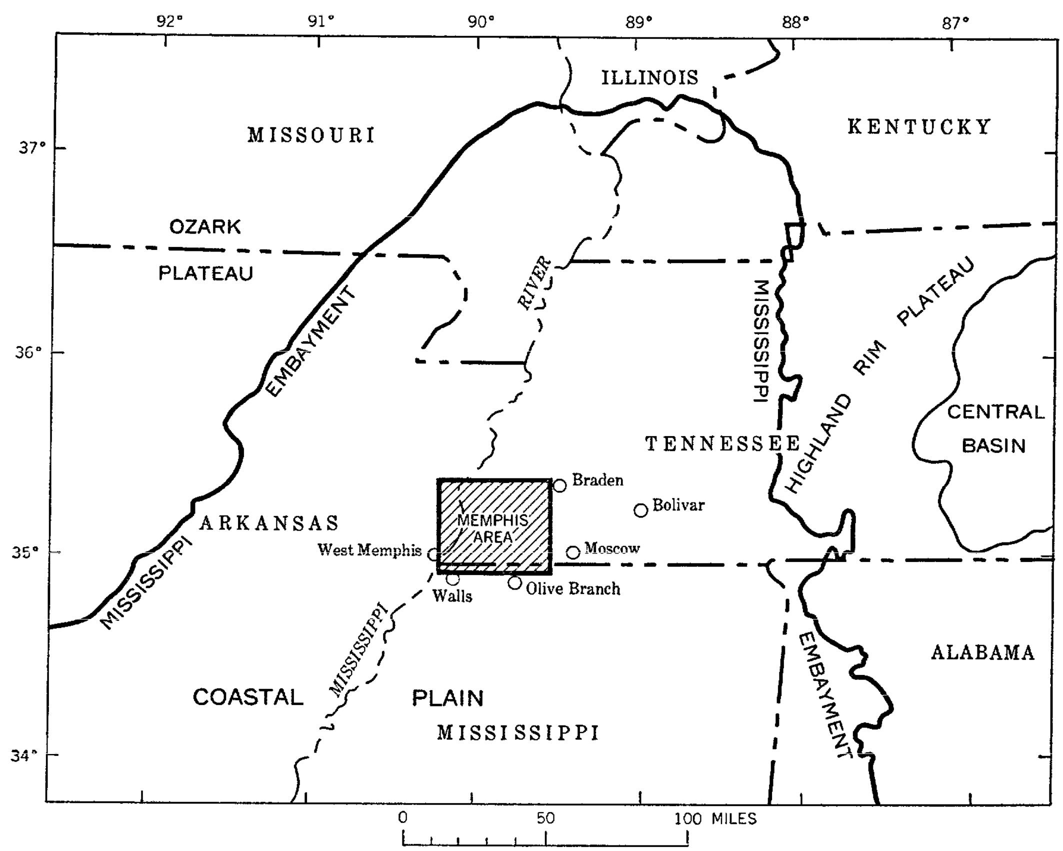


FIGURE 1.—Generalized physiographic map of the northern Mississippi embayment showing the location of the project area.

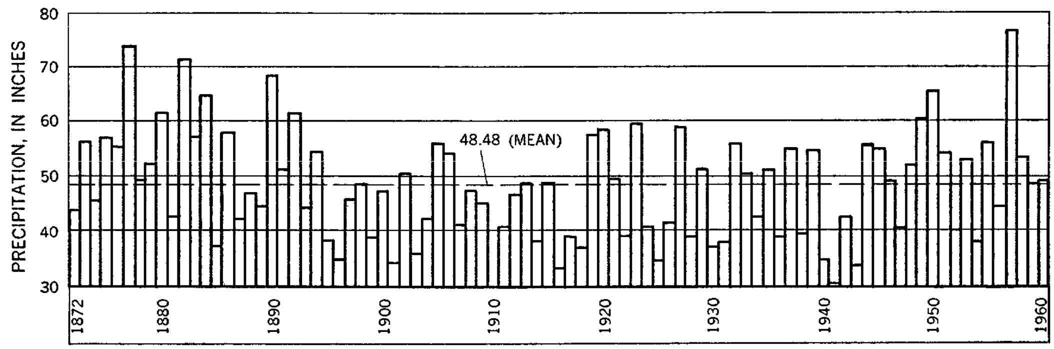


FIGURE 2.—Graph showing annual precipitation at Memphis, Tenn.

inches in 1941. The wet season usually begins in late November and ends in April. Rainfall at Moscow and Bolivar (fig. 1) in the outcrop or recharge area of the principal aquifers, is slightly greater than that in the Memphis area.

The Memphis area (fig. 1) consists mostly of a gently rolling upland ranging in elevation from about 400 feet in the eastern part of Shelby County to about 200 feet on the alluvial plain of the Mississippi River. The maximum topographic relief is about 200 feet, but the local relief of individual topographic features seldom exceeds 40 feet. The upland area is terminated by a bluff 50 to 150 feet high along the eastern margin of the alluvial plain of the Mississippi River. This virtually flat plain, which is approximately 210 feet above sea level, is about 3 miles wide along the east side of the Mississippi River except in the vicinity of Memphis; at Memphis the river flows along the base of the bluff.

The principal streams that drain the Memphis area are the Wolf and Loosahatchie Rivers and Nonconnah Creek, all of which flow north-northwestward and discharge into the Mississippi River. These streams have wide flood plains that are generally adequate to accommodate flood waters during the rainy reason. Some sections of the channels of these and smaller tributaries have been artificially deepened for more effective drainage of the lowland areas. In the past all three major streams have flowed throughout the year; however, in recent years Nonconnah Creek was dry in its lower reach for short periods during the dry season from July to October.

Memphis is a large industrial center; the principal industries produce hardwood lumber and cotton and associated products. The Memphis Chamber of Commerce reported 765 industries in Memphis (1958–59), 120 of which have their own water-supply wells. More than half the total ground-water pumpage from the area is from these wells.

The 1960 U.S. Census shows that the population of Memphis and Shelby County has approximately doubled since 1930. The successive census figures are as follows:

Population of Memphis and Shelby County, Tenn.

Year	Memphis	Shelby County
1930	253, 143	306, 482
1940	292, 942	358, 250
1950	396, 012	482, 393
1960	497, 524	627, 019

PREVIOUS INVESTIGATIONS

The earliest reports describing the geology and the ground-water resources of the Memphis area were by Safford (1869, 1890) and Glenn (1906). Wells (1931) described the artesian water supply of Memphis and, in a subsequent report (1933), the ground-water resources of West Tennessee, including a more detailed discussion of ground-water conditions in the Memphis area. Since the beginning of the cooperative program in 1940, progress reports have been published by Kazmann (1944), Schneider and Cushing (1948), and Criner and Armstrong (1958).

Regional and local studies relating to the geology of the Memphis area were made by Fisk (1944), Caplan (1954), Stearns and Armstrong (1955), and Stearns (1957).

Records of water levels from 1936 through 1955 have been reported by the U.S. Geological Survey (issued annually). Earlier measurements were reported by Wells (1931, 1933).

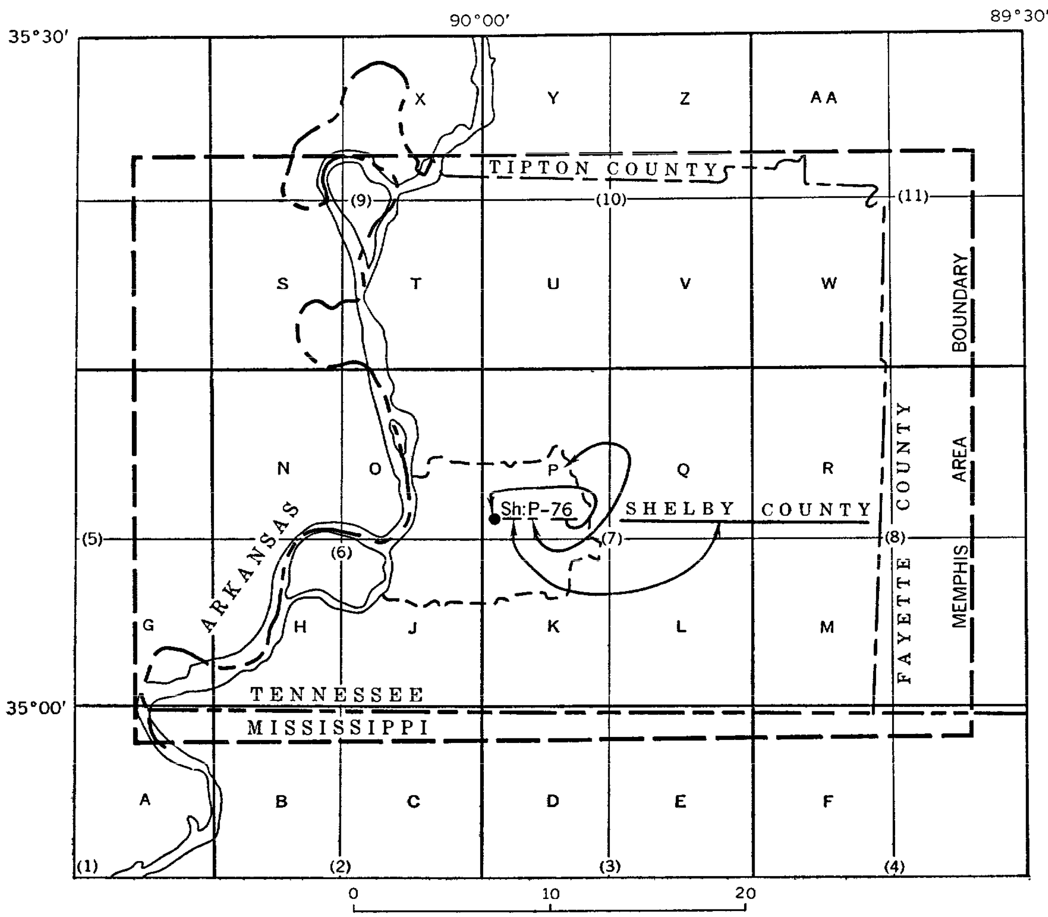
ACKNOWLEDGMENTS

The assistance and cooperation of many city and county officials, industry representatives, drilling contractors, and well owners were helpful in the collection of data for this report. Mr. J. J. Davis, Director, Water Division, and Messrs. A. J. Rumley and Hugh Mills, Memphis Light, Gas, and Water Division, provided essential well and water-use data from the city records and assisted greatly in the investigation. Mr. E. C. Handorf and Mr. W. M. Craddock, of the Memphis and Shelby County Health Department have, through their interest in the Memphis area water supply, contributed substantially to the study. Drilling contractors, industries, and individual well owners also were especially helpful in providing well data, permitting use of wells for geophysical and hydraulic tests, and furnishing information on water use in the area.

WELL-NUMBERING SYSTEM

Figure 3 illustrates the standard system for numbering wells in this report. Each well number consists of of three units: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7½-minute topographic quadrangle, or 7½-minute quadrant of a 15-minute quadrangle, in which the well is located; and (3) a number generally indicating the numerical order in which the wells were inventoried.

The index map (fig. 3) shows the 15-minute topographic quadrangles of the U.S. Army Corps of Engineers that include Shelby County and adjacent areas described in this report. The example, well Sh: P–76, is in Shelby County, in the northwest quadrant (7½-minute quadrangle designated "P") of the Bartlett 15-minute quadrangle and is identified as well 76 in the numerical sequence.



15-MINUTE TOPOGRAPHIC QUADRANGLES

1. HORSESHOE LAKE (1954) NE¼
2. HORN LAKE (1961) N½
3. HERNANDO (1944) N½
4. BYHALIA (1948) NW¼
5. EDMONSON (1951) SE¼
6. MEMPHIS (1961)
7. BARTLETT (1961)
8. COLLIERVILLE (1948) W½
9. JERICHO (1952)
10. MILLINGTON (1961)
11. MASON (1954) W½

FIGURE 3.—Map showing topographic quadrangles in the Memphis area and showing the well-numbering system used in Tennessee.

In this report the county designation "Sh" is omitted in figures. Well numbers in adjoining counties in Tennessee are preceeded by the county abbreviation. Wells in adjoining States are not numbered.

At Memphis, the Memphis Light, Gas, and Water Division many years ago established their own well-numbering system. According to this plan, blocks of numbers were assigned for the city's five existing well fields (pl. 1) and other blocks of numbers were reserved for future well fields. The block assignments are as follows:

1–49	Parkway Field	200–249	McCord Field
50–99	Sheahan Field	250–299	(Not assigned)
100–149	Allen Field	300–349	Hickory Hill (Lichterman) Field (proposed)
150–199	Miscellaneous wells at scattered locations (abandoned)		

Listed below are city-owned wells in use as of January 1962 and those that have been withdrawn from use. Well numbers followed by the letters "A," "B," and so on, indicate first, second, and so on, replacement wells for those withdrawn from use. For convenient reference, the wells owned by the Memphis Light, Gas, and Water Division are listed below, together with the corresponding numbers assigned by the U.S. Geological Survey.

City	*Geological Survey*	*City*	*Geological Survey*	*City*	*Geological Survey*
1	Sh:O–125	15A	Sh:O–150	30	Sh:O–175
1A	126	16	151	31	176
2	127	16A	152	32	177
2A	128	17	153	33	178
3	129	18	154	34	179
4	130	19	155	35	180
4A	131	19A	156	36	P– 77
5	132	20	157	37	78
6	133	20B	158	38	O–181
6A	134	21	159	39	182
7	135	21A	160	40	183
7A	136	22	161	41	184
9	137	22A	162	42	185
9A	138	22B	163	43	186
10	139	22C	164	44	187
10A	140	23	165	45	188
11	141	23A	166	46	189
11A	142	24	167	47	190
12	143	24A	168	50	K– 37
12A	144	25	169	51	38
13	145	26	170	52	39
13A	146	26A	171	53	40
14	147	27	172	54	41
14A	148	28	173	54A	42
15	149	29	174	55	43

City	*Geological Survey*	*City*	*Geological Survey*	*City*	*Geological Survey*
55A	Sh:K- 44	80	Sh:P- 84	123	Sh:J-116
56	45	81	K- 69	124	117
57	46	82	70	125	118
57A	47	83	71	126	119
57B	48	84	72	127	120
57C	49	85	73	128	121
58	50	86	74	130	122
59	51	86S	75	131	123
60	52	87	76	133	124
61	53	88	77	134	125
61A	54	101	J- 96	135	126
62	55	102	97	136	127
63	56	103	98	137	128
64	57	104	99	193	P- 76
65	58	105	100	201	Q- 29
66	59	106	101	202	30
67	60	107	102	203	31
68	61	108	103	204	32
69	62	109	104	205	33
70	63	110	105	207	34
71	64	111	106	208	35
72	65	112	107	209	36
73	66	113	108	210	37
74	P- 79	114	109	218	38
75	80	115	110	219	39
76	81	116	111	220	40
77	K- 67	117	112	221	41
77A	68	118	113	222	42
78	P- 82	121	114	307	L- 39
79	83	122	115	324	40

GENERAL GEOLOGY OF THE AQUIFER SYSTEMS

The Memphis area is in the northern part of the East Gulf Coastal Plain, near the axis of the Mississippi embayment structural trough (fig. 1). About 3,000 feet of unconsolidated clay, silt, sand, and gravel has been deposited in this area, and these sediments provide a record of the several invasions and recessions of the sea and the intervening periods of erosion that have occurred since the beginning of Cretaceous time. This wedge-shaped sequence of deposits thickens southward toward the Gulf of Mexico and westward toward the Mississippi River.

Stearns and Armstrong (1955, p. 6–7) and Stearns (1957, p. 1084–1085) described the depositional environmental relations and defined three sedimentary rock types that best illustrate these relations in the northern part of the Mississippi embayment. These types are described briefly as follows:

Back-beach clay and sand.—Back-beach beds consist of light-colored clay, lignite, and discontinuous beds of sand. The clay beds, in contrast with those of a more marine environment, are characterized by the presence of leaf imprints and the general absence of glauconite. These clay and sand deposits are of limited areal extent and therefore cannot be traced easily in the subsurface, even by means of geophysical logs of closely spaced wells. The irregularly interbedded sediments in the upper part of the Claiborne Group (table 1) are typical of the back-beach deposits.

Shallow-water near-shore sand.—Well-sorted sand interbedded with glauconitic and fossiliferous clay is characteristic of the shallow-water near-shore deposits. The sand is areally extensive, in contrast with the back-beach deposits. Where sand beds grade laterally or vertically into back-beach beds, they contain lignite and wood fragments; where they grade into deeper-water clay beds, they contain glauconite. The sandy middle unit ("1,400-foot" sand) of the Wilcox Group (table 1) in the Memphis area is typical of the shallow-water near-shore deposits.

Deeper water clay and shale.—The deeper water clay and shale is medium gray to dark gray and contains marine fossils, calcareous beds, and glauconite. These beds are thick and areally extensive and therefore are easily recognized and traced in the subsurface by means of drillers' logs and geophysical logs of wells. In the Memphis area, typical deposits of this category are the marine facies of the Jackson(?) Formation and the upper clay unit of the Wilcox Group.

DESCRIPTION OF THE GEOLOGIC UNITS

The Memphis area is underlain by about 3,000 feet of clay, silt, sand, and gravel ranging in age from Cretaceous through Recent. These sediments were deposited on the limestone rocks of Paleozoic age that form the bedrock floor of the Mississippi embayment syncline. This report deals primarily with the geology related to the two principal aquifers in the Memphis area, and for this reason only the stratigraphic units of Eocene and younger age are discussed in detail. These units (table 1) include the major aquifers, the "1,400-foot" sand of the Wilcox Group, and the "500-foot" sand of the Claiborne Group (Kazmann, 1944, p. 2).

WILCOX GROUP

On the basis of drillers' logs and geophysical logs of wells in the Memphis area, the Wilcox Group is divided into a lower clay unit, a middle sand unit ("1,400-foot" sand), and an upper clay unit (Criner and Armstrong, 1958, p. 3).

The lower unit of the Wilcox Group consists of gray to greenish-gray lignitic clay which grades upward into silt and fine-grained sand deposits. The percentage of sand increases upward in this unit, perhaps representing a transitional phase between the marine Porters

TABLE 1.—*Geologic units underlying the Memphis area*

System	Series	Group	Stratigraphic unit	Thickness (feet)	Description and relation to water
Quaternary	Recent		Alluvium	0–200	Alluvial sand, clay, and gravel. Few domestic wells. Could be important source of water for some industrial uses.
Quaternary	Pleistocene		Loess	0–100	Wind-deposited silt. (Topographically higher than alluvium.) Low permeability. Not a source of ground water.
Quaternary	Pleistocene and (or) Pliocene [1]		Terrace deposits	0–160	Alluvial sand and gravel. Several domestic wells. Could be major source of water for industrial and irrigation uses.
Tertiary	Eocene		Jackson(?) Formation (lower part may include some Claiborne beds)	0–330	Gray, bluish-gray, greenish-gray, and tan clay; minor amounts of lignite and fine-grained sand. Generally impermeable and considered to be upper confining beds for water in "500-foot" sand.
Tertiary	Eocene	Claiborne	"500-foot" sand (upper part may include some Jackson(?) beds)	500–800	Fine- to coarse-grained sand; minor amounts of lignite and tan clay and silt; thin clay and lignite lenses. Thick clay bed locally at base. Coarse channel sands locally at base. Very good aquifer from which 90 percent of water in Memphis area is obtained.
Tertiary	Eocene	Wilcox	Upper clay unit	200–395	Gray, greenish-gray, and brown carbonaceous clay. Thin lignite and fine-grained sand lenses locally. Low permeability confines water in "500-foot" and "1,400-foot" sands.
Tertiary	Eocene	Wilcox	Middle sand unit ("1,400-foot" sand)	150–300	Fine- to medium-grained sand; minor amounts of lignite and clay lenses. Second principal aquifer which supplies about 10 percent of water used in Memphis area.
Tertiary	Eocene	Wilcox	Lower clay unit	190–250	Gray, greenish-gray, and brown carbonaceous clay, and lignite; sandy near top. Impermeable lower confining bed for water in "1,400-foot" sand.

[1] See p. O39.

Creek Clay and the predominately sandy middle unit of the Wilcox. The clay unit ranges in thickness from 190 feet in test well Fa: W–1 about 30 miles northeast of Memphis near Braden, Fayette County, to 250 feet in well Sh: U–12, 3.5 miles south of Millington, Shelby County (pl. 1).

The middle sand unit, referred to as the "1,400-foot" sand by Criner and Armstrong (1958, p. 3), consists mostly of unconsolidated well-sorted fine- to medium-grained sand. Logs of a few wells in the Memphis area show thin interbedded lenses of clay, but these beds probably are not areally extensive. The sand ranges in thickness from 150 feet in test well Fa: W–1 near Braden, Fayette County, to 240 feet in well Sh: U–12, 3.5 miles south of Millington, Shelby County (pl. 1). The thickness increases westward to 300 feet in an oil-test well 7 miles west of West Memphis, Ark.

The upper unit of the Wilcox Group in the Memphis area consists of dark-gray or brown lignitic clay containing local lenses of silty and sandy clay from 1 to 50 feet thick. Thin beds of fine-grained sand cemented with iron oxide form "rock" layers a few inches thick in many parts of the unit. The upper clay of the Wilcox grades upward to a sandy clay; however, the contact with the overlying sand of the Claiborne Group is distinct, as is indicated by geophysical logs (pl. 1) of wells in the area. The thickness of the upper clay section varies greatly, ranging from 200 to 395 feet in the Sheahan well field in the south-central part of Shelby County.

CLAIBORNE GROUP

The Claiborne Group in the Memphis area is represented by the "500-foot" sand, which has been divided into lower and upper parts by Criner and Armstrong (1958, p. 7–8). This subdivision was based on the different lithologies of the two parts and on their separation in much of the area by clay beds as much as 150 feet thick. Electrical logs and drillers' logs of wells show that the lower part of the Claiborne varies greatly in thickness and contains a greater number of clay beds that are thicker and more extensive than those in the upper part. Even the thickest of the clay beds, however, are not continuous, so that no particular bed can be considered as a hydrologic boundary between distinctive lower and upper parts. In this report, therefore, the "500-foot" sand is considered as a single hydrologic unit. Generally the Claiborne Group is characterized by a greater proportion of clay in the lower part and by a gradation in sand particle size from fine to medium grained in the lower part to medium to coarse grained in the upper part. The thickest and most extensive clay bed underlies the central part of the Memphis area and is in the lower part of the Claiborne Group.

724–489—64——2

The thickness of the Claiborne Group ranges from 500 feet in test well Fa: W–1 near Braden, Fayette County, to 800 feet in well Sh: J–104 in the southern part of the city of Memphis (pl. 1). The top of the "500-foot" sand was indicated in geophysical logs of wells as the level at which the sediments change from predominantly sand to predominantly clay or silt. The contacts were picked to define a hydrologic unit ("500-foot" sand regardless of geologic age. For this reason the upper part of the unit as shown on plate 1 may include some sandy beds belonging to the overlying Jackson(?) Formation.

JACKSON(?) FORMATION

The Jackson(?) Formation overlies and confines the "500-foot" sand. Locally the two units interfinger with one another, and the contact between them represents a hydrologic boundary rather than a precise stratigraphic horizon (pl. 1).

The Jackson(?) Formation is composed of dark-gray to greenish-gray, dark-blue, or dark-brown clay. It is generally carbonaceous and contains very fine quartz sand along bedding planes. The formation is absent in southeastern Shelby County but is as much as 330 feet thick in the Parkway well field.

Fisk (1944, fig. 67, p. 62) distinguished a lower marine and an upper nonmarine facies in the Jackson(?) Formation. The marine facies closely follows the present course of the Mississippi River and extends northward at least 25 miles to Lauderdale County; there an exposure contains glauconite, foraminifera, shark teeth, and bones of sea animals. Fossil plants and leaves are abundant, and seams of lignite as much as 10 feet thick are common in the nonmarine facies.

TERRACE DEPOSITS AND ALLUVIUM

The terrace deposits ranges from a few feet to about 160 feet in thickness and are composed mostly of coarse-grained quartz sand and fine-grained iron-stained quartz and chert gravel. Thin lenses of silty ocher-colored clay are common in the lower part. The bottom 3 inches to 4 feet of sand and gravel generally is cemented with limonite. Although the contact with the Jackson(?) Formation represents an erosional surface, thin lenses of reworked Jackson(?) clay and sand form a transitional zone at the base of the terrace deposits in many places; geophysical logs show a gradation from one unit to the other.

The terrace deposits occur as an irregular belt parallel to the Mississippi River and also occur along the larger streams in the area. The deposits thin gradually eastward and are absent in many places as a result of erosion or nondeposition.

Two terraces were recognized by Glenn (1906, p. 41–44), who designated the higher as Pliocene and the lower as Pleistocene. Fisk

(1944, p. 63) considered them both to be of Pleistocene age. Because geophysical logs show no consistent correlation points, by means of which the terrace deposits can be divided in the subsurface, they are considered as a single unit in this report.

The alluvium ranges from 0 to 200 feet in thickness and is composed of sand, clay, silt, and gravel. It is confined to narrow strips along the principal streams and in most places is subject to flooding and reworking. The coarsest material is generally near the present stream channels, and the finest is near the featheredges of the deposits.

The alluvium is lithologically similar to the underlying terrace deposits, and the contact cannot be determined from geophysical logs. However, samples of the alluvium locally contain carbonaceous material and decaying vegetation which aid in distinguishing between the two units.

GEOLOGIC STRUCTURE

The Memphis area is near the axis of the Mississippi embayment syncline, which plunges southward at a rate of about 10 feet per mile in the vicinity of Memphis. The syncline began to form in Late Cretaceous time (Fisk, 1944, p. 8, 64; and Caplan, 1954, p. 5) as a result of regional subsidence centered along the present coast of the Gulf of Mexico. The axis of the structural trough approximately follows the present course of the Mississippi River.

As the region subsided, faulting of the unconsolidated sediments and the underlying Paleozoic rocks occurred, forming a rectangular pattern of faults and fractures trending northeast and northwest (Fisk, 1944, p. 64, 66). One of the major faults in this system, the Big Creek fault (Fisk, 1944, p. 66), trends northeast from near West Helena, Ark., along the western edge of the Memphis area to Reelfoot Lake near the Tennessee-Kentucky border; at Reelfoot Lake it appears to be related to the New Madrid (Missouri) fault system. This fault is of particular significance because it apparently restricts the movement of ground water from the west into the Memphis area.

A major fault is suggested by an abrupt bend in the Mississippi River near the mouth of Nonconnah Creek and by electrical logs of wells that indicate as much as 50 feet of displacement of geologic units in the Hickory Hill well field in the south-central part of the area. If such a fault exists, it has so far had little effect on the movement of water in the "500-foot" sand.

HYDROLOGY OF THE AQUIFER SYSTEMS

GEOLOGIC CONTROL OF GROUND WATER IN THE MEMPHIS AREA

The size, shape, and degree of interconnection of the open spaces between rock particles control the amount of water that can be accepted, stored, and eventually discharged to wells or by natural subsurface ground-water movement. In the Memphis area all ground water is obtained from unconsolidated deposits of sand and gravel.

Deposits of rounded well-sorted rock particles are the most permeable water-bearing materials because ground water can move freely through them toward pumping wells and into the aquifer in its recharge area. Mechanical analyses of sand samples from the "500-foot" and "1,400-foot" sands in the Memphis area show the sand particles to be well sorted but angular to subangular in shape. Although compaction and cementation affect the water-bearing properties of sand aquifers, these processes are of minor significance in the Memphis area, where cemented beds are rare and are seldom more than 1 foot thick. Faulting may also affect the ground-water conditions in an area by displacement of strata or by formation of a semi-impermeable barrier along the faulted zone. In the Memphis area the only structural deformation believed to affect ground-water movement is the previously described Big Creek fault, which restricts the inflow of ground water from the west. Relative positions of aquifers and confining clay beds also affect ground-water conditions in the Memphis area. In the outcrop area of the "500-foot" and "1,400-foot" sands east of Shelby County, water-table conditions exist. West of the outcrop, or recharge, area, however, confining beds of clay overlie the aquifers, and the water is under artesian pressure. As the water moves downdip in the westward dipping aquifers, the pressure surface becomes progressively higher above the confining clay beds which overlie the aquifers.

TEXTURE OF AQUIFER MATERIALS

More than 400 sand samples collected from many drilled wells in the Memphis area were analyzed to determine the distribution of particle size and the degree of sorting. These analyses give an indication of the hydraulic characteristics of the rocks because the size and sorting of the sand grains determine, to a great degree, the permeability and porosity. Coarse-grained sediments are less porous than fine-grained sediments; but because the pores are larger in the coarse-grained sediments, they are more permeable and will allow water to move through them more readily. Poorly sorted sediments are both less porous and less permeable than well-sorted sediments.

Comparison of one sample with another can best be made by comparing their respective sorting coefficients. The sorting coefficient is defined as the square root of the 25 percentile divided by the 75 percentile (Trask, 1932, p. 72). A value of 1 (unity) represents the highest possible degree of sorting. A sorting coefficient smaller than 2.5 indicates a well-sorted sample; 3, a normal sample; and 4.5 or higher, a poorly sorted sample. Sorting coefficients of samples from both the "500-foot" and "1,400-foot" sands (fig. 4) range from 1.1 to 1.3. The steepness of the curves (fig. 4), also shows that the sand is well sorted.

The size-distribution curves also show that the grain size of material from the "1,400-foot" sand is fine to medium and that the grain size of material from the upper part of the "500-foot" sand is medium to coarse. Analyses of samples from the lower part of the "500-foot" sand are not shown in figure 4, but the particle-size distribution in the lower part is known to be similar to that in the "1,400-foot" sand.

In summary, particle-size distribution and sorting coefficient of aquifer materials are a measure of the aquifer's capability to transmit water to wells and therefore are useful in determining the best zone in the aquifer to be screened in a well and the type and opening size of screen to be used.

EFFECTS OF GROUND-WATER WITHDRAWAL

The most conspicuous effect of withdrawal of water from an aquifer is the decline of water level that causes a cone of depression to form in the water surface surrounding the point of withdrawal. The size of

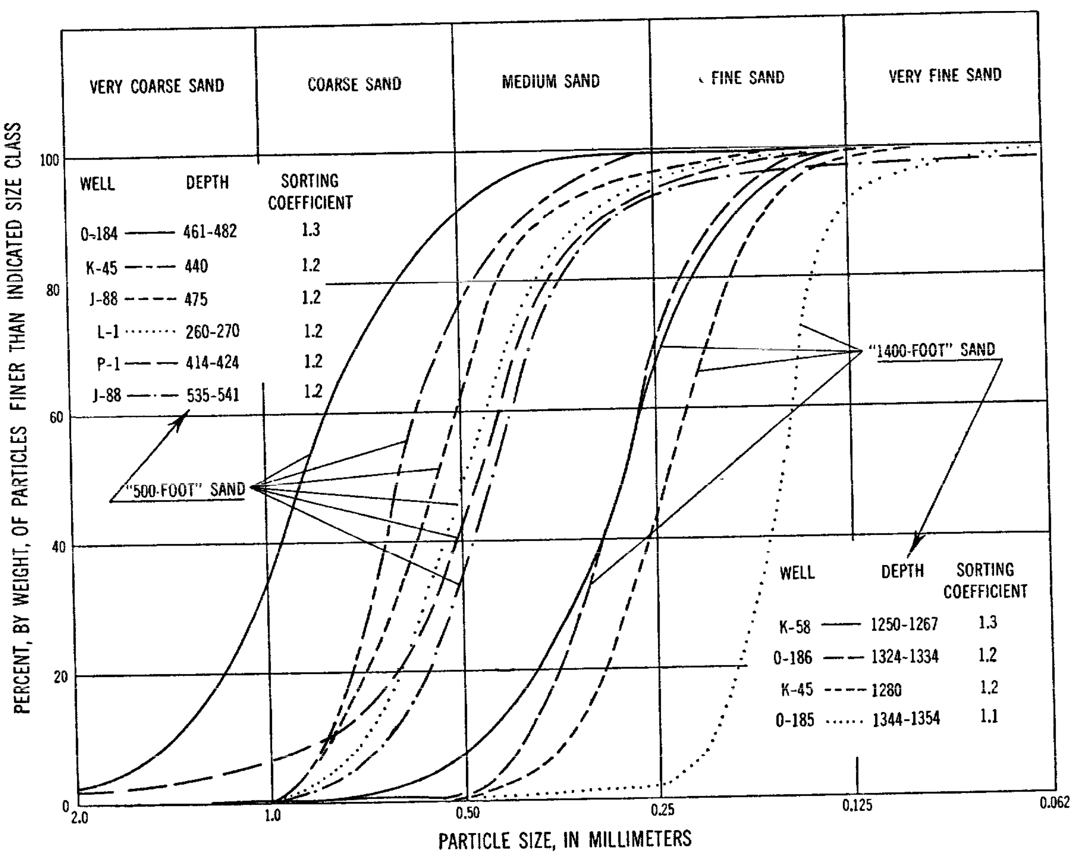


FIGURE 4.—Graphs showing the particle-size distribution in samples from the "500-foot" and "1,400-foot" sands.

the cone of depression formed by pumping a well or group of wells depends on the rate and amount of withdrawal and the hydraulic characteristics of the aquifer. Near the edge of the cone, the water-level depression or drawdown is small and, in effect, immeasurable because it is less than fluctuations caused by atmospheric-pressure changes and other influences. The theoretical distance to the edge of the cone of depression for a typical well field in the "500-foot" sand in the Memphis area pumping at an average rate of 10 mgd (million gallons per day) is about 5 miles from the center of withdrawal.

Increases in the annual rate of withdrawal have accelerated the lowering of the piezometric surface in the entire Memphis area so that the hydraulic gradient (slope of the water or pressure surface) is continually steeping. Consequently, larger amounts of water are transmitted into the area to supply the increased withdrawal. Figure 5 shows the Memphis municipal pumpage since 1898, and figure 6 shows the total municipal and industrial pumpage from the "500-foot" and the "1,400-foot" sands and the resulting water-level declines in the Memphis area from 1935 through 1960. As the rate of withdrawal increases, the regional cone of depression is expanded and deepened.

Under natural conditions, water was discharged from the "500-foot" and "1,400-foot" sands by subsurface flow to the west, thence southward along the axis of the embayment. Beginning with the first well drilled into the "500-foot" sand in 1886 (Lundie, 1898, p. 5–6), pumping has constantly increased, causing ground water to move into the enlarging cone of depression, thus eventually causing natural discharge as subsurface flow to stop.

THE "500-FOOT" SAND AQUIFER

DELINEATION

The "500-foot" sand in the Memphis area is delineated as a hydrologic unit although it includes all the deposits of the Claiborne Group. Geophysical logs of wells were used to identify the top and bottom of the aquifer as limited by the overlying and underlying confining clay. Most of the logs show distinct differences between the aquifer and the confining clay beds; however some show gradational changes from predominantly clay to predominantly sand beds. In the absence of a distinct and abrupt sand-clay contact, the boundary is selected arbitrarily at the middle of the transition zone in order to determine the average thickness of the aquifer. Delineated on this basis, the aquifer also may include some sandy beds of the lower part of the Jackson (?) Formation. In some parts of the area the Jackson (?) is not present, and the "500-foot" sand is overlain directly by terrace deposits com-

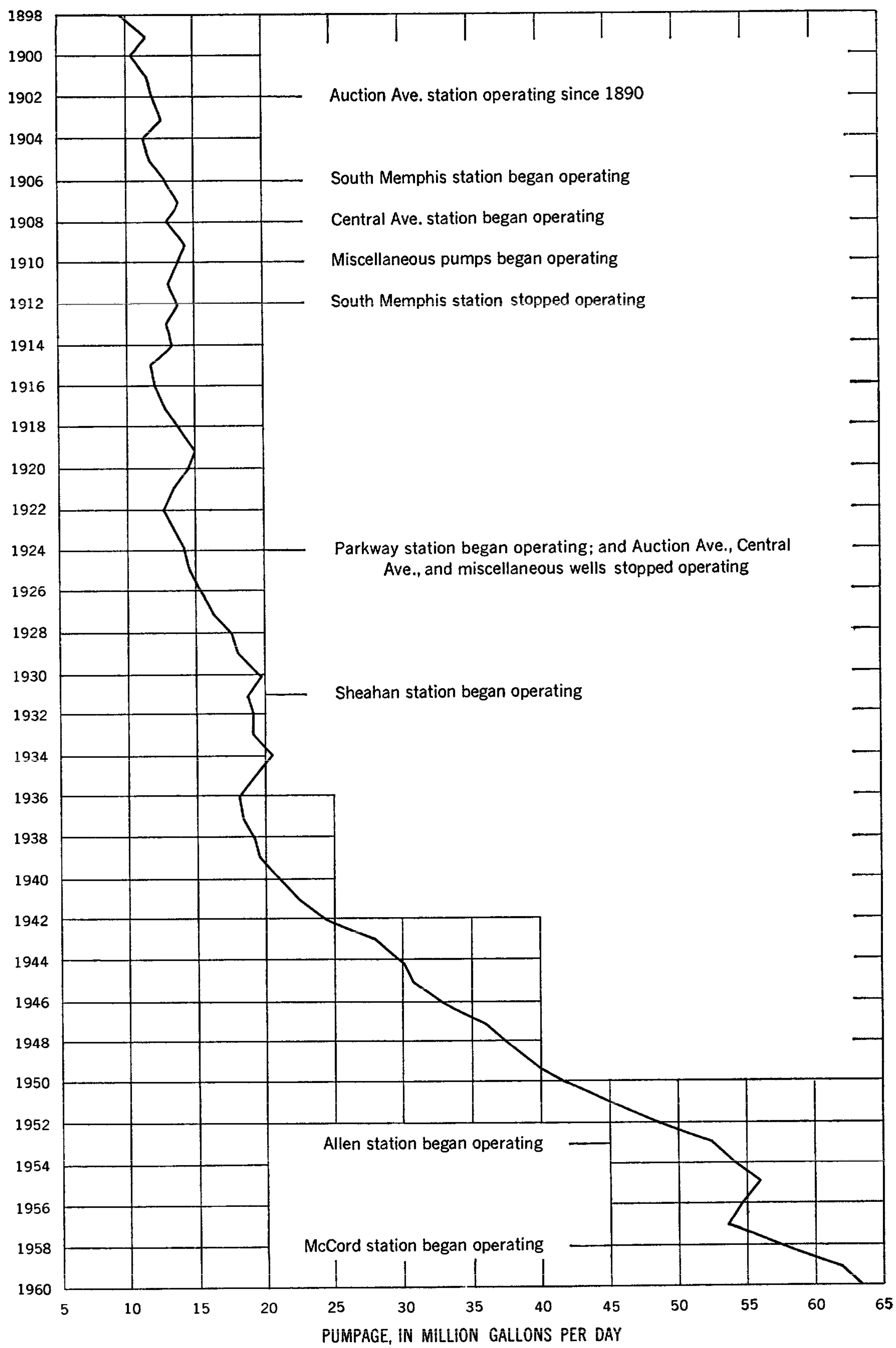


FIGURE 5.—Memphis municipal pumpage, 1898–1960.

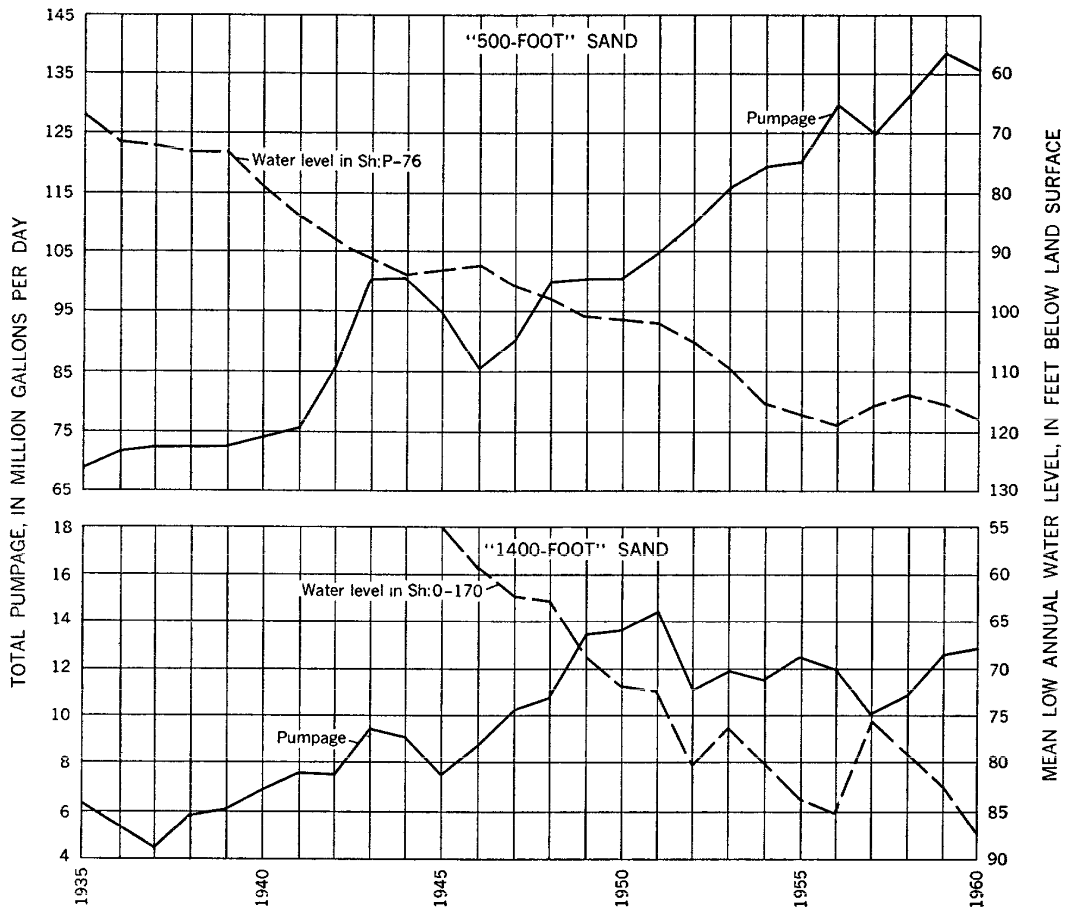


FIGURE 6.—Relation between total pumpage from the "500-foot" and "1,400-foot" sands and water-level declines in the Memphis area, 1935–60.

posed of coarse sand and gravel. These deposits are hydrologically connected with the "500-foot" sand in such areas but are not considered a part of the aquifer.

Plates 2 and 3 show the elevation and configuration of the top and bottom, respectively, of the "500-foot" sand in the Memphis area. These maps and the geologic section (pl. 1) show that the "500-foot" sand ranges from 500 to 800 feet in thickness, averaging about 700 feet thick, and dips toward the northwest at a rate of about 13 feet per mile. The volume of the aquifer, calculated from the contour maps, is about 25 trillion (25×10^{12}) cubic feet in the 1,300 square mile area shown in plates 2 and 3.

WATER LEVELS

DECLINE CAUSED BY PUMPING

Ground-water withdrawal from the "500-foot" sand for municipal and industrial use in the Memphis area has increased from about 68 mgd in 1935, the first year for which records are available, to about 135 mgd in 1960. This withdrawal, which averages about 100 mgd for the period, has formed a major cone of depression under the city of Memphis, where most of the pumping is concentrated, and has formed smaller superimposed cones under the Parkway, Allen, and Sheahan well fields (pl. 4). The regional relation between ground-water withdrawal and water-level decline in the "500-foot" sand is best illustrated by the hydrograph of well Sh: P–76 (fig. 7). This well is in the center of the major or regional cone of depression and is approximately equidistant from the smaller superimposed cones of depression caused by pumping in the Parkway, Allen, and Sheahan well fields. During 1935–60 an average rate of withdrawal of about 100 mgd resulted in a water-level decline of about 50 feet in well Sh: P–76, or about one-half foot decline for each million gallons pumped per day. Figure 8 shows progressively smaller declines in well Sh: O–1, 8 miles north of the center of pumping, and in well Sh: Q–1, 10 miles east of the center of pumping. Figure 9 shows still smaller declines in wells Sh: U–2, 15 miles north, and Fa: W–2 (Fayette County), 30 miles northeast of the center of heavy pumping.

The rate of water-level decline has increased since the early 1950's, at which time the rate of pumping increased to an average of about 120 mgd (1950–60) compared with an average of about 90 mgd for the preceding period (1935–59). The maximum decline for the period 1950–60 is about 47 feet in the Allen well field (pl. 5), which was placed in operation in early 1953. About 75 percent of this decline occurred in the first year of operation of this field. Smaller declines occurred in the Parkway and Sheahan well fields (pl. 5) during this period because these fields have been in operation since 1924 and 1931, respectively (fig. 5), and the rates of decline in each have decreased as their cones of depression have expanded and established a stable hydraulic gradient. The 24-foot decline in the McCord well field occurred after early 1958, when the field began operation. As in the Allen well field, the rate of decline in the early years of operation is greater than that in subsequent years, provided the rate of ground-water withdrawal remains the same.

Prior to 1958, when the McCord well field began operation, water levels in the field declined slowly and steadily (fig. 10) as a result of overall pumpage in the Memphis area. In 1958, the water level in an observation well near the McCord well field (fig. 10) declined about 18 feet for an average pumping rate of 12.5 mgd. Thus the relation between the water-level decline in this observation well and the pumpage of the well field was about 1.5 feet for each 1 mgd pumped. The next pronounced change in the rate of pumping occurred during the summer of 1960 when, between June and August, the pumping rate decreased from about 11.5 to 7.5 mgd. The water level in wells near

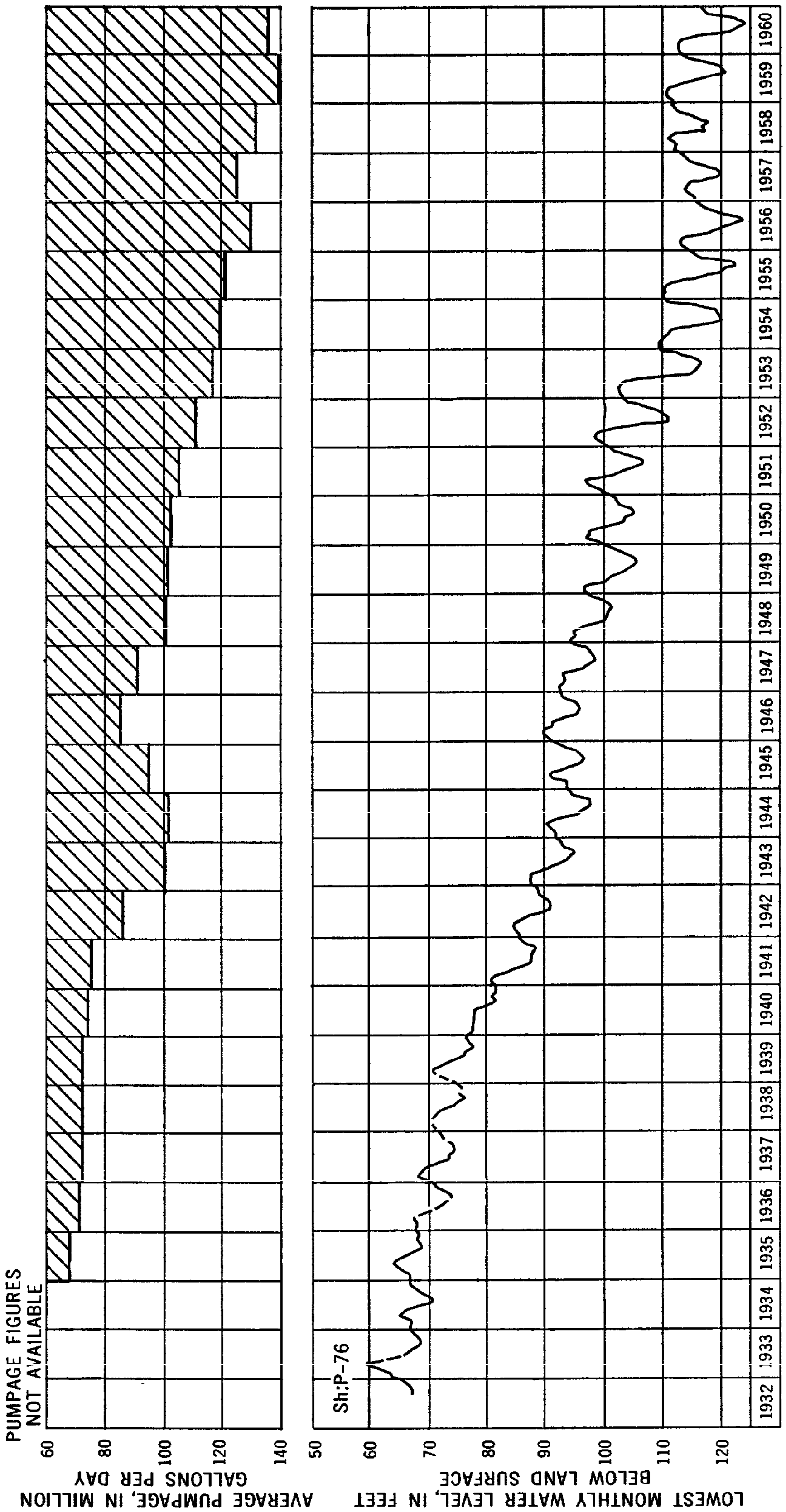


FIGURE 7.—Relation between ground-water withdrawal from the "500-foot" sand and water-level decline in the center of concentrated pumping.

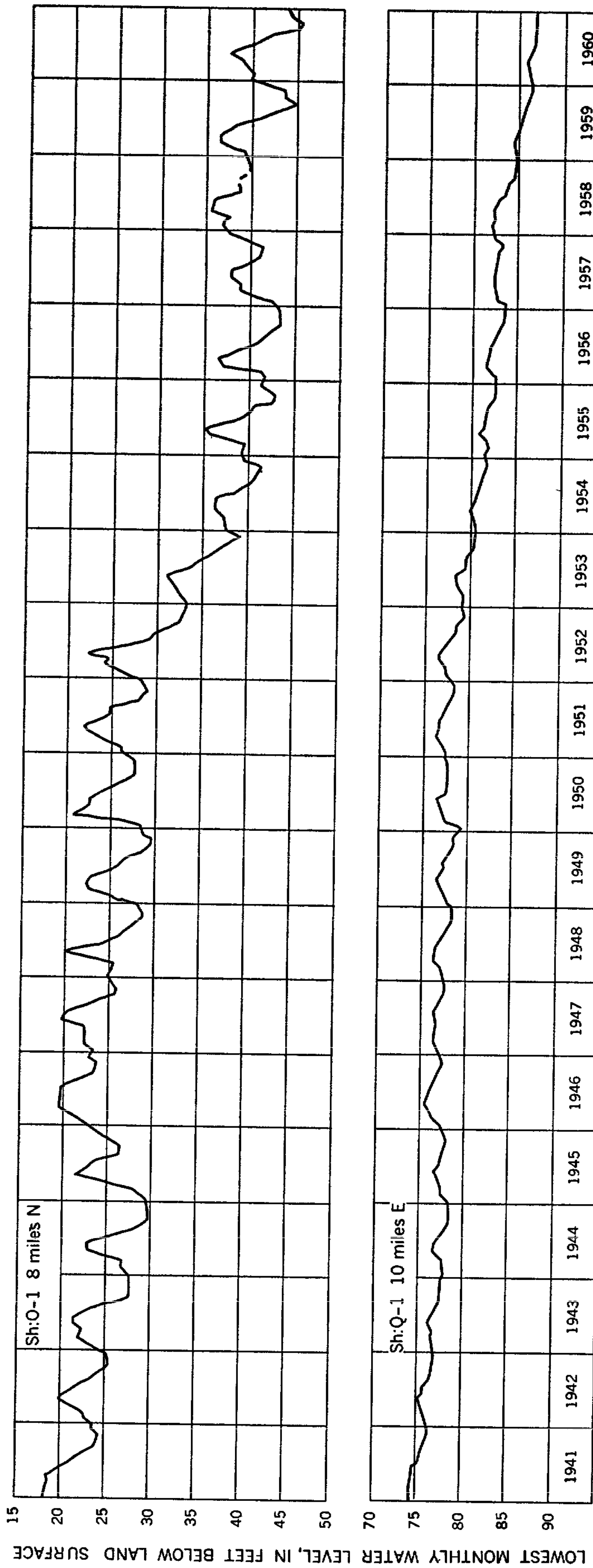


FIGURE 8.—Declines of water level in the "500-foot" sand, 8 and 10 miles from the center of concentrated pumping in the Memphis area.

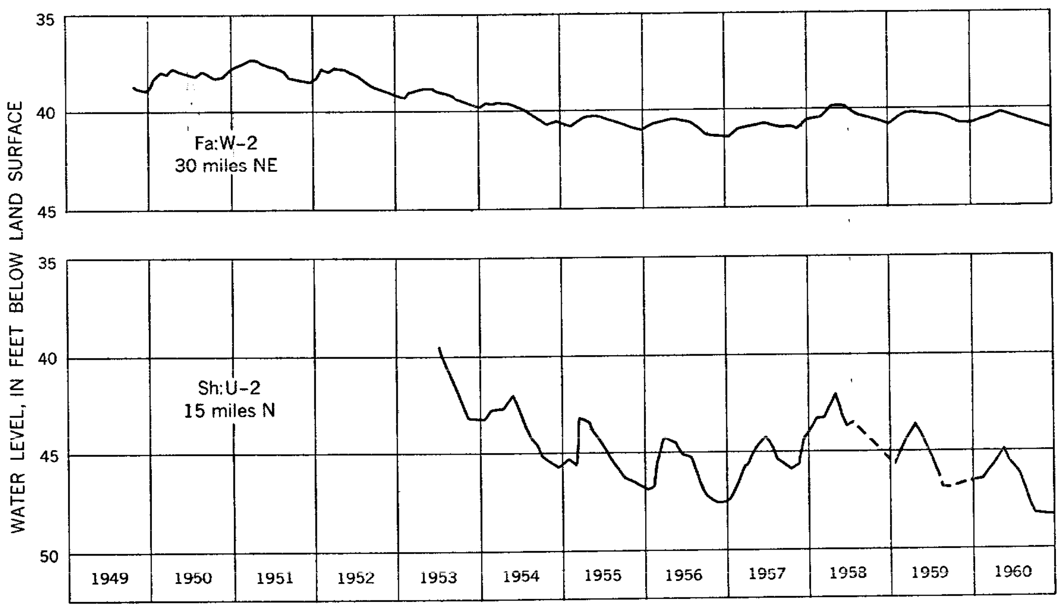


FIGURE 9.—Declines of water level in the "500-foot" sand, 15 and 30 miles from the center of concentrated pumping in the Memphis area.

the well field rose about 4 feet. Normally during this part of the year, the water level declines about 2 feet. Therefore, the effective recovery resulting from the pumpage reduction was about 6 feet. This again indicates a ratio between water-level rise or decline in the selected observation wells and pumpage of about 1.5 feet for each 1 mgd change in rate of pumping. Similiar determinations for the Allen (fig. 11) and Sheahan (fig. 12) well fields indicate ratios of 1.1 to 1 and 1.5 to 1 (feet of decline or rise to each million gallons per day increase or decrease in pumping) for these fields, respectively. The production ratio for the Allen well field is less because pumping has not continued long enough for the piezometric surface to stabilize in this newer well field. The production ratio for all well fields in the area should increase as water levels decline toward more stable pumping levels.

The distribution of production wells in the Parkway well field with respect to observation wells make it impossible to show a consistent relationship between the water level and the pumpage in this well field (fig. 13). The fluctuations resulting from seasonal and intermittent pumping are the only discernible parts of water-level changes. Figure 13 shows that a reduction of pumpage during 1945–49 did not cause a rise of water level in observation well Sh: O–153. This well is in the eastern part of the well field where the pumping rate was increased to offset the reduction in pumping in the western part of the well field. However, records of short-term observation wells indicate that the relation between water level and pumping differs little from that of the other well fields or of the entire Memphis area.

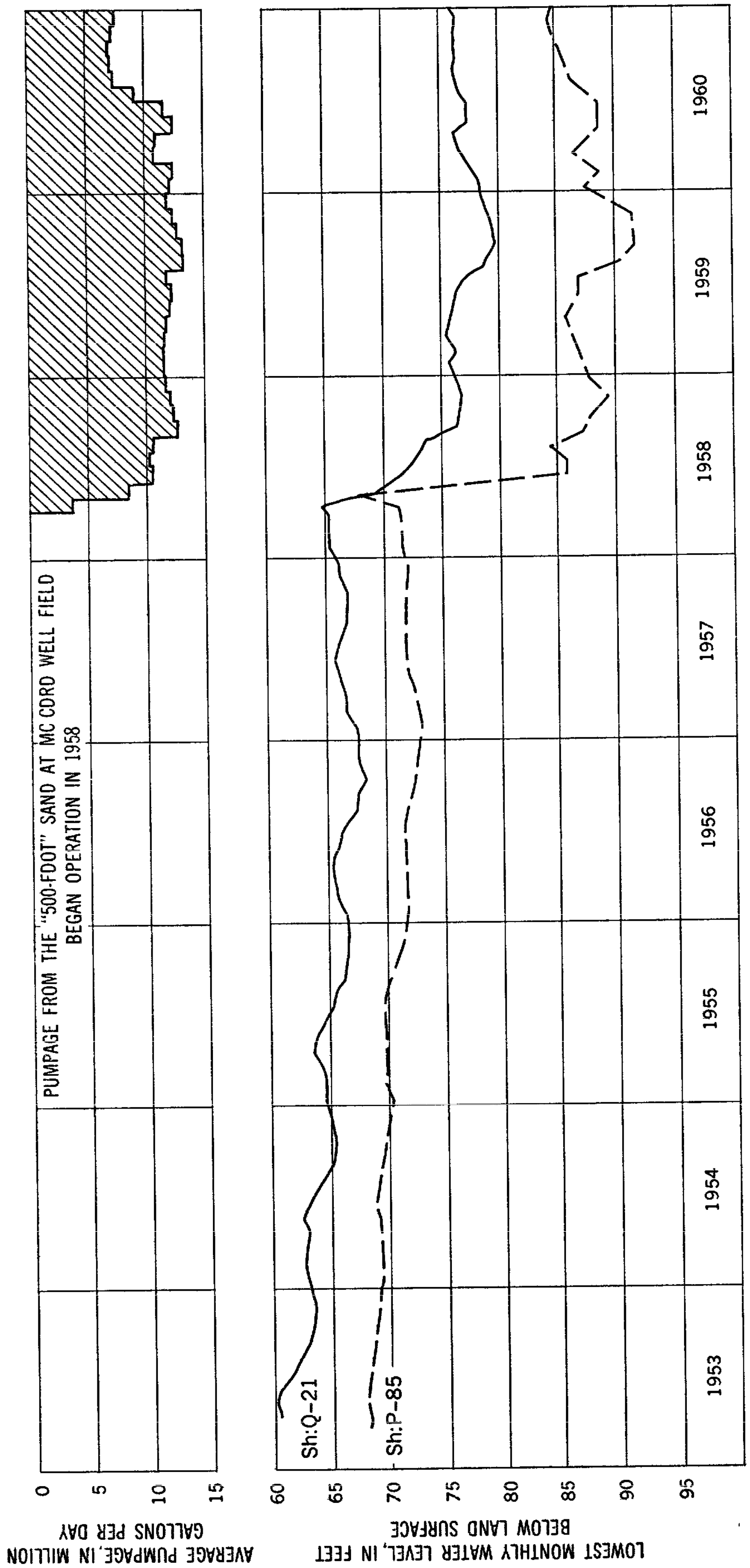


FIGURE 10.—The relation between pumping and water level ("500-foot" sand) in the McCord well field, Memphis, Tenn.

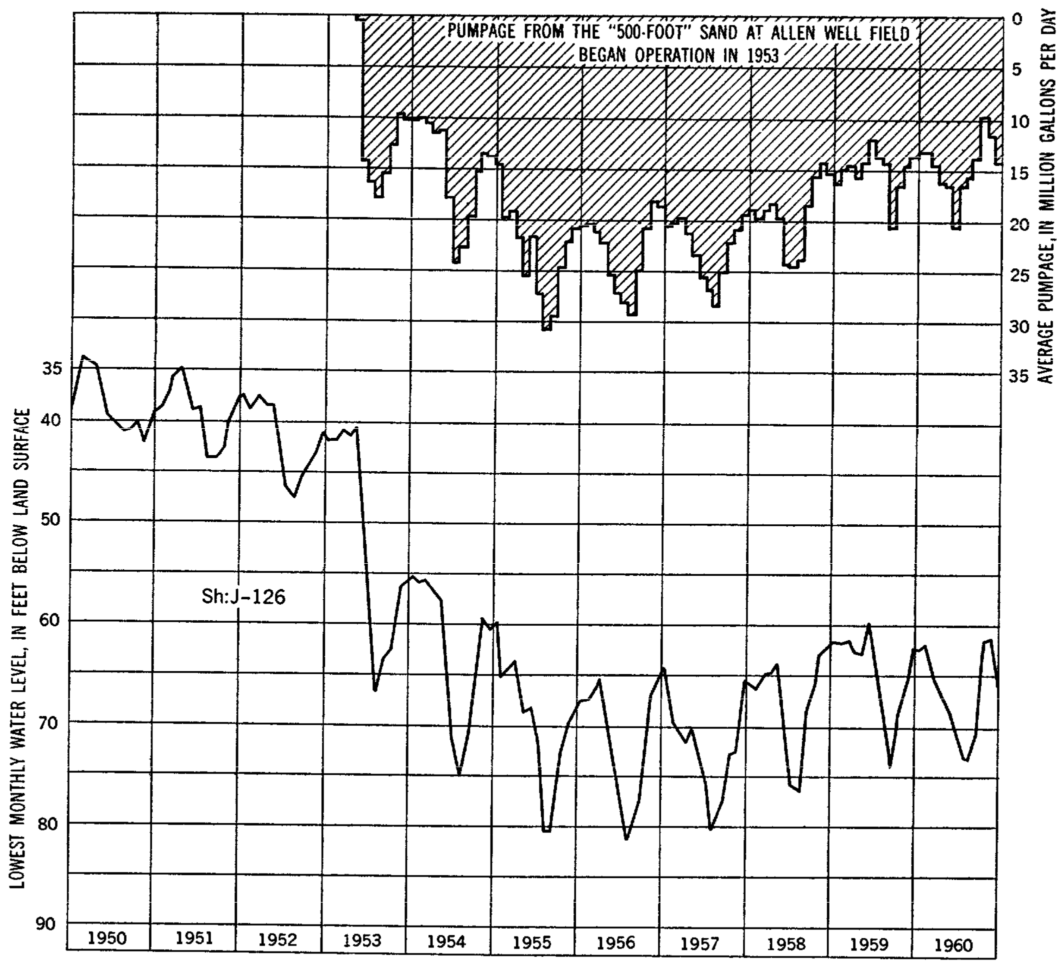


FIGURE 11.—The relation between pumping and water level ("500-foot" sand) in the Allen well field, Memphis, Tenn.

The hydrographs from observation wells equipped with recording gages generally show that those wells within or near the area of greatest withdrawal have their lowest water level in August each year, reflecting the highest monthly rate of withdrawal. Figures 7–9 show the declining trend of water level in the "500-foot" sand at various distances from the center of pumping as well as the annual low water level. The lowest annual water level occurs progressively later in observation wells that are farther from the center of pumping. The greater the distance, the greater the lag in the time of arrival of the effect of pumping. The lowest annual water level in observation well Fa:W–2 (fig. 9), which is 30 miles from the theoretical center of pumping, occurs in late December or early January, or about 4 months after the annual low water level in Memphis. The effect of cyclical pumping in the Memphis area, where the pumping is greater in summer than winter, is a wavelike motion of alternate low and high water levels traveling outward at a decreasing rate from the center of pumping. The cause of this wavelike phenomenon is believed to be a com-

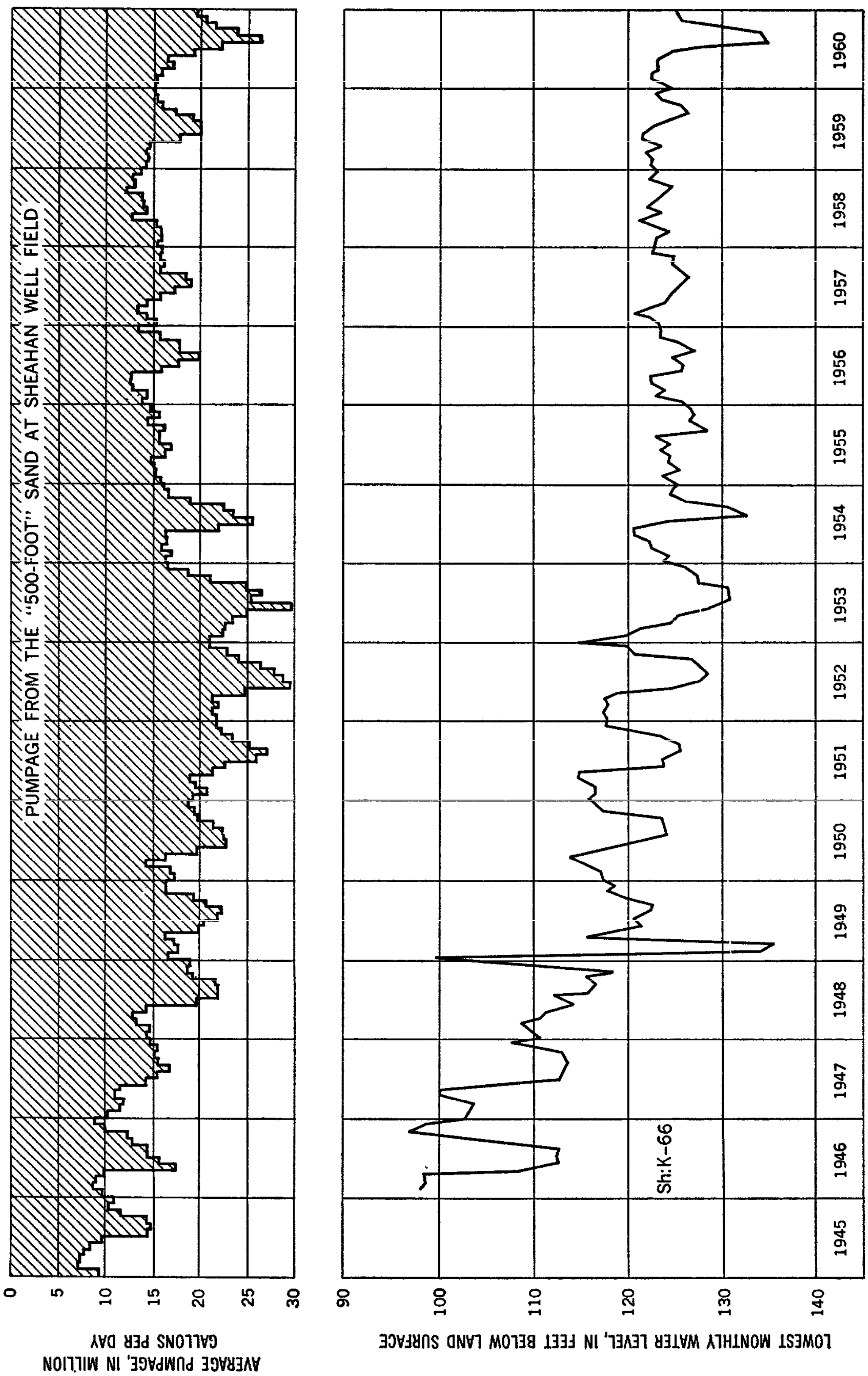


FIGURE 12.—The relation between pumping and water level ("500-foot" sand) in the Sheahan well field, Memphis, Tenn.

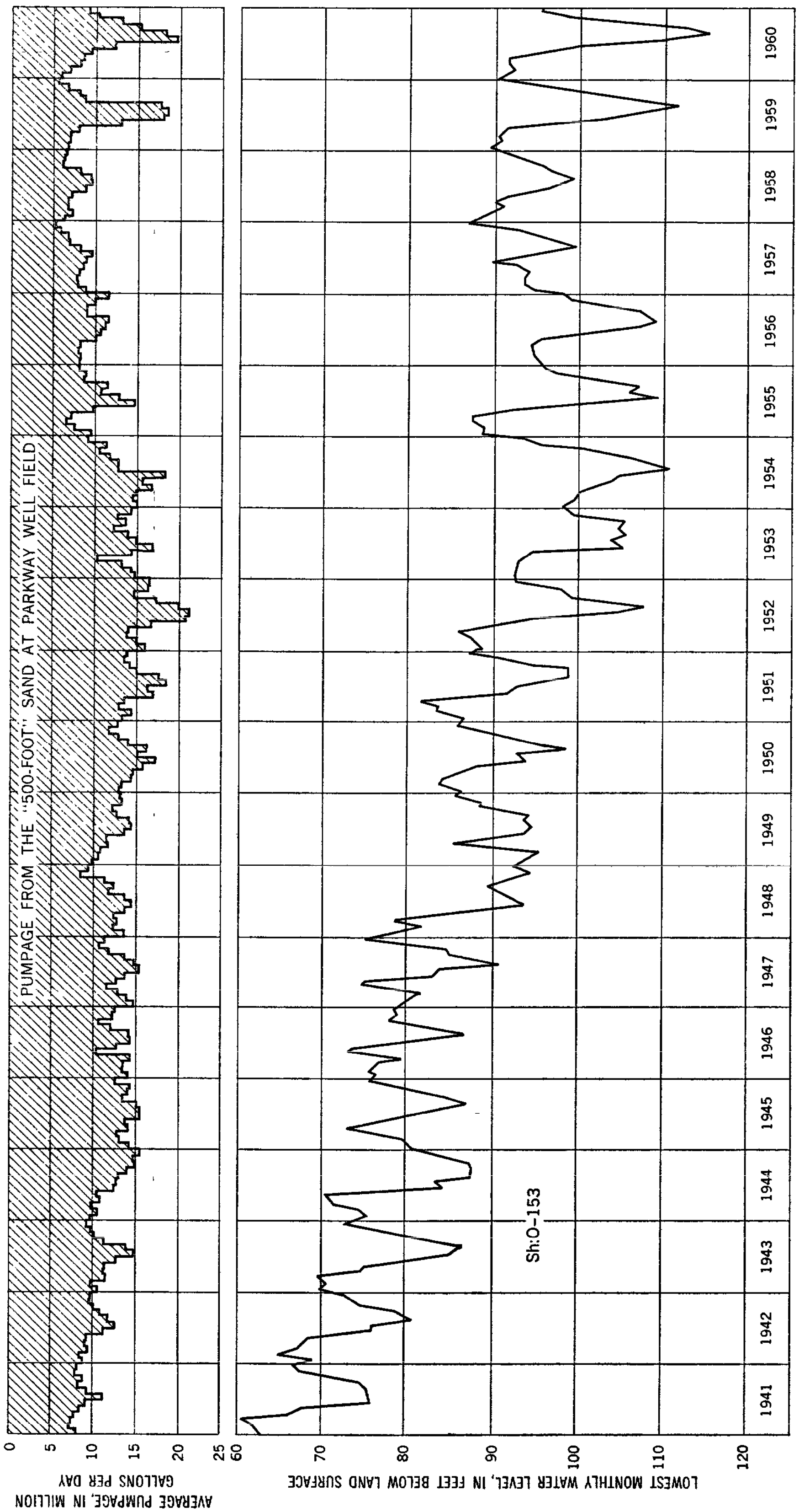


FIGURE 13.—The relation between pumping and water level ("500-foot" sand) in the Parkway well field, Memphis, Tenn.

bination of several factors including the degree of confinement, elasticity, and transmissibility of the aquifer. This effect should be considered when proposing locations of future well fields so that advantage can be made of the time lag of arrival of low water level. In a practical example, a typical well field about 20 miles from Memphis would be pumping at its lowest seasonal rate at a time when water levels are lowest and pumping most water at the time when water levels are highest.

Hydrographs of observation wells in the "500-foot" sand (figs. 7–9) indicate that the annual decline of the piezometric surface can be reasonably estimated for given rates of pumping. These figures show the fluctuations and general decline of water level in the Memphis area near the center of pumping (fig. 7), about 8 and 10 miles from the center of pumping (fig. 8), and 15 and 30 miles from the center of pumping (fig. 9). The theoretical center of pumping in the area is about the location of observation well Sh: P–76 (pls. 4, 6). Figure 9 shows that the seasonal fluctuation of water level in well Fa: W–2 about 30 miles northeast of Memphis in Fayette County is nearly 1 foot. The overall water-level trend is a declining one, although there are short periods of a rising water level caused by reductions in pumping rate, recharge to the aquifer, or both. This observation-well record reflects the regional water-level fluctuations and is less affected by small changes in pumping in Memphis. The seasonal range of water-level fluctuation in well Sh: U–2 in Memphis (fig. 9) has been about 3.5 feet except in 1957, a year of record-high rainfall. The record of this well also indicates the regional water-level trend, but the effect of changes in pumping in Memphis is more pronounced in this record than in that of well Fa: W–2.

FLUCTUATION

Precipitation causes water-level fluctuations in wells by recharging the aquifer in its outcrop area, by seeping through the overlying clays, where they are thin or missing, and, to a minor extent, by loading. The effect of recharge to the aquifer caused by unusually high precipitation is illustrated in the hydrograph of well Fa: W–2 for 1957 (fig. 9). The water level in this well under normal conditions of rainfall and pumping in the Memphis area would have declined about 0.3 foot in 1957. Instead, the water level rose about 0.8 foot, an effective change of 1.1 feet. Past records indicate that a reduction of pumpage of 10–20 mgd in Memphis would have been required to cause a 1.1-foot change in water level in this observation well. The annual average daily pumpage in 1957 was only about 1 mgd less than in the previous year. Therefore, the rise of water level in 1957 was largely due to recharge from heavy rainfall in the outcrop area of the "500-foot" sand.

724-489—64——3

Loading of an aquifer, as by passing railroad trains and by rainfall, may also cause water-level fluctuations; but for a specific load the net water-level change is zero, and no rising or declining trend results. Generally, the water level rises as a load is applied then decreases rapidly even though the load may remain. Wells (1931, p. 25) believed that the Mississippi River added water to the "500-foot" sand, because a series of water-level measurments in wells along the river were higher when the river was high. Data collected by Kazmann (oral communication, 1954), however, indicated that loading of the aquifer by the weight of rapidly rising water in the river caused the water level also to rise in certain wells. In agreement with Kazmann's conclusion, it is doubtful that the river would have furnished water to the aquifer even if there had been a hydraulic connection between the river and the aquifer, because at that time (1931) the water level in the aquifer was about as high as the level of the river.

Atmospheric-pressure fluctuations may cause as much as a foot of change in water-level, depending partly on the rapidity of the change in pressure. These are basically daily-cycle fluctuations and are considered only during strict aquifer performance tests when water-level measurements are corrected for barometric effect. Within a short time the pressure-influenced water level regains its original level, often with the assistance of a reverse change in atmospheric pressure. The net change in water level resulting from atmospheric pressure change is zero over a period of time, generally 1 day.

HYDRAULIC CHARACTERISTICS

The amount of water that can be pumped from an aquifer perennially depends primarily on the capacity of the aquifer to transmit water from areas of recharge to areas of discharge, the amount of water available for recharge, and the amount of water in storage in the aquifer. To estimate the amount of water that can be pumped perennially with proper accuracy, the hydraulic characteristics of the aquifer must be known. Aquifer performance or pumping tests are the most economical method of determining the hydraulic characteristics. These characteristics are permeability (P), transmissibility (T), and storage (S). These and other terms used to describe the hydrologic properties of rocks were defined by Meinzer (1923), Wenzel (1942), and Ferris and others (1962).

Pumping tests consist of observing the rate of drawdown in observation wells for a given uniform rate of pumping in a nearby well or of observing the rate of water level recovery in a pumped well, or observation wells, after pumping stops. Pumping-test data were analyzed by standard methods, and the results were approximately the same as the values of the hydraulic characteristics. For this reason the less laborious semilog-plot method is used in this report.

Figure 14 shows a semilog plot and sample analysis of pumping-test

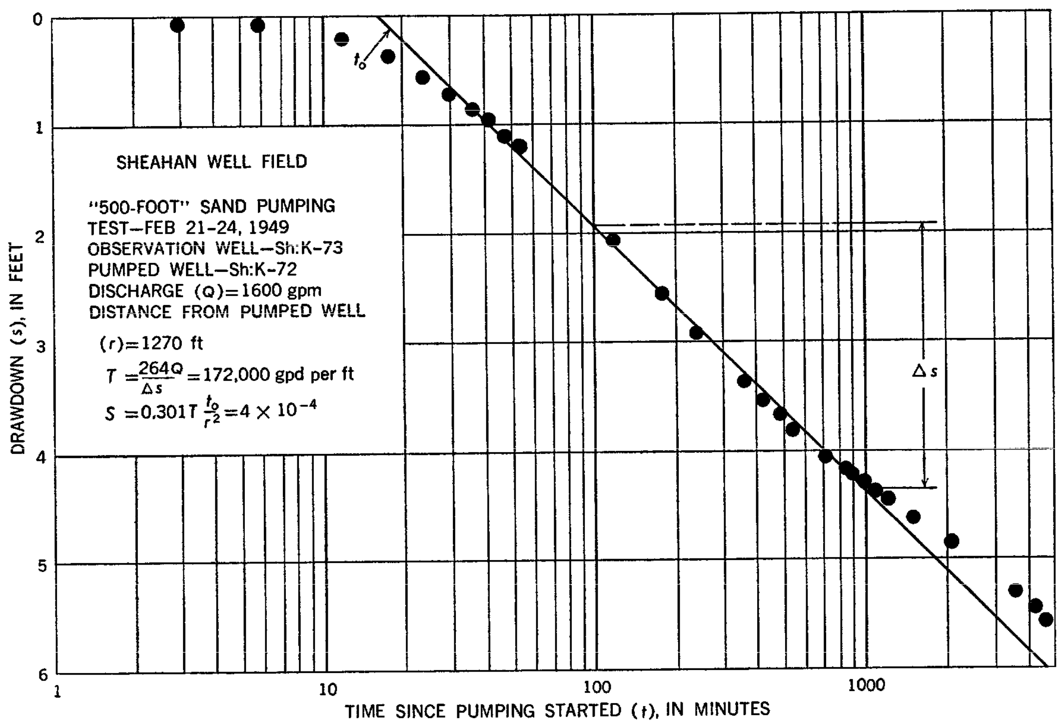


FIGURE 14.—Sample computations of transmissibility and storage coefficients for the "500-foot" sand using plotted pumping-test data.

data from wells in the "500-foot" sand. The figure also shows the procedure for computing the hydraulic characteristics of the aquifer.

The numerical values of hydraulic characteristics determined by pumping tests reflect the effects of all material within the zone of influence of pumping in the aquifer. This zone extends horizontally to the perimeter of the cone of depression of the pumping well. Its vertical influence may not extend to the bottom of the aquifer because of the anisotropy of the formation and partial penetration of the wells. As a result, a single pumping test provides hydraulic constants determined by the part of the aquifer affected during the test. These values are adequate for predicting aquifer response for that particular affected area under conditions generally the same as those prevailing during the period of the test. The values of the hydraulic characteristics of the total volume of the aquifer were determined by averaging the results of all tests and adjusting them for partial penetration of wells and other factors.

The wells that were used in all tests of the "500-foot" sand in the Memphis area are less than 500 feet deep and penetrate from 5 to 15 percent of the total thickness of the aquifer. Local clay lenses are present in above and (or) below the screens of some wells. The wells range in diameter from 4 to 20 inches; well screens range in diameter from 3 to 12 inches and in length from 10 to 120 feet.

Specific capacity of wells ranges from 10 to 100 gpm per foot of drawdown. The coefficient of transmissibility determined by analyses of data from these tests ranged from 100,000 to 410,000 gpd per ft, and the coefficient of storage from 1×10^{-4} to 3×10^{-3}. The average adjusted coefficients of the "500-foot" sand for the total thickness of the aquifer throughout the entire area are about 400,000 gpd per ft and 3×10^{-3} for T and S, respectively. Average values are used in this report to make quantitive determinations, and these values will be adequate for future determinations where artesian conditions prevail.

RECHARGE AND MOVEMENT

Recharge to the "500-foot" sand aquifer generally occurs in the areas where it lies at or near the land surface. Percolation of rainfall directly through the sandy soil in the outcrop area and seepage from streams recharge the aquifer where it crops out in the rolling hills 30–60 miles east of Memphis. The annual precipitation at Moscow and Bolivar, Tenn., in the recharge area, is slightly greater than at Memphis (fig. 2), and rainfall is fairly well distributed throughout the year.

In addition to recharge in the outcrop area, the "500-foot" sand locally receives some water from the overlying terrace deposits wherever the clay bed that generally underlies the terrace deposits is sandy or thin and where streams have cut deeply into the clay bed. Nonconnah Creek, formerly a perennial stream, now has periods of abnormally low flow in its lower reach during part of the year and has been dry during the latter part of the dry season in recent years. This change in its regimen is attributed to increased recharge to the "500-foot" sand as a result of the decline of water level in the aquifer within the past few years. Recharge to the aquifer probably is increasing as the effect of pumping in the Memphis area reaches the outcrop area and areas where seepage can occur.

The rate of water movement depends on the transmissibility of the aquifer and the hydraulic gradient. In general, the greater the rate of discharge, the more rapid the movement of water through the aquifer along the flow path. However, limitations on the maximum possible rate of movement are determined by the aquifer characteristics, not by the rate of discharge.

The movement of water in the Memphis area before development of the "500-foot" sand began was probably along the dip of the formation—locally westward in the area and regionally southward down the dip of the embayment. Water-level records indicate that the hydraulic gradient between Collierville and Memphis was about 5×10^{-4} in 1886. Using this value for the hydraulic gradient and an average transmissibility of 4×10^5 gpd per ft for the "500-foot" sand aquifer, about 1 million gallons of water moved across each 1-mile section of the aquifer each day in 1886. The eastern boundary of the area is about 30 miles in length; therefore, the average rate of water entering the Memphis area in 1886 was about 30 mgd. If we assume that stable conditions existed at that time, the rate of natural discharge was equal to the recharge rate.

The present direction of movement of ground water in the Memphis area is generally toward central Memphis from all directions as shown on plate 4. Water-level contours (pl. 4) indicate that more water is derived from the east-southeast; probably because transmissibility is greater in that part of the area, the dip of the "500-foot" sand is toward the northwest (figs. 5, 6), and the nearest area of recharge lies to the southeast. The amount of water moving across the 260-foot contour on plate 4 is about 60 mgd. Total inflow is tabulated in the section on pumping.

The amount of water moving into the area from the west is small, probably because the Big Creek fault forms a hydraulic boundary restricting inflow. Further increases in pumping in the Memphis area will produce steeper gradients and induce a greater amount of water to flow toward the centers of pumping.

The present rate of movement of ground water in the "500-foot" sand in the southeastern part of the area is estimated to be approximately 70 feet per year toward the west-northwest under a hydraulic gradient of about 5 feet per mile (9×10^{-4}). At the edge of the area of heavy withdrawal, approximately 3 miles from the present city limits (pl. 3), the gradient steepens to about 10 feet per mile and the rate of ground-water movement increases accordingly to about 140 feet per year. In and near the well fields, the velocity of flow is even greater. In the northeastern part of the area, the hydraulic gradient is about 3 feet per mile, and the rate of movement about 40 feet per year.

PUMPING

An average of about 135 mgd was pumped from the "500-foot" sand in 1960. A little less than half this amount was for municipal use, and a little more than half was for industrial use. Pumping records reported monthly to U.S. Geological Survey indicate that industrial pumping is nearly constant and that municipal pumping may vary as much as 100 percent from summer to winter. Figure 6 shows the average daily pumping rate for each year since 1935. The effect of the areal distribution of pumping is shown on the piezometric map (pl. 4) and on the isodecline map (pl. 5).

As previously stated, the natural discharge moving out of the Memphis area toward the west and thence southward along the axis of the embayment was about 30 mgd in 1886. Natural discharge probably ceased when the water level was lowered to about 200 feet above mean sea level in central Memphis. The hydraulic gradient created by pumping in Memphis probably was sufficient to stop the natural discharge from the area by 1940.

The total amount of water pumped from the "500-foot" aquifer between 1886 and 1960 is estimated to be about 1.9 trillion gallons (1.9×10^{12}). If it is assumed that $S=3\times10^{-3}$ and that the water level declined 60 feet between 1886 and 1960, then the total amount of water pumped from storage is about 12 billion gallons. This quantity is less than 1 percent of the total pumpage since 1886—that is, an average of about 1 percent of the water pumped each year was derived through depletion of storage in the aquifer.

A water-control budget for the "500-foot" sand aquifer was computed using the low-water-level contours for 1960 (pl. 4) and checked against the average daily pumping rate for 1960. Inflow into the Memphis area was determined to be generally as follows:

Inflow	*Million gallons per day*
Across eastern boundary	60
Across northern boundary	20
Across southern boundary	25
Across western boundary [1]	29
Depletion of storage	1
Total	135
Average daily pumping rate for 1960	135

[1] Includes leakage from rocks above aquifer and inflow of water from other sources.

THE "1,400-FOOT" SAND AQUIFER

DELINEATION

Delineation of the "1,400-foot" sand in the Memphis area is based on the same hydrologic considerations as is delineation of the "500-foot" sand. The upper and lower boundaries (pls. 6, 7) were determined primarily by interpretation of electric and gamma-ray logs which show distinct contacts (pl. 1) of the sand with its confining clay formations. The confining clay formations are thick and for practical purposes may be considered impermeable. The aquifer is continuous throughout the area and dips toward the west at a rate of about 25 feet per mile. The sand probably crops out 60–80 miles east of Memphis although in some areas it is overlapped by the "500-foot" sand (Schneider and Blankenship, 1950). The thickness of the aquifer increases from about 150 feet in the eastern part of the Memphis area to about 300 feet in the western part. The volume of the aquifer in the 1,300 square mile area is about 7 trillion cubic feet (7×10^{12}).

WATER LEVELS

DECLINE CAUSED BY PUMPING

The relation between water-level fluctuations and pumping in municipal well fields is shown in figures 15 and 16, The two observation wells represented are in the Parkway and Sheahan well fields and clearly show the effect of changes in pumping rates, although the water-level fluctuations cannot be correlated quantitatively with the pumping from each well field because fluctuations caused by natural phenomena obscure the fluctuations caused by pumping. These two municipal well fields and one industrial plant well field are the only ones in Shelby County having one or more wells screened in the "1,400-foot" sand. Nearly all the observation wells are close to production wells in these fields, and intermittent pumping of the production wells often masks any areal water-level trend that might be noted in an observation well several hundred feet from a well field.

The water-level fluctuations in observation wells at greater distances from the areas of heavy withdrawal (fig. 17) are less pronounced, and the hydrographs of these wells reflect regional trends of water level.

The hydrographs in figure 17 show that, except for during 1957 and 1958, the average seasonal fluctuation in well Fa:W–1, about 30 miles northeast of Memphis, is about 1.2 feet; and in well Sh:U–1, about 15 miles north of Memphis, it is about 3.5 feet, or about three times that in well Fa:W–1. The ratio of the logarithms of the two distances mentioned above is also 3, so that a rule can be inferred as follows, relating distance to seasonal fluctuations:

$$\frac{\log 30}{\log 15} \times \text{seasonal fluctuation at 30 miles} = \text{seasonal fluctuation at 15 miles.}$$

This may be a general rule for predicting water-level fluctuations and decline in the Memphis area and possibly other similar areas where no observation wells exist, but it has not been proven.

In wells in the "1,400-foot" sand, water levels declined at an almost constant rate until 1952 as a result of gradual increases in pumping. In 1952 pumping was decreased (fig. 17). However, the trend of decline continued (fig. 17) until 1957 because drought conditions in the outcrop or recharge area of the aquifer prevented immediate replenishment of the water pumped from the Memphis area. Since 1957 the water level has remained about constant. No significant trend of decline is expected until several more wells are developed in this aquifer or until another prolonged drought occurs.

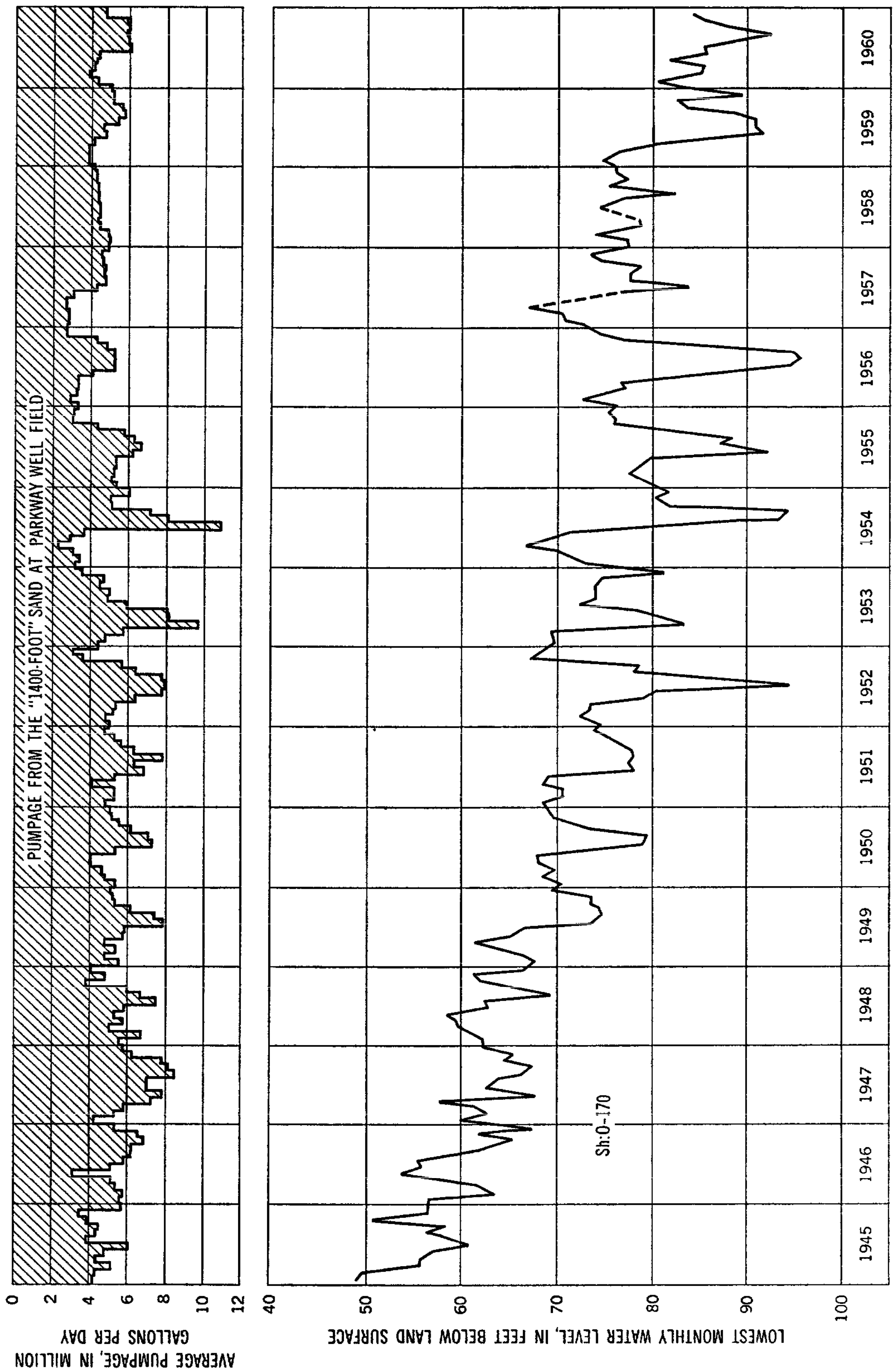


FIGURE 15.—The relation between pumping and water level ("1,400-foot" sand) in the Parkway well field, Memphis, Tenn.

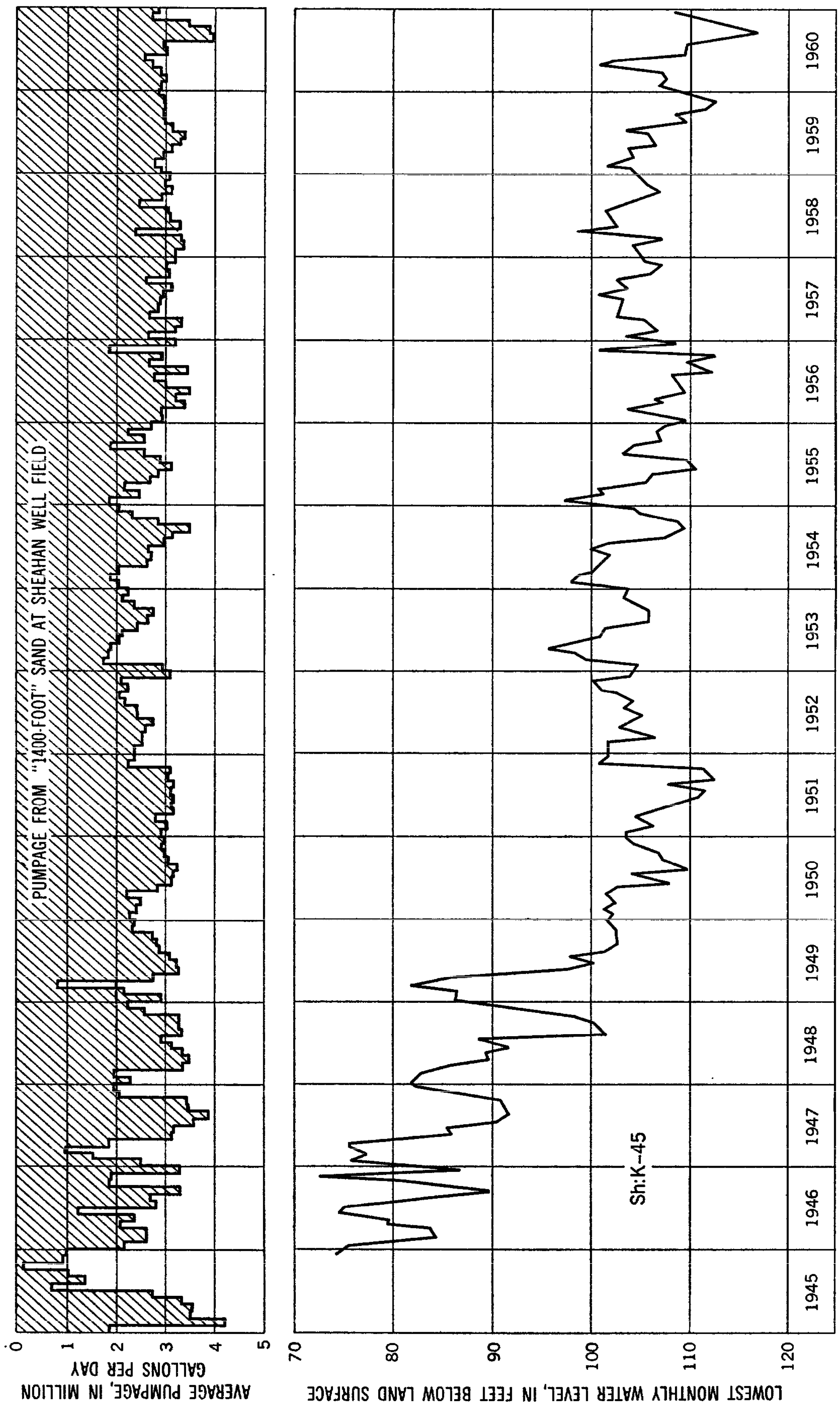


FIGURE 16.—The relation between pumping and water level ("1,400-foot" sand) in the Sheahan well field, Memphis, Tenn.

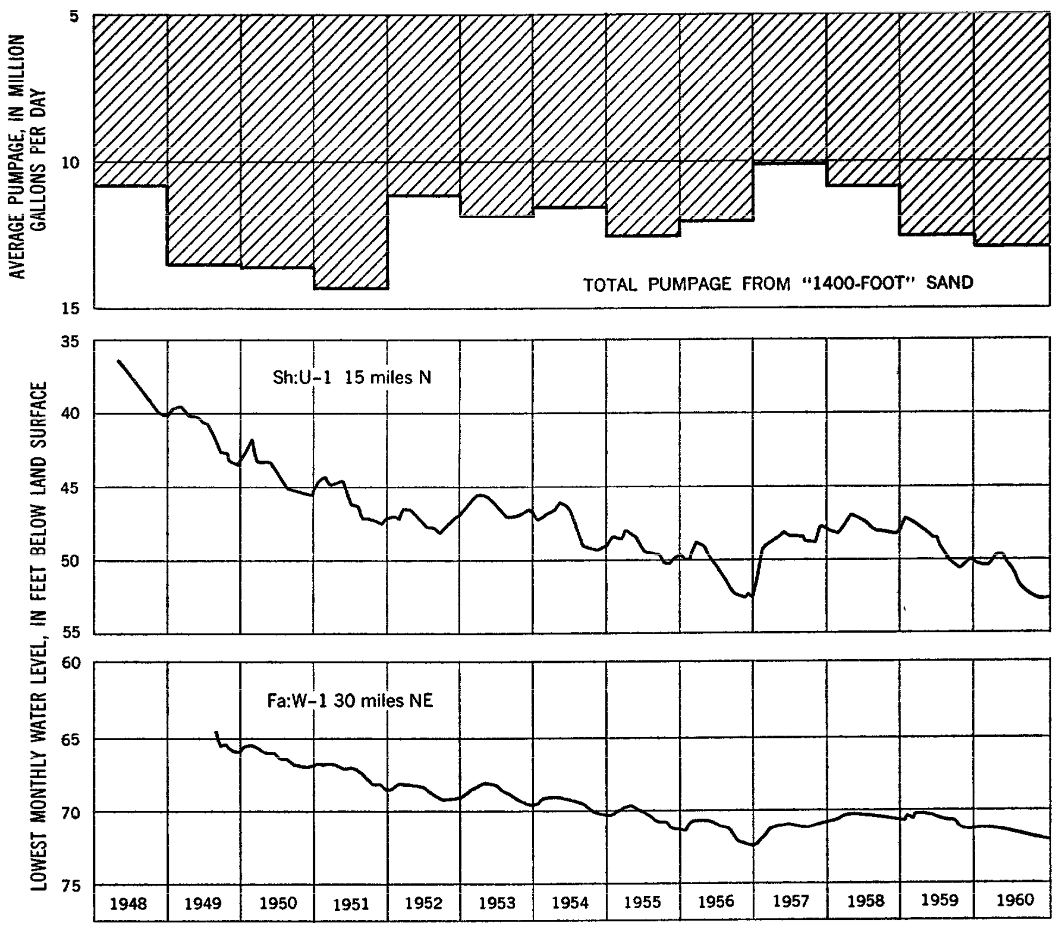


FIGURE 17.—The relation between total pumpage from the "1,400-foot" sand in the Memphis area and water levels in wells Sh : U–1 and Fa : W–1, 15 and 30 miles, respectively, from the center of pumping.

FLUCTUATION

Water levels in the "1,400-foot" sand fluctuate in response to the same causes discussed earlier for the "500-foot" sand. Fluctuations resulting from atmospheric-pressure changes are slightly more pronounced because the aquifer is under higher artesian pressure and its barometric efficiency is greater. Water level fluctuations resulting from loading are negligible because of the structural support of the greater thickness of material above the aquifer.

Since 1957, water levels have fluctuated primarily in response to rainfall in the outcrop area of the "1,400-foot" sand aquifer. Hydrographs (fig. 17) show that water levels rose from 1957 to 1959 during a period of normal to above normal precipitation even though pumping increased slightly over the same period. The regional rise of water level is similar to the rise of water level in the "500-foot" sand (fig. 9) during the same period.

HYDRAULIC CHARACTERISTICS

The numerical values of the hydraulic characteristics of the "1,400-foot" sand determined from seven tests in the three well fields in Memphis cover a rather narrow range.

	Average	*Minimum*	*Maximum*
T	3×10^{-4}	90,000	140,000
S	3×10^{-4}	1.5×10^{-4}	4×10^{-4}

An example of test data is shown in figure 18. The highest values of the coefficients were from tests at the Parkway well field (pl. 6), where the thickness of the "1,400-foot" sand is about 15 percent greater than in the other well fields.

The yields of the wells used in the tests ranged from 400 to 1,600 gpm (gallons per minute). The wells range in diameter from 8 to 24 inches. The well screens are 8–10 inches in diameter, 55–120 feet in length, and penetrate less than 50 percent of the thickness of the aquifer.

The aquifer-test results indicate that the "1,400-foot" sand is almost an ideal artesian aquifer. The changes of water level in observation wells in response to changes in the rate of withdrawal were almost instantaneous, indicating near-perfect vertical confinement between the clay boundaries. The barometric efficiency of the aquifer ranged from 75 to more than 95 percent, also indicating near perfect confinement.

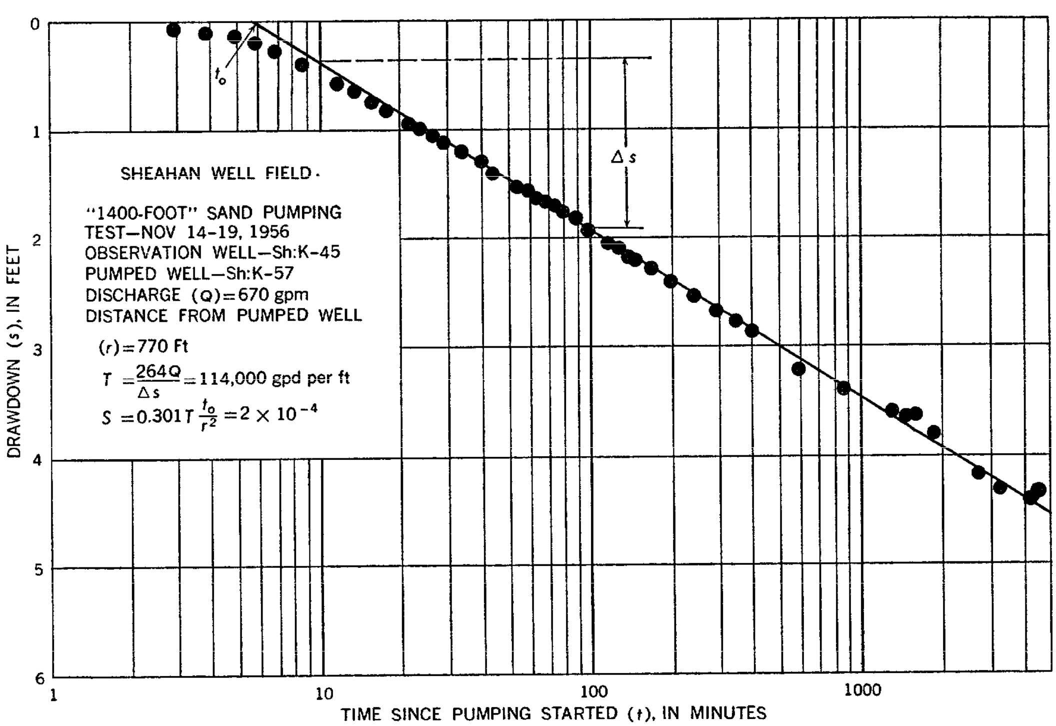


FIGURE 18.—Sample computations of transmissibility and storage coefficients for the "1,400-foot" sand using plotted pumping-test data.

Tests made in the same well fields in 1944 and later show that the hydraulic characteristics of the aquifer have not changed appreciably in about 15 years.

The hydraulic constants determined for the "1,400-foot" sand are more reliable than those for the "500-foot" sand, and the constants may be used more etxensively because the "1,400-foot" sand is more uniform in texture and thickness.

RECHARGE AND MOVEMENT

In some part of the outcrop area where the "1,400-foot" sand is in contact with the bottom of the "500-foot" sand, the "500-foot" sand outcrop serves as the recharge area for both aquifers (Schneider and Blankenship, 1950, chart 1). Where the sand is exposed at the surface, it receives recharge from precipitation and from seepage from streams. The rate of recharge is influenced by the rate and amount of precipitation, as indicated by hydrographs of wells in the "1,400-foot" sand (fig. 17) which show that the water levels rose in 1957, a year of unusually high rainfall.

The rate of recharge before the development of wells in the aquifer began, based on available data and the assumption that recharge was equal to the natural discharge at that time was about 5 mgd to the Memphis area. The present rate of recharge is unknown but is less than the pumping rate for the area.

The amount of water moving toward a well is proportional to the hydraulic gradient of the cone of depression. Generally, the hydraulic gradient increases as the rate of pumping increases. If the pumping rate remains constant, the cone of depression expands and the hydraulic gradient tends to flatten, other factors being equal, until an equilibrium slope is established. The 1960 rate of withdrawal from the "1,400-foot" sand was about 13 mgd, and this quantity has not varied more than 20 percent during the past decade. The hydrographs of wells Fa : W−1 and Sh : U−1 (fig. 17) show that the hydraulic gradient established in the "1,400-foot" sand has flattened and remained about constant several miles from the area of heavy withdrawal for the past decade also. The gradient 15–30 miles from central Memphis is about 3 feet per mile (or 5.7×10^{-4}), and the rate of movement of water is about 40–50 feet per year.

Water-level data for 1924 (Schneider and Cushing, 1948, p. 9) show that the hydraulic gradient before development of wells in the "1,400-foot" sand was 2.5×10^{-4} and that the transmissibility was 1.2×10^{5} gpd per ft. Based on these figures the average amount of water that moved westward across a 1-mile section of the "1,400-foot" sand aquifer was about 0.16 mgd, compared to 1 mgd for the "500-foot" sand aquifer.

This rate of movement is equal to the natural discharge and recharge before the development of wells in the aquifer.

PUMPING

The average daily rate of withdrawal of water from the "1,400-foot" sand in the Memphis area between 1935 and 1960 is shown in figure 6. During the period 1947–60 the annual pumpage ranged from 10 to 14 mgd and averaged about 12 mgd. The slope of the present hydraulic gradient in the area 15–30 miles from the center of heavy withdrawal has developed in response to this constant rate of withdrawal, and near-equilibrium conditions of discharge, recharge, and water level now exist.

In 1924, before the development of wells in the "1,400-foot" sand, was equal to the amount of recharge, or about 5 mgd. Pumps within the area now intercept all the water that formerly was discharged naturally from the area.

Total discharge, or the amount of water withdrawn from 1924 to 1960, is about 120 billion gallons. If we use a coefficient of storage of 3×10^{-4} and a total water-level decline of 74 feet (in the Parkway well field), the amount of storage depletion in the aquifer is about 12 billion gallons. The average annual rate of depletion of storage in the aquifer is 10 percent of the present average daily rate of pumping, or about 1 mgd.

OTHER AQUIFERS

The Ripley Formation of Cretaceous age may be a major source of water in the future. The top of the Ripley lies about 2,600 feet below land surface at Memphis, and, at present, only one well, in the Parkway well field, is screened in the formation. The piezometric surface of this aquifer is more than 100 feet above land surface, and when this well was allowed to flow, it produced about 35 gpm. The water contains more than 1,000 ppm (parts per million) total dissolved solids and is not fit for most uses without treatment.

Terrace deposits consisting of sand and gravel of Pleistocene and (or) Pliocene age may also be a major future source of water. These deposits lie at or near land surface where they are present and may be as much as 160 feet thick. Several domestic wells screened in this aquifer yield as much as 50 gpm, and it is probable that large capacity wells could be developed in some places in the area. Water from the terrace deposits is hard but generally contains less iron than does the water from either of the principal aquifers. Water from the terrace deposits is suitable for some industrial uses without treatment, though none of the industries in the area use water from this source.

QUALITY OF WATER

Water that moves through underground formations comes into contact with and dissolves soluble material in the rocks, thereby changing the chemical quality of the water. Differences in the quality of ground water reflect differences in the geologic environment in the water-bearing formations. Formations lying at considerable depth below the surface and those which yield water derived from distant sources usually contain water that is more highly mineralized than do those which lie at shallow depth or obtain water from nearby sources. A complete discussion of the significance of the chemical and physical characteristics of water was prepared by Lohr and Love (1954, p. 3–13).

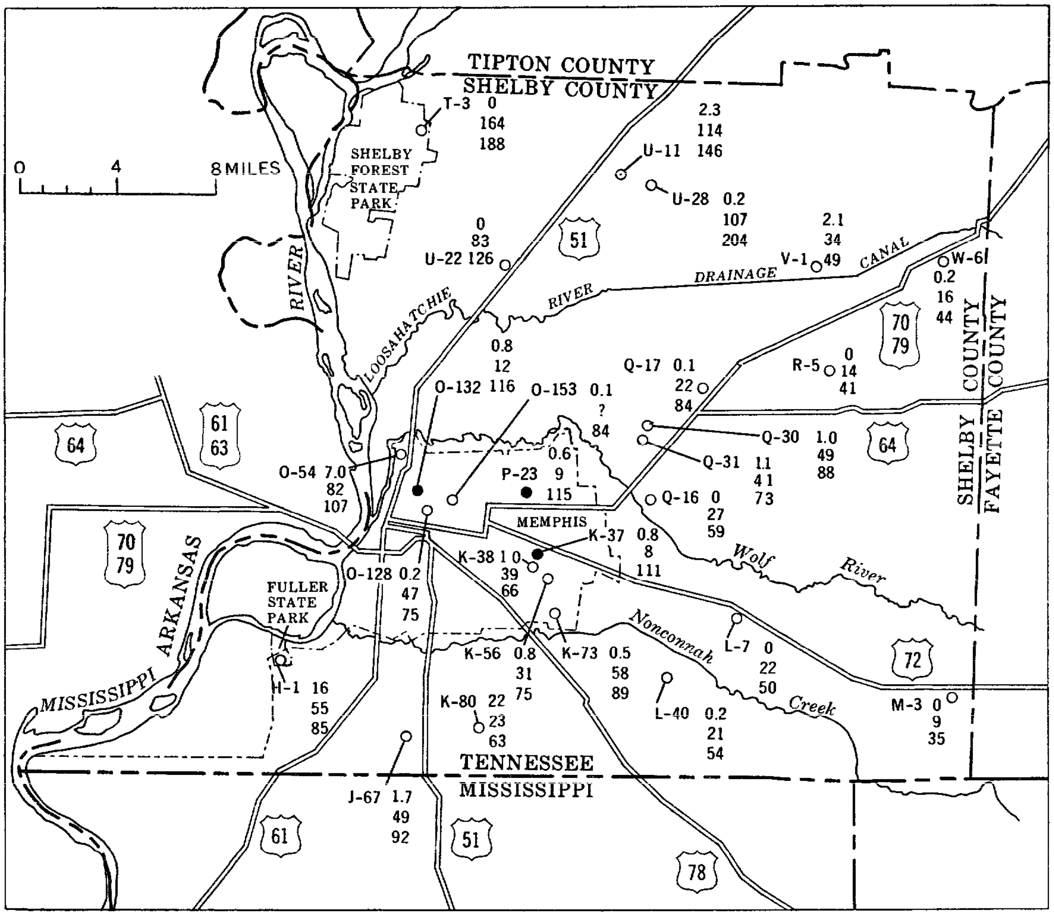
The value of a water supply is largely dependent on the quality of the water required for various uses. Water from the two principal aquifers in the Memphis area is of good chemical quality for municipal use and contains chemical constituents in concentrations well below those recommended by the U.S. Public Health Service for water used on interstate carriers. Iron concentration and hardness of water are usually the most troublesome chemical qualities. Iron concentration, hardness, and total dissolved solids in selected samples from the two principal aquifers are shown in figure 19.

The bacteriological quality of water from the "500-foot" and "1,400-foot" sand aquifers in the Memphis area is excellent because of the great depth to the water and because a local ordinance requires filling of abandoned wells with clay and cement. The only aquifer which could become seriously polluted from the land surface is the terrace deposits, and this aquifer is not used extensively for supply where pollution would be likely.

Industrial wastes and sewage do not currently pose a pollution problem, because these materials are discharged to the Mississippi River and are not allowed to accumulate in large amounts at any place in the area. Discharge of waste water to wells is prohibited by municipal ordinance in Memphis and Shelby County.

WATER IN THE "500-FOOT" SAND

The chemical quality of water in the "500-foot" sand is good. The only dissolved constituents that are troublesome are iron, free carbon dioxide, and, in a few places, hydrogen sulfide. Iron is easily removed by aeration and filtration, and most free carbon dioxide and hydrogen sulfide escape as the water is pumped from the ground or during the aeration for iron removal.



EXPLANATION

Sh:U-11 ○
Well screened in "500-foot" sand

Sh:K-37 ●
Well screened in "1400-foot" sand

Well number Sh:H-1 ○ 16—Iron (ppm)
55—Hardness as $CaCO_3$ (ppm)
85—Dissolved solids (ppm)

FIGURE 19.—Iron concentration, hardness, and total dissolved solids of water from selected wells in the "500-foot" and "1,400-foot" sands.

The water temperature ranges from 61° to 64°F, depending on the depth from which the water is pumped. The temperature of the ground water in the Memphis area increases about 1°F per 100 feet of depth below the ground surface, starting at 61° F at a depth of about 100 feet.

The water is generally soft. The average hardness determined from random sampling is about 40 ppm, having a range from 10 to 170 ppm. The highest values, above 60 ppm, may be a result of harder water leaking from the overlying terrace deposits and mixing with water in the "500-foot" sand. More water will probably be induced from the shallower formation as pumping continues to increase.

Determinations of pH made immediately after samples were collected showed the water to be acid, but a neutral condition was approached within a few minutes after collection as a result of the escape of carbon dioxide. The average pH of the water after it has been standing for a few hours is about 6, indicating a slightly acid condition. A typical chemical analysis of water from the "500-foot" sand is shown in table 2. The sample was analyzed several days after it was collected, and for this reason the pH determination was comparatively high.

TABLE 2.—*Typical chemical analysis of water from the "500-foot" sand*

[Chemical analysis of water from well sh:O-128 in the "500-foot" sand. Well data: diameter, 10 inches; depth, 567 ft; drilled, 1943. Water data: color, 6; pH, 7.0; temperature, 62° F; date of collection, 4-2-51; specific conductance (micromhos at 25° C) 123. Analysis by U.S. Geol. Survey]

Constituent	*Parts per million*	*Equivalents per million*	*Constituent*	*Parts per million*	*Equivalents per million*
Aluminum (Al)	0.0	-------	Sulfate (SO_4)	3.2	0.067
Silica (SiO_2)	13	-------	Chloride (Cl)	3.0	.085
Iron (Fe)	.44	-------	Fluoride (F)	.0	.000
Calcium (Ca)	10	0.499	Nitrate (NO_3)	.4	.006
Magnesium (Mg)	5.5	.452	Dissolved solids	81	-------
Sodium (Na)	8.2	.357	Hardness as $CaCO_3$:		
Potassium (K)	1.3	.033	Total	48	-------
Bicarbonate (HCO_3)	72	1.180	Noncarbonate	0	-------

The water for municipal use in Memphis is treated for iron removal only. This treated water, which includes water from the "1,400-foot" sand, contains about 100 ppm total dissolved solids. A few of the industries requiring water of special chemical quality treat the water for the removal of certain constituents, but most of them use the water untreated. The Memphis Light, Gas, and Water Division is equipped to add chlorine to the water as a protective measure, but chlorine is not routinely added.

WATER IN THE "1,400-FOOT" SAND

The chemical quality of water from the "1,400-foot" sand is good (table 3), but the water is generally more highly mineralized than water from the "500-foot" sand. The hardness (as $CaCO_3$) is lower, ranging from 5 to 17 ppm. Water from the "1,400-foot" sand is untreated for municipal use, except for iron removal, and is mixed with water from the "500-foot" sand in the municipal system. Treatment for iron removal also removes the small amount of free carbon dioxide and hydrogen sulfide from the water.

Table 3 shows a typical chemical analysis of water from the "1,400-foot" sand. The pH is neither representative of water in the formation nor representative of water immediately after pumping, because the analysis was made several days after collection of the water sample.

During this time the escape of free carbon dioxide from the water caused an increase in the pH. No carbon dioxide or pH determinations have been made immediately after collection of water samples from this formation, but such analyses probably would be similar to those made of water from the "500-foot" sand.

TABLE 3.—*Typical chemical analysis of water from the "1,400-foot" sand*

[Chemical analysis of water in well Sh:K-58 in the "1,400-foot" sand. Well data: diameter, 8 inches; depth 1,305 ft; drilled in 1941. Water data: color, 17; temperature 70°F; date of collection, 4-2-51; specific conductance (micromhos at 25°C), 160. Analysis by U.S. Geol. Survey]

Constituent	*Parts per million*	*Equivalents per million*	*Constituent*	*Parts per million*	*Equivalents per million*
Aluminum (Al)	0. 7	-------	Sulfate (SO_4)	5. 1	0. 106
Silica (SiO_2)	12	-------	Chloride (Cl)	2. 0	. 056
Iron (Fe)	. 60	-------	Fluoride (F)	. 1	. 005
Calcium (Ca)	2. 7	0. 135	Nitrate (NO_3)	. 5	. 008
Magnesium (Mg)	1. 3	. 107	Disolved solids	112	-------
Sodium (Na)	35	1. 522	Hardness as $CaCO_3$		
Potassium (K)	2. 5	. 064	Total	12	-------
Bicarbonate (HCO_3)	101	1. 655	Noncarbonate	0	-------

Samples collected in 1927 and at infrequent intervals afterward indicate that the quality of water in the "1,400-foot" sand has remained constant. If leakage to the aquifer occurred in substantial amounts from rocks either below or above, it would undoubtedly be noted in the chemical analyses of the water because of the difference in quality of water in adjacent formations. The constancy of quality in the area where the pressure head is lowered considerably is further indication that the clays confining this artesian aquifer have very low permeability.

WATER IN OTHER AQUIFERS

Chemical analyses of the few samples of water obtained from the terrace deposits in the Memphis area show that the water is generally hard but that it contains less iron and carbon dioxide than does the water from the two principal aquifers. The average hardness (as $CaCO_3$) of water from the "500-foot" sand is about 40 ppm, and the average hardness of water from the terrace deposits, about 200 ppm. If the "500-foot" sand is locally recharged by seepage from the terrace deposits in any part of the area, sampling for chemical quality may be used to indicate the location and amount of such recharge. This should be one of the objectives of a continuing investigation.

Analyses of several samples of water from the only well screened in the Ripley Formation (about 2,600 ft deep) in the Memphis area show that the water contains more than 1,000 ppm total dissolved solids and is saline. The chemical quality of the water has not changed appreciably since the first sample was collected in 1927. Samples of water from this aquifer 80–100 miles east of Memphis contain as little

724-489—64——4

as one tenth of the amount of dissolved solids found in water at Memphis, thus indicating the rate of change in chemical quality as the water moves downdip toward Memphis.

FACTORS AFFECTING FUTURE USE AND DEVELOPMENT

The foremost consideration at present is whether or not pumping from the principal aquifers in the Memphis area can continue to increase each year, as it has in the past, without causing the abandonment of many wells or a major change in the chemical quality of the water. The answer is a qualified "yes," although, as the development of new wells in the aquifers continues, pumping costs rise primarily as a result of declining piezometric surface and the higher initial cost of developing new wells at greater depths. Other factors which may affect future development include loss of artesian head, change in chemical quality as a result of induced recharge from adjacent formations or from surface water in certain locations, change in hydraulic characteristics of the aquifer, development of wells in shallower or deeper aquifers, development of surface-water supplies where water-quality tolerances are lower, and discovery of new industrial processes which may reduce or increase water consumption. All these factors are of immediate concern in long-range water management, but none appear to offer reasons for curtailment of development of wells at the current rate in either of the principal aquifers. Some of the factors, such as development of surface-water supplies and development of wells in deeper or shallower aquifers, would tend to conserve water in the "500-foot" and "1,400-foot" sands.

Water wells can be developed in either of the principal aquifers anywhere in the Memphis area, but the amount of water discharged by a well per unit drawdown of water level, defined as specific capacity, cannot be predicted accurately because of the nonhomogeniety of the sands and the sporadic presence of clay beds of varying thicknesses in some parts of the area. The size, capacity, and type of construction of a well, the size and length of the well screen, the kind of gravel envelope around the screen, the pumping rate, and the hydraulic properties of the water-bearing formation in the vicinity of the well affect the specific capacity. Theoretically, transmissibility can be used to predict specific capacity of a proposed well where other factors are known. The specific capacity of wells in the Memphis area ranges from a few to more than 100 gpm per foot of drawdown for wells of all sizes and all types of construction. The specific capacity of an average 10-inch well in the "500-foot" sand is about 30 gpm per foot of drawdown.

In the area east of a southwest-trending line through Collierville, Tenn., and Olive Branch, Miss., the water level in the "500-foot" sand has declined below the top of the aquifer, and nonartesian conditions now prevail in that area. As pumping continues to increase, the artesian-nonartesian boundary will migrate toward Memphis, and, eventually, when the water level in Memphis has declined 300–400 feet below land surface, nonartesian conditions will encompass the entire area. When the present annual pumping rate is doubled, the boundary will have advanced to the present city limits of Memphis. If the current annual increase in pumping rate continues and if the present areal pumping pattern continues to develop, nonartesian conditions will reach the city limits of Memphis in about 30 years (1990). Variations in the future pumping pattern may hasten or delay the approach of nonartesian conditions in the "500-foot" sand. The present practice of wider well and well-field spacing will tend to preserve the artesian condition.

The impending loss of artesian head in the aquifer is not cause for alarm. On the contrary, water levels should fluctuate less and decline more slowly. Some water may be induced from the overlying terrace deposits and cause a change in the chemical quality of water, although probably not a significant amount. The amount of land subsidence resulting from dewatering of the aquifer will probably be immeasurably small unless the water level declines several hundred feet below the top of the aquifer. Nonartesian conditions will result in a relatively small additional cost of developing deeper wells and a slightly higher cost of pumping.

Development of wells in, and use of water from, the "500-foot" sand probably will continue so long as the quality of the water is satisfactory. The coefficient of transmissibility for the "1,400-foot" sand is about 1.2×10^5 gpd per ft, and for the "500-foot" sand about 4×10^5. The ratio is about 1 to 3, indicating that three times as much water may move through the "500-foot" sand. The hydraulic diffusivity, defined as the ratio of the coefficient of transmissibility to the coefficient of storage, for the "1,400-foot" sand is 4×10^8, and the "500-foot" sand it is 1.33×10^8. The ratio is 3 to 1, which indicates that the effect of any change in the rate of discharge travels three times farther in the "1,400-foot" sand. The estimated rate of movement of water under natural conditions, prior to development of the "1,400-foot" sand aquifer, was about 0.16 mgd for each 1-mile-wide section of the aquifer; for the "500-foot" sand, about 1 mgd. These values indicate that the ultimate capacity or economic yield of the "1,400-foot" sand is about 16 percent of that of the "500-foot" sand under similar conditions.

ADEQUACY OF THE AQUIFER ANALYSIS

Determinations of the rate of movement of water, the natural and artificial discharge, the indication and effect of recharge, and the hydraulic characteristics of the two principal aquifers in the Memphis area are results of the application of mathematical formulas to the data collected for these purposes. Geological and geophysical data collected during the investigation contributed to, and tended to verify, these results. The analyses are adequate for the current (1960) rate of pumping and location of well fields. Only the total amount of water involved and its rate of movement is expected to change significantly in the future. The hydraulic characteristics described in this report may be used to predict the results of these changes throughout the area except where the "500-foot" sand is no longer under artesian pressure. Tests will have to be conducted in areas where nonartesian conditions exist to determine the hydraulic characteristics of the aquifer. In such areas, however, pumping is expected to have a less pronounced effect on the water level than it has in the artesian part of the area.

In general the aquifer analysis as presented in this report is sufficiently adequate to predict with reasonable accuracy the future water-level changes for given rates of pumping, either greater or smaller than the present rate. The analysis also indicates that greater amounts of water may be pumped from both aquifers without impairing the water supply or seriously affecting the quality of water.

CONCLUSIONS

The two principal aquifers of the Memphis area are the "500-foot" and "1,400-foot" sands, from which practically all the water used in the area is pumped. The present (1960) rate of withdrawal is about 150 mgd, 135 mgd of which is pumped from the "500-foot" sand. Of the inflow to the area through the "500-foot" sand, excluding leakage from streams and adjacent aquifers, about 45 percent is from the east, about 20 percent is from the south, about 15 percent is from the north, and about 10 percent or less is from the west. The remaining 10 percent of the water derived annually from the "500-foot" sand comes from depletion of storage as a result of declining water level and from leakage from the overlying terrace deposits which, in turn, may be partly recharged by streams and by precipitation. Faults in the area may influence water movement and water levels by retarding the inflow of water from the west.

Pumping tests were made to determine the hydraulic characteristics of that section of the "500-foot" sand aquifer adjacent to the well screens. From the values obtained, the full thickness of the aquifer is estimated to have a coefficient of transmissibility of about 4×10^5 gpd per ft and a coefficient of storage of about 3×10^{-3}. The long-range effect on water levels in the area may be determined by using these coefficients for any given rate of pumping and computing the future drawdown. For example, if the present pumping rate from the "500-foot" sand remains constant, water levels will cease to decline within a few years. However, if the annual pumping rate from the "500-foot" sand continues to increase at the present rate of approximately 5 mgd per year, water levels will decline at about the same rate as at present unless future wells and well fields are located at greater distances from the present centers of pumping.

The water level in the "500-foot" sand in the southeastern part of the Memphis area has declined to a few feet below the top of the aquifer. The line marking the boundary between artesian and nonartesion conditions is slowly advancing toward Memphis, and, in about 30 years, nonartesian conditions may exist over the entire area. No detrimental effect can be forecast, though the quality of the water pumped may change slightly as water is induced from adjacent formations and streams. Water-level fluctuations and the overall decline in water levels probably will be less pronounced than at the present, although transmissibility will decrease as the aquifer is drained.

The "1,400-foot" sand, an almost ideal artesian aquifer, is a secondary aquifer because it is only about one fourth as thick as the "500-foot" sand and, therefore, can furnish only one fourth as much water or less. The coefficient of transmissibility in the "1,400-foot" sand is 1.2×10^5 gpd per ft, or about the same as that in the "500-foot" sand per unit of thickness. The storage coefficient is 3×10^{-4} indicating that less water is derived from storage per foot of water-level decline than is derived from the "500-foot" sand. The effect of pumping on the water level in this aquifer is also more pronounced at greater distances from the center of pumping than is the effect on the water level in the "500-foot" sand, primarily because of the greater artesian head in the "1,400-foot" sand.

The present (1960) rate of pumping from the "1,400-foot" sand in the Memphis area is about 13 mgd, and a total of about 120 billion gallons is estimated to have been withdrawn since the first wells were developed in 1924. The aquifer is primarily a standby source of water for the city of Memphis.

Part of this investigation was directed toward answering specific questions relating to water supply that might be asked by those charged with planning for an expanding community. Kazmann (1944, p. 17–18) expressed the problems of the Memphis area water supply in the form of nine questions. These questions require that the maximum amount of water that can be pumped safely from the aquifers be determined. That limit cannot be determined at present because the change from artesian to nonartesian conditions and the decentralization of pumping tends to increase the maximum safe amount of water that may be obtained in the area. Therefore, the answers to Kazmann's questions are qualified and reflect the status of knowledge of the area for the period ending with this investigation. The questions will continue to be the basis for a logical continuing investigation if supplemented by other pertinent questions which are listed in the final pages of this report.

1. What is the origin of the ground water obtained in the Memphis area?

At present about 90 percent of the water obtained from the "500-foot" sand originates as underground inflow into the area. Less than 1 percent of the water comes from depletion of the storage of the aquifer. The remainder, about 10 percent, is leakage from the overlying terrace deposits or from other sources of recharge in the area.

About 10 percent of the water obtained from the "1,400-foot" sand comes from depletion of the storage of the aquifer. The other 90 percent probably originates as inflow into the area.

2. Is more water being taken from the underground sources than nature puts back each year? If so, what is the excess of average withdrawal over input? If not, what is the ultimate safe yield of the water-bearing formations?

Presently, the answer is yes. More water is being taken from the aquifers than is being replaced each year because of the annual increase in pumping. However, if the annual pumping rate remained constant, equilibrium conditions would be reached within a few years, and the amount of recharge would equal discharge on an annual basis.

If each aquifer is considered as a unit ending at the boundary of the Memphis area and if a comparison is made of what is added to each of these units by inflow and any other processes with what has been taken out, then the difference is the amount of depletion of storage of each aquifer in the area. The average annual rate of depletion of storage of the "500-foot" sand in the area is less than 1 percent of the annual pumping rate, or about 1 mgd. Therefore, 99 percent of the water taken annually from the "500-foot" sand within the area is replaced by recharge.

Similarly, about 90 percent or more of the water that has been taken from the "1,400-foot" sand in the area has been replaced. Rising water levels in this aquifer indicate that recharge has been greater than discharge during the past 4 years.

3. Are the water-bearing formations continuous between the outcrops (if any) and the well fields?

The answer is yes. This continuity is shown by the influence of pumping from both the "500-foot" and the "1,400-foot" sands on the water levels in observation wells 30 miles northeast of Memphis (figs. 9, 17). Recharge to the aquifers resulting from above-normal rainfall in 1957 is also noted (figs. 9, 17) in both observation wells. These facts indicate that the two aquifers are hydraulically continuous between their outcrop areas and the well fields in the Memphis area. Continuity within the area is proven by geophysical logs.

4. How much water are the formations capable of transmitting each day?

Throughout their total thickness in the Memphis area, the "500-foot" sand has a coefficient of transmissibility of 4×10^5 gpd per ft, and the "'1,400-foot" sand, about 1.2×10^5 gpd per ft. The amount of water the formations are capable of transmitting is indicated by these coefficients and by the hydraulic gradient in each aquifer in the area. The present steepest gradient outside the area of heavy pumping is about 10 feet per mile in the "500-foot" sand, and about 4 mgd is transmitted in each 1-mile-wide section of the aquifer along a north-south line in the vicinity of well Sh: Q–1 (pl. 2). The present steepest gradient is about 3 feet per mile in the "1,400-foot" sand, and about 0.36 mgd is transmitted in each 1-mile-wide section of the aquifer in the vicinity of the Sheahan well field (pl. 2). The extent to which these gradients can be increased is unknown, but it is certain that both aquifers can supply more water than is presently pumped from them.

5. Is the limit on water withdrawals set by the recharge to the formations or the transmissibility of the formations?

The limit on water withdrawal for a well field or for a small part of the Memphis area depends on the transmissibility of the aquifer and the geohydrologic conditions in the vicinity of the well field. For example, the presence of a local clay lens in the aquifer will lower the limit of withdrawal for a well field. Similar clay lenses may be so spaced in or near the outcrop area to prevent maximum recharge that would otherwise take place. The present annual pumping rate in the Memphis area is not great enough to determine which of the two factors limit the rate of withdrawal. If the rates of recharge under ultimate development of the aquifers are assumed to be the same as those prior to development, then the limit on withdrawal would be set by the recharge to the formations. However, perennial streams flowing across the sandy outcrop areas strongly suggests the possibility of large amounts of rejected recharge. The amount and maximum possible rate of recharge may be great enough that withdrawals may be limited by the transmissibilities of the formations. This limitation appears to be the most likely conclusion.

6. Are the chemical quality and temperature of ground water changing or are they constant within certain limits?

The water samples analyzed since 1927 show that the chemical quality of water from both aquifers varies little with time except for the hardness of "500-foot"-sand water which appears to be increasing in the north-central part of the area (fig. 19). The temperature of water in the "500-foot" sand ranges from 61° to 64° F depending on the depth of the well; the temperature of water in the "1,400-foot" sand ranges from 70° to 71° F.

7. What directions are the most promising for the establishment of new well fields and what is the most desirable well spacing?

The preferable direction for the establishment of new well fields in the "500-foot" sand is unknown, although the southeastern part of the area is indicated because the greater rate of inflow is from that direction. The hydraulic characteristics of the aquifer under nonartesian conditions, the hydrologic condition of the outcrop area, and the influence of geologic features in the area could alter the selection of preferable direction as pumping continues.

The question of well spacing is primarily a problem of economics relating to water production and transportation. Obviously, the greater distance between production wells causes less interference, but the cost of distributing the water on the land surface is greater. The drawdown in a well pumping 1,000 gpm from the "500-foot" sand is about 50 feet. If the allowable interference of another pumping well is 10 percent of its own drawdown and the wells are similar in construction and depth to presently used wells in the Memphis area, the well spacing should be 1,000 feet or more. If the wells are constructed using longer screens, a greater thickness of the aquifer would be effective, and closer well spacing would be allowable.

The preferable direction for the development of new well fields in the "1,400-foot" sand is roughly north and south of Memphis or perpendicular to the flow path of water moving downdip in the aquifer into the area. Well spacing, under requirements similar to those for the "500-foot" sand should be 1,000 feet or more.

8. What is the relationship between ground-water levels and quantities of water pumped in the area?

Water levels decline in the Memphis area as a result of increases in pumping. The water levels would cease to decline if the total annual pumping rate remained constant for a few years. Generally, for the "500-foot" sand, the decline in Memphis is about 1 foot for each 1-mgd increase in water production in Memphis. In observation wells about 30 miles northeast of Memphis, the water-level decline is less than 0.1 foot for each 1-mgd increase in water production in Memphis.

The water-level decline in the "1,400-foot" sand is at present as much as four times greater than that in the "500-foot" sand for each 1-mgd increase in water production.

9. How much water is being obtained from each water-bearing formation?

Approximately 1.9 trillion gallons of water was pumped from the "500-foot" sand from 1886 to 1960. Records of pumpage are accurate, and during the past several years more than half the daily pumpage in the area was metered and reported monthly to the U.S. Geological Survey. The 1960 rate of pumping was about 135 mgd. All the water pumped from the "1,400-foot" sand is metered also, and more than 95 percent of the daily pumpage is reported monthly. The total amount of water pumped from the "1,400-foot" sand from 1924 to 1960 was about 120 billion gallons. The 1960 rate of pumping was about 13 mgd.

Supplemental questions which need to be answered during the continuing investigation in order to promote further efficient management of the water supply in the Memphis area are:

1. What is the amount of recharge perennially available, and can the aquifers accept and transmit the total available recharge?
2. What are the steepest hydraulic gradients that can be established in the aquifers?

3. What are the hydraulic characteristics of the aquifers under impending nonartesian conditions, and will surface-water resources in the area be affected?
4. What are the effects of faults and similar structural controls on water production?
5. What are the interference effects, resulting from different heads or water levels in the aquifers, between aquifers?
6. What is the change in chemical quality of water as production from the aquifers continues? Is it significant, and is there a trend toward greater change?
7. Will streamflow be significantly affected as the effect of pumping in Memphis extends to the outcrop area of the two principal acquifers?
8. Should the shallower terrace deposits or alluvium be considered a major source of water, or are they being drained by leakage to the "500-foot" sand?
9. What are the legal and economic aspects of continued development?

There are no apparent reasons why development of wells in the two principal aquifers of the Memphis area should not continue, although the supply is not unlimited. Any evidence of overdevelopment would probably be noted during the continuing future investigation in sufficient time to prepare solutions to the problem or to recommend that alternate sources of supply be developed. The potential water production from the two aquifers is much greater than the present yield, and the possibility of overdevelopment of either aquifer in the immediate future is remote.

REFERENCES

Caplan, W. M., 1954, Subsurface geology and related oil and gas possibilities of northeastern Arkansas: Arkansas Resources and Development Comm., Div. Geology Bull. 20.

Criner, J. H., and Armstrong, C. A., 1958, Ground-water supply of the Memphis area: U.S. Geol. Survey Circ. 408, 20 p.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U.S. Geol. Survey Water-Supply Paper 1536–E, 174 p.

Fisk, H. N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: U.S. Dept. Army, Mississippi River Comm., 78 p.

Glenn, L. C., 1906, Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geol. Survey Water-Supply Paper 164, 173 p.

Kazmann, R. G., September 1944, The water supply of the Memphis area: U.S. Geol. Survey open-file report, 66 p.

Lohr, E. W., and Love, S. K., 1954, The industrial utility of public water supplies in the United States, 1952; Pt. 1 *of* States east of the Mississippi River: U.S. Geol. Survey Water-Supply Paper 1299, 639 p.

Lundie, John, 1898, Report on the waterworks system of Memphis, Tennessee: Memphis, Tenn., 46 p.

Meinzer, O. E., 1923, Outline of ground-water hydrology with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Safford, J. M., 1869, Geology of Tennessee: Nashville, Tennessee Bur. Agriculture and Commerce, 550 p.

——— 1890, The water supply of Memphis: Tennessee Board of Health Bull., v. 5.

Schneider, Robert, and Blankenship, R. R., 1950, Subsurface geologic cross section from Claybrook, Madison County, to Memphis, Shelby County, Tennessee: Tennessee Div. Geology Ground-Water Inv. Prelim. Chart 1.

Schneider, Robert, and Cushing, E. M., 1948, Geology and water-bearing properties of the "1,400-foot" sand in the Memphis area: U.S. Geol. Survey Circ. 33, 13 p.

Stearns, R. G., 1957, Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi embayment: Geol. Soc. America Bull., v. 68, no 9, p. 1077–1100.

Stearns, R. G., and Armstrong, C. A., 1955, Post-Paleozoic stratigraphy of western Tennessee and adjacent portions of the upper Mississippi embayment: Tennessee Div. Geology Rept. of Inv. 2, 29 p.

Trask, P. D., 1932, Origin and environment of source sediments of petroleum: Houston Tex., American Petroleum Inst., 323 p.

U.S. Geological Survey, issued annually, Water levels and artesian pressure in observation wells in the United States in 1936–39: U.S. Geol. Survey Water-Supply Papers 817, 840, 845, 886.

——— issued annually, Water levels and artesian pressure in observation wells in the United States in 1940–55, pt. 2, Southeastern States: U.S. Geol. Survey Water-Supply Papers 907, 937, 945, 987, 1017, 1024, 1072, 1097, 1127, 1157, 1166, 1192, 1222, 1266, 1322, 1405.

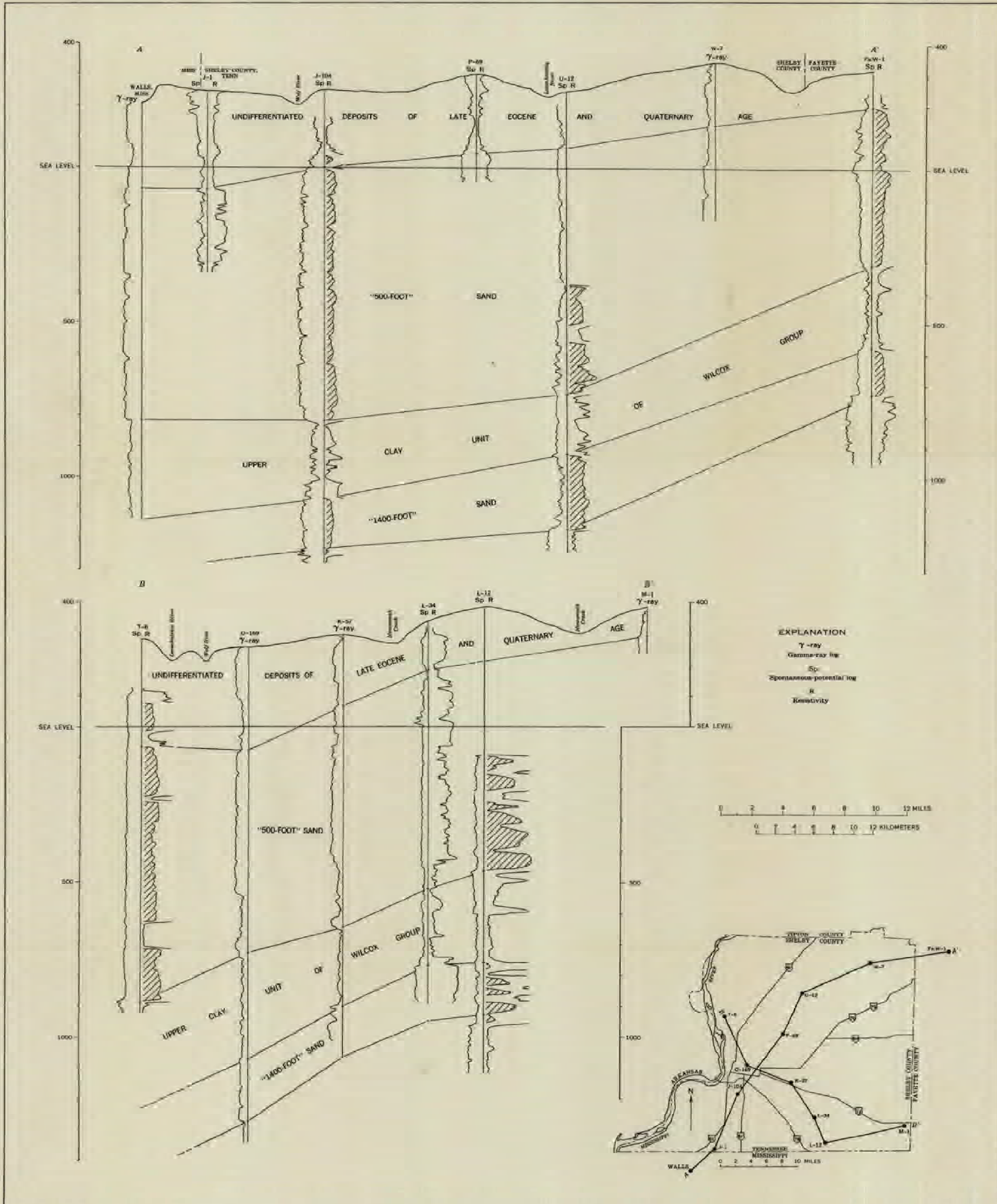
Wells, F. G., 1931, A preliminary report on the artesian water supply of Memphis, Tennessee: U.S. Geol. Survey Water-Supply Paper 638–A, 34 p.

——— 1933, Ground-water resources of western Tennessee: U.S. Geol. Survey Water-Supply Paper 656, 311 p.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials: U.S. Geol. Survey Water-Supply Paper 887, 192 p.

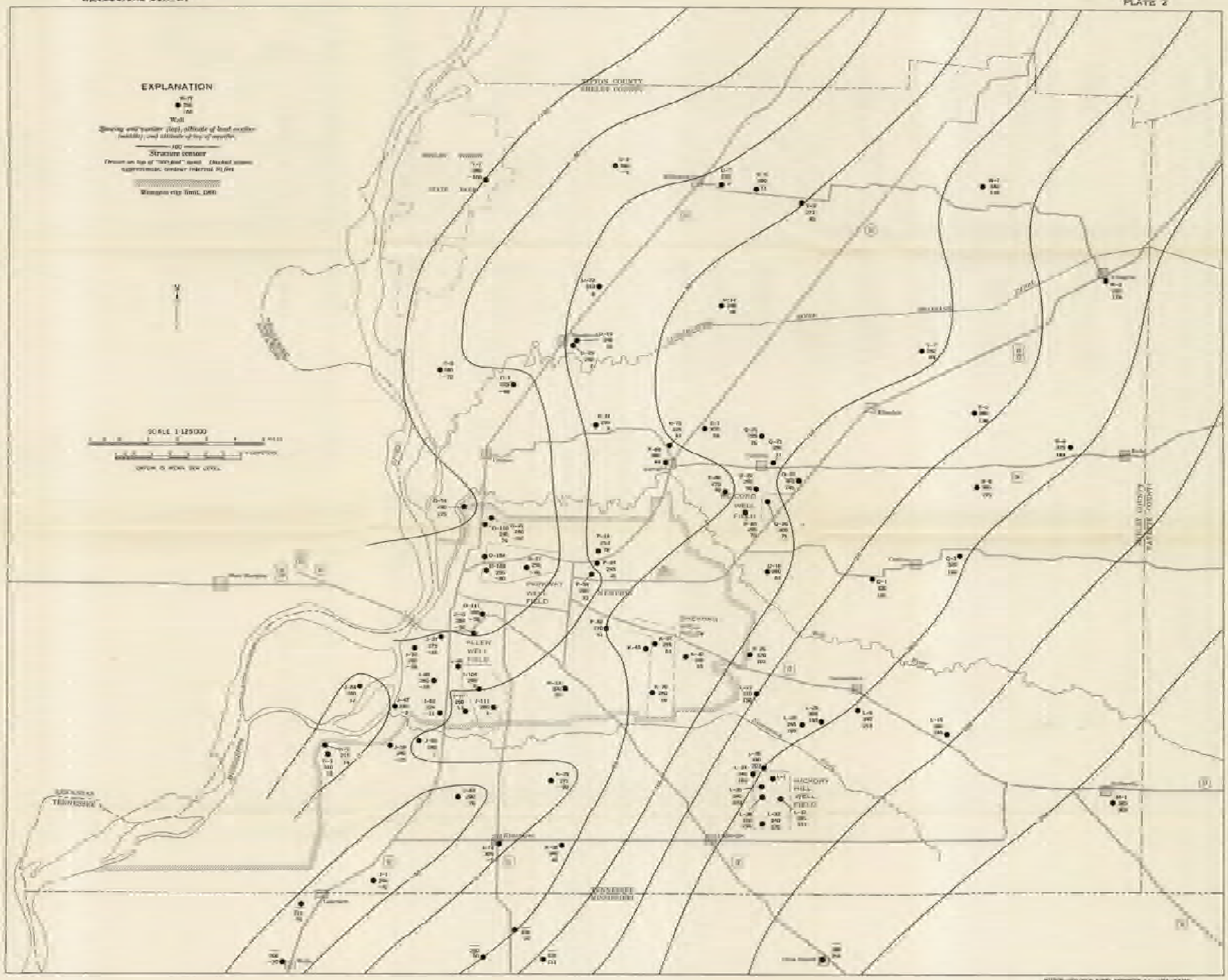
INDEX

[Italic numbers indicate major references]



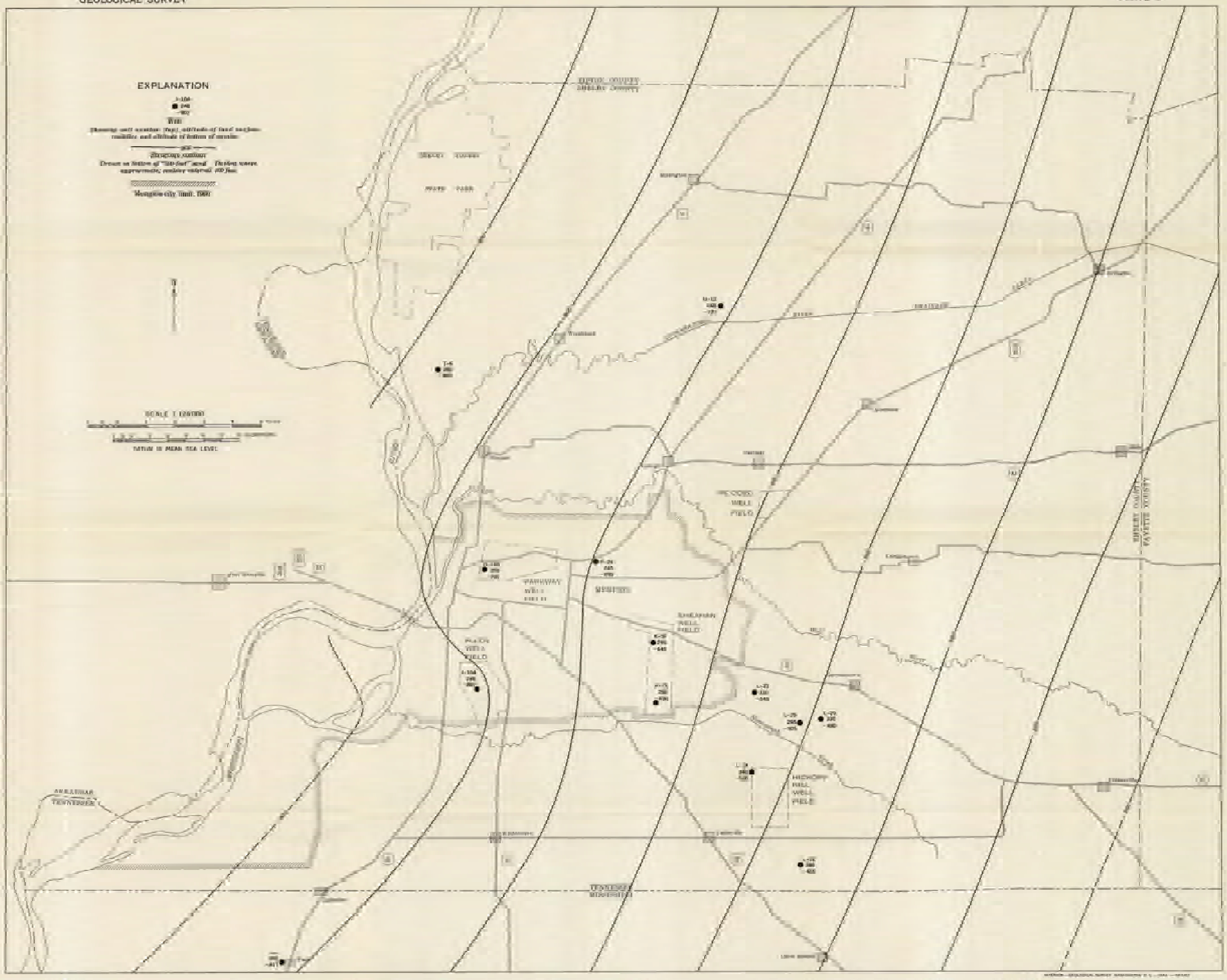
GEOLOGIC SECTIONS OF THE MEMPHIS AREA, TENNESSEE

724-489 O - 64 (In pocket)



Base and geology by J. H. Criner

STRUCTURE MAP SHOWING CONFIGURATION OF THE TOP OF THE "500-FOOT" SAND, MEMPHIS AREA, TENNESSEE

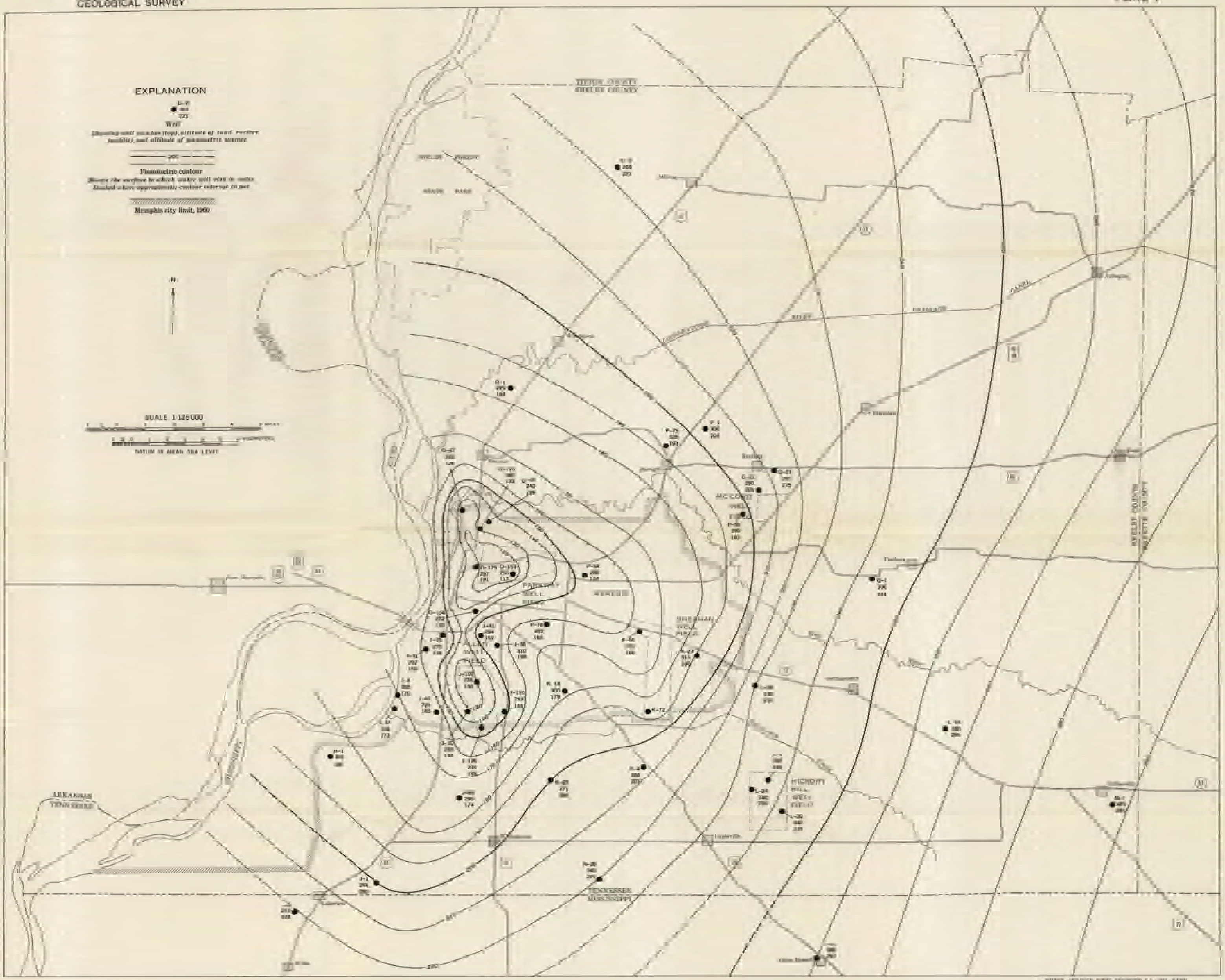


Base and geology by J. H. Criner

STRUCTURE MAP SHOWING CONFIGURATION OF THE BOTTOM OF THE "500-FOOT" SAND, MEMPHIS AREA, TENNESSEE

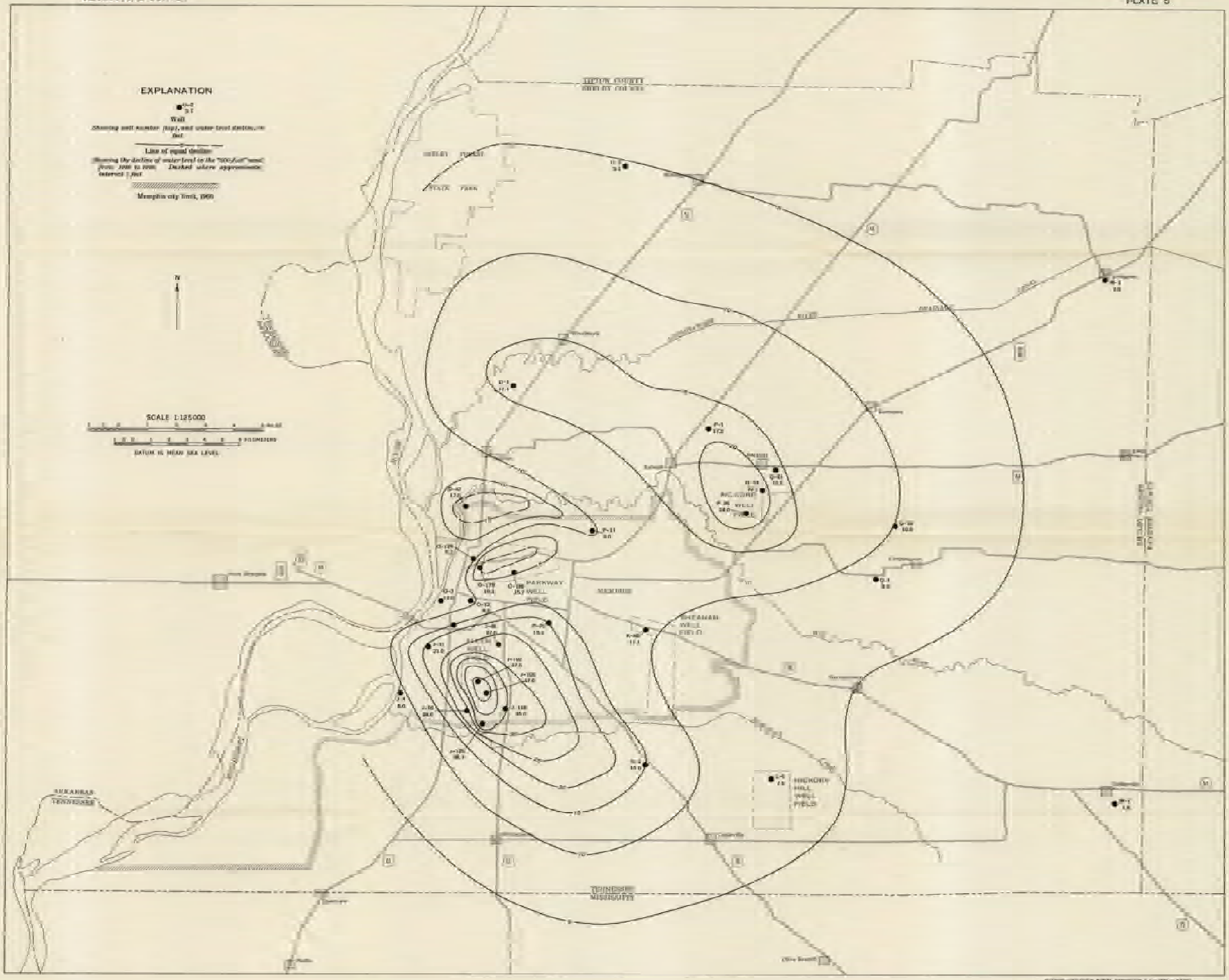
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

WATER-SUPPLY PAPER 1779-O
PLATE 4

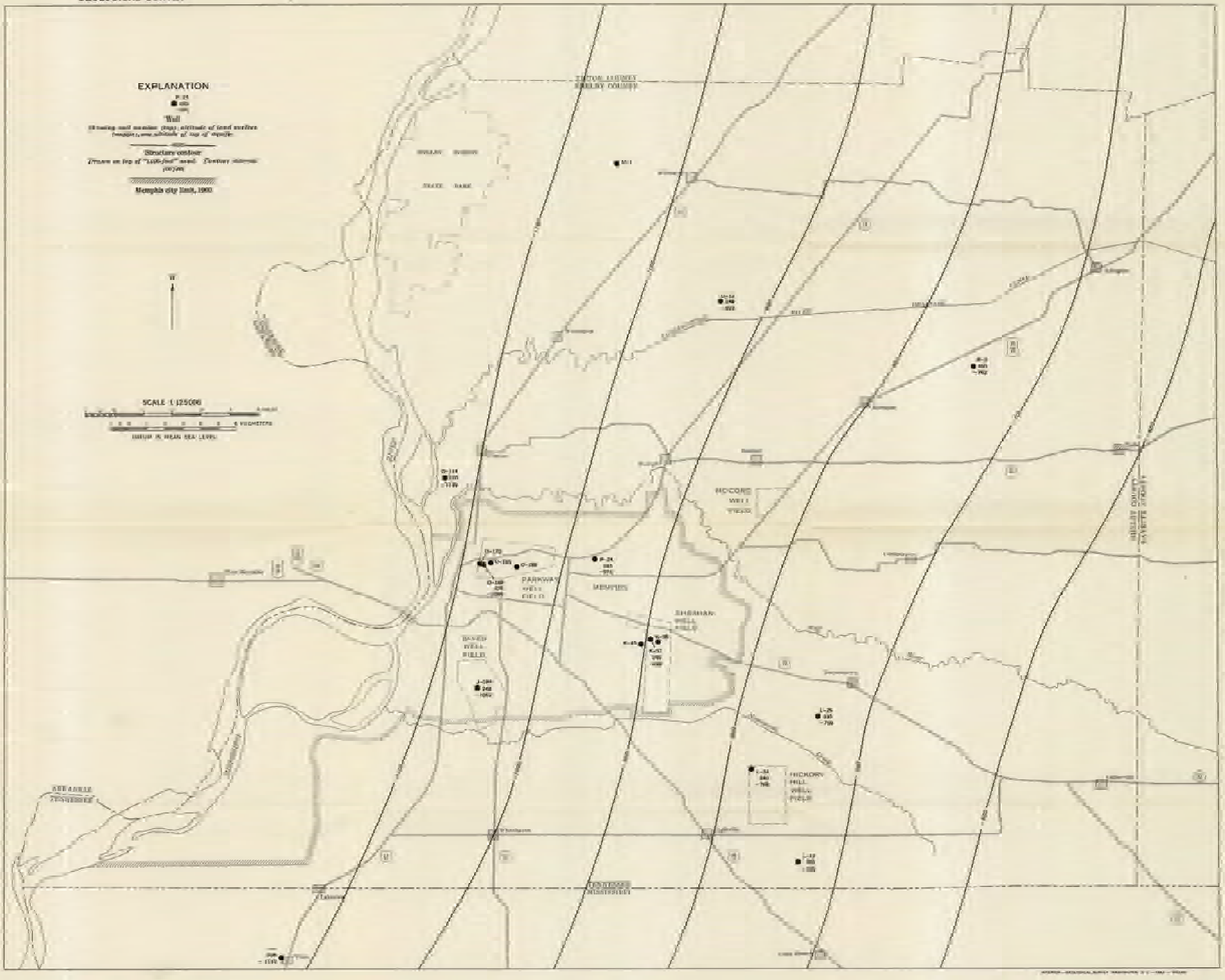


Base and geology by J. H. Criner

MAP SHOWING CONFIGURATION OF THE PIEZOMETRIC SURFACE OF THE "500-FOOT" SAND IN AUGUST 1960, MEMPHIS AREA, TENNESSEE



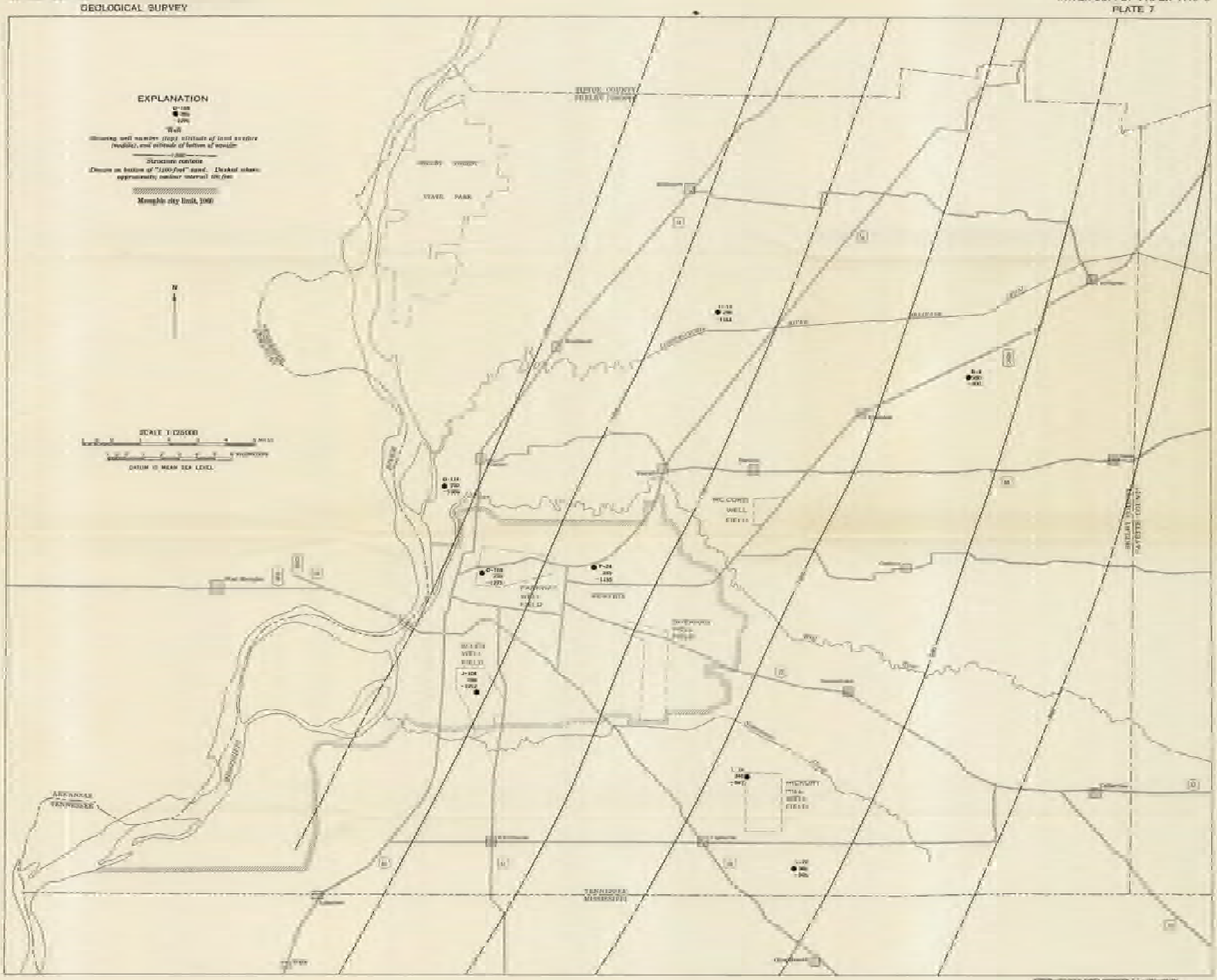
MAP SHOWING DECLINE OF WATER LEVEL IN THE "500-FOOT" SAND, 1950-60, MEMPHIS AREA, TENNESSEE



STRUCTURE MAP SHOWING CONFIGURATION OF THE TOP OF THE "1400-FOOT" SAND, MEMPHIS AREA, TENNESSEE

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

WATER-SUPPLY PAPER 1779-O
PLATE 7



Base and geology by J. H. Criner

STRUCTURE MAP SHOWING CONFIGURATION OF THE BOTTOM OF THE "1400-FOOT" SAND, MEMPHIS AREA, TENNESSSEE

EXHIBIT 3

G. K. Moore, Geology and Hydrology of the Claiborne Group in Western Tennessee, Geological Survey Water-Supply Paper 1809-F ("1965 USGS Report")

Geology and Hydrology of the Claiborne Group in Western Tennessee

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1809-F

Prepared in cooperation with the Tennessee Department of Conservation Division of Water Resources

Moore—GEOLOGY, HYDROLOGY, CLAIBORNE GROUP, WESTERN TENNESSEE—Geological Survey Water-Supply Paper 1809-F TEXT

Geology and Hydrology of the Claiborne Group in Western Tennessee

By GERALD K. MOORE

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1809-F

Prepared in cooperation with the
Tennessee Department of Conservation
Division of Water Resources

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1965

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

[Plates are in separate volume]

TABLES

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

GEOLOGY AND HYDROLOGY OF THE CLAIBORNE GROUP IN WESTERN TENNESSEE

By Gerald K. Moore

ABSTRACT

The area of western Tennessee underlain by the Claiborne Group is about 7,200 square miles and lies on the east flank of the syncline that forms the Mississippi embayment. It includes the Mississippi Alluvial Plain and part of a dissected upland plateau. The Claiborne Group dips to the northwest at 10–25 feet per mile and ranges in altitude from 600 feet above mean sea level in the outcrop area to 900 feet below mean sea level near the embayment axis.

The Claiborne Group is tentatively subdivided into five units including, in ascending order, the Meridian Sand Member of the Tallahatta Formation, the Basic City Shale Member of the Tallahatta Formation, the Sparta Sand, an unnamed clay unit, and an unnamed sand unit. The two major aquifers in the Claiborne Group are the "500-foot" sand and the unnamed sand unit. The top of the "500-foot" sand is correlated with the top of the Sparta Sand; and the base, with the base of the Claiborne Group. The "500-foot" sand ranges in thickness from 200 to 750 feet and consists mainly of very fine to coarse sand or gravel. It also contains layers of white to blue, pink, gray, or brown clay, which constitute only a small percentage of the total thickness. The unnamed sand unit ranges from 0 to 210 feet in thickness and consists mostly of white, gray, or brown fine-grained lignitic sand. An estimated 75 percent of the ground water withdrawn in western Tennessee (west of the northward-flowing segment of the Tennessee River) is taken from the "500-foot" sand and the unnamed sand unit.

The quantities of water available to wells from the "500-foot" sand are currently adequate for all municipal and industrial needs. The permeability of this aquifer is about 570 gallons per day per square foot. An estimated 155 mgd (million gallons per day) is pumped from the "500-foot" sand, about 140 mgd is discharged from the aquifer as the base flow of surface streams, and about 40 mgd is discharged from the report area as underflow. Water from the "500-foot" sand contains objectionable quantities of iron in the western half of the report area. Otherwise the quality of the water is suitable for most needs.

Quantities of water adequate for domestic use and for small municipal systems can be obtained from the unnamed sand unit in most of the report area. The field permeability of this aquifer is probably about 270 gallons per day per square foot. About 8 mgd is discharged into adjacent formations, and about

2 mgd is withdrawn by pumping. Water from the unnamed sand unit contains objectionable quantities of iron in the western half of the report area. Otherwise the water from this aquifer is of good quality.

Ground-water supplies in both the "500-foot" sand and the unnamed sand unit will be adequate for the predicted rate of municipal growth and economic development for many years to come. If the hydraulic gradient in the "500-foot" sand were increased to 19 feet per mile, the average dip of the top of the aquifer, about 578 mgd would be transmitted downdip.

Similarly, the unnamed sand unit would transmit about 34 mgd downdip under a hydraulic gradient of 10 feet per mile. Furthermore, additional amounts of water could be induced into the report area as underflow from adjacent States.

The anticipated effects of additional large scale development are (1) a drop in local and regional water levels in proportion to the increase in pumpage, (2) an increase in the net inflow of ground water from adjacent States, and (3) an increase of recharge to the aquifers at the expense of streamflow.

INTRODUCTION

Owing to its broad distribution and water-bearing characteristics, the Claiborne Group supplies an estimated 75 percent of the ground water withdrawn in western Tennessee (west of the northward flowing segment of the Tennessee River). To provide adequate information regarding the occurrence, availability, quality, and use of ground water from the Claiborne Group, an intensive investigation was undertaken in 1958 by the U.S. Geological Survey in cooperation with the Tennessee Division of Water Resources as part of a study of all the principal aquifers (water-bearing units) in western Tennessee. The order in which each aquifer was to be studied was based primarily on the aquifer's economic importance and on the need for information. Because of its importance the Claiborne Group was selected for early study, and the results of the study are presented in this report.

LOCATION OF AREA

The area of this report coincides with the part of western Tennessee that is underlain by geologic formations of the Claiborne Group (fig. 1). It is bounded on the north by Kentucky, on the south by Mississippi, and on the west by the Mississippi River. The east boundary is formed by the easternmost extent of the Claiborne Group in western Tennessee. As thus defined, the area covers about 7,200 square miles, or 65 percent of western Tennessee.

PURPOSE AND SCOPE

The purpose of this report is: (1) to define the limits of the water-bearing zones in the Claiborne Group, (2) to explain the hydrologic functions of these aquifers, (3) to describe the chemical

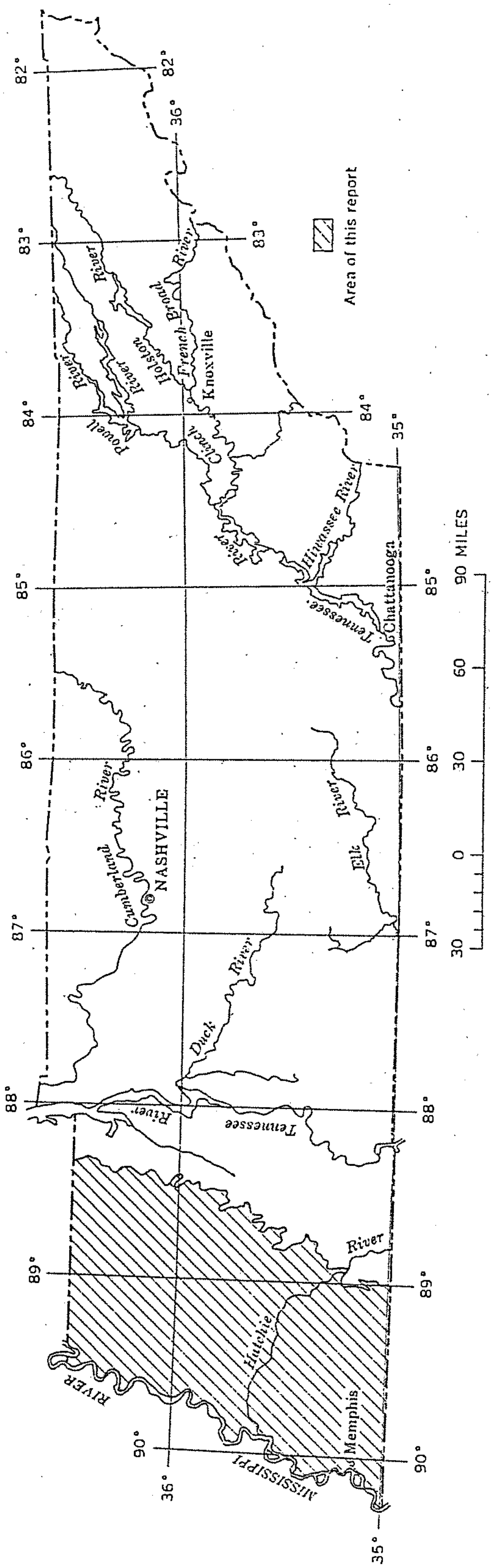


FIGURE 1.—Location of report area.

quality of the water contained in them, and (4) to determine the effects of past and future development on the overall adequacy of the water supply. Many effects are superimposed on the natural system by surface-water impoundment and ground-water pumping for domestic, municipal, agricultural, and industrial use. Discussed in this report are the effects of pumping on surface runoff, the effects of pumping on water levels, and the amount of water available for future development.

An effective appraisal of the ground-water resources of an aquifer system can be accomplished only through comprehensive studies of the aquifers' physical properties and surroundings. Brief, pertinent descriptions of the geography and geology of the area underlain by the Claiborne Group, therefore, constitute a part of this report.

PREVIOUS INVESTIGATIONS

The first systematic investigation of ground water in Tennessee was made by Glenn (1906). Later, Wells (1933) described in some detail the character and extent of the aquifers underlying western Tennessee. Several recent reports have discussed the geology or occurrence and chemical quality of ground water in part or all of the report area. Lanphere (1955) described the chemical quality of water in the aquifers and discussed the methods of treatment used to render the water suitable for municipal supplies. Stearns and Armstrong (1955) revised the Cretaceous and Tertiary geologic terminology for Tennessee. Schreurs and Marcher (1959) discussed the aquifer characteristics and water use in the Dyersburg quadrangle, a part of the present report area. A fairly comprehensive report on the hydrology of the Memphis area by Criner, Sun, and Nyman (1963) discussed some of the effects of municipal and industrial pumping on the aquifers in Shelby County.

ACKNOWLEDGMENTS

The author is grateful to those who aided in the collection of data for this study. Citizens, city officials, well drillers, and representatives of industries throughout the report area cooperated in supplying information on wells and made wells available for water-level observations, electric and gamma-ray logging, pumping tests, and the collection of water samples for chemical analysis.

In particular, the author wishes to thank the Layne-Central Co. and the Watson Co. of Memphis for supplying data on wells from their files.

Much of the data on the Memphis area was obtained from ground-water studies made in cooperation with the Light, Gas, and Water Division of the city of Memphis.

GEOGRAPHY

SURFACE FEATURES

The area underlain by the Claiborne Group in Tennessee is entirely within the east flank of the upper Mississippi embayment region of the Gulf Coastal Plain (Fenneman, 1938, p. 84) and includes part of the Plateau Slope (Safford, 1869, p. 110) and the Mississippi Alluvial Plain (Fenneman, 1938, p. 83). The land surface forms a broad plateau that slopes southwestward and ends abruptly at the Chickasaw bluffs (Safford, 1869, p. 110), which overlook the flood plain of the Mississippi River. From a high of about 700 feet above sea level along the Tennessee-Mississippi drainage divide east of the report area, the plateau descends toward the Mississippi River to an altitude along the crest of the Chickasaw bluffs of 390 feet in the northwest and 300 feet in the southwest. The plateau is partly dissected and consists of broad stream valleys and rolling uplands. Other common surface features of the plateau are hills produced by erosion.

The Mississippi Alluvial Plain lies at the foot of the Chickasaw bluffs and consists of a low, flat area that is about 10 miles wide in the northwestern part of the report area and gradually narrows toward the southwest corner of the area. It finally disappears where the Mississippi River impinges on the Chickasaw bluffs a short distance north of Memphis.

DRAINAGE

The report area is drained by six major streams, which have low gradients and flow into the Mississippi River. From north to south, these streams are the Obion, Forked Deer, Hatchie, Loosahatchie, and Wolf Rivers and Nonconnah Creek. Except for Nonconnah Creek, all these streams are perennial. The longest stream is the Hatchie River, which is 120 miles long. Although the Obion River flows southwestward, the other five streams flow west-northwestward to within a few miles of the Mississippi River, where their channels swing to the southwest.

The major part of the low flows of these streams is maintained by discharge from the aquifers of the Claiborne Group.

PRECIPITATION

Records of the U.S. Weather Bureau show that the average annual precipitation in western Tennessee is 50.42 inches. This amount provides excess recharge to the aquifers and thus insures the perennial flow of most rivers and creeks. Moreover, about 58 percent of the precipitation falls between November of one year and April of the following year, which is the period of active recharge to the ground-water aquifers. The wettest month is January, having an average rainfall of 5.96 inches; and the driest is October, having an average of 2.85 inches. The annual snowfall is generally 4–6 inches. Droughts lasting 15–30 days are not uncommon in late summer and fall, and heavy downpours of 3–3.5 inches of rain in 24 hours occur on an average of once each year (Hershfield, 1961, chart 43). The average monthly precipitation in western Tennessee is shown in the following table.

Average monthly precipitation, in inches, in western Tennessee

Month	Precipitation	Month	Precipitation
January	5.96	July	4.04
February	4.65	August	3.05
March	5.28	September	3.30
April	4.42	October	2.85
May	4.16	November	4.27
June	3.96	December	4.47

GEOLOGY OF THE CLAIBORNE GROUP

NAME AND DEFINITION

The name Claiborne Group was applied by Conrad (1856, p. 257–258) to beds constituting the "Lower or older Eocene" and underlying the Jackson Group in the vicinity of Vicksburg, Miss. For many years the lower boundary of the Claiborne Group was in dispute. As used in Tennessee and in this report, the Claiborne Group overlies the Wilcox Group, underlies the Jackson(?) Formation, and is middle Eocene in age.

SUBDIVISION

Prior to this investigation, divisions of the Claiborne Group were not determined in Tennessee, and the group was not correlated with formations in adjacent parts of Mississippi and Arkansas. Study of 33 geophysical logs and 25 lithologic logs shows that the Claiborne can be partly subdivided on a tentative basis and that the geologic units can be correlated with equivalent units in adjacent areas (pl. 1). As considered in this report, the Claiborne Group in Tennessee consists of five units, which include, in ascending order, the Meridian Sand Member of the Tallahatta Formation (Brown, 1947, pl. 4), the Basic City Shale Member of the Tallahatta Formation (Brown, 1947, pl. 4), the Sparta Sand, an "unnamed clay unit," and an "unnamed sand unit." The character and stratigraphy of these units, as shown on electrical and gamma-ray logs, are shown on plate 1. The older units thicken toward the south and west and are thickest in southwestern Shelby County near the axis of the Mississippi embayment (pl. 1). The unnamed clay and sand units, however, are thickest in southeastern Lake County, but they decrease in thickness in all directions from this locale. The faults shown on plate 1 were determined from the structure-contour maps (pls. 3, 4).

A comparison of the stratigraphic section used in some previous reports with that used in this report is shown in table 1. The geologic and hydrologic properties of the various formations are summarized in table 2.

The Meridian Sand Member of the Tallahatta Formation is the basal unit in the Claiborne Group of Tennessee. This unit is equivalent to the Meridian Sand Member of the Tallahatta Formation of Mississippi as shown by Brown (1947, pl. 4) and correlates with the Carrizo Sand (Hosman, 1962, p. 389) of Arkansas. Like the Carrizo Sand of Arkansas, the sand facies of the Meridian in Tennessee is distinctively micaceous.

The Basic City Shale Member of the Tallahatta Formation (Brown, 1947, pl. 4) is probably equivalent to the Cane River Formation of Arkansas.

In 1947 Brown (1947, p. 37 and pl. 4) described the Tallahatta Formation as consisting of the Meridian Sand Member and the Basic City Shale Member and as underlying the Kosciusko Sand (of former usage) in the northernmost part of Mississippi. In the present report, the contact between the Basic City Shale Member and the Sparta Sand (pl. 1) is considered to be about 120 feet higher in the section than the equivalent contact between the Tallahatta Formation and the Kosciusko Sand shown by Brown (1947, pl. 4). This revision of Brown's section is based on the author's interpretation of the electric logs of several wells that have been drilled in northern Mississippi since Brown published his findings.

The upper contact of the Sparta Sand in western Tennessee (pl. 1) correlates with the upper contact of the Kosciusko Sand in Mississippi, as shown by Brown (1947, pl. 4). In Tennessee the Sparta Sand underlies two unnamed units.

A clay unit directly overlies the Sparta and is overlain in turn by a unit composed predominantly of sand. These units may be equivalent to the Cook Mountain and Cockfield Formations of Mississippi and Arkansas, but no definite correlation can be made at this time. As the stratigraphy of these unnamed units resembles that of the underlying formations of the Claiborne Group, the unnamed units are considered to be part of the Claiborne Group for the purposes of this report. The unnamed sand unit, for example, is a continuous body of sand in nearly all the report area; whereas sand lenses in the overlying Jackson(?) Formation are thin and discontinuous, even over short distances.

TABLE 1.—*Geologic column for the Eocene of western Tennessee*

Wells (1933)		Stearns and Armstrong (1955)		Cushing, Boswell, and Hosman (1964)	This report		
Jackson formation		Jackson and Claiborne groups	"500-foot" sand ?	Jackson(?) Formation	Jackson(?) Formation		
				Claiborne Group, undifferentiated	Unnamed sand unit		Claiborne Group
					Unnamed clay unit		
Wilcox group	Grenada formation [1]				Sparta Sand	"500-foot" sand	
					Basic City Shale Member of the Tallahatta Formation		
	?						
	Holly Springs sand				Meridian Sand Member of the Tallahatta Formation		
		Wilcox group		Wilcox Group, undifferentiated	Wilcox Group, undifferentiated		
	Ackerman formation [1]						

[1] Term no longer used by the U.S. Geol. Survey.

TABLE 2.—*Generalized geologic section of the Eocene formations of western Tennessee and their water-bearing characteristics*

System	Series	Group	Formation	Thickness (feet)	Lithologic character	Water-bearing properties
Tertiary	Eocene	Jackson	Jackson(?) Formation	0–400	Predominantly a gray or greenish-gray clay. A few layers of fine-grained gray sand. Partly lignitic.	Generally impervious. Sand layers yield small quantities of water to a few domestic wells.
		Claiborne	Unnamed sand unit.	0–210	White to gray or brown fine-grained lignitic sand and interbedded clays.	Yields as much as 400 gpm to municipal wells. Downdip the water contains sufficient iron to require aeration for most uses.
			Unnamed clay unit.	25–150	White to red or tan partly lignitic clay.	Does not yield water to wells.
			Sparta Sand (Kosciusko Sand).	100–260	Massive lignitic argillaceous sands and a few interbedded clay layers.	A prolific aquifer—the "500-foot" sand. Yields as much as 2,000 gpm to municipal and industrial wells. Downdip, the water contains sufficient iron to require aeration for most uses.
			Basic City Shale Member of the Tallahatta Formation.	50–295	Beds of white to gray lignitic sand and typically micaceous clay.	
			Meridian Sand Member of the Tallahatta Formation.	85–195	Beds of typically micaceous lignitic sand and a few interbedded clay layers.	
		Wilcox		0–700	Massive beds of gray to tan micaceous clay and sand and a few beds of lignitic clay.	The clay beds do not yield water to wells. Contains a major aquifer—the "1400-foot" sand of the Memphis area.

LOWER PART OF THE CLAIBORNE GROUP ("500-FOOT" SAND)

For some time the term "500-foot sand" (Klaer, 1940, p. 92) has been used to designate the principal aquifer from which Memphis obtained its water supply. The base of this unit was defined and correlated with the base of the Claiborne Group by Stearns and Armstrong (1955, p. 4). The top of the "500-foot" sand has never been defined geologically but has been considered to be the hydrologic top of the aquifer in the Memphis area. For the purposes of this report, the top of the "500-foot" sand is correlated with the top of the Sparta Sand. As such, the "500-foot" sand includes two formations (table 1) but constitutes a single areally extensive aquifer that ranges in thickness from 750 feet in southwestern Shelby County to 200 feet in northeastern Weakley County.

The outcrop area of the "500-foot" sand in western Tennessee is a broad belt extending northeastward across the State (pl. 4). The east boundary of this belt corresponds with the east edge of the report area. The west edge of the belt extends from the northeast corner of Weakley County to the southeast corner of Shelby County and is marked by the intersection of the top of the Sparta Sand with the land surface. The area of outcrop covers about 2,100 square miles. The upper and lower contacts of the "500-foot" sand were projected from the subsurface by means of the structure-contour lines on plates 3 and 4.

Sand composes most of all three units in the "500-foot" sand. Beds of white to blue, pink, gray, or brown clay constitute only a small percentage of the total thickness. In the subsurface, the sand is thick bedded, white to brown or gray, very fine grained to gravelly, and partly argillaceous, micaceous, and lignitic. The sand grains range from clear to white and from well rounded to subangular. Mechanical analyses of samples from the Memphis area indicate that the grain size varies both vertically and laterally but that the sands are generally well sorted. As much as 85–95 percent of the drill samples obtained from 5- to 10-foot intervals in the "500-foot" sand is retained on adjacent sieves (Criner and Armstrong, 1958, p. 8). The thin indurated "rock" layers penetrated in many places by drilling are probably iron-cemented sandstones. The "500-foot" sand lacks marine fossils but contains an abundant flora, which was described by Berry (1916). In 1916, however, the Claiborne Group was thought to be absent in Tennessee, and both Claiborne and Wilcox floras are listed by Berry as being Wilcox in age.

The relations between the various lithologies in the "500-foot" sand as well as the changes in thickness are shown by means of a fence diagram and isopach map (pl. 2). Wells on the fence diagram were projected at right angles into the lines of section. The location of the faults shown was determined on the structure-contour maps (pls. 3, 4). Control points for the isopach map were established by overlaying the structure-contour maps of the top and of the bottom of the "500-foot" sand.

UPPER PART OF THE CLAIBORNE GROUP

The upper part of the Claiborne Group is divided in this report into the unnamed clay and unnamed sand units. The outcrop areas of the unnamed clay and unnamed sand have not been determined, but both units probably crop out in narrow belts west of and adjacent to the outcrop area of the "500-foot" sand. These belts should be broadest near the Tennessee-Kentucky line and should diminish in width progressively southward owing to a gradual decrease in the thickness of both units.

UNNAMED CLAY UNIT

The unnamed clay unit overlies the Sparta Sand (pl. 1) and consists predominantly of white to red or tan partly lignitic clay. In the southern and eastern parts of the report area, the unit is partly silty and sandy. Siderite concretions and kaolin were reported from this interval in one well. The unnamed clay unit averages about 80 feet in thickness, but it ranges in thickness from 110 feet in southeast Lake County to 25 feet in the southernmost part of the report area.

The unnamed clay unit is overlain by the unnamed sand unit. The contact is generally well defined in the subsurface. Where the Jackson(?) Formation and the unnamed sand unit have been eroded, as in the southernmost part of the report area (pl. 1), the unnamed clay unit is overlain by terrace deposits.

UNNAMED SAND UNIT

The unnamed sand unit comprises the youngest beds in the Claiborne Group. It is an aquifer in the area of study because it consists mainly of permeable white to gray or brown fine-grained argillaceous lignitic sand. In Lake County and western Dyer County, the unit is clayey but contains a fairly persistent basal sand. The unnamed sand unit has an average thickness in the report area of 100 feet and a maximum thickness of 210 feet in southeastern Lake County. It is completely overlapped by terrace deposits in the southernmost part of the report area.

In the rest of the area, the unnamed sand is overlain by the Jackson(?) Formation, the lower part of which is predominantly clay.

STRUCTURE

The report area lies on the east flank of the syncline that forms the upper Mississippi embayment. Structurally the embayment is a downwarped, partly downfaulted, trough in Paleozoic rocks. The axis of the embayment has migrated in past geologic time but now approximates the course of the Mississippi River (pls. 3, 4). Subsidence and deposition near the present embayment axis began in Late Cretaceous time but were most active during Eocene time (Stearns and Armstrong, 1955, p. 8). A slight shift in the Mississippi-embayment axis occurred during deposition of the "500-foot" sand; evidence for this shift can be seen by comparing the location of the axis shown on the structure-contour map on the base of the "500-foot" sand (pl. 3) with the location of the axis shown on the structure-contour map on the top of the "500-foot" sand (pl. 4). The approximate depth to either contact at any particular site can be computed by finding the difference between the altitude of the land surface at the site and the altitude of the contact as shown on the maps (pls. 3, 4).

The strike of the "500-foot" sand is northeast except in the northern part of the report area, near the Mississippi-embayment axis. The unit dips to the northwest on the east side of the embayment axis and to the southeast on the west side of the axis. The base of the "500-foot" sand dips approximately 25 feet per mile, whereas the top of the "500-foot" sand dips only 19 feet per mile. The difference in the rates of dip indicates a westward thickening of the unit, which was probably caused by regional subsidence concurrent with deposition.

The top of the unnamed sand unit strikes northeast and dips northwest at approximately 10 feet per mile. The base of this unit ranges in altitude from about 500 feet above to 300 feet below mean sea level. Data were inadequate to construct structure-contour maps of the top and bottom of the unnamed sand unit.

Two faults are indicated within the report area by the structure-contour maps of the top and bottom of the "500-foot" sand (pls. 3, 4). The largest of the two faults trends northwest from the northwest corner of Dyer County across southeastern Lake County and northwestern Obion County and into Kentucky. The average displacement along this fault is 100–150 feet. Some preliminary movement along the fault plane during deposition of the "500-foot" sand seems to be indicated by the relatively thick section of the unit on the east side of the fault (pl. 2). At some time after deposition, however, further movement along the fault tilted the eastern block to the south and produced the structure indicated on the contour

768-379—65——3

maps. The New Madrid earthquake of 1811–12, which created Reelfoot Lake in Lake County (Fuller, 1912, p. 75), may have been caused by recent movement along this fault. The second major fault in the report area trends west-northwest from west-central Crockett County to north-central Lauderdale County. The average displacement is 60 feet.

The structure in southern Shelby County (pls. 3, 4) suggests the possible presence of minor faults in this area. No faults are shown on the maps, however, as their existence is uncertain.

SUMMARY OF GEOLOGIC HISTORY

The presence of lignite and varicolored clays in the Claiborne Group indicates continental or brackish-water deposition. Although the Wilcox clays underlying the Claiborne Group are also nonmarine, the Claiborne overlaps these sediments in the outcrop area. Hence, the contact may represent a major stratigraphic unconformity (Stearns, 1957, p. 1092). Minor oscillations of sea level (and the resulting stream grading) probably accounted for the four major lithologic breaks that have been used to subdivide the Claiborne Group. Differential subsidence of the embayment area during deposition probably accounts for variations in formation thickness. Because the lithology of the Claiborne Group changes to that of a shallow-water marine facies in De Soto and northern Tunica Counties, Miss., the shoreline during Claiborne time was probably approximately along the present Tennessee-Mississippi line. This position of the shoreline is partly confirmed by the presence of heavy minerals (commonly indicative of seashores) in the Sparta Sand and Basic City Shale Member in Shelby County.

At some time after deposition of the Jackson(?) Formation and before deposition of the terrace deposits, the Jackson(?) Formation and the unnamed sand unit were removed by erosion in the southernmost part of the report area (pl. 1).

GROUND-WATER RESOURCES OF THE CLAIBORNE GROUP

SOURCE OF GROUND WATER

Ground water is the water beneath the land surface that issues, or may be pumped, from wells or springs. The primary source of ground water is precipitation. Nearly all the water that falls as precipitation runs off as streamflow, evaporates from wetted surfaces, is transpired by plants, or is held in the soil by molecular forces, which counteract the downward force of gravity. Nonetheless, some of the water that falls as precipitation seeps through the soil zone until it reaches the water table and then enters the zone of saturation, a zone beneath the land surface in which all openings are filled with water.

OCCURRENCE AND MOVEMENT OF GROUND WATER

Ground water occurs in the zone of saturation under water-table (unconfined) conditions and under artesian (confined) conditions. Water-table conditions exist where the upper surface of an aquifer is exposed to atmospheric pressure. The water level in a well that taps a water-table aquifer coincides with the upper surface of the zone of saturation. Artesian conditions exist where water in an aquifer is confined under pressure greater than atmospheric pressure between relatively impermeable beds. The pressure in an artesian aquifer causes the water level in a well that taps the aquifer to rise above the base of the upper confining bed.

In the outcrop area of the Claiborne Group, ground water occurs partly under water-table conditions and partly under artesian conditions owing to the presence of impermeable beds or other fine-grained material below, within, and above the aquifers. Elsewhere in the report area, artesian conditions exist in the Claiborne aquifers.

Ground water in the Claiborne Group moves slowly (probably not more than a few feet per day) from areas of recharge to areas of discharge. The rate of movement is controlled by the permeability and hydraulic gradient of the aquifer through which the water moves. In a water-table aquifer the hydraulic gradient is determined by the slope of the water table, but in an artesian aquifer the gradient is determined by the slope of the "piezometric surface," a term used to denote the surface to which the water from a given aquifer will rise under its full head.

The water table or piezometric surface of an aquifer slopes downward from areas of ground-water recharge or inflow to areas of ground-water discharge or outflow. Irregularities in the shape and slope of the surface, however, result from influences such as topography, lithology and structure of the aquifer, areas and rates of ground-water withdrawal, and areas of surface-water impoundment. The contour lines for the piezometric surface of the "500-foot" sand and the unnamed sand unit (pls. 5, 6) were constructed from water-level measurements made on January 27–29, 1960. As the direction of ground-water movement is from areas of high hydraulic head to areas of low head, movement is generally at right angles to the contour lines of the piezometric surface. The water moves relatively slowly where the surface slopes gently and faster where the slope is steeper, if the permeability of the aquifers is constant or nearly constant.

As shown by plates 5 and 6, ground water in the "500-foot" sand and the unnamed sand unit generally flows west-northwestward or northwestward until it approaches the axis of the Mississippi embayment. Along the embayment axis, water flows south-southwestward or southwestward and leaves the report area as underflow.

In the outcrop area of the "500-foot" sand, the water-level contour lines curve to the east or southeast and approximately parallel the major streams. In these areas, ground water is discharging into the surface streams.

The depression of the piezometric surface of the "500-foot" sand in Shelby County (pl. 5) is caused by pumping, which is centered in the northwest corner of Memphis. The area influenced by this pumping is delineated by the dotted line (pl. 5) just north of Shelby and Fayette Counties. Ground water south of this line is susceptible to capture by pumping in the Memphis area.

The configuration of the piezometric surface of the unnamed sand unit, as shown by the contour lines on plate 6, indicates that part of the ground water in this aquifer is discharged in northern Shelby County.

On the basis of the contour of the piezometric surface, the areas where flowing wells could be completed in the "500-foot" sand and the unnamed sand unit are considered to be where shown in plates 5 and 6, respectively. These areas are confined in general to the flood plains of streams and to the Mississippi Alluvial Plain. At present, very few flowing wells are completed in the Claiborne aquifers because (1) most of the areas of potential flow are subject to periodic flooding by streams and (2) shallower aquifers yield water suitable for domestic, stock, and irrigation use.

SIGNIFICANT WATER-LEVEL FLUCTUATIONS

Neither the water table nor the piezometric surfaces of the artesian aquifers in the report area are stationary; they fluctuate in response to many different factors such as precipitation, pumping of wells, changes in barometric pressure, earth tides, earthquakes, and loading of the land surface. These factors vary in magnitude and time and produce an irregular and sometimes complicated record of water levels. The only fluctuations that are considered in this report, however, are those due to precipitation and pumping because these factors have the largest and longest lasting effects upon water levels.

In areas not affected by pumping, water levels in the Claiborne aquifers generally fluctuate less than 2 feet between yearly highs and lows. These changes are caused mainly by variations in the amount of precipitation. The seasonal fluctuations in a few wells in and near the outcrop belt of the Claiborne Group and near surface streams, however, have a considerably greater amplitude.

Hydrographs (water-level records) of selected wells tapping the aquifers in the Claiborne Group are shown in figures 2 and 3. The location of these wells is shown in figure 4. The hydrograph for well Fa:W-2 (fig. 3) shows that water levels generally declined from 1951–57, rose slightly in 1958, declined slightly from 1959–61, and rose again in the early part of 1962. These fluctuations are probably a direct result of above or below average precipitation during the 6-month period of recharge ending in April of each

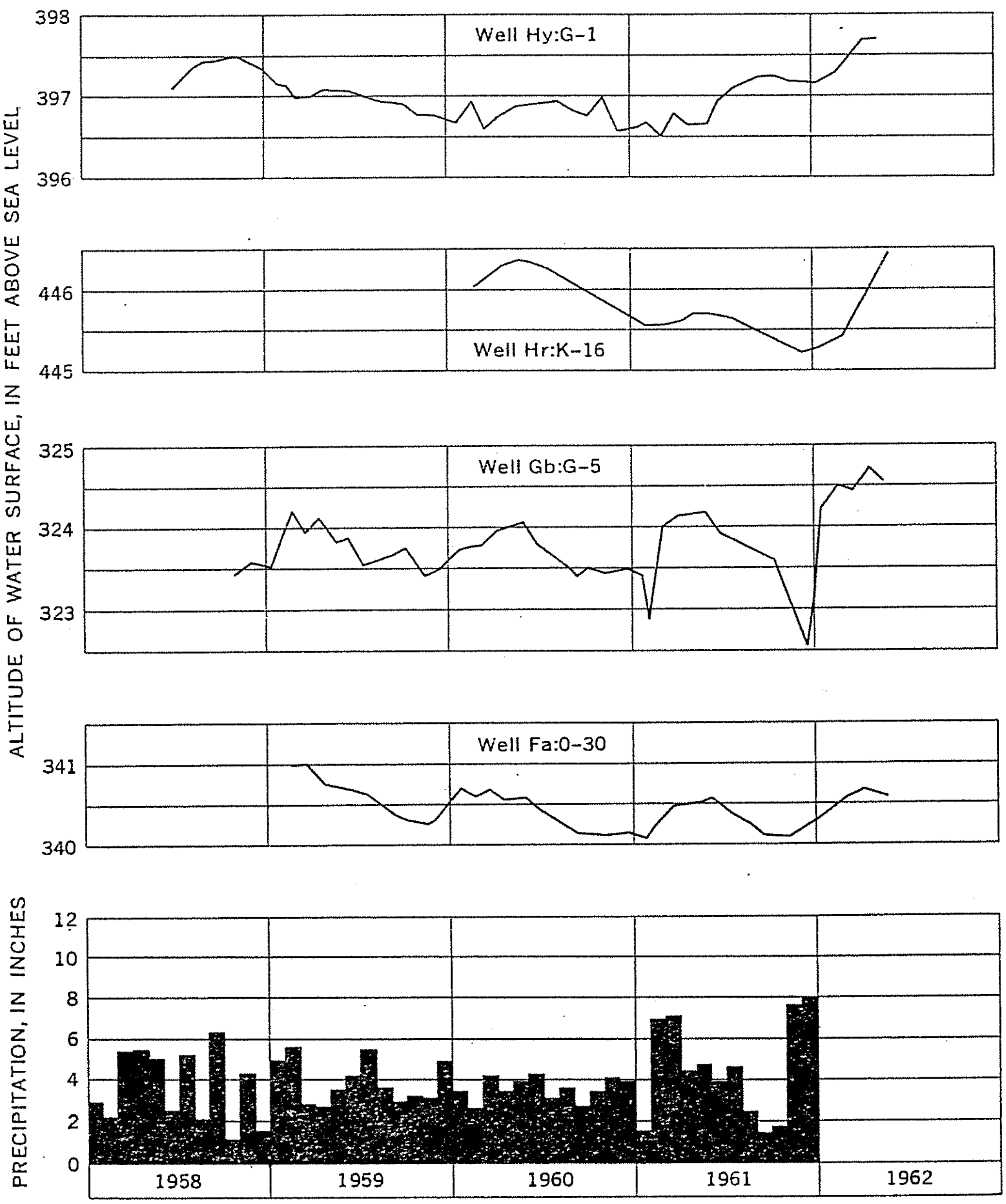


FIGURE 2.—Relationship between water levels in wells completed in the "500-foot" sand and average precipitation in western Tennessee.

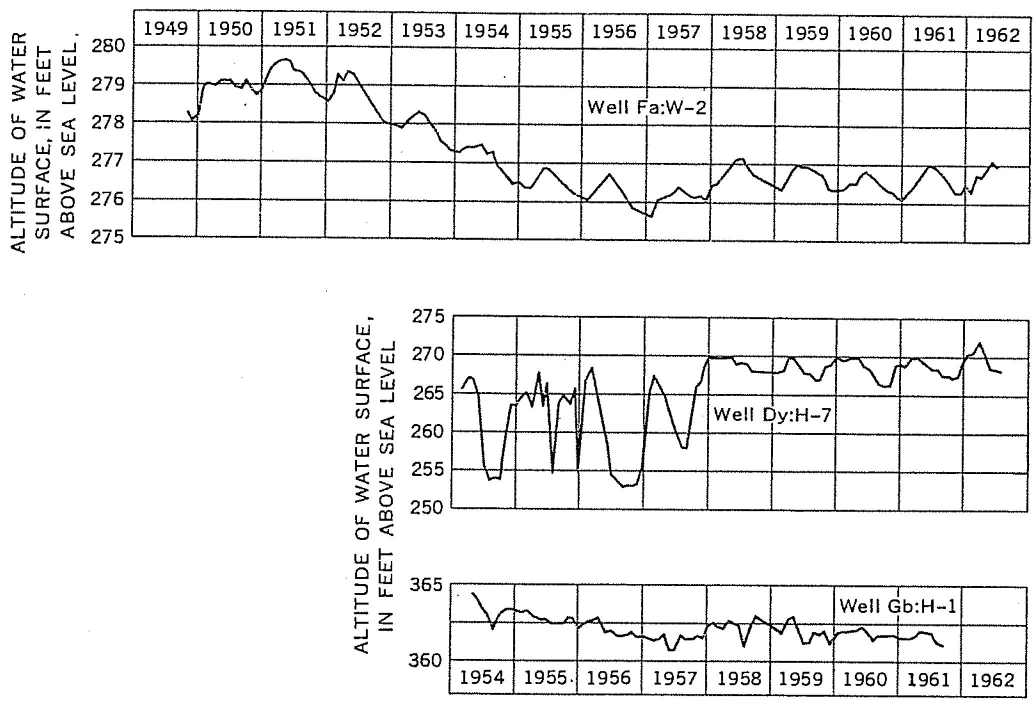


FIGURE 3.—Fluctuation of water levels in wells completed in the "500-foot" sand.

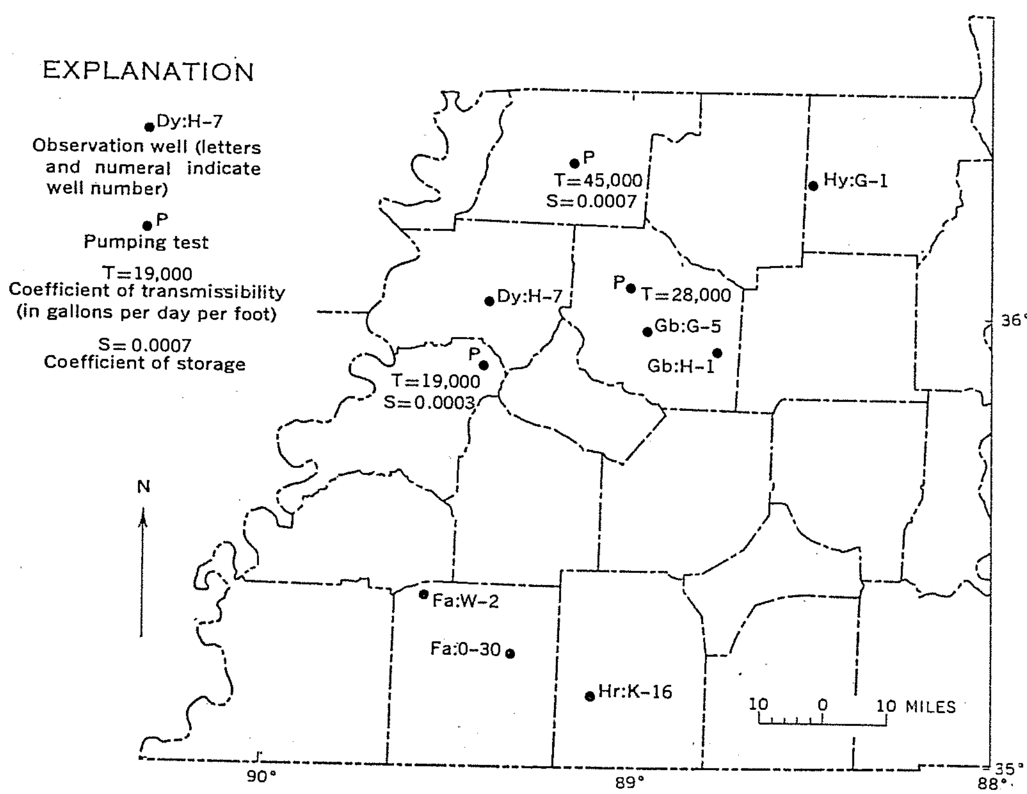


FIGURE 4.—Selected observation wells, pumping-test sites, and coefficients of transmissibility and storage in the unnamed sand unit.

year. Several years of above average precipitation during the seasonal recharge period might raise water levels to near the 1951 levels.

All four wells indicated in figure 2 and well Fa: W–2, in figure 3, are completed in the "500-foot" sand. The total seasonal fluctuation of water levels in these wells ranges from 0.5 to 2.2 feet. Wells Hr: K–16, Fa: O–30, and Hy: G–1 tap the sand in its outcrop area, whereas wells Fa: W–2 and Gb: G–5 tap the sand in the subsurface, farther downdip.

Wells Dy: H–7 and Gb: H–1 (fig. 3) are completed in the "500-foot" sand near centers of municipal-pumping areas at Dyersburg and Milan, respectively. The effect of pumping on water levels in nearby wells depends on several factors, including the amount of pumpage, the permeability and storage characteristics of the aquifer, and the distance of the observation well from the center of pumping. The seasonal fluctuations of water level caused by precipitation are partly obscured in the hydrographs for wells Dy: H–7 and Gb: H–1 (fig. 3) by larger fluctuations caused by variations in the rate of pumping. In the period 1954–57, daily pumpage at Dyersburg ranged between 1.5 and 7 mgd (million gallons per day), and the maximum seasonal fluctuation in water level in well Dy: H–7 during this period was 14.5 feet. In the interval 1958–61, daily pumpage ranged between 1 and 2.5 mgd, and the maximum seasonal fluctuation was 4.6 feet.

AQUIFER LIMITS

"500-FOOT" SAND

The "500-foot" sand is present over about 7,200 square miles in western Tennessee and averages about 450 feet in thickness. The volume of this aquifer is about 600 cubic miles. If the average porosity is 25 percent of its volume, the "500-foot" sand contains 150 cubic miles, or 170 trillion gallons, of water in storage.

The altitudes of the bottom and top of the "500-foot" sand are shown on plates 3 and 4, respectively. The approximate depth to either contact can be calculated from these maps by finding the difference between the contact altitude and the land-surface altitude at any desired point.

Clay layers locally separate the "500-foot" sand into several aquifers. Layers 20 feet thick or more are generally extensive enough laterally to effect an initial hydrologic separation over the area occupied by the average well field. The clay in the basal part of the Basic City Shale Member of the Tallahatta Formation is found throughout the western part of the report area, but few of the other clays have more than local distribution.

UNNAMED SAND UNIT

In western Tennessee the unnamed sand unit is distributed over about 6,500 square miles and averages about 100 feet thick. If the porosity is 25 percent of its volume, the aquifer contains 31 cubic miles, or 34 trillion gallons, of water in storage.

In Lake and western Dyer Counties the unnamed sand unit probably yields only enough water for domestic supplies, but elsewhere it is generally sufficiently thick to yield enough water for small municipal and industrial supplies. The aquifer occurs at a depth of 350 feet or less nearly everywhere that it is present in the subsurface.

At Union City, layers of clay separate the unnamed sand into two aquifers. Elsewhere the effect of interbedded clays upon the hydrology of the unit is unknown.

AQUIFER HYDRAULICS

HYDRAULIC PRINCIPLES

Under natural conditions, the water level in a well corresponds to the water table or piezometric surface of the aquifer. When the well is pumped, the water level in the well drops, a hydraulic gradient toward the well is produced, and a depression is created in the water table or piezometric surface. This depression is nearly in the form of an inverted cone having its apex at the well. The greater the rate of pumping from the well, the greater is the depth of the cone of depression. As pumping continues, the water level in the well continues to decline and the depth of the cone of depression increases, but at a continually decreasing rate, until the cone captures or diverts enough water to balance the discharge from the well. When this balance occurs, the water level in the pumping well ceases to decline and equilibrium conditions exist. If equilibrium conditions are not reached after several days or weeks of pumping, the water level in the well generally reaches a state of virtual equilibrium, wherein additional decline in the water level is insignificant except over long periods of time.

The quantity of water that the Claiborne aquifers will yield to wells over a long period of time depends principally upon the dimensions, permeability, and storage capacity of the aquifers. The dimensions of the aquifers have been determined by geologic studies. The last two properties constitute the hydraulic function of the aquifers and are determinable by aquifer tests. Once determined, the values of these hydraulic properties can be used to predict the effects of pumping and the theoretical yield of wells.

The permeability of an aquifer determines its capacity to transmit water. This function is generally expressed as the coefficient of transmissibility, which is defined as the number of gallons of water per day (gpd) that flows through a strip of the aquifer 1 foot wide, measured at right angles to the direction of flow, under a hydraulic gradient of 1 foot per foot. It is expressed in dimensions of gallons per day per foot (gpd per ft). The field coefficient of permeability is defined as the flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at the prevailing temperature in the aquifer; it is expressed in dimensions of gallons per day per square foot (gpd per sq ft). Hence, the field coefficient of permeability can be calculated for a given aquifer by dividing the coefficient of transmissibility of the aquifer by the saturated thickness of the aquifer.

The storage capacity of an aquifer is computed and expressed as the coefficient of storage. This unit is the volume of water that the aquifer releases or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. It has no dimensions, because it is a ratio. The coefficient of storage is commonly 0.1–0.3 for a water-table aquifer, compared with 0.001 or less for an artesian aquifer; the difference is due to the fact that water-table and artesian aquifers differ in the relative amounts of water released or taken into storage with changes in water level. For example, as the water table is depressed near a pumping well, a relatively large quantity of water is drained from the water-bearing material through which the water table falls. In an artesian aquifer, however, the interstices remain filled, and only a small amount of water is released from storage as the hydrostatic pressure declines; this apparent accretion of water from storage is mainly a result of elastic compaction of the aquifer and the confining beds. The practical effect of the difference between the storage capacities of water table and artesian aquifers is that pumping at a given rate from an artesian aquifer lowers the water level faster than does pumping at the same rate from an equivalent aquifer under water-table conditions.

When aquifer tests are made to determine the hydraulic properties of aquifers, the rate of withdrawal of water from the pumped well is controlled and measured carefully, and the effects of pumping on the water level are measured in one or more observation wells that are screened in the same aquifer. The coefficients of transmissibility and storage can then by computed by analyzing the pumping-test data in the manner described by Wenzel (1942), Brown (1953), or Walton (1962).

"500-FOOT" SAND

During the hydrologic investigation of the "500-foot" sand, 11 aquifer tests lasting from less than 1 hour to as much as 16 hours were conducted at towns outside the Memphis area. The coefficients

768-379—65——4

of transmissibility and storage were obtained from semilog plots of drawdown or of recovery of water levels in the manner described by Brown (1953, p. 858).

The results of the aquifer tests were evaluated by comparing them with the results from much longer tests in the Memphis area, where pumping tests that lasted 2–17 days were made at five well fields. In addition, 10 other tests lasting 2–48 hours were made in the Memphis area. The coefficients of transmissibility computed from all the Memphis-area tests ranged from 50,000 to 400,000 gpd per ft, although most values were between 150,000 and 320,000 gpd per ft. For the same group of tests the coefficients of storage ranged from 0.0001 to 0.003. In comparison, the coefficients of transmissibility determined from the short pumping tests that were made outside the Memphis area ranged from 20,000 to 220,000 gpd per ft, and the coefficients of storage ranged from 0.0001 to 0.0006. The results of the short pumping tests are very consistent with those obtained from much longer tests in Memphis, considering that the "500-foot" sand is thickest in the Memphis area.

All wells tested were partially penetrating and most were screened near the top of the "500-foot" sand aquifer. Nearly all the values of transmissibility and storage, therefore, indicate the hydraulic character of only the upper part of the aquifer. The coefficient of transmissibility of 400,000 gpd per ft is probably representative, however, of the entire thickness (700 ft) of the "500-foot" sand in the Memphis area. The field coefficient of permeability is therefore 570 gpd per sq ft. Lines of theoretically equal transmissibility in the "500-foot" sand throughout the report area (pl. 7) are based on this value and on the known range in aquifer thickness. Plate 7 also shows the range in transmissibility as computed from pumping tests that were made in the wells that partly penetrate the "500-foot" aquifer. Wells constructed similarly to those used for the pumping tests and located in an area in which the aquifer has the same transmissibility would probably yield about the same amount of water.

Both apparent and potential coefficients of transmissibility are highest in Shelby County, where the aquifer is thickest, and decrease in value to the northeast (pl. 7). Transmissibilities of at least 50,000 gpd per ft are indicated for the "500-foot" sand nearly everywhere in the report area.

Transmissibility values can be used to estimate the relative yield of a well in terms of its specific capacity, which is defined as the number of gallons per minute a well will yield for each foot of drawdown of the water level. The specific capacity of a well depends primarily on the hydraulic characteristics of the aquifer, the period of pumping, and the construction and degree of development

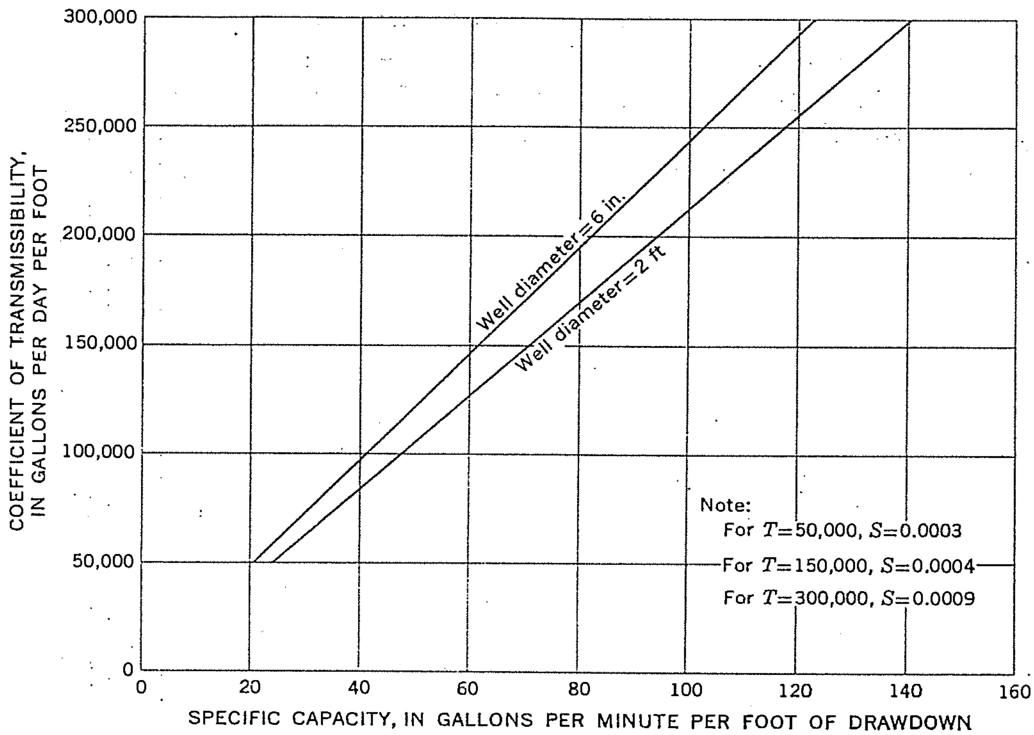


FIGURE 5.—Relationship of specific capacity of wells after 1 day of pumping to the transmissibility of the "500-foot" sand.

of the well. The maximum specific capacities that can be obtained for the range of transmissibilities in the "500-foot" sand are shown in figure 5. Wells having diameters between 6 inches and 2 feet would have theoretical specific capacities that plot between the two curves. In practice, the specific capacity of most wells ranges from 60 to 80 percent of the values indicated in figure 5, because the well only partly penetrates the aquifer and because of well and screen loss. The coefficients of storage used in computing the curves in figure 5 are average values.

Another significant use of the coefficients of transmissibility and storage is the determination of the effects of pumping at specified rates of discharge upon water levels at various times and at various distances from the pumped wells (the amount of interference). Drawdowns of water level were computed and plotted to show theoretical time and distance-drawdown relationships. The theoretical drawdown that would result at given times and distances in an aquifer having the range in coefficients of transmissibility and storage determined for the "500-foot" sand is shown in figure 6. As the water-level drawdown in the aquifer is directly related to the discharge, pumping rates of 1000, 1500, or 2,000 gpm (gallons per minute) would result in drawdown of two, three, and four times, respectively, those shown in figure 6 at the same time and distance and for the same values of transmissibility and storage. The coeffi-

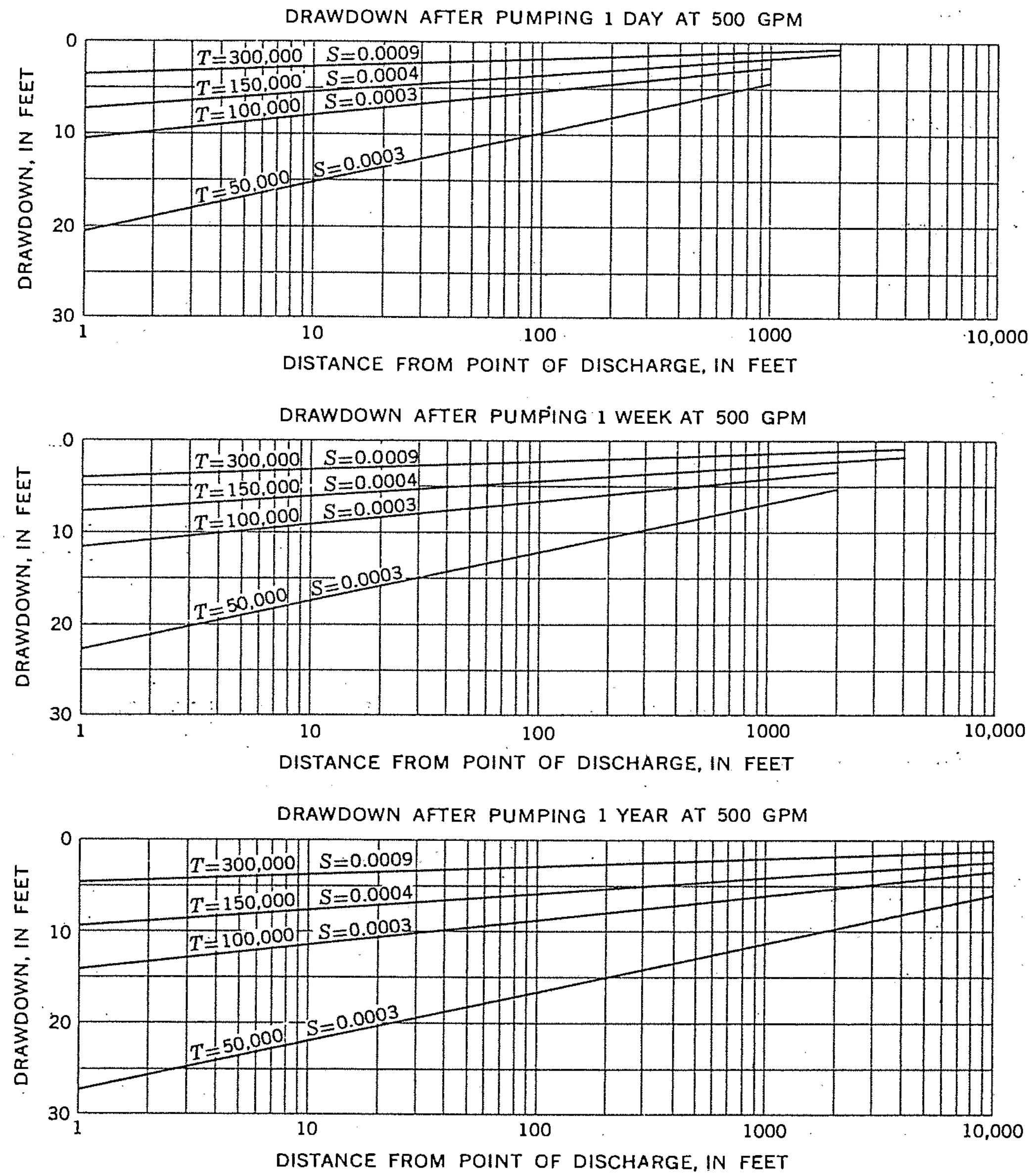


FIGURE 6.—Theoretical drawdowns at given times and distances in an ideal aquifer having the range in transmissibility and storage determined for the "500-foot" sand.

cients of storage used in computing the curves in figure 6 are average values.

UNNAMED SAND UNIT

Three aquifer tests were made using wells screened in the unnamed sand unit to determine the hydraulic characteristics of this aquifer. The location of the wells and the calculated coefficients of transmissibility and storage are shown in figure 4. The maximum transmissibility was determined to be 45,000 gpd per ft at Troy. Whether this value represents the transmissibility for the entire 170-foot thickness of the aquifer at Troy or indicates local anomalous conditions is not known. The unnamed sand unit is finer grained than the "500-foot" sand, however, and the foregoing value is reasonable for the entire thickness. If so, the average field coefficient of permeability for the unnamed sand aquifer is about 265 gpd per sq ft. In general, the results of pumping tests in the unnamed sand suggest higher transmissibilities in the northern and eastern parts of the area underlain by this unit.

The maximum specific capacities that can be determined for the known range in transmissibilities in the unnamed sand aquifer are shown in figure 7. In practice, most wells have specific capacities 20–40 percent less than these values, the difference depending on the design and the degree of development of individual wells.

The theoretical drawdown that would result at given times and distances for the range in coefficients of transmissibility and storage determined for the unnamed sand unit is shown in figure 8. Other conditions remaining the same, pumping rates of 200, 300, or 400 gpm would result in drawdowns of water levels two, three, and four times those shown in figure 8.

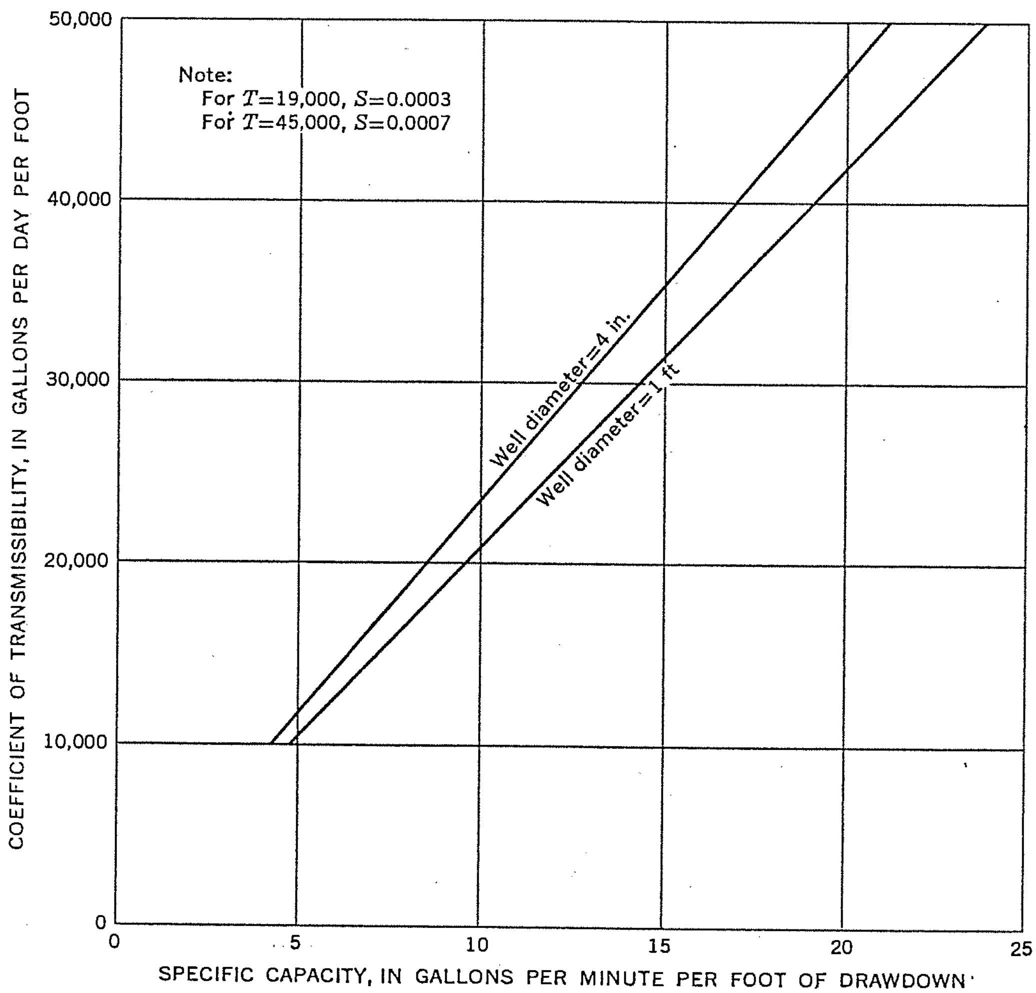


FIGURE 7.—Relationship of specific capacity of wells after 1 day of pumping to the transmissibility of the unnamed sand unit.

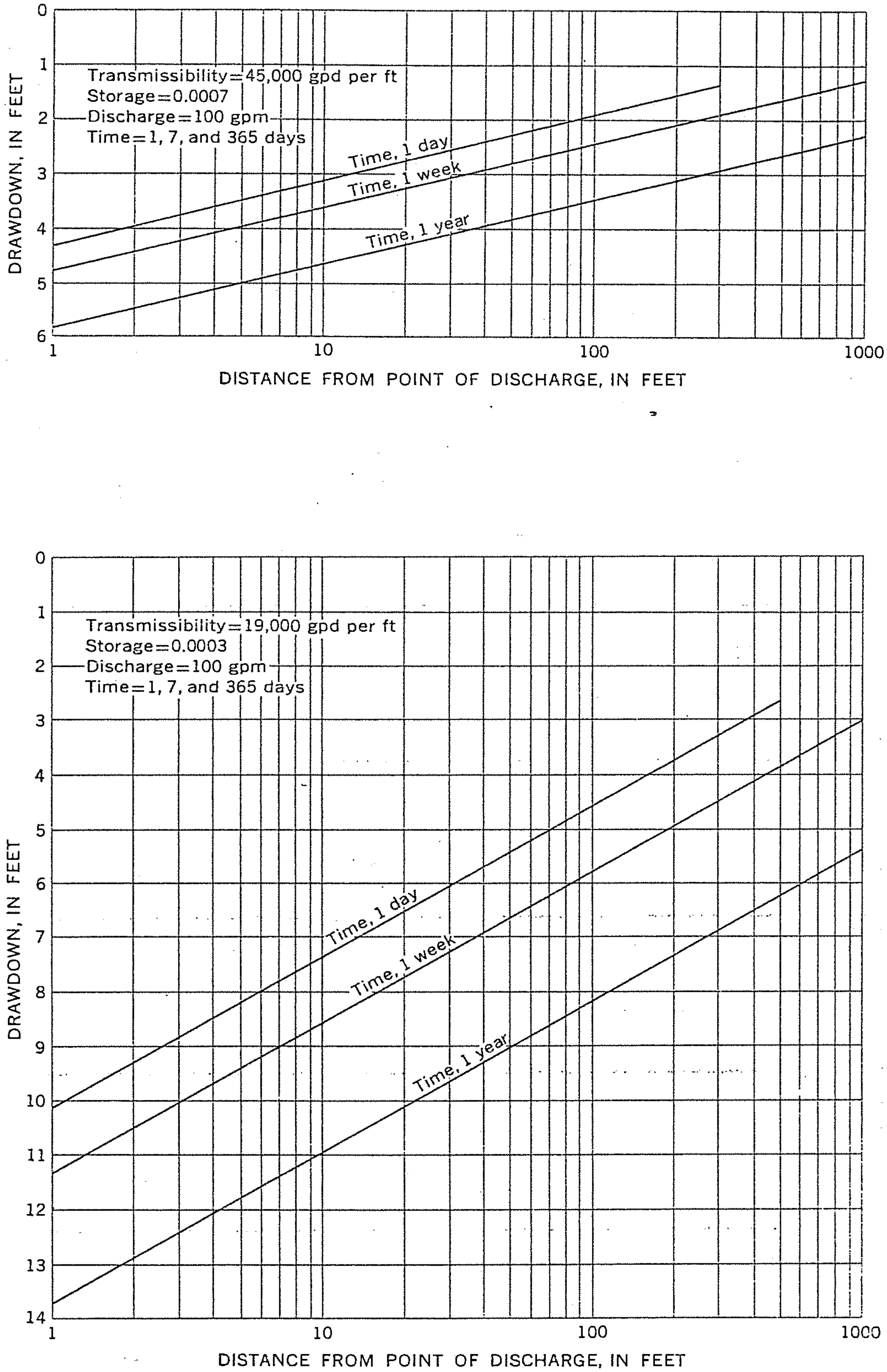


FIGURE 8.—Theoretical drawdown at given times and distances in an ideal aquifer having the range in transmissibility and storage determined for the unnamed sand unit.

OPERATION OF THE AQUIFER SYSTEMS

RECHARGE AND DISCHARGE

On an annual basis, recharge balances discharge plus or minus any change in storage. The aquifers in western Tennessee, however, receive an excess of potential recharge from precipitation. Because depletion of storage is very small, the amount of recharge to the aquifers of the Claiborne Group can be calculated approximately by totaling the amounts of water annually pumped or discharged from the aquifers. Most recharge to the Claiborne Group occurs by infiltration of precipitation in the outcrop areas of the aquifers. Some additional recharge is also received by seepage from adjacent formations and by underflow from adjacent States. The various amounts of recharge and discharge to and from the aquifers are summarized in table 3.

TABLE 3.—*Water budgets, in million gallons per day, in 1960 for the aquifers of th Claiborne Group*

[Amounts that are discharged to the streams are neglected]

"500-foot" sand	
Recharge:	
Recharge from precipitation on the outcrop area in Tennessee	133
Underflow from the north	3
Underflow from the south	25
Underflow from the west	20
Accretion from adjacent formations	10
Total average recharge	191
Discharge:	
Estimated pumpage	155
Underflow along the Mississippi-embayment axis	37
Total average discharge	192
Depletion of storage	1
Unnamed sand unit	
Recharge:	
Recharge from precipitation on the outcrop area in Tennessee	8
Underflow from the north	1
Accretion from adjacent formations	1
Total average recharge	10
Discharge:	
Estimated pumpage	2
Discharge to adjacent formations	8
Total average discharge	10

Practically all recharge from precipitation to the Claiborne Group occurs from November 1st of one year through April 30th of the following year. In the intervening months, May–October, evapotranspiration exceeds rainfall, and nearly all rain that seeps into the ground is absorbed by the soil. Little, if any, reaches the water table.

In the 750 square miles of the outcrop belt of the "500-foot" sand that is influenced by pumping in Shelby County, the average recharge from precipitation in 1960 was 80 mgd. In the remaining 1,350 square miles of the outcrop belt of the "500-foot" sand, the average recharge from precipitation was about 53 mgd in 1960. Thus, the total recharge to the "500-foot" sand from precipitation averaged 133 mgd in 1960. In the unnamed sand unit the average withdrawal and discharge of 8 mgd of water in 1960 was replaced by recharge from precipitation on the outcrop area.

A considerable amount of water in the aquifers of the Claiborne Group in Tennessee enters the State as underflow from the north, south, and west. Under natural conditions, about 3 mgd flowed into the State from Kentucky through the "500-foot" sand in 1960, and about 1 mgd flowed into the State through the unnamed sand unit. An undetermined amount of water flowed toward the Mississippi-embayment axis from Arkansas and Missouri in the northern part of the report area, but most, if not all, of this water left Tennessee as underflow along the axis of the embayment in the southern part of the area. Additional amounts of water were induced into Tennessee from the south and west because of pumping; this movement of water is discussed on page F28 as an effect of pumping.

Some of the water that flows downdip through the "500-foot" sand leaves Tennessee as underflow along the axis of the Mississippi embayment (pl. 5). This volume of water was calculated from the hydraulic gradient (pl. 5) and from the transmissibility (pl. 7) of the "500-foot" sand and was about 37 mgd in 1960. Most of this water was captured by pumping at Memphis, however.

EFFECTS OF PUMPING AND INTERAQUIFER MOVEMENT OF GROUND WATER

Prior to the development of water supplies from the "500-foot" sand, the amount of ground water that entered Shelby County from the east through the "500-foot" sand was estimated by Criner, Sun, and Nyman (1963, p. 50) to have been about 30 mgd. In 1960, under conditions of heavy pumping, the amount of ground water moving eastward into Shelby County through the "500-foot" sand was estimated at 60 mgd (Criner, Sun, and Nyman, 1963, p. 51). The additional water probably resulted chiefly from a reduction in surface runoff. No significant effect upon the flow of the major rivers in the outcrop area of the "500-foot" sand, however, has been observed. Wolf River, for example, has one of the largest base flows per square mile of drainage area of any river in the State. Any reduction in the base flow of the streams east of Shelby County has been obscured by the variations in base flow caused by factors other than the increased flow through the "500-foot" sand.

A factor that also might account for the lack of an observable effect of pumping from the "500-foot" sand on surface runoff is the apparent time lag between peak seasonal pumping and annual low water levels in the outcrop area of the "500-foot" sand. At a distance of 15–30 miles from the center of pumping in Memphis, the time lag between peak pumping and low water level is 1–4 months (Criner, Sun, and Nyman, 1963, p. 40). Consequently, the effect of peak pumping from July through September might not affect water levels in the recharge area of the "500-foot" sand until the interval November–January. The practical result of this time lag would be a reduction in the amount of direct surface runoff in the November–January period rather than a reduction in base flow during the period of peak pumping from July through September.

The major streams in the report area probably do not discharge any water into the Claiborne aquifers except possibly within the area influenced by pumping at Memphis.

Seepage from adjacent geologic formations accounts for a small amount of recharge in the report area. This process is significant in the Memphis area, where the "500-foot" sand is overlain and confined by thin partly silty or sandy clays. Possible sources for this recharge are water in the unnamed sand unit, the alluvial and terrace deposits, and the "1,400-foot" sand of the Wilcox Group. In the report area about 8 mgd moves through the unnamed sand toward the axis of the Mississippi embayment. This water then flows south along the axis and is discharged into the Mississippi River alluvium, terrace deposits, and probably the "500-foot" sand in or just west of Shelby County.

Additional amounts of water are apparently discharged from terrace deposits into the "500-foot" sand in the southern part of Shelby County. Pumping in Shelby County has lowered water levels in the "500-foot" sand below those in the terrace deposits, and a hydraulic gradient between the two aquifers has been established. As a result of this downward seepage, the water table in the terrace deposits has dropped to some extent, and Nonconnah Creek is now dry part of the year, whereas it was formerly a perennial stream.

Criner, Sun, and Nyman (1963, p. 54) gave the following ground-water budget for the "500-foot" sand in Shelby County:

Inflow	*Million gallons per day*
Across east boundary	60
Across north boundary	20
Across south boundary	25
Across west boundary; leakage from above and other sources	29
Depletion of storage	1
Total	135
Average pumping rate for 1960	135

The information available on water levels west of the Mississippi River is inadequate to determine directly the inflow into Shelby County across the west boundary. Probably no more water is moving across the west boundary than across the north boundary, however. Although hydraulic gradients have been established from the north and west by pumping, the inflow from both directions is moving updip in the "500-foot" sand. If Shelby County receives 20 mgd across the west boundary, then, from the foregoing water budget, 9 mgd is recharged to the aquifer from adjacent geologic formations.

The hydraulic head in the "500-foot" sand is higher than that in the underlying "1,400-foot" sand of the Wilcox Group, except in Shelby County, where the reverse is true. Moreover, the "500-foot" sand partly overlaps the Wilcox Group where they crop out, as discussed on page F12, and occupies the higher position topographically. A net discharge of water into the older unit probably occurs, but the amount of this discharge cannot be estimated at present.

Outside Shelby County, seepage from overlying formations into the Claiborne aquifers is apparently confined to isolated local areas. In some of these areas, pumping lowers the water level in the Claiborne aquifers enough to induce water into them from the overlying formations, such as alluvial deposits. The total amount of water added to the Claiborne aquifers in these areas is probably about 1 mgd for the "500-foot" sand and 1 mgd for the unnamed sand unit.

The total accretion from adjacent formations is probably about 10 mgd for the "500-foot" sand and about 1 mgd for the unnamed sand unit.

Under conditions of heavy pumping in Memphis, 25 mgd has been diverted into Shelby County as underflow through the "500-foot" sand from Mississippi, and probably an additional 20 mgd enters the county as underflow through the "500-foot" sand from Arkansas.

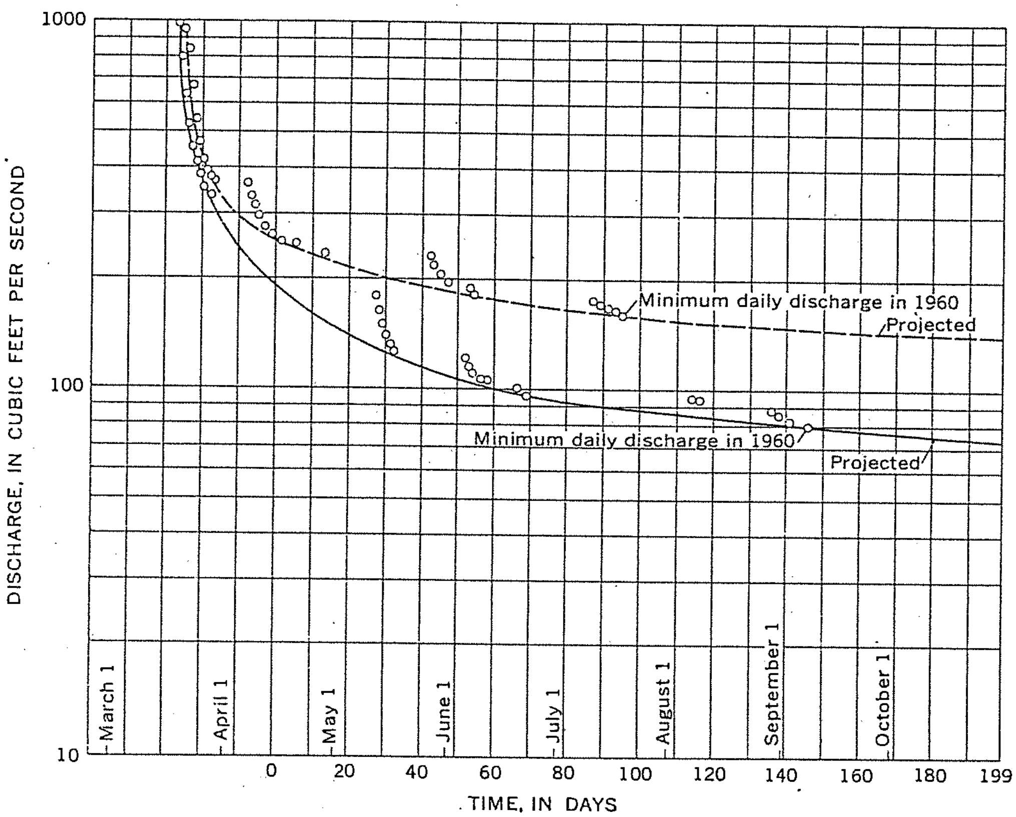
Discharge from the "500-foot" sand that is not balanced by recharge results in a depletion of water in storage and a lowering of water levels. These changes occur chiefly in Shelby County, where the amount of pumpage is continuing to increase year after year. Criner, Sun, and Nyman (1963, p. 54) estimated that an average 1 mgd of the total pumpage in the Memphis area is derived from storage.

GROUND-WATER STORAGE AND BASE FLOW OF STREAMS

A large amount of water is temporarily stored in the Claiborne aquifers during the winter months, and much of this water is then discharged to streams in the outcrop areas during the following seasons. This water constitutes the base flow of the perennial streams in the outcrop area of the Claiborne Group. The aquifers discharge water for two reasons: (1) there is a hydraulic gradient between the uplands and the stream bed and (2) the aquifers are essentially full of water, and additional water cannot be transmitted downdip under existing hydraulic gradients.

The relationships between the changes in ground-water levels, the changes in the depth and discharge of streams, and the variations in precipitation and evapotranspiration are complex. The seasonal trends of these factors can generally be isolated from the shorter term complexities, however. During the period from April through November, as discussed on page F26, practically no water recharges the Claiborne aquifers. Because the aquifers continue to discharge water from April through November, although at a decreasing rate, the amount of water in storage in the aquifers recedes. Therefore, a curve drawn through the lowest points on the stream hydrographs during this period approximately defines the recession of discharge to the streams from the upland areas of outcrop of the aquifers (neglecting bank storage and evapotranspiration). The area under this curve approximately represents the total amount of water discharged from the various aquifers in the basins.

The recession of ground-water discharge for the basins of Wolf River at Rossville and of South Fork Obion River near Greenfield is shown in figure 9. The base-flow data obtained at these stations are probably representative of ground-water discharges from the "500-foot" sand. On the basis of the stream hydrographs and of well hydrographs, the period selected for analysis was April 15–October 31, 1960. Because of a series of rains in the fall, the total discharge of the streams during this season exceeded the ground-water discharge; therefore, parts of both curves are projected.



Wolf River at Rossville (dashed-line curve): location, lat, 35°03′15″, long 89°32′30″; period of plot, March 21–July 19, 1960; drainage area, 503 square miles.

South Fork Obion River near Greenfield (solid-line curve): location, lat 36°07′05″, long 88°48′39″; period of plot, March 19–September 7, 1960; drainage area, 431 square miles.

FIGURE 9.—Recession of ground-water discharge in two basins during April 15–October 31, 1960.

The volumes of ground water discharged from the "500-foot" sand during the 1960 period of recession were calculated from the recession curves in figure 9. The volume of water represented by the area beneath the curves was calculated in five or ten day segments (depending on the slope of the curve) and then totaled.

In the Wolf River basin above Rossville, 21.7 billion gallons of water was discharged from the outcrop area of the "500-foot" sand in 1960. In the South Fork Obion River basin above Greenfield, 12.5 billion gallons was discharged. If the mean of these values represents the average volume of discharge from the "500-foot" sand, about 76 billion gallons of water was discharged to streams crossing the outcrop area during the 1960 period of recession. This volume of discharge is equivalent to a depth of 2.1 inches of water over the 1,350 square miles of the outcrop area. These calculations can be checked by comparing the amount of aquifer discharge with the total seasonal luctuation of ground-water levels. The following table lists the various declines of water level that would result in the "500-foot" sand for four different porosities if 76 billion gallons of water were lischarged from the aquifer:

Porosity (percent)	*Water-level decline (inches)*
20	10.5
25	8.4
30	7
35	6

The actual seasonal fluctuation of water level in the outcrop area of the "500-foot" sand ranged from about 6 to 12 inches in 1960.

WATER QUALITY

The quality of the ground water in the report area is primarily a result of the solvent power of the water. This power is greatly increased by the presence of dissolved carbon dioxide. Some carbon dioxide is dissolved from the air by rainwater, but organic soils generally contain much more of this gas than does the atmosphere. Therefore, as rainwater percolates into and through an organic soil zone, it dissolves additional amounts of carbon dioxide and thus forms a weak acid solution that can dissolve certain minerals in the earth's crust. In general, the farther the water travels and the longer the water remains underground, the more mineral matter it dissolves.

The chemical suitability of water for domestic and municipal use is commonly judged by comparison with standards of the U.S. Public Health Service (1962) for water used on common carriers in interstate commerce. Individuals can become adjusted to drinking water containing larger amounts of chemical constituents than those recommended by the Health Service, but water of inferior quality should be avoided wherever possible. The chemical quality of water in the Claiborne aquifers is within the limits established in the Public Health Service standards for all constituents except iron. The iron content of water in the Claiborne aquifers within the report area ranges from 0 to 16 ppm (parts per million), whereas the recommended limit is 0.3 ppm. Individual chemical analyses of water from most municipal water supplies from the Claiborne aquifers in western Tennessee were reported by Lanphere (1955).

In general, the chemical quality of water from the Claiborne Group at a given locale may be expected to show little or no change with time. For example, analyses of water from selected wells in the report area showed no significant change in quality between 1929 and 1961 (J. H. Hubble, U.S. Geol. Survey, written commun., 1962). Some changes in water quality might occur, however, where significant quantities of water are withdrawn from a new well or well field owing to the induction of water of better or poorer quality into the aquifer.

"500-FOOT" SAND

Wells near the outcrop area of the "500-foot" sand yield water that is generally low in all chemical constituents and somewhat acidic, as evidenced by a relatively low pH (the negative logarithm of hydrogen ion activity). Because of the low pH and probably because of the presence of dissolved oxygen (Moore, 1962, p. 134), water pumped from wells near the outcrop area generally corrodes iron piping.

Downdip in the aquifer, contents of calcium, magnesium, iron, and bicarbonate in the water progressively increase (pl. 8), and acidity correspondingly decreases. The increase in calcium, magnesium, and bicarbonate probably results from the slow solution of available calcium and magnesium minerals as the ground water moves downdip. The solution of these materials reduces the amount of carbonic acid in the water and thereby probably accounts for the downdip decrease in acidity, if no carbon dioxide is added to the system.

The increase in the iron content (pl. 8) of the water downdip in the "500-foot" sand is presumably the result of a shift from an oxidizing environment near the outcrop area to a reducing environment near the axis of the Mississippi embayment (Moore, 1962, p. 134).

Nearly all municipal supplies taken from the "500-foot" sand near the embayment axis must be aerated, and most supplies must also be filtered. These processes precipitate the dissolved iron in the form of an oxide and then remove the iron oxide from suspension. Aeration also liberates excess carbon dioxide and hydrogen sulfide gas, thereby making the water less corrosive and more palatable.

The distribution of iron, hardness, pH, and temperature in water from the "500-foot" sand is shown in figure 10. The range and median values of most chemical constituents are listed in table 4.

UNNAMED SAND UNIT

The data currently available are inadequate to show graphically the downdip changes in chemical quality of water in the unnamed sand unit. There is, however, an apparent downdip increase in mineral constituents and temperature. The range and median values of most chemical constituents in water from the unnamed sand unit are shown in table 4. The temperature of the water in this aquifer ranges from 59°F to 63°F.

Aeration and filtration are used to remove iron from the water for municipal supplies in the northwestern part of the report area. No other treatment is used for the chemical content of the water.

TABLE 4.—*Summary of chemical analyses of water from selected wells developed in the "500-foot" sand and unnamed sand unit in western Tennessee*

[Results in parts per million, except as otherwise indicated. Analyses made by the Quality of Water Branch, U.S. Geol. Survey]

Chemical constituent or property	"500-foot" sand (33 analyses)			Unnamed sand unit (11 analyses)		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Silica (SiO_2)	3.3	12	21	11	18	33
Iron (Fe)	.0	.5	14	.1	.7	16
Calcium (Ca)	1.3	5.8	31	3.5	12	31
Magnesium (Mg)	.4	1.9	15	1.2	4.6	14
Sodium (Na)	1.9	5.6	17	2.4	9.6	29
Potassium (K)	.2	.9	7.5	.5	1.2	6.6
Carbonate (CO_3)	0	0	4	0	0	0
Bicarbonate (HCO_3)	8.0	29	170	21	82	190
Sulfate (SO_4)	.0	2.2	9.7	1.1	2.6	17
Chloride (Cl)	.6	3.0	19	1.5	3.4	26
Fluoride (F)	.0	.1	.6	.0	.0	.1
Nitrate (NO_3	.0	.6	10	.0	.4	20
Dissolved solids (residue at 180° C)	19	57	150	33	120	180
Hardness as $CaCO_3$	6.0	22	140	14	49	140
Specific conductance (micromhos at 25° C)	23	84	270	39	170	300
pH	5.6	6.2	8.0	6.0	6.1	7.7

WATER USE

The availability of large quantities of ground water from the Claiborne aquifers has been an important factor in the economic development of the report area. All known municipal, industrial, and domestic water users and most irrigation water users rely on ground water for their source of supply. In 1960 the average pumpage from the "500-foot" sand was about 155 mgd, and the average pumpage from the unnamed sand unit was about 2 mgd.

Detailed surveys of water use have been made in three localities in the report area. Use of pumpage from the "500-foot" sand in Shelby County was found to be 45 percent municipal and 55 percent industrial and other. In the Dyersburg quadrangle (Schreurs and Marcher, 1959, p. 40), use of pumpage was 51 percent municipal, 20 percent industrial, and 28 percent other. A survey of Madison County found pumpage use to be 44 percent municipal, 35 percent industrial, and 21 percent other. On the basis of these results, use of pumpage from the aquifers of the Claiborne Group is estimated to be 46 percent municipal, 44 percent industrial, and 10 percent other.

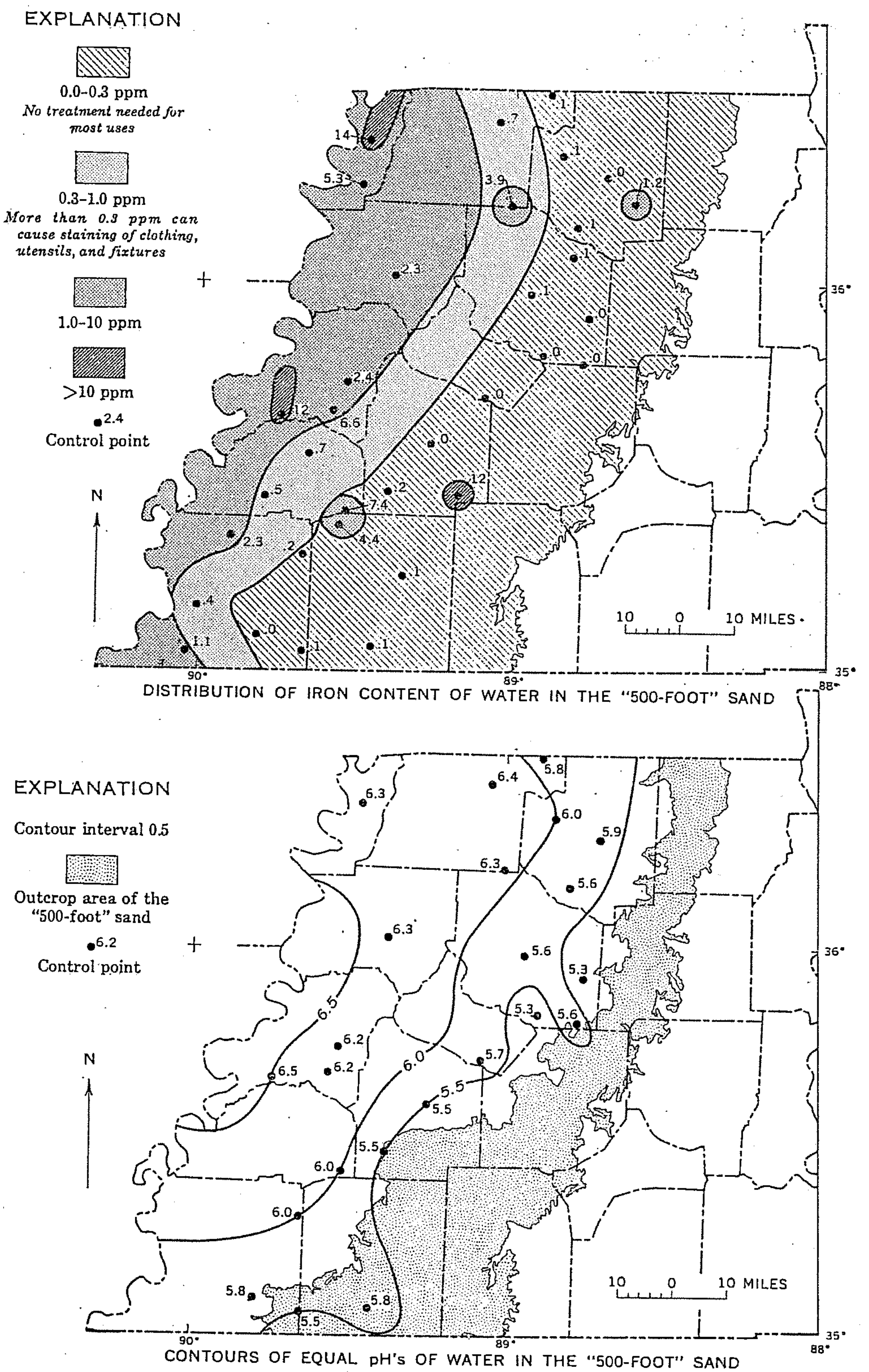
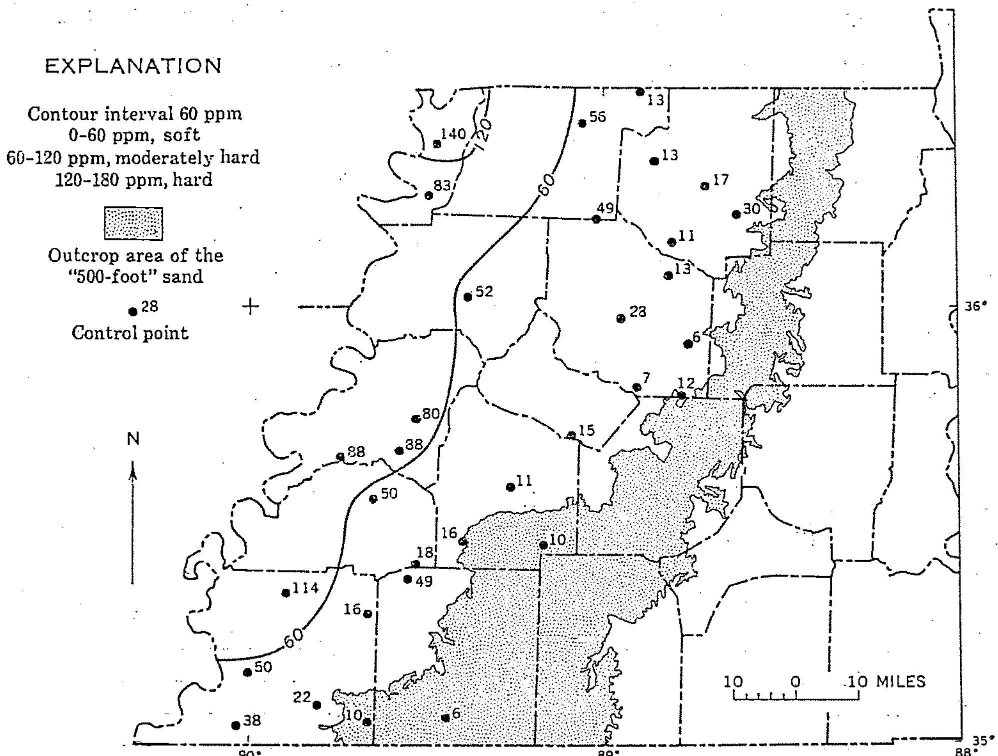
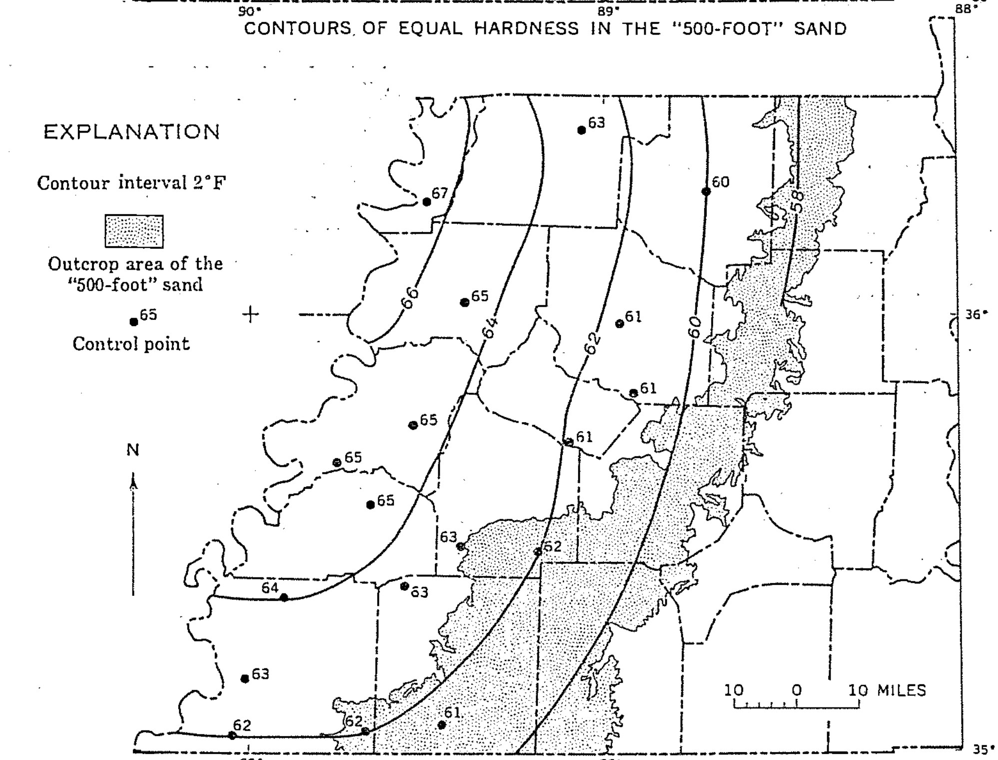


FIGURE 10.—Distribution of iron, hardness, pH, and temperature in water



CONTOURS OF EQUAL HARDNESS IN THE "500-FOOT" SAND



CONTOURS OF EQUAL TEMPERATURES IN THE "500-FOOT" SAND

from the "500-foot" sand. Data collected during the period 1951–61.

The average municipal pumpage from the "500-foot" sand in Shelby County during 1960 was about 61.5 mgd. This total may be broken down by utility district as follows:

Utility district	*Average daily pumpage from the "500-foot" sand (thousands of gallons)*	*Utility district*	*Average daily pumpage from the "500-foot" sand (thousands of gallons)*
Memphis Light, Gas, and Water Division	58,540	Millington	490
Arlington	10	Raleigh	330
Collierville	240	Whitehaven	1,450
Ellendale	[1] 300	Woodstock	[1] 50
Germantown	110	Total	61,520

[1] Estimated.

Outside Shelby County, 29 towns pumped an average of about 9.7 mgd from the "500-foot" sand in 1960. The approximate pumpage at each town is as follows:

Town	*Average daily pumpage from the "500-foot" sand (thousands of gallons)*	*Town*	*Average daily pumpage from the "500-foot" sand (thousands of gallons)*
Bells	75	Maury City	[1] 10
Bradford	80	Medina	100
Brighton	[1] 20	Milan	500
Brownsville	475	Moscow	[1] 15
Cottage Grove	6	Ridgely	175
Covington	400	Ripley	380
Dresden	250	Somerville	180
Dyersburg	1,400	South Fulton	250
Gibson	10	Stanton	60
Gleason	100	Tiptonville	300
Greenfield	150	Trenton	1,000
Henning	15	Union City	1,200
Humboldt	2,000	Whiteville	75
Kenton	100		
Martin	375	Total	9,716
Mason	15		

[1] Estimated.

Towns that use water from the unnamed sand unit pumped an average of about 0.9 mgd in 1960. These towns and the average daily pumpage are listed as follows:

Town	*Average daily pumpage from the unnamed sand (thousands of gallons)*	*Town*	*Average daily pumpage from the unnamed sand (thousands of gallons)*
Alamo	200	Sharon	100
Dyer	220	Troy	60
Gates	[1] 10		
Halls	175	Total	915
Rutherford	150		

[1] Estimated.

The highest monthly pumpage for municipal use generally occurs in July or August; the minimum monthly pumpage is generally in February.

Industrial pumping from the Claiborne aquifers is concentrated in the larger population centers. No complete survey of industrial water use has been made, but pumpage is estimated at an average of 70 mgd.

Withdrawal for domestic and stock use is concentrated in and near the outcrop areas of the Claiborne aquifers. The unnamed sand unit is also used for domestic supplies in the downdip areas, where shallower aquifers are missing or yield water of poor quality.

Irrigation is used on a supplemental basis in western Tennessee. Crops are normally irrigated one time in each growing season. Irrigation wells withdraw water from the Claiborne aquifers in Crockett, Fayette, Gibson, Haywood, Madison, Shelby, and Weakley Counties. The total capacity of all pumps is about 25,000 gpm. About 34 percent of the total capacity can be pumped in Shelby County, and 33 percent can be pumped in Gibson and Weakley Counties (McLemore, 1958, p. 15, 16). The quantity of water withdrawn, however, depends largely on the distribution of areas of deficient rainfall and, therefore, varies considerably from year to year. Average annual withdrawal of ground water for irrigation is about 150 million gallons.

WELL CONSTRUCTION

A well is an engineering device to divert ground water from its natural flow path for use by man. Where relatively small quantities of water are desired, well-design criteria may be of minor importance. It is often the objective, however, to construct a well capable of producing 500–2,000 gpm. In the construction of such high yielding wells, proper methods of well design, construction, and development should be used to insure maximum efficiency.

The two major factors of well construction that determine the yield of a well at a particular site are the amount of penetration of the aquifer by the well and the effective diameter of the well. The amount of penetration of the aquifer is defined as the ratio of the length of a screen in a saturated aquifer to the total thickness of the aquifer, usually expressed as a decimal. If this ratio is one, the penetration is said to be complete; but if the ratio is less than one, the penetration is called partial. The amount of penetration is generally more important than effective diameter in determining well yields. Increasing the penetration of an isotropic artesian aquifer will generally increase the yield of the well. According to Ahrens (1958, fig. 3), an increase in penetration from 0.2 to 0.4 will increase the ultimate yield of a well in an ideal aquifer by as much as 85 percent.

The effective diameter of a well is determined by the amount of development that the well has undergone, the thickness and relative permeability of a gravel pack (if used), the type and amount of perforation in the screen or casing, and the actual diameter of the well. The degree of well development has a considerable influence in determining the effective diameter of a well. Various methods of pumping, surging, and backwashing a newly completed well remove the finer grained materials surrounding the screen and greatly increase the permeability of the aquifer in this zone. Theis, Brown, and Meyer (1954, p. 6) stated that the effect of well development in many instances may be "the same as if a well 10 feet in diameter were placed in an undeveloped aquifer."

The use of a gravel pack—a sand or gravel wall placed between the well screen and the aquifer surrounding the well—can increase the effective diameter of a well by increasing the permeability of the materials outside the well screen in a manner similar to well development. The cost of installing a gravel pack should be balanced, however, against the results that could be obtained by spending the same amount of money on additional well development.

The inside diameter of a well screened in sand or gravel has only a small effect on its productivity relative to other wells in the same locality and in the same aquifer. If a pumping well has a radius of influence of at least 1,000 feet under equilibrium conditions, doubling the diameter of the pumped well would result in a sustained yield increase of less than 10 percent (Ahrens, 1958, p. 28, 30). This relation should be considered in deciding whether or not to construct a well having a diameter substantially larger than required for the installation of the necessary pumping equipment to deliver the desired yield.

WELL INTERFERENCE

In municipal and industrial well fields, interference between closely spaced wells in some places causes excessive drawdown of water levels. In effect, well interference or the decline of water-level in a well caused by pumping nearby wells results in a decrease in the available drawdown and, hence, in the ultimate capacity of the well. Thus, interference is a form of mutual pirating. The problem is chiefly one of economics—namely, whether the cost of pumping water from lower levels is less than the cost of longer pipelines that would be required to transport water from wells spaced farther apart.

A satisfactory method of reducing interference, which has not been extensively used in western Tennessee, is the placing of wells in a given field in groups that include as many wells as there are aquifers and the screening of each well in a different aquifer. In this way, little or no interference would be evident between wells in the same group and, therefore, the length of pipeline that would be needed to collect a given amount of water could be considerably reduced.

The group method would be particularly adaptable in the area underlain by the aquifers in the Claiborne Group; because within these units, clay layers locally separate the water-bearing sands and create virtually separate aquifers. Moreover, the Claiborne is underlain by the Wilcox Group and the Ripley Formation throughout the report area and, in places, is overlain by alluvium and terrace deposits. Each of these units contains one or more aquifers; thus, the number of wells in a given group could be increased.

In the development of wells in the same aquifer, the most favorable arrangement is in a straight line at right angles to the direction of ground-water flow. This arrangement provides the maximum amount of available drawdown in the wells as a group by minimizing interference between wells and, thus, permits the wells to be closer together. As a result, the cost of both pumping and piping the water from a given number of wells is minimized.

AQUIFER POTENTIAL AND FUTURE DEVELOPMENT

The maximum quantity of water that can be pumped from the "500-foot" sand on a sustained basis is limited only by the capacity of the aquifer to store and transmit water. If the hydraulic gradient of the "500-foot" sand were increased to the average dip of the top of aquifer (19 ft per mile), the "500-foot" sand would transmit downdip from the outcrop area about 578 mgd, or the equivalent of 5.8 inches of precipitation per year. Infiltration in the outcrop area could greatly exceed the 5.8 inches that the aquifer would be able to transmit downdip under the assumed gradient of 19 feet per mile, owing to the abundance of rainfall in the outcrop area.

Total pumpage from the "500-foot" sand in Shelby County has not increased at a constant rate through the years. For the period 1958–62, however, the average increase was more than 5 mgd each year (J. H. Criner, U.S. Geol. Survey, oral commun., 1963). If the average increase in pumpage were more than 5 mgd each year from 1960 to 1980, total pumpage at the end of this period would exceed 230 mgd.

Increased future pumping at Memphis will have significant effects upon the system of aquifers in the Claiborne Group. The area of influence of pumping (pl. 5) will increase with the rate of pumping, and recharge will increase in turn; but the absolute expansion of these factors cannot be determined at present. For example, the expansion of the area of influence would not be a straight-line function of the increase in pumping because additional recharge from surface streams, precipitation, and adjacent geologic formations would result from increased hydraulic gradients. The problem of estimating the future effects of increased pumping in the Memphis area can be simplified, however, by assuming that the percentage of water entering Shelby County as underflow through the "500-foot" sand from all directions will be proportional to that of 1960. As mentioned previously, total pumpage in the Memphis area was 135 mgd in 1960. Fifty-nine percent of the total water pumped entered Shelby County as underflow from the north and west. This amount of water was probably replaced in the "500-foot" sand by infiltration of 2.2 inches of the precipitation that fell on the southern 35 percent of the outcrop belt of the "500-foot" sand in Tennessee. If the percentage of the outcrop belt of the "500-foot" sand that is within the area of influence expands as the area influenced by Memphis pumping expands, table 5 shows approximately the rates of annual infiltration and the resulting average hydraulic gradients as pumpage in Memphis increases to 200 mgd and 300 mgd.

TABLE 5.—*Predicted possible pumping conditions in the Memphis area when pumpage reaches 200 mgd and 300 mgd*

[Transmissibility across the north and west boundaries of Shelby County is 350,000 gpd per ft]

Case	Percent of outcrop area of "500-foot" sand within area of influence of pumping	Rate of annual infiltration required (inches)	Average hydraulic gradient across north and west boundaries of Shelby County (ft per mile)
	200 mgd		
A	40	5.0	
B	50	4.0	
C	60	3.3	11
D	70	2.9	
E	80	2.5	
	300 mgd		
A	40	7.5	
B	50	6.0	
C	60	5.0	17
D	70	4.3	
E	80	3.7	

The effects of future increases in pumping at Memphis will be (1) a reduction and possible seasonal loss of base flow in streams within the area-of-influence of pumping, (2) a drop in water levels that will be directly proportional to the increase in pumpage and inversely proportional to the distance from the center of pumping and, therefore, a reduction in the amount of water in storage, (3) a capture of some of the water being discharged from the State as underflow and an increase in the inflow of water from adjacent States, (4) an increase in leakage from other aquifers through the confining beds, and (5) a change from artesian to water-table conditions in the eastern part of the county.

Outside Shelby County, municipal pumpage from the "500-foot" sand was probably about 4.8 mgd in 1929 (Wells, 1933), 8.1 mgd in 1951 (Lanphere, 1955), and 9.7 mgd in 1960. On the basis of these three values, municipal pumpage will probably reach 13 mgd by the year 1980 and 16 mgd by the year 2000. If other pumpage increased proportionally, the total pumpage by the year 1980 would be 28 mgd, and by the year 2000, 35 mgd.

Pumpage from the "500-foot" sand outside Shelby County was very small (9.7 mgd) in 1960 compared with the amount of water potentially available. The "500-foot" sand has the capacity to transmit at least 372 mgd from the outcrop area to centers of pumping outside Shelby County. Additional amounts of water might also be induced into the area north of Shelby County as underflow from Kentucky, Arkansas, and Missouri.

If the hydraulic gradient of the unnamed sand unit were increased to the average dip of the top of that unit (about 10 ft per mile), about 34 mgd, or the equivalent of 1.4 inches of precipitation per year, would be transmitted downdip from the outcrop area and would be available for use. This amount is about 17 times the present pumpage.

Municipal pumpage from the unnamed sand unit was about 0.25 mgd in 1929 (Wells, 1933), 0.64 mgd in 1951 (Lanphere, 1955), and 0.92 mgd in 1960. Hence, the average annual increase in municipal pumpage from 1929–60 is assumed to have been about 21,000 gpd. At this rate of increase, municipal pumpage would be about 1.1 mgd by the year 1980 and 1.5 mgd by the year 2000. If other pumpage increased proportionally, total pumpage by the year 1980 would be 2.3 mgd, and by the year 2000 it would be 3.3 mgd. The latter figure of 3.3 mgd is far below the 34 mgd that is probably available from the unnamed sand unit.

Thus, ground-water supplies in both the "500-foot" sand and the unnamed sand unit will be adequate for the predicted rate of municipal growth and economic development for many years to come. Future development should be undertaken with the full knowledge that the net increase in pumpage will be offset by an increase in the inflow of ground water from other States, a decrease in the base flow of streams crossing the outcrop areas of the Claiborne aquifers, or both.

SUMMARY AND CONCLUSIONS

There are two major aquifers in the Claiborne Group: the "500-foot" sand and an unnamed sand unit. The "500-foot" sand is present beneath about 7,200 square miles in western Tennessee and has an average thickness of about 450 feet in the subsurface. The unnamed sand unit underlies about 6,500 square miles and has an average thickness of about 100 feet.

Water in both aquifers of the Claiborne Group is under artesian pressure except in some parts of the outcrop area. Wells developed in the aquifers flow where the piezometric surface is higher in altitude than the land surface. Flowing wells may be developed in the Claiborne aquifers on the flood plains of most major rivers that drain the region underlain by the Claiborne deposits and in part of the Mississippi Alluvial Plain. Elsewhere the water level ranges from just below land surface to as much as 150 feet below land surface.

Wells in the Claiborne aquifers yield moderate to large amounts of water of good chemical quality. The coefficients of transmissibility in the "500-foot" sand, determined from 26 aquifer tests, ranged from 20,000 to 400,000 gpd per ft, and the coefficients of storage ranged from 0.0001 to 0.003. The theoretical specific capacities of most wells in the "500-foot" sand range from 22 gpm per ft of drawdown for a transmissibility of 50,000 gpd per ft and a 6-inch-diameter well to 141 gpm per ft of drawdown for a transmissibility of 300,000 gpd per ft and a 24-inch-diameter well. The coefficients of transmissibility in the unnamed sand unit, determined from three aquifer tests, ranged from 19,000 to 45,000 gpd per ft, and the coefficients of storage were 0.0003 and 0.0007. The theoretical specific capacities of most wells in this aquifer range from 8 gpm per ft of drawdown for a 4-inch well and a transmissibility of 20,000 gpd per ft to 19 gpm per ft of drawdown for a 12-inch well and a transmissibility of 40,000 gpd per ft.

The chemical quality of water in the Claiborne aquifers is well within the limits of Public Health Service standards in all constituents except iron. Iron content in the report area ranges from 0.0 to 16 ppm, whereas the recommended limit is 0.3 ppm. Aeration and filtration are necessary to remove iron from the water that is used for many municipal supplies.

Although new wells are continually being developed in western Tennessee, the ground-water supply from the aquifers in the Claiborne Group will be adequate to supply the needs of the water users within the report area for many years to come. In 1962 the total withdrawal from the Claiborne aquifers was about 157 mgd, whereas these aquifers are probably potentially capable of delivering at least

00 mgd. The anticipated effects of additional large scale develop-
nent from the Claiborne aquifers are (1) a drop in local and re-
;ional water levels in proportion to the increase in pumping, (2) an
ncrease in the net inflow of ground water from adjacent States, and
3) an increase of recharge to the Claiborne aquifers in the areas of
utcrop at the expense of surface runoff.

REFERENCES

hrens, T. P., 1958, Water well engineering, part 3: Water Well Jour., v. 12, no. 12, p. 18, 19, 28, 30–32.

rmstrong, C. A., 1955, Memorandum on the post-Paleocene subsurface stratigraphy of the Memphis area, Tennessee: U.S. Geol. Survey open-file report.

erry, E. W., 1916, The lower Eocene floras of southeastern North America: U.S. Geol. Survey Prof. Paper 92.

rown, G. F., 1947, Geology and artesian water of the alluvial plain in northwestern Mississippi: Mississippi Geol. Survey Bull. 65.

rown, R. H., 1953, Selected procedures for analyzing aquifer test data: Jour. Am. Water Works Assoc., v. 45, no. 8, p. 844–866.

riner, J. H., and Armstrong, C. A., 1958, Ground-water supply of the Memphis area: U.S. Geol. Survey Circ. 408.

riner, J. H., Sun, P-C. P., and Nyman, D. J., 1963, Hydrology of the aquifer systems in the Memphis area, Tennessee: U.S. Geol. Survey open-file report.

onrad, T. A., 1856, Observations on the Eocene deposits of Jackson, Mississippi, with descriptions of thirty-four new species of shells and corals: Acad. Nat. Sci. Philadelphia Jour., v. 7, p. 257–258.

ushing, E. M., Boswell, E. H., and Hosman, R. L., 1964, General geology of the Mississippi embayment: U.S. Geol. Survey Prof. Paper 448–B.

enneman, N. M., 1938, Physiography of eastern United States: New York and London, McGraw-Hill Book Co.

uller, M. L., 1912, The New Madrid earthquake: U.S. Geol. Survey Bull. 494.

lenn, L. C., 1906, Underground waters of Tennessee and Kentucky west of the Tennessee River: U.S. Geol. Survey Water-Supply Paper 164.

ershfield, D. M., 1961, Rainfall frequency atlas of the United States: U.S. Weather Bur. Tech. Paper 40.

osman, R. L., 1962, Correlation of the Carrizo Sand in Arkansas and adjacent States: Geol. Soc. America Bull., v. 73, no. 3, p. 389–394.

laer, F. H., 1940, Water levels and artesian pressure in wells in Memphis: U.S. Geol. Water-Supply Paper 907, p. 92–101.

anphere, C. R., 1955, Geologic source and chemical quality of public groundwater supplies in western Tennessee: Tennessee Div. Geology Rept. Inv. 1.

AcLemore, C. K., 1958, Irrigation in Tennessee: Tennessee Dept. Conserv. and Commerce, Water Resources Div.

Aoore, G. K., 1962, Downdip changes in chemical quality of water in the "500-foot" sand of western Tennessee: U.S. Geol. Survey Prof. Paper 450–C, p. 133–134.

afford, J. M., 1869, Geology of Tennessee: Nashville, State of Tennessee.

chreurs, R. L., and Marcher, M. V., 1959, Geology and ground-water resources of the Dyersburg quadrangle, Tennessee: Tennessee Div. of Geology Rept. Inv. 7.

tearns, R. G., 1957, Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi embayment: Geol. Soc. America Bull., v. 68, no. 9, p. 1077–1100.

Stearns, R. G., and Armstrong, C. A., 1955, Post-Paleozoic stratigraphy of western Tennessee and adjacent portions of the upper Mississippi embayment: Tennessee Div. Geology Rept. Inv. 2.

Theis, C. V., Brown, R. H., and Meyer, R. R., 1954, Estimating transmissibility from specific capacity: U.S. Geol. Survey Ground Water Note 24.

U.S. Public Health Service, 1962, Drinking water standards: Federal Register, Mar. 6, p. 2152–2155.

Wells, F. G., 1933, Ground-water resources of western Tennessee, *with a discussion of the* Chemical Character of the water, by F. G. Wells and M. D. Foster: U.S. Geol. Survey Water-Supply Paper 656.

Walton, W. C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Rept. Inv. 25.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods: U.S. Geol. Survey Water-Supply Paper 887.

○

EXHIBIT 4

Deposition of Richard Spruill
September 28, 2017
(Excerpts)

In the Matter Of:

STATE OF MISSISSIPPI Vs.

CITY OF MEMPHIS

RICHARD SPRUILL

September 28, 2017

ALPHA REPORTING CORPORATION

1st in Reporting, 1st in Service, 1st in Technology

We Bridge the State and Cover the Nation!

www.alphareporting.com

800-556-8974

126

Q. In the context of a transboundary aquifer like the Middle Claiborne, how do you define good groundwater management practices?

A. That question is the foundation of my philosophy about development of good groundwater management practices. Good groundwater management practices are based on understanding the groundwater system in sufficient detail to actually offer management strategies.

Those management strategies should be based on, in my opinion, developing the groundwater resources where they are most sustainable and have the least impact on the environment and moving the water to where it is needed. That is the fundamental principal to operate on in my company called Groundwater Management Associates.

I believe we should develop our groundwater resources where they are most sustainable, have the least impact on the groundwater system and people in the region, even if it means moving the water from where it is most sustainable to where it is actually needed.

127

Q. What would you change about MLG&W pumping practices to make them consistent with your definition of good groundwater management practices?

A. Are you asking what would I do now or what would I have done when the well field was being envisioned?

Q. What would you do now?

A. I would think about trying to minimize the cone of depression. The cone of depression is the problem. A cone of depression is a lowering of a pressure surface.

The aquifer, even though beneath and around these wells, remains completely saturated with water even during pumping. The water that is derived at these wells is derived from an instantaneous release of water within the aquifer as the head is lowered by pumping in the well.

The volume of water that is released from the pore spaces in this aquifer is associated with the expansion of water molecules and the slight compression of the aquifer, and we're talking those extra. Those are the water

128

molecules we're drinking and consuming. The aquifer pore spaces remain completely saturated with water.

The only way I can get water out of a confined aquifer is to reduce the pressure in the aquifer. If you want to minimize the impact of that withdrawal, you have to start looking at how to control the nature and extent of the cone of depression. The lateral extent of the cone of depression is independent of the number of gallons per minute you pump out of a well. It is a function of transmissivity, storage coefficient and time. We call it the theoretical limit of the cone of depression. That is pretty simple to calculate if you know the transmissivity of the aquifer, the storage coefficient of the aquifer and time.

I mention that because a pumping rate of 10 million, 50 million, 100 million gallons a day effects the cone of the depression but not the lateral extent.

You asked the question what would I do. What can you do to minimize the cone of depression? You said with respect to what we

129

have now. You could reduce the pumping time because the extent of the cone of depression, remember, is a function of time. Transmissivity you can't change. Storage coefficient you can't change. It is a property of the aquifer. You can change pumping time.

If you reduce pumping time, the cone of depression shrinks in its lateral extent. You can reduce pumping rates. I'm listing the things that you can do to minimize the impact. You can reduce pumping times. The wells that I design and the well fields that I design are based on producing the amount of water you need for an average-day demand by pumping the wells for no more than twelve hours each. My design philosophy is design enough wells to produce your average-day demand by pumping for no more than twelve hours per day per well.

That means you can shut that well off, and the cone of depression lessens, and operate another well. That also decreases the depth. It will decrease the depth if you decrease the pumping rate from individual wells.

I wasn't systematic. That drives me

crazy. You can reduce pumping time and rate. You can do both. You can physically move the well field to a location where it will have less impact on the groundwater system and transport the water to where it is needed. And based on some interesting and new technology that exists all around the world, but I find no examples of it yet in Tennessee, you can find a source of water and inject that water at a proper location within the cone of depression and actually increase the pressure of the aquifer. That process is called aquifer storage and recovery. The acronym is ASR.

To me it is a very do-able and reasonable solution in some of these interstate cases. I've listed all the things you can do in a modern well field to minimize impacts.

Q. Thank you for that.

A. Maybe there is some more. There is another. It goes above that final one. That is increase well-spacing. We can't do that with existing wells. That's why I didn't mention it.

There are a whole list of things that you can do if you knew all this stuff when you

started developing the well field. Well-spacing would be a critical issue at that time.

Q. I take it that all of these, I counted six things that you identified, that could be done, all of them cost money to some extent?

A. Yes.

MR. ELLINGBURG: Would you tell me what they are? I've only got five in my list. I've been trying to keep up.

MR. BRANSON: Increased well spacing was the last one.

MR. ELLINGBURG: Reduce pumping time and rates, well-spacing, physically move wells.

THE WITNESS: Create barriers by injection of water at critical locations.

Q. (BY MR. BRANSON) ASR?

A. ASR.

Q. All of those cost money to some extent?

A. Yes.

Q. Have you studied how much they would cost to implement in Tennessee in the Middle Claiborne?

A. I've done some calculations. I know a lot about ASR I've defined, quite a few of them,

one of which happens to be on Hilton Head Island, are strategically located to deal with the issue of migration of salt water. I have a good handle on how much it would cost to inject water.

The interesting thing with ASR is that most people who say let's build an ASR well will go forward with everything, and in the final analysis they will say where do we get the water to inject underground?

An ASR well doesn't come with its own water supply. You will have to have a supply of water. The ASR technology is not cost-prohibitive. It is hundreds of thousands of dollars for a properly-designed ASR well, but you have to find a source of water.

Q. Have you studied whether any of these six techniques that you identified, really five, because one of they was both, would be feasible to implement in Tennessee?

A. I've given a lot of thought to it, yeah. I've looked at the nature and extent of the Sparta Sand Aquifer, and I know that from my analysis of hydraulic properties that I've seen

in the literature, there is great potential to produce water to meet the demand of this region by moving some of the wells to a different location and minimizing the impact.

Q. You are talking about moving the wells further north in Shelby County away from the state border?

A. Yeah, mostly.

Q. You've not studied the economic cost to Tennessee for doing that?

A. I've not. I've got some understanding of what an individual well costs and what pipeline transmission costs are because I deal with that all the time in my own business. I'm not saying that it is a cheap fix. It can be done.

Q. Do you have an opinion about whether pumping in DeSoto County, Mississippi, is consistent with good groundwater management practices as you've described them?

A. Based on what I've been able to learn about some of those wells in DeSoto County, they were permitted by the state using at least some of the criteria that I mentioned earlier that

134

are in the DEQ regulatory framework that says, okay, I want a new well in DeSoto County, I want to pump a million gallons of water per day, and I believe that in the process of permitting those wells there was attention paid to those design criteria offered by the state.

Those design criteria are based on knowledge of the hydraulic properties of the aquifer, mostly transmissivity. That table really deals with transmissivity. You can use the transmissivity of the aquifer to think about and design wells at a certain spacing based on the interference patterns. You can't do that without understanding at least the transmissivity of the aquifer.

Q. You've referenced that table you referred to earlier. Could I put in a request to have that produced?

MR. ELLINGBURG: I think you can get it on-line. I'll get the table.

MR. BRANSON: Okay.

MR. ELLINGBURG: I'll get the Mississippi groundwater regulations.

MR. BRANSON: I want to know the

135

specific regulations that Dr. Spruill is citing.

Q. (BY MR. BRANSON) Have you studied whether the pumping from the Southaven well in DeSoto County is consistent with good groundwater management practices in your view?

A. I've not been able to determine how many hours a day that well is pumping. When I say good groundwater management practices, I don't know how far it is from other wells and how much interference there is between each of those wells.

If that well-spacing was approved by the state based on that regulatory framework, it moves in the direction of good management practices in my mind. If it was simply placed at the location where the water was needed, then to me that's not good management practice.

My philosophy is develop the water resources where they are most sustainable and have the least impact and move the water to where it is needed.

Q. Are you saying -- under your definition of good groundwater management practices is it ever permissible for a state to have a well near

136

the border where the cone of depression extends into another state? Is that something that disqualifies a well from being consistent with good groundwater management practices in your view?

A. I think it is incredibly problematic. States ought to consider the impacts of that cone of depression moving across the state. The way to deal with that issue is what I have already described, to limit the pumping time.

I'm simply saying this: If you know how fast the cone of depression expands outward, if you are close to the border, don't let it extend beyond the state or to it extend along the state for a short time period and it recovers from twelve hours of pumping and twelve hours of rest. Then the impact is minimized.

I think that states should implement really serious mitigation strategies that are required for wells that have impacts on other wells, on other users.

A good example would be in case here in Memphis with TVA. It was well-known if you pump a bunch of more water out of the ground, it

137

could have an impact with respect to increasing groundwater contamination moving downward into the aquifer through Paleo channels, called by Dr. Waldron "holes." If you are going to produce that, there should be mitigation strategies. How can you stop that groundwater contamination if you allow those wells to be permitted?

Q. The last bullet here on Page 3 of Exhibit 1 says "the best management strategy for sustainability of groundwater resources involves withdrawing groundwater at a rate that is equal to or less than the recharge rate of the aquifer being developed." Do you see that?

A. Yes.

Q. Do you have an opinion that MLG&W's pumping is happening at a rate that is greater than the recharge rate in the Middle Claiborne?

A. Did you use the word "penultimate"? This is my penultimate opinion about how to manage groundwater resources.

MR. ELLINGBURG: He said "penultimate" was next to the last. He has a very specific definition which is probably in the dictionary.

Q. (BY MR. BRANSON) The very last bullet on Page 3.
A. That's my penultimate example of how to develop and maintain a sustainable groundwater resource. That is to make sure that you know what the recharge rate is. I wrote this statement because after studying extensively groundwater models, various reports, so forth, that the recharge rate for the Memphis aquifer in both Tennessee and Mississippi is unknown. If the recharge rate is unknown, how can you guarantee that you are withdrawing water that is equal to or less than that rate? The rate is unknown.
I published a paper with my mentor, Ralph Heath, from the U.S. Geological Survey, that addressed the issue of recharge rate. We concluded in this publication that the recharge rate for a really-important aquifer in the coastal plain of North Carolina was only about two to six million gallons of water per day per county. The recharge rate we think is known. We took that recharge rate calculation. I think we probably settled on six million gallons of

water a day per county. We said that if you are taking 15 million gallons, 24, you are out of balancing. You should start systematic reduction of water to get you to that recharge rate.
In some areas we determined it to be as low as a couple million gallons a day. We said that to water purveyors, that you are pumping eight million gallons of water a day. The recharge rate is two. You are out of balance. This is what we're going to do. We're going to let you pump at eight million gallons a day for six years. On the first day of the seventh year you have got to reduce it by 25 percent, and get to do that five more years.
You can't have a best-management practice unless you know that recharge rate. This statement was aimed at what we all know in this area, that we don't know the recharge rate. The recharge rate is not just the rate of recharge over there on those hills. I'm pointing to the east. It is the recharge rate of water coming into the aquifer all along its path from Paleo channels or whatever else might

recharge that aquifer system.
I didn't make the statement here that MLG&W is withdrawing groundwater at a rate different from the recharge rate. I'm simply saying somebody better determine that rate.
Q. Understood. You also, then, don't know whether pumping in DeSoto County is extracting groundwater at a rate greater than the recharge rate because the recharge rate isn't known?
A. Right. I would think they are closer to pumping at the recharge rate than they are in Shelby County because they are pumping a whole lot less.
Q. You don't know one way or the other?
A. I don't know what the recharge rate is there, either.
Q. Let's go to Page 36.
A. Same document?
Q. Yes. I want to focus on Figure 17. This depicts your reproduction of a potentiometric map that was generated by Leggette, Brashears & Graham, right?
A. Yes.
Q. Did you take any independent steps to

verify the accuracy -- you'll understand it if I refer to it as LBG?
A. Yes.
Q. Did you take any steps to understand the accuracy of this map or rely on LBG for that?
A. I've read the various Brahana studies extensively. What I think occurred here from my discussions with Dave Wiley is that he imported the Brahana model, which means he took the Brahana model from some source and put it on his company computer, and he utilized that computer to produce this model output.
Q. I take it you didn't rerun the model to generate this model output?
A. No, absolutely not.
Q. Did you in the purpose -- in the process of preparing your opinions in this case did you run any model yourself?
A. No.
Q. Did you go back and compare the Figure 17 generated by LBG to the results published by Brahana?
A. I don't believe I looked specifically

at this map and compared it to a similar map in the Brahana model, nor do I know whether or not LBG improved the Brahana model with any data input. I don't know. When I say "data input," at specific locations or cells, I don't know if they added additional transmissivity, storage coefficients or leakance values into the model.

Q. I'd like to point you to the yellow triangle. What is shown on this map is that groundwater that originates within the yellow triangle area of the Middle Claiborne according to this map would have flowed across the state boundary under natural conditions? When I say "state boundary," I mean the Mississippi-Tennessee boundary.

A. Yes. There is only one vertical line on that triangle. That's the eastern line with the yellow end on the east with arrows pointing to that.

Q. I see that.

A. This is the boundary between unconfined conditions to the right and confined conditions to the left. The edge of that triangle, the vertical line, is the boundary between

unconfined groundwater conditions to the east and confined groundwater conditions to the west.

Q. Okay.

A. If you were to put a pencil point anywhere on that vertical line marking the eastern boundary and draw a flow line, there would be flow according to this model over a really, really long period of time from that location to the Mississippi-Tennessee border.

To make it clear, some of those flow lines can be really short and some could be as long as twelve miles. Back to my point. Yes, water would ultimately make it from that vertical line over to Mississippi after periods of --

Q. Over to Tennessee?

A. -- over to Tennessee after periods of six to eight hundred years or more. In three hundred years it might travel a little more than a mile.

Q. Your sentence on the bottom of Page 35 spilling over to Page 36 says "The groundwater flow lines indicate that almost all groundwater in Northern Mississippi originated in

Mississippi flowed within the aquifer in Mississippi and discharged upward to overlying aquifers and ultimately to the Mississippi River within the State of Mississippi." Do you see that?

A. Yes.

Q. You say "almost all" in that sentence. Is that because you are excluding the water that originated in the yellow triangle?

A. Yes. That's the only water according to this model run that flows under the prevailing hydraulic gradient, which you can clearly see on this diagram, towards Tennessee over long periods of time ultimately moving into Tennessee.

Q. If you look at many of these flow lines on this Figure 17, they extend into Arkansas, correct?

A. Yeah. I don't know who drew these flow lines. I don't think I drew them. What was your question?

Q. The flow lines as shown and drawn on this Figure 17, many of them extend into Arkansas, correct?

A. Yeah. Yes.

Q. That is indicating that over a long-enough time horizon groundwater flowing along those flow lines would eventually make its way into Arkansas, correct?

A. No. Maybe some of it. Flow lines are really interesting. They are constructs. They are something drawn by human beings based really simply on a two-dimensional concept. When you look at this flow line, the one south of the Tennessee-Mississippi border that goes from east to west, the brain says to you that's a flow line with flow like this, horizontal flow pointing in the direction of east to west. What you can't see in this flow line is the vertical dimension of flow. I'm going to use my right arm to show a flow line directly toward you.

Q. For the record, he is pointing directly at me.

A. From above you would see this flow line pointing directly at you. From above this flow line it would look the same, but it has a vertical flow component. From above this flow line would the same orientation.

aquifer to store in the aquifer has to be proven to not create an adverse reaction when it comes in contact with the existing water underground, and it can't cause an adverse reaction with the minerals that make up the aquifer of choice. We call that water-water and water-rock interactions.

In order to that usually the first ASR well will involve coring and collection of samples. At this location coring and collection of an is samples because the aquifer is often as much as 500 feet down more or less. It is very costly to get that done. Then the ASR wells are a quarter million dollars each.

Q. I'm going to try to be very specific.

A. Okay.

Q. Do you plan on providing or testifying as to any opinion regarding the cost involved in ASR?

A. No one has asked me to do that.

MR. ELLINGBURG: Let me interject this: Certainly for this phase of the hearing. What might be done later --

MR. DAVID BEARMAN: We've all agreed to

that.

MR. ELLINGBURG: I wanted to make sure.

Q. (BY MR. DAVID BEARMAN) Do you plan on giving any testimony about the cost of any of the factors that you talked about relating to groundwater management?

A. For wells in the state of Tennessee?

Q. Yes.

A. I've not been asked to do that.

Q. What about for the wells in Mississippi?

A. I've not been asked to go that, but I've been asked to evaluate the cost of impacts of the cone of depression in Mississippi.

Q. Have you estimated the cost associated with the impact of the cone of depression?

A. Not completely. I have attempted to calculate the amount of lost water from storage associated with the cone of depression, and my first attempt was a very generalized one because, as you just pointed out with your concentric circles, there is isn't a single value for drawdown as you move away from the cone. Calculating the amount of head loss will

require a lot more work.

Q. You are not planning -- there is certainly nothing in your report about that?

A. Correct.

Q. You are not planning at this point to give any opinions on cost associated with the cone of depression?

MR. ELLINGBURG: No, no, if he performs a calculation, we will provide to you. He discussed how he would do it, and we've talked about, but it wasn't completed in time for the reports. It is not so much cost as it was volume of water.

MR. DAVID BEARMAN: Obviously for myself, and he can speak for Tennessee, we will leave the deposition open to the extent there is any supplementation and reserve our right to object to anything that is brought after the deposition.

MR. ELLINGBURG: Certainly.

MR. BRANSON: Tennessee has the same position on that.

Q. (BY MR. DAVID BEARMAN) On Page 31 of your initial report, that's Exhibit 1 -- are you

with me?

A. Yes, sir, Page 31.

Q. The end of that first paragraph, "Calculations of the impacts of one pumping well at approximately 1,500 gallons per minute on the water levels should be considered in light of the large scale impacts resulting from 185 wells pumping 180 million gallons per day along the Mississippi-Tennessee border." Do you see that?

A. Yes, I do.

Q. Where are the 175 wells that you are talking about?

A. It was an estimate of the number of wells north of the Tennessee-Mississippi border.

Q. This says "along" the Mississippi-Tennessee border.

A. Well, yeah.

Q. So that's not accurate?

A. It is in my mind because these wells are pretty close to the border.

Q. How close?

A. A few miles some of them.

Q. It says "175 wells," Dr. Spruill. There is not 175 wells in that area, is there?

238

A. Okay. There is not 175 wells right along the border, but there are 175 wells pumping. My statement here deals with the very issues that you raised on the previous page, and I simply took the information from this Layne GeoSciences report and I pointed out exactly what you went through in great detail about how big the cone of depression is from one well.

My statement simply is if you have 175 wells in the area of southwestern Tennessee, maybe not right long the Mississippi-Tennessee border, somebody ought to figure out the impacts of a large number of wells knowing that one well pumping at 1,500 GPM can have a significant impact.

Q. Do you know how many wells there are in Mississippi within one mile of the Tennessee-Mississippi border?

A. I don't think there are many. I don't know the exact number.

Q. Where did you get the 180 million gallons per day?

A. It was on a graph that I described to you earlier that somebody said they would like

239

to see, the graph of MLG&W pumping.

Q. Did you get that from David Wiley?

A. I don't know if I got that figure from him or not. I just don't know.

Q. 175 wells, where did that number come from?

A. I'm sure that I saw it in a report in the literature somewhere.

Q. Is that what you believe to be the number of wells in Shelby County total?

A. I don't know. I think it is probably pretty close.

MR. DAVID BEARMAN: Mike, I don't quite remember, but in case Mr. Branson did not request them, I'm asking that you produce the particle tracks or particle-tracings from David Wiley that showed vertical movement that Dr. Spruill considered.

MR. ELLINGBURG: Sure.

Q. (BY MR. DAVID BEARMAN) Dr. Spruill, in your conversations with Mr. Branson you mentioned a 2013 model. Does that refer to the 2013 version of the MERAS model?

A. Yes. With respect to that question, I

240

remember very distinctly seeing a figure in Mr. Langseth's deposition -- I mean in his reports that was a figure that I believe came from a Mississippi Embayment regional aquifer study, but I'm not sure which one it came from. It is the one that shows the equipotential surface in the outcrop areas that was the basis for Mr. Langseth's particle-tracking. My gut feeling is it came from another version of this model.

This particular model, the USGS MERAS model, is one in a whole series of variations of the original model. For example, the MERAS groundwater flow model Clark and others of 2001 hereafter is referred to as Model Version 1.1, which was modified from Model Version 1.0 Clark and Hart 2009. So there is a series of these MERAS models, and one of them has a figure that Mr. Langseth used.

Q. Are you planning on offering any opinions about Dr. Langseth's report or his rebuttal report at trial?

A. If I'm asked.

Q. Have you been asked?

241

A. I've been asked to review Mr. Langseth's report. I haven't provided a written response.

Q. Have you been asked to offer any opinions with respect to Dr. Langseth's report or his rebuttal report or the opinions within those reports?

A. I have some opinions about his report, yes.

Q. My question is, are you planning to testify about any of those opinions?

A. If I'm asked to express an opinion about what I know and believe regarding Mr. Langseth's report, I certainly plan to do that.

Q. What I need to know is every opinion that you have about Mr. Langseth's report.

A. Wow. Could I see Mr. Langseth's report?

Q. There is nothing in your June report or your July, 2017, addendum that addresses Dr. Langseth's opinions, right?

A. That's correct. I think that's a timing issue with respect to when his report was

EXHIBIT 5

Deposition of Brian Waldron
September 27, 2017
(Excerpts)

In the Matter Of:

STATE OF MISSISSIPPI vs

CITY OF MEMPHIS

BRIAN WALDRON

September 27, 2017

Q. Okay. How do you get a hydraulic head if you don't have any pressure?
A. You have a hydrostatic pressure of the water, but you don't have an overburdened pressure as you would in a confined system.
Q. Okay. In the confined aquifers above and below the Middle Claiborne -- strike that.
How do you get leakage from above into the Middle Claiborne Aquifer, how does that take place?
A. In Shelby County?
Q. Uh-huh.
A. What happens is that you have a higher head in the saturated aquifer above that is higher than the potential head in the confined aquifer below, and the gradient is downward.
Q. Okay. Does that situation exist in Shelby County, Tennessee?
A. Yes.
Q. What brought about the circumstances under which water would migrate from the upper aquifer downward into the Middle Claiborne?
A. The withdrawal of groundwater within the Middle Claiborne resulted in the potentiometric head dropping below that of the water table in the

unconfined section.
Q. Pumping, right?
A. Pumping, withdraw, yes.
Q. I mean, all the water coming out of the Middle Claiborne at the current time is being pumped, isn't it?
MR. DAVID BEARMAN: Object to form.
MR. BRANSON: Object to form.
A. Depends on your location.
BY MR. ELLINGBURG:
Q. Is there still a location where the water coming out of the Middle Claiborne Aquifer in Shelby County is free flowing?
MR. BRANSON: Object to form.
Q. The confined portion of the -- let me slow down. See, this is why I shouldn't talk fast or even loud.
Is there any area in Shelby County, Tennessee in which water, groundwater originating in the Middle Claiborne Aquifer is free flowing to and across the surface at this time?
A. No.
Q. Okay. And so the water that is --
A. In the outcrop region near Collierville, the confining unit along the eastern border of

Shelby County subcrops, and at that point the Middle Claiborne can provide water to the surface water systems at its base.
Q. Is that at the transition from the unconfined to the confined formation?
A. It is past the transition.
Q. Okay.
A. At the unconfined.
Q. And so about how far?
A. It's -- physically it's at the -- it's at that point back.
Q. It's at that edge?
A. It can be at that edge and back.
Q. Okay.
A. Where exactly that is, I do not know.
Q. Right. But the water that is actually being produced is all being pumped, right?
MR. BRANSON: Object to form.
MR. DAVID BEARMAN: Object to the form.
BY MR. ELLINGBURG:
Q. The water that is being produced out of the confined portion of the Middle Claiborne Aquifer is all being pumped, is it not?
MR. DAVID BEARMAN: Object to the

form.
A. Produced for what purpose?
Q. For industrial or human consumption in Shelby County?
A. Yes.
Q. Thank you.
A. Yes, sir.
Q. Do you know the extent to which leakage is occurring in Shelby County from the upper aquifer down into the Middle Claiborne confined aquifer?
A. There is an estimation of mixing.
Q. An estimation -- you said there is an estimation of mixing?
A. Of mixing.
Q. And what is that estimation?
A. I do not know off the top of my head.
Q. Can you give me an order of magnitude?
A. From what reference point?
Q. Okay. When you say "an estimation of mixing," who has made the estimation of mixing?
A. Dan Larsen.
Q. Dan Larsen?
A. Uh-huh.
Q. And when was that done?
A. It's over a number of years. There's a

recent publication, but I don't recall the actual values.
Q. Okay. What is the recent publication?
A. Journal of Contemporary Water Research and Education published 2016.
Q. Can you show me where you're looking at that?
A. (Witness complies.)
Q. Thank you. Okay. It's the second entry under your publications list?
A. Yes, sir.
Q. Thank you. That article is titled Application of Environment Tracers in the Memphis Aquifer and Implication for Sustainability of Groundwater Resources in Memphis Metropolitan Area. And you were one of the co-authors of that?
A. Yes, sir.
Q. And so what are the implications for sustainability in the Memphis metropolitan area in summary?
A. There is a contribution of water from the unconfined portion -- the unconfined aquifer downward into the confined Middle Claiborne that provides an added quantity or source of water to production from the Middle Claiborne.

Q. And approximately where is that taking place?
A. That leakage is occurring primarily through the breaches in the Upper Claiborne aquitard.
Q. And throughout Shelby County?
A. Piecemeal.
Q. Have those breaches all been located?
A. The breaches that we know of have been approximated. Their locations have been approximated.
Q. Are you confident you know of all the breaches at this time?
A. We do not know of all the breaches at this time.
Q. Okay. Is it yours or Mr. Larsen's opinion that those breaches have either been caused by or they have been increased in size by the amount of pumping that is taking place within Shelby County, Tennessee?
A. No.
Q. No?
A. No.
Q. And how did you reach that conclusion?
A. These are geologic creations, not induced

at all by the pumping. We are able to see the style of formation of these breaches as paleochannels due to old erosion scars or tectonic activities.
Q. Have you examined other areas of recharge that currently exist for the confined portion of the Middle Claiborne Aquifer within Shelby County, Tennessee other than the breaches in the confining layer?
A. Yes.
Q. And what are they?
A. Groundwater surface water interaction primarily along the Loosahatchie River.
Q. Aloosahatchie River?
A. Loosahatchie. You know?
COURT REPORTER: That one I have.
Q. Well, I don't.
A. L-O-O-S-A-H-A-T-C-H-I-E, Loosahatchie.
Q. And where is that river located?
A. It is -- the river flows as a tributary on the northern section of -- northern portion of Shelby County east to west.
Q. And so it's a losing stream in terms of its contribution to the Middle Claiborne?
A. It varies seasonally.

Q. Depending upon the amount of water in the river?
A. Yes, sir.
Q. Okay.
A. Depending upon the stage of water in the river.
Q. I'm sure that's more accurate so I will accept that.
A. Okay.
Q. I thank you. Based on your knowledge of the --
A. I need to add.
Q. Yes, sir. Go ahead. Any time you want to.
A. Yeah, I'm sure. We have a project with TVA looking in southwest Memphis to look at the leakage -- potential leakage of water from the Mississippi River Alluvium into the middle -- the hydraulic connection between the two, that's a better representation.
Q. To determine whether it is a -- it is now entering recharge?
A. No. If there is hydraulic connection between the two systems.
Q. Right. So projects with the TVA in the

A. Yes, sir.
Q. Okay. And my simple question is, is it your position that all of the water within the confined portion of the Middle Claiborne Aquifer system is interstate water freely available to both states?
MR. BRANSON: Object to form.
MR. DAVID BEARMAN: Object to the form. Asked and answered.
MR. ELLINGBURG: No, it isn't.
A. The water would be interstate. I would require additional clarification when you speak to freely available to both parties.
BY MR. ELLINGBURG:
Q. Okay. But you're saying that whether that water in the Middle Claiborne Aquifer that -- let's say that gallon of water. Let's make it a gallon of water. Okay. And that gallon of water is under natural conditions predevelopment residing in the middle of DeSoto County, Mississippi. So it's miles and miles from the border. So based on your definition is that gallon of water interstate water?
A. Yes. Because it's of the same water that is moving across the state line. It's of the same

body.
Q. It's in the same body of water. So it's just like a big underground lake is what you're saying?
MR. BRANSON: Object to form.
Q. Is that right?
A. No. It's not an underground lake. It's just the fact that the -- there is no -- there is not a differentiation -- hang on.
Q. Okay.
A. I got distracted.
Q. I think they're telling us lunch is here. So I will withdraw. So even if under natural conditions that water that I have located in the middle of DeSoto County, Mississippi, would not flow, not move, not travel to, not ever reside in the state of Tennessee, it is still interstate water under your definition; is that correct?
A. Yes. Yes.
Q. Okay. Because it can be pumped?
MR. BRANSON: Object to form.
A. No.
Q. Well, I mean, that's the only way that it would end up in Tennessee, isn't it? The water under -- if we move from predevelopment

conditions, the only way that gallon of water residing in the middle of DeSoto County, Mississippi, based on everything you know, the only way it would ever end up in Tennessee is if it was -- it was drawn towards Tennessee by virtue of lowering of the hydraulic heads?
A. No.
MR. BRANSON: Object to form.
A. Because the investigation that we conducted shows a natural movement of water from Mississippi into Tennessee in that direction.
Q. So you're saying that your study shows that in the middle of DeSoto County, before there was ever any pumping, the water was flowing into Tennessee?
A. Yes.
Q. Okay. And how long did your investigation determine it would take the water to flow from the middle of DeSoto County -- by middle I mean northwest orientation. Okay. How long are you saying that it would take for that water that is in the middle of DeSoto County going south to find its way into Tennessee?
MR. BRANSON: Object to the form. Going south?

A. We never -- I never conducted that type of investigation.
Q. But your analysis did conclude that that water in the middle of DeSoto County would naturally flow into Tennessee?
A. We did not specifically look at an apportionment of a volume. We looked at the gradient and that the gradient shows that groundwater is moving from Mississippi into Tennessee during predevelopment conditions.
Q. And down that deep in DeSoto County, ten miles away from the border?
A. I have to look to see how far our contour goes. It's limited by the data that we have that it was -- I know it went into DeSoto County.
Q. So the natural flow path according to you for all of the confined groundwater in Mississippi is toward Tennessee?
MR. BRANSON: Object to form.
MR. DAVID BEARMAN: Object to the form.
BY MR. ELLINGBURG:
Q. In DeSoto County?
MR. BRANSON: Object to form.
A. I have to look at the gradients, all the

98

contours, but from the data that we had there was a general movement of water, not in totality, going from Mississippi into Tennessee.
Q. So is it your opinion that the pumping in Shelby County has had any impact on the groundwater and storage in Mississippi?
A. The pumping in Shelby County is -- has created a cone of depression that is extended south, west, north and east, in those directions.
Q. Well, when you say that it has created a cone of depression into DeSoto County, Mississippi, is that south, right?
A. Yes, sir.
Q. Is there any less groundwater in terms of volume residing in the state of Mississippi because of that pumping in Shelby County, Tennessee, or not?
A. I have not conducted a detailed analysis of that. We conducted an estimation of volume difference in the 2015 paper between predevelopment and Traders 2007 potentiometric surface map.
Q. Is it possible as a groundwater hydrologist to look at the reduction in total available drawdown within a confined aquifer

99

formation and estimate the amount of groundwater that has actually been lost out of that formation as a result of that total available drawdown?
A. Well, if you know how much you're pumping, you know how much you took out, then that is what was lost.
Q. Well, what I'm asking is a little different question.
A. Okay.
Q. And I'm just asking if it's possible, and if it is, how you do it. If you're -- if you have knowledge of the hydrological characteristics of a confined aquifer, and the hydraulic heads have been reduced as a result of pumping in the area of wells.
A. Uh-huh.
Q. Which that's what the cone of depression is, right?
A. Correct.
Q. Is it possible for you to estimate the amount of water that has been taken out of that area covered by the cone of depression based on those reductions in the potentiometric surface?
MR. DAVID BEARMAN: Object to the form.

100

Q. And the total available drawdown that is associated with that?
MR. DAVID BEARMAN: Object to the form.
Q. We'll stop in a minute.
A. Okay. Yes.
Q. Okay. Have you ever done that for the -- for the reduction in the pressure shown in Mississippi that are associated with the wells in Shelby County, Tennessee?
A. No, sir.
Q. Okay. Nobody has ever asked you to, right?
A. No.
Q. What is total available drawdown?
A. That is the available amount of groundwater to pumping that would not reach the screen.
MR. ELLINGBURG: Okay. Let's take a break for lunch.
(Lunch recess.)
BY MR. ELLINGBURG:
Q. What kind of control does the State of Tennessee exercise over the permitting and drilling of wells in Shelby County to your

101

knowledge?
MR. BRANSON: Objection. Foundation.
A. I only know the permitting process from the county side.
Q. To your knowledge what is required of a person or a -- theoretical person or real person, since we just had this conversation about persons, but what is required to obtain a permit to drill a new well in Shelby County, Tennessee?
A. You submit an application to Shelby County Health Department.
Q. Any other requirements you know of?
A. Call 811 before you dig.
Q. Okay. And what does that application to the Shelby County Health Department require you to provide?
A. It requires that you provide a location and a generalized construction log and the depth of the well.
Q. Are there any regulations that you're aware of in Shelby County that control the depth to which wells can be permitted, new wells can be permitted in Shelby County?
MR. BRANSON: Object to form.
A. Not to my knowledge.

development?
Q. For development, for actual pumping and use on the surface?
A. Yes.
Q. To your knowledge does Memphis have any immediate plans to turn off all of their well fields and MLGW?
A. No.
Q. To your knowledge do any of the cities that you provide well head protection services for intend to stop their pumping?
A. No.
Q. So as long as that pumping takes place, there is a reduction in the amount of water available for development within the confined Middle Claiborne Aquifer in DeSoto County, Mississippi; is that --
A. I don't know that.
MR. BRANSON: Object to form.
MR. DAVID BEARMAN: Object to the form.
BY MR. ELLINGBURG:
Q. What?
A. I don't know that.
Q. And why don't you know that?

A. Because that is specific to a singular location where water is coming from. Yet a cone of depression under its context would be ideally radial and, therefore, it's coming from multiple directions. And, therefore, you would have to take into account the availability of water coming from these other directions in your calculation of conservation of mass.
Q. But that is reflected actually by the cone -- if the cone of depression covers most of DeSoto County, Mississippi -- or have you ever -- have you ever seen the cone of depression?
A. I have.
Q. Does it extend well down into DeSoto County, Mississippi?
MR. DAVID BEARMAN: Object to the form.
MR. BRANSON: Object to form.
A. The cone of depression from where?
BY MR. ELLINGBURG:
Q. From the MLGW well fields.
A. A portion of it does.
Q. Okay. Within that portion as long as that pumping takes place, there is less water for development in that area in DeSoto County,

Mississippi, is there not?
MR. BRANSON: Object to form.
A. I think it also depends upon other stressors besides just MLGW.
Q. And what are the other stressors?
A. Municipalities in the state of Mississippi also withdrawing water.
Q. Do you know how much they're pumping?
A. No.
Q. And what about municipalities and industrial users in the -- into Shelby County, Tennessee, are they stressors?
A. Yes.
Q. That are independent of MLGW?
A. Can you repeat that little different --
Q. I'm saying other municipalities and utilities than MLGW and industrial users in Shelby County, Tennessee, who are pumping are also putting stresses on the aquifer; is that correct?
A. On the Middle Claiborne Aquifer, yes.
Q. Right. Is the Middle Claiborne a defined hydrological unit?
A. Yes.
Q. And I think I asked about this earlier, but if the existing well fields were moved further

north in Tennessee within the Middle Claiborne, would that reduce the extent of the cone of depression that is extended into the state of Mississippi?
MR. BRANSON: Object to form.
A. To an -- I don't want to say extreme. To the level of needing pumping elsewhere into Tennessee would produce a more localized cone of depression around those wells.
Q. Right. So if some of -- if you shut off more of the wells closer to Mississippi and you moved those further north into Tennessee, that would have a -- that would reduce the cone of depression being extended into Mississippi if you're pumping the same volume of water; is that correct?
A. Possibly so. Yeah.
Q. I mean, when you said "possibly so," I mean, it's probable, isn't it, that if you moved that pumping further north into Tennessee away from Mississippi border it would have less impact just based on basic groundwater hydrology science?
A. Correct.
Q. That that cone of depression would then move forward -- further north with those wells,

EXHIBIT 6

Richard K. Spruill Expert Report
Addendum #1
July 31, 2017

EXPERT REPORT
Addendum #1

Hydrogeologic Evaluation and Opinions
for State of Mississippi versus
State of Tennessee, City of Memphis,
and Memphis Light, Gas & Water Division

PREPARED FOR:
Daniel Coker Horton & Bell, P.A.
265 North Lamar Boulevard, Suite R
Oxford, Mississippi 38655
Telephone: (662) 232-8979

PREPARED BY:
Groundwater Management Associates, Inc.
4300 Sapphire Court, Suite 100
Greenville, North Carolina 27834
Telephone: (252) 758-3310

July 31, 2017

Richard K. Spruill

Richard K. Spruill, Ph.D
Principal Hydrogeologist

I. Introduction

Groundwater Management Associates (GMA) was retained by the firm of Daniel Coker Horton & Bell, P.A. (DCH&B) to provide expert geologic and hydrogeologic consulting regarding the origin and distribution of groundwater, interactions between surface water and groundwater, natural and man-induced migration patterns of groundwater, and specific topics regarding the geology and hydrogeology of predominantly sandy sediments in the Eocene-age Middle Claiborne Group that host the Sparta-Memphis Sand aquifer system in northwestern Mississippi and southwestern Tennessee. GMA's services included production of an expert report by Dr. Richard Spruill that focused on known or likely impacts on groundwater distribution and migration patterns within the Sparta-Memphis Sand (aka, SMS, Sparta Sand, Memphis Sand, Sparta Aquifer, Memphis Aquifer, Middle Claiborne aquifer, among others) in response to historic and ongoing pumping in Shelby County, Tennessee.

The expert report was produced for DCH&B on June 30, 2017. The report provided here is Addendum #1 to that expert report, and it is primarily an evaluation and critique of (1) the 2015 report by Waldron and Larsen that forms the basis of claims that, prior to intense pumping in Tennessee, the Sparta-Memphis Sand (SMS) has always had substantial northwestward-directed groundwater flow from Mississippi across the state border and generally into the area of the City of Memphis and Shelby County, Tennessee, and (2) the expert reports submitted on June 30, 2017, by two of the three individuals retained on behalf of the State of Tennessee, the City of Memphis, and the Memphis Light, Gas & Water Division (MLGW). My review and evaluation of new or previously-available information have not changed the opinions that I provided in my expert report.

II. Qualifications

I, Richard K. Spruill, am submitting this addendum to my expert report dated June 30, 2017. My descriptions, interpretations, conclusions, and professional opinions described within this expert report addendum are subject to revision, expansion, and/or retraction as additional information becomes available. Reference materials considered and evaluated, and my *curriculum vitae*, are provided as Appendix A and Appendix B of the expert report, respectively. Additional reference materials considered as part of this addendum are listed in Appendix A-1.

Richard K. Spruill

Richard K. Spruill, Ph.D., P.G.
Principal Hydrogeologist

III. Summary of General Opinions Provided in My Expert Report

The opinions provided in my expert report dated June 30, 2017, are summarized below.

- The Sparta-Memphis Sand, also known as the Middle Claiborne Aquifer or the Memphis Aquifer, is an important source of potable groundwater within northwestern Mississippi and southwestern Tennessee. Most of the Sparta-Memphis Sand is a hydraulically-confined aquifer that consists of geologic deposits that accumulated within the Mississippi Embayment approximately 40 million years ago. The Sparta-Memphis Sand is inclined (dips) toward the west from areas where the unit outcrops in both Mississippi and Tennessee. These sandy deposits thicken toward the center of the Embayment, which generally coincides with the present trace of the Mississippi River.
- The Middle Claiborne contains several lithologic constituents, including the Sparta Sand, that comprise an aquifer that has accumulated groundwater over many thousands of years. Historically, most of that groundwater originated as surface precipitation that infiltrated the formation where it is exposed at or near the surface, and that groundwater migrated generally westward in both states to create a source of high-quality groundwater that did not naturally flow to any significant extent in a northerly direction out of Mississippi and into Tennessee.
- The Sparta-Memphis Sand is the most productive source of high-quality groundwater available in northwestern Mississippi and southwestern Tennessee.

- Massive withdrawal of groundwater by pumping wells operated by Memphis Light, Gas and Water (MLGW) in southwestern Tennessee has reduced substantially the natural hydraulic pressures existing in the Sparta-Memphis Sand in both Tennessee and Mississippi, and these withdrawals have artificially changed the natural flow path of Mississippi's groundwater in this aquifer from westward to northward toward MLGW's pumping wells. This groundwater withdrawal has dramatically reduced the natural discharge of Mississippi's groundwater in the Sparta-Memphis Sand to the Mississippi River's alluvial aquifer system within the state of Mississippi.
- The taking of Mississippi groundwater by MLGW's pumping has decreased the total amount of available groundwater in the Sparta-Memphis Sand available for development in Mississippi, thus increasing the cost of recovering the remaining available groundwater from the aquifer within the broad area of depressurization (aka, cone of depression) created by MLGW's pumping.
- The intensity of pumping that has been, and continues to be, conducted by MLGW is not consistent with good groundwater management practices, and denies Mississippi the ability to fully manage and utilize its own groundwater natural resource.
- The best management strategy for sustainability of groundwater resources involves withdrawing groundwater at a rate that is equal to or less than the recharge rate of the aquifer being developed.

IV. Summary of General Opinions Provided in Addendum #1

The following is a summary of my opinions provided within this addendum to my expert report. The opinions summarized below are based upon (1) my education, training, and experience, (2) detailed study of the geology and hydrogeology of the Mississippi Embayment, (3) evaluation of the specific geological and hydrological characteristics of the pertinent geological formations in north Mississippi and west Tennessee, (4) specific resources and materials referred to and identified with this report, and (5) careful evaluation of expert reports submitted by two of three representatives for the defendants.

Overall, it is my opinion that these reports do not directly address the geological and hydrological issues that must be addressed in any dispute between states over the right to regulate and take groundwater naturally occurring and present within each separate state. High-quality groundwater stored underground in hydraulically-confined aquifers over thousands of years is a valuable and finite natural resource. Each state regulates the use of its groundwater resources. Unlike rivers and streams that generally reveal their presence and water supply at the surface, each confined aquifer has unique characteristics based on the local geology which determine the groundwater's origin, movement, quality, availability, and the amount of development through pumping that can be undertaken consistent with long-term sustainability. Because of these unique characteristics, the natural resource question must be focused on the specific origin, characteristics, and flow of groundwater that is subject to the regulations of each state while it naturally resides within its borders.

The two expert reports that I evaluated appear to intentionally conflate geologic relationships and the common presence of groundwater without significant scientific analysis of the actual groundwater that occurs naturally within the separate states of Mississippi and Tennessee. Groundwater is the natural resource that must be examined for the purpose of its regulation, protection, conservation, and sustainability. Beyond the failure of these two reports to deliver clear, credible scientific analysis, the hydrological analysis that was offered was not developed using well-established methodologies or reliable data, and therefore should not be considered in determining whether the disputed groundwater is "interstate" or "intrastate" groundwater.

I offer the following opinions on the three main areas of review that I performed in connection with preparation of my expert report addendum.

- I performed a detailed evaluation of the study published by Waldron and Larsen (2015) that purports to provide a superior and more accurate depiction of the natural, pre-pumping hydraulic pressures (the "equipotential surface") in the

Middle Claiborne aquifer (aka, SMS) in the vicinity of the Mississippi-Tennessee border in and near Shelby County, Tennessee. I consider the dataset employed by Waldron and Larsen (2015) to be wholly unreliable, thus rendering their depiction of the SMS' pre-development (1886) equipotential map meaningless in the context of sound science and the litigation under discussion.

- Mr. Larson's (no relation to Dr. Larsen) expert report can be distilled to one opinion; the Middle Claiborne aquifer, and all groundwater stored over many thousands of years within it, is an interstate resource. To reach that conclusion, Larson: (1) conflates a massive geologic feature (Claiborne Group sedimentary deposits) with a hydrogeologic feature (water producing portions within the Claiborne Group that qualify as an aquifer system); (2) takes the simplistic view that, because a geological formation qualifying as an aquifer system may cross state lines, all of the groundwater residing within that formation must be considered an interstate resource, apparently without regard to current or pre-development patterns of flow within each separate state; (3) conveniently ignores the natural manner by which the groundwater was recharged and moves over many hundreds to thousands of years; and (4) claims that because a specific agency of the federal government (United States Geological Survey; USGS) created a regional computer model to mimic aspects of the regional aquifer system, that entire system is obviously an interstate resource. In my opinion, Mr. Larson's core opinion and his supporting justifications do not represent a disciplined scientific analysis or interpretation of the available geological and hydrological evidence.
- The expert report by Dr. Waldron is a curious mixture of arguments. He adopts and argues the superiority of a study in which he participated (Waldron and Larsen, 2015), and he attacks the work of the same USGS scientists that Mr. Larson holds in high esteem. In my opinion the Waldron and Larson (2015) report is so badly flawed as to render Waldron's conclusions gleaned from that study fundamentally unreliable.
- I provide opinions and illustrative examples, calculations, and analogies that reveal some of the special characteristics of groundwater not considered in these three reports, including the surprisingly slow rate of movement of groundwater

in the subsurface. In my opinion, there is no doubt that the groundwater within the Middle Claiborne (aka, SMS) aquifer beneath Mississippi is an intrastate natural resource under natural conditions, especially when one considers the component of time that Mr. Larson and Dr. Waldron elect to disregard.

V. Scope of Addendum #1

On June 30, 2017, the City of Memphis, MLGW, and the State of Tennessee submitted three expert reports as part of the defense of the litigation initiated by the State of Mississippi that is being addressed herein. Specifically, expert reports were submitted by Dr. David Langseth, Mr. Steven Larson, and Dr. Brian Waldron. I was tasked with evaluating, critiquing, and responding to the two latter reports. The Langseth report is being addressed by another expert for the State of Mississippi. Section VI of my Addendum #1 report evaluates and summarizes the 2015 publication by Dr. Waldron and Dr. Daniel Larsen that is integral to arguments made by these parties. The Waldron and Larsen report states that "*The pre-development map constructed from* [our] *research will have direct bearing on what injury, if any, can be substantiated*" (Waldron and Larson, 2015, page 5). Appendix B-1 provides my detailed analysis of the historic data used by Waldron and Larsen (2015) to produce what they consider to be the most correct and reliable equipotential map available that shows the pre-development distribution of hydraulic head in the Sparta-Memphis Sand aquifer and the natural pattern of groundwater flow. Sections VII and VIII of my Addendum #1 address the expert reports submitted by Mr. Larson and Dr. Waldron, respectively.

VI. Summary of My Evaluation of the 2015 Report by Waldron and Larsen

The Waldron and Larsen (2015) report was evaluated in connection with preparation of my expert report and this addendum. I summarize herein some basic aspects of the work described in that publication that render their interpretations and conclusions unreliable for determining the natural characteristics of the groundwater in Mississippi, which has been, and continues to be, pumped out of Mississippi and into Tennessee to a measurable degree.

VI.1 Introduction

The purpose of Waldron and Larsen's 2015 study (W&L 2015) was clearly to contradict the accuracy of the USGS' pre-development groundwater flow patterns in the boundary region between Mississippi and Tennessee, with special emphasis on flow patterns in the Sparta-Memphis Sand in the vicinity of the City of Memphis and Shelby County, Tennessee. Figure 4 of W&L 2015 is the final summary of their investigation and the pertinent figure discussed here, so it is reproduced below as Figure 1 for discussion in this addendum to my report. Appendix B-1 of my addendum provides a detailed evaluation of the data sources reportedly used by W&L 2015. In this section, I summarize my opinions regarding the data relied on within W&L 2015, the methods and assumptions used in their study, and the errors embedded in their analysis of, and conclusions regarding, pre-development groundwater flow in the SMS aquifer in northwestern Mississippi and southwestern Tennessee.

W&L 2015 states that significant extraction of groundwater from the Sparta-Memphis Sand (aka, Middle Claiborne aquifer) began in 1886 with the first commercial production well installed in the City of Memphis, and that withdrawals from the aquifer "*in Shelby County, Tennessee, has continued to increase exponentially since 1886*" (Waldron and Larsen, 2015, page 3). W&L 2015 reports that "current" withdrawals are 712,000 cubic meters per day (m^3/day), which is approximately 188,089,000 gallons per day (gpd). However, it appears that the "exponential" withdrawal volume in Shelby County, Tennessee, was reached long before the present; "*a maximum of 190 Mgal/d* (190 million gpd; mgd) w*as reached in 1974*" (Criner and Parks, 1976, page 1). In fact, I contend that the graph by Criner and Parks (1976) provided below as Figure 2 shows that there was a linear increase during the first 10 years of withdrawals from the SMS, no obvious increase for the following quarter century (steady at ~33 mgd), and a linear increase in withdrawals between approximately 1920 and 1975.

Figure 1: Waldron and Larsen (2015) Pre-Development Equipotential Map for the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer)

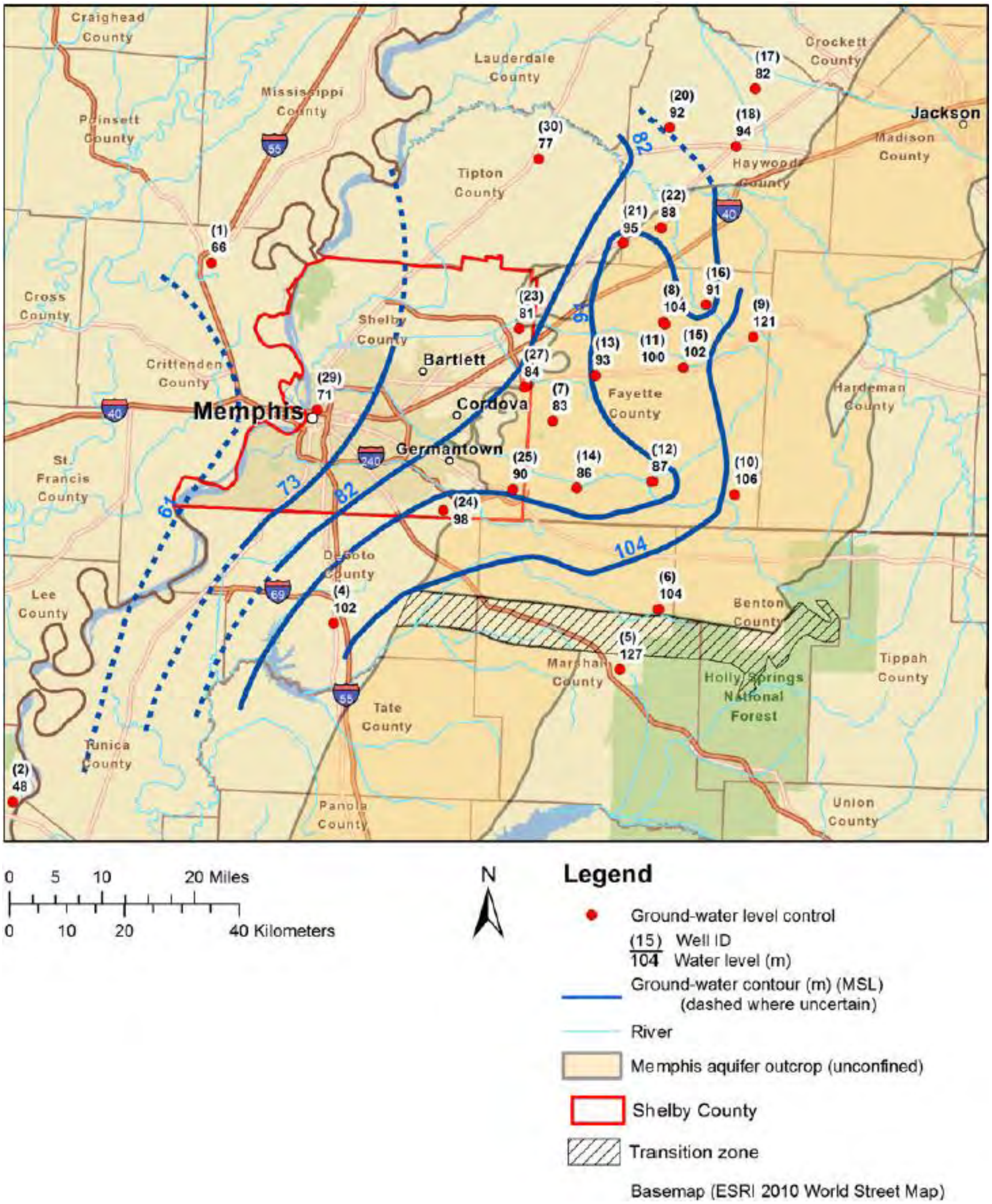


Figure 2: Criner and Parks (1976) Graph of Groundwater Withdrawals from the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) between 1886 and 1975.

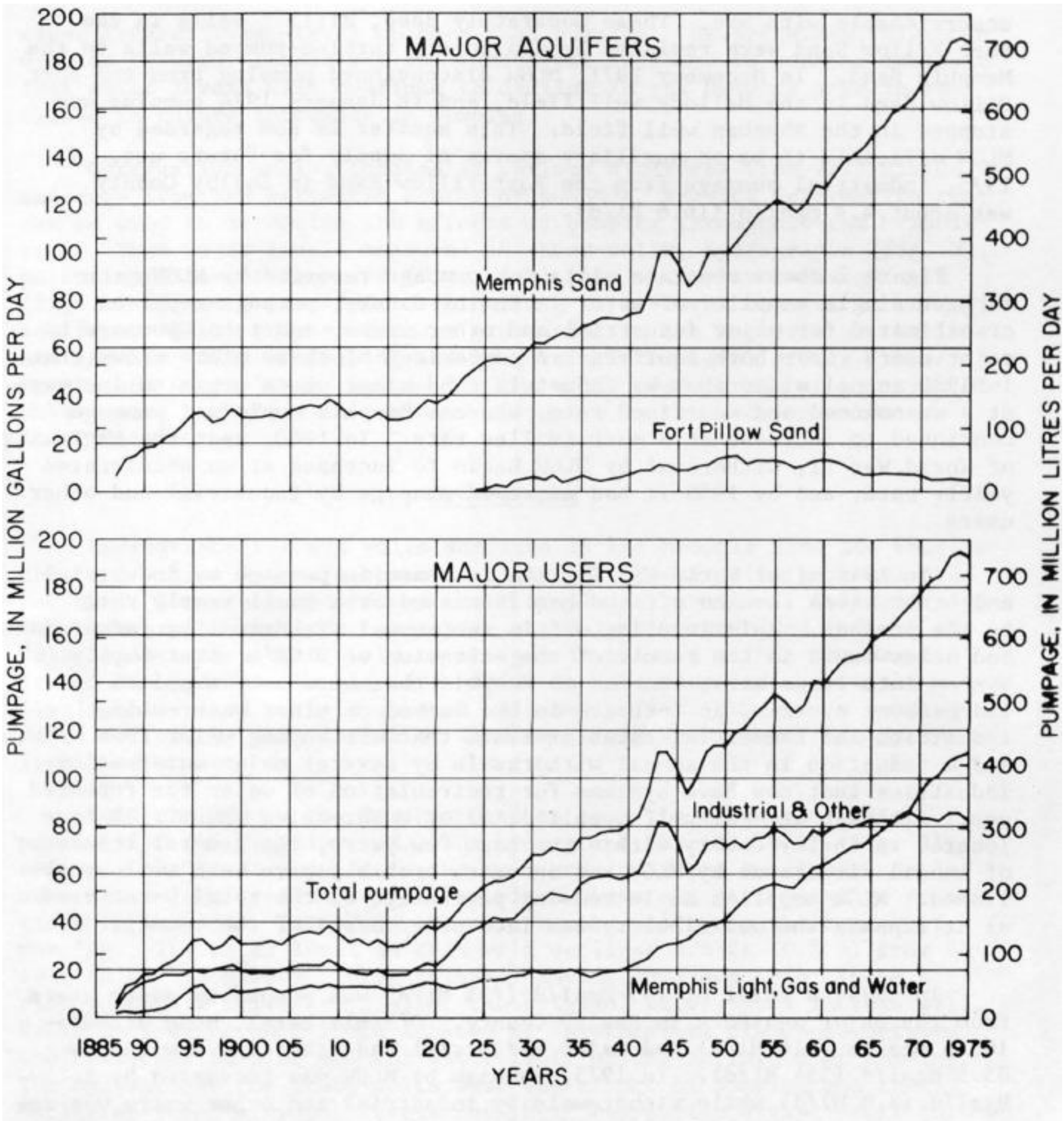


Figure 2.--Pumping rates from major aquifers by major users in Shelby County, Tennessee, 1887-1975.

W&L 2015 is focused on (1) critiquing a pre-development equipotential map for the SMS produced by Criner and Parks (1976), and (2) evaluating a data set that they consider to be more pertinent and robust than that employed by Criner and Parks. W&L 2015 does not mention a study by the USGS (Reed, 1972) which pre-dates, and shows good agreement with, the report by Criner and Parks (1976). Waldron and Larsen's apparent goal was to produce their own pre-development equipotential map (Figure 1) that could be used to contradict the USGS study that showed "*zero or no flow according to Criner and Parks (1976)*" for the trans-border migration of SMS groundwater from Mississippi to Tennessee. Waldron and Larsen used their new and purportedly superior equipotential map to determine that "*the estimated average quantity of flow from Mississippi into Shelby County around the time of pre-development was approximately 220,000 m^3/day*" (~58,118,000 gpd) (W&L, 2015, page 151).

VI.2 Comments on the Report by Criner and Parks (1976)

Before discussing the flaws and errors in the data used and conclusions reached in W&L 2015, some background on the Criner and Parks (1976) report is useful to provide context for W&L 2015.

- Criner and Parks (C&P) were USGS employees who acknowledge that their report was "*Prepared in cooperation with the City of Memphis* (and) *Memphis Light, Gas and Water Division*" (C&P, 1976, page I). However, this was an independent USGS investigation and report funded by the United States government.
- Criner and Parks do not estimate the volume of SMS groundwater flowing from Mississippi into Tennessee prior to or after extensive pumping in Tennessee. The report does, however, make it unambiguously clear that "*one of the effects of escalating pumping* (in the Memphis area) *has been the development of a broad cone of depression in the originally, <u>nearly flat</u>, potentiometric surface*" of the SMS (C&P, 1976, page 14, emphasis added).
- The C&P report states that the evaluation of water-use patterns in the vicinity of Memphis and Shelby County, Tennessee, "*did <u>not</u> include pumpage from a few thousand suburban and rural wells <u>nor</u> any wells in the Arkansas and Mississippi parts of the Memphis area*" but that the "*annual pumpage from these wells probably does <u>not</u> amount to more than an additional 2 or 3 percent of the total pumpage values given in this report*" (C&P, 1976, page 35, emphasis added).

- C&P relied upon historic water-level data "*for six wells screened in the Memphis Sand*" that "*were selected for their long-term record and their areal distribution…within the Memphis area*" (C&P, 1976, page 11). Significantly, C&P only relied upon data from "*observation wells, located at various distances from well fields and away from the estimated center of pumping*" (C&P, 1976, page 11).
- Measurements from those six well-documented observation wells were "*projected backward in time to illustrate the probable original* (pre-1886) *water level with respect to the land surface*" (C&P, 1976, page 11) to illustrate the most likely configuration of the pre-development equipotential surface for hydraulically-confined portions of the SMS aquifer (Figure 3). It is significant that Criner and Parks only employed data from confined portions of the SMS aquifer system. Problems introduced by mixing water-level data for confined and unconfined portions of an aquifer were discussed in my expert report, and the topic is revisited below in the context of the Waldron and Larsen (2015) study and their pre-development map.
- While the Criner and Parks study was not perfect, it employed data from reliable sources, and their pre-development equipotential map (Figure 3) provides a reasonably-sound basis for illustrating, testing, and refining changes to the SMS' equipotential surface that have resulted from intense and localized groundwater withdrawals in southwestern Tennessee.
- Criner and Parks were fully aware that their methods could not yield the data necessary to produce the most detailed and accurate pre-development equipotential map, but their resulting map (Figure 3) provides a reasonable basis for illustrating subsequent changes to the SMS' equipotential surface as a result of intense and localized groundwater withdrawals in southwestern Tennessee.
- The pre-development equipotential map (Figure 3) produced by C&P (1976) correlates reasonably well with equipotential maps produced for the SMS within other studies (e.g., Reed, 1972). Likewise, USGS and other computer simulations of the pre-development equipotential surface for the SMS yields patterns that generally agree with the interpretation by C&P (e.g., LBG, 2014). In fact, the map produced as Figure 4 of W&L 2015 being discussed herein is the only significant interpretation of the pre-development equipotential surface within the SMS in

Tennessee and northwest Mississippi that differs considerably from the work of all other researchers.

- W&L 2015 does not mention the earlier USGS study (Reed, 1972) that produced a pre-development (1886) equipotential map for the SMS (Figure 4) that appears remarkably similar in the vicinity of southwestern Tennessee to the interpretation produced by Criner and Parks (1976). A comparison of the map by C&P (1972) with the pertinent portion of the map by Reed (1972) is provided below (Figure 5).
- Significantly, the recent expert report by Mr. Steven Larson (page 20, paragraph 54) identifies the Reed (1972) pre-development equipotential surface as the basis for the regional computer modeling of the SMS conducted by the USGS (e.g., Clark and Hart, 2009). (See Section VII below)

Figure 3: Criner and Parks (1976) Equipotential Map for Confined Portions of the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) in 1886.

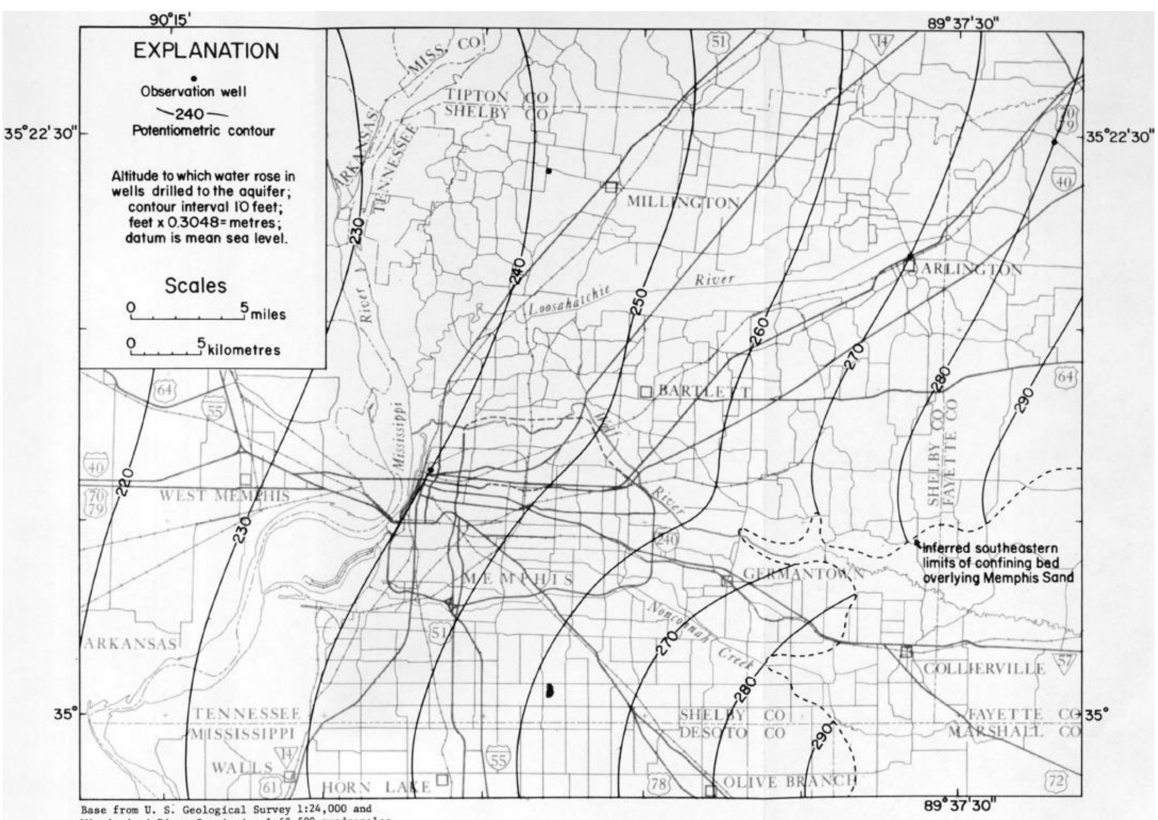


Figure 4: Reed (1972) Equipotential Map for Confined Portions of the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) in 1886. (Note: the image was converted to black-and-white and the contrast was enhanced to facilitate readability.)

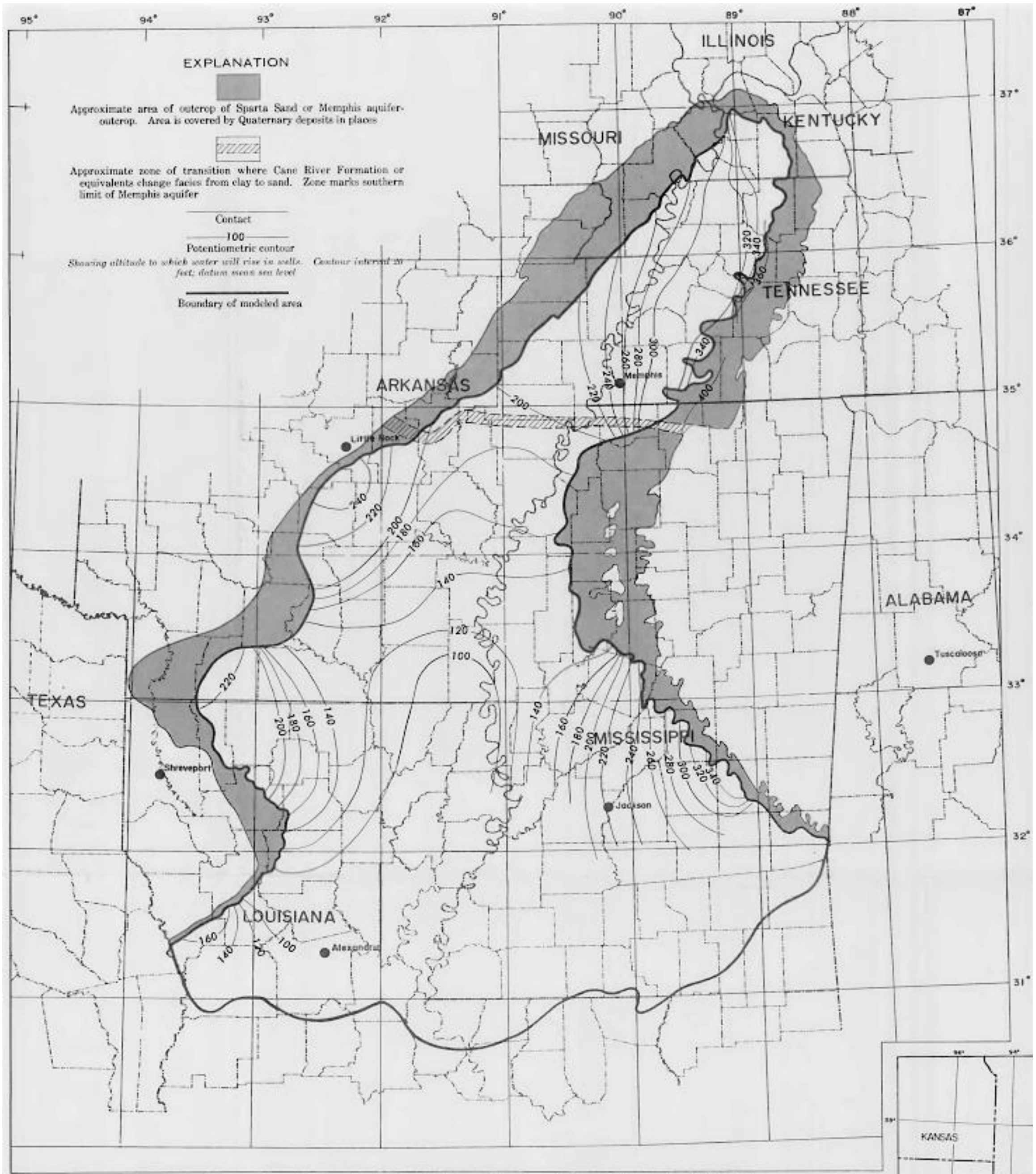
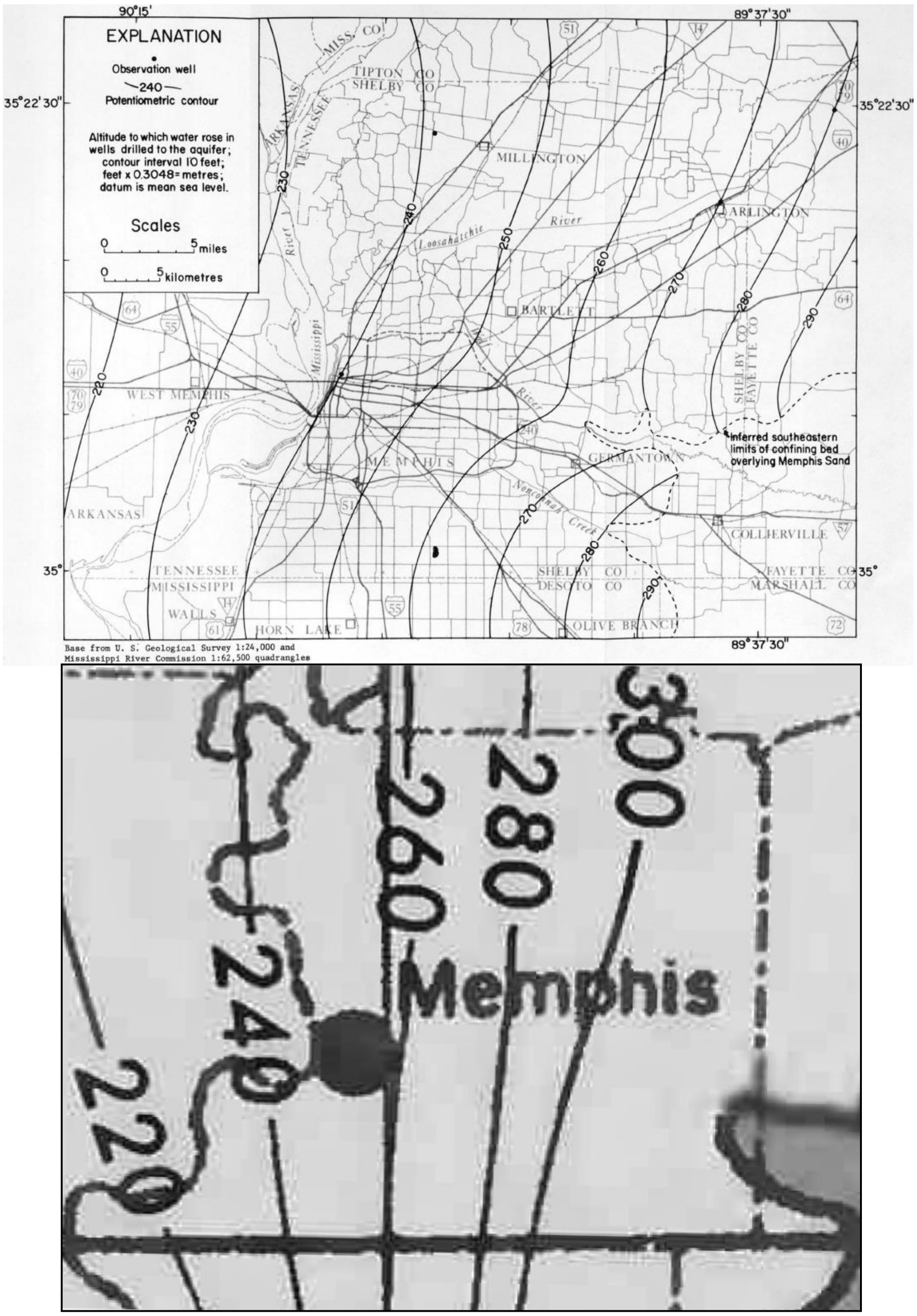


FIGURE 2.—Potentiometric surface of the Sparta Sand and Memphis aquifer in 1886.

Figure 5: Comparison of Equipotential Maps for Confined Portions of the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) in 1886 Produced by Criner and Parks (1976) and Reed (1972), Top and Bottom, Respectively.

(Note: The image for Reed (1972) was converted to black-and-white, contrast was enhanced, and the image was cropped, rotated slightly, and scaled to better match the area shown in the map by Criner and Parks (1972).)



VI.3 Summary of Flaws in Data and Methods Used in the Waldron and Larsen (2015) Study

Hydrogeologists have long recognized that accurate and meaningful results and interpretations of the distribution of hydraulic head and patterns of groundwater flow within an aquifer can <u>only</u> occur if significant controls are maintained during collection of water-level data from properly designed new and/or vetted existing monitoring wells. It is particularly critical to ensure that such controls are applied when evaluating an unconfined aquifer because that system is characterized by downward-directed flow patterns in local recharge areas, and upward-directed flow patterns in local discharge areas. These flow patterns <u>cannot</u> be quantified or evaluated properly in unconfined aquifers by using data from wells that have long sections of screens and/or have unknown construction details. Examination of the data sources cited by W&L 2015, and the locations assigned for many of their "well" data points used to create their Figure 4, reveals that they elected to combine indiscriminately data from confined and unconfined portions of the Sparta-Memphis Sand aquifer. Waldron and Larson's decision to combine these disparate data, in addition to the fundamentally flawed nature of the data itself, render the interpretation of the SMS' pre-development equipotential surface in W&L 2015 meaningless, and also explains why their interpretation is considerably different from that of USGS researchers (e.g., Reed, 1972; Criner and Parks, 1976).

The following additional observations and opinions reinforce my conclusions and opinions that Waldron and Larsen's (2015) alternative interpretation of the pre-development equipotential surface for the SMS is fundamentally flawed.

- The abstract of W&L 2015 states that *"The basis of the* (MS v. TN) *lawsuit was potentiometric maps of groundwater levels for the Memphis aquifer that showed under suggested pre-development conditions no flow occurring across the Mississippi-Tennessee state line, but subsequent historic potentiometric maps show a cone of depression under the City of Memphis with a clear northwesterly gradient from Mississippi into Tennessee."* This statement contains two notable mischaracterizations. First, Mississippi acknowledges that there was some limited, natural, cross-border exchange of groundwater prior to development, but that does not materially change its position about the location of this Mississippi groundwater resource. Second, Mississippi's claim is not based solely on pre- and post-development potentiometric maps, but also on the results of a calibrated groundwater-flow model produced by Leggette, Brashears & Graham, Inc. (LBG) early in this dispute, and that model has been refined and updated to include all currently available data appropriate for use. LBG's modeling confirms the natural pre-development flow pattern, and clearly demonstrates the formation of a vast cone of depression extending from MLGW's well fields to deep within Mississippi which has changed the natural east to west flow in Mississippi to south to north in response to MLGW's pumping. Not only has the intense pumping in Shelby County, Tennessee, changed the natural direction of movement in the Mississippi groundwater, but this high-volume pumping has significantly accelerated the velocities of groundwater flow from Mississippi toward MLGW's pumping centers. This process and its impact were well established by the mid-1970s; the report by Criner and Parks (1976) identified a dramatic five- to seven-fold steepening of the pre-development SMS hydraulic gradient between 1886 and 1970 (to 10 feet per mile) between Olive Branch, Mississippi, and MLGW's Allen well field (C&P, 1976, page 11).

- In addition to their use of ambiguous, uncertain, or clearly defective historic data from wells of unknown construction to develop a map based on those completely unreliable data, W&L 2015 employed numerous errant assumptions in manipulating the elevation references that introduced additional uncertainty and error into their already-flawed analysis. I discuss these issues below.
- In summary, Waldron and Larsen (2015) produced "*FIGURE 4. Pre-development Potentiometric Surface for the Memphis Aquifer from This Study.*" by relying upon data that are inherently unreliable and should not have been used to draw any conclusions, let alone to produce their Figure 4, making it scientifically unreliable.

A complete evaluation of the specific data employed by Waldron and Larsen (2015) is provided in Appendix B-1 of this expert report. I summarize below some very serious issues that demonstrate the lack of value in the historical data used by W&L to prepare their flawed Figure 4.

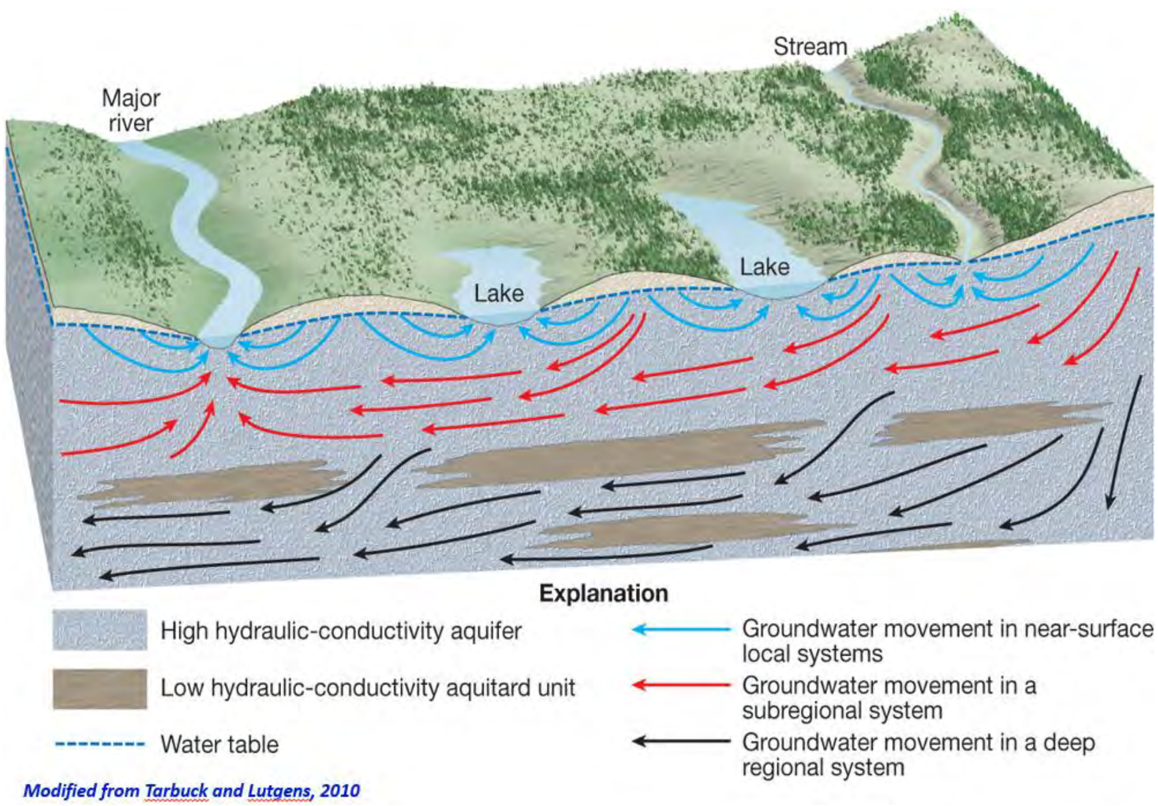
1. Many "wells" cited W&L 2015 *are <u>not</u> actually wells.* Instead, those "wells" are generic observations or claims about zones that were being targeted in particular areas for the potential drilling of water-supply wells in the late 1800s or very early 1900s. In the following discussion, I will refer to all W&L 2015 data points as "wells" to simplify the discussion, but the fact remains that a significant percentage of the data cited in W&L 2015 is invalid for this reason alone.
2. Exact locations for most wells used by W&L were simply not known, so they estimated the locations based on various lines of information, narrative , and/or assumption. W&L 2015 assumed land surface elevations based upon criteria of their choosing, and those values often do not match the elevations reported in the three source documents that date from 1903 and 1906 (see Appendix B-1).
3. Methods of measurement of water levels are not documented in any of the three original source reports. This fact alone introduces an unacceptable level of uncertainty for the stated or assigned values for depth to groundwater.
4. All of these historic measurements represent a period of time that post-dates the start of municipal/commercial pumping in the vicinity of Memphis in 1886, typically by at least a decade.
5. Historic water-level values in the three data-source reports used in W&L 2015 are listed as whole numbers in feet, which, at best, provide accuracy to the nearest foot (~0.305 meters). W&L rounded all land elevations used for calculating water level elevations to the nearest meter, which further degrades the accuracy of contoured head values presented on their Figure 4.
6. Historical records of groundwater measurements do not specify the pumping conditions of the wells. It is not known if the reported water levels were measured during active pumping or under non-pumping (static) conditions.
7. Reference points for water-level measurements are not given. Many of the historical publications list the depth to water below the "mouth" of the well, and the height of the mouth of the well (above or below land surface) is not listed.
8. The total head difference presented in Figure 4 of W&L 2015 is 79 meters (259 feet). W&L 2015 reported the estimated vertical errors for land surface elevations of up to 5.5 meters (18 feet; approximately a 7% error). The estimated vertical error for elevation reference does <u>not</u> take into account the inherent error in

rounding values to the nearest meter for each water level value used for contouring head in Figure 4.

9. Head values used to produce Figure 4 of W&L 2015 do not consider the effects of well construction on the reliability of the water level data. If a well installed into a confined aquifer does not have a properly grouted casing seal, there will be vertical hydraulic interconnection with the unconfined surficial aquifer via the ungrouted borehole. Until relatively recently, it was common practice to 'seal' water-supply well casings using very little grout that typically extended just a short distance below the land surface. Historic records used in W&L 2015 to obtain water level data do <u>not</u> provide <u>any</u> information about well construction and grouting.
10. Figure 4 of W&L 2015 does <u>not</u> discriminate between head values representing confined and unconfined portions of the aquifer system, and fully 60 percent of the data set used by W&L represent wells that are placed within <u>unconfined</u> portions of the SMS aquifer. In contrast, maps produced by Criner and Parks (1976) and Reed (1972) only consider groundwater-flow conditions in the <u>confined</u> portions of the aquifer. The distinction between confined and unconfined portions of the aquifer system correlates with the differences in regional versus local groundwater flow systems, respectively, as illustrated generically below in Figure 6.
11. W&L's dataset lists Well #3 (Forest City, Arkansas), but the well was excluded from their map even though it is located closer to Memphis than many other wells used to construct their Figure 4. Well #3 had an estimated elevation of 28 meters, the lowest head value reported in W&L 2015. Had this data point been used in contouring, the orientation of groundwater flow via equipotential lines in the confined portion of the aquifer system would have been more westerly, rather than northwesterly. Two other wells (#1 and #2) in eastern Arkansas were used to construct Figure 4, and W&L 2015 offers no justification for ignoring Well #3.
12. W&L 2015 commonly uses the land surface elevation as the head elevation for wells reported to be free-flowing (artesian). That assignment of head elevation is not accurate because those values are too low for those locations. By definition, a free-flowing (artesian) well has a hydraulic head that is at some elevation *above*

the local land surface. To determine the correct head for free-flowing wells, the well must be equipped with a pressure gauge, or the well casing must be extended above the land surface to a height that prevents free flow of water from the top of the pipe. Only then can the amount of hydraulic pressure above the land surface at those locations be determined accurately. The historic records relied upon by W&L 2015 never include this information, so it not scientifically-reliable data to use to produce their Figure 4.

Figure 6: Local versus Regional Groundwater Flow Systems in Unconfined and Confined Aquifers, Respectively.



13. Figure 4 of W&L 2015 contains numerous errors in contouring the pre-pumping equipotential surface, including: (1) an inconsistent contour interval that varies from 9 to 13 meters, (2) assigning Well #16 (Taylor's Chapel, Tennessee) a head value of 91 meters, but the data point is contoured incorrectly on the inside (i.e., lower elevation) of the 91-meter contour line, (3) Well #17 (Bell Eagle, Tennessee) is located in a contoured area that should give the well a head

elevation greater than 91 meters, but the value assigned to Well #17 is only 82 meters, and (4) Well #6 (Hudsonville, Mississippi) has an estimated head elevation of 104 meters, yet the well is shown almost 6 miles (~9,500 meters) up-gradient from the 104 meter contour line in an area where W&L's contouring indicates that the elevation should be more than 106 meters. Collectively, these issues demonstrate that W&L's Figure 4 does not conform to standard contouring rules and thus presents a fundamentally flawed interpretation of the pre-pumping equipotential surface in the aquifer system.

14. An area of low head elevation is illustrated in Figure 4 in southern Tennessee near the Mississippi border. The head representation of this area is dominated by values assigned to Wells #12 (Moscow, Tennessee) and #14 (Rossville, Tennessee). These are fundamentally flawed data points that should not have been considered for pre-pumping equipotential contouring. Historic data for Well #12 does not reflect a specific well at a known location, and there is no specific reference of water level for Well #12, only the meaningless statement that "*water is found in abundance at depths of 60 to 80 feet".* In the context of the discussion by Glenn (1906), these depths identify drilling target depths at which known water-producing strata occur, not the depth of the water level in any well. Similarly, the data from Well #14 at Rossville, Tennessee, does not include a reported water level in a well. Like Well #12, it only reflects a general statement of the drilling depth to a sand layer from which water can reportedly be obtained. Simply put, there are no reported water level values for Wells #12 and #14 that can be used to construct Figure 4. When the fictitious head values assigned to these wells are removed from Figure 4 of W&L 2015, there is no longer any indication of a steep pre-development hydraulic gradient directed northward.

15. It is clear that most of the water levels presented in Figure 4 of W&L 2015 are not scientifically supportable. At many locations, Waldron and Larsen's map suggests pre-development equipotential surface elevations that are actually lower than more recent post-development observations. This is especially noticeable in areas of eastern and central Fayette County, Tennessee. A comparison of head elevations shown in Figure 4 of W&L 2015 with post-development equipotential measurements shown in Schrader (2008) indicates that Moscow, Tennessee, has

a post-development head of approximately 107 meters, which is 20 meters (more than 65 feet) higher than the estimated pre-development head. The estimated head at Moscow, Tennessee, presented on Figure 4 of W&L 2015 is significantly in error because this location is within the well-known pumping cone of depression centered on Shelby County, Tennessee. Likewise, there is a post-development head of approximately 96 meters at Rossville, Tennessee, which is 10 meters (more than 32 feet) higher than the estimated pre-development equipotential values shown in Figure 4 of W&L 2015. These are two clear examples of egregious errors in the interpretations of W&L 2015.

The following are my concluding opinions regarding Waldron and Larsen's approach to investigating and illustrating the pre-development groundwater flow patterns in their study area:

- The study lacks the rigorous data control that is essential to producing any meaningful hydrological interpretations or conclusions.
- Minimal data control requirements include precisely known locations and elevations of the measuring point at the tops of well casings. The specific screened interval(s) of the wells must be known, not assumed. Well construction records should also be available and considered, in addition to other information such as driller's logs. Measured depth to water in the well must be reported. It must be known that the well has not been pumped recently (i.e., the water level is static) and that there are no nearby wells pumping from the same aquifer. The data used by Waldron and Larsen in their 2015 study *do not meet any of these requirements*, making their Figure 4, and any conclusions or inferences drawn from it, completely unreliable.
- As described and illustrated in my report, monitoring wells with short screen intervals placed at accurately known depths must be used for evaluations of groundwater flow in unconfined aquifer systems. Data in the Waldron and Larson 2015 report indicate that this was not done.
- Interpretations of flow patterns based on incomplete or inaccurate well and head data fail to account for local flow patterns in the unconfined portions of the

groundwater system, wherein groundwater generally moves from recharge to discharge areas along circuitous flow paths, as illustrated above in Figure 6.

- Groundwater flow patterns in unconfined portions of the groundwater system are complex, and reflect relatively small, local groundwater 'basins.' Data for the unconfined aquifer system should never be used to define groundwater flow patterns in the confined portions of the aquifer system which reflect regional flow patterns.
- Considering the unreliability of the data employed, and the fundamental errors identified in their study, I assert that (1) Waldron and Larson did *not* provide a scientifically-reliable basis to support the pre-development distribution of hydraulic head and associated flow patterns for the SMS aquifer that are described and illustrated as Figure 4 in their 2015 report, and (2) there is no meaningful application of their work or their interpretations in Figure 4 to the border region between northwestern Mississippi and southwestern Tennessee.
- Interpretations by other researchers regarding the pre-development equipotential surface of the Middle Claiborne aquifer are properly focused on the confined portions of the groundwater system, and thus provide the best evidence and basis for accurate groundwater modeling and evaluation.
- It is my opinion that, with limited variations near the common border between Mississippi and Tennessee, the natural groundwater flow in the confined portions of the Middle Claiborne aquifer and other regional aquifers in both Mississippi and Tennessee is from eastern recharge areas toward western discharge areas. As demonstrated by computer simulations (e.g., LBG, 2014), there is a small area near the border between Mississippi and Tennessee where limited cross-border flow may occur under natural conditions. However, almost all groundwater in these regionally-important aquifers in Mississippi originates from recharge occurring inside the state. This groundwater naturally travels within the confined portions of the aquifer system in Mississippi and, absent intense pumping in Tennessee, the same water ultimately discharges to the Mississippi River many thousands of years later by moving upward through younger strata.

VI.3 Failure by Waldron and Larsen (2015) to Consider the Time Component

Time, specifically geologic time, is a key aspect of groundwater flow and aquifer hydraulics that must be considered in evaluating confined groundwater as a natural resource. It is easy for a layman to examine a groundwater equipotential map or computer simulation and assume incorrectly that the groundwater is migrating at a significant rate. As described in my expert report, time and flow velocity are what clearly separate concepts of surface water flow at the land surface from groundwater flow in geological materials.

The velocity of groundwater flow in a particular location can be described by the relationship between the hydraulic gradient (dh/dl), the aquifer's porosity (n), and the permeability (hydraulic conductivity, or k) of the aquifer. The velocity of the horizontal component of groundwater flow (V_h) can be calculated as $V_h = (k/n)*(dh/dl)$. I have assumed, for purposes of this illustration, that the SMS has the following parameters: an average k of 51.8 feet/day (mean of the range per Waldron and Larsen, 2015), 30 percent porosity (per page 6 of Dr. Waldron's expert report), and an average pre-development hydraulic gradient of 0.00033 feet/foot (per Criner and Parks, 1976). These values yield a calculated V_h of 0.057 feet/day (20.8 feet/year), which translates to only 2,725 feet (~0.5 miles) of natural groundwater migration between 1886 and 2017 (131 years) *if* there had been no steepening of the hydraulic gradient by massive pumping in Shelby County, Tennessee.

In my report, I noted that a relatively slow example of stream flow will transport water more than 16 miles in a day, which is more than 30 times as far in a single day as what the SMS groundwater would have migrated in 131 years if not for the intense pumping in Shelby County, Tennessee. Put another way, my hypothetical stream will transport a specific quantity or mass (packet) of surface water farther in a single day than an equivalent packet of groundwater in the SMS would travel in 4,061 years <u>if</u> the groundwater is flowing under the <u>pre-development</u> hydraulic gradient. The roughly five-fold steepening of the hydraulic gradient attributed to copious withdrawals in Shelby County, Tennessee, by Criner and Parks (1976) accelerated flow velocity to a calculated SMS groundwater flow rate towards Tennessee of approximately 120 feet per year.

The border between Mississippi and Tennessee along the east-west length of Shelby County is approximately 37.6 miles in length. Assuming the pre-development hydraulic gradient of Criner and Parks (1976) and flow parallel to that state boundary at approximately 20.8 feet per year, my back-of-the-envelope calculations indicate that a generic packet of SMS groundwater would require more than 9,500 years for SMS groundwater to traverse this 37.6-mile east to west trip within Mississippi. The United States is only 241 years old, or roughly 1/40th of the 9,500-year age of that illustrative groundwater packet migrating parallel to the state boundary located between Shelby County, Tennessee, and DeSoto County, Mississippi. For all practical intents, the natural groundwater in the SMS in Mississippi would *not* have left the state to any appreciable degree if massive quantities of groundwater had not been pumped out of the SMS in Shelby County, Tennessee. Nevertheless, even though groundwater may be flowing slowly, the area and thickness of the SMS are large, and the volumes of water moving each day across the Mississippi-Tennessee border under the influence of pumping in Shelby County, Tennessee, are immense. This subject is addressed in Section VIII.

VII. Summary of My Evaluation of the Expert Report by Steven Larson

I have evaluated the expert report submitted by Mr. Steven P. Larson in support of the defendants. Mr. Larson cites four (4) core opinions in support of his conclusion that "*the groundwater of the Middle Claiborne aquifer is an interstate water resource*" (Page 2, paragraph 4). His four opinions are essentially variations on an initial position that conflates a broad regional view of the Middle Claiborne aquifer (aka, the SMS) with the more nuanced issues that exist at the border area between northwestern Mississippi and southwestern Tennessee. I address Larson's four opinions individually below in the order that he presents them.

Larson, page 2: "*Opinion 1. The Middle Claiborne aquifer and the groundwater within it constitute an interstate resource because they form a single hydrological unit that extends beneath eight states: Louisiana, Mississippi, Tennessee, Arkansas, Alabama, Kentucky, Illinois, and Missouri.*"

Larson disregards the differences between a geologic formation and an aquifer. The Eocene-age geologic materials comprising the Claiborne Group include multiple formations of varying lithology, specifically including the deposits known as the Sparta Sand and Memphis Sand in Mississippi and Tennessee, respectively. Those geologic deposits are <u>not</u> an aquifer except where saturated by groundwater and where other criteria are met, such as the ability to produce sufficient quantities of water for use by people. The solid materials and/or the water moving slowly through that regional aquifer system most certainly does not represent a single, homogeneous entity.

The Sparta-Memphis Sand and related time-contemporaneous geologic deposits do exist beneath multiple states within the structural sedimentary basin known as the Mississippi Embayment. Larson's claim is incorrect that "*As in all aquifers, the groundwater in the Middle Claiborne aquifer is hydraulically and hydrologically connected. There is no physical impediment that precludes groundwater from migrating across State boundaries under natural conditions within the Middle Claiborne aquifer.*" (page 2, paragraph 5). In fact, most named aquifers are highly complex mixtures of rock, sediment, and water. The rate and direction of groundwater migration and 'connection' in those aquifers under natural conditions varies tremendously, both vertically and horizontally, as a function of the geology and setting of a specific location. This inherent heterogeneity is most certainly true of the SMS on the scale of the Mississippi Embayment that Larson is focusing on in his expert report. For example, in the vicinity of the Mississippi-Tennessee border area, the SMS contains a 'transition' zone (a sedimentary facies change) in northern Mississippi (e.g., Hosman and others, 1968; Reed, 1972) at roughly 34.8 degrees north latitude where the relatively low-permeability Cane River Formation to the south becomes more sandy and permeable, thus 'thickening' the Sparta Sand as it merges with the Memphis Sand north of the 'transition' zone (see Figure 4) to 'become' what is termed here the Sparta-Memphis Sand. Likewise, it is well known that "...*there are many normal faults with vertical displacements ranging from about 50 to 150 feet*" that crosscut and displace the SMS in and near Shelby County, Tennessee (Kingsbury and Parks, 1993, page 1). Differences in sedimentary lithology and/or vertical and lateral continuity of the SMS can and do influence greatly the rate and pattern of groundwater flow within the Middle Claiborne aquifer system, especially at the scale of the Mississippi-Tennessee border region under discussion here.

Another key aspect of inherent aquifer heterogeneity involves geologic time. Virtually all aquifers consist of materials with relatively high and low permeability. If groundwater migration in more permeable portions of the aquifer occurs at, for example, a rate of 20 feet per year, then flow in low-permeability portions of that same aquifer may occur at a rate several orders of magnitude slower (e.g., 0.02 feet per year). Hydrogeologists have long recognized that hydraulic head patterns change significantly at boundaries between materials with different permeability, and therefore flow patterns will also change. One simply cannot claim that because similar solid geologic materials hosting groundwater exist across multiple states, the entrained groundwater necessarily behaves the same in all places and at all times; that is simply not true. The pervasive hydraulic 'connection' that Mr. Larson claims is only present as a pressure distribution within confined portions of an aquifer, not as any wholesale exchange of groundwater due to the important but too often overlooked component of <u>time</u> that I discussed in the previous section. My professional experience has shown that there can be substantial differences in aquifer geology and hydraulic characteristics within a single well field, to say nothing of an area the size of Shelby County, Tennessee, or the larger Mississippi-Tennessee border region under discussion herein.

Larson, page 3: **"***Opinion 2. The Middle Claiborne aquifer and the groundwater within it constitute an interstate water resource because they are hydrologically connected to other bodies of interstate groundwater and surface water***."** Larson claims that the Mississippi Embayment Regional Aquifer System Study (MERAS) produced by the USGS, a computer modeling framework or tool, can "...*be used to refer to either the aquifer system or the aquifer study because they are essentially one and the same*." (page 3, paragraph 9). Here, he improperly conflates a very large and extremely complex natural system with a computer simulation that attempts to mimic some aspects of the natural system by employing a necessarily large number of simplifying assumptions; these two things are most certainly <u>*not*</u> "one and the same" in <u>any</u> sense. Larson attempts to merge these two distinct things by invoking the scientific reputation of the USGS to support an opinion that is not an expert geological or hydrological opinion. Larson actually acknowledges that he is conflating a physical system with a computer simulation to meet his objective by stating that "*The fact that the numerical models of the Middle Claiborne are grounded on interstate connections and intend to simulate interstate conditions further supports my view that the groundwater within the Middle Claiborne aquifer is an interstate resource*." (page 3, paragraph 10).

While one USGS publication describes their computer framework as a "...*tool that is useful for interstate sustainability issues while focusing on a particular State*..." (Clark et al., 2013, page 2), my search of the pertinent MERAS literature has revealed that this is the <u>only</u> instance where the USGS has used the words 'interstate' or 'intrastate' in <u>any</u> context. Likewise, Larson's claim that "...*a hydrologist cannot create a numerical model of the groundwater in the Middle Claiborne aquifer without reference to the MERAS as a whole*." (page 13, paragraph 44) is astonishing and conflicts with the facts. Computer simulations have long been created, tested, and used by many entities other than the USGS, sometimes in order to capture and evaluate details or scenarios that cannot be simulated accurately by the MERAS code because of the inherent limitations and simplifying assumptions of the USGS' tool. Furthermore, depending on Mr. Larson's use of his broad definition of the term 'MERAS', it is not necessary for a computer simulation to consider all confining beds and permeable zones above and/or below an aquifer of interest to evaluate specific issues of interest.

Larson, page 4: "*Opinion 3. The groundwater within the Middle Claiborne aquifer under Mississippi is an interstate water resource because, under any reasonable assumptions, none of the groundwater beneath Mississippi, under current or historical conditions, would remain permanently within* ***Mississippi's territory*.**" Larson states that "*Groundwater that is "stored" within the aquifer system is not static*." (page 4, paragraph 11) From a technical standpoint, groundwater in the SMS in Mississippi is not 'static', nor is it flowing dynamically like surface water. Larson simply ignores the key components of natural groundwater flow direction and time of travel. My illustrative calculations in the expert report and in this addendum report represent the scientific reality that groundwater within Mississippi in the SMS aquifer originated and resided within Mississippi's state territory for thousands of years under natural conditions on a slow-motion journey that has lasted many times longer than the United States has been in existence. Larson's <u>only</u> acknowledgement of the time component of groundwater flow is misleading at best: "*Because groundwater moves continuously (albeit slowly) under natural conditions, it eventually would have left Mississippi's territory – with or without any pumping – and would have been replaced by new groundwater recharge*..." (page 4, paragraph 12). The fact that this groundwater would *eventually* naturally leave Mississippi many thousands of years after it initially entered the subsurface by recharge has <u>no</u> practical application to the issue of whether the groundwater is a natural resource within the territory of the state of Mississippi.

Larson's justifying paragraph 13 contains several fundamental misstatements about hydrogeology that appear designed to confuse or misrepresent the concept of an aquifer's groundwater budget. I surmise that Larson is attempting to justify his unsupported notion that massive groundwater pumping in Tennessee has not had, and will not have, any meaningful impact on Mississippi's natural groundwater resources. From a hydrologic standpoint, the reduction of pressure in a confined aquifer system induced by pumping will not only change the pattern and velocity of flow, it reduces the volume of recoverable groundwater and well yield, thus limiting the quantity that can be withdrawn by a well and increasing the total cost of recovery.

Larson, page 4: **"***Opinion 4. The United States Geological Survey has repeatedly recognized that the Middle Claiborne aquifer is an interstate resource***."** This is not an expert opinion of a geologist or hydrologist. Nor have I located a single written instance where the USGS has referred to the Middle Claiborne aquifer as an "interstate resource". As stated above, the USGS did use the word 'interstate' on one occasion, describing their computer framework as a "...*tool that is useful for interstate sustainability issues while focusing on a particular State*..." (Clark et al., 2013, page 2). This single statement by the USGS is not a comment about, or opinion on, any aspect of any state's claim to, or management of, the naturally present groundwater within its borders.

The mission of the USGS is to serve the national interest by supplying scientific information that others may then use to make informed decisions. The USGS does not have the mandate or authority to manage groundwater or dictate patterns of groundwater use within the borders of the separate states. The USGS has developed a computer simulation that it makes available to others (e.g., individual states) to better understand and visualize how groundwater within a large regional system of aquifers behaves, and that tool facilitates simulation of past, present, and future events on a groundwater system or component of interest. How the USGS *views* aquifer systems is important to how they choose to study those features, and potentially to make recommendations that may assist the state's use and regulation of its groundwater resources. However, the USGS does not address the rights of the respective states regarding the groundwater within their borders, and it specifically does not address the origin and location of the specific groundwater in Mississippi that is in dispute.

To summarize, Mr. Larson's position that the groundwater in the entire Middle Claiborne aquifer is an interstate resource is predicated on: (1) conflation of a massive geologic feature (Claiborne Group sedimentary deposits) with a hydrogeologic feature (water-producing portions of an aquifer system); (2) a simplistic view that, because the geology of an aquifer system may exist across state lines, the groundwater within that system must be considered an interstate resource, and specifically without regard to the natural hydrologic conditions under which the groundwater was recharged, exists, and ultimately discharges within separate states; and, (3) what he contends to be authoritative declarations of the USGS that he adopts as support for his opinion. As such, his opinions do not address the factual and scientific issues relating to the specific groundwater underlying Mississippi and Tennessee which are critical to understanding the natural occurrence, availability, sustainability, protection, and conservation involved in this dispute. These are the issues that are unique to each specific occurrence of groundwater natural resources that must be evaluated in each dispute of this type.

VIII. Summary of My Evaluation of the Expert Report by Brian Waldron

I have evaluated the expert report submitted by Dr. Brian Waldron in support of the defendants. Waldron focuses throughout his report on the question of "*whether the groundwater in the middle Claiborne aquifer is an 'interstate resource'*" (page 2, paragraph 5). Groundwater is the issue at the heart of this legal matter, but the emphasis by Waldron is on the Middle Clairborne aquifer, which he defines as "*part of a larger set of aquifers within the regional geologic framework, the Mississippi Embayment*..." (page 2, paragraph 6). He cites two (2) core opinions in support of his conclusion that "*the water in the aquifer is an interstate water resource*" (Page 2, paragraph 8).

Waldron, page 2: "*Opinion 1: The Middle Claiborne aquifer extends continuously underneath Tennessee and Mississippi, and groundwater in the* ***aquifer is not and has never been "confined" to the borders of Mississippi or*** *any other state*." In his justifications for Opinion 1, Waldron introduces a convoluted definition of the term "confined" by stating that "*Mississippi's use of the term 'confined' implies that groundwater within a singular aquifer such as the Middle Claiborne does not flow laterally across state lines even though the geologic formation is continuous*..." (page 3, paragraph 11). I do not know the origin or intent of the verbiage that Waldron is supposedly referencing, but it is my opinion that the term "confined" is a hydrologic term with a specific meaning, and groundwater flows in both confined and unconfined aquifers in response to changes in hydraulic head.

I generally agree with the hydrologic use of the term "confined" as Waldron employs it (page 3, paragraph 10), although I disagree with Waldron that the presence of a less permeable layer (e.g., clay) above an aquifer necessarily makes the aquifer confined. For example, an aquifer with a clay layer above the aquifer that has a static water level below the top of the aquifer is not confined in a hydrologic sense because it exhibits a large value for storativity. Confined aquifers have small values of storativity relative to unconfined aquifers, and the degree of confinement of an aquifer is based on the actual value of storativity of that aquifer.

A single important scientific fact absent in Waldron's analysis and description of groundwater flow in the Middle Claiborne aquifer is the concept of groundwater velocity, or the amount of distance that groundwater travels per unit of *time*. My opinion is that groundwater in the Middle Claiborne aquifer naturally flows very slowly. Using the aquifer characteristics that I describe above in Section VI, and assuming Criner and Parks' (1976) pre-development hydraulic gradient in the SMS, groundwater in northwestern Mississippi would only be expected to move approximately 1,456 feet in an average human's lifetime (70 years times 20.8 feet per year), a distance of less than 0.3 miles! Even under Criner and Parks' (1976) pumping-steepened hydraulic gradient, the groundwater in the SMS would be moving from Mississippi and toward Memphis and Shelby County, Tennessee, at a rate of approximately 120 feet per year, or a distance of less than 1.6 miles in a lifetime. Considering such slow velocities, I can understand how the non-scientific community could perceive that groundwater is "confined" to a general location such as a state or county. Relative to a human life span, or even the age of the United States, groundwater seems to be immobile, and it certainly is *not* flowing at a rate anywhere close to that of stream or river water. Of course, MLGW's pumping continued after 1976, thus further steepening hydraulic gradients towards its well fields.

Regarding Waldron's use of the term "confined" for aquifer systems, it is my opinion that groundwater naturally flows very slowly in all portions of the Middle Claiborne aquifer. The fact that researchers such as the USGS have produced groundwater flow models that "…*treat as fundamental the fact that the Middle Claiborne aquifer is a single hydrological unit*" (page 3, paragraph 13) has nothing to do with the degree of hydraulic confinement of the aquifer. Waldron's entire discussion of whether or not groundwater is 'confined' to within Mississippi's borders is based on a failure to understand and/or acknowledge the component of natural flow time, and specifically the inherently slow nature of groundwater flow.

Waldron, page 3: **"***Opinion 2: Under predevelopment conditions, there was substantial flow of groundwater within the Middle Claiborne aquifer from Mississippi into Tennessee***."** Many of Waldron's claims in support of his second opinion are based on his own publication (Waldron and Larsen, 2015) regarding the predevelopment distribution of hydraulic head in the border region between northwestern Mississippi and southwestern Tennessee. He provides a detailed discussion of his perceptions of the many problems with water-level data used in other studies, primarily those performed by the USGS (e.g., Criner and Parks, 1976). As I describe above in Section III, it is ironic that Waldron and Larsen's 2015 analysis of pre-development hydraulic conditions in the Middle Claiborne aquifer relies upon data which fail to meet the rigorous criteria necessary for such studies (also see Appendix B-1 of my addendum report). I reiterate my opinion that the Waldron and Larsen (2015) interpretation of the SMS' pre-development equipotential surface is fundamentally and fatally flawed, and thus provides no reliable information about interstate flow prior to intense pumping in Shelby County, Tennessee.

I acknowledged in my expert report, and I reaffirm here, that there probably was a relatively small component of groundwater flow directed from Mississippi to Tennessee during pre-development time, as demonstrated by several studies other than Waldron and Larsen (2015). But, Waldron's extensive discussion of groundwater-flow patterns in a narrow strip of land adjacent to the state border (e.g., his Figure 10 on page 22) is, in my opinion, little more than a distraction. The more important issues concern the regional-scale flow patterns, velocity, and residence time of groundwater in the Middle Claiborne aquifer, especially in the context of post-development pumping by Tennessee. Extensive pumping of the SMS aquifer in southwestern Tennessee has altered significantly the natural groundwater-flow patterns, dramatically increased the hydraulic gradient toward MLGW's well fields, and markedly increased the rate and volume of groundwater flowing from Mississippi into Tennessee. Confined portions of the SMS aquifer are impacted significantly by those groundwater withdrawals and reductions in hydraulic pressure. Although groundwater flows very slowly in confined portions of the aquifer, the water is indeed moving. Groundwater in the aquifer within the State of Mississippi on the whole flows from recharge areas located in Mississippi, through the confined aquifer within Mississippi at very slow rates, and most of the water ultimately discharges to overlying aquifers and/or to streams and the Mississippi River within the State of Mississippi.

Waldron appears to be claiming in his expert report that groundwater is automatically an "interstate" resource if <u>any</u> component of groundwater flow in a regionally-extensive aquifer is directed from one State to another State under natural conditions over an extremely long period of time. I disagree completely with such an expansive definition. Waldron cites the fatally-flawed, pre-development equipotential map and study byEven if W&L 2015 (see Section VI) to claim (page 25, paragraph 51) that the volume of pre-pumping flow of groundwater from Mississippi to Tennessee in 1886 was approximately 49,136,000 gpd (~186,000 cubic meters per day, or m^3/day). Waldron concludes that by 2008, pumping had only increased the cross-border flow from Missississippi to Tennessee by about 9,250,000 gpd (~35,000 m^3/day), which equates to less than five (5) percent of the total daily withdrawals in Shelby County, Tennessee. If one assumes that Waldron's number are correct, then he is implicitly acknowledging that pumping in Shelby County, Tennessee, is causing about 3.38 Billion gallons of groundwater to leave Mississippi and enter Tennessee each year due to MLGW's pumping.

Assuming a north-south aquifer width of 300 miles, an aquifer thickness of 500 feet, and a hydraulic gradient of 0.001 feet per foot, I calculate that the <u>total</u> flow in the Middle Claiborne aquifer in Mississippi is approximately 591,740,000 gallons per day (~2,240,000 m^3/day). Even if one accepts Waldron's estimated volume of groundwater that left Mississippi and entered Tennessee under natural, pre-development conditions, that volume is roughly eight (8) percent of the total flow occurring solely within the State of Mississippi. The volume of water flowing from one state to another along a narrow section of a shared border should <u>not</u> be used to evaluate the nature of groundwater flow on a more regional scale, and it should not serve at the basis for defining the intrastate versus interstate nature of the groundwater resource.

<u>IX. Concluding Opinions</u>

From a hydrological perspective, the ultimate decision to classify groundwater in the Claiborne aquifer as an intrastate versus an interstate resource should be based on overall flow patterns within the aquifer, and not on flow patterns in the border region between states, as implied by Dr. Waldron's report. Alternatively, Mr. Larson's view that groundwater flow in a stratigraphically-equivalent aquifer located elsewhere in a very large sedimentary basin (e.g., northeastern Texas), and as modeled with a computer program replete with inherent assumptions and simplifications, has no potential bearing on this issue. It is well known that groundwater-flow patterns in an aquifer located within a state can be dramatically altered by groundwater withdrawals occurring nearby within adjacent states. An example of the impact of groundwater withdrawals on flow patterns in an adjacent state is the case of Hilton Head Island, South Carolina, a focus area for my own research for more than a decade. Prior to any development on Hilton Head Island, groundwater in the preferred aquifer was from south to north across the island. Extensive pumping by the City of Savannah, Georgia, located south of Hilton Head Island, resulted in a reversal of the natural groundwater-flow direction and caused saltwater to migrate into the aquifer beneath the island. Development in Georgia has rendered much of the preferred aquifer beneath Hilton Head Island unusable without costly treatment. This is but one example of predevelopment groundwater flow being dramatically changed by withdrawals initiated in an adjacent state.

It is clear that some aquifers extend over very large areas, including multiple states. However, the geographic distribution of those aquifers does not define the groundwater resources as interstate. Imagine a layer of coal that underlies the border region between two states; is the coal layer an interstate or intrastate resource? Would one state have the right to directionally bore and mine the coal from beneath the adjacent state? My opinion is that the answer to that question is <u>no</u>. Likewise, groundwater in the case of the Middle Claiborne aquifer in Mississippi is an intrastate resource that would not leave the state to any appreciable extent in the absence of intense pumping in adjacent Tennessee.

There is no dispute that withdrawing more than 180 Million gallons per day in southwestern Tennessee has changed the natural flow patterns in the Middle Claiborne aquifer in the trans-border region. Unless these withdrawals are reduced dramatically, the groundwater-flow patterns will <u>not</u> be returned to their natural, pre-development condition. The development potential of the natural groundwater resource (e.g., available drawdown) in northwestern Mississippi has been adversely impacted by the large-scale and long-term withdrawals in southwestern Tennessee. I fully described this impact on total available drawdown and the concept of a well's specific capacity in my expert report.

Mr. Larson and Dr. Waldron have evaluated and relied upon the work of the USGS very differently within their respective expert reports. On the one hand, Larson seems to believe that the USGS' computer modeling framework and tool can, and should, be used as a basis for classifying all SMS groundwater as a shared interstate natural resource. Conversely, Waldron provides a detailed critique of the work of the USGS, criticizing the quality of their underlying database and their analyses and interpretations of the pre-development groundwater conditions. In fact, the USGS is <u>not</u> an aquifer management or regulatory organization, it is a federal, taxpayer-funded scientific organization with the following water-related mission statement: "*Information about water is fundamental to the national and local economic well-being, protection of life and property, and effective management of the Nation's water resources. The USGS works with partners to monitor, assess, and conduct targeted research on the wide range of water resources and conditions, including streamflow, groundwater, water quality, and water use and availability*". (https://www.usgs.gov/science/mission-areas) The USGS' Water Resources Mission (https://water.usgs.gov/mission.html) is "*To provide reliable, impartial, timely information that is needed to understand the Nation's water resources. WRD actively promotes the use of this information by decision makers to –*

- *Minimize the loss of life and property as a result of water-related natural hazards, such as floods, droughts, and land movement. Effectively manage ground-water and surface-water resources for domestic, agricultural, commercial, industrial, recreational, and ecological uses.*
- *Protect and enhance water resources for human health, aquatic health, and environmental quality.*
- *Contribute to wise physical and economic development of the Nation's resources for the benefit of present and future generations.*

It is my opinion that the USGS does <u>not</u> exist to provide management directives or options for use of the groundwater resources by individual states. I find <u>no</u> consistent evidence in any USGS reports or statements that the agency has defined <u>any</u> specific groundwater resources as "interstate" with respect to state use or management options.

Several important concepts should be considered regarding classification of the groundwater resources of the Middle Claiborne aquifer as intrastate versus interstate. Because <u>no</u> criteria have been developed and vetted for classification of groundwater resources as either intrastate or interstate, my opinion is that management of the groundwater resources of individual states should be left to the individual states. In this particular case involving this particular aquifer system, I see no hydrological basis for either state claiming a right to take any groundwater that occurs naturally in the other state without the neighboring state's permission. Different natural geological and hydrological conditions might demonstrate the presence of groundwater resource that is naturally shared by more than one state that simply cannot be developed by both states without producing an unreasonable impact on the other, but case under litigation here is not such a situation.

What are the specific criteria to be used to establish the definition of intrastate versus interstate groundwater resources? I have not found any statements by Dr. Waldron or Mr. Larson in their reports to clearly define the meaning of the term <u>interstate groundwater resource</u>, or identify valid general or specific criteria that can be used to define an interstate groundwater resource. In the remainder of this section, I offer my opinions on this subject, as an experienced practicing hydrogeologist specializing in the evaluation, development, and management of groundwater resources in aquifer systems analogous to those of the Mississippi Embayment.

First, it is my opinion that the claims by Waldron and/or Larson are <u>*NOT*</u> criteria that can be used to define the nature or classification of intrastate versus interstate groundwater resources. It is my opinion that:

- An aquifer system is *not* an interstate resource because the aquifer's geologic framework (i.e., solid parts of the system such as grains of sand, sedimentary rock, etc.) extends over large areas.
- An aquifer system is *not* an interstate resource because hydrogeologists and hydrologists study aquifer systems over large areas.
- An aquifer system is *not* an interstate resource because some well-meaning scientists have produced groundwater computer models that extend over multi-state regions.
- An aquifer system is *not* an interstate resource because a small percentage of groundwater flowing in the aquifer crosses the boundary from one state to another state.
- An aquifer system in *not* an interstate resource because a scientist says it is an interstate resource based on an interpretation of what the USGS may or may not have said.

It is my opinion that the definition of an intrastate groundwater resource must be based on the fate of water in the groundwater system under natural conditions. If the majority of groundwater in an aquifer enters the groundwater system by recharge within a specific state, and that water flows *VERY* slowly through the aquifer within that same state, such that the water remains in the state for *VERY* long periods of time before ultimately being discharged from the groundwater system, then that groundwater is an intrastate resource.

Aquifers are *not* rivers of water flowing underground. The residence time for groundwater in the hydraulically-confined portions of the Middle Claiborne aquifer within Mississippi is measured in thousands of years, not days. Groundwater in this important and valuable aquifer is a life-sustaining resource for the residents of Mississippi, and it is an intrastate resource as based on my definition.

It is also my opinion that decisions regarding the classification of groundwater resources as intrastate versus interstate should not be conducted without a detailed consideration of the advantages and disadvantages of such a classification on the ability of a state to protect and manage the resource for the full benefit of its citizens. My professional experience has provided many examples of groundwater resource management issues that involve the problematic withdrawal of water from regionally-extensive confined aquifer systems by water purveyors located in border regions between states. In my experience, it is *not* the withdrawal of groundwater from these aquifers by production well fields located significant distances from state borders that is problematic. The conflicts occur in border regions between states when water purveyors unilaterally develop large-scale groundwater systems near state borders and create regional-scale cones of depression. My recommendation is to encourage states to use their state-specific regulatory framework to *not* allow the development of large-scale pumping centers located in trans-border regions if scientific studies indicate that such development will have a clear detrimental impact on the groundwater resources of the neighboring state.

Appendix A-1: List of References

This list supplements Appendix A of the expert report, and it includes references cited in Addendum #1. Additional documents and data may be reviewed or considered.

Arthur, J.D. and Taylor, R.E., 1998, Ground-Water Flow Analysis of the Mississippian Embayment Aquifer System, South-Central United States, U.S. Geological Survey Professional Paper 1416-I, 148 p.

Clark, B.R., and Freiwald, D.A., 2011, A new tool to assess groundwater resources in the Mississippi embayment: U.S. Geological Survey Fact Sheet 2011–3115, 4 p.

Clark, B.R., and Hart, R.M., 2009, The Mississippi embayment regional aquifer study (MERAS): Documentation of a groundwater-flow model constructed to assess water availability in the Mississippi embayment: U.S. Geological Survey Scientific Investigations Report 2009–5172, 61 p.

Clark, B.R., Westerman, D.A., and Fugitt, D.T., 2013, Enhancements to the Mississippi Embayment Regional Aquifer Study (MERAS) Groundwater-Flow Model and Simulations of Sustainable Water-Level Scenarios, U.S. Geological Survey Scientific Investigations Report 2013-5161, 29 p.

Criner, J.H., and Parks, W.S., 1976, Historic water-level changes and pumpage from the principal aquifers of the Memphis area, Tennessee: 1886–1975: U.S. Geological Survey Water-Resources Investigations Report 76–67, 45 p.

Kingsbury, J.A., and Parks, W.S., 1993, Hydrogeology of the principal aquifers and relation of faults to interaquifer leakage in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93–4075, 18 p.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416–B, 19 p.

Larson, S.P., 2017, Expert report of Steven P. Larson, 46 p.

Leggette, Brashears & Graham, Inc., 2014, Update report on diversion and withdrawal of groundwater from northern Mississippi into the state of Tennessee, 24 p.

Reed, J.E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geological Survey Hydrologic Atlas, HA 434, 5 maps.

Schrader, T.P., 2008, Potentiometric surface in the Sparta-Memphis aquifer of the Mississippi Embayment, spring 2007: U.S. Geological Survey Scientific Investigations Map 3014, 1 sheet.

Waldron, B., 2017, Expert report of Brian Waldron, Ph.D., 37 p.

Waldron, B., and Larson, D., 2015, Pre-development groundwater conditions surrounding Memphis, Tennessee: Controversy and unexpected outcomes, Journal of the American Water Resources Association, v. 51, p. 133-153.

Appendix B-1: Evaluation of the Well Data Used by Waldron and Larsen (2015) to Produce Figure 4 of Their Report

Data Sources Cited by Waldron and Larsen (2015)

Crider, A.F., and Johnson, L.C., 1906, Summary of the underground-water resources of Mississippi: U.S. Geological Survey Water-Supply and Irrigation Paper No. 159, 86 p.

Fuller, M.L., 1903, Contributions to the hydrology of eastern United States: U.S. Geological Survey Water-Supply and Irrigation Paper No. 102, 522 p.

Glenn, L.C., 1906, Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geological Survey Water-Supply and Irrigation Paper No. 164, 173 p.

Well #1 at Turrell, Arkansas (Fuller, 1903). Exact location of the well is not known. Location of the Baker Lumber Company property was apparently selected from a search of the name Baker within the Tyranza Township. Then, the land surface elevation was estimated for this property location. Local elevations at Turrell range from approximately 202 feet (61.5 M) at Big Creek to approximately 225 feet (68.6 M) in the center of Turrell. Well construction details are not reported (i.e., screen interval of the well and whether or not the casing was grouted). Method of water depth measurement is not reported. Height of the top of well casing is also not reported.

Well #2 at Helena, Arkansas (Fuller, 1903). Means of water level measurement not specified. Accuracy of reading reported is unknown. Well construction details (screened interval and status of grouting of the well casing) are unknown. Status of well pumping relative to water-level measurement is unknown (i.e., was the reported water level the original static level or had the well been in operation for some period of time before the water level was reported). Water level is referenced below the "mouth" of the well, but the height of the well "*mouth*" relative to land surface is not referenced. Because the elevation of the original "*mouth*" of the well is unreported, and because Waldron and Larsen rounded the reported water level to the nearest meter, it is incorrect to list the estimated vertical error as 0.0 M within Table 1. Rounding the water level from 30 feet to 9 meters already introduces a minimum error of 0.146 meters.

Well #3 at Forest City, Arkansas (Fuller, 1903). Well construction details (screen placement, grout interval, and height of "*mouth*" of the well) are unknown. Rounding of water level from 160 feet to 49 meters incorporates an error of 0.22 meters. Rounding of the land surface elevation to the nearest whole meter also incorporates an error. Likewise, the unknown height of the "*mouth*" of the well adds uncertainty as to the elevation reference for the reported water level. Therefore, it is incorrect to represent the estimated vertical error as 0.0 meters. Status of well pumping relative to water-level measurement is unknown (i.e., was the reported water level the original static level or had the well been in operation for some period of time before the water level was reported).

Well #4 at Hernando, Mississippi (Crider and Johnson, 1906). The data source describes, in general terms, some information about depth, stratigraphy, yield, and water level for "*a well in Hernando*." Ownership of the well and the well's specific location are not provided. Methods of measurement of water level are not presented. Waldron and Larsen summarize information about the well in Table 1. The reported well depth (165 feet on Table 1) does not match the documentation in Crider and Johnson (1906) where the total drilling depth can be calculated to be 220 feet. Well construction details (depth, screened interval, and depth of any grout seal) are not presented in Crider and Johnson. Waldron and Larsen locate the well at the "*City center*" and they estimate the land surface elevation to be 109 meters AMSL. A review of the USGS topographic quadrangle map of Hernando indicates that land surface elevation within Hernando ranges from about 350 feet (106.7 meters) to over 400 feet (~122 meters), a range of more than 15 meters. However, Waldron and Larsen suggest that their estimated vertical error is only 4.2 meters. Furthermore, the method of measurement of the estimated water level, the date of measurement, and whether the water level is an original static level versus the reported level in 1906 after some years of pumping at the reported 150 gallons per minute is unknown.

Well #5 at Holly Springs, Mississippi (Fuller, 1903). Reportedly, there are two adjacent wells on the same site. It is not known how the water-level was measured and whether or not one or both of the wells on site may have been pumping. Height of the mouth of the well is unreported. Waldron and Larsen report that method of location is "*Located in the town center.*" Exact location of well (and associated land elevation) is unknown. Local land elevation at Holly Springs varies from 530 feet (161.5 m) to 620 feet (189 m) AMSL. Waldron and Larsen indicate a vertical error of only 2.5 meters, but clearly the elevation error is likely much greater than that.

Well #6 at Hudsonville, Mississippi (Fuller, 1903). The data source does not identify specific well location at Hudsonville. Waldron and Larsen researched property records from 1900 census to identify property that they assumed to represent the well site, they then assumed a location (and associated elevation) on that property. The local topography near Hudsonville includes significant elevation variances, ranging from about 460 feet (140 m) to about 520 feet (158.5 m). Therefore, the potential elevation error for the well location could be as much as 18.5 meters. The height of the mouth of the well above land surface is unknown. The method of water-level measurement and the accuracy of measurement is unknown. The depth of the well is reported to be 168 feet, and the well was indicated to have only 15 feet of water depth. Details of well construction are unknown, including type and depth of well opening, construction method, and grout seal (if any). The reported water depth of 153 feet is much deeper than would be expected for an unconfined section of the aquifer, especially considering that the nearby perennial stream (Coldwater River) at Hudsonville has a local elevation of 460 feet (140 m). The calculated water elevation (104 m) presented in the Waldron report would be 36 meters <u>lower</u> than the Coldwater River elevation. This would not be expected if the Memphis Aquifer were unconfined at Hudsonville. Based upon documentation of Well #6 at Hudsonville, it is not appropriate to rely upon this well for mapping the pre-development potentiometric surface mapping for the aquifer.

Well #7 at Canadaville, Tennessee (Glenn, 1906). However, the discussion of groundwater conditions at Canadaville is <u>not</u> about any specific individual well example. Glenn discusses generalities about depths of wells and estimated depths to groundwater levels. Waldron and Larsen incorrectly list a specific well at Canadaville with a depth of 150 feet. No such well is mentioned in Glenn for this location. Likewise, the mention of depth to the water level being 125 feet is not specific to a particular well. Rather, the report states "*Some small bored wells, ranging from 90 to 140 feet in depth, yield an abundant supply of good soft water, but in the deeper wells it rises only within 125 feet of the surface.*" It is important to note that topography in the area near Canadaville varies from a high of about 477 feet (145 M) MSL to a low of about 375 feet (114 M). Because no specific well location is referenced in Glenn for the reported 125 feet depth to groundwater, the selection of an estimated land surface elevation in the Waldron report is arbitrary and unreliable. The elevation error for this estimated location could be as much as 31 meters, depending upon the specific location selected as representative of the well site used for Well #7. The water-level contouring presented in Waldron and Larsen's Figure 4 or their report is strongly influenced by the estimated water level value shown for Well #7. This is unfortunate, because the cited reference for this water-level does not reflect any specific well location in the area.

Well #8 at Claxton, Tennessee (Glenn, 1906). The discussion of conditions at Claxton does <u>not</u> reference any specific well, and instead Glenn describes wells typical in the area and states that wells "*may go 75 to 100 feet deep, and the water rises within about 40 feet of the surface.*" The location selected for the well is based upon an interview with an elderly lady who supposedly worked for the Claxton family. No specific details of well locations are available for this station. Clearly this discussion of generalities and approximations should not be relied upon for contouring of an equipotential map.

Well #9 at Ina, Tennessee (Fuller, 1903). The exact location of the well is not known. The location of the well was assumed by Waldron and Larsen based upon property records and research of the OMNI Gazetteer. Well location and elevation cannot be verified, and the height of the well opening is not known. The reported well depth and water depth cannot be verified, and the method of water-level measurement (and accuracy of measurement) is also not known. Using topographic maps, the land elevation near Ina ranges from 480 feet (146 m) to 520 feet (158 m).

Well #10 at LaGrange, Tennessee (Glenn, 1906). The exact locations of wells referenced in the source publication are not known. General statements are made about wells being drilled to 175 and 213 feet depth. No specific measurement of water depth is referenced for these wells in LaGrange. Waldron and Larsen assume incorrectly that well depth equates to non-pumping water level depth by selecting a water depth of 194 feet (59 m). Because one well referenced by Glenn was stated to be 175 feet depth, it is certainly not clear that the depth to water was less than 175 feet pre-development. There is no reasonable way that one could conclude that the pre-development water level could be as deep as 194 feet at LaGrange. It is obvious that there is <u>no</u> reliable means of determining a pre-development water level for the Town of Lagrange to use for preparing an equipotential contour map. Furthermore, the Glenn (1906) publication states explicitly that the Town of LaGrange is "*532 feet above the sea.*" But, the Waldron report selects a land surface elevation of 165 meters (541 feet) for calculating a water elevation. Because the specific locations of wells are not known, the adjustments of land elevation for this datum are based upon assumptions that simply cannot be tested. The estimated water level for LaGrange are totally unreliable and further render the pre-pumping equipotential map of Figure 4 to be incorrect.

Well #11 at Moorman, Tennessee (Glenn, 1906).. As with many other wells used by Waldron and Larsen to produce their pre-development equipotential map, the exact location of the well(s) is not identified. Glenn reports that, "*One 103 feet deep struck water of good quality at 53 feet.*" This statement does not say that the static water level was 53 feet deep, it just implies that water was "*struck*", which could mean that water-bearing strata were encountered at 53-feet depth during drilling. The non-pumping water level is not known for this well. Nonetheless, Waldron and Larsen chose to use the 53 feet depth as a non-pumping water level for a well with an unknown location and unknown construction. Furthermore, the location listed in Table 1 of Waldron and Larsen is "*Intersection of Hwy 222 and Winfrey*" which corresponds closely to the location of Well #8 at Claxton.

Well #12 at Moscow, Tennessee (Glenn, 1906). Again, the reference provided by Glenn only relates to the target depth of drilling at which water-producing materials are reportedly encountered. No specific wells are referenced as to location and specific construction details. Glenn makes <u>no</u> explicit statement referring to the depth to which water is measured in a well, let alone under non-pumping conditions, so this location should not be used for contouring the pre-development equipotential surface of the aquifer. Instead, Waldron and Larsen chose to arbitrarily select the location of the "*well*" at the town center, which is not supported by any specific historical records. Glenn also reports generally that "*...water is found in abundance at depths of 60 to 80 feet*". Waldron and Larsen assumed a specific value of 69 feet as the water level for their mapping purposes, which is 9 feet below the reported minimum depth of 60 feet referenced by Glenn. There is no justification for Waldron and Larsen's arbitrary assignment of this water level depth. Finally, Table 1 incorrectly lists the estimated water elevation as 27 meters; the estimated value shown on Figure 4 for this station is 87 meters.

Well #13 at Oakland, Tennessee (Fuller, 1903). Specific location of the well is not known from information presented by Fuller. Waldron and Larsen arbitrarily select a location in the center of a block defined by four roads, even though the "s*upplemental information*" in their Table 1 states that there is "*no location information*". Based upon a USGS topographic map, the land elevation at Oakland ranges from 350 to 400 feet elevation. Waldron and Larsen use an assumed land elevation at the assumed well location of 116 meters (380.5 feet), but the actual well elevation could be as low as 107 meters to as high as 122 meters, depending on where the actual well was originally located. Although the depth to the water level in the well is reported as 75 feet below the "mouth" of the well, the method of water-level measurement is not stated, and the degree of accuracy of this water level is simply not known. Also, the height of the "mouth" of the well above land surface is not known. Finally, the original source (Glenn, 1906) states that "*At Oakland, elevation 388 feet, the wells are from 60 to 125 feet in depth.*" This information suggests that water level depths shallower than 75 feet may have occurred at Oakland prior to extensive pumping of the aquifer at Memphis.

Well #14 at Rossville, Tennessee (Glenn, 1906). No specific location of a well is given for the Town of Rossville. Waldron and Larsen arbitrarily selected a well location at the intersection of Main Street and the railroad. Glenn actually states that "*At Rossville, elevation 311 feet, water is obtained from white sand beneath a layer of pipe* *clay at 28 to 35 feet*". No well depth is reported, and no specific water level measurement is reported for a well tapping the "white sand". Waldron and Larsen assumed a depth to water of 32 feet (10 M) for the pre-development water level at Rossville, but this assumption is not supported by any actual data for a well at Rossville.

Well #15 at Somerville, Tennessee (Glenn, 1906).. Glenn presents some generalities about multiple wells drilled from depths of 100 to 150 feet at Somerville. No specific well location is described, however, Glenn does reference a land elevation of 356 feet (108.5m). Inexplicably, Waldron and Larsen decided to adjust the assumed land surface elevation at Somerville upward by 8 meters (or 26 feet) based upon their arbitrary selection of the well location. This is a large adjustment and injects a significant potential error to the Well #15 data. Furthermore, Waldron and Larsen use a water depth of 50 feet (15 m) for this location, despite Glenn's specific statement that "*The water rises in some of these* (wells) *within 50 feet of the surface*". Because Glenn's term "*within*" means inside of or less than, assigning 50 feet as the water depth for Well #15 will produce a water elevation that is too low. [Fuller (1903) mentions a specific well owned by C.W. Robertson, but the location of that well is still not known.]

Well #16 at Taylor's Chapel, Tennessee (Fuller, 1903). The exact location of well is not identified. Waldron and Larsen assumed a land surface elevation of 109 meters (357.5 feet). Local topography of the Taylor's Chapel area ranges from approximately 340 feet to 370 feet in the vicinity of Taylor's Chapel church and the Taylor's Chapel cemetery. Water depth is reported at 60 feet below the "mouth" of the well, but the actual elevation of the "mouth" is not known. Means and accuracy of the water depth measurement is not reported. Glenn (1906) provides additional information about water depth at Taylor's Chapel, stating that "*At Taylors Chapel water is obtained from some good strong springs and wells that range from 25 to 125 feet in depth. In many places at depths of 30 to 40 feet a stratum of black mud is struck, averaging about 40 feet thick and furnishing foul-smelling water. It is underlain by a thin ironstone layer and when this is pierced good water, that rises 30 or 40 feet, is found in abundance.*" Based on Glenn's description, a well drilled to 70 or 80 feet depth would have a non-pumping water level of 30 to 50 feet depth. This suggests that the 60 feet water depth assigned by Waldron and Larsen to the Taylor's Chapel area may be too deep by 10 to 30 feet.

Well #17 at Belle Eagle, Tennessee (Fuller, 1903). Fuller does not indicate the land surface elevation of Belle Eagle or the exact location of the well used by Waldron and Larsen. The well location is only referenced relative to a property owner (R.H. Taylor). The USGS topographic map of the Belle Eagle area indicates that local land elevation ranges between approximately 320 and 370 feet AMSL. The method of water depth measurement and height of the well casing are not reported. Well construction details are not provide, nor is information about the lithology of sediments encountered or tapped by the well. The well depth is 70 feet, which makes it uncertain if this well actually penetrates the Memphis Sand.

Well #18 at Brownsville, Tennessee (Glenn, 1906). Glenn states that the land surface elevation at Brownsville is 344 feet (105 meters) AMSL. Waldron and Larsen adjusted the assigned land elevation upward to 108 meters AMSL. Glenn reports multiple wells at Brownsville, and the water level depth (14 meters) reported for Well #18 is apparently an average from a number of wells in Brownsville. Averaging the depth to water is inappropriate where the land surface elevation has variability. The topographic variation at Brownsville is substantial (ranging locally from less than 337 feet to more than 390 feet AMSL). The method of water depth measurement is not reported, nor is the height of the top of well casing. Glenn describes large withdrawals (150,000 to 500,000 gallons per day) from individual municipal wells at Brownsville. The original (pre-development) static water level at Brownsville is not reported. Considering the large withdrawals reported from multiple wells at Brownsville, one must conclude that the water levels reported by Glenn have been lowered as a result of local groundwater withdrawals. Therefore, these water-levels cannot be equated with pre-development groundwater levels, but Waldron and Larsen elected to do so anyway.

Well #19 at Forked Deer, Tennessee (Fuller, 1903). No data on the land surface or exact well location is provided by Fuller for the well at Forked Deer. Waldron and Larsen estimated the land surface to be 106 meters AMSL based upon the well owner named H.A. Rainey. The method of water depth measurement is not reported, nor is the height of the top of well casing. Waldron and Larsen describe the well as being free flowing, but Fuller lists the depth to water at -0 feet. If the well was a free-flowing artesian well, then the static water level would actually be at some (unknown) height above the top of the well casing.

Well #20 at Ged, Tennessee (Glenn, 1906). The elevation was determined for Ged by triangulation "from current road intersections to historic location". The "Hinkle well" was located "half a mile" in no specific direction from the town of Ged on "high ground". So, it seems the elevations assigned to the town and to the Hinkle well are essentially guesses that render any water level elevation data suspect or useless. The Hinkle well is listed as having a water level that rises to "within" 60 feet of the surface. Waldron and Larsen assign 60 feet (18m) as the depth to water at this unknown location on "high ground". The reality is that Waldron and Larsen have no reliable knowledge of the well location or depth to water at Ged.

Well #21 at Keeling, Tennessee (Glenn, 1906). Very minimal well information is listed by Glenn, essentially that there are a number of wells in the area and one of them is 96 feet deep with a water-level within 46 feet of the land surface. The exact location of that, or any, well is not known. The land surface elevation was estimated based upon a general location of the town, and the land surface elevation in the immediate vicinity of Keeling can vary by more than 40 feet. Well construction details are not reported, nor is the method of measuring the depth to water. Lithology penetrated by the well is not reported, and it is not known if the well reported by Glenn actually taps the Memphis Sand.

Well #22 at Stanton Depot, Tennessee (Glenn, 1906). Glenn says that the <u>town</u> elevation is 290 feet AMSL, but there is no mention of land surface elevation for any specific well in or near the town. Glenn states that water rose to within 40 feet of the land surface when an "indurated layer had been penetrated", but there is no mention of a specific well or location. Waldron and Larsen decided that the land surface elevation at the "well" was 13 meters (41 feet) <u>higher</u> than the elevation reported by Glenn.

There is no justification for making this large adjustment in land surface elevation. If the depth to water was 40 feet and the land surface was 290 feet, as stated by Glenn, then the water-level elevation would be 250 feet (76 meters) AMSL. The method of water depth measurement, the height of the top of well casing, and the construction of the well are not reported by Glenn.

Well #23 at Arlington, Tennessee (Fuller, 1903). The depth of the well listed in Waldron and Larsen's Table 1 (228 feet) does not match the original data provided by Fuller (221 feet). Waldron and Larsen incorrectly report the water-level elevation that they assigned to Well #25 in Table 1 as 25 meters, although they correctly list the water level elevation (81 meters) on Figure 4. The exact location of the well is not known. The land surface elevation was estimated based upon a general location of the town. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #24 at Bleak, Tennessee (Glenn, 1906). Only minimal well information is listed by Glenn, although he reports that there is a well 176 feet deep with a water level within 47 feet of the land surface. The exact location of the well is not known, and Bleak is no longer an established town. The land surface elevation was estimated based upon a general location of the town from a 1916 U.S. Soils Map. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #25 at Collierville, Tennessee (Glenn, 1906). Glenn states that there are two wells, six feet apart, at depths of 239 and 248 feet with water levels between 95 and 100 feet below land surface. Waldron and Larsen assigned 95 feet as the depth to water, but that depth could just as easily have been 100 feet based on Glenn's report. Once again, the water-level elevation is incorrectly listed in Waldron and Larsen's Table 1 as 27 meters, although the correct water level value (90 meters) is listed on Figure 4. The method of water depth measurement is not reported. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #26 at Cordova, Tennessee (Fuller, 1903). The location of the well is not known, and the land surface elevation was estimated based upon a general location of the historic community. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #27 at Eads, Tennessee (Fuller, 1903). Minimal well details are reported by Fuller. The exact location of the well is not known, and the land surface elevation was estimated based upon a general location of the well owner from the 1910 Census. The local relief of the land surface elevation in Eads varies by as much as 50 feet, so a significant potential error is introduced by not knowing the location and assigning an elevation for the well head. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known. Fuller reported that the well was 100 feet deep, so it may be too shallow to be open to the confined aquifer.

Well #28 at Massey, Tennessee (Fuller, 1903). Fuller provides minimal well information. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #29 at Memphis, Tennessee (Glenn, 1906). Minimal details are provided in the original data source. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known. Glenn states that the well is "artesian", and Waldron and Larsen uses the land surface elevation to assign the water elevation, which by the very definition of a free-flowing well tapping a confined aquifer is too low. The height of the water elevation above the "mouth of the well" is not known.

Well #30 at Covington, Tennessee (Glenn, 1906). The discussion of conditions at Covington does not reference any specific well, and instead describes typical wells in the area by stating that the wells "*may go 75 to 100 feet deep, and the water rises within about 40 feet of the surface.*" Clearly, such a discussion of generalities and approximations should not be relied upon for contouring an equipotential map. This same situation describes other "wells" used by Waldron and Larsen (e.g., Well #8).

Well #31 at Ina, Tennessee (Fuller, 1903). The exact location of the well is not known, and the location and elevation were assumed based upon property records and research into the OMNI Gazetteer. Well construction, height of the well opening and method of measuring the depth to water are not known. USGS topographic maps indicate that the land elevation near Ina ranges from 480 feet (146 m) to 520 feet (158 m), so any assumed elevation based upon property records without specific details of a well location can result in an error in elevations assigned to the land surface and water level of up to 40 feet .

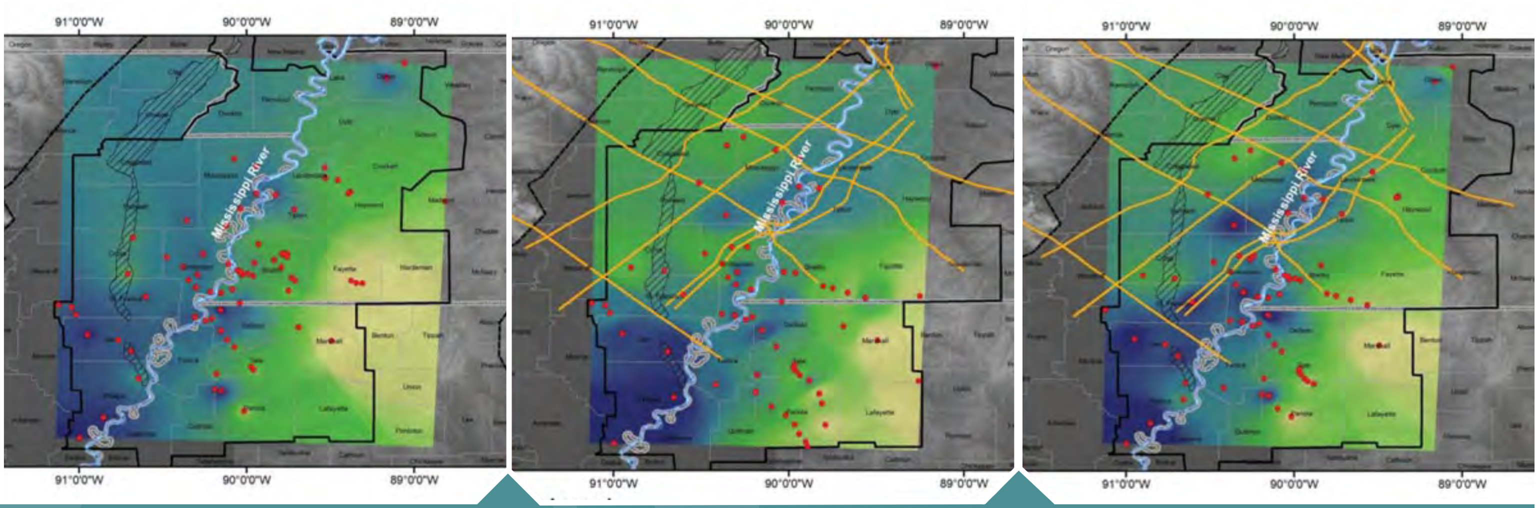
EXHIBIT 7

B. Waldron, D. Larson, et al,
Mississippi Embayment Regional Ground Water Study
EPA 600/R-10/130
January 2011
(Excerpts)

EPA 600/R-10/130 | January 2011 | www.epa.gov/ada

United States
Environmental Protection
Agency

Mississippi Embayment Regional Ground Water Study



Office of Research and Development
National Risk Management Research Laboratory, Ada, Oklahoma 74820

MS SCT 000787

Perform geologic mapping of the region

A hydrostratigraphic analysis of an aquifer system aims to identify the extent and hydrologic characteristics of water-bearing rocks and sediments in an aquifer system. Although the hydrostratigraphy of tertiary aquifers in the Mississippi Embayment (ME) has been evaluated on regional (Boswell et al., 1968, Cushing et al., 1964; Hosman et al., 1968; Cushing et al., 1970; Hosman and Weiss, 1991), state and local (Criner et al., 1964; Payne, 1968; 1973; 1975; Parks and Carmichael, 1989; 1990a; 1990b; Brahana and Broshears, 2001) scales, a hydrostratigraphic analysis at a subregional scale in the tri-state region of northern Mississippi, eastern Arkansas, and western Tennessee is needed to address stratigraphic problems and water resource sustainability. Because lithostratigraphic nomenclature and aquifer conceptualization differ among states, careful stratigraphic correlation and detailed aquifer assessment are needed to ensure consistency in hydrogeologic modeling. In addition, hydrostratigraphic subdivisions of aquifers and confining units may be necessary to assess water resources at the subregional scale.

The objectives of this section are outlined as follows:

- Acquire geologic, stratigraphic, and geophysical data in the region that will enable development of a detailed sub-regional model of the major drinking-water aquifers in the region: Memphis and Fort Pillow aquifers.
- Assess the extent, physical characteristics, and connectivity of the Memphis and Fort Pillow aquifers, as well as their relationship to other regional aquifers, such as the Mississippi Alluvial and shallow fluvial/alluvial aquifers, and intervening confining units.
- Assess the quality of existing hydrostratigraphic data and quantitatively assess where the existing data are insufficient in extent or quality to accurately model the aquifer system

These objectives have been addressed by acquiring geologic and geophysical data from state and U.S. Geological Survey offices as well as private data sources and compiling the results into a master database. The geophysical log data, which are the primary sources of stratigraphic information, were evaluated for their quality of log signal, accuracy of well location and number of correlative, useful log plots. Data meeting the quality thresholds were used to evaluate downhole lithologic variations in each borehole. Existing stratigraphic reports and publications were used to correlate lithology to geologic formations and hydrostratigraphic units (aquifers and confining units) and interpret the stratigraphic and structural relationships. The geologic formations were then correlated between individual boreholes to produce regional cross-sections. These regional cross-sections were used to evaluate not only stratigraphic variations in the units but also lithologic variations within the units and probable faults that displace the strata. The idea of this process was not to develop new stratigraphic units, but rather to merge stratigraphic and structural concepts across state boundaries, where different nomenclature and definitions are applied. Quality of the geophysical log data was quantified by ranking the data according to Table App1 (see Appendix Geophysical Logs) from the Project QAPP. Logs were deemed acceptable with a rank of ≥ 6.

The refined stratigraphic cross-sections were then used to interpret well logs that exist between the section lines to improve data coverage across the study area. Following this process, contour surfaces of the stratigraphic bases of formations were created.

The interpolation process involves achieving a best-fit curve between data points to produce the surface. The residual from the best-fit process is used as an indicator of the accuracy of the stratigraphic model. Areas of high residual (high error) are considered areas that require further study to accurately depict the stratigraphic and structural complexities of the associated aquifer systems.

The results of both the cross-section and surface-map studies provide the framework for guiding hydrostratigraphic and hydrologic investigations in subsequent project phases.

Geophysical Log Analysis

Geophysical log analysis involved a review of published literature on Tertiary stratigraphy and hydrostratigraphy of the Mississippi Embayment (ME) region (Figure 1), as well as pertinent studies of correlative Gulf Coast strata. The review of the regional stratigraphy allowed nomenclature across the three states to be correlated and problems identified. A preliminary Tertiary stratigraphic correlation chart was developed and subsequently applied to the interpretation of geophysical log data.

Previous studies have shown that the stratigraphic character of the Claiborne and Wilcox groups changes at approximately the Tennessee-Mississippi state line (Figure 2), which has caused past problems in correlation (Moore, 1965) and assessment of water resources (Hosman and Weiss, 1991; Brahana and Broshears, 2001). In this study, the Fort Pillow Sand, Flour Island, Memphis Sand, Cook Mountain, and Cockfield formations as defined in Moore (1965), Hosman et al. (1968), Moore and Brown (1969), Fredericksen et al. (1982), and Hosman (1996) are mapped in Tennessee and in adjacent regions of Arkansas and Mississippi. Correlative Paleocene and Eocene geologic units (Cushing et al., 1964;

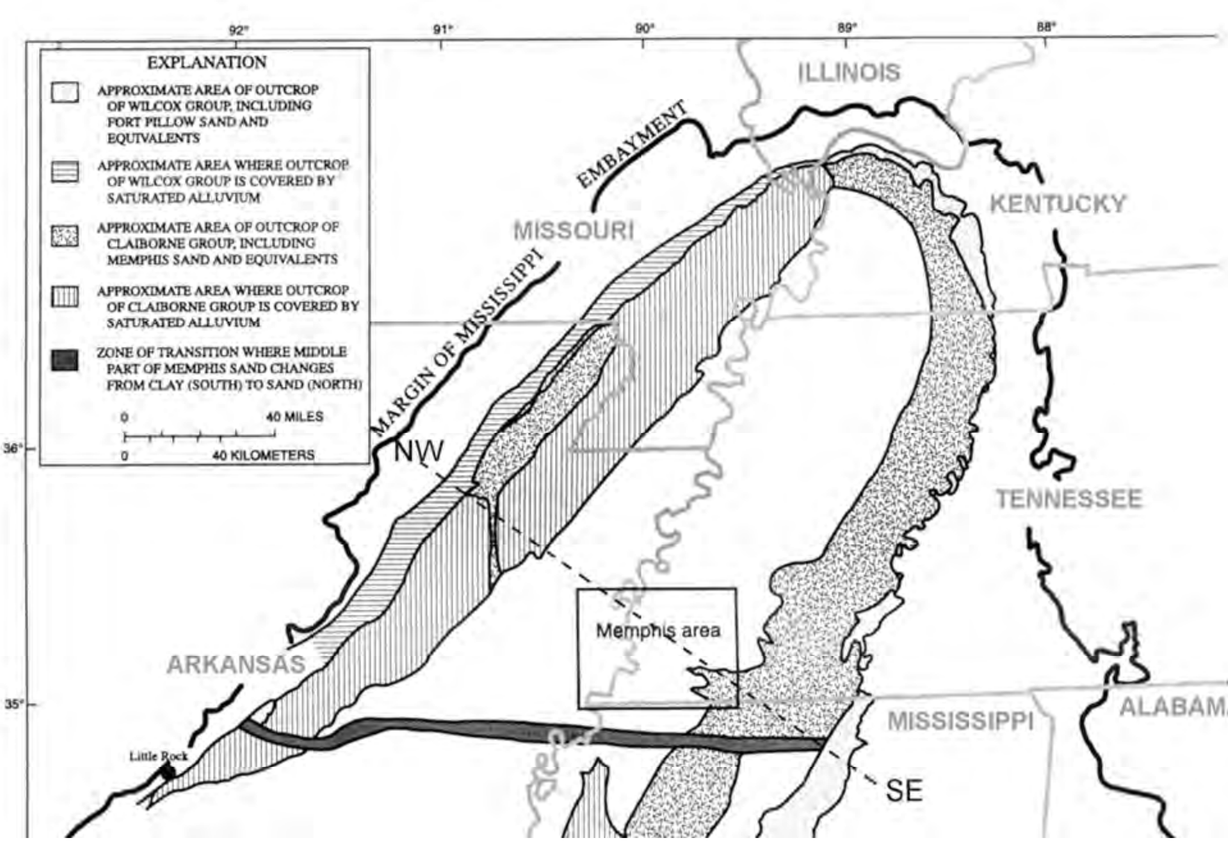


Figure 2. *Map of the northern Mississippi Embayment (NME) showing approximate distribution of outcrop and subcrop of the Wilcox and Claiborne group sediments (From Brahana and Broshears, 2001). Dashed line shows trace of cross-section shown in Figure 3.*

Mancini and Tew, 1991; Dockery, 1996; McFarland, 2004) were mapped in Mississippi and Arkansas where they are well-defined. In general, the stratigraphic nomenclature used in each of the states is used where clear division of geologic formations can be made.

We obtained high-quality geophysical logs from the various log libraries, digitized and scaled the log information, and correlated the known Paleocene- through Holocene-age geologic units within the region. The primary data for this effort exist as paper geophysical and geologic logs obtained during drilling of most water wells and all petroleum exploration wells. Other sources of data (geologic logs, geologic maps, seismic lines, etc.) were used to augment the geophysical log data where available. However, identification of stratigraphic units from geologic logs, unless accompanied by detailed biostratigraphic data or correlative geophysical data, is commonly ambiguous. Geologic units defined in mapping (e.g., Russell and Parks, 1975; Thompson, 2003a, b, c, and d) are difficult to reconcile with downdip subsurface expressions of stratigraphic units observed on geophysical logs. Thus, geologic map data are used to constrain the distribution of stratigraphic units only in outcrop areas. Seismic data are limited in the region and generally do not provide sufficient detail to define individual stratigraphic units within the shallow Tertiary section.

Geophysical logs were obtained from several sources, including the University of Memphis Ground Water Institute (GWI), USGS offices, State Geology offices, and private companies. The GWI houses an extensive log library for western Tennessee and a voluminous exploration geophysical log dataset obtained by North American Coal Company. In addition, geophysical and geologic logs were obtained from the Mississippi Department of Environmental Quality, Arkansas Soil and Water Conservation Commission, and USGS offices in Little Rock and Nashville. The logs utilized by the USGS MERAS study (Hart et al., 2008; Hart and Clark, 2008) in Tennessee and Arkansas were incorporated into our database; however, some of the logs from northern Mississippi were not available at the time of our analysis. In addition, a limited set of industry logs was obtained through the Nashville USGS office (Carmichael, pers. comm., 2007).

Geologic correlation and construction of cross-sections

The lithological variation in the Paleocene through Holocene-age geologic units in the northern Mississippi Embayment is generally limited to various clastic sediments and coal (Cushing et al., 1964). The geophysical log interpretation of these sediments is generally straightforward; however, finely interbedded fine sand, silt and clay are difficult to differentiate. Geologic correlation is completed by matching digitized log patterns, representing geologic formations or members, among spatially distant boreholes. Initial studies indicate that log patterns for several of the geologic formations are not consistent over the region (Owen and Larsen, 2005; Martin, 2008). In this case, marker horizons, such as the Zilpha Shale interval, were used where present to correlate formations. If no marker horizons are evident in the log, then average thicknesses of geologic formations were used to approximate correlations. Observation of evidence for uplift or subsidence of the tops or bottoms of formations in multiple correlated sections was used, along with other information (seismic cross-sections, regionally interpolated surfaces, etc.), to assess the presence of fault offsets of the sedimentary package. Interpreted faults through the sedimentary package were compared to those identified in regional studies of faulting in the Mississippi Embayment (Ervin and McGinnis, 1975; Thomas, 1991; Schweig and Van Arsdale, 1996; Cox et al., 2001; Parrish and Van Arsdale, 2004; Cox et al., 2006; Csontos et al., 2008).

A principle objective of the first phase of the project is to use the available data to construct detailed litho- and hydro-stratigraphic models of the study area and thus determine where existing data are insufficient to constrain the hydrostratigraphic model. In an effort to address this objective, structure contour maps of the stratigraphic units were prepared. These surface maps are a precursor to construction of quasi-three-dimensional litho- and hydro-stratigraphic models. The principle data used to construct the surfaces is the base elevations of stratigraphic units, which are obtained from the interpreted geophysical logs and cross-sections. The structure contour surfaces were constructed using the inverse-distance-weighted

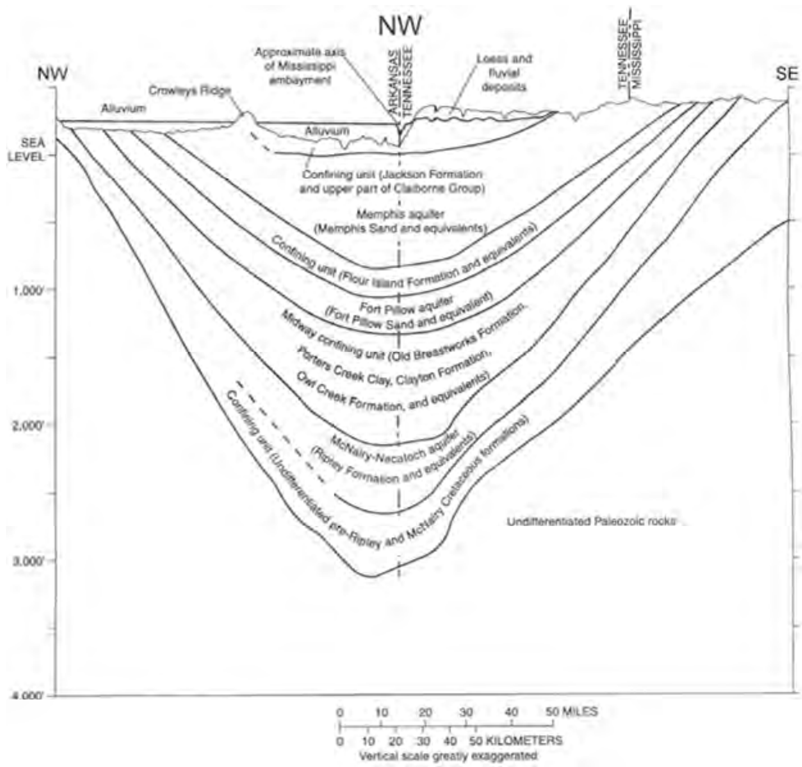


Figure 3. *Cross-section through the northern Mississippi Embayment (NME) showing the generalized stratigraphy (From Brahana and Broshears, 2001). See Figure 2 for location of cross-section.*

(IDW) method. IDW was chosen because it is effective in contouring limited numbers of data points. Best fit was determined by minimization of the root mean square (RMS) error. These interpolated surfaces provide a baseline for determining where additional data are needed to constrain the three-dimensional lithostratigraphic and hydrostratigraphic models necessary in subsequent project phases.

Geologic Background

The Mississippi Embayment

The Mississippi Embayment (ME) is a broad south-plunging trough filled with Upper Cretaceous and Paleogene marine to non-marine sediments overlain by a veneer of Pliocene and Quaternary fluvial sediments and Pleistocene loess (Cushing et al., 1964; Cox and Van Arsdale, 1997). At the southern margin of the ME, where it merges with the Gulf Coast, the post-Cretaceous sedimentary fill is approximately 2 km thick and the embayment is approximately 600 km across from WNW to ESE (Figure 3). The southern margin of the ME also corresponds to the craton-ward limit of the Appalachian-Ouachita detachment (Thomas, 1991). The trend of the trough of the ME roughly follows the ancient Reelfoot Rift (Ervin and McGinnis, 1975), suggesting that Precambrian-early Cambrian extensional structures exert a prominent control on the tectonic evolution of the ME (Howe and Thompson, 1984; Marshak and Paulsen, 1996; Csontos et al., 2008).

The geologic formation and evolution of the Mississippi Embayment was first examined in detail by Stearns (1957) and Stearns and Marcher (1962). Their general interpretation involves structural doming of the northern ME during Early Cretaceous time to form the Pascola Arch followed by deposition of the Upper Cretaceous Tuscaloosa Fm. around the eastern and southern margins of the arch. Subsidence in the region of the Pascola Arch followed, leading to the broad, shallow ME basin. The northern ME was filled subsequently with Upper Cretaceous through upper Eocene strata as well as thin sections of Oligocene and Miocene deposits to the south where the ME merges with the Gulf Coast (Cushing et al., 1964). Formation and subsidence within the ME have been variably interpreted to be related to distal effects of the Appalachian-Ouachita orogenesis (Cushing et al., 1964) or opening of the Gulf of Mexico (Ervin and McGinnis, 1975; Kane et al., 1981; Braile et al., 1986). More recently, Cox and Van Arsdale, 1997; Van Arsdale and Cox, 2007 proposed that the ME formed in response to the track on the Bermuda hot spot beneath the weak crust underlying the Reelfoot Rift. As the hot spot passed beneath the ME it caused magmatism along the ancient rift margins as well as doming and erosion. Following passage of the hot spot, the topographic dome underwent thermal subsidence leading to accommodation space that was filled by the Upper Cretaceous through Eocene succession. The magmatic and exposure history of the ME is consistent with the hot spot migration hypothesis (Cox and Van Arsdale, 1997; Van Arsdale and Cox, 2007); however, detailed stratigraphic tests of the model have yet to be conducted.

Sedimentary deposition within the Mississippi Embayment began in the early Cretaceous, mainly in the southeastern and southwestern portions of the ME where the Gulf Coast system merges with ME strata (Cushing et al., 1964). Lower Cretaceous strata are largely missing in the central ME, where an angular unconformity exists between Upper Cretaceous strata and older deposits (Murray, 1961; Cox and Van Arsdale, 1997). Basal Upper Cretaceous gravels (Tuscaloosa Group) were deposited in a crescent-shaped arc along the eastern margin of the ME (Stearns and Marcher, 1962). These deposits grade upward and westward into the marginal marine and marine strata of the Eutaw Fm. and Selma Group. The Cretaceous deposits within the ME are thickest along the southeastern and southwestern margins and thin substantially in the northern and northwestern ME (Cushing et al., 1964; Hosman, 1996). The upper contact of Cretaceous deposits in the Gulf Coast is locally disturbed and erosional, which has been interpreted to have resulted from tsunami associated with the K-T impact event (Smit et al., 1996). No stratigraphic evidence of tsunami at the K-T boundary is observed in the northern ME (Patterson, 1998), and erosion is consistent with regression associated with relative sea-level fall.

The bulk of sedimentary deposition within the ME occurred during the Paleocene and Eocene, and is recorded in Midway, Wilcox, Claiborne, and Jackson group sediments (Cushing et al., 1964; Hosman, 1996; Van Arsdale and TenBrink, 2000). The Cenozoic stratigraphy is discussed in detail below, with most of the emphasis placed on the Wilcox and Claiborne groups that include the major Tertiary aquifers in the ME (Hosman et al., 1968; Hosman and Weiss, 1991). The post-Jackson sedimentary history of the ME includes minor deposition of Oligocene and Miocene strata in the southern-most part of the ME and wide-spread non-deposition and/or erosion during the Oligocene and Miocene throughout the central and northern ME (Cushing et al., 1964; Hosman, 1996; Van Arsdale and TenBrink, 2000). The Pliocene and Pleistocene depositional history of the ME is mainly that of fluvial incision and terrace formation (Fisk, 1944; Austin et al., 1991; Saucier, 1994; Blum et al., 2000; Rittenour et al., 2005; Van Arsdale et al., 2008).

The structural history of the Mississippi Embayment is strongly influenced by the structural grain of the Reelfoot Rift (Howe and Thompson, 1984; Johnston and Schweig, 1996; Cox et al., 2001a; Parrish and Van Arsdale, 2004; Csontos et al., 2008; Martin, 2008). However, additional structural control is provided by NW-SE-trending lineaments and fault zones (Howe and Thompson, 1984; Stark, 1997; Cox, 1988; Cox et al., 2001b), creating a series of structural blocks that tilt and rotate in response to applied compressional stresses (Csontos, 2007). The effects of these fault structures on the Tertiary stratigraphy in the study area have been studied mostly along the southeastern margin of the Reelfoot rift in Tennessee and Arkansas (Cox et al., 2001a; Parrish and Van Arsdale, 2004; Csontos et al., 2008), but a recent study by Martin extended these investigations into northern Mississippi (Martin, 2008), thus, encompassing the MERGWS study area.

Current seismicity in the northern ME is focused along the NE-trending New Madrid fault system (Schweig and Van Arsdale, 1996), although lesser seismicity also defines the southeastern structural margin of the ancient Reelfoot rift (Chiu et al., 1997; Cox et al., 2001a). During the Holocene, however, both the southeastern structural margin of the Reelfoot rift (Cox et al., 2006) and the NW-SE-trending Sabine and Arkansas River fault zones (Cox et al., 2007) may have defined loci of seismicity, indicating that Holocene seismicity is not confined in time or space to the New Madrid zone.

Tertiary and Quaternary Stratigraphy of the Mississippi Embayment

The Tertiary and Quaternary stratigraphy of the Mississippi Embayment (ME) has been reviewed in several regional papers (Table 1) (Stearns, 1957; Cushing et al., 1964; Hosman, 1996; Van Arsdale and TenBrink, 2000) as well as in state-specific publications (Table 2) (Dockery, 1996; McFarland, 2004). Details of the stratigraphy have been developed in local studies (e.g., Moore and Brown, 1969; Russell and Parks, 1975; Fredericksen et al., 1982; Thompson, 1995) that are not always amenable to regional correlation. To better enable correlation of local geology to the regional scale, it is important to understand the depositional character of the geologic units of interest and use this information as identifiable markers during interpretation. Such information is presented below. The details and associated correlation problems are discussed in the results section.

The basal Midway Group disconformably overlies Cretaceous (Maestrichtian) strata across the entire ME. The Maestrichtian-Danian stage boundary is a type I unconformity (Mancini and Tew, 1991), indicating exposure occurred across most or all of the continental shelf. The basal marine sands of the Paleocene Clayton Formation grade abruptly into marine clay and fine sand of the Porters Creek Clay. The Porters Creek Clay is marine throughout the entire ME (McFarland, 2004;

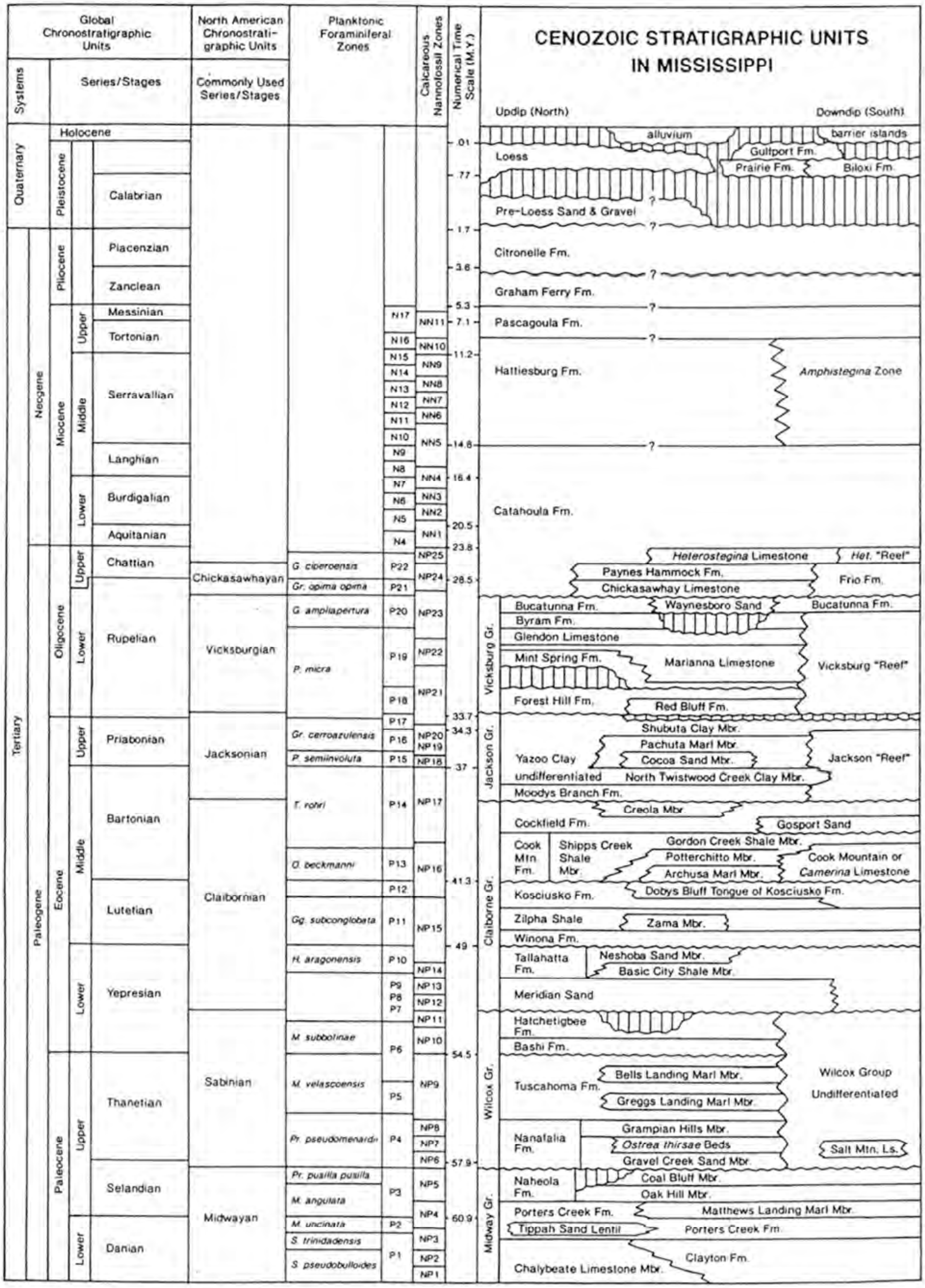
Table 1. Geologic and hydrostratigraphic units correlated throughout the Mississippi Embayment (From Hart et al., 2008).

ERATHEM	SYSTEM	EPOCH	GROUP	LOUISIANA	ARKANSAS Southern	ARKANSAS Northeastern	MISSOURI	KENTUCKY	TENNESSEE	MISSISSIPPI	ALABAMA	Hydrogeologic units
CENOZOIC	QUATERNARY	HOLOCENE / PLEISTOCENE		Alluvium and terrace deposits				Alluvium and loess deposits		Alluvium, terrace, and loess deposits	Alluvium and terrace deposits	Mississippi River Valley alluvial aquifer
	TERTIARY	OLIGOCENE	Vicksburg	Vicksburg Formation	Not present in study area					Vicksburg Formation		Vicksburg-Jackson confining unit
		EOCENE	Jackson	Jackson Formation								
			Claiborne	Cockfield Formation							Gosport Sand	Upper Claiborne aquifer
				Cook Mountain Formation								Middle Claiborne confining unit
				Sparta Sand		Memphis Sand		Sparta Sand	Memphis Sand	Sparta Sand	Lisbon Formation	Middle Claiborne aquifer
				Cane River Formation				Tallahatta Formation		Zilpha Clay Winona Sand Tallahatta Formation	Tallahatta Formation	Lower Claiborne confining unit
				Carrizo Sand						Meridian Sand Member		Lower Claiborne aquifer[1]
		UPPER PALEOCENE	Wilcox	Dolet Hills Formation	Undifferentiated	Flour Island Formation		Wilcox Formation	Flour Island Formation	Undifferentiated	Hatchetigbee Formation	Middle Wilcox aquifer
						Fort Pillow Sand		No Wilcox deposits identified as being of Paleocene age	Fort Pillow Sand		Bashi Formation Tuscahoma Sand Nanafalia Formation	Lower Wilcox aquifer
				Undifferentiated Naborton Formation		Old Breast-works Formation			Old Breast-works Formation			
			Mid-way	Midway Group								Midway confining unit

[1]Lower Claiborne aquifer includes the upper Wilcox aquifer in some portions of Mississippi

Modified from Hosman and Weiss, 1991

Table 2. Geologic correlation diagram for Cenozoic strata in Mississippi (from Dockery, 1996).



MS SCT 000822

Fredericksen et al., 1982; Russell and Parks, 1975), suggesting that its original extent may have been substantially greater. The upper Midway Group in Mississippi includes the Naheola Fm (Dockery, 1996), which is not defined in either Arkansas or Tennessee. The Naheola includes two members, the Oak Hill and the Coal Bluff, which are well-defined in eastern central Mississippi. The Oak Hill rests conformably on the Porters Creek Clay and represents a coarsening-upward sequence that includes interbedded clay, silt, and fine-grained sand (Thompson, 1995). Coal Bluff rests with unconformity on the Oak Hill and includes fine- to coarse-grained sand interbedded with clay, silt, and lignite (Thompson, 1995). The upper part of the Coal Bluff is highly weathered and contains bauxitic to kaolinitic clays. Similar weathered strata are observed in exposures of the basal "Wilcox" Fm. in southwestern Tennessee (Russell and Parks, 1975) suggesting that a Coal Bluff equivalent is present in western Tennessee.

The Wilcox Group rests with unconformity on the underlying Midway Group, although the lithological distinction between Midway and Wilcox strata is locally gradational across the boundary (Hosman, 1996). In eastern central Mississippi, which is the southeastern corner of the ME, four formations define the Wilcox Group: Nanafalia, Tuscahoma, Bashi, and Hatchetigbee formations (Dockery, 1996; Thompson, 1995). The Nanafalia Formation consists of two members, the Gravel Creek Sand and Grampian Hills members. The Gravel Creek Sand contains a prominent sand interval interbedded with clay, silt, sand, and lignite. The Grampian Hills is generally finer grained than the Gravel Creek Sand with a basal sand interval followed by clay, silt and fine- to medium-grained sand interbedded with multiple lignite seams (Thompson, 1995). The overlying Tuscahoma Fm. is lithologically similar to the underlying Grampian Hills member of the Nanafalia Fm.; however, two depositional cycles of basal sand and overlying fine-grained clay, silt, sand, and lignite are observed. Furthermore, the Grampian Hills contains prominent correlative marginal marine intervals (Dockery and Thompson, 1996), whereas the Tuscahoma is almost entirely non-marine, except near the Alabama state line. The Bashi overlies the Tuscahoma Fm. disconformably and represents the basal Eocene strata in the Gulf Coast (Mancini and Tew, 1991). The Bashi Formation is distinctive and mappable in Mississippi only near the Alabama state line where it is a marine interval with glauconitic sands and marls (Thompson, 1995). The Bashi grades laterally into basal sands in the Hatchetigbee Formation in western Alabama (Gibson, 1982), and shows similar relationships in Mississippi (Thompson, 1995; Thompson, 2003a; b; c; d). The Hatchetigbee Fm. contains interbedded clay, silt, sand, and lignite.

The Wilcox Group in the central and northern ME comprises three formations: The Old Breastworks, Fort Pillow Sand, and Flour Island formations (Table 3) (Moore and Brown, 1969; Hosman, 1996; Van Arsdale and TenBrink, 2000; Brahana and Broshears, 2001). Frederiksen et al. (1982), in a biostratigraphic study of the New Madrid test wells in southeastern Missouri, correlate the Old Breastworks to the Naheola Fm (Oak Hill member) based on dinoflagellate species and lithologic similarity, suggesting that the Old Breastworks Fm. belongs to the Midway Group. The Old Breastworks Fm. is not defined in surface exposures in western Tennessee, where the Wilcox Fm. rests directly on Porters Creek Clay (Russell and Parks, 1975). The Fort Pillow Sand is a coarse sand that thickens into the axis of the ME and is roughly correlative to the Nanafalia Fm. (Cushing et al., 1964; Hosman, 1996). The Flour Island Formation is mainly lignitic silt with interbedded clay and fine sand. The lower part of the Flour Island is calcareous and glauconitic at the Fort Pillow test well (Moore and Brown, 1969), but only non-marine strata are present in the New Madrid test wells (Frederiksen et al., 1982).

The Wilcox Group is exposed along Crowley's Ridge in northeastern Arkansas, but is undivided. The composite thickness is approximately 780 ft thick and composed of sands, silt, clay, and lignite (Meissner, 1984). Significant lignite seams are present only in the upper half of the Wilcox Group.

Table 3. Lithostratigraphy and hydrostratigraphy in the Memphis, Tennessee, area (From Brahana and Broshears, 2001).

System	Series	Group	Stratigraphic unit	Thick-ness	Hydrologic unit	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Surficial Aquifer	Sand, gravel, silt, and clay. Underlies the Mississippi Alluvial Plain and alluvial plains of streams in the Gulf Coastal Plain. Thickest beneath the Alluvial Plain, where commonly between 100 and 150 feet thick; generally less than 50 feet thick elsewhere. Provides water to farm, industrial, and irrigation wells in the Mississippi Alluvial Plain.
	Pleistocene		Loess	0-65		Silt, silty clay, and minor sand. Principal unit at the surface in upland areas of the Gulf Coastal Plain. Thickest on the bluffs that border the Mississippi Alluvial Plain; thinner eastward from the bluffs. Tends to retard downward movement of water-providing recharge to the fluvial deposits.
Quaternary and Tertiary(?)	Pleistocene and Pliocene (?)		Fluvial Deposits (terrace deposits)	0-100		Sand, gravel, minor clay and ferruginous sandstone. Generally underlies the loess in upland areas, but are locally absent. Thickness varies greatly because of erosional surfaces at top and base. Provides water to many domestic and farm wells in rural areas.
Tertiary	Eocene	?	Jackson Formation and upper part of Claiborne Group ("capping clay")	0-370	Confining Unit	Clay, silt, sand, and lignite. Because of similarities in lithology, the Jackson Formation and upper part the Claiborne Group cannot be reliably subdivided based on available information. Most of the preserved sequence is equivalent to the Cook Mountain and overlying Cockfield Formations, but locally the Cockfield may be overlain by the Jackson Formation. Serves as the upper confining unit for the Memphis Sand.
		Claiborne	Memphis Sand ("500-foot" sand)	500-890	Memphis aquifer	Sand, clay, and minor lignite. Thick body of sand with lenses of clay at various stratigraphic horizons and minor lignite. Thickest in the southwestern part of the Memphis area; thinnest in the northeastern part. Principal aquifer providing water for municipal and industrial supplies east of the Mississippi River, primary source of water for the City of Memphis.
	?	Wilcox	Flour Island Formation	140-310	Confining unit	Clay, silt, sand, and lignite. Consists primarily of silty clays and sandy silts with lenses and interbeds of fine sand and lignite. Serves as the lower confing unit for the Memphis Sand and the upper confining unit for the Fort Pillow Sand.
	Paleocene		Fort Pillow Sand ("1400-foot" sand)	92-305	Fort Pillow aquifer	Sand with minor clay and lignite. Sand is fine to medium. Thickest in the southwestern part of the Memphis area; thinnest in the northern and northeastern parts. Once the second principal aquifer supplying the City of Memphis; still used by an industry. Principal aquifer providing water for municipal and industrial supplies west of the Mississippi River.
			Old Breastworks Formation	180-350	Midway confining unit	Clay, silt, sand, and lignite. Consists primarily of silty clays and clayey silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining unit for the Fort Pillow Sand, along with the underlying Porters Creek Clay, Clayton Formation, and Owl Creek Formation.

The Claiborne Group rests disconformably on the Wilcox Group deposits across the ME, suggesting that a type 1 sequence boundary exists between the units (Mancini and Tew, 1991; Ingram, 1992). In northern Mississippi, the lower and middle Claiborne includes five formations (Dockery, 1996): Meridian Sand, Tallahatta Formation, Winona Sand, Zilpha Shale, and Kosciusko Formation. The Meridian Sand is fine- to coarse-grained sand with characteristic crossbedding (Cushing et al., 1964). Although Thomas (1942) in a comprehensive study of the Claiborne in Mississippi assigned the Meridian to the Wilcox Group, later studies have confirmed its proper inclusion within the Claiborne (Bybell and Gibson, 1985; Hosman, 1996). The Tallahatta Formation consists of dark greenish-gray clay and siliceous to glauconitic siltstone and fine- to coarse-grained sandstone in the Basic City Shale member and generally non-glauconitic fine- to medium-grained sand and gray clay in the Neshoba sand member (Thomas, 1942). The Winona Sand is predominantly medium- to coarse-grained glauconitic sand and is easily identified in surface exposures by its dark red weathering color. The Zilpha Shale is a dark gray, carbonaceous, glauconitic, and sparsely fossiliferous clay (Cushing et al., 1964). The Winona Sand and Zilpha Shale are only observed in central and southern Mississippi, although correlative but lithologically distinct intervals are described in both Arkansas and Tennessee (Moore, 1965; Hosman, 1996). The Kosciusko Fm. consists of medium-grained sand with interbedded light gray, light greenish-gray, and rarely dark gray shale (Thomas, 1942).

The lower and middle Claiborne Group in southeastern Arkansas includes the Carrizo Sand, Cane River Formation, and Sparta Sand (Cushing et al., 1964; Payne, 1968; 1972; 1975). The Carrizo Sand is correlative to the Meridian Sand in Mississippi (Payne, 1975; Hosman, 1996). The Cane River Fm. is roughly equivalent to the Tallahatta Formation, Winona Sand, and Zilpha Shale in Mississippi (Payne, 1972). The Sparta Sand is correlative to the Kosciusko Formation in Mississippi (Hosman, 1996). North of the 35° parallel, the Cane River pinches out and the entire lower and middle Claiborne section is dominated by the Memphis Sand (Hosman, 1996). Similarly in western Tennessee, Moore (1965) correlated the Tallahatta Formation and Sparta Sand to the Memphis ("500-foot") Sand. The Memphis Sand was formally defined in the Fort Pillow test well (Moore and Brown, 1969) in Lauderdale County, Tennessee, and later correlated throughout the northern ME (Frederiksen et al., 1982; Parks and Carmichael, 1990a; Hosman, 1996). The Memphis Sand is predominantly fine- to coarse-grained sand with subordinate carbonaceous and lignitic silt and clay and lignite (Parks and Carmichael, 1990a). Clay intervals correlative to the Basic City Shale and Zilpha Shale are locally identified (Moore, 1965; Parks and Carmichael, 1990a).

Throughout the study area, the Kosciusko Fm., Sparta Sand, and Memphis Sand are overlain with disconformity by the upper Claiborne Cook Mountain and Cockfield Formations (Thomas, 1942; Cushing et al., 1964; Moore and Brown, 1969; Frederiksen et al., 1982). The Cook Mountain Fm. in central Mississippi consists of a lower glauconitic, fossiliferous sandy marl or limestone overlain by sandy carbonaceous clay (Thomas, 1942; Hosman, 1996). However, in western Tennessee the Cook Mountain Fm. is mainly silt and clay with local intervals of fine sand (Parks and Carmichael, 1990a). The contact between the Cook Mountian and Cockfield formations is conformable and transitional. In central Mississippi, the sandy shale of the Cook Mountain Fm. grades upward into sand, lignitic silty shale, and lignite of the Cockfield Formation (Thomas, 1942). The lithology of the Cockfield Fm. is remarkably consistent across the northern ME (Moore and Brown, 1969; Frederiksen et al., 1982; Parks and Carmichael, 1990b; Hosman, 1996).

The Jackson Group has limited extent in the northern and central ME, and is given only formational status in Tennessee. The Jackson Formation crops out along the Mississippi River bluffs in western Tennessee and along the southern part of Crowley's Ridge in Arkansas (Cushing et al., 1964). The Jackson strata overlie the Claiborne Group with disconformity and typically include fossiliferous, glauconitic sandy marl that grades upward into calcareous clay and locally sand in central Mississippi (Hosman, 1996). The Jackson Formation in western Tennessee is lithologically indistinct from the underlying Cockfield Fm. and is typically not differentiated (Parks and Carmichael, 1990b; Moore and Brown, 1969).

The upper surface of the Paleocene-Eocene ME sedimentary system is a time-transgressive erosional surface upon which Pliocene through modern stream deposits and late Pleistocene loess have been laid (Fisk, 1944; Potter, 1955; Austin et al., 1991; Saucier, 1994; Van Arsdale et al., 2008). Because the sequence is associated with the progressive, though punctuated, denudation history of the ME, the oldest deposits are at the highest interfluvial elevations and the youngest deposits are within the modern-day valleys. The Pliocene Upland Complex, also known as the Lafeyette Gravel (Potter, 1955), is present in western Tennessee, northwestern Mississippi, and along Crowley's Ridge in eastern Arkansas (Austin et al., 1991; Van Arsdale et al., 2008). Van Arsdale et al. (2008) used an extensive borehole dataset to map the distribution of the Upland Complex throughout the region and demonstrate its origin as an ancient high-level terrace of the Mississippi River, potentially as much as 5.5 Ma old. Subsequent incision and subsequent terrace formation has led to formation of several terrace levels and associated sand and gravel deposits along the Mississippi River-Ohio River valley system (Austin et al., 1991; Saucier, 1994; Blum et al 2000; Rittenour et al., 2003; 2005) and western Tennessee tributaries (Saucier, 1987; Rodbell, 1996; McClure, 1999). Late Pleistocene terraces were further mantled with loess in the region (Austin et al., 1991; Rodbell et al., 1997; Rutledge et al., 1996; Markewich et al., 1998). The modern Mississippi Valley alluvium consists largely of gravel and sand capped by silt and loess (Saucier, 1994). Pleistocene depositional patterns within the Mississippi Valley appear to be strongly affected not only by glacial processes and climate (Saucier, 1994; Blum et al., 2000; Rittenour et al., 2005), but also tectonic subsidence and uplift along orthogonal Reelfoot Rift faults (Csontos et al., 2008).

Hydrostratigraphic Units within the Central Mississippi Embayment

The lithostratigraphic units described above are divided into a series of hydrostratigraphic units (Tables 1 and 3). Hydrostratigraphic units are defined based on their ability to produce water at an efficient rate. Aquifers are water-producing zones and confining units are generally poor water-producing zones, but more importantly provide confinement to water in underlying and overlying aquifers. The hydrostratigraphic terminology applied to the ME has changed over the past 120 years as stratigraphic studies have better defined the lithology and extent of units, and hydrogeologic studies have better defined the water-producing zones and their hydraulic properties. As mentioned previously, definition of hydrostratigraphic units vary depending on the scale of studies. For example, local studies of ground water tend to use state- or subregion-based nomenclature, such as those applied in the Memphis area (Criner and Parks, 1976; Brahana and Broshears, 2001). Regional scale studies use more generic nomenclature, such as that defined for the ME by the USGS Regional Aquifer-System Analysis (RASA) (Hosman and Weiss, 1991). Most recently, the USGS has completed a regional hydrostratigraphic analysis focusing on the ME (Table 4) (Hart and Clark, 2008; Hart et al., 2008) as a part of the Mississippi Embayment Regional Aquifer Study (MERAS). For the purposes of the present study, which is subregional in scale, the regional hydrostratigraphic terms from Hart et al. (2008) with some modifications discussed below will be applied to the general discussion (Table 1), although the local nomenclature in the Memphis area (Brahana and Broshears, 2001) will be applied to more detailed discussions.

The Tertiary ME aquifer system is confined at the base by the Midway confining unit. The clay-rich nature of this unit limits passage of water; however, water could potentially move through this and other confining units along faults (Kingsbury and Parks, 1993). Regionally, two aquifers are defined within the Wilcox interval, the Lower and Middle (Table 1). However, within the study area the Middle Wilcox aquifer is not distinguished from the lower Memphis aquifer (lower part of Memphis Sand in Table 1) north of the Mississippi-Tennessee state line (Thompson, 2003a, b, c, and d). The Lower Wilcox aquifer is equivalent to Fort Pillow Sand in western Tennessee (Parks and Carmichael, 1989) and northeastern Arkansas (Brahana and Broshears, 2001) and the sandy upper part of the Nanafalia and lower part of the Tuscahoma (Hosman, 1996). The Lower Wilcox is confined by the underlying Midway confining unit and fine-grained intervals within the overlying Flour Island Formation (Tennessee and Arkansas) and Tuscahoma Formation (northern Mississippi). The Flour island is a confining unit within the northern ME.

The Claiborne interval includes three regional aquifers. In northern Mississippi and adjacent Arkansas, the Lower and Middle Claiborne aquifers are separated by the Lower Claiborne confining unit. However, the Lower Claiborne confining unit laterally pinches out near the Tennessee-Mississippi stateline (and in adjacent Arkansas), such that the Lower and Middle Claiborne aquifers merge to form the Memphis aquifer in western Tennessee and adjacent Arkansas (Hart et al., 2008; Hosman and Weiss, 1991; Parks and Carmichael, 1990a). The Middle Claiborne confining unit is equivalent to the Cook Mountain Formation throughout the study area (Hart et al., 2008; Hosman and Weiss, 1991; Parks, 1990). Graham and Parks (1986), Parks (1990), Bradley (1991), Parks and Mirecki (1992), Parks et al. (1995), Larsen et al. (2003), Waldron et al. (2009), and others have noted that the Middle Claiborne confining unit is locally absent or contains transmissive facies which permit vertical recharge to the Memphis aquifer. The Upper Claiborne aquifer, within the Cockfield Formation, is generally thin and discontinuous in the study area and is thickest east of the Mississippi alluvial valley (Parks and Carmichael, 1990b). The Upper Claiborne aquifer is locally unconfined in western

EXHIBIT 8

Richard K. Spruill Expert Report
June 30, 2017

EXPERT REPORT

Hydrogeologic Evaluation and Opinions for
State of Mississippi versus
State of Tennessee, City of Memphis,
and Memphis Light, Gas & Water Division

PREPARED FOR:
Daniel Coker Horton & Bell, P.A.
265 North Lamar Boulevard, Suite R
Oxford, Mississippi 38655
Telephone: (662) 232-8979

PREPARED BY:
Groundwater Management Associates, Inc.
4300 Sapphire Court, Suite 100
Greenville, North Carolina 27834
Telephone: (252) 758-3310

June 30, 2017

Richard K. Spruill, Ph.D., P.G.
Principal Hydrogeologist

I. Introduction

Groundwater Management Associates (GMA) was retained by the firm of Daniel Coker Horton & Bell, P.A. (DCH&B) to provide expert geologic and hydrogeologic consulting regarding the origin and distribution of groundwater, interactions between surface water and groundwater, natural and man-induced migration patterns of groundwater, and specific topics regarding the geology and hydrogeology of predominantly sandy sediments comprising the Eocene-age Middle Claiborne Group that host the Sparta-Memphis Sand aquifer system in northwestern Mississippi and southwestern Tennessee. GMA's services included producing this expert report, which is focused on known or likely impacts on groundwater distribution and migration patterns within the Sparta-Memphis Sand (aka, the Sparta Sand, Memphis Sand, Memphis Aquifer, and other variations) in response to historic and ongoing pumping in Shelby County, Tennessee.

This expert report was produced for DCH&B using information available from publicly-available maps and reports from a variety of sources, including federal agencies such as the United States Geological Survey (USGS). This information was used in combination with the professional training and experience of the report's author, Dr. Richard K. Spruill, to develop opinions about the geologic and hydrogeologic setting of the study area. A partial list of resources and documents that were reviewed or employed to prepare the expert report is provided as Appendix A.

II. Qualifications

Richard K. Spruill, Ph.D, is GMA's Principal Hydrogeologist, president, and co-owner of the firm. Dr. Spruill's professional practice is focused on the hydrogeological exploration, evaluation, development, sustainable management, and protection of groundwater resources. He has been a geologist for over 40 years, and he is licensed in North Carolina as a professional geologist. Since 1979, Dr. Spruill has been a faculty member in the Department of Geological Sciences at East Carolina University (ECU), Greenville, North Carolina. He teaches hydrogeology, mineralogy, petrology, field geology, and physical geology at ECU. Dr. Spruill has provided litigation support and testified previously regarding geology, hydrogeology, water resources, and environmental contamination. His *curriculum vitae* is provided as Appendix B.

I, Dr. Richard K. Spruill, am the author of this expert report. My descriptions, interpretations, conclusions, and professional opinions described within this expert report are subject to revision, expansion, and/or retraction as additional information becomes available.

III Summary of General Opinions

The following is a summary of my opinions provided within this expert report. The opinions itemized below are based on (1) my education, training, experience, (2) detailed study of the geology and hydrogeology of the Mississippi Embayment, (3) evaluation of the specific geological and hydrological characteristics of the pertinent geological formations in north Mississippi and west Tennessee, and, (4) specific resources and materials referred to and identified with this report.

- The Sparta-Memphis Sand, also known as the Middle Claiborne Aquifer or the Memphis Aquifer, is an important source of potable groundwater within northwestern Mississippi and southwestern Tennessee. Most of the Sparta-Memphis Sand is a hydraulically-confined aquifer that consists of geologic deposits that accumulated within the Mississippi Embayment approximately 40 million years ago. The Sparta-Memphis Sand is inclined (dips) toward the west from areas where the unit crop out in both Mississippi and Tennessee. These sandy deposits thicken toward the center of the Embayment, which generally coincides with the present trace of the Mississippi River.
- The Middle Claiborne formation contains several lithologic constituents, including the Sparta Sand, that comprise an aquifer that has accumulated groundwater over many thousands of years. Historically, most of that groundwater originated as surface precipitation that infiltrated the formation where exposed at or near

the surface, and that groundwater migrated generally westward in both states to create a source of high-quality groundwater that did not naturally flow to any significant extent in a northerly direction out of Mississippi and into Tennessee.

- The Sparta-Aquifer Sand is the most productive source of high-quality groundwater available in the states of Mississippi and Tennessee.
- Massive withdrawal of groundwater by pumping wells operated by Memphis Light, Gas and Water (MLGW) in southwestern Tennessee has reduced substantially the natural hydraulic pressures existing in the Sparta-Memphis Sand in both Tennessee and Mississippi, thus artificially changing the natural flow path of Mississippi's groundwater in this aquifer from westward to northward toward MLGW's pumping wells. This groundwater withdrawal has dramatically reduced the natural discharge of Mississippi's groundwater in the Sparta-Memphis Sand to the Mississippi River's alluvial aquifer system within the state of Mississippi.
- The taking of Mississippi's groundwater by MLGW's pumping has decreased the total amount of available groundwater in the Sparta-Memphis Sand available for development in Mississippi, thus increasing the cost of recovering the remaining available groundwater from the aquifer within the broad area of depressurization (aka, cone of depression) created by MLGW's pumping.
- The intensity of pumping that has been, and continues to be, conducted by MLGW is not consistent with good groundwater management practices, and denies Mississippi the ability to fully manage and utilize its own groundwater natural resource.
- The best management strategy for sustainability of groundwater resources involves withdrawing groundwater at a rate that is equal to or less than the recharge rate of the aquifer being developed.

Richard K Spruill

Richard K. Spruill, Ph.D., P.G.
Principal Hydrogeologist

IV.   Principles of Groundwater Hydrogeology

This section of the expert report provides an overview of key aspects of groundwater hydrogeology, especially as it pertains to the Sparta-Memphis Sand (aka, Memphis Aquifer or Middle Claiborne Aquifer) in northwestern Mississippi and southwestern Tennessee. Geologic and hydrogeologic details of the Sparta-Memphis Sand (SMS) are described elsewhere in the report.

Because groundwater availability depends on specific aspects of the local and regional geologic setting, it is not found in 'usable' quantities everywhere in the subsurface. The location, age, quality, movement, and availability of groundwater for human exploitation are determined by the actual geologic materials (i.e., aquifer) that host the water (e.g., sand) and the geologic and hydraulic characteristics of the aquifer system. This introduction to the basic principles of groundwater hydrology is generally tailored to be applicable to the groundwater system of the Middle Claiborne Group in northwest Mississippi and southwest Tennessee, and an analysis of the natural characteristics of the groundwater that is in legal dispute.

Groundwater originates as precipitation at the land surface, and some of that precipitation infiltrates the surface and enters the subsurface. In some places, groundwater originates as seepage through the bottoms and sides of surface water channels or basins, as well as by migration from other groundwater-bearing materials (e.g., 'confining units' that enclose some aquifers). Groundwater is located in the subsurface within small pore spaces located between rock and mineral particles and/or within fractures or other types of secondary porosity (e.g., voids in limestone from dissolved shell fragments).

Because groundwater typically moves through the subsurface at a rate of only a few feet or tens of feet per year, the water at a particular location and depth may have been in the subsurface for many years, decades, or millennia. By way of comparison, groundwater flowing at 1 foot per day is generally considered to be fast, while the velocity of water flowing in a stream is typically more than 1 foot per second (more than

16 miles/day). Another way to look at this generic comparison is that the 'fast' groundwater flow would require roughly 230 years to travel the same 16 miles that the hypothetical stream could transport water during one day.

Groundwater hydrogeology employs unique terms and concepts. To simplify the discussion provided below, the following are some (modified) definitions of terminology from a well-known USGS primer (Heath, 1983).

AQUIFER: A water-bearing layer of rock (or sediment) that will yield water in a usable quantity to a well or spring.

CONE OF DEPRESSION: The depression of (hydraulic) heads around a pumping well caused by the withdrawal of water.

CONFINING BED: A layer of rock (or sediment) having very low hydraulic conductivity that hampers the movement of water into and out of an aquifer.

DRAWDOWN: The reduction in head at a point caused by the withdrawal of water from an aquifer.

EQUIPOTENTIAL LINE: A line on a map or cross section along which total heads are the same.

FLOW LINE: The idealized path followed by particles of water.

GROUND WATER: Water in the saturated zone that is under a pressure equal to or greater than atmospheric pressure.

(HYDRAULIC) HEAD See TOTAL HEAD

HYDRAULIC CONDUCTIVITY: The capacity of a rock (or sediment) to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

HYDRAULIC GRADIENT: Change in head per unit of distance measured in the direction of the steepest change.

POROSITY: The voids or openings in a rock (or sediment). Porosity may be expressed quantitatively as the ratio of the volume or openings in a rock (or sediment) to the total volume of the rock (or sediment).

POTENTIOMETRIC SURFACE: A surface that represents the total head in an aquifer; that is, it represents the height above a datum plane (such as sea level) at which the water level stands in tightly cased wells that penetrate the aquifer.

SATURATED ZONE: The subsurface zone in which all openings are full of water.

SPECIFIC CAPACITY: The yield of a well per unit drawdown (commonly expressed as gallons per minute per foot of drawdown).

STORAGE COEFFICIENT: The volume of water released from storage in a unit prism of an aquifer when the head is lowered a unit distance.

STRATIFICATION: The layered structure of sedimentary rocks.

TOTAL (HYDRAULIC) HEAD: The height above a datum plane of a column of water. In a ground-water system, it is composed of elevation head and pressure head.

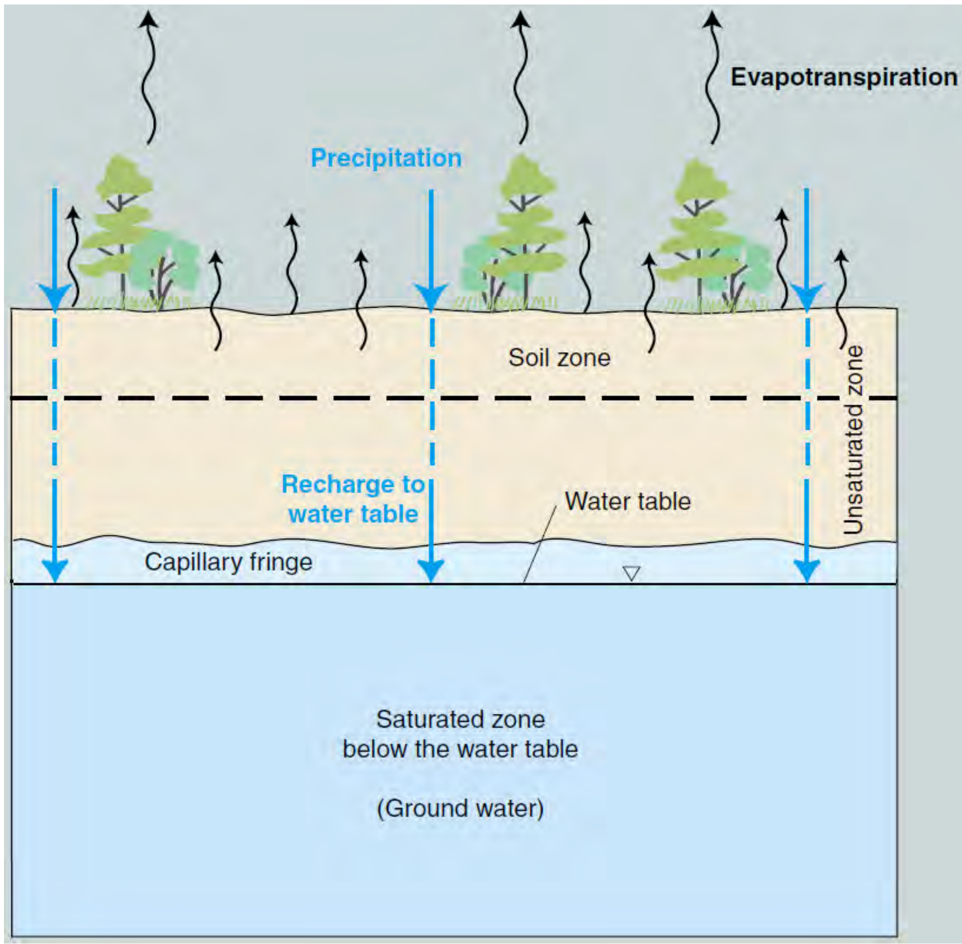
TRANSMISSIVITY: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness.

UNSATURATED ZONE: The subsurface zone, usually starting at the land surface, that contains both water and air.

WATER TABLE: The level in the saturated zone at which the pressure is equal to the atmospheric pressure.

Groundwater occurs in two basic zones that are defined by the degree of water saturation (Figure 1). The unsaturated zone occurs below the land surface where the primary and secondary porosity of the earth materials present will contain both air and water. Groundwater in the unsaturated zone is not available for extraction or exploitation by people. All porosity is filled with water in the saturated zone (Figure 1), and the boundary between the saturated zone and the overlying unsaturated zone is called the water table (discounting the capillary fringe where groundwater is at less than atmospheric pressure). Groundwater in the saturated zone is potentially recoverable, although there may be practical or financial limitations that preclude extraction.

Figure 1: Groundwater Distribution in the Shallow Subsurface (modified from Alley et al., 1999)

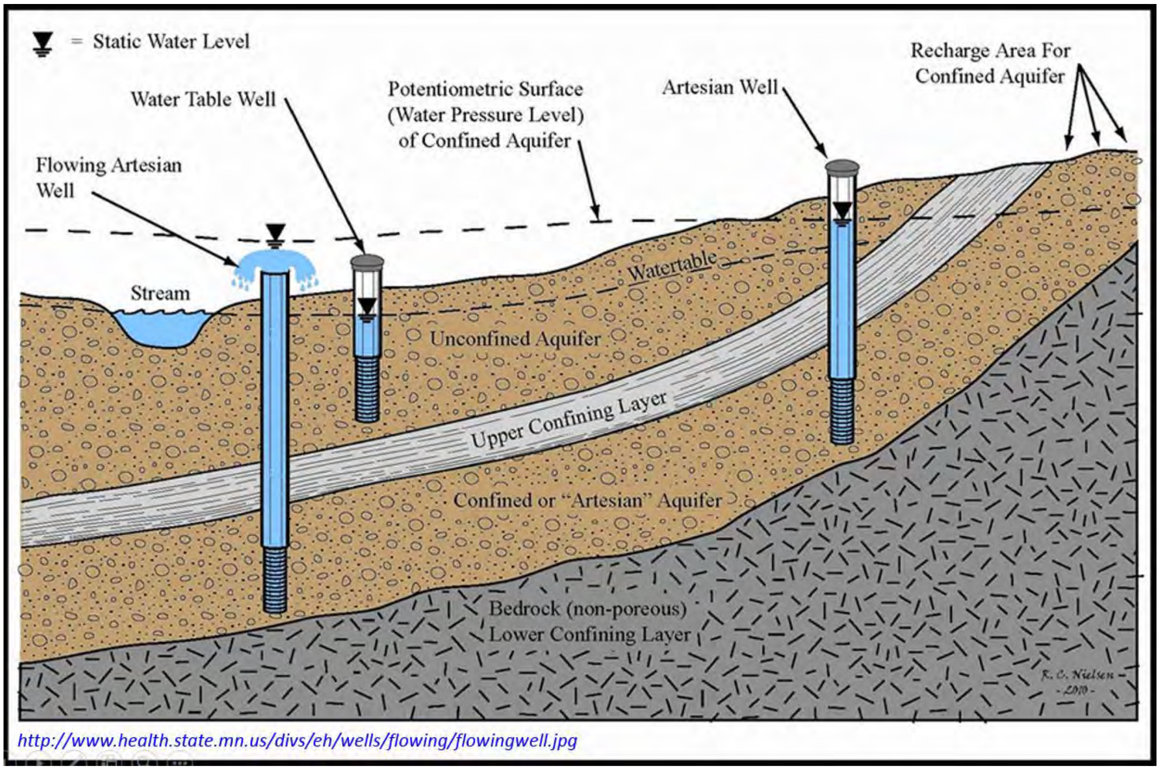


Aquifers consist of groundwater hosted by unconsolidated sedimentary deposits (e.g., sand) or consolidated rocks. To be considered an aquifer, there must be adequate interconnection of the primary and/or secondary porosity such that the geologic materials can hold, transmit, and release groundwater in sufficient volumes for some purpose (e.g., a water-supply well). There is no minimum area, thickness, or quantity of groundwater potentially 'useable' or 'extractable' by people that must exist before a mass of groundwater-bearing geologic material can be termed an aquifer. Water-bearing sediments or rocks may be exploited by people as a significant source of water in one place, thus constituting an aquifer, but the same combination of water and solid materials might not constitute a viable aquifer at a different place or time.

Aquifers can be classified by the degree of hydraulic confinement (pressurization). The water table scenario described above represents an unconfined aquifer, and an unconfined aquifer may also be referred to as a water table aquifer. New water additions to an unconfined aquifer originate directly above the aquifer at the land surface. A confined aquifer is fully saturated, and it is enclosed above and below by materials with relatively low permeability (e.g., clay). Groundwater in a confined aquifer is typically pressurized, and the degree of pressurization (hydraulic head) can be measured directly in a well open only to the confined aquifer. The hydraulic head is measured inside the well as the elevation of the water at a position above (more shallow than) the top of the aquifer's upper surface. Laymen often refer to such aquifers as "artesian", and a well tapping a confined aquifer will flow freely at the surface without pumping if the hydraulic head is at an elevation above the land surface. Most wells tapping a confined aquifer do not flow freely at the surface, or they may flow until the elevation of the hydraulic head decreases to an elevation below the land surface. These terms and scenarios are illustrated in Figure 2.

Movement of groundwater in the subsurface can be complex, but some basic patterns are common. Groundwater will flow in response to local and regional pressure distributions, and specifically toward areas with lower hydraulic pressure. A common scenario is that groundwater migrates from areas of aquifer recharge toward areas of groundwater discharge. For an unconfined aquifer, these two areas generally correspond to upland areas and surface water (e.g., a river), respectively. In the case of simple porous materials, such as a well-sorted sand, flow occurs around the individual sand grains and through the interconnected pore spaces. Flow occurs in pathways that are perpendicular to decreases in the local hydraulic gradient. Contouring the distribution head on an equipotential map will illustrate the aquifer's pressure distribution, and the associated groundwater-flow pattern can be deduced from that head distribution.

Figure 2: Confined versus Unconfined Aquifers and Artesian Wells



Likewise, flow through fractured geologic materials will occur in direct response to hydraulic pressure distributions, but the actual pathways are dictated by the orientations, lengths, and apertures (widths) of multiple, intersecting fractures. The resulting flow patterns in fractured-rock aquifers can be very complex, and flow may occur in directions that may appear unrelated to indicators commonly used for simple porous media flow (e.g., relative positions of aquifer recharge and discharge areas).

Although groundwater flow in the real world is often complex, even in the case of simple porous media such as a sand aquifer, groundwater generally migrates along curving pathways that display pronounced downward or upward flow components in aquifer recharge areas and discharge areas, respectively. These curved pathways are pronounced, and may be complex, in unconfined aquifers because they reflect local flow systems controlled by proximity of recharge and discharge areas. In contrast, flow pathways in confined aquifers are typically controlled by more regional recharge and discharge features, and flow internal to the confined aquifer can be simple relative to the same aquifer material in an unconfined aquifer.

To further simplify the concept of groundwater flow, one can focus on two primary vectors, the horizontal component of flow and the vertical component of flow. In reality, groundwater flows in response to the net influence of both components, and not merely the horizontal component that is often assumed by examining an equipotential map. The velocity of groundwater flow in a particular area of interest can be described by the relationship between the hydraulic gradient (dh/dl), the aquifer's porosity (n), and the permeability (hydraulic conductivity, or k) of the aquifer. The velocity of the horizontal component of groundwater flow (V_h) can be calculated as $V_h = (k/n)*(dh/dl)$. For a well-sorted sand aquifer with 25% porosity, a k of 10 feet/day, and a hydraulic gradient (pressure difference) of 0.001 feet/foot, the V_h is calculated to be 0.04 feet/day, or 14.6 feet/year. If (only) the porosity in this example is reduced to 1%, a value typical of fractured rock aquifers, the V_h increases to 1 foot/day, or 365 feet/year.

Three aspects of groundwater flow and calculated groundwater velocity are highlighted by the example provided above. First, the values assigned to an aquifer (e.g., k) must be determined as carefully as possible and be representative of the aquifer across the area of interest. Second, increasing or decreasing the porosity assigned to the aquifer will produce large variations in calculated groundwater velocity. Finally, groundwater generally does not move very far during a typical American's lifetime, roughly on the order of 1,000 to 3,000 feet for most aquifers. In contrast, low-permeability materials enclosing a confined aquifer may have groundwater-flow velocities that are several orders of magnitude slower than flow in the adjacent aquifer.

The natural hydraulic gradients and flow patterns within an aquifer are disrupted by pumping groundwater from a well, but the degree of change produced is determined by aquifer characteristics and the rate and duration of pumping. Adjacent to the pumping well, the flow pattern is redirected toward the well, commonly in a radial pattern centered on the well. With increasing distance from the pumping well, the effects of decreasing pressure (drawdown) dissipate, and the result is a cone-shaped area of depressed hydraulic head. The diameter and vertical depth of the cone of depression are manifestations of the inherent physical characteristics of the aquifer and the pumping well. In an unconfined aquifer, physical drainage of pore spaces occurs within the cone of depression. In a confined aquifer, the cone of depression is manifest in the reduction of hydraulic pressure about the well, and the aquifer remains fully saturated as long as the total hydraulic head remains above the top of the aquifer. The cone of depression caused by pumping from a confined aquifer can be very large, thus reducing the quantity of water available to other users. Multiple pumping wells will have coalescing cones of depression that have an additive effect that enlarges the area of the aquifer that experiences declining pressure. This additive impact on water levels in wells is exemplified by excessive pumping of the Sparta-Memphis Sand aquifer in the Memphis metropolitan area that has caused water levels in northwestern Mississippi to decline. This subject is addressed more fully in Section V of this expert report.

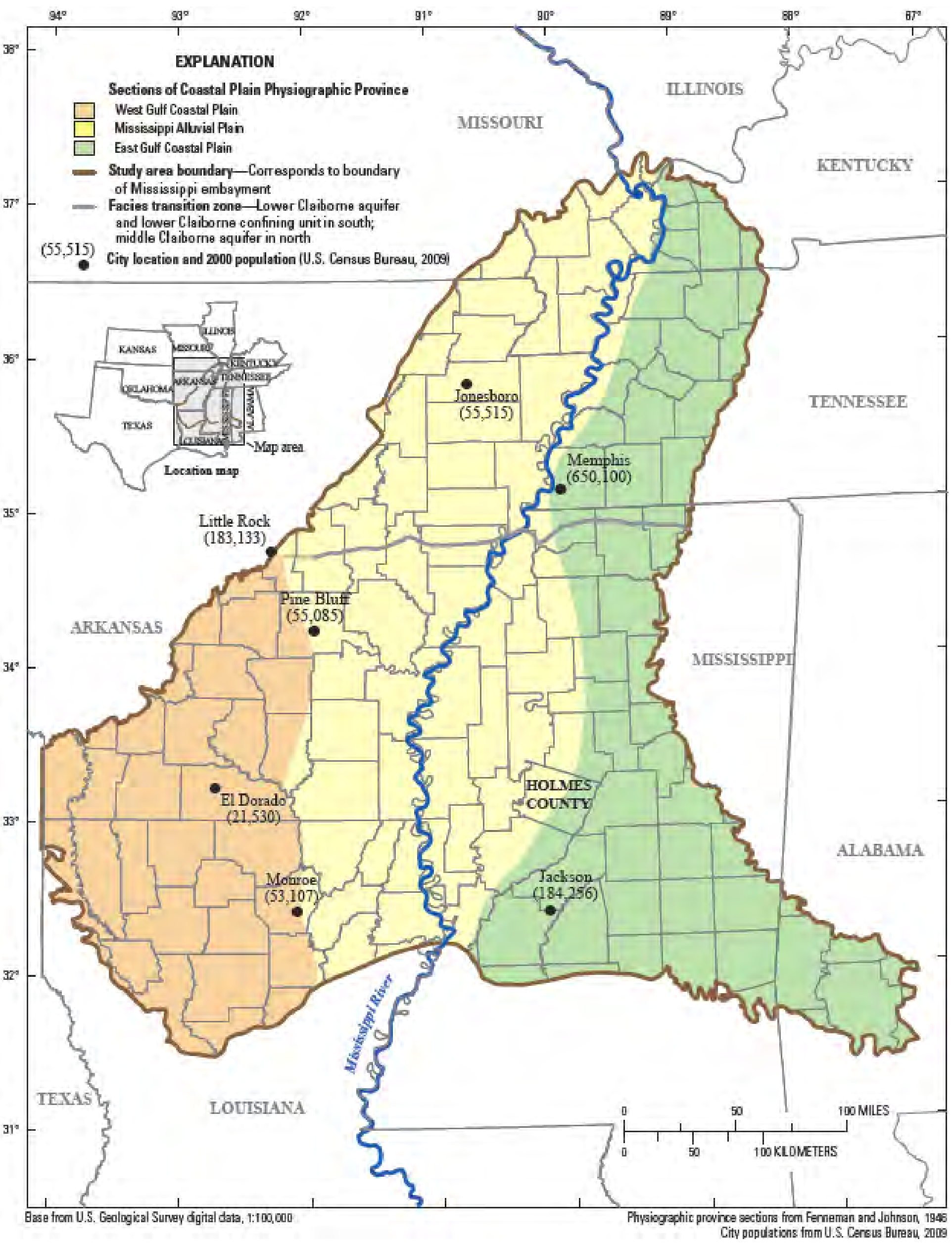
V. Geology and Hydrogeology of the Mississippi Embayment

This section of the expert report provides an introduction to the regional geologic origin and setting of the major basin (i.e., the Mississippi Embayment) that hosts the Sparta-Memphis Sand in northwestern Mississippi and southwestern Tennessee. Geologic and hydrogeologic aspects of the SMS are also described here and elsewhere in the report.

V.1 Introduction to the Origin of the Mississippi Embayment

The Mississippi Embayment is present in portions of eight states: Tennessee, Mississippi, Louisiana, Alabama, Illinois, Missouri, Arkansas, and Texas. The Embayment encompasses three physiographic provinces (Figure 3): the West Gulf Coastal Plain, the East Gulf Coastal Plain, and the Mississippi River Alluvial Plain. The Mississippi Alluvial Plain and East Gulf Coastal Plain are the provinces located in Tennessee and Mississippi, and these areas are the focus of this report.

Figure 3: Physiographic Provinces of the Mississippi Embayment (Clark et al., 2011, Figure 1)



Around 300 million years ago, the Appalachian Mountains and the Ouachita Mountains formed a single, long mountain chain. There was no break in the Appalachian-Ouachita mountain range where the Mississippi Embayment and the Mississippi River exist today. This mountain range was formed when different continental masses collided and formed a geologic 'supercontinent' called Pangea. The Mississippi Embayment began forming about 230 million years ago in the Triassic Period at the time that dinosaurs were first beginning to appear and when Pangea began to fracture and fragment. The Appalachian-Ouachita range formed the southern margin of the North American tectonic plate, and the area south of the range would become the South American tectonic plate and the Gulf of Mexico. The most common explanation for the Mississippi Embayment involves movement and interactions between these tectonic plates that caused down-warping and fracturing (rifting) of the earth's crust to create a deep basin that collected the sediments eroding from the adjacent highlands (Clark et al., 2011). However, the origin of the Embayment may be more complicated than originally thought, and a combination of moving tectonic plates and local uplift over unusually-hot portions (hot spots) of the earth's mantle may have shaped the surface (Van Arsdale and Cox, 2007).

The Appalachian-Ouachita mountain range has moved slowly and (relatively) westward with time. At about 95 million years ago, in the Cretaceous Period, the Mississippi Embayment was located over a hot spot in the earth's mantle that today is known as the Bermuda hot spot. The crust of the earth rose in elevation in response magma that moved upward toward the surface at the hot spot, and associated fractures and faulting created linear zones of weakness in the crust. Preferential weathering of that fractured crust resulted in erosion and removal of much of the Appalachian-Ouachita mountain range in the vicinity of the hot spot. Within a few million years, the hot spot activity had decreased to the extent that the crust and underlying mantle became cooler and contracted. The once-elevated and eroding mountain range decreased significantly in elevation, thus forming a trough (basin) that accumulated both terrestrial (e.g., stream) and marine sedimentary deposits within the Mississippi Embayment.

V.2 General Sedimentary Stratigraphy of the Mississippi Embayment

Sediments accumulating in the nascent Mississippi Embayment were deposited on the ancient Paleozoic Era bedrock of the eroded and subsided Appalachian-Ouachita mountain range. The oldest deposits known from the basin are marine sediments deposited in the Late Cretaceous (~95 million years ago to 65 million years ago), and they are predominantly calcareous sands, chalks, marls, and clay that are grouped together as the McNairy-Nacatoch Formations (Grubb, 1998; Cushing et al., 1964).

Cenozoic Era sediments that overly the McNairy-Nacatoch Formations were deposited in the Tertiary Period between 65 million years ago and approximately 3 million years ago. From oldest to youngest, these deposits are subdivided into the Midway, Wilcox, Claiborne, and the Jackson-Vicksburg groups (Grubb, 1998). Thick sand beds characterize the Wilcox and Claiborne groups (Figure 4), while finer grained deposits of clay and silt dominate the Midway and Jackson-Vicksburg groups. Sediments deposited during the Quaternary Period are less than approximately 3 million years old, and are predominantly sands, silts, and clays deposited by the Mississippi River (Figure 4).

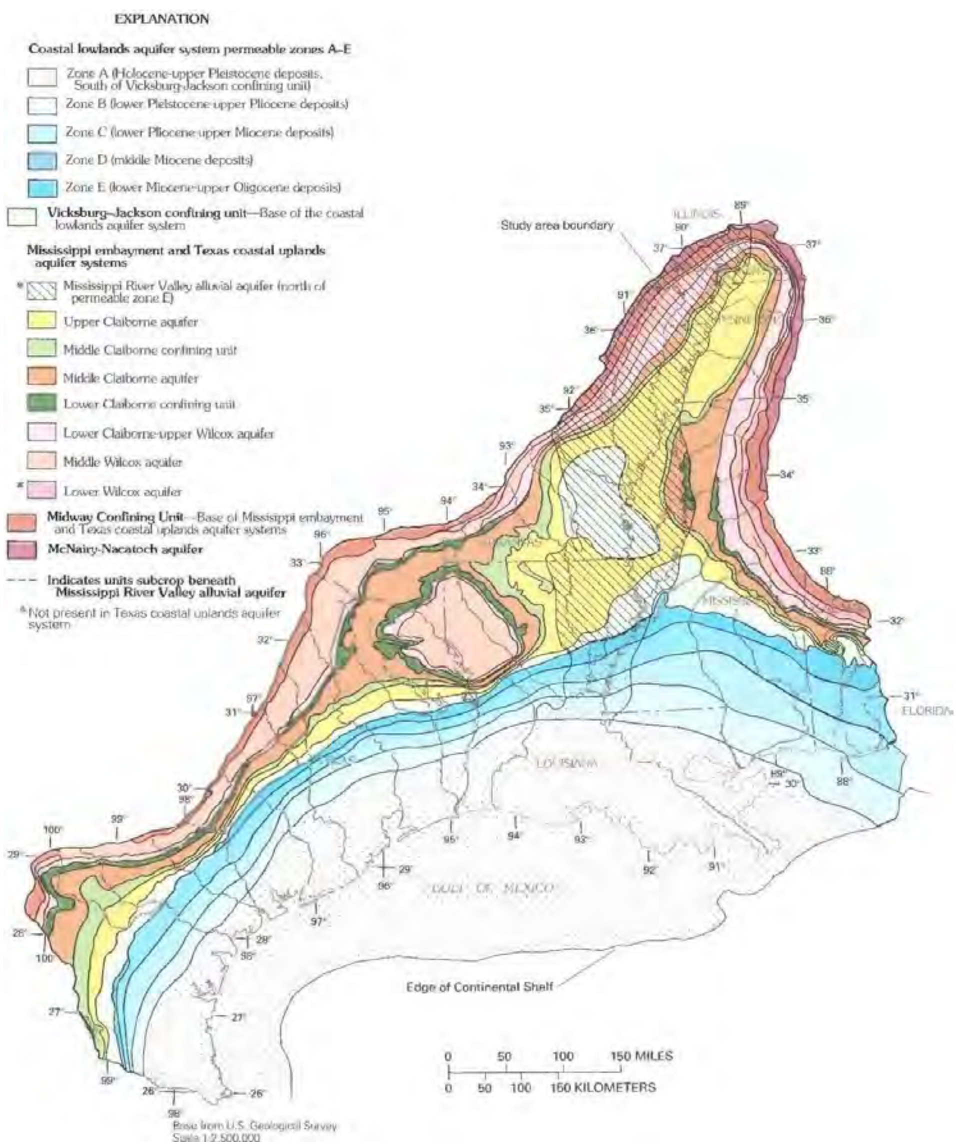
Figure 4: Stratigraphic Correlation of Paleocene and Younger Sedimentary Units and Aquifers in Northern Mississippi and Western Tennessee (Haugh, 2016, Table 1)

System	Series	Group	West Tennessee	Northern Mississippi	Regional hydrogeologic unit
Quaternary	Holocene and Pleistocene		Alluvium	Alluvium	Shallow aquifer
Quaternary	Pleistocene		Fluvial Deposits (terrace deposits)	Fluvial Deposits (terrace deposits)	
Tertiary	Eocene	Claiborne	Cockfield Fm	Cockfield Fm	Upper Claiborne aquifer
			Cook Mountain Fm	Cook Mountain Fm	Middle Claiborne confining unit
			Memphis Sand (Memphis aquifer)	Sparta Sand (Sparta aquifer)	Middle Claiborne aquifer
				Zilpha Clay	Lower Claiborne confining unit
				Lower sands in the Claiborne Group	Lower Claiborne-Upper Wilcox aquifer
		Wilcox	Flour Island Fm	Upper sands in the Wilcox Group	
	Paleocene		Fort Pillow Sand (Fort Pillow aquifer)	Lower sands in the Wilcox Group	Middle Wilcox aquifer
			Old Breastworks Fm		Lower Wilcox aquifer
		Midway	Porters Creek Clay	Porters Creek Clay	Midway confining unit
			Clayton Fm	Clayton Fm	

V.3 General Hydrogeology of the Mississippi Embayment

There are three major aquifer systems in the Mississippi Embayment recognized in the vicinity of southwestern Tennessee and northwestern Mississippi (Figure 4): The Wilcox System (composed of the lower, middle, and upper Wilcox Aquifers), the Claiborne System (composed of the lower, middle, and upper Claiborne Aquifers), and the shallow alluvial aquifer system located within the Mississippi River valley. Figure 5 shows the areal exposures of these aquifers at the land surface.

Figure 5: Surface Distribution of Regional Aquifers and Confining Units in the Mississippi Embayment and Gulf Coastal Plain (Grubb, 1998, Figure 7)



In northwestern Mississippi and western Tennessee, most of the Lower Claiborne and Upper Wilcox Aquifers are confined (i.e., are 'artesian' aquifers). The Lower Claiborne Aquifer and the Upper Wilcox Aquifer are often considered to form one aquifer, and they are separated by a confining layer from the overlying Middle Claiborne Aquifer.

The Claiborne Group is a package of sediments deposited in the Mississippi Embayment approximately 40 million years ago during the middle of the Eocene Epoch of the Cenozoic Era. Historically, the Middle Claiborne Aquifer was called the 500 Foot Sand to reflect the typical depth of the sands being targeted for water-supply wells in the Mississippi-Tennessee border area (Criner et al., 1964). In Tennessee, the names Memphis Sand or Memphis Aquifer (Figure 4) are synonymous with the Middle Claiborne Aquifer. In Mississippi, the upper part of the Middle Claiborne Aquifer is called the Sparta Sand (e.g., Clark et al., 2011), which is correlative with the upper part of the Memphis Sand (Figure 4). The Claiborne and Wilcox Aquifer Systems are the major sources of public water supply in the vicinity of the City of Memphis, both north and south of the Mississippi-Tennessee border. Of these, the Middle Claiborne Aquifer is the primary source of water used to supply municipalities and individual home owners, and that aquifer has experienced the most obvious impacts from extensive pumping in Shelby County, Tennessee. The Middle Claiborne Aquifer in western Tennessee and northwestern Mississippi is inclined (dips) generally westward from where the sand deposits crop out to beneath the Mississippi River.

The upper part of the Middle Claiborne Aquifer (i.e., the Sparta Sand) is the primary water-producing zone exploited by municipal well fields (Clark et al., 2011), and the name Sparta-Memphis Sand is employed in this expert report to refer to the Middle Claiborne Aquifer that is being pumped extensively in Shelby County, Tennessee. The terms Middle Claiborne Aquifer or Memphis Aquifer are considered synonymous with the SMS for purposes of this expert report. It is important to recognize that pumping has also impacted the Lower Claiborne-Upper Wilcox Aquifer, and focus on the SMS is <u>not</u> intended to discount pumping impacts on that deeper aquifer system.

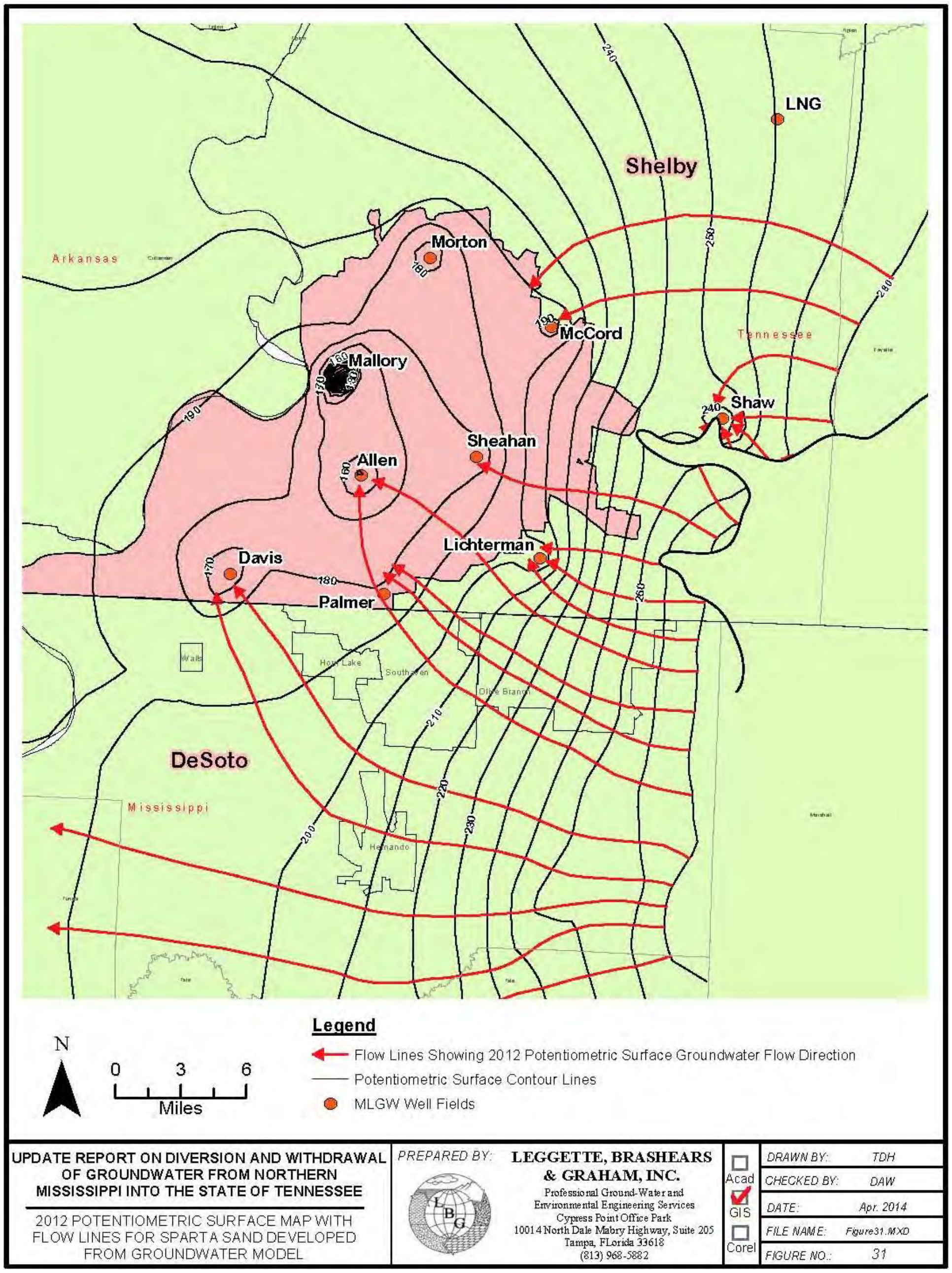
The Mississippi River Alluvial Aquifer (aka, Surficial Aquifer) lies atop these mostly-buried Eocene-age aquifers, and the Surficial Aquifer is exposed at the surface within the Mississippi River floodplain. This aquifer is generally unconfined, and consists of sands, silts, and clays deposited by the Mississippi River during the Quaternary Period (Clark et al., 2011). The Surficial Aquifer is the primary groundwater source used by agriculture throughout much of the Mississippi Embayment.

V.4 Groundwater Withdrawals and Impacts

Groundwater withdrawals within the Mississippi Embayment are used primarily for public consumption and agriculture (Clark et al., 2011). The largest population center in the Mississippi Embayment area is the City of Memphis in Shelby County, Tennessee, and the county has an approximate population of 900,000. In the vicinity of the Mississippi-Tennessee border and generally near the City of Memphis, the middle of the Claiborne Group is dominated by sand deposits that are identified as the Sparta-Memphis Sand. Memphis withdraws water primarily from the SMS (aka, Middle Claiborne Aquifer or Memphis Aquifer). The SMS is a confined aquifer in the vicinity of Memphis, so withdrawal of up to 162 million gallons per day from more than 170 production wells operated by Memphis Light, Gas and Water (MLGW) has produced a large, composite cone of depression (an area of lower pressure) centered on MLGW's 10 well fields.

MLGW is one of the world's largest groundwater-based water-supply systems. Groundwater from the Mississippi Embayment aquifers in Tennessee and Mississippi has been used since the late 1800's. Water service for Memphis began in 1870, and Memphis withdrew approximately 30 million gallons of water per day (mgd) from 1895 to 1900 (Grubb, 1998). Withdrawals increased to over 180 mgd by 2005 (Clark et al., 2011), and the predictable result is that MLGW's withdrawals have produced a broad, coalesced cone of depression centered on Shelby County (Figure 6). The cone(s) of depression result in changes in the pattern of the horizontal component of groundwater flow within the SMS and in the underlying Lower Claiborne-Upper Wilcox Aquifer system, as well as inducing or accelerating vertical flow across confining units separating the SMS from overlying and underlying aquifers.

Figure 6: Cones of Depression and Groundwater Flow Paths Associated with Municipal Well Fields in Shelby County, Tennessee (LB&G, 2014, Figure 31)



Groundwater generally flows from recharge areas toward discharge areas. Significant recharge for the SMS occurs where the sand deposits are exposed (and unconfined) at the land surface in the eastern portion of the Mississippi Embayment in Tennessee and Mississippi (Figure 7), as well as vertical recharge from the overlying Surficial Aquifer.

The source of recharge water is predominantly rainfall in the areas where the SMS crops out at the surface (Grubb, 1998). Groundwater in the SMS discharges upward to streams (local flow paths) and the Mississippi River (regional flow paths).

Figure 7: Block Diagram Illustrating Surface Recharge and Groundwater Flow Paths within the Sparta-Memphis Sand Aquifer in Northern Mississippi (LB&G, 2014, Figure 6)

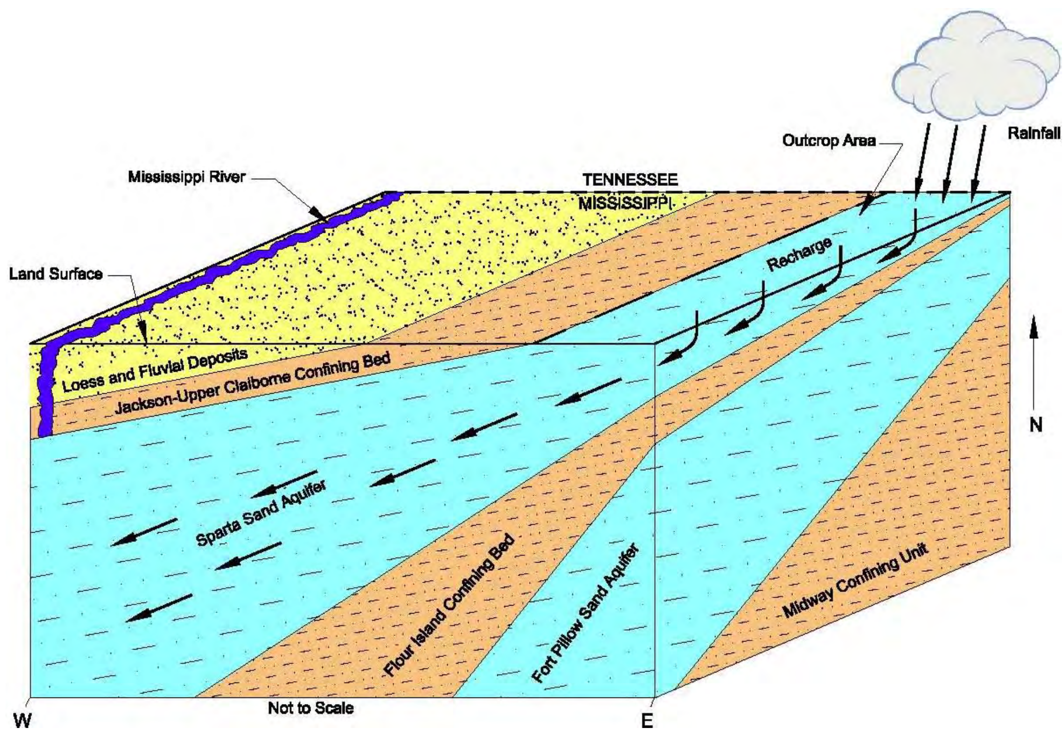
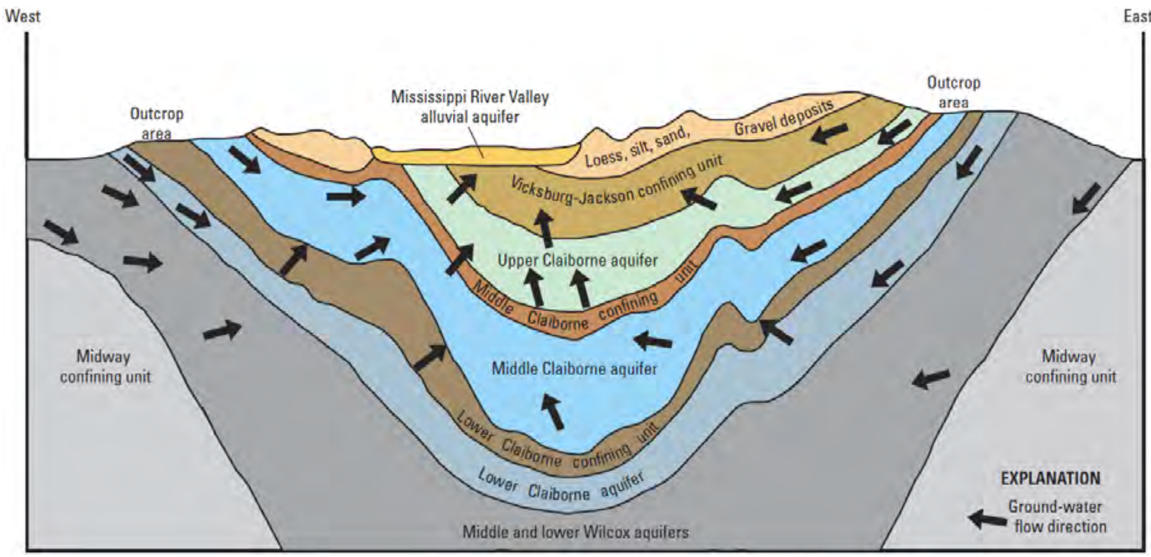


Figure 8 is a schematic east-west cross section (side view) through the Mississippi Embayment that includes arrows depicting the general pattern of groundwater flow before development began in the late 1800s. Some regional flow paths for water movement were as long as 200 miles from the recharge area to the discharge area. However, some local flow paths were shorter and were influenced by local topography and the density of streams and other surface water features in the recharge areas. Figure 9 illustrates the natural pre-development potentiometric (pressure) surface for the confined Middle Claiborne Aquifer. Arrows show that the direction of natural groundwater flow in the SMS in the vicinity of Memphis was generally directed from east to west (Figure 9).

Figure 8: Schematic West-East Cross-Section of the Geology of the Mississippi Embayment and Generalized Pre-Development Groundwater Flow Patterns (modified from Figure 4 of Hart et al., 2008)



The natural patterns of groundwater flow have been transformed as a result of extensive pumping (Arthur and Taylor, 1998; Grubb, 1998; Clark et al., 2011). Withdrawal of groundwater from wells has lowered the pressure in the Sparta-Memphis Sand, causing water in higher pressure areas to move within the SMS toward the lower pressure area of the pumping wells. Individual cones of depression centered on MLGW's well fields in Shelby County have coalesced to create a broad area of depressed hydraulic pressure within the SMS (see Figure 6). Not only do withdrawals change the natural directions of the horizontal component of groundwater flow within the aquifer, but water can be induced to flow vertically across confining units from one aquifer to another. Figure 10 presents a map by Arthur and Tayler (1998) showing the potentiometric surface of the Middle Claiborne Aquifer (SMS) in 1987, long after intense exploitation of this aquifer began. Arrows show the direction of groundwater flow in the vicinity of Tennessee and Mississippi, with obvious flow being directed toward the municipal well fields in Shelby County, Tennessee.

Figure 9: Pre-Development Groundwater Equipotential Map and Flow Patterns in the Middle Claiborne Aquifer (modified from Plate 5 of Arthur and Taylor, 1998)

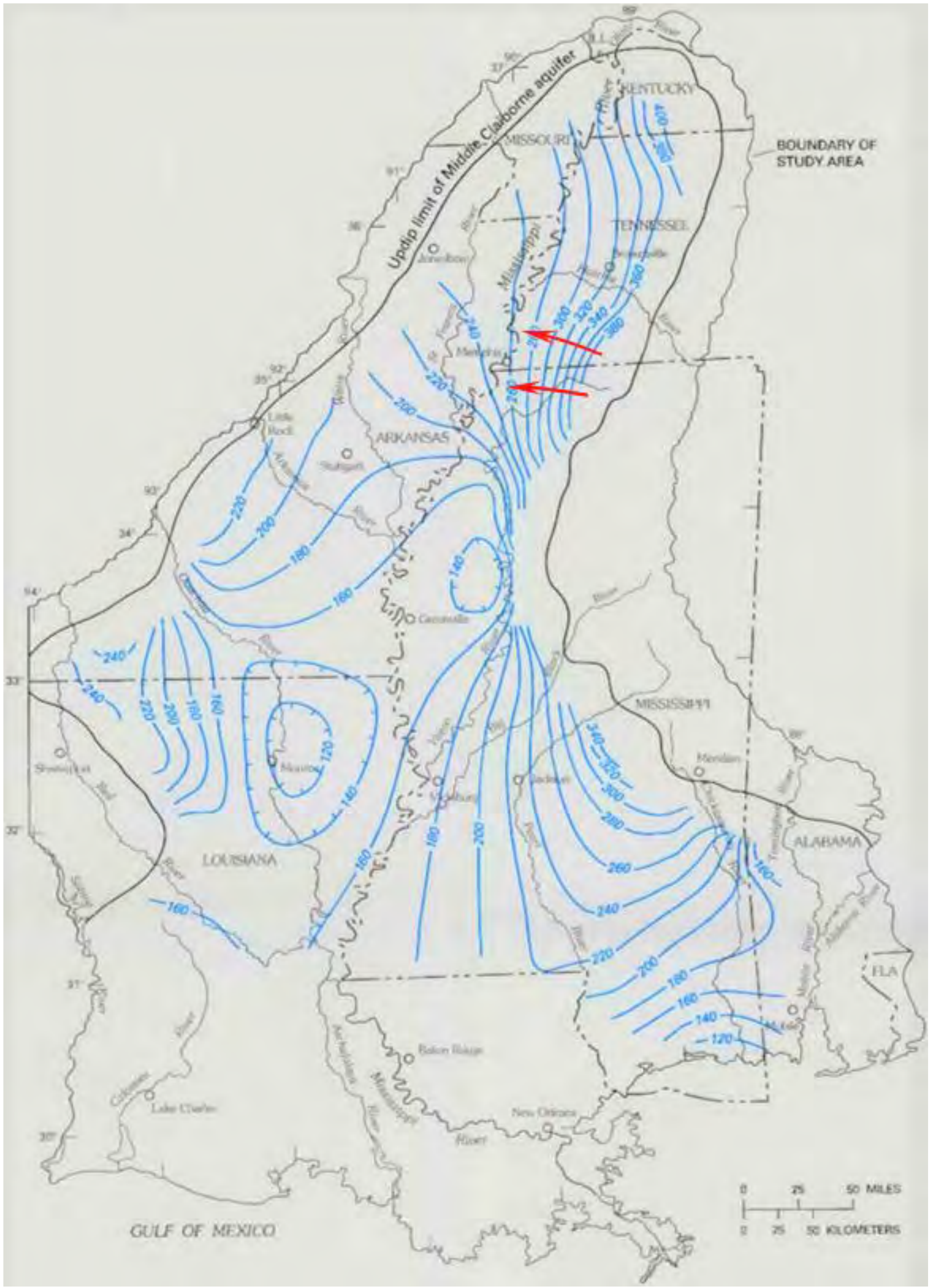
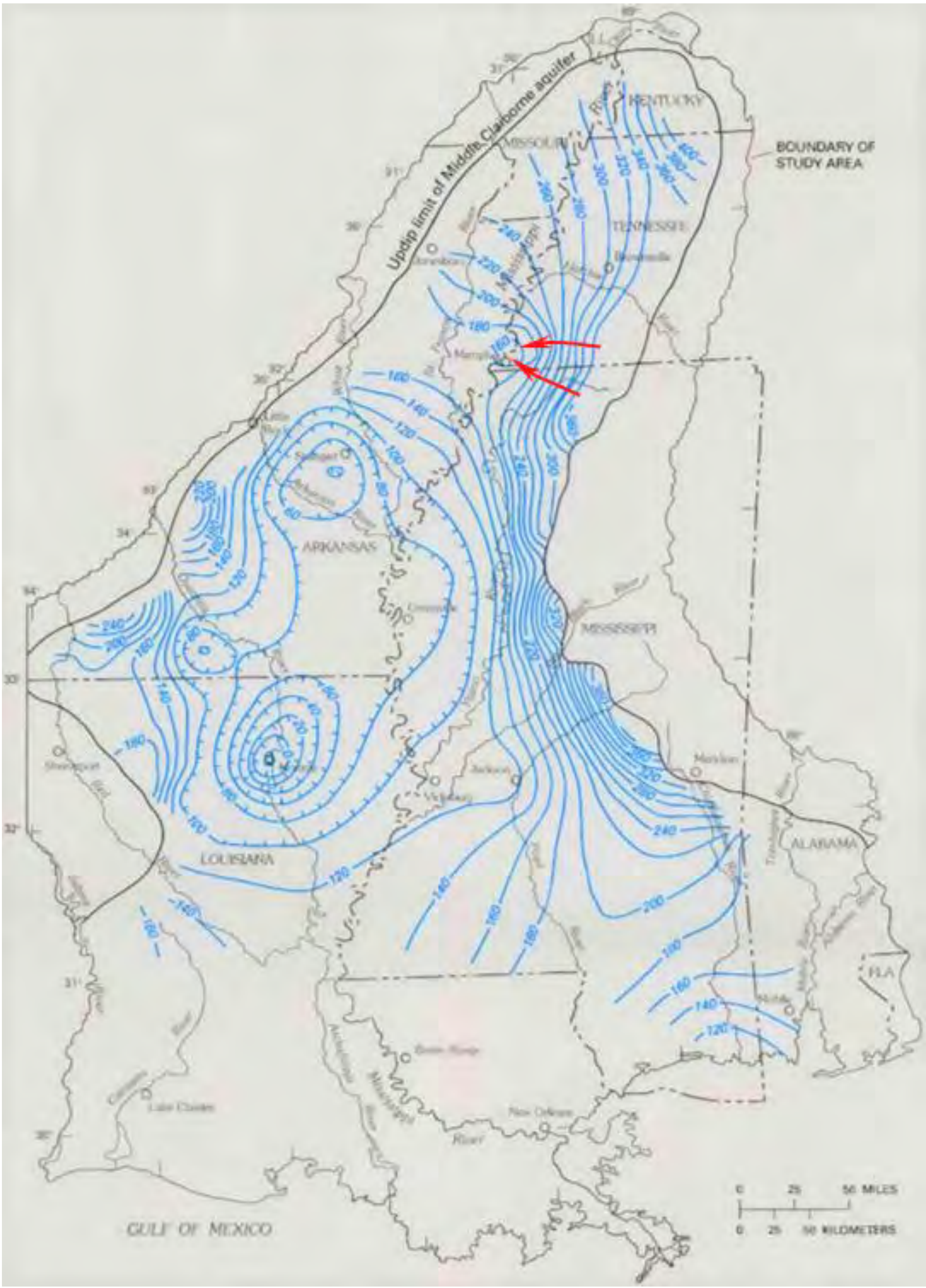


Figure 10: Post-Development Groundwater Equipotential Map and Flow Patterns in the Middle Claiborne Aquifer (modified from Plate 7 of Arthur and Taylor, 1998)



Even after extensive and protracted well-field withdrawals, recharge to the aquifer system will still occur through the Surficial Aquifer and the aquifer outcrop areas in the eastern part of the Mississippi Embayment in Tennessee and Mississippi. However, most water recharging the aquifer systems has been diverted to major pumping centers in Shelby County, and discharge is no longer directed upward to the Mississippi River (regional flow paths) and to smaller streams (local flow paths) in the vicinity of the well fields. For example, the USGS has reported that groundwater movement in the summer of 2006 was predominantly directed downward from the channels of rivers and streams to offset the demand from pumping in the deeper confined aquifers (Clark et al., 2011). This change in groundwater discharge patterns resulted in reduced stream flow because the base flow of the streams was being taken indirectly by pumping of the SMS aquifer.

Prior to extensive development of the Middle Claiborne Aquifer in Tennessee, groundwater that existed in the SMS for thousands of years was primarily migrating westward from recharge areas in the eastern outcrop belt of the SMS (Clark et al., 2011). The SMS received relatively small contributions of water from the adjacent Surficial Aquifer and Lower Claiborne Aquifer, and a minor amount of water was also contributed by the Upper Wilcox Aquifer. It has been estimated (Brahana and Broshears, 2001) that roughly half of the groundwater in the Sparta-Memphis Sand being recovered by pumping in Shelby County, Tennessee, originates as predominantly horizontal flow in the SMS, and the other half of the extracted water is derived from vertical leakage across the aquifer's confining layers and the overlying surficial aquifer and underlying confined aquifers.

V.4 Current Groundwater Conditions in the Sparta-Memphis Sand

Voluminous and ongoing withdrawals in the vicinity of Memphis, Tennessee, have changed the pre-development patterns of groundwater flow within the Sparta-Memphis Sand in southwestern Tennessee and northwestern Mississippi. Historically, recharge to the SMS occurred in eastern areas of the Mississippi Embayment where the Eocene-age sand deposits are exposed at the surface. That groundwater moved generally westward until it ultimately discharged upward to the Mississippi River channel thousands of years later. Prior to intense pumping of the SMS, groundwater flowed horizontally from east to west in the regional aquifer systems, essentially parallel to the Tennessee-Mississippi state line. Therefore, the flow of groundwater that had existed within Mississippi's borders for thousands of years was directed from east to west across the state prior to development, so the recharge originating in each state remained within that state.

The withdrawal of large quantities of groundwater from the SMS for many decades by large municipal well fields in Shelby County, Tennessee, has modified significantly the natural east-to-west groundwater-flow pattern, thus diverting large quantities of high-quality groundwater from within Mississippi to Tennessee. The Surficial Aquifer, an important area of groundwater discharge for the Sparta-Memphis Sand prior to intense withdrawals, is now a significant source of recharge water for the SMS. Today, groundwater flows toward MLGW's well fields from multiple directions, as well as vertically across confining units separating the SMS from adjacent aquifers. Specifically, groundwater previously contained within, and moving entirely within, Mississippi now flows interstate toward pumping centers in Tennessee, and the rate of that flow has increased because intense pumping by MLGW has produced substantially steeper hydraulic gradients (e.g., compare Figures 9 and 10). Groundwater that was once part of Mississippi's natural resources long before it became a state has been taken, and is still being taken, by Tennessee for the benefit of its citizens.

VI. Groundwater Flow Patterns in Unconfined Versus Confined Aquifers

Unconfined and confined groundwater systems are fundamentally different in several significant ways. The hydraulic properties of the two systems, such as hydraulic conductivity, transmissivity, and storage coefficient, can vary in different parts of each system. Hydraulic conductivity, often referred to by non-technical individuals as permeability, is a measure of the ability of sediments or rocks to transmit water through a unit cross sectional area, under a unit hydraulic gradient, in a given amount of time, usually one day. Hydrogeologists describe differences in aquifer materials by evaluating the directional and locational differences in hydraulic conductivity. The terms homogeneous, heterogeneous, isotropic, and anisotropic are used to describe variations in hydraulic conductivity within aquifers at different locations, and in different directions at a given location. In general, the major water-producing aquifer systems in the Mississippi-Tennessee border region are heterogeneous and anisotropic.

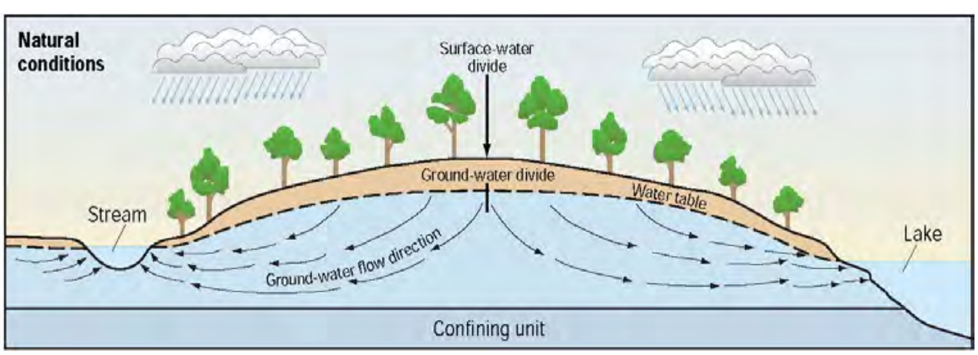
Transmissivity is used to describe the flow of groundwater through aquifers, and it is defined as the hydraulic conductivity multiplied by the thickness of the aquifer. Transmissivity is a property that is commonly determined to understand and quantify how much water moves through, and thus can be recovered from, an aquifer.

Storage coefficient is a measure of the volume of water taken into, or released from, the pore spaces in a unit volume of the aquifer material per foot of head change. The actual value of the storage coefficient of confined and unconfined aquifers is significantly different, and the actual value is used by hydrogeologists to distinguish between the two types of aquifers. Although aquifers are often subdivided as confined or unconfined, the actual degree of confinement can vary and is based on storage coefficient.

VI.1 Unconfined Aquifers

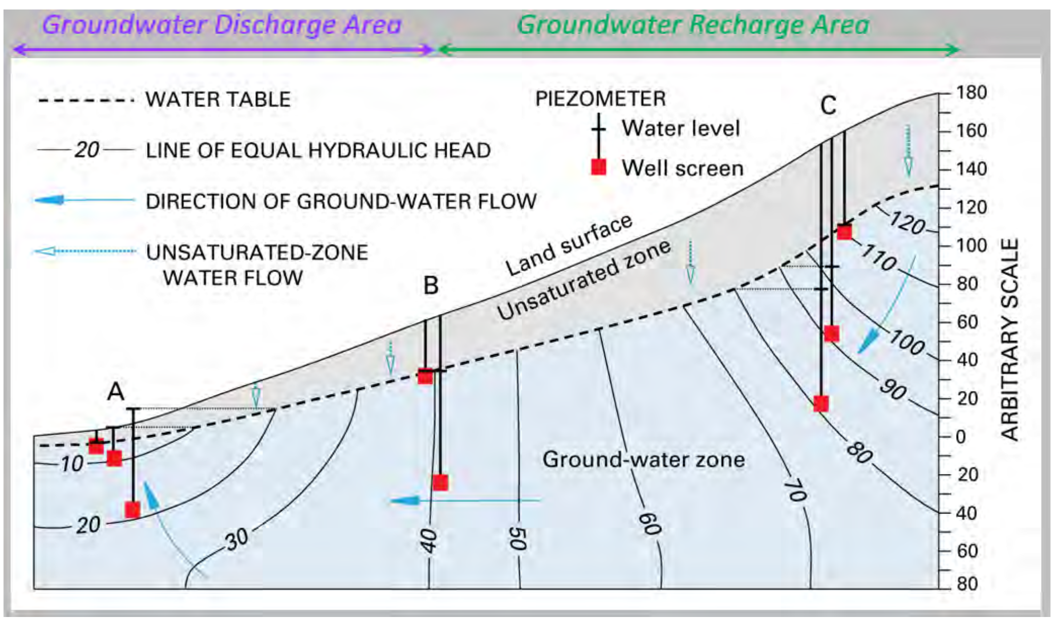
Groundwater flow patterns in unconfined portions of the groundwater system are extremely complex. To illustrate these patterns, Figure 11 is a generalized groundwater illustration that depicts flow in the shallow groundwater system from a groundwater divide in an elevated area to the location of a stream or lake located at lower elevations. Groundwater flow in this system follows a circuitous path from upland areas to lowland areas where groundwater ultimately discharges to the surface water body.

Figure 11: Unconfined Aquifers and Local Flow Systems (Modified from Grannemann et al., 2000)



Hydrogeologists have documented this pattern of circuitous groundwater flow in numerous unconfined aquifers by installing nested piezometers. Piezometers are specially designed wells with short intake areas (screens) which can be used to measure the water level, and hence the pressure, in the aquifer at specific depths. Note the locations and depths of the piezometers in Figure 12, and the value of pressure (head) illustrated with small triangles for each piezometer. Based on these types of studies in numerous locations, hydrogeologists have determined that groundwater flows with a downward-directed component in upland areas (called recharge areas), then it flows horizontally before changing to flow direction that is directed upward in low-lying areas (called discharge areas).

Figure 12: Piezometers are used to define Groundwater Recharge, Discharge, and Flow Patterns in Unconfined Aquifers (modified from Winter et al., 1998)



There are two important points to emphasize regarding the concept of recharge and discharge areas. First, groundwater flow patterns in unconfined areas <u>cannot</u> be determined unless wells are installed to different depths and the screen intervals are short and installed precisely. Wells with long screens <u>cannot</u> be used to evaluate depth-

specific head changes. Wells with short screens with unknown depths cannot be used to evaluate groundwater flow patterns in unconfined aquifer systems
Second, recharge areas in unconfined aquifer systems are based on downward-directed flow patterns and a decrease in total hydraulic head with increasing depth. Discharge areas in unconfined aquifer systems are based on upward-directed flow patterns and an increase in total hydraulic head with increasing depth. The boundary between recharge and discharge areas must be determined using nested piezometers which do not show a change in head with increasing depth. It is a common misconception that recharge and discharge areas can be determined by casual observation of differences in the elevation of the land surface (i.e., topography).

The unconfined groundwater system response to withdrawal of water from water-supply wells is complex. Withdrawal of groundwater from wells reduces the pressure in the aquifer in and near the well, resulting in a 'cone of depression' centered on the well. In unconfined aquifers, there is slow gravity drainage of water from the pore spaces in the aquifer above the developing cone of depression. Two important changes result from this gravity drainage within the cone: (1) the thickness of the unconfined portion of the aquifer is reduced within the cone, and (2) the transmissivity of the unconfined aquifer is reduced because of the reduction in thickness of the saturated portion of the aquifer.

Groundwater in the unconfined portions of most groundwater systems is often characterized by poor water quality relative to confined aquifer systems. For a variety of reasons, wells often produce lower yields from unconfined aquifers than do wells in confined aquifers. This is true in many areas of northwestern Mississippi and western Tennessee, where most water-supply wells do not tap the unconfined portions of the groundwater system.

VI.2 Confined Aquifers

Confined aquifers, such as major portions of the Wilcox and Claiborne Aquifer Systems, are characterized by beds or layers of material that have the ability to yield useable quantities of groundwater to wells open to these layers. In most cases, these aquifers are overlain and underlain by layers of material with reduced ability to transmit useable quantities of groundwater water (i.e., confining layers). Thus, hydrogeologists define aquifers and confining layers in terms of the relative ability of these materials to transmit groundwater, but non-technical individuals often assume incorrectly that confining beds are incapable of transmitting and producing groundwater. This ability of confining layers to transmit groundwater, even at significantly reduced rates relative to aquifers, is important because the slow movement of groundwater across confining layers is a significant component of the natural recharge for confined aquifer systems.

By definition, the pressure in a confined aquifer, under natural conditions, is such that the water level in a well tapping the confined aquifer will rise above the top of the aquifer at the well. In some aquifers, the water level in the well will rise above the land surface, and the well can be constructed in a manner that will allow the well to flow freely. In other instances, the water level in the well is below the land surface, but above the top of the aquifer. Hydrogeologists will often describe these as either a free flowing or non-free flowing well in a confined aquifer (see Figure 2).

Groundwater flow in confined aquifers is often less complex than in the unconfined portions of the groundwater system. For example, in major portions of the confined groundwater system, groundwater flow is often parallel with the top and/or bottom of the aquifer for significant horizontal distances, equipotential lines are often near-vertical in orientations, and withdrawals of groundwater from wells tapping these aquifers does not cause a reduction in thickness of the aquifer. Therefore, the transmissivity of confined aquifers is not reduced by groundwater withdrawals from wells unless the water level in the aquifer is lowered below the upper surface of the aquifer.

Many municipalities prefer to use groundwater from confined aquifers for three reasons: (1) water quality in confined aquifers is generally better than in unconfined aquifers, (2) the transmissivity of confined aquifer is not reduced by reduction in head (unlike unconfined aquifers), and (3) the total available drawdown, a measure of the number of feet that the water level in an aquifer can be reduced without harm to the aquifer, is generally greater in a confined aquifer than in an unconfined aquifer.

VI.3 Total Available Drawdown and Specific Capacity of Wells

The discussion of total available drawdown provided here refers only to the response of water levels in wells in confined aquifers. Pumps installed in wells constructed in confined aquifers will typically have the pump intakes located above the top of the confined aquifer so that the pumping water level cannot be lowered below the top of the aquifer. Hydrogeologists define total available drawdown as the number of feet (or meters) between the top of the aquifer and the water level in a non-pumping well tapping the aquifer (i.e., the static water level). For example, consider a confined aquifer with a top of aquifer elevation of 400 feet above mean sea level (AMSL) and a static water level of 600 feet AMSL. The aquifer has 200 feet of total available drawdown. That aquifer parameter can be used, in conjunction with the measurement called specific capacity of a well, to determine a theoretical maximum yield of a well.

Specific capacity is a term used extensively in the water-supply industry to evaluate the yield potential of a water-supply well. Specific capacity is the withdrawal rate of a well (measured in gallons per minute), divided by the amount of water level change (total drawdown) which occurs during a specific period of withdrawal. A common period for reporting specific capacity is 24 hours of pumping, but there is no fixed time requirement for reporting specific capacity.

The specific capacity of a well pumped at 1,000 gallons per minute (gpm) for 24 hours with 40 feet of drawdown is reported as $(25\ \text{gpm/foot of drawdown})_{24\ \text{hours}}$. Specific capacity is an important aspect of water-supply well hydraulics because it can be combined with total available drawdown to calculate a well's (theoretical) maximum yield. For example, the confined aquifer well described previously with 200 feet of total available drawdown and a 24-hour specific capacity of 25 gpm/foot of drawdown can (theoretically) produce 5,000 gpm.

Reductions in total available drawdown will reduce the theoretical maximum yield of a well. A variety of factors can reduce the total available drawdown, including regional decline in water levels due to changes in precipitation or recharge rates, and the impacts of other pumping wells in the area. In the example well described above, every foot of reduction of the total available drawdown results in a corresponding loss of 25 gpm. If 100 feet of total available drawdown is lost due to impacts from nearby pumping wells, then 2,500 gpm are no longer available to be pumped from the impacted well.

The example provided here is modeled on an evaluation of municipal wells in the northern part of Mississippi that tap the Claiborne Aquifer. The City of Southaven water-supply well No. 2 (also called the Airways Well) had a reported specific capacity of approximately 20 gpm/foot of drawdown when it was completed in 2002 (LGS, 2002). For every foot of reduction in the total available drawdown caused by external factors, such as withdrawals from other wells operating in the area, the theoretical maximum yield of the Airways Well decreases by 20 gpm.

VI.4 Size of the Cone of Depression Surrounding a Confined Aquifer Well

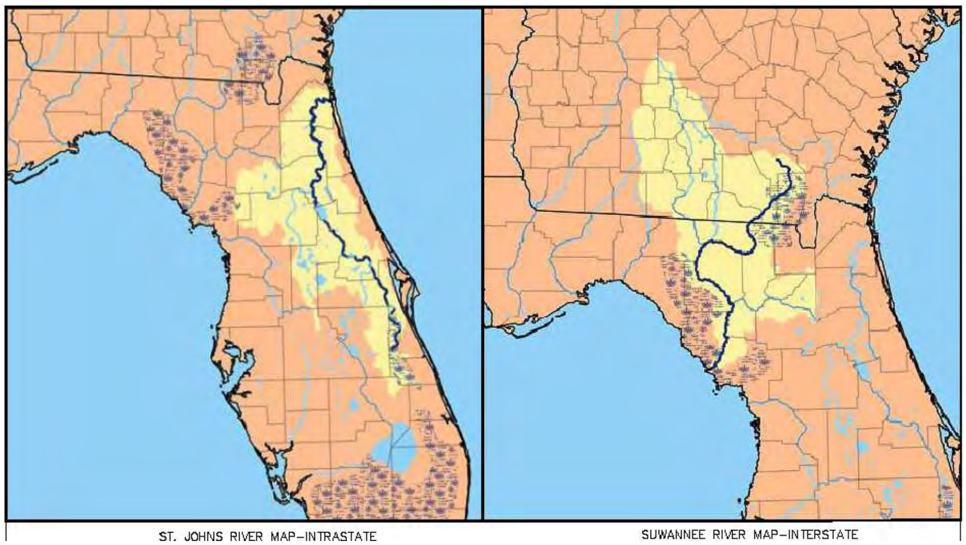
The shape of the cone of depression associated with a pumping well in a confined aquifer has two important aspects. First, the depth of the cone adjacent to the well is controlled by the hydraulic properties of the aquifer, the pumping rate, and the pumping period. The theoretical lateral limit of the cone of depression is independent of the pumping rate, and is instead a function of the hydraulic properties of the aquifer and the amount of pumping time. The theoretical limit of the cone of depression of the City of Southaven's well was calculated to be 90,000 feet, or approximately 17 miles (LGS, 2002). While this number may seem large to the casual observer, it should be remembered that this is the distance from the water-supply well beyond which there is theoretically zero water-level impact. The more important calculation for the Southaven well is, that at a distance of 27,000 feet (~5.1 miles) from the production well, the amount of water-level reduction in the cone of depression is 9.5 feet if the well is pumped at a rate of 1,500 gpm (LGS, 2002). Another production well at that location 27,000 feet away from the Southaven well would suffer a loss of theoretical maximum yield of 190 gpm (9.5 feet of loss in head X 20 gpm/foot = 190 gpm). Hydrogeologists commonly produce these types of well-interference calculations to determine the impacts on an aquifer system caused by one or more production wells. The important point here is that wells constructed and operated within the cones of depression of other production wells have significant cumulative impacts on the groundwater system, the most important of which is the ultimate reduction in the theoretical maximum yield of a well at any specific location. Calculations of the impacts of one pumping well at approximately 1,500 gpm on the water-levels should be considered in light of the large-scale impacts resulting from 175 wells pumping 180 million gallons per day along the Mississippi-Tennessee border.

VI.5 Opinions on Availability of Groundwater in the SMS Under Natural Conditions and Territorial Considerations

Aquifers are geological formations composed of naturally-occurring materials (e.g., sand, silt, limestone, etc.) that are capable of transmitting useable quantities of groundwater. Aquifers are essentially just conduits through which groundwater flows as a natural resource under natural conditions. A sand or rock layer with no groundwater moving into and through its pore spaces is not an aquifer any more than a dry river bed is a river. However, when water is added to either system under natural conditions, the forces of nature determine the ultimate availability of the water in both systems. The determination of the source and natural availability of surface water and groundwater within a specific state or territory under natural conditions requires entirely different analyses.

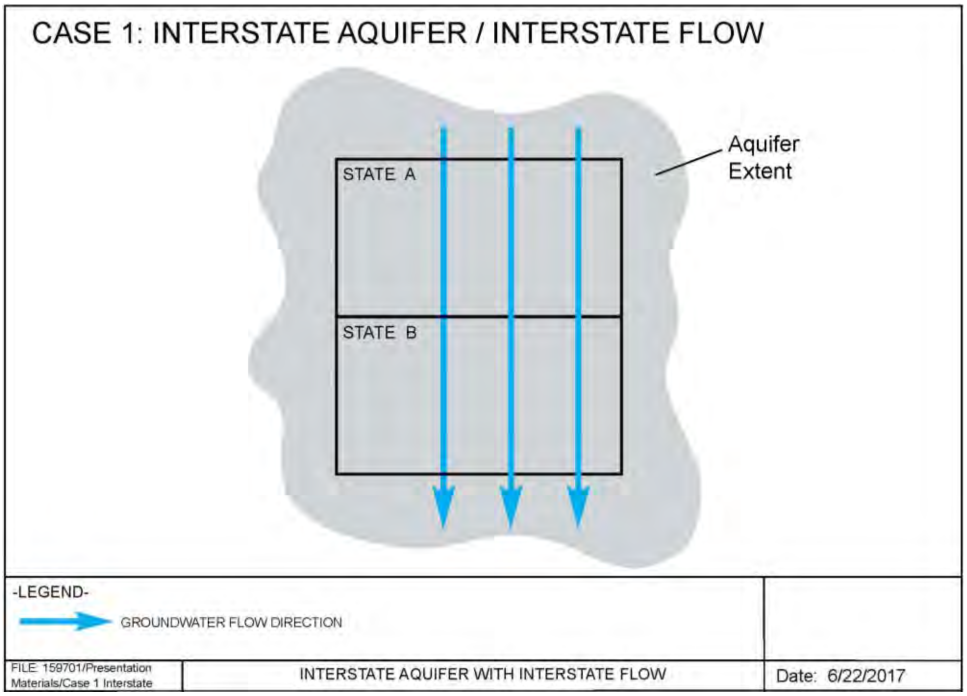
Fresh water is one of our most important natural resources, and its availability has become a major concern in many parts of the United States and elsewhere. Claims to surface water have historically been recognized based on the location and flow path of the water under natural conditions. Figure 13 illustrates this point with two rivers in Florida. The St. Johns River originates in, and resides entirely within, the State of Florida, and it ultimately discharges to the Atlantic Ocean. The Suwannee River originates in Georgia, travels through Florida, and discharges to the Gulf of Mexico. The river water in the first example is a natural resource of Florida, while the water in the second river is a natural resource shared by both states, a well-established concept based on the locations of the respective watersheds (drainage basins) from which the water is derived and the flow paths of the rivers.

Figure 13: Drainage Basin and Channel location of an Intrastate River (left) and an Interstate River (right) in Florida (modified from Wikipedia)

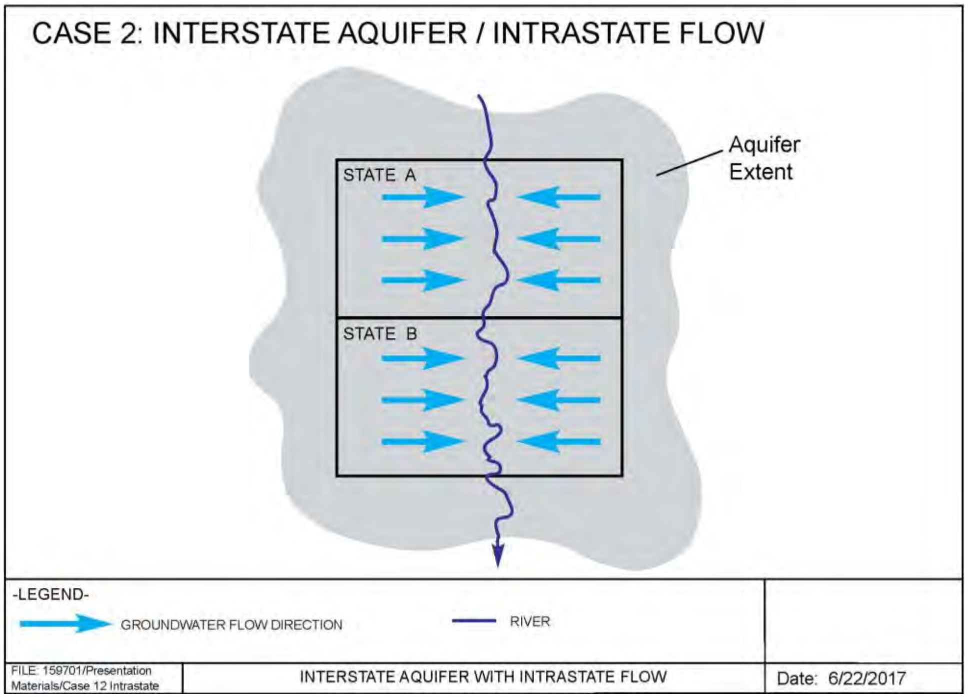


The natural territorial accumulation and flow of surface water along the lowest path created by geological processes is visible to the entire world. While it is not as visible, thus making it inherently more complicated, the natural territorial accumulation and flow of groundwater within a confined aquifer is also determined by geological forces and identifiable by application of the concepts described in this expert report. Using my analysis of the Sparta-Memphis Sand Aquifer, I present two hypothetical cases to illustrate how the groundwater within a confined aquifer may or may not be a shared natural resource like the two rivers in Florida illustrated above, and I draw a distinction between Intrastate and Interstate groundwater.

- Case 1. Figure 14 is a map of a regionally extensive aquifer, and two states sharing an east-west border lie entirely within the extent of the aquifer. Because of the regional geology, the natural groundwater flow within the aquifer is directed from north to south, and the groundwater flow lines clearly cross the east-west border between the two states. In this case, the groundwater accumulates within, and flows through, both states under natural conditions, thus the groundwater is a shared natural resource under natural conditions analogous to an interstate river.



- Case 2. Figure 15 is a map of a regionally extensive aquifer, and two states sharing an east-west border lie entirely within the extent of the aquifer. In this case, a river running southward bisects both states. Because of the geologic conditions, the natural groundwater flow within this aquifer is directed toward the river from both the east and the west. In this case, the groundwater accumulation and flow is confined to each state, as shown by flow lines parallel to the boundary separating the two states. In this example, the groundwater accumulates and flows (for millennia) through one state under natural conditions to its discharge area located within that state. Therefore, the groundwater is that state's natural resource under natural conditions, and the groundwater is analogous to the water in an intrastate river.



Although these hypothetical examples are simple, they are applicable to this litigation. The fundamental question in the specific case of groundwater flow in the northern part of the Mississippian Embayment, and specifically in the Wilcox and Claiborne Aquifer Systems, is: What is the nature of groundwater flow within an aquifer system that is laterally extensive, and what did a groundwater flow net (flow lines and equipotential contours) look like during the pre-development time frame? The only viable way to answer this question is to carefully examine the flow patterns in the confined portions of these aquifer systems <u>prior</u> to any significant development of the groundwater system (i.e., the construction and operation of groundwater production well fields).

Several researchers have produced analyses of the pre-development flow patterns for the Wilcox and/or Claiborne Aquifer Systems for the border region of northwestern Mississippi and southwestern Tennessee, including (1) numerous studies by the United States Geological Survey and (2) investigations by private and academic scientists and engineers. Examples for each group of researchers are described below.

Studies by the United States Geological Survey include the work by Cushing et al. (1964), which provides a good summary of stratigraphy of the Mississippi Embayment.

The Cushing et al. report does not include a groundwater flow net, but it does provide important information regarding the orientation and thickness of major Eocene-age deposits within the Mississippi Embayment. Other hydrogeological reports by the USGS include Criner and Parks (1976), Arthur and Taylor (1998), Clark et al. (2011), and Hart et al. (2016). Figure 9 shows the Arthur and Taylor (1998) interpretation of the pre-development equipotential surface for the Middle Claiborne Aquifer, to which I have two representative groundwater-flow lines, one in northwestern Mississippi and another in southwestern Tennessee. Both flow lines indicate that groundwater within each state flows generally westward and away from recharge areas where the Middle Claiborne's sediments crop out. In the case of both states, that groundwater originates in, resides in, travels in, and ultimately discharges from the aquifer system within each state. Figure 10 illustrates the change in hydraulic gradients and flow patterns resulting from extensive pumping in Shelby County, Tennessee.

Notable reports by private and academic scientists and engineers that address the pre-pumping conditions in the Claiborne Aquifer System for the Memphis area include Legette, Brashears, and Graham (2014) and Waldron and Larson (2015). In the next two sections of this expert report, I highlight the pre-development equipotential map produced by Legette, Brashears, and Graham, and I provide my opinions about Waldron and Larson's analysis.

VI.6 The Legette, Brashears, and Graham (2014) Pre-Development Equipotential Map

In 2014, Legette, Brashears, and Graham, Inc. (LBG) produced a MODFLOW-based groundwater-flow model for the principal aquifers in the Mississippi-Tennessee border region, specifically in the area that includes the large wellfields operated by the City of Memphis in Shelby County, Tennessee. LBG's pre-development and post-development equipotential surfaces for the SMS aquifer are shown in Figures 16 and 17, respectively. Figure 17 clearly illustrates the natural groundwater accumulation and flow in both Mississippi and Tennessee prior to intense pumping in the vicinity of Memphis. The groundwater flow lines indicate that almost all groundwater in northern Mississippi originated in Mississippi, flowed within the aquifer in Mississippi, and discharged upward to overlying aquifers and (ultimately) to the Mississippi River within the state of Mississippi. Figure 18 demonstrates that the predominantly eastward flow of Mississippi's groundwater has been converted to a northward-directed flow by intense pumping in Shelby County, Tennessee.

Figure 17: Legette, Brashears, and Graham, Inc. (2014) Pre-Development Equipotential Map for the Sparta-Memphis Sand Aquifer (modified to highlight groundwater-flow paths)

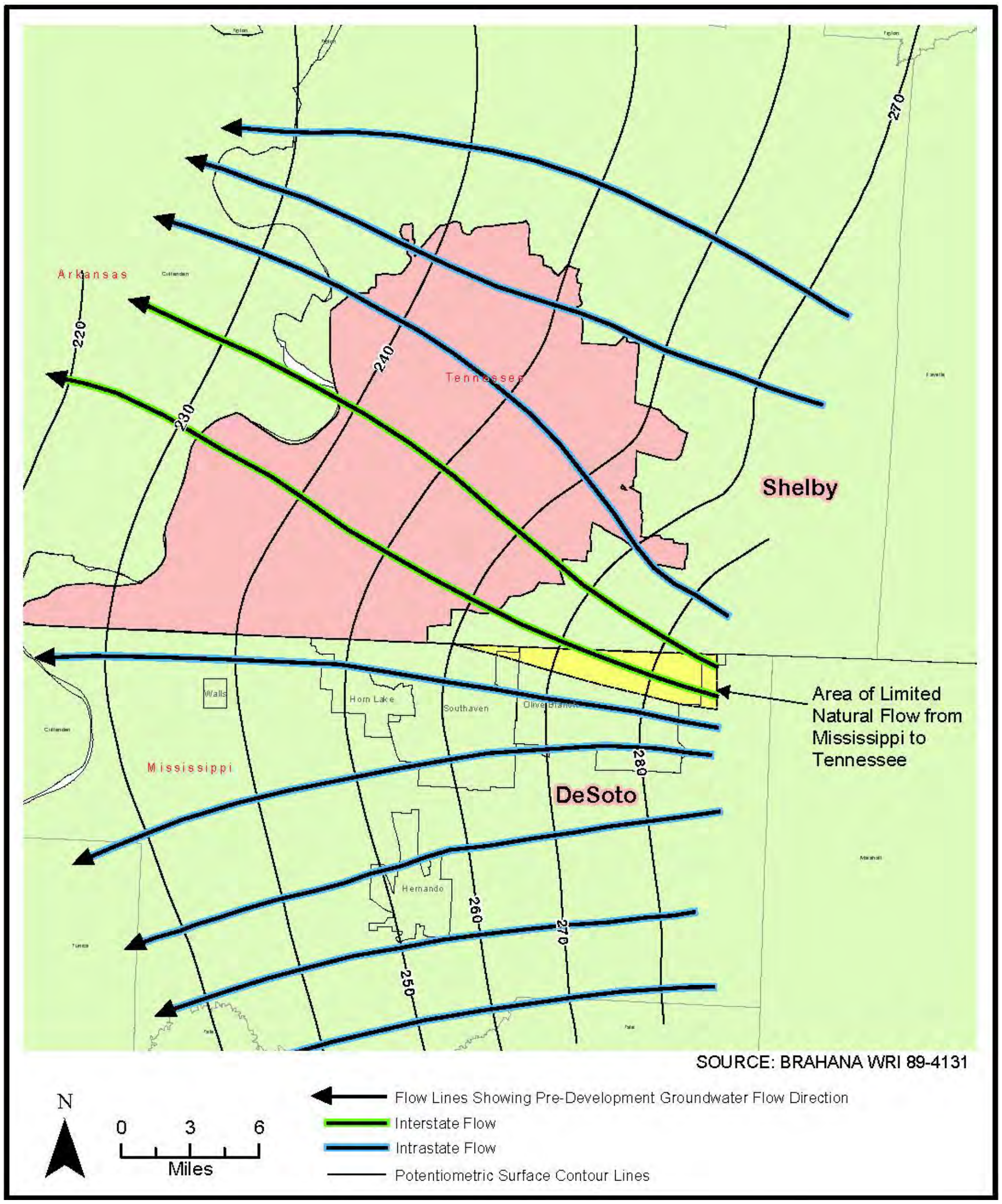
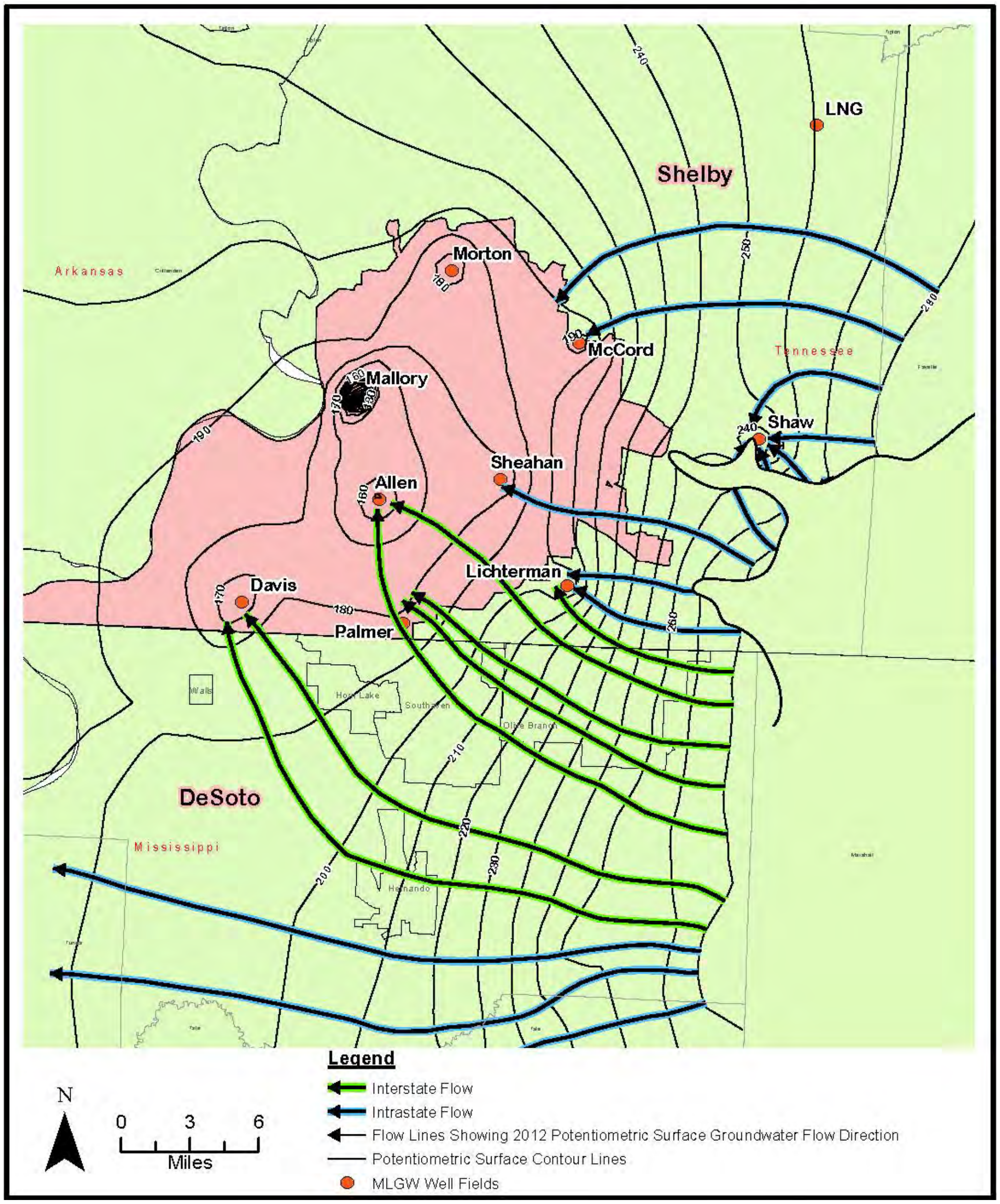


Figure 18: Legette, Brashears, and Graham, Inc. (2014) Post-Development Equipotential Map for the Sparta-Memphis Sand Aquifer (modified to highlight groundwater-flow paths)



VI.7 The Waldron and Larson (2015) Report

The Waldron and Larsen (2015) report was evaluated in connection with preparation of this expert report. After careful study of the report and their data sources, I did not rely upon the study by Waldron and Larson (2015) because it relies on inaccurate and unreliable data, it does not follow established hydrogeological methodology, and it contains unsupportable conclusions. In my opinion, the Waldron and Larson (2015) report is an unreliable source of information for scientific hydrogeological analysis of, and expert opinion regarding, issues concerning groundwater resources in the Mississippi-Tennessee border area. I reserve the right to offer a response or rebuttal to any opinions that may be provided by Waldron and Larson regarding their work.

Appendix A: List of References

This is not a comprehensive list of resources and documents that were reviewed or employed in preparation of the expert report, and additional documents and data may be reviewed or considered.

Alley, W.M., 2007, Another water budget myth: The significance of recoverable ground water in storage: Ground Water, v. 45, no. 3, p. 251.

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of Ground-Water Resources, U.S. Geological Survey Circular 1186

Arthur, J.K., and Taylor, R.E., 1990, Definition of the hydrogeologic framework and preliminary simulation of ground-water flow in the Mississippi embayment aquifer system, Gulf coastal plain, United States: U.S. Geological Survey Water-Resources Investigations Report 86-4364, 97 p.

Arthur, J.D. and Taylor, R.E., 1998, Ground-Water Flow Analysis of the Mississippian Embayment Aquifer System, South-Central United States, U.S. Geological Survey Professional Paper 1416-I, 148 p.

Berris, P.G., 2016, Mississippi V. Tennessee: Resolving an Interstate Groundwater Dispute, Duke Journal of Constitutional Law & Public Policy Sidebar, Vol. 12, 17 pages.

Brahana, J.V., and Broshears, R.E., 2001, Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee, U.S. Geological Survey Water-Resources Investigations Report 89-4131, 56 p.

Brahana, J.V., and Mesko, T.O., 1988, Hydrogeology and preliminary assessment of regional flow in the Upper Cretaceous and adjacent aquifers in the northern Mississippi embayment: U.S. Geological Survey Water-Resources Investigations Report 87–4000, 65 p.

Clark, B.R., and Hart, R.M., 2009, The Mississippi embayment regional aquifer study (MERAS): Documentation of a groundwater-flow model constructed to assess water availability in the Mississippi embayment: U.S. Geological Survey Scientific Investigations Report 2009–5172, 61 p.

Clark, B.R., Hart, R.M., and Gurdak, J.J., 2011, Groundwater Availability of the Mississippi Embayment, U.S. Geological Survey Professional Paper 1785, 62 p.

Cox, R.T., and Van Arsdale, R.B., 1997, Hotspot Origin of the Mississippi Embayment and Its Possible Impact on Contemporary Seismicity, Engineering Geology, Vol. 46, pp. 201-216.

Cox, R.T., Cox and Van Arsdale, R.B., 2002, The Mississippi Embayment, North America: A First Order Continental Structure Generated by the Cretaceous Superplume Mantle Event, Journal of Geodynamics, Vol. 34, pp. 163-176.

Crider, A.F., and Johnson, L.C., 1906, Summary of the underground-water resources of Mississippi: U.S. Geological Survey Water-Supply and Irrigation Paper No. 159, 86 p.

Criner, J.H., and Parks, W.S., 1976, Historic water-level changes and pumpage from the principal aquifers of the Memphis area, Tennessee: 1886–1975: U.S. Geological Survey Water-Resources Investigations Report 76–67, 45 p.

Criner, J.H., Sun, P-C.P., and Nyman, D.J., 1964, Hydrology of Aquifer Systems in the Memphis Area, Tennessee, U.S. Geological Survey Water-Supply Paper 1779-O, 54 pages.

Cushing, E.M., Boswell, E.H., and Hosman, R.L., 1964, General Geology of the Mississippi Embayment, U.S. Geological Survey Professional Paper 448-B, 24 pages.

Cushing, E.M., Boswell, E.H., Speer, P.R., and Hosman, R.L., 1970, Availability of water in the Mississippi embayment: U.S. Geological Survey Professional Paper 448–A, 11 p.

Driscoll, F.G., 1986, "Groundwater and Wells", Second Edition, Johnson Screens, St. Paul, Minnesota, 1089 p.

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

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

Freiwald, D.A., and Johnson, S.F., 2007, Monitoring of Sparta aquifer recovery in southern Arkansas and northern Louisiana, 2003–07: U.S. Geological Survey Fact Sheet, 2007–3102, 4 p.

Fuller, M.L., 1903, Contributions to the hydrology of eastern United States: U.S. Geological Survey Water-Supply and Irrigation Paper No. 102, 522 p.

Glenn, L.C., 1906, Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geological Survey Water-Supply and Irrigation Paper No. 164, 173 p.

Graham, D.D., 1982, Effects of urban development on the aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 82–4024, 20 p.

Grubb, H.F., 1998, Summary of hydrology of the regional aquifer systems, Gulf Coastal Plain, south-central United States: U.S. Geological Survey Professional Paper 1416–A.

Hall, N.D., and Regalia, J., 2016, Interstate groundwater law revisited: *Mississippi v. Tennessee*: Virginia Environmental Law Journal, v. 34, p. 152-203

Hao, Y., Magnani, M.B., McIntosh, K., Waldron, B., and Guo, L., 2013, Quaternary deformation along the Meeman-Shelby Fault near Memphis, Tennessee, imaged by high-resolution marine and land seismic reflection profiles: Tectonics, v. 32, p. 1-15.

Hart, R.M., and Clark, B.R., 2008, Geophysical log database for the Mississippi Embayment Regional Aquifer Study (MERAS): U.S. Geological Survey Scientific Investigations Report 2008–5192, 8 p.

Hart, R.M., Clark, B.R., and Bolyard, S.E., 2008, Digital surface and thicknesses of selected hydrogeologic units within the Mississippi Embayment Regional Aquifer Study (MERAS): U.S. Geological Survey Scientific Investigations Report 2008–5098, 33 p.

Haugh, C.J., 2016, Evaluation of effects of groundwater withdrawals at the proposed Allen combined-cycle combustion turbine plant, Shelby County, Tennessee: U.S. Geological Survey Scientific Investigations Report 2016–5072, 8 p.

Hays, P.D, Lovelace, J.K., and Reed, T.B., 1998, Simulated response to pumping stress in the Sparta aquifer of southeastern Arkansas and north-central Louisiana, 1998–2027: U.S. Geological Survey Water-Resources Investigations Report 98–4121, 25 p.

Heath, R.C., 1983, Basic Ground-Water Hydrology, United States Geological Survey, Water-Supply Paper 2220, 86 p.

Heath, R.C., 1984, Ground-Water Regions of the United States, United States Geological Survey, Water-Supply Paper 2242, 78 p.

Heath, R.C., 1988, Hydrogeologic Setting of Regions *in* Black, W., J.S. Rosenshein, and P.R. Seaber, eds., The Geology of North America, Volume O-2, Hydrogeology: Geological Society of America, p. 15-23.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416–B, 19 p.

Johnston, A.C., 1982, A major Earthquake Zone on the Mississippi, Scientific American, April 1982, Vol. 246, pp. 60-68.

Kingsbury, J.A., and Parks, W.S., 1993, Hydrogeology of the principal aquifers and relation of faults to interaquifer leakage in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93–4075, 18 p.

Kleiss, B.A., Coupe, R.H., Gonthier, G.J., and Justus, B.J., 2000, Water quality in the Mississippi Embayment, Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky,1995–98: U.S. Geological Survey Circular 1208, 36 p.

Larson, R.L., 1991, Latest Pulse of Earth: Evidence for a Mid-Cretaceous Super Plume, Geology, Vol. 19, pp. 547-550.

Layne GeoSciences, 2002, City of Southaven, Mississippi, Test Well Hydrogeologist Report, 3 pages plus attachments.

Leggette, Brashears & Graham, Inc., 2014, Update report on diversion and withdrawal of groundwater from northern Mississippi into the state of Tennessee, 24 p.

Lloyd, O.B., and Lyke, W.L., 1995, Hydrologic Atlas of the United States, Section K: Illinois, Indiana, Kentucky, Ohio, and Tennessee, U.S. Geological Survey Hydrologic Investigations Atlas 730-K, 30 pages.

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States, 2000: U.S. Geological Survey Circular 1279, 46 p.

McKee, P.W., and Clark, B.R., 2003, Development and calibration of a ground-water flow model for the Sparta aquifer of southeastern Arkansas and north-central Louisiana and simulated response to withdrawals, 1998–2027: U.S. Geological Survey Water-Resources Investigations Report 03–4132, 71 p.

McKee, P.W., and Hayes, P.D., 2002, The Sparta aquifer: A sustainable resource?: U.S. Geological Survey Fact Sheet FS-111-02, 4 p.

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

Memphis Light, Gas and Water Division (MLGW), City of Memphis, 2016, 2016 Water Quality Report, 8 pages.

Memphis Light, Gas and Water Division (MLGW) website; http://www.mlgw.com/about/

Memphis Light, Gas and Water Division (MLGW), City of Memphis, 2016, 2016 Water Quality Report, 8 pages.

Memphis Light, Gas and Water Division (MLGW) website; http://www.mlgw.com/about/

Miller, J.A., and Appel, C.L., 1997, Hydrologic Atlas of the United States, Section D: Kansas, Missouri, and Nebraska; U.S. Geological Survey Hydrologic Investigations Atlas 730-D, 24 pages.

Mississippi Department of Environmental Quality, 2015, Records of public-supply wells in Mississippi, 2015: Mississippi Department of Environmental Quality, Office of Land and Water Resources, Groundwater Planning and Protection Division, 87 p.

Moore, D.W., and Diehl, S.F., 2004a, Surficial geology of the southeast Memphis quadrangle, Shelby County, Tennessee: U.S. Geological Survey Scientific Investigations Map 2822, Ver. 1.0, 1 Sheet.

Moore, D.W., and Diehl, S.F., 2004b, Surficial geology of the southwest Memphis quadrangle, Shelby County, Tennessee: U.S. Geological Survey Scientific Investigations Map 2823, ver. 1.0, 1 sheet.

Odum, J.K., Luzietti, E.A., Stephenson, W.J., Shedlock, K.M., and Michael, J.A., 1995, High-resolution, shallow, seismic reflection surveys of the northwest Reelfoot Rift boundary near Marston, Missouri: U.S. Geological Survey Professional Paper 1538-P, 18 p.

Parks, W.S., 1990, Hydrogeology and preliminary assessment of the potential for contamination of the Memphis aquifer in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 90-4092, 39 p.

Parks, W.S., and Carmichael, J.K., 1990a, Altitude of Potentiometric surface, Fall 1985, and historic water-level changes in the Memphis aquifer in Western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 88-4180, 8 p.

Parks, W.S., and Carmichael, J.K., 1990b, Geology and ground-water resources of the Memphis Sand in Western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 88-4182, 30 p.

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

Payne, D.F., 2009, Effects of seal-level rise and pumpage elimination on saltwater intrusion in thew Hilton Head Island area, South Carolina, 2004-2104: U.S. Geological Survey, Scientific Investigations Report 2009-5251, 97 p.

Ransom, C., III, Landmeyer, J.E., Logan, W.R., and Childress, J.M., 2006, Evaluation of the downward movement of saltwater to the Upper Floridan Aquifer in the Savannah, Georgia, and Hilton Head Island, South Carolina, area: Bureau of Water, South Carolina Department of Health and Environmental Control, Technical Publication No. 011-06, 48 p.

Reed, J.E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geological Survey Hydrologic Atlas, HA 434, 5 maps.

Renken, R.A., 1998, Hydrologic Atlas of the United States, Section F: Arkansas, Louisiana, and Mississippi, U.S. Geological Survey Hydrologic Investigations Atlas 730-F, 27 pages.

Schrader, T.P., 2004, Status of water levels and selected water-quality conditions in the Sparta-Memphis aquifer in Arkansas and the Sparta aquifer in Louisiana, spring-summer 2001: U.S. Geological Survey Scientific Investigations Report 2004–5055, 57 p.

Schrader, T.P., 2008, Potentiometric surface in the Sparta-Memphis aquifer of the Mississippi Embayment, spring 2007: U.S. Geological Survey Scientific Investigations Map 3014, 1 sheet.

Schrader, T.P., and Jones, J.S., 2007, Status of water levels and selected water-quality conditions in the Sparta-Memphis aquifer in Arkansas and the status of water levels in the Sparta aquifer in Louisiana, spring 2005: U.S. Geological Survey Scientific Investigations Report 2007–5029, 66 p.

Stanton, G.P., 1997, Potentiometric surface and specific conductance of the Sparta and Memphis aquifers in eastern Arkansas, 1995: U.S. Geological Survey Water-Resources Investigations Report 97–4119, 16 p.

Stephenson, L.W., Logan, W.N., Waring, G.A., and Howard, C.S., 1928, The ground-water resources of Mississippi, with discussions of the chemical character of the waters: U.S. Geological Survey Water-Supply Paper 576, 515 p.

Taylor, R.E., and Arthur, J.K., 1989, Hydrogeology of the Middle Wilcox aquifer system in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 89-4036, 2 sheets.

Thomas, E.P., 1942, The Claiborne, Mississippi State Geological Survey, University of Mississippi, 96 p.

U.S. Geological Survey, 2009, USGS water data for the Nation, accessed February 6, 2017, at *http://waterdata.usgs.gov/nwis*.

Van Arsdale, R.B., and Cox, R.T., 2007, The Mississippi's Curious Origins, Scientific American, January 2007, Vol. 296, pp. 76 -82.

Waldron, B., and Larson, D., 2015, Pre-development groundwater conditions surrounding Memphis, Tennessee: Controversy and unexpected outcomes, Journal of the American Water Resources Association, v. 51, p. 133-153.

Waldron, B., Larson, D., Hannigan, R., Csontos, R., Anderson, J., Dowling, C., and Bouldin, J., 2011, Mississippi embayment regional ground water study: U.S. Environmental Protection Agency, EPA 600/R-10/130, 174 p.

Williams, R.A., Stephenson, W.J., Odum, J.K., and Worley, D.M., 2001, Seismic-reflection imaging of Tertiary faulting and related post-Eocene deformation 20 km north of Memphis, Tennessee: Engineering Geology, v. 62, p. 79-90.

Williamson, A.K., Grubb, H.F., and Weiss, J.S., 1990, Ground-Water Flow in the Gulf Coast Aquifer Systems, South Central United States-A Preliminary Analysis, U.S. Geological Survey Water-Resources Investigations Report 89-4071, 124 pages.

Winter, T.C., J.W. Harvey, O.L. Franke, W.M. Alley, 1999, Ground Water and Surface Water - A Single Resource, United States Geological Survey, United States Geological Survey Circular 1139, Denver, Colorado.

Appendix B: *Curriculum Vitae* for Dr. Richard K. Spruill

4300 Sapphire Court, Suite 100
Greenville, North Carolina 27834
Telephone (252) 758-3310
www.gma-nc.com

Richard K. Spruill, Ph.D, PG

President/Principal Hydrogeologist

Education

Ph.D. Geology, University of North Carolina, Chapel Hill, NC (1980)
M.S. Geology, East Carolina University, Greenville, NC (1978)
B.S. Geology, East Carolina University, Greenville, NC (1974)

Professional Registrations and Service

Professional Geologist in North Carolina (License #942)
Executive Committee member National Association of State Boards of Geology (ASBOG) (2007-2012)
Founding Director of Coastal Water Resources Center, East Carolina Univ. (2010-2013)
Chairman, North Carolina Board for Licensing of Geologists (2006-2010)
Subject Matter Expert, National Association of State Boards of Geology (ASBOG) (2005-2007)

Professional Experience

Groundwater Management Associates, Inc. - Greenville, NC (1986 to Present)

President and Principal Hydrogeologist

Provides technical oversight, directs, and participates in hydrogeological projects, including groundwater resource evaluation and planning, wellfield and well design, borehole logging and evaluation, aquifer test design and interpretation, and other hydrological assessment projects. Clients include engineering firms, municipalities, industry, and attorneys.

Technical Expertise

- Groundwater hydrology
- Surface water hydrology
- Public water supply
- Groundwater resource evaluation and planning
- Wellfield and well design
- Coastal plain, piedmont, and mountain hydrogeology
- Safe yield of aquifers
- Groundwater policy education and implementation
- Aquifer storage and recovery (asr)
- Groundwater chemistry
- Coastal plain geology and geomorphology
- Mineralogy and mineral chemistry
- Igneous and metamorphic petrology
- Isotope geology

East Carolina University - Greenville, NC (1979 to Present)

Associate Professor of Geology, Department of Geological Sciences

Instructor for undergraduate and graduate geology and hydrogeology courses, supervising professor for graduate hydrogeology research projects, groundwater and

Instructor for undergraduate and graduate geology and hydrogeology courses, supervising professor for graduate hydrogeology research projects, groundwater and surface water research, community (local and state) outreach and education concerning hydrological issues.

Graduate-Level Courses Taught at East Carolina University

- Groundwater Hydrology (GEOL 5710/5711)
- Seminar in Computer Applications in Hydrology (GEOL 6522)
- Advanced Groundwater/Surface Water Hydrology (GEOL 7920)
- Geochemistry (GEOL 6400)
- Tectonic Analysis of North America (GEOL 6570)
- Volcanology Seminar (GEOL 5500 and GEOL 6703)
- Readings in Isotope Geochemistry (GEOL 6532)

Teaching Recognition at East Carolina University

- Robert L. Jones Award for Teaching Excellence (1981)
- University-wide Outstanding Teacher Award – Finalist (1989, 1992)

Publications

McCoy, C.A., Corbett, D.R., Cable, J.E., and. Spruill, R.K, 2007. Hydrogeological characterization and quantification of submarine groundwater discharge in the southeast Coastal Plain of North Carolina, Journal of Hydrology, v. 339, p. 159-171

Heath, R.C., and Spruill, R.K., 2003, Cretaceous Aquifers in North Carolina: Analysis of Safe Yield Based on Historical Data: Hydrogeology Journal, v. 11, p. 249-258

Woods, T. L., Fullagar, P. D., Spruill, R.K., and Sutton, L. C., 2000, Strontium Isotopes and Major Elements As Tracers of Ground Water Evolution: Example from the Upper Castle Hayne Aquifer of North Carolina: Ground Water, v. 38, no. 5, p. 762-771

Reynolds, J.W., and Spruill, R.K., 1994, Groundwater Flow Stimulation for Management of a regulated Aquifer System: A case study in the North Carolina Coastal Plain: Journal of Groundwater, v.29, no. 10, p.

Spruill, R.K., Reynolds, J.W., 1993, Hydrogeology and Groundwater Management Activities at the Lee Creek Mine of Texasgulf Inc.: The Compass, v.70, no. 1, p. 36-44.

Mauger, R.L., Spruill, R.K., Christopher, M.T.., and Shafiquallah, M., 1983, Petrology and Geochemistry of Peralkaline Metagranite and Metarhyolite Dikes, Fountain Quarry, County, North Carolina: Southeastern Geology, v.24, no. 2, p. 67-89

Spruill, R.K., Lawrence, D.P., and Moncla, A.M., 1987, Petrochemical, Geochemical and Geophysical Evaluation of the Rocky Mount Igneous Complex, Northeastern Piedmont, North Carolina, in, Whittecar, G.R. (ed.) Geological Excursions in Virginia and North Carolina: Guidebook for Field Trips 1-7: Geological Society of America, Southeastern Section, p. 229-237

Mauger, R.L., Spruill, R.K., Lawrence, D.P., and Moncla, A.M., 1987, Geology and Petrology of the Fountain and Rocky Mount Granite Quarries, Eastermost Piedmont, North Carolina, in Whittecar, G.R. (ed), Geological Excursions in Virginia and North Carolina: Guidebook for Field Trips No. 1-7: Geological Society of America, Southeastern Section, p. 219-229

<u>*Abstracts*</u>

Spruill, R.K., 1977, Geology of the Rancho Penas Azules Area, Chihuahua, Mexico, Geological Society of America, Abstracts with Programs, v.9, p. 75

Spruill, R.K., 1980, Petrology and Geochemistry of Peralkaline Volcanics of the Sierra Campana, Chihuahua, Mexico: Geological Society of America, Abstracts with Programs, v.12, p. 211

Wedemeyer, R.C., and Spruill, R.K., 1980, Geochemistry and Geochronology of the Sims Granite, Eastern Carolina State Belt: Geological Society of America, Abstracts with Programs, v.12, p. 211

Spruill, R.K., McDowell, F.W. and Mauger, R.L., 1981, Strontium Isotope Geochemistry and K-Ar ages of Cretaceous to Oligocene rocks from the Calera-del Nido Range. Chihuahua, Mexico: Geological Society of America, Abstracts with Programs, v.13, p. 107-108

Stirewalt, G.W., Harper, S.B., and Spruill, R.K., 1981, Mesoscopic Structure and Geochronology of the Buckhorn Pluton and enveloping Rocks of the Raleigh Belt. Chatham County, North Carolina—Evidence of late Paleozoic Movement in the Eastern Piedmont: Geological Society of America, Abstracts with Programs, v.13, p. 36

Spruill, R.K., 1983, Petrologic and Strontium Isotopic Evidence for the Origin of Andesites from the Upper Volcanic Supergroup, Chihuahua, Mexico: Geological Society of America, Abstracts with Programs, v. 15. p. 90

Mauger, R.L., Spruill, R.K., and Shafiquallah, M., 1983, Petrology and Geochronology of a Metamorphosed Cambrian (?) Peralkalic Granite from Fountain, Eastern Carolina State Belt, North Carolina: Geological Society of America, Abstracts with Programs, v. 15, p. 45

Riggs, S.R., Snyder, S.W., and Spruill, R.K., 1984, Ferruginization and Phosphatization of Foraminifera in Pleistocene/Holocene Sands of the Mid-Atlantic Continental Shelf: American Association of Petroleum Geologists Bulletin. V.68, no. 4, p. 521

Sans, J.R., Spruill, R.K., Muchlenbachs, K. and Mauger, R.L., in 1984, Oxygen and Strontium Isotope Data for a Peralkaline Metagranite from Fountain, Eastern Carolina State Belt: Geological Society of America, Abstracts with Programs, v. 16, no.2, p. 86

Snyder, S.W., Hale, W.R., Riggs, S.R., Spruill, R.K., and Waters, V.J., 1984, Occurrence of Clinoptilolite as Moldic Fillings of Foraminiferal Tests in Continental Margin Sediments: Geological Society of America, Abstracts with Programs. V.16, no. 6, p. 662

Danahy, T.V., Neal, D.W., and Spruill, R.K., 1984, Diagenesis in the Hillsdale Limestone (Miss.), Virginia: Geological Society of America, Abstracts with Programs, v. 17, no.2, p. 460

Corbitt, C.L., and Spruill, R.K., 1986, Geology of the Portis Gold Mine, Eastern Carolina Slate Belt, Franklin County, North Carolina: Geological Society of America, Abstracts with Programs, v. 17, no. 2, p. 85

Campbell, S.K., and Spruill, R.K., 1986, Geology , Petrology, and Geochemistry of the Lemon Springs Pluton and Associated Rocks, Lee County, North Carolina Geological Society of America, Abstracts with Programs, v. 18, no 2., p. 214

Spruill, R.K., Mauger, R.L., and McDowell, F.W., 1986, Geochemistry and Petrogenesis of Intraplate Peralkaline Ash-flow Rhyolites, Central Chihuahua, Mexico: International Volcanological Congress, New Zealand Section, p. 209

Mauger, R.L., and Spruill, R.K., 1987, A Geologic Excursion to Fountain Quarry, Easternmost Piedmont, Pitt County, North Carolina: Geological Society of America. Abstracts with Programs, v.19, p. 96

Moncla, A.M., and Spruill, R.K., 1987, Petrology, Geochemistry, and Geochronology of the Rocky Mount Igneous Complex, Northeastern NC Piedmont: Geological Society of America, Abstracts with Programs, v. 19, p. 119

Schiappa, C.S., Lawrence, D.P., and Spruill, R.K., 1987, Petrology and Geochemistry of the Coronaca Pluton, Greenwood County, South Carolina: Geological Society of America, Abstracts with Programs, v. 19, p. 127

Spruill, R.K. and Johnson, J.J., 1988, Hydrology of the Lower Castle Hayne Aquifer near Washington, North Carolina: Geological Society of America, Abstracts with Programs, v. 20, no. 2, p. 60

Spruill, R.K., and Tarravechia, R.J., 1989, An Evaluation of Rn-222 Levels in Groundwater from Granite and Sedimentary Cover, with results of an In-situ Remediation Technique: Geological Society of America, Abstracts with Programs, v.21, no. 3, p. 41

Volosin, M. L., and Spruill, R. K., 2001, The Position of the Fresh Water-Salt Water Interface in Aquifers Underlying Six Counties In Northeastern North Carolina: GSA Abstracts with Programs, v. 33, no. 2, p. 62

Foldesi, C. P., and Spruill, R. K., 2001, Utilization of the Cretaceous Aquifer System for Aquifer Storage and Recovery of Treated Surface Water in Greenville, NC: GSA Abstracts with Programs, v. 33, no. 2, p. 62.

Spruill, R. K., 2008, The ASBOG Fundamental and Practice Examinations: The Development and Administration of a National Examination: Third International Professional Geology Conference, Flagstaff, AZ, accepted, Abstract Volume to be determined

Humphrey, M. B., Gould, R. G., Muse, D. A., and Spruill, R. K., 2008, Wastewater Reclamation Utilizing an Abandoned Limestone Quarry – An Innovative Non-Discharge Alternative: Submitted to the North Carolina Water Works Association – accepted, Abstract Volume to be determined

Holley, J.K., and Spruill, R.K., 2012, Groundwater Resource Management and Saltwater Intrusion Mitigation, Roanoke Island, Dare County, North Carolina, Geological Society of America Annual Meeting, Charlotte, North Carolina.

Holley, J.K., Campbell, S.K., and Spruill, R.K., 2015, Challenges and Lessons Learned in the Construction and Operation of Aquifer Storage Recovery (ASR) Wells, North Carolina AWWA-WEA, Contemporary Topics in Water/Wastewater Construction, Greenville, NC.

Holley, J.K., Campbell, S.K., Spruill, R.K., and Smith, K.A., 2015, The Hydrostratigraphic Framework of Onslow County, North Carolina, North Carolina AWWA-WEA, 14th Annual Spring Conference, Wilmington, NC.

Litigation Support

2016 Expert witness deposition in the case of State of North Carolina et al. Vs. Duke Energy Progress, LLC, Superior Court for Wake County, North Carolina, File Number 13-CVS-11032 and in the case of State of North Carolina et al. Vs. Duke Energy Carolinas, LLC, Superior Court for Mecklenburg County, North Carolina, File Number 13-CVS-14661.

Retained by John Suttles, Southern Environmental Law Center, Chapel Hill, North Carolina.

2011 Expert witness trial testimony in Onslow Water and Sewer Authority v. Boggs and Rogers, Onslow County Superior Court. Retained by David Nash, Hogue Hill Jones Nash & Lynch, LLP.

2011 Expert witness trial testimony in Michael Allison, et al. v. ExxonMobil Corporation, et al., Circuit Court for Baltimore County, No. 03-C-07-003809. Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2010 Expert witness testimony, Frye-Reed Hearing in Michael Allison, et al. v. ExxonMobil Corporation, et al., Circuit Court for Baltimore County, No. 03-C-07-003809. Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2010 Expert witness deposition in Michael Allison, et al. v. ExxonMobil Corporation, et al., Circuit Court for Baltimore County, No. 03-C-07-003809. Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PCs.

2008 Expert witness trial testimony in Kurt Peterson et al., v. D.R. Horton, Inc., Circuit Court for Montgomery County, Maryland, Case No. 268778-V (Consolidated with cases: 269276-V; 270293-V; 272020-V; 272479-V; 272480-V). Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2007 Expert witness deposition in Kurt Peterson et al., v. D.R. Horton, Inc., Circuit Court for Montgomery County, Maryland, Case No. 268778-V (Consolidated with cases: 269276-V; 270293-V; 272020-V; 272479-V; 272480-V). Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2006 Expert witness deposition in Hope Koch, et al. v. John R. Hicks, et al., United States District Court, Southern District of New York, No. 05-cv-05745-SAS. Retained by Mary V. Koch, Law Office of Peter G. Angelos, PC.

2006 Expert witness deposition in Curl, et al. v. American Multimedia, Inc., et al., and Brown et al. v. American Multimedia, Inc., et al., Superior Court of Alamance County, North Carolina, File Nos. 03 CVS 493 and 03 CVS 663. Retained by Richard Watson and James F. Hopf.

2006 Expert witness deposition in Richard A. Smith and April L. Smith v. Thomas Brothers Oil & Gas, Inc, et al., Superior Court of Caswell County, North Carolina, File No. 03 CVS 226. Retained by James F. Hopf.

2005 Expert witness trial testimony in Ellison v. Gambill Oil Company, Inc., et al., Superior Court of Watauga County, North Carolina, File No. 03 CVS 428. Retained by Warren A. Hutton.

2004 Expert witness deposition in Vines, et al. v. Gambill Oil Company, Inc., et al., Superior Court of Watauga County, North Carolina, File Nos. 02 CVS 467, 02 CVS 498, 02 CVS 776 and 03 CVS 428. Retained by James F. Hopf, Claude D. Smith, Warren A. Hutton and Paul R. Dickinson, Jr.

2003 Expert witness deposition in Joel & Janice Drum v. Schronce and Superior Petroleum and Fuel Company, Inc., Superior Court of Catawba County, North Carolina, File No. 01 CVS 3998. Retained by James F. Hopf.

1999 Expert witness deposition in Robert J. & Kathleen Leary, et al. v. Eastern Fuels, Inc., Superior Court of Currituck County, North Carolina, File No. 97 CVS 326. Retained by James F. Hopf.

1998 Expert witness deposition in King, et al. v. Conoco, Inc., et al., Superior Court of New Hanover County, North Carolina, File Nos. 97 CVS 02670 & 97 CVS 02672. Retained by James F. Hopf.

1998 Expert witness trial testimony in Grant, et al. v. E.I. Dupont, Inc., United States District Court, Eastern District of North Carolina, File No. 4:91-CV-55-H. Retained by Marvin Blount, Jr. and James F. Hopf.

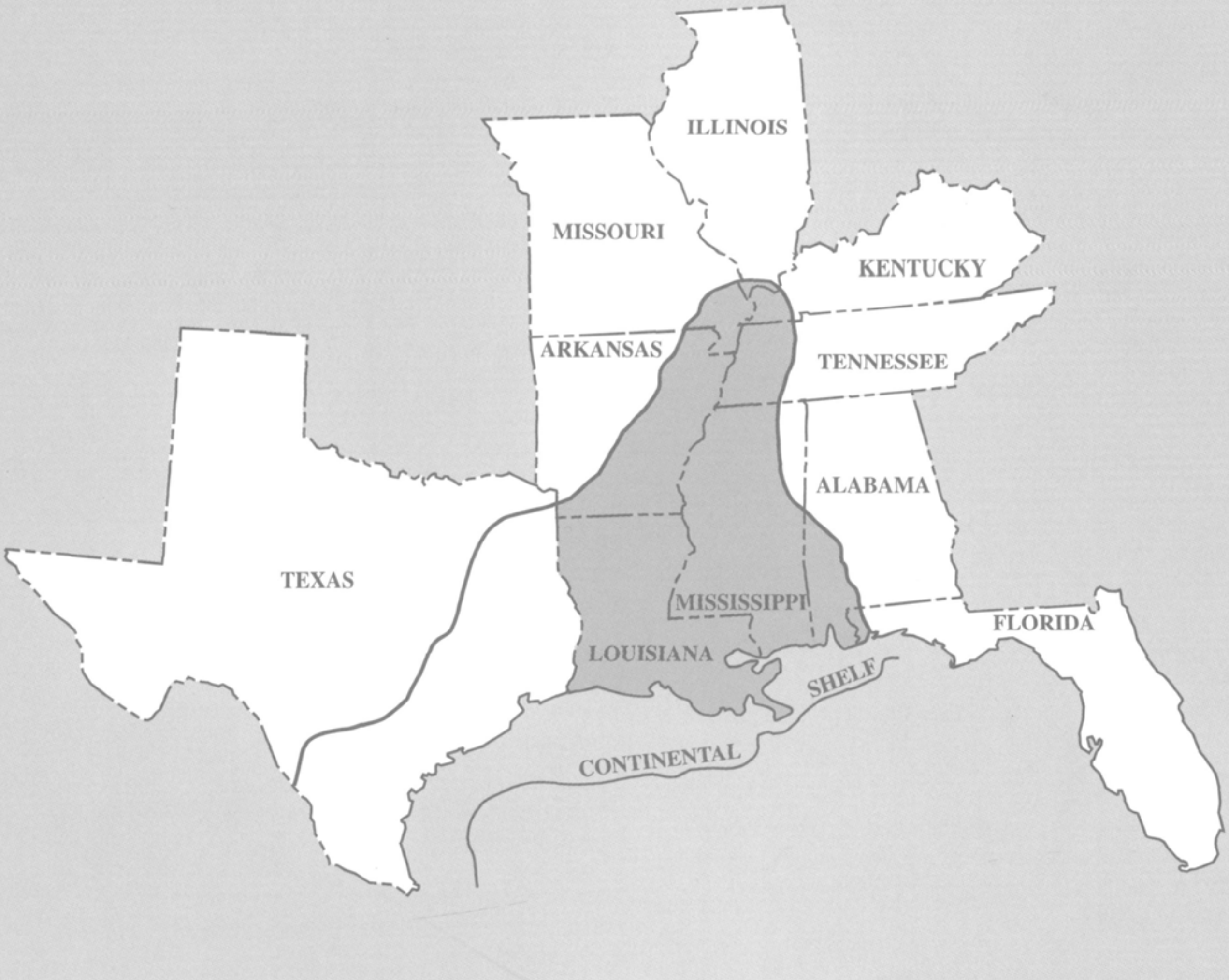
1994 Expert witness trial testimony in Shamrock Fuels, Inc., et al. v. McGraw Edison Company, Cooper Industries, Inc., et al., United States District Court, Eastern District of Kentucky at London, Civil Action No. 92-129. Retained by Marvin Blount, Jr. and James F. Hopf.

EXHIBIT 9

J. Kerry Arthur and Richard E. Taylor
Ground-Water Flow Analysis of the Mississippi Embayment
Aquifer System, South-Central United States
USGS 1416-J

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

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. Department of the Interior
U.S. Geological Survey

PROFESSIONAL PAPER 1416–I

Availability of Publications of the U.S. Geological Survey

Order U.S. Geological Survey (USGS) publications from the offices listed below. Detailed ordering instructions, along with prices of the last offerings, are given in the current-year issues of the catalog "New Publications of the U.S. Geological Survey."

Books, Maps, and Other Publications

By Mail

Books, maps, and other publications are available by mail from—

USGS Information Services
Box 25286, Federal Center
Denver, CO 80225

Publications include Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, Fact Sheets, publications of general interest, single copies of permanent USGS catalogs, and topographic and thematic maps.

Over the Counter

Books, maps, and other publications of the U.S. Geological Survey are available over the counter at the following USGS Earth Science Information Centers (ESIC's), all of which are authorized agents of the Superintendent of Documents:

- Anchorage, Alaska–Rm. 101, 4230 University Dr.
- Denver, Colorado–Bldg. 810, Federal Center
- Menlo Park, California–Rm. 3128, Bldg. 3, 345 Middlefield Rd.
- Reston, Virginia–Rm. 1C402, USGS National Center, 12201 Sunrise Valley Dr.
- Salt Lake City, Utah–2222 West, 2300 South (books and maps available for inspection only)
- Spokane, Washington–Rm. 135, U.S. Post Office Building, 904 West Riverside Ave.
- Washington, D.C.–Rm. 2650, Main Interior Bldg., 18th and C Sts., NW.

Maps only may be purchased over the counter at the following USGS office:

- Rolla, Missouri–1400 Independence Rd.

Electronically

Some USGS publications, including the catalog "New Publications of the U.S. Geological Survey" are also available electronically on the USGS's World Wide Web home page at **http://www.usgs.gov**

Preliminary Determination of Epicenters

Subscriptions to the periodical "Preliminary Determination of Epicenters" can be obtained only from the Superintendent of Documents. Check or money order must be payable to the Superintendent of Documents. Order by mail from—

Superintendent of Documents
Government Printing Office
Washington, DC 20402

Information Periodicals

Many Information Periodicals products are available through the systems or formats listed below:

Printed Products

Printed copies of the Minerals Yearbook and the Mineral Commodity Summaries can be ordered from the Superintendent of Documents, Government Printing Office (address above). Printed copies of Metal Industry Indicators and Mineral Industry Surveys can be ordered from the Center for Disease Control and Prevention, National Institute for Occupational Safety and Health, Pittsburgh Research Center, P.O. Box 18070, Pittsburgh, PA 15236–0070.

Mines FaxBack: Return fax service

1. Use the touch-tone handset attached to your fax machine's telephone jack. (ISDN [digital] telephones cannot be used with fax machines.)
2. Dial (703) 648–4999.
3. Listen to the menu options and punch in the number of your selection, using the touch-tone telephone.
4. After completing your selection, press the start button on your fax machine.

CD-ROM

A disc containing chapters of the Minerals Yearbook (1993–95), the Mineral Commodity Summaries (1995–97), a statistical compendium (1970–90), and other publications is updated three times a year and sold by the Superintendent of Documents, Government Printing Office (address above).

World Wide Web

Minerals information is available electronically at **http://minerals.er.usgs.gov/minerals/**

Subscription to the catalog "New Publications of the U.S. Geological Survey"

Those wishing to be placed on a free subscription list for the catalog "New Publications of the U.S. Geological Survey" should write to—

U.S. Geological Survey
903 National Center
Reston, VA 20192

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1416–I

1998

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, ***Secretary***

U.S. GEOLOGICAL SURVEY

Thomas J. Casadevall, ***Acting Director***

Library of Congress Cataloging-in-Publication Data

Arthur, J. Kerry
Ground-water flow analysis of the Mississippi embayment aquifer system, South-Central United States / by J. Kerry Arthur and Richard E. Taylor.
p. cm.— (U.S. Geological Survey professional paper ; 1416–I)
(Regional aquifer-system analysis—Gulf coastal plain)
Includes bibliographical references.
Supt. of Docs. no. : I 19.16 : 1416–I
1. Groundwater flow—Mississippi Embayment. 2. Aquifers—Mississippi Embayment. I. Taylor, R. E. (Richard Erwin), 1934–. II. Title. III. Series. IV. Series: Regional aquifer-system analysis—Gulf coastal plain.
GB1197.7.A75 1998
551.49'0976—dc21 97–15963
CIP

ISBN 0-607-87150-4

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

MS SCT 002960

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 (1×10^{-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 1×10^{-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

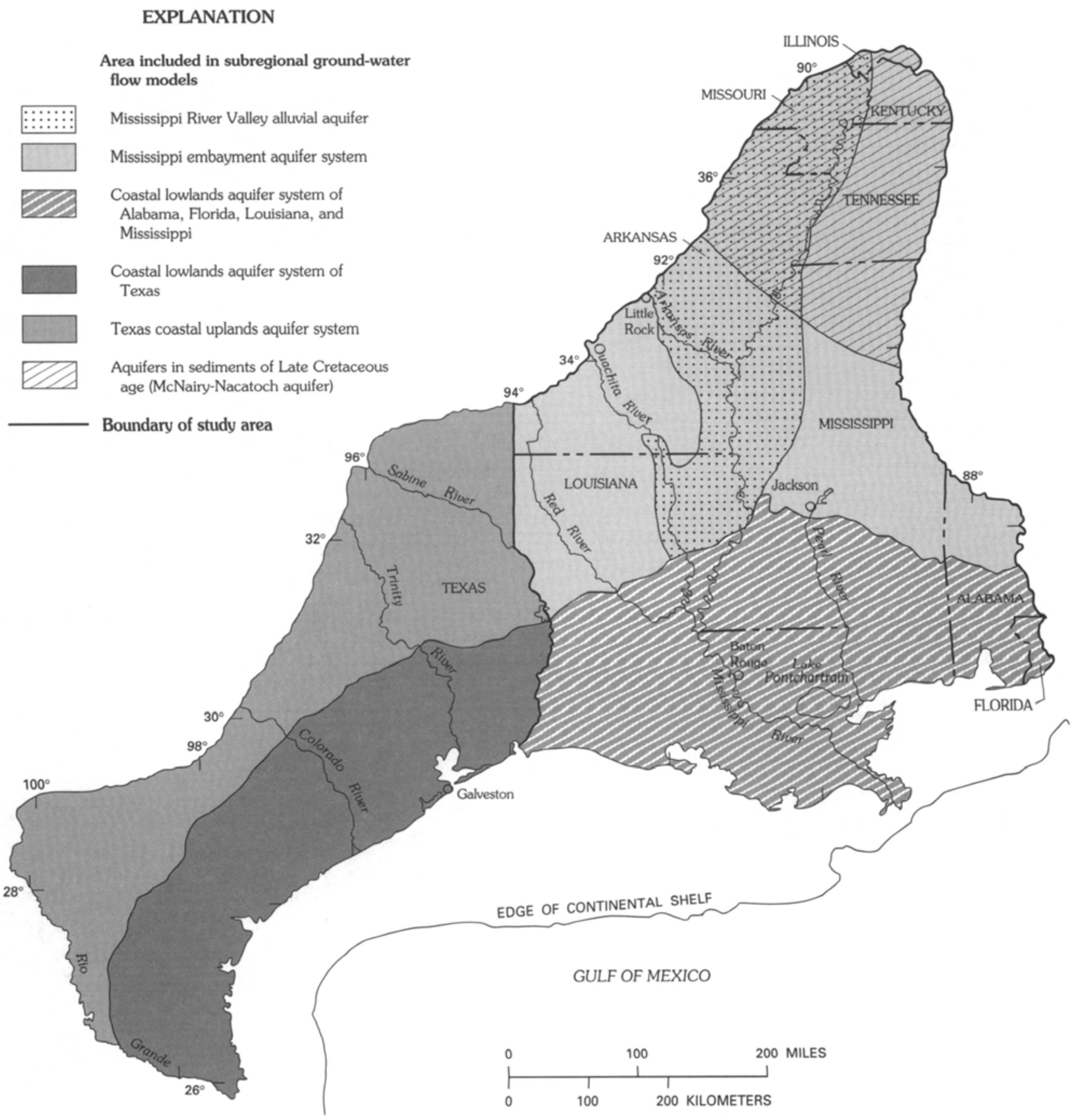


FIGURE 2.—Areal extent of subproject models in the Gulf Coast Regional Aquifer-System Analysis (RASA) study. Modified from Ryder (1988).

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

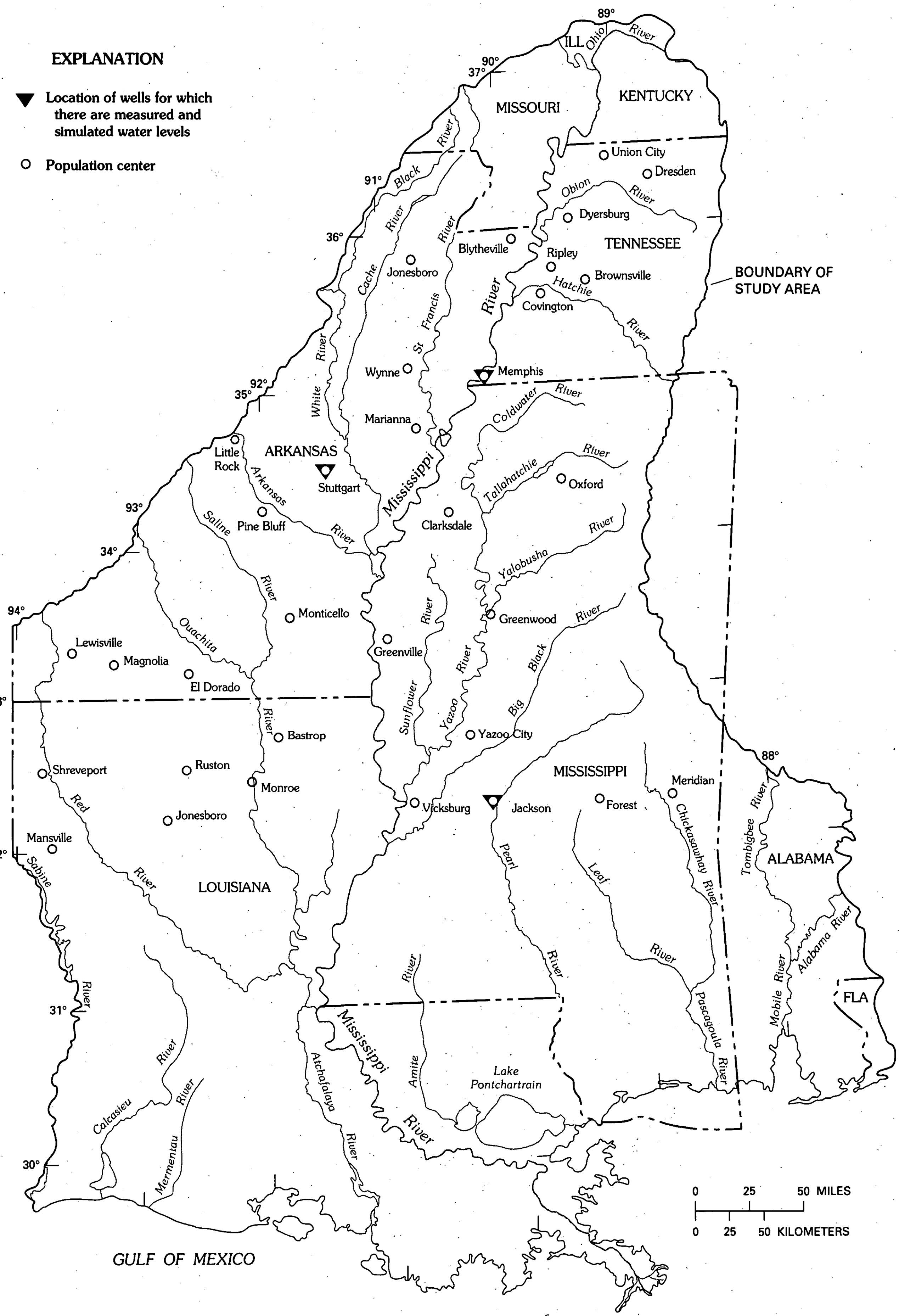

EXPLANATION
Location of wells for which there are measured and simulated water levels
Population center
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
33°
32°
31°
30°
88°
ILL
Ohio
River
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
FLA
Union City
Dresden
Obion
River
Dyersburg
Blytheville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

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.

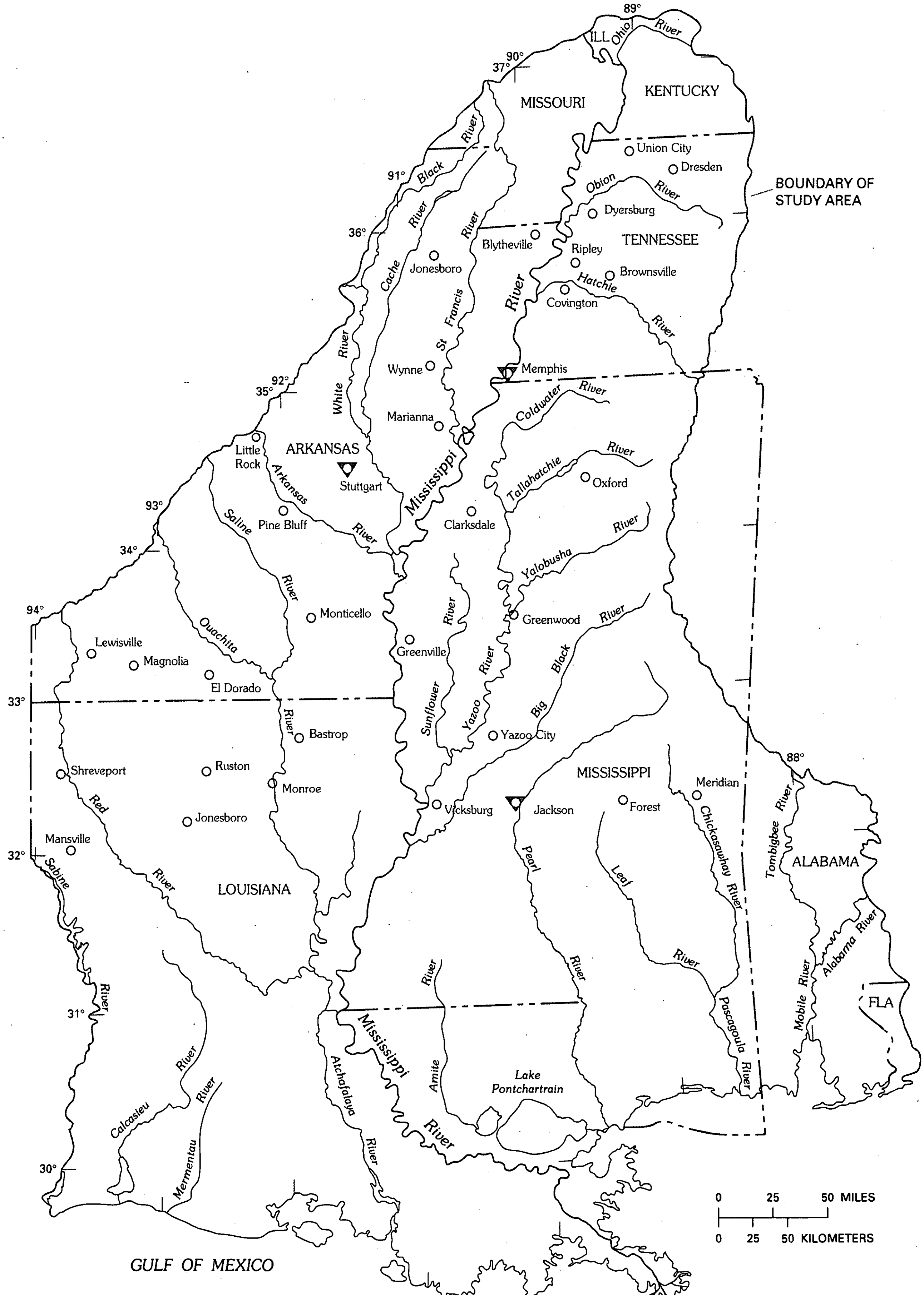

89°
90°
37°
ILL
Ohio
River
MISSOURI
KENTUCKY
River
Union City
Dresden
91°
Black
Obion
River
BOUNDARY OF
STUDY AREA
Dyersburg
36°
River
River
TENNESSEE
Blytheville
Ripley
Cache
Jonesboro
Brownsville
Hatchie
Covington
St Francis
River
River
River
Wynne
Memphis
92°
35°
White
Coldwater
River
Marianna
Little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

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.

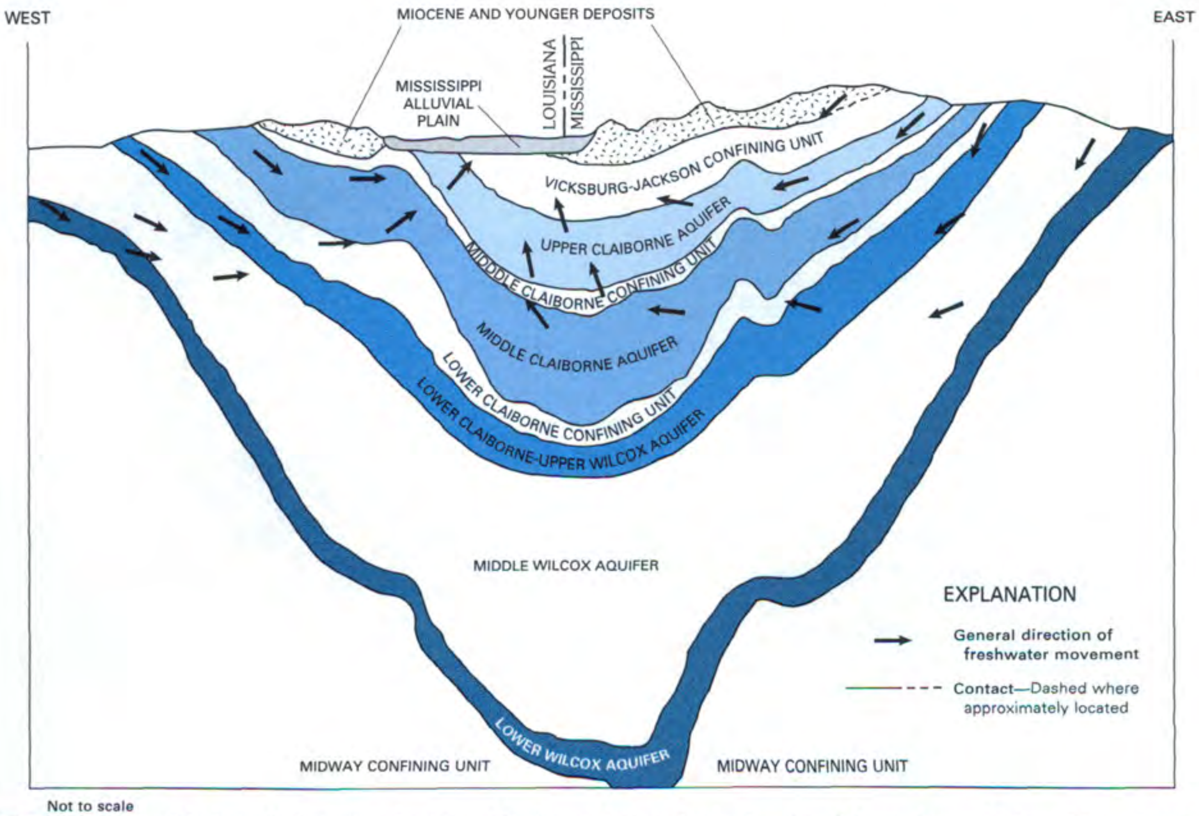


FIGURE 5.—Idealized hydrogeologic section, Louisiana, Mississippi, just south of a line from Monroe, La., to Jackson, Miss. Arrows indicate general direction of freshwater movement. Dashed line indicates contact is approximately located. Modified from Payne (1976, fig. 2).

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 1×10^{-5} to 1×10^{-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 1×10^{-6}. Storage coefficients generally range between 2.5×10^{-5} and 2.5×10^{-4} in the freshwater zones of these five aquifers; the middle Claiborne aquifer has values of more than 2.5×10^{-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 1×10^{-5} ft/d for the thick marine clays of the Vicksburg-Jackson confining unit to 1×10^{-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 7*A*. 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).

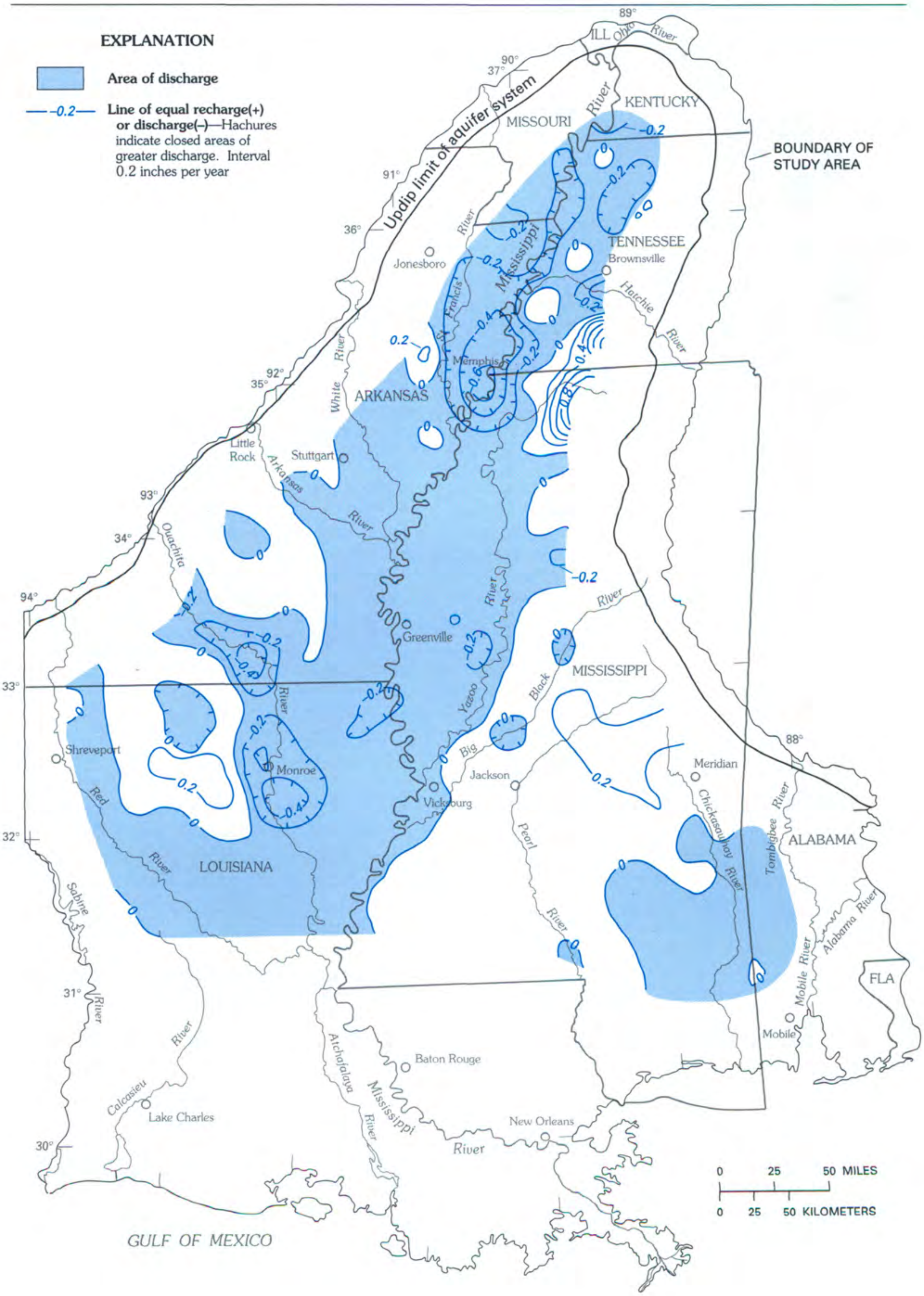
LATERAL AND INTERAQUIFER FLOW

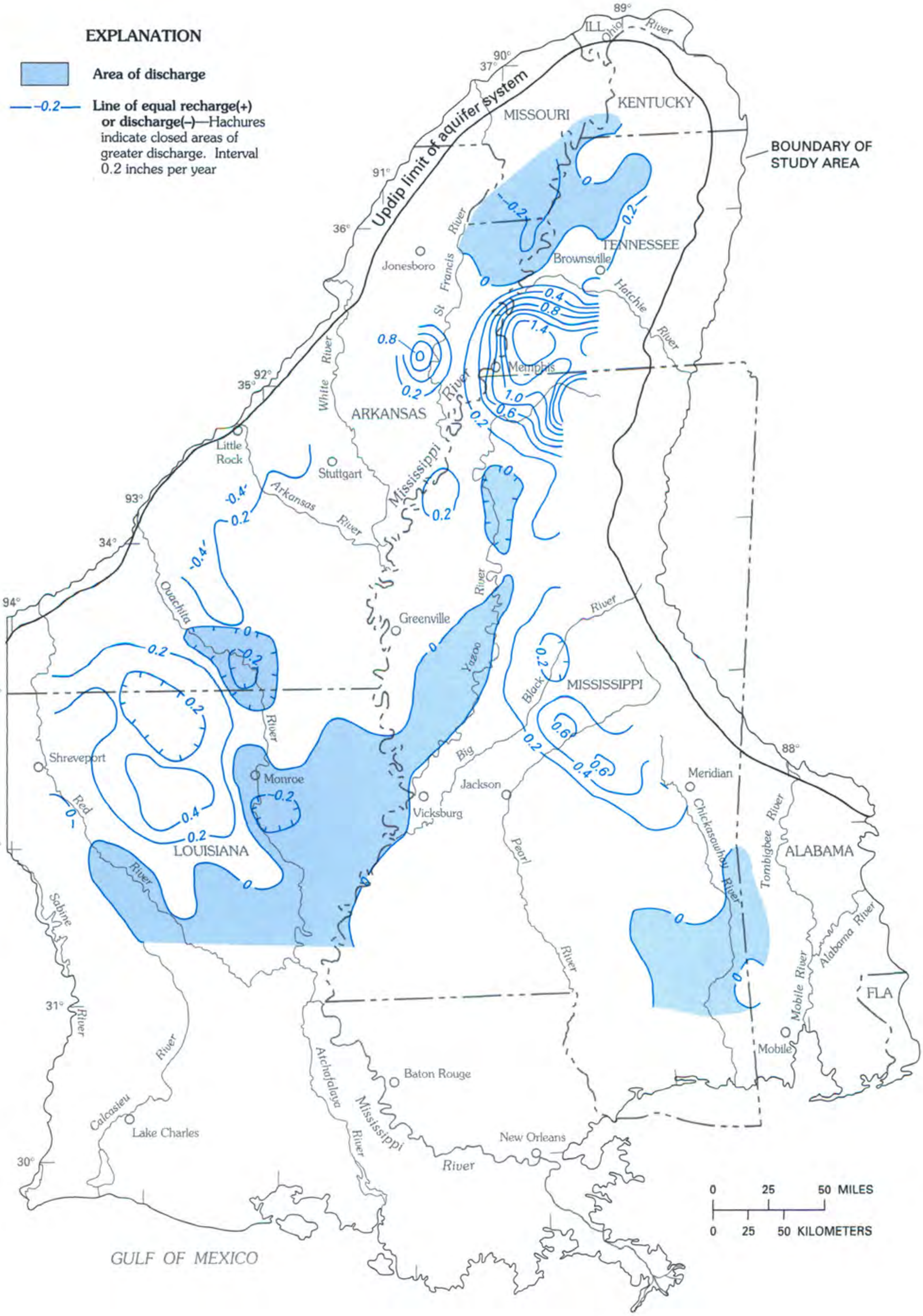
Most water entering the Mississippi embayment aquifer system in outcrop areas moves predominantly downward along a relatively short flow path and is discharged to nearby streams, seeps, and springs. The remainder of the flow moves laterally downdip to the confined area of the aquifer system. Downdip 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
Ohio River
KENTUCKY
MISSOURI
TENNESSEE
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
FLA
Jonesboro
Brownsville
Memphis
Little Rock
Stuttgart
Greenville
Shreveport
Monroe
Vicksburg
Jackson
Meridian
Mobile
Baton Rouge
Lake Charles
New Orleans
Mississippi River
St. Francis River
Hatchie River
White River
Arkansas River
Ouachita River
Yazoo River
Big Black River
Pearl River
Red River
Sabine River
Calcasieu River
Atchafalaya River
Chickasawhay River
Tombigbee River
Mobile River
Alabama River
GULF OF MEXICO
0 25 50 MILES
0 25 50 KILOMETERS
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
33°
32°
31°
30°
88°


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
GULF OF MEXICO
Jonesboro
Brownsville
Memphis
Little Rock
Stuttgart
Greenville
Shreveport
Monroe
Vicksburg
Jackson
Meridian
Mobile
Baton Rouge
Lake Charles
New Orleans
Ohio River
St Francis River
White River
Mississippi River
Arkansas River
Ouachita River
Red River
Sabine River
Calcasieu River
Atchafalaya River
Yazoo River
Big Black River
Pearl River
Hatchie River
Chickasawhay River
Tombigbee River
Mobile River
Alabama River
0 25 50 MILES
0 25 50 KILOMETERS

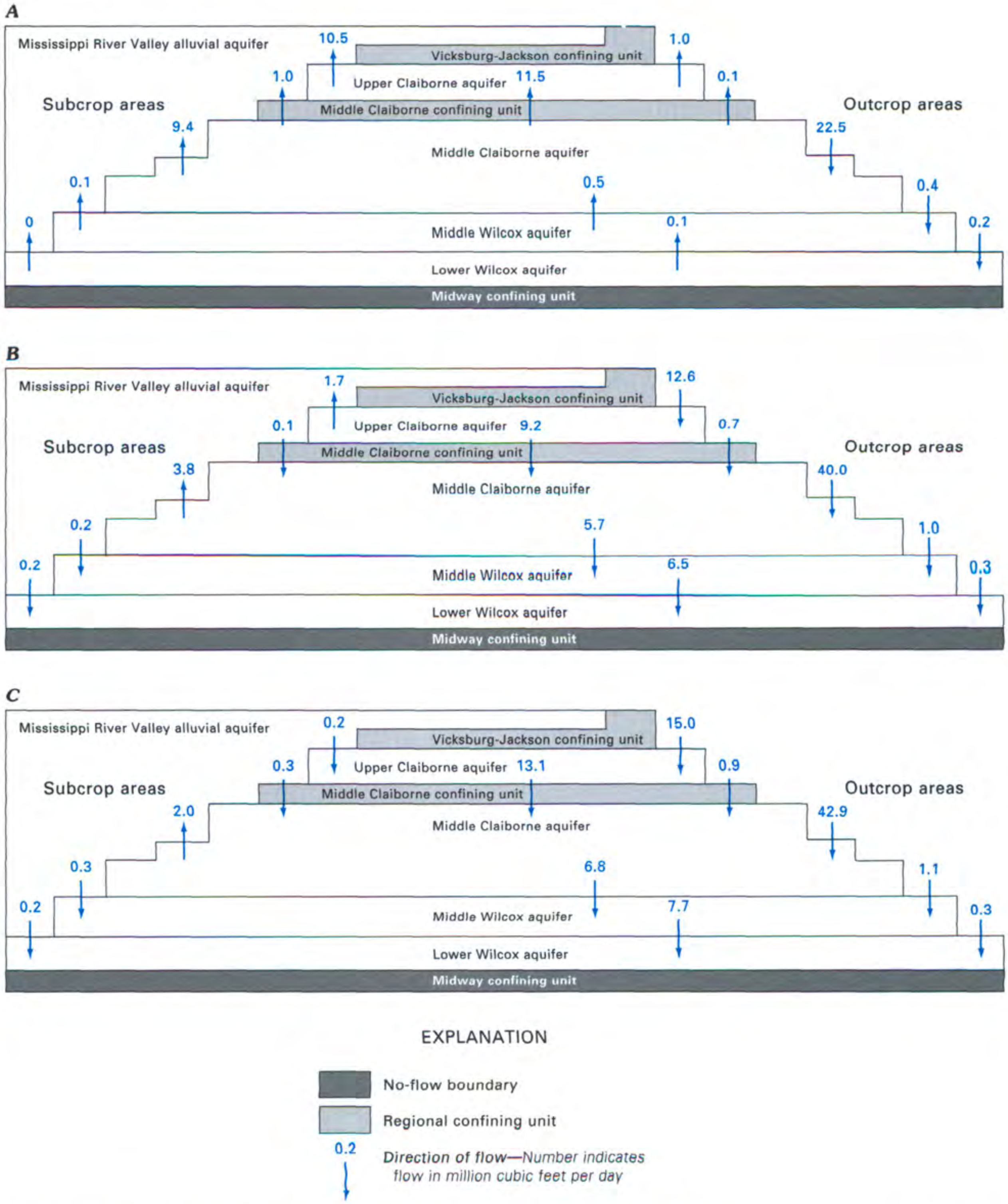


FIGURE 8.—Simulated rates of vertical flow in northern area for (*A*) predevelopment (1986), (*B*) 1987, and (*C*) 2000 conditions (20 percent pumpage increase from 1987 conditions).

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

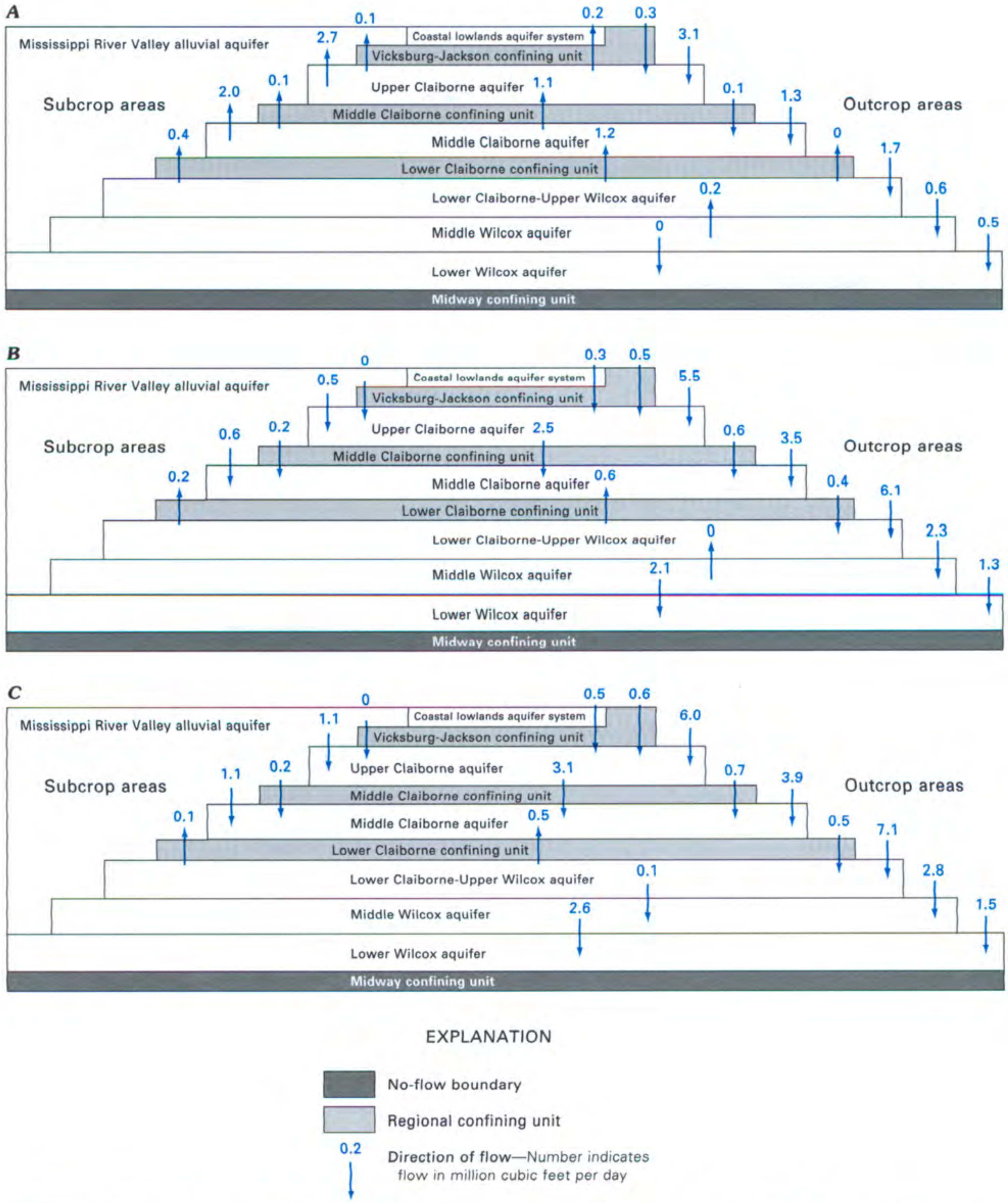


FIGURE 9.—Simulated rates of vertical flow in eastern area for (*A*) predevelopment (1986), (*B*) 1987, and (*C*) 2000 conditions (20 percent pumpage increase from 1987 conditions).

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

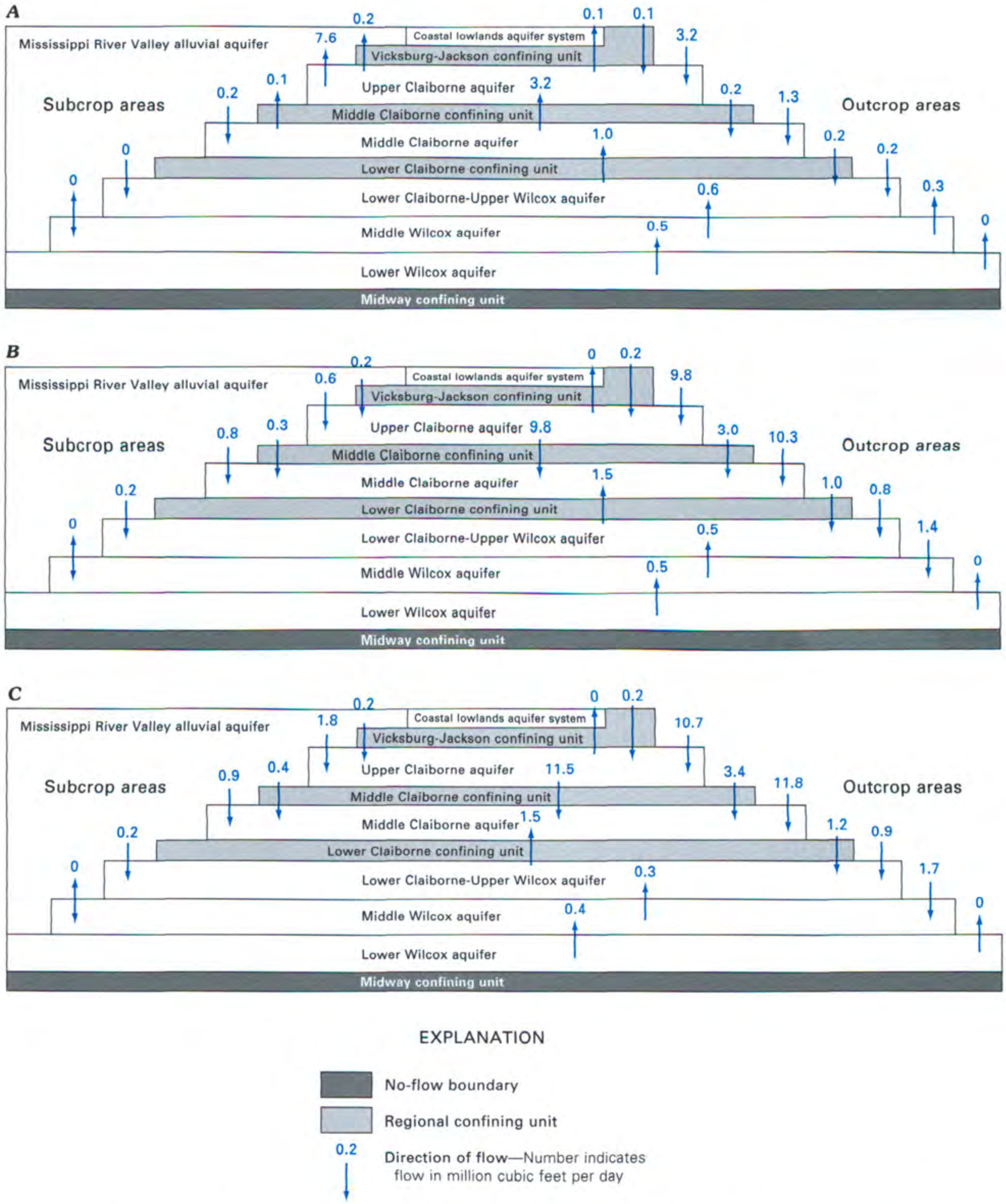


FIGURE 10.—Simulated rates of vertical flow in western area for (*A*) predevelopment (1986), (*B*) 1987, and (*C*) 2000 conditions (20 percent pumpage increase from 1987 conditions).

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

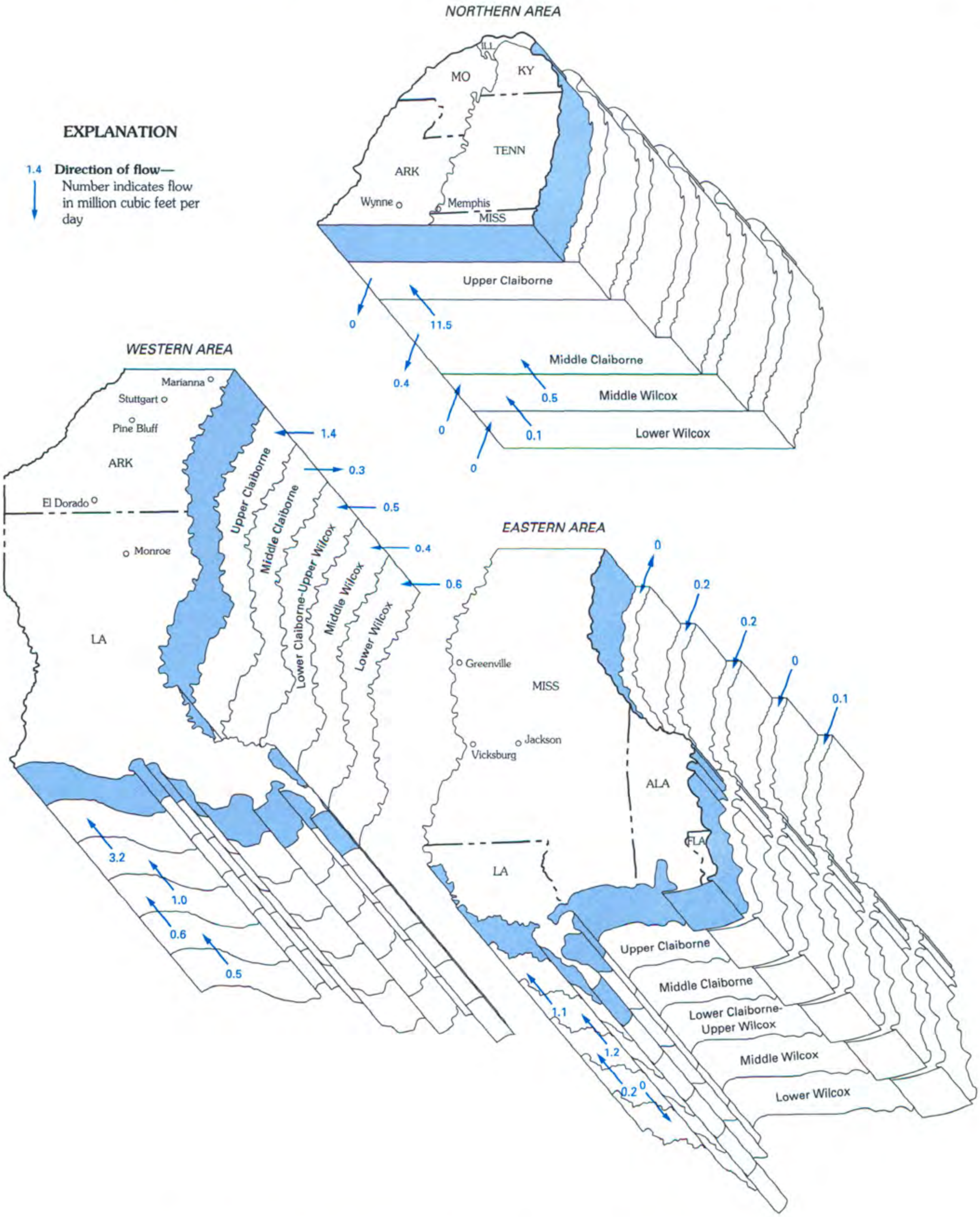


FIGURE 11.—Simulated predevelopment horizontal flow between areas and vertical flow between aquifers.

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

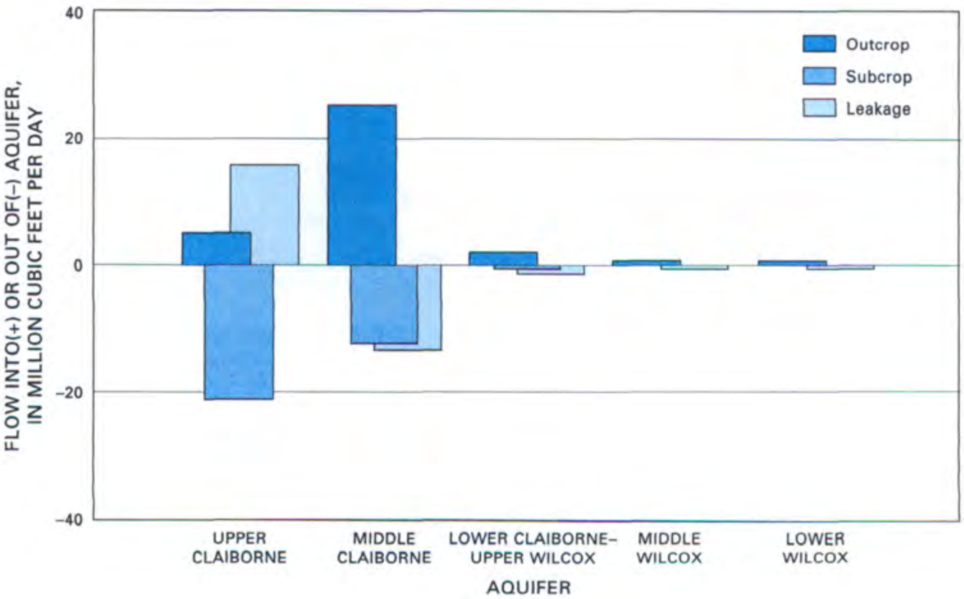


FIGURE 12.—Simulated predevelopment flow budget for aquifers in the study area.

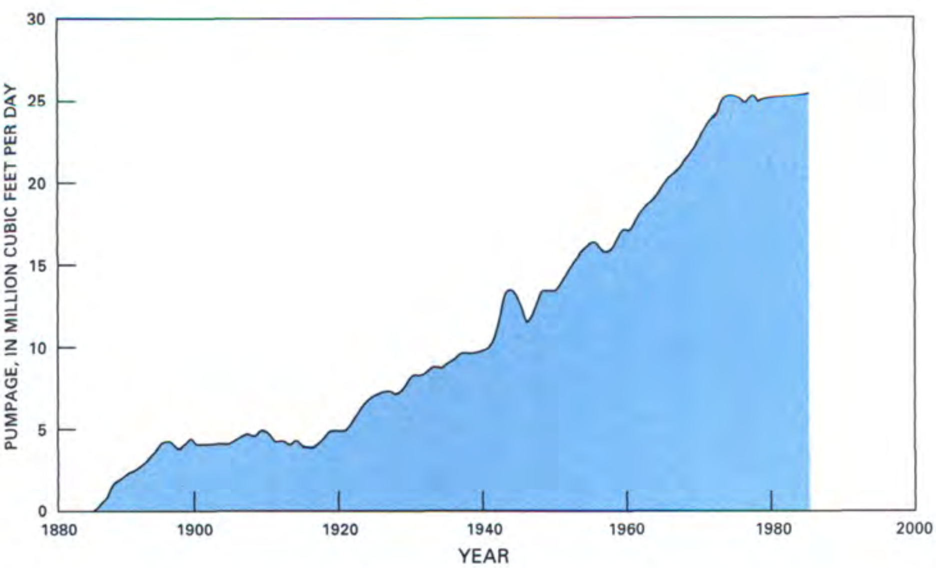


FIGURE 13.—Pumpage (1886–1985) from the middle Claiborne aquifer in the Memphis (Shelby County), Tennessee, area. Modified from Criner and Parks (1976).

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.

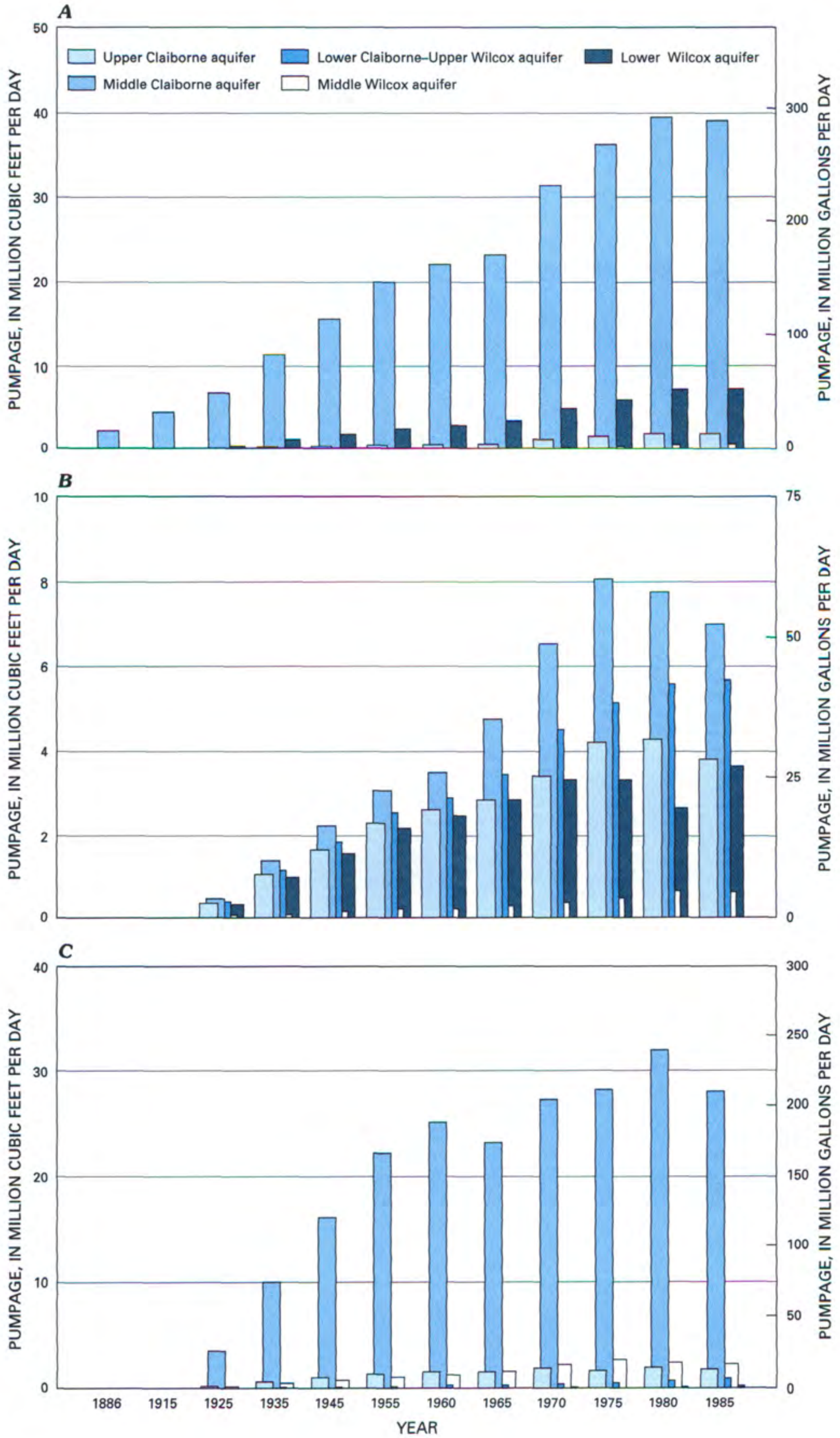


FIGURE 14.—Pumpage from aquifers in (*A*) northern, (*B*) eastern, and (*C*) western areas of the study area.

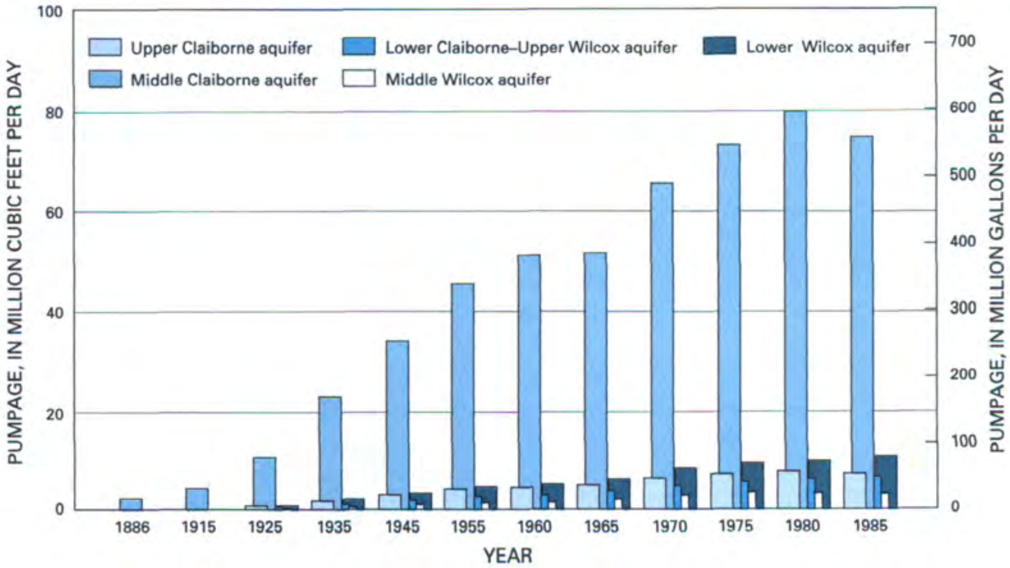


FIGURE 15.—Total pumpage from aquifers in study area.

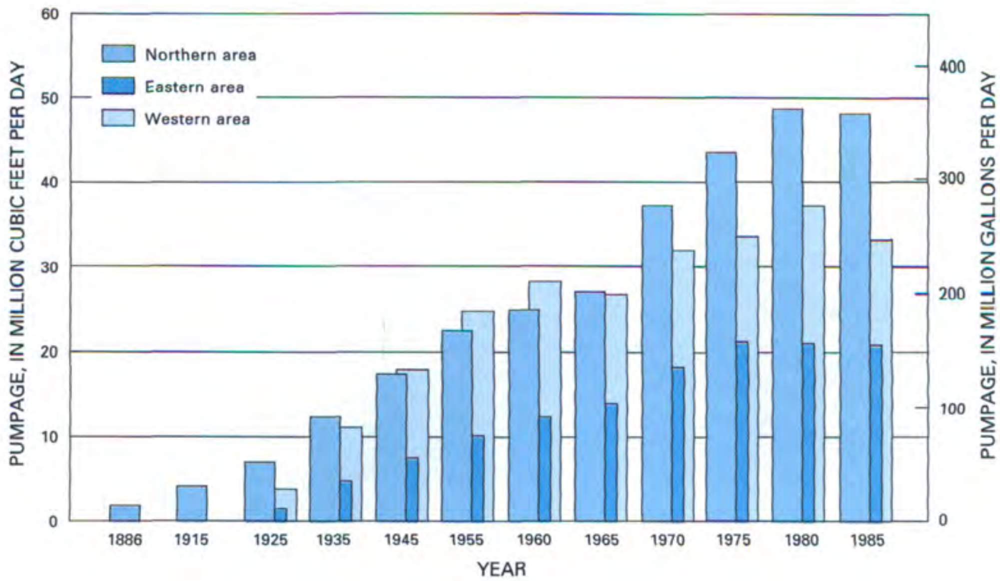


FIGURE 16.—Total pumpage in northern, eastern, and western areas of the study area.

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

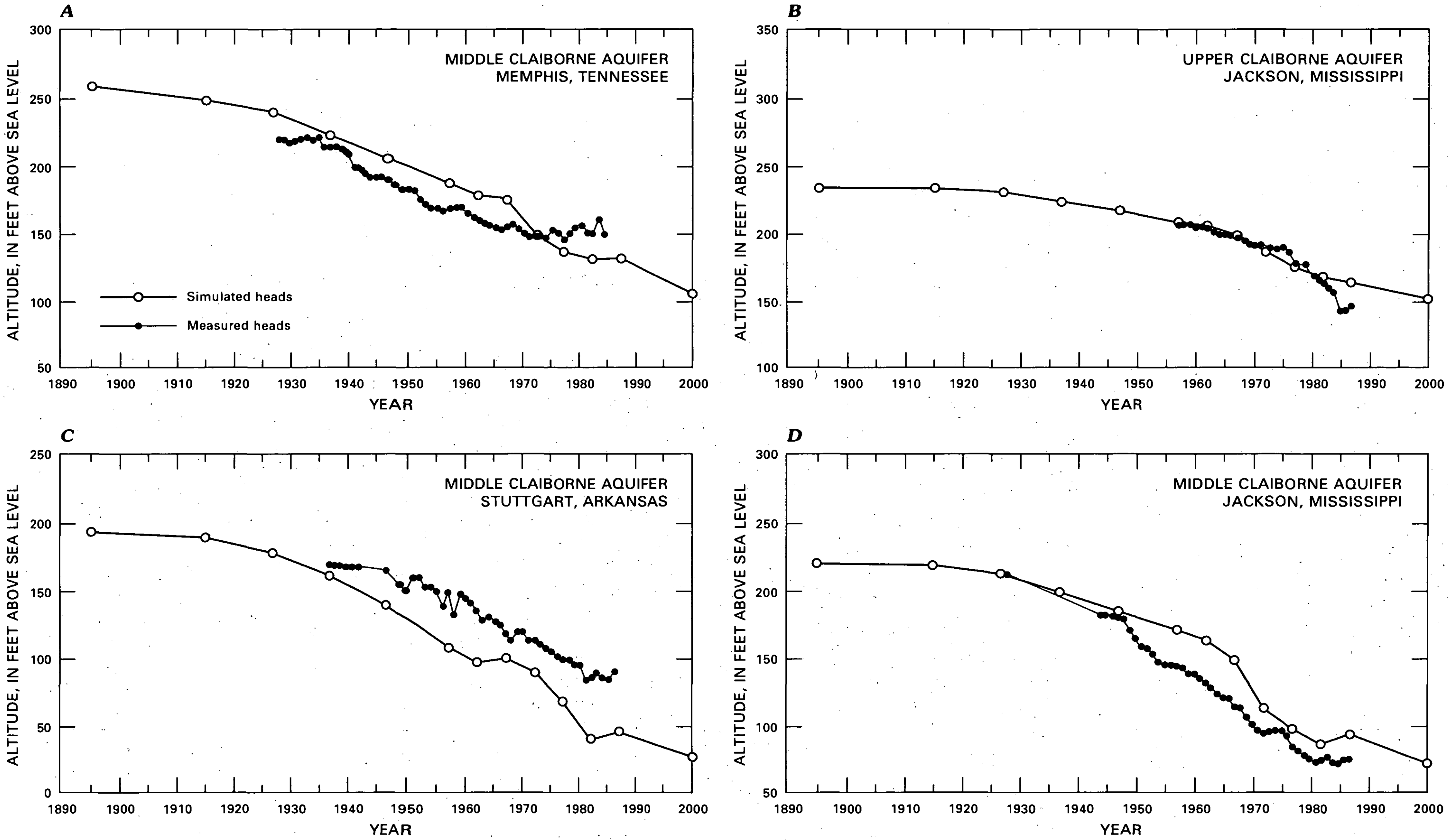


FIGURE 17.—Measured and simulated water levels for selected wells. See figure 3 for well locations.

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 *7B*, 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

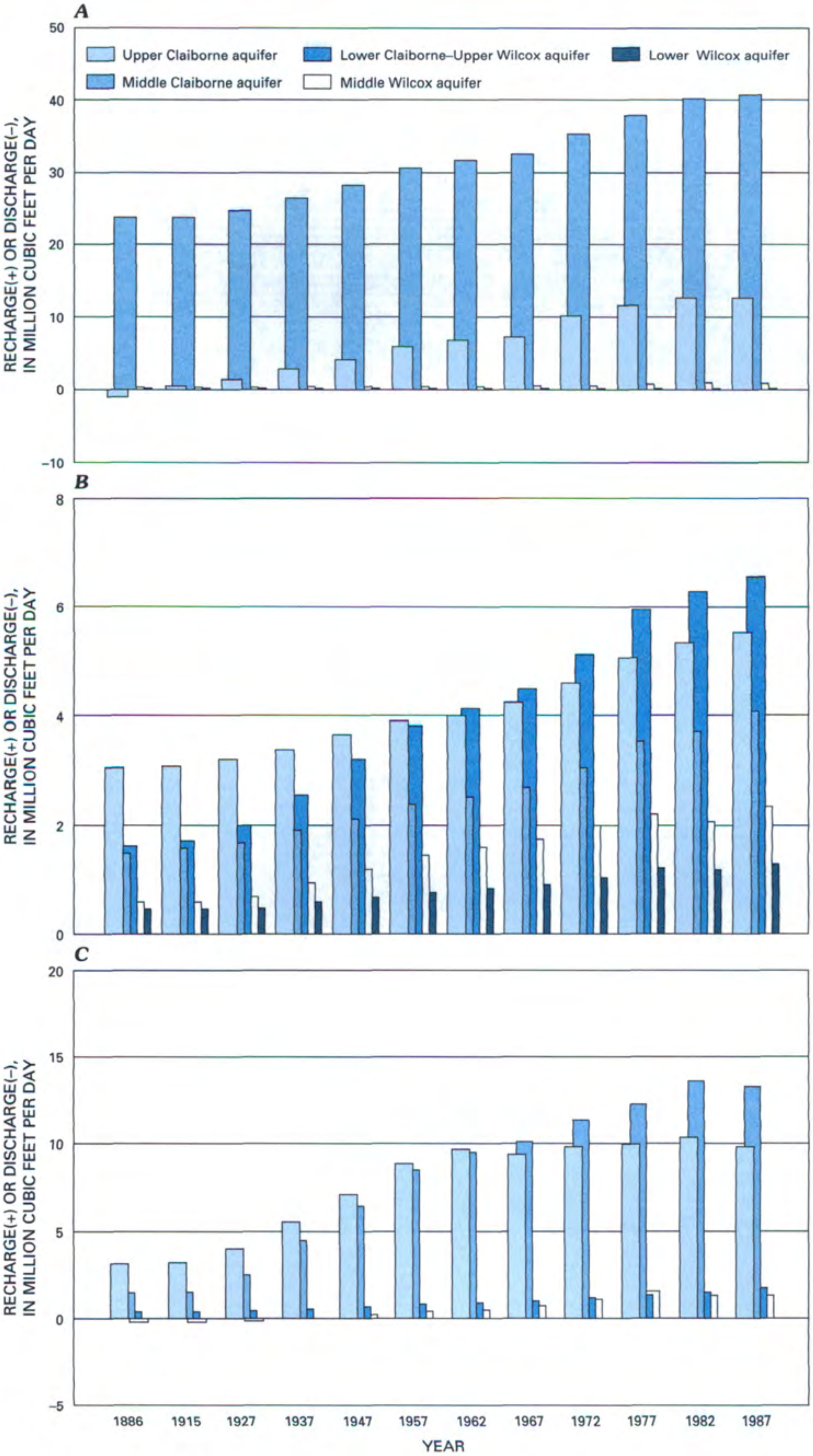


FIGURE 18.—Net recharge and discharge in aquifer outcrops in the (*A*) northern, (*B*) eastern, and (*C*) western areas.

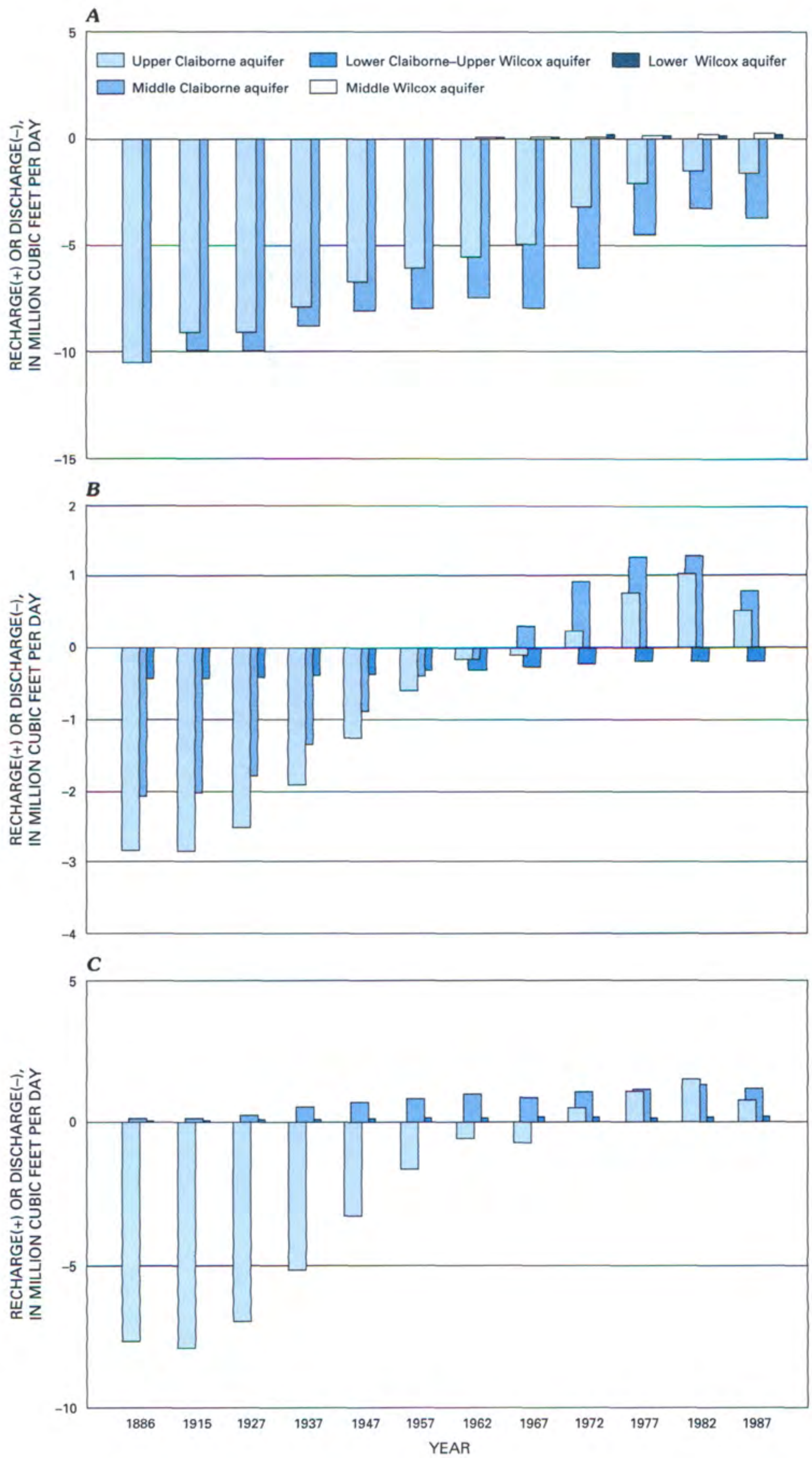


FIGURE 19.—Net recharge and discharge in aquifer subcrops of the Mississippi River Valley alluvial aquifer in (*A*) northern, (*B*) eastern, and (*C*) western areas.

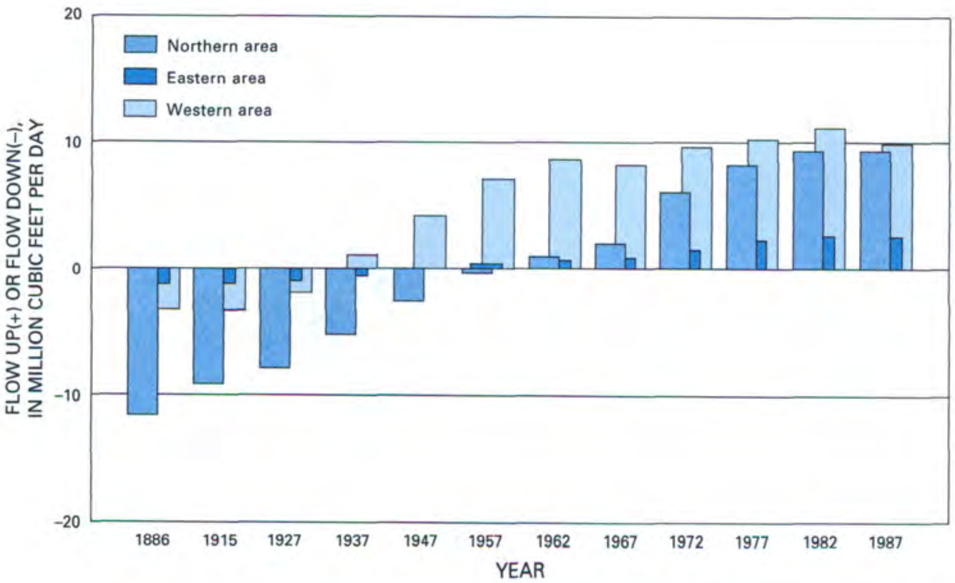


FIGURE 20.—Vertical flow between the upper Claiborne and middle Claiborne aquifers.

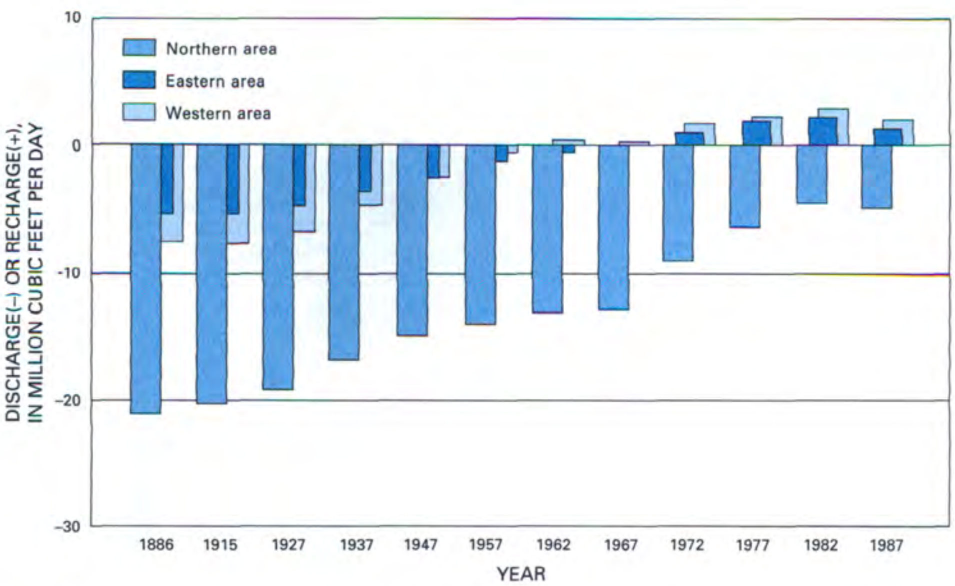


FIGURE 21.—Net discharge from the Mississippi embayment aquifer system to the Mississippi River Valley alluvial aquifer in the northern, eastern, and western areas.

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

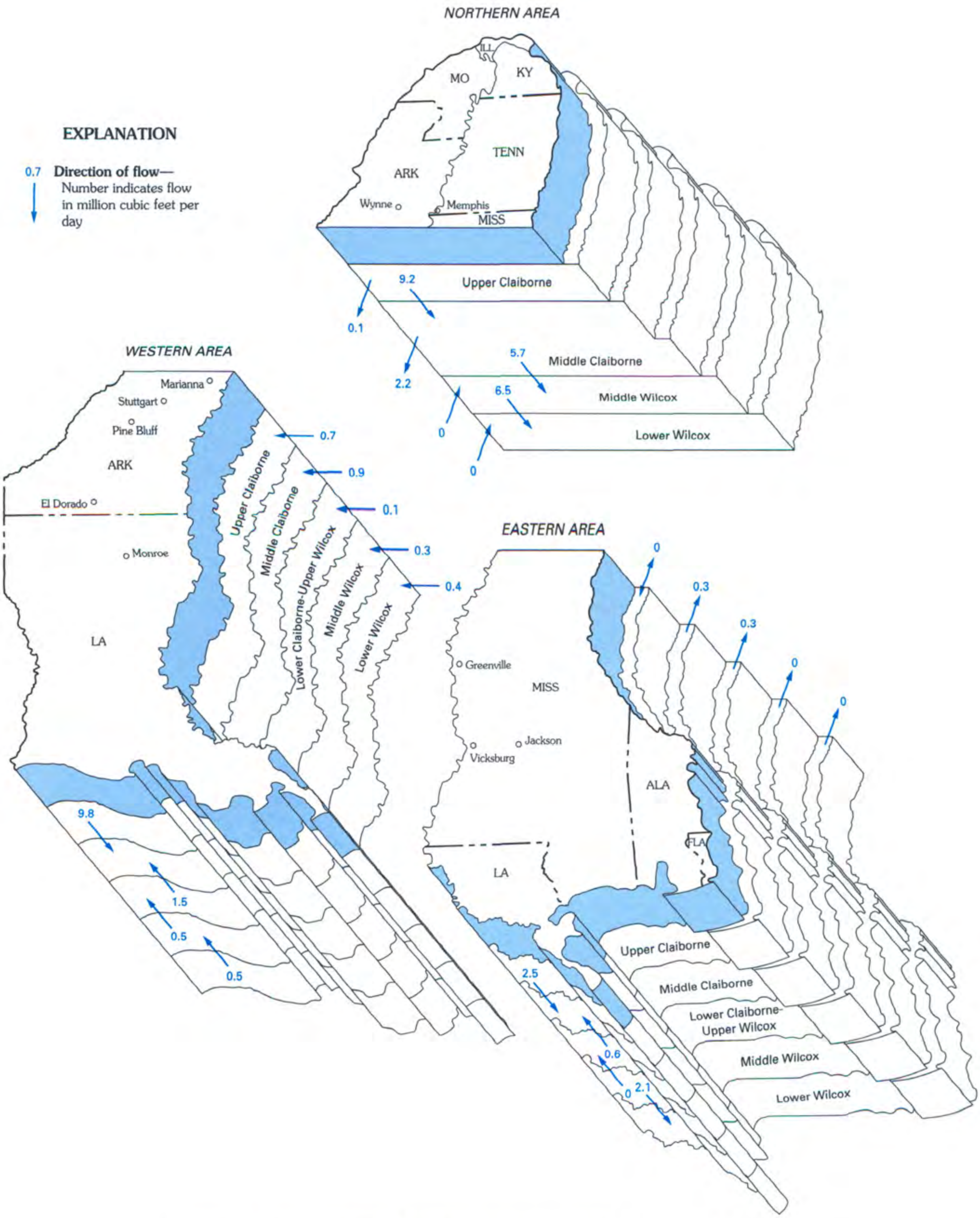


FIGURE 22.—Simulated horizontal flow between areas and vertical flow between aquifers, 1987.

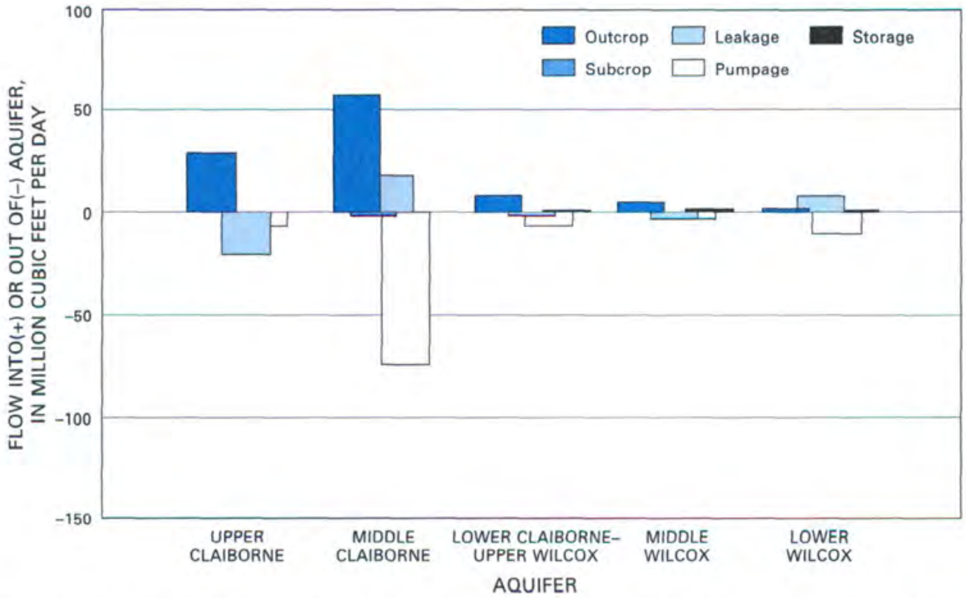


FIGURE 23.—Simulated 1987 flow budget for aquifers in study area.

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

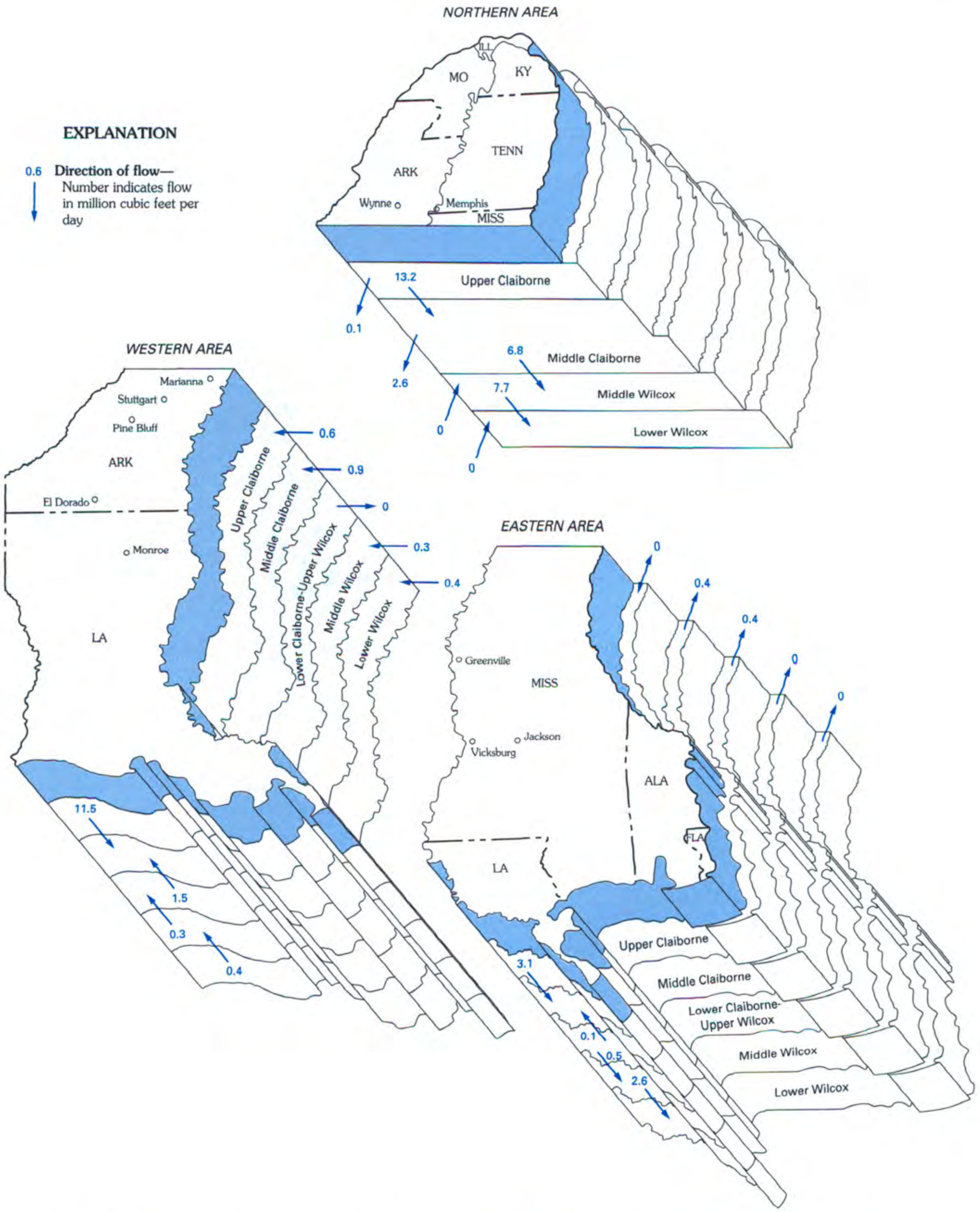


FIGURE 24.—Simulated horizontal flow between areas and vertical flow between aquifers, year 2000, assuming a uniform 20 percent increase in pumpage over 1985 rates.

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)

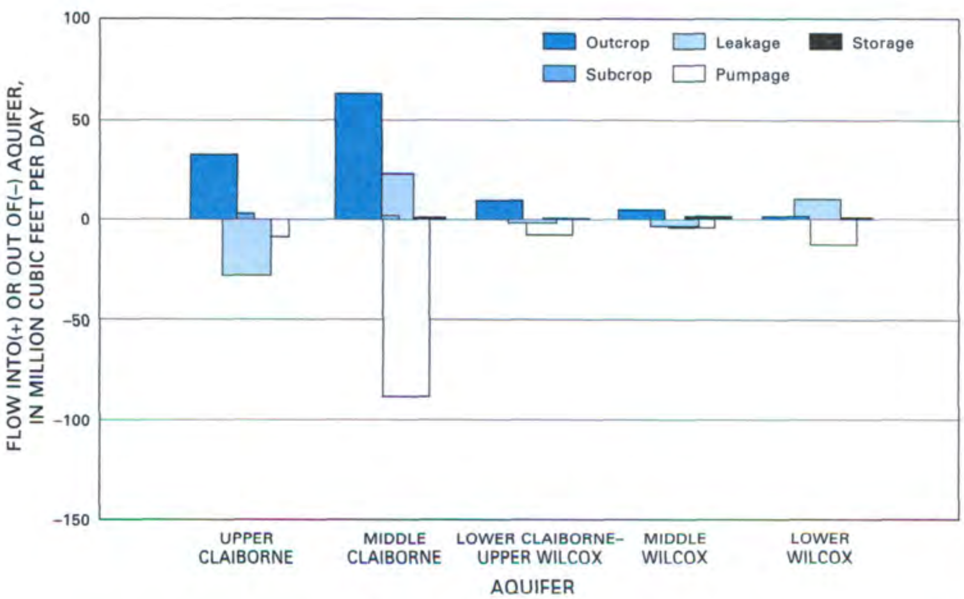


FIGURE 25.—Simulated year 2000 flow budget for aquifers in study area, assuming a uniform 20 percent increase in pumpage over 1985 rates.

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.

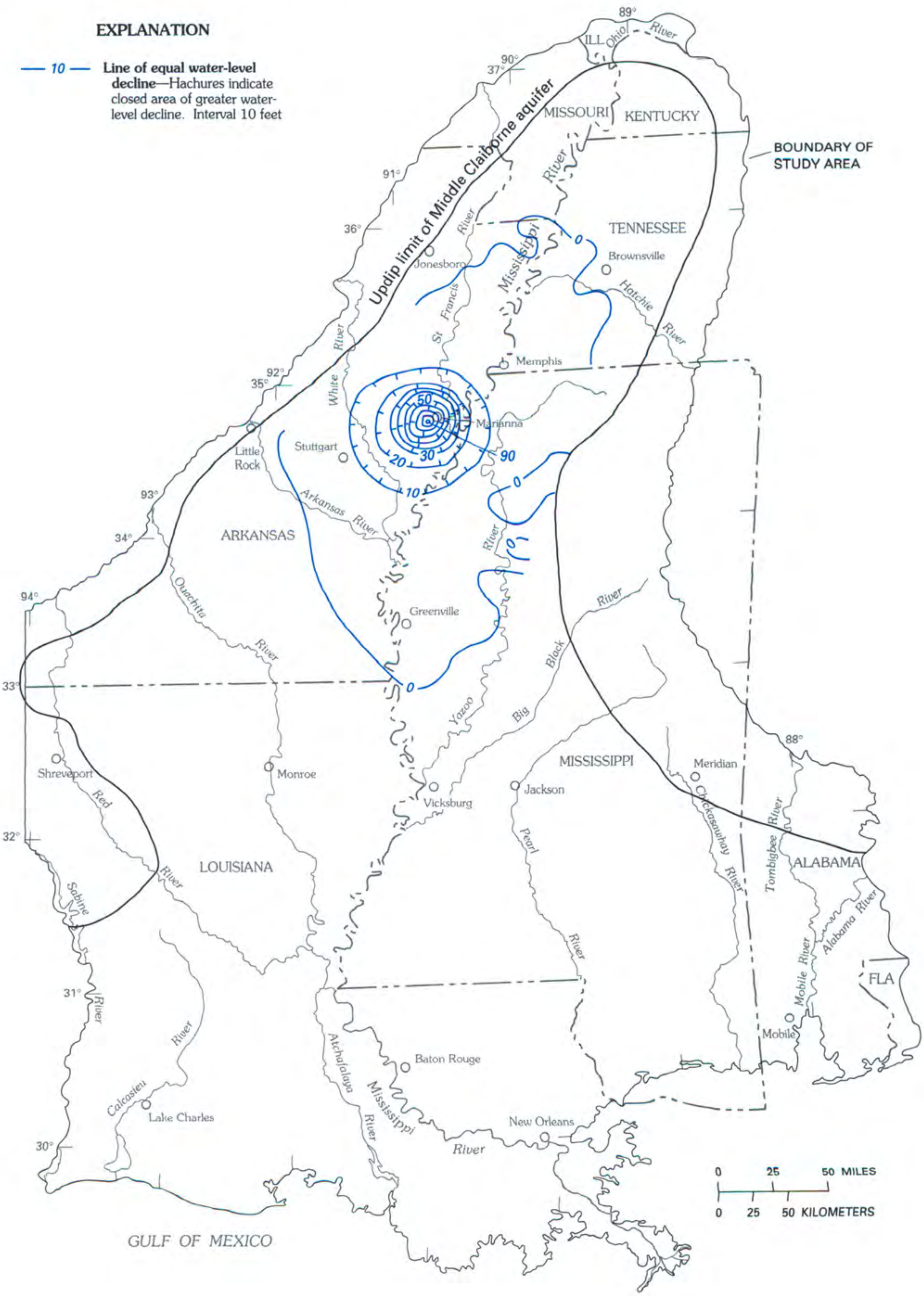
The upper Claiborne aquifer is the youngest and uppermost of the five aquifers studied and is composed predominantly of the Cockfield Formation. The upper Claiborne aquifer averages about 250 feet in thickness in the subsurface and is the most extensive subcropping aquifer in that it directly underlies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

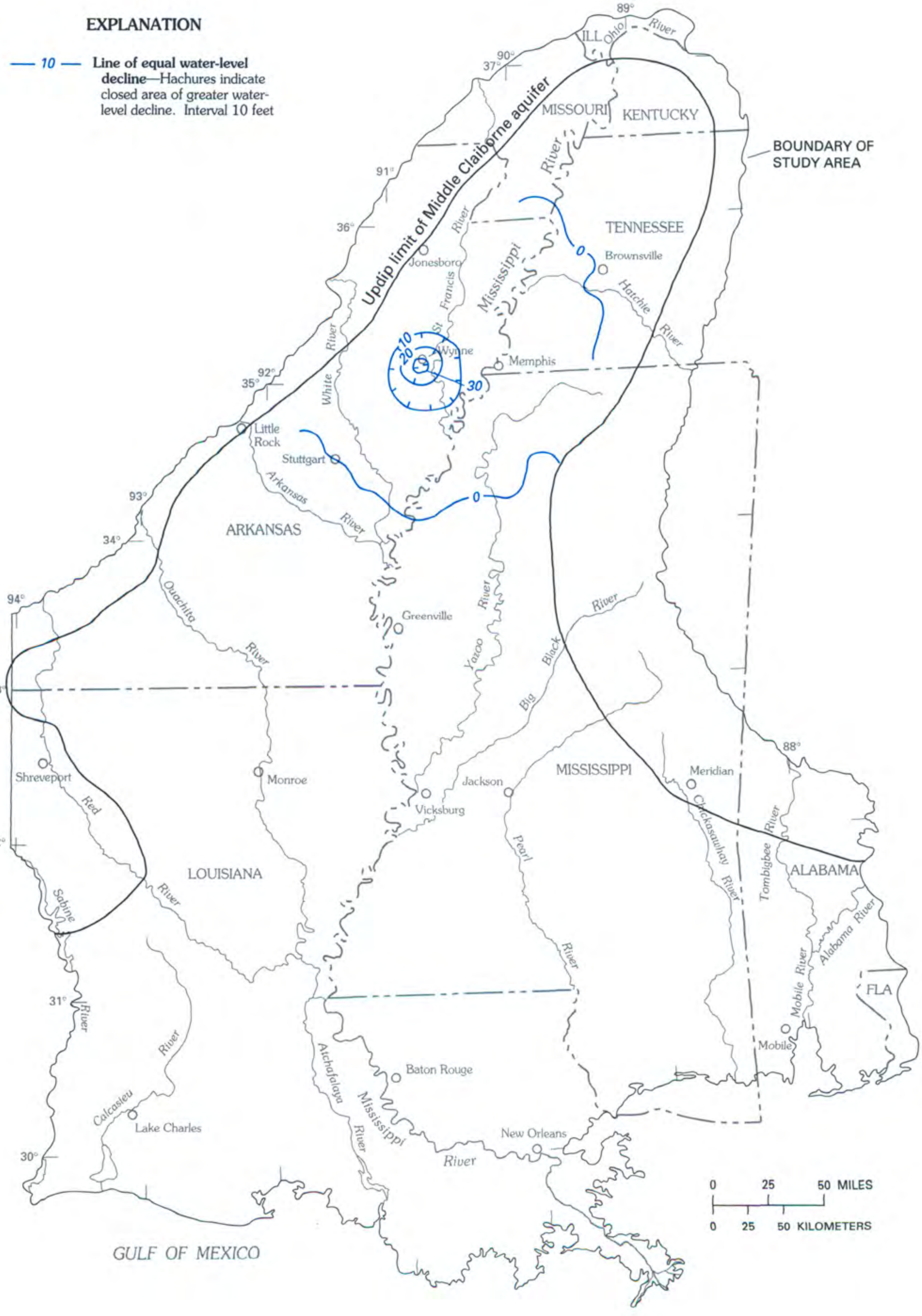
The middle Claiborne aquifer, composed mostly of the Sparta Sand in the southern two-thirds of the study area and the Memphis Sand in Tennessee, east-central Arkansas, southeastern Missouri, southwestern Kentucky, and northwestern Mississippi, is the most extensively developed of the five aquifers. In 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
LOUISIANA
ALABAMA
FLA
Ohio River
Mississippi River
St Francis River
White River
Hatchie River
Arkansas River
Ouachita River
Yazoo River
Big Black River
Red River
Sabine River
Pearl River
Chickasawhay River
Tombigbee River
Mobile River
Alabama River
Calcasieu River
Atchafalaya River
Jonesboro
Brownsville
Memphis
Marianna
Stuttgart
Little Rock
Greenville
Shreveport
Monroe
Vicksburg
Jackson
Meridian
Mobile
Baton Rouge
Lake Charles
New Orleans
GULF OF MEXICO
0 25 50 MILES
0 25 50 KILOMETERS
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
33°
32°
31°
30°
88°
0
10
20
30
50
90


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
0
10
20
30
ILL
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
FLA
Ohio River
Mississippi River
St Francis River
White River
Arkansas River
Ouachita River
Red River
Sabine River
Calcasieu River
Atchafalaya River
Yazoo River
Big Black River
Pearl River
Hatchie River
Chickasawhay River
Tombigbee River
Mobile River
Alabama River
Jonesboro
Brownsville
Wynne
Memphis
Little Rock
Stuttgart
Greenville
Shreveport
Monroe
Vicksburg
Jackson
Meridian
Baton Rouge
New Orleans
Lake Charles
Mobile
GULF OF MEXICO
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 2.5×10^{-5} and 2.5×10^{-4} in the freshwater zones. Vertical hydraulic conductivity values of confining units range from 1×10^{-5} ft/d for the marine clays of the Vicksburg-Jackson confining unit to 1×10^{-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.

SELECTED REFERENCES

Ackerman, D.J., 1987, Generalized potentiometric surface of the Sparta-Memphis aquifer, eastern Arkansas, spring 1980: U.S. Geological Survey Water-Resources Investigations Report 87-4282, scale 1:500,000, 1 sheet.

———1989, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States—A preliminary assessment of the regional flow system: U.S. Geological Survey Water-Resources Investigations Report 88-4028, 74 p.

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

Arthur, J.K., and Taylor, R.E., 1990, Definition of geohydrologic framework and preliminary simulation of ground-water flow in the Mississippi embayment aquifer system, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 86-4364, 97 p.

Baker, R.C., Hewitt, F.A., and Billingsley, G.A., 1948, Ground-water resources of the El Dorado area, Union County, Arkansas: University of Arkansas Bulletin 12, v. 42, 39 p.

Bedinger, M.S., Stephens, J.W., and Edds, J., 1960, Decline of water levels in the Pine Bluff area: Arkansas Geological and Conservation Commission, Little Rock, Special Ground-Water Report 2, 10 p.

Bicker, A.R., Jr., 1969, Geological map of Mississippi: Mississippi Geological Survey, scale 1:500,000, 1 sheet.

Boswell, E.H., 1975, The lower Wilcox aquifer in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 60-75, scale 1:500,000, 1 sheet.

——— 1976, The Meridian–upper Wilcox aquifer in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 76-79, scale 1:500,000, 1 sheet.

Brahana, J.V., 1982, Two-dimensional digital ground-water model of the Memphis Sand and equivalent units, Tennessee, Arkansas, Mississippi: U.S. Geological Survey Open-File Report 82-99, 55 p.

Brahana, J.V., and Mesko, T.O., 1988, Hydrogeology and preliminary assessment of regional flow in the upper Cretaceous and adjacent aquifers in the northern Mississippi embayment: U.S. Geological Survey Water-Resources Investigations Report 87-4000, 65 p.

Bryant, C.T., Ludwig, A.H., and Morris, E.E., 1985, Ground water problems in Arkansas: U.S. Geological Survey Water-Resources Investigations Report 85-4010, 24 p.

Covay, K.J., 1985, Ground-water resources of the Rayville-Delhi area, northeastern Louisiana: Louisiana Department of Transportation and Development, Office of Public Works, Water-Resources Technical Report 37, 22 p.

Criner, J.H., and Parks, W.S., 1976, Historic water-level changes and pumpage from the principal aquifers of the Memphis area, Tennessee—1886-1975: U.S. Geological Survey Water-Resources Investigations Report 76-67, 45 p.

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

Cushing, E.M., Boswell, E.H., Speer, P.R., and Hosman, R.L., 1970, Availability of water in the Mississippi embayment: U.S. Geological Survey Professional Paper 448–A, 13 p.

Devery, D.M., 1982, Subsurface Cretaceous strata of Mississippi: Mississippi Department of Natural Resources, Bureau of Geology, Information Series 82-1, 24 p.

Edds, Joe, and Fitzpatrick, D.J., 1985, Maps showing altitude of the potentiometric surface and changes in water levels of the Sparta Sand and Memphis Sand aquifers in eastern Arkansas, spring 1984: U.S. Geological Survey Water-Resources Investigations Report 85-4223, scale 1:500,000, 1 sheet.

Fenneman, N.M., 1938, Physiography of the Eastern United States: McGraw-Hill, 714 p.

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

Graham, D.D., 1979, Potentiometric map of the Memphis Sand in the Memphis area, Tennessee, August 1978: U.S. Geological Survey Water-Resources Investigations Report 79-80, scale 1:500,000, 1 sheet.

———1982, Effects of urban development on the aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 82-4024, 20 p.

Graham, D.D., and Parks, W.S., 1986, Potential for leakage among principal aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 85-4295, 46 p.

Grubb, H.F., 1984, Planning report for the Gulf Coastal Regional aquifer system analysis in the Gulf of Mexico coastal plain, United States: U.S. Geological Survey Water-Resources Investigations Report 84-4219, 30 p.

———1987, Overview of the Gulf Coast regional aquifer-system analysis, *in* Vecchioli, John, and Johnson, A.I., eds., Aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph 9, p. 101-118.

Guyton, W.F., and Rose, N.A., 1955, Report on ground-water conditions in El Dorado area, Arkansas: El Dorado Chamber of Commerce, 18 p.

Halbert, H.N., 1977, Use of water in Arkansas, 1975: Arkansas Department of Commerce, Arkansas Geological Commission, Water Resources Summary 9, 28 p.

Harvey, E.J., Callahan, J.A., and Wasson, B.E., 1964, Ground-water resources of Hinds, Madison, and Rankin Counties, Mississippi: Mississippi Board of Water Commission Bulletin 64-1, 38 p.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 24 p.

Holland, T.W., and Ludwig, A.H., 1981, Use of water in Arkansas, 1980: Arkansas Department of Commerce, Arkansas Geological Commission, Water Resources Summary 14, 30 p.

Hosman, R.L., 1988, Geohydrologic framework of the Gulf Coast Plain: U.S. Geological Survey Hydrologic Investigations Atlas HA-695, scale 1:2,500,000, 2 sheets.

Hosman, R.L., Long, A.T., Lambert, T.W., and others, 1968, Tertiary aquifers in the Mississippi embayment, *with discussion of* Quality of the water, by H.G. Jeffery: U.S. Geological Survey Professional Paper 448–D, 19 p.

Hosman, R.L. and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416-B, 19 p.

Klein, H., Baker, R.C., and Billingsley, G.A., 1950, Ground-water resources of Jefferson County, Arkansas: Arkansas University of Science and Technology Research Series 19, 44 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Lower Mississippi Regional Comprehensive Study, 1974, Regional climatology hydrology and geology, appendix C, volume I: 279 p.

Martin, Angel, Jr., and Early, D.A., 1987, Statistical analysis of aquifer-test results for nine regional aquifers in Louisiana: U.S. Geological Survey Water-Resources Investigations Report 87-4001, 26 p.

Martin, Angel, Jr and Whiteman, C.D., Jr., 1989, Regional ground-water flow in the coastal lowlands aquifer system in parts of Alabama, Florida, Louisiana, and Mississippi—A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 88-4100, 88 p.

———in press, Hydrology of the coastal lowlands aquifer system in parts of Alabama, Florida, Louisiana, and Mississippi: U.S. Geological Survey Professional Paper 1416–H.

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

Mesko, T.O., Ackerman, D.J., and Williamson, A.K., 1990, Ground-water pumpage from the Gulf Coast Aquifer System, 1960–85, South Central United States: U.S. Geological Survey Water-Resources Investigations Report 89-4180, 177 p.

Moore, G.K., 1965, Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geological Survey Water-Supply Paper 1809–F, 44 p.

Newcome, Roy, Jr., 1971, Results of aquifer tests in Mississippi: Mississippi Board of Water Commissioners Bulletin 71-2, 44 p.

———1976, The Sparta aquifer system in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 76-7, scale 1:500,000, 3 sheets.

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

———1970, Geohydrologic significance of lithofacies of the Cockfield Formation of Louisiana and Mississippi and of Yegua Formation of Texas: U.S. Geological Survey Professional Paper 569–B, 14 p.

———1972, Hydrologic significance of lithofacies of the Cane River Formation or equivalents of Arkansas, Louisiana, Mississippi, and Texas: U.S. Geological Survey Professional Paper 569–C, 17 p.

———1975, Geohydrologic significance of lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas and the Meridian Sand of Mississippi: U.S. Geological Survey Professional Paper 569–D, 11 p.

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

Reed, J.E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geological Survey Hydrologic Investigations Atlas HA-434, 1 sheet.

Rollo, J.R., 1960, Ground water in Louisiana: Louisiana Department of Conservation, Geological Survey, and Department of Public Works, Water Resources Bulletin 1, 84 p.

Ryals, G.N., 1980a, Potentiometric surface maps of the Sparta Sand, northern Louisiana and southern Arkansas, 1900, 1965, 1975, and 1980: U.S. Geological Survey Open-File Report 80-1180, scale 1:500,000, 1 sheet.

———1980b, Potentiometric surface of the Carrizo-Wilcox aquifer, Bienville, Red River, northern Natchitoches, and southern Webster Parishes, Louisiana: U.S. Geological Survey Open-File Report 80-1179, map, scale 1:500,000, 1 sheet.

Ryder, P.D., 1988, Hydrology and predevelopment flow in the Texas Gulf Coast aquifer system: U.S. Geological Survey Water-Resources Investigations Report 87-4248, 228 p.

Ryder, P.D., and Ardis, A.F., in press, Hydrology of the Texas gulf coast aquifer systems: U.S. Geological Survey Professional paper 1416–E.

Sampson, R.J., 1978, Surface II graphics system: Kansas Geological Survey Series on Spacial Analysis 1, 240 p.

Schneider, Robert, and Cushing, E.M., 1948, Geology and water-bearing properties of the "1400-foot" sand in the Memphis area: U.S. Geological Survey Circular 33, 13 p.

Spiers, C.A., 1977a, The Cockfield aquifer in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 77-17, scale 1:500,000, 3 sheets.

———1977b, The Winona-Tallahatta aquifer in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 77-125, scale 1:500,000, 3 sheets.

Sun, R.J., ed., 1986, Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978-84: U.S. Geological Survey Circular 1002, 264 p. [out of print].

Tait, D.B., Baker, R.C., and Billingsley, G.A., 1953, The ground-water resources of Columbia County, Arkansas, a reconnaissance: U.S. Geological Survey Circular 241, 25 p.

Trudeau, D.A., and Buono, Anthony, 1985, Projected effects of proposed increased pumpage on water levels and salinity in the Sparta aquifer near West Monroe, Louisiana: Louisiana Department of Transportation and Development, Office of Public Works, Water Resources Technical Report 39, 70 p.

Wasson, B.E., 1980a, Sources for water supplies in Mississippi: Mississippi Research and Development Center Bulletin, 112 p.

———1980b, Potentiometric map of the lower Wilcox aquifer in Mississippi, fall 1979: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-597, scale 1:500,000, 1 sheet.

———1980c, Potentiometric map of the Meridian-upper Wilcox aquifer in Mississippi, fall 1979: U.S. Geological Survey Water-Resources Investigations Report 80-590, scale 1:500,000, 1 sheet.

———1980d, Potentiometric map of the Winona-Tallahatta aquifer in northwestern Mississippi, fall 1979: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-598, scale 1:500,000, 1 sheet.

———1981a, Potentiometric map of the Sparta aquifer in Mississippi, fall 1980: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1051, scale 1:500,000, 1 sheet.

———1981b, Potentiometric map of the Cockfield aquifer in Mississippi, fall 1980: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1053, scale 1:500,000, 1 sheet.

Weiss, J.S., 1986, Mapping dissolved-solids concentrations in highly mineralized ground water of the Gulf Coast aquifer systems using electric logs: Geological Society of America Abstracts with Programs, p. 784.

Weiss, J.S., and Williamson, A.K., 1985, Subdivision of thick sedimentary units into layers for simulation of ground-water flow: Ground Water, v. 23, no. 6, p. 767–774.

Williamson, A.K., Grubb, H.F., Weiss, J.S., 1990, Ground-water in the Gulf Coast aquifer systems, south central United States—A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 89-4071, 124 p.

Wilson, T.A., and Hosman, R.L., 1987, Geophysical well-log data base for the Gulf Coast aquifer systems, south-central United States: U.S. Geological Survey Open-File Report 87-677, 213 p.

Selected Series of U.S. Geological Survey Publications

Books and Other Publications

Professional Papers report scientific data and interpretations of lasting scientific interest that cover all facets of USGS investigations and research.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars are reports of programmatic or scientific information of an ephemeral nature; many present important scientific information of wide popular interest. Circulars are distributed at no cost to the public.

Fact Sheets communicate a wide variety of timely information on USGS programs, projects, and research. They commonly address issues of public interest. Fact Sheets generally are two or four pages long and are distributed at no cost to the public.

Reports in the **Digital Data Series (DDS)** distribute large amounts of data through digital media, including compact disc-read-only memory (CD-ROM). They are high-quality, interpretive publications designed as self-contained packages for viewing and interpreting data and typically contain data sets, software to view the data, and explanatory text.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are produced on request (unlike formal USGS publications) and are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports can consist of basic data, preliminary reports, and a wide range of scientific documents on USGS investigations. Open-File Reports are designed for fast release and are available for public consultation at depositories.

Maps

Geologic Quadrangle Maps (GQ's) are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps (GP's) are on topographic or planimetric bases at various scales. They show results of geophysical investigations using gravity, magnetic, seismic, or radioactivity surveys, which provide data on subsurface structures that are of economic or geologic significance.

Miscellaneous Investigations Series Maps or **Geologic Investigations Series (I's)** are on planimetric or topographic bases at various scales; they present a wide variety of format and subject matter. The series also incudes 7.5-minute quadrangle photogeologic maps on planimetric bases and planetary maps.

Information Periodicals

Metal Industry Indicators (MII's) is a free monthly newsletter that analyzes and forecasts the economic health of five metal industries with composite leading and coincident indexes: primary metals, steel, copper, primary and secondary aluminum, and aluminum mill products.

Mineral Industry Surveys (MIS's) are free periodic statistical and economic reports designed to provide timely statistical data on production, distribution, stocks, and consumption of significant mineral commodities. The surveys are issued monthly, quarterly, annually, or at other regular intervals, depending on the need for current data. The MIS's are published by commodity as well as by State. A series of international MIS's is also available.

Published on an annual basis, **Mineral Commodity Summaries** is the earliest Government publication to furnish estimates covering nonfuel mineral industry data. Data sheets contain information on the domestic industry structure, Government programs, tariffs, and 5-year salient statistics for more than 90 individual minerals and materials.

The Minerals Yearbook discusses the performance of the worldwide minerals and materials industry during a calendar year, and it provides background information to assist in interpreting that performance. The Minerals Yearbook consists of three volumes. Volume I, Metals and Minerals, contains chapters about virtually all metallic and industrial mineral commodities important to the U.S. economy. Volume II, Area Reports: Domestic, contains a chapter on the minerals industry of each of the 50 States and Puerto Rico and the Administered Islands. Volume III, Area Reports: International, is published as four separate reports. These reports collectively contain the latest available mineral data on more than 190 foreign countries and discuss the importance of minerals to the economies of these nations and the United States.

Permanent Catalogs

"Publications of the U.S. Geological Survey, 1879–1961" and **"Publications of the U.S. Geological Survey, 1962–1970"** are available in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971–1981" is available in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Annual supplements for 1982, 1983, 1984, 1985, 1986, and subsequent years are available in paperback book form.

Arthur and Taylor—GROUND-WATER FLOW ANALYSIS, MISSISSIPPI EMBAYMENT AQUIFER SYSTEM—U.S. Geological Survey Professional Paper 1416–I

ISBN 0-607-87150-4

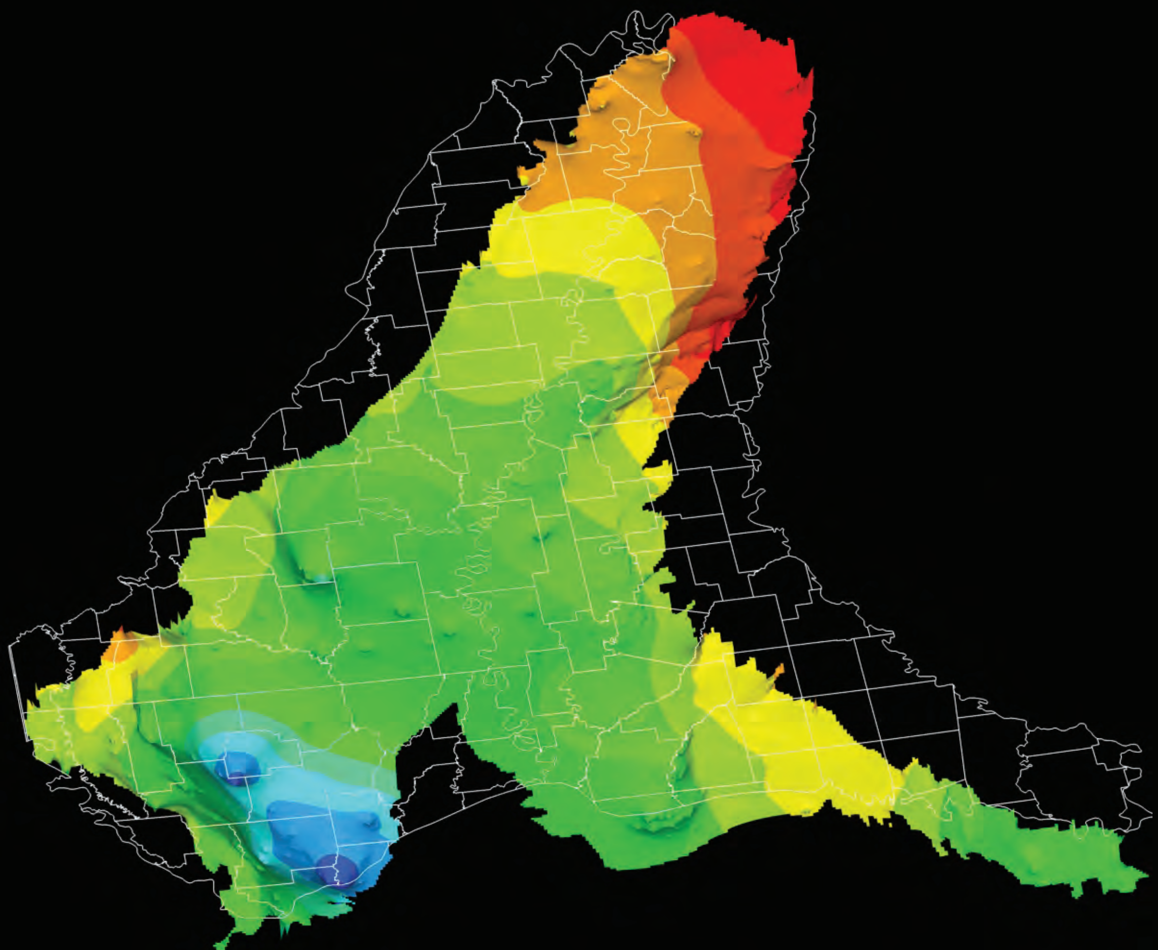
9 780607 871500

EXHIBIT 10

B.R. Clark & R.M. Hart
The Mississippi Embayment Regional Aquifer Study (MERAS):
Documentation of a Groundwater-Flow Model Constructed to
Assess Water availability in the Mississippi Embayment
USGS Scientific Investigations Report 2009-5172

Groundwater Resources Program

The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment



Scientific Investigations Report 2009–5172

U.S. Department of the Interior
U.S. Geological Survey

Cover description. Oblique view of 2007 simulated hydraulic heads of the middle Claiborne aquifer.

The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment

By Brian R. Clark and Rheannon M. Hart

Groundwater Resources Program

Scientific Investigations Report 2009-5172

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Clark, B.R., and Hart, R.M., 2009, The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a groundwater-flow model constructed to assess water availability in the Mississippi Embayment: U.S. Geological Survey Scientific Investigations Report 2009-5172, 61 p.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (^{3}/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter pr second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L).

The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment

By Brian R. Clark and Rheannon M. Hart

Abstract

The Mississippi Embayment Regional Aquifer Study (MERAS) was conducted with support from the Groundwater Resources Program of the U.S. Geological Survey Office of Groundwater. This report documents the construction and calibration of a finite-difference groundwater model for use as a tool to quantify groundwater availability within the Mississippi embayment. To approximate the differential equation, the MERAS model was constructed with the U.S. Geological Survey's modular three-dimensional finite-difference code, MODFLOW-2005; the preconditioned conjugate gradient solver within MODFLOW-2005 was used for the numerical solution technique. The model area boundary is approximately 78,000 square miles and includes eight States with approximately 6,900 miles of simulated streams, 70,000 well locations, and 10 primary hydrogeologic units. The finite-difference grid consists of 414 rows, 397 columns, and 13 layers. Each model cell is 1 square mile with varying thickness by cell and by layer. The simulation period extends from January 1, 1870, to April 1, 2007, for a total of 137 years and 69 stress periods. The first stress period is simulated as steady state to represent predevelopment conditions.

Areal recharge is applied throughout the MERAS model area using the MODFLOW-2005 Recharge Package. Irrigation, municipal, and industrial wells are simulated using the Multi-Node Well Package. There are 43 streams simulated by the MERAS model. Each stream or river in the model area was simulated using the Streamflow-Routing Package. The perimeter of the model area and the base of the flow system are represented as no-flow boundaries. The downgradient limit of each model layer is a no-flow boundary, which approximates the extent of water with less than 10,000 milligrams per liter of dissolved solids.

The MERAS model was calibrated by making manual changes to parameter values and examining residuals for hydraulic heads and streamflow. Additional calibration was achieved through alternate use of UCODE-2005 and PEST. Simulated heads were compared to 55,786 hydraulic-head measurements from 3,245 wells in the MERAS model area. Values of root mean square error between simulated and observed hydraulic heads of all observations ranged from 8.33 feet in 1919 to 47.65 feet in 1951, though only six root mean square error values are greater than 40 feet for the entire simulation period. Simulated streamflow generally is lower than measured streamflow for streams with streamflow less than 1,000 cubic feet per second, and greater than measured streamflow for streams with streamflow more than 1,000 cubic feet per second. Simulated streamflow is underpredicted for 18 observations and overpredicted for 10 observations in the model. These differences in streamflow illustrate the large uncertainty in model inputs such as predevelopment recharge, overland flow, pumpage (from stream and aquifer), precipitation, and observation weights.

The groundwater-flow budget indicates changes in flow into (inflows) and out of (outflows) the model area during the pregroundwater-irrigation period (pre-1870) to 2007. Total flow (sum of inflows or outflows) through the model ranged from about 600 million gallons per day prior to development to 18,197 million gallons per day near the end of the simulation. The pumpage from wells represent the largest outflow components with a net rate of 18,197 million gallons per day near the end of the model simulation in 2006. Groundwater outflows are offset primarily by inflow from aquifer storage and recharge.

Introduction

Fresh groundwater in the Mississippi embayment can be found in alternating formations of sand, silt, and clay. The uppermost of these formations is the Mississippi River Valley alluvial aquifer (alluvial aquifer), which can provide well yields of 300 to 2,000 gal/min. The alluvial aquifer exists at land surface and covers much of the embayment area within the Mississippi Alluvial Plain. One of the next most widely used aquifers is the middle Claiborne aquifer, which can provide well yields of 100 to 500 gal/min (up to 1,500 gal/min in the Memphis area). The middle Claiborne aquifer, in some areas, lies several hundred feet beneath land surface. Decades of pumping from the alluvial aquifer for irrigation and from the middle Claiborne aquifer for industry and public-water supply have affected groundwater levels throughout the northern Mississippi Embayment in Arkansas, Louisiana, Mississippi, and Tennessee. Since the Gulf Coast Regional Aquifer System Analysis (GCRASA) study was completed in 1985, groundwater withdrawals have increased ranging from 37 percent at Memphis, Tennessee (17th largest city in the United States), to 132 percent in the agricultural areas of Arkansas from 1985 to 2000. Groundwater withdrawals for agriculture have caused water-level declines in the alluvial aquifer in Arkansas of at least 40 feet in 40 years (Schrader, 2001) while withdrawals from the middle Claiborne aquifer in Arkansas have resulted in declines of more than 360 feet since the 1920's (Scheiderer and Freiwald, 2006). These declines have prompted concerns over water availability and quality for agriculture and industry.

The Mississippi Embayment Regional Aquifer Study (MERAS) was conducted with support from the Groundwater Resources Program of the U.S. Geological Survey (USGS) Office of Groundwater to assess groundwater availability within the Mississippi embayment (fig. 1). The primary tool used in the assessment of groundwater availability is the MERAS groundwater-flow model.

Purpose and Scope

The purpose of this report is to document the construction and calibration of the MERAS groundwater-flow model of the Mississippi embayment. The current purpose of the model is to assist in the estimation of available groundwater in the Mississippi embayment aquifer system. The model was constructed to benefit concurrent and future investigations involving groundwater-withdrawal scenarios, optimization, particle transport, and monitoring network analysis.

Previous Investigations

Previous investigations of groundwater flow in the Mississippi embayment are numerous. Some early examples were the 1906 investigation of the underground waters of northern Louisiana (Veach, 1906) and 1928 investigation of groundwater resources of Mississippi (Stephenson and others, 1928). In the 1980's, the USGS began the GCRASA. The GCRASA compiled data and simulated groundwater flow in three main parts: the Mississippi River Valley alluvial aquifer, the Mississippi embayment aquifer system, and the gulf coastal lowland aquifer system (U.S. Geological Survey, 2008a). Other reports documenting groundwater-flow simulations within the MERAS flow system include Reed (1972), Brahana and Mesko (1988), Fitzpatrick and others (1990), Mahon and Ludwig (1990), Sumner and Wasson (1990), Mahon and Poynter (1993), Ackerman (1996), Arthur and Taylor (1998), Hays and others (1998), Arthur (2001), Brahana and Broshears (2001), McKee and Clark (2003), Stanton and Clark (2003), and Reed (2003).

Methods of Analyses

The primary method used to analyze the groundwater-flow systems is through the use of a numerical model to simulate groundwater flow. The viability of the numerical model is tested by comparing transient, simulated hydraulic-head values and streamflows from the groundwater-flow model with measurements from wells and stream gages. Details of the numerical model are listed in the next section, followed by a description of the limitations and assumptions of the model.

Numerical Model

For the MERAS model, the modular finite-difference code, USGS MODFLOW-2005 (Harbaugh, 2005), was used to approximate the solution of the equations governing three-dimensional (3D) groundwater flow. Because MODFLOW-2005 was used as the model simulation code, an additional advantage is the ability to investigate local areas within MERAS using the Local Grid Refinement package of MODFLOW-2005 (Mehl and Hill, 2007). The preconditioned conjugate gradient solver (Hill, 1990) was used for the numerical solution technique. The groundwater-flow system is represented by a set of grid cells, within which the hydraulic properties are the same. Each cell has three finite-difference equations describing the flow through it, which can be solved for either steady-state or transient conditions to simulate water-level changes within the flow system resulting from pumping stress over discrete periods of time. The model simulates 137 years (1870–2007) of system response to stress by using 69 stress periods.

Study Area Description

The model area encompasses approximately 78,000 mi^2 in an area known as the Mississippi embayment, referred to hereafter as the embayment (fig. 1). The model area boundary crosses eight States and includes approximately 6,900 mi of simulated streams, 70,000 well locations, and 10 primary hydrogeologic units. These hydrogeologic units include two primary aquifers—the Mississippi River Valley alluvial aquifer and the Middle Claiborne aquifer (Hart and others, 2008). The model area lies within parts of three physiographic sections, West Gulf Coastal Plain, East Gulf Coastal Plain, and Mississippi Alluvial Plain sections of the Coastal Plain physiographic province (fig. 1).

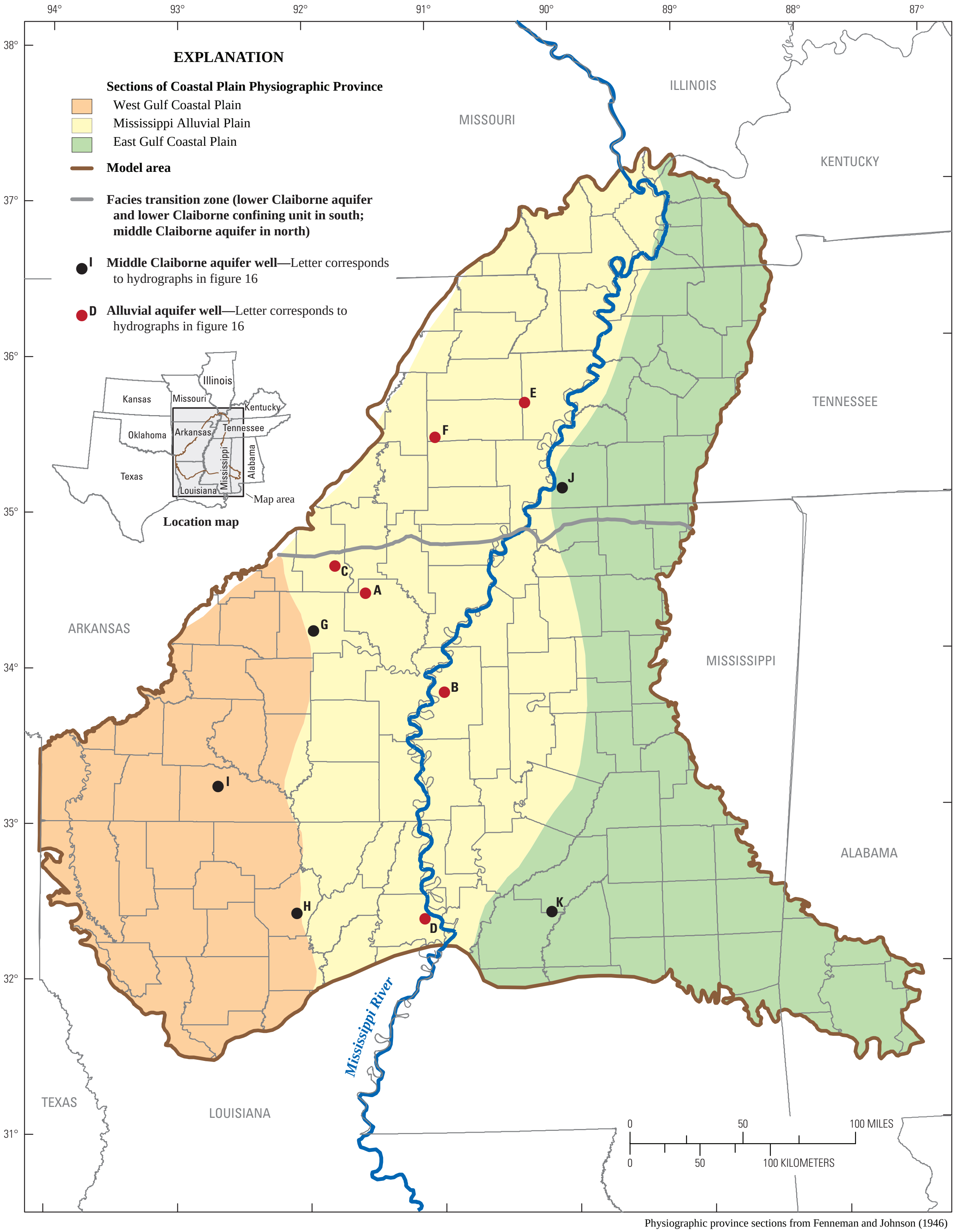


Figure 1. Location of the model area and Coastal Plain physiographic province sections.

Geologic History and Setting

The geologic history of the area began as downwarping and rifting as a result of the Ouachita orogeny occurring at the end of the Paleozoic era. Downwarping and downfaulting proceeded as a result of sediment loading during the Mesozoic era (Hosman, 1996). Many of the structural features and fault zones continued to develop into the Tertiary Period. Because of the continental extension, the embayment lies within a plunging syncline with the axis roughly paralleling the present-day Mississippi River and plunges south toward the Gulf of Mexico. Cyclic invasions by transgressing and regressing seas through the Cretaceous and Tertiary Periods created the synclinal shape resulting in older rock units cropping out on the periphery of the embayment (Arthur and Taylor, 1998). The units exposed within the model area are Cenozoic in age and consist primarily of Tertiary and Quaternary sands and gravels, silts, and clays.

Geologic Structural Features

The primary geologic structures in the model area consist of fault zones, basins, and uplifts, which were created in the late Paleozoic era and continued into the Tertiary Period. The New Madrid fault zone is located in the northern part of the model area and roughly parallels the axis of the embayment and is responsible for the downfaulting of the upper end of the syncline (Hosman, 1996). The Arkansas fault zone generally trends west-east across southern Arkansas and consists of multiple parallel normal faults and grabens (fig. 2). The Pickens-Gilbertown fault zone appears to be in alignment with the Arkansas fault zone and trends from west-central Mississippi southeastward across Mississippi and southwestern Alabama (Hosman and Weiss, 1991). There are three major structural highs within the model area. The Sabine uplift is located in eastern Texas and western Louisiana, the Monroe uplift located in southeastern Arkansas-northwestern Louisiana, and the Jackson dome in southern Mississippi. These uplifts control the alignment and position of axis of the embayment in the southern part of the model area.

Climate

The climate of the embayment is moderate with a mean annual precipitation of 48 inches in the north to 56 inches in the south. Precipitation is distributed fairly evenly throughout the year with the greatest amounts generally occurring in April and the least in October (Kleiss and others, 2000). The average temperature ranges from 58ºF in the north to 66ºF in the south (Cushing and others, 1970; National Oceanic and Atmospheric Administration, 2009). Much of the precipitation is lost through evapotranspiration and runoff to the streams in the model area (fig. 3).

Land Use

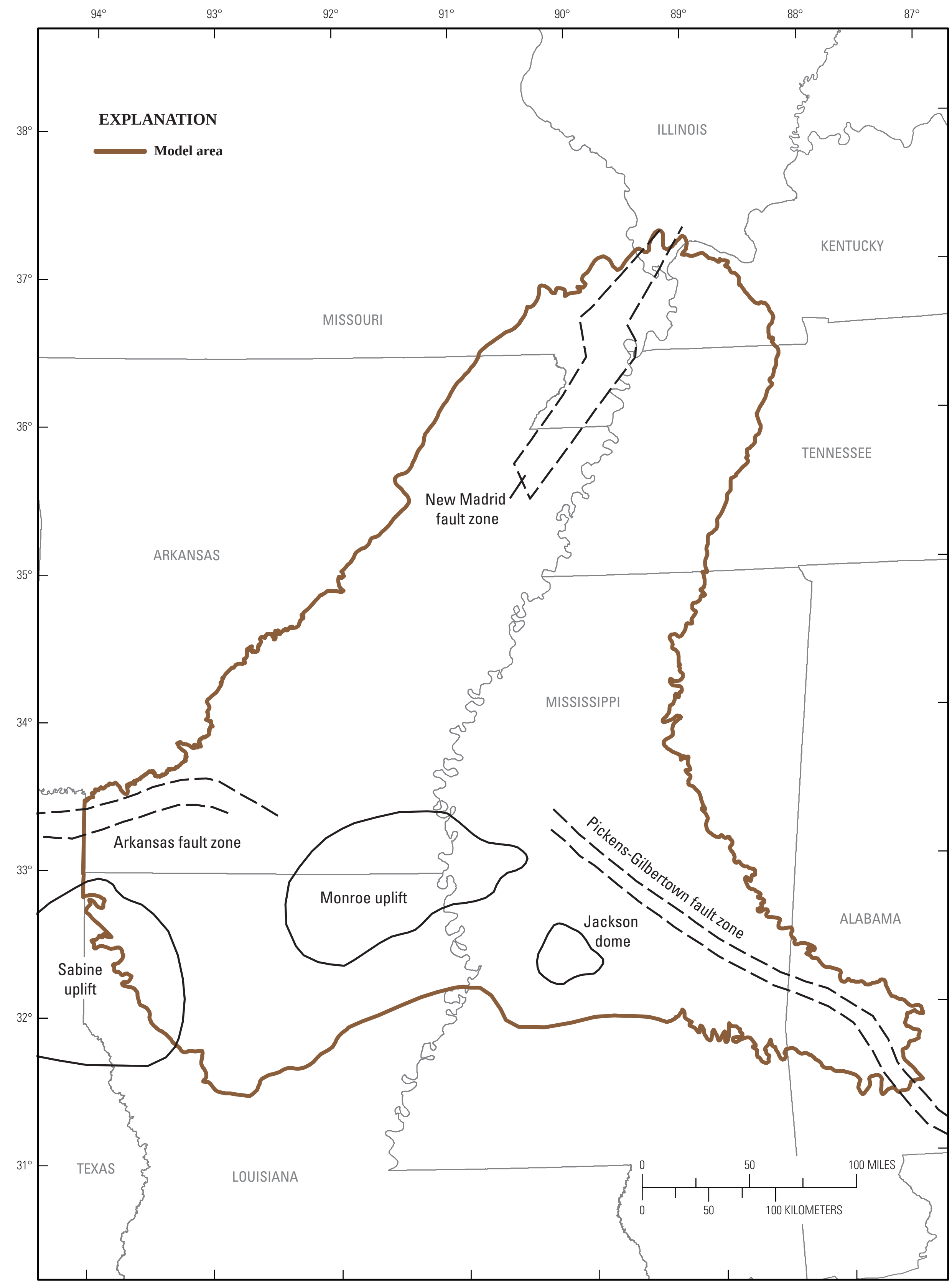
Land use in the embayment is primarily agricultural (fig. 4). Approximately 8 billion gallons per day of groundwater is pumped each year to meet irrigation requirements in Arkansas, Louisiana, and Mississippi (Hutson and others, 2004). Irrigated land accounts for approximately 45 percent of the model area, forested land is 38 percent, water and wetlands is 14 percent, and urban land is 3 percent of the total area (U.S. Geological Survey, 2008b). About 7 percent of the irrigated land is used for rice production, 22 percent for cotton, 35 percent for soybean, 5 percent for corn and wheat, 10 percent for pasture, and 2 percent for other crops or nonagricultural land (Stuart and others, 1996). The largest urban area includes the city of Memphis, Tennessee, which historically has relied heavily on groundwater pumpage to meet its municipal requirements (Parks and Lounsbury, 1976). Ninety-four percent of groundwater withdrawals in Arkansas were for irrigation, and surface irrigation is the predominant application method in Arkansas, Louisiana, Mississippi, and Missouri (Hutson and others, 2004).

Recharge

Recharge within the embayment is from infiltration of precipitation, stream losses, and infiltration of irrigation return flow. Though few (if any) studies have been conducted in the embayment to determine actual recharge rates, many model simulations have used recharge rates of 0.8 to 2.6 in/yr (Ackerman, 1996; Arthur, 2001; Mahon and Poynter, 1993; Stanton and Clark, 2003). Additional recharge may be introduced through adjacent or underlying aquifers, such as the McNairy-Nacatoch system or the Ozark aquifer system. Groundwater flow from the adjacent and underlying systems is considered negligible compared to the overall flow within the Mississippi embayment aquifer system and is ignored in this study.

Hydrogeologic Units

The major hydrogeologic units in the MERAS model include 10 units described by Hart and others (2008) (table 1). These include the Mississippi River Valley alluvial aquifer (hereafter referred to as the alluvial aquifer), the Vicksburg-Jackson confining unit, the upper Claiborne aquifer, the middle Claiborne confining unit, the middle Claiborne aquifer, the lower Claiborne confining unit, the lower Claiborne aquifer, the middle Wilcox aquifer, the lower Wilcox aquifer, and the Midway confining unit (table 1). As noted in Hart and others (2008), the lower Claiborne confining unit and the lower Claiborne aquifer undergo a facies transition and merge into the middle Claiborne aquifer in the northern part of the model area (fig. 1).



Modified from Hosman and Weiss (1991)

Figure 2. Primary geologic structural features.

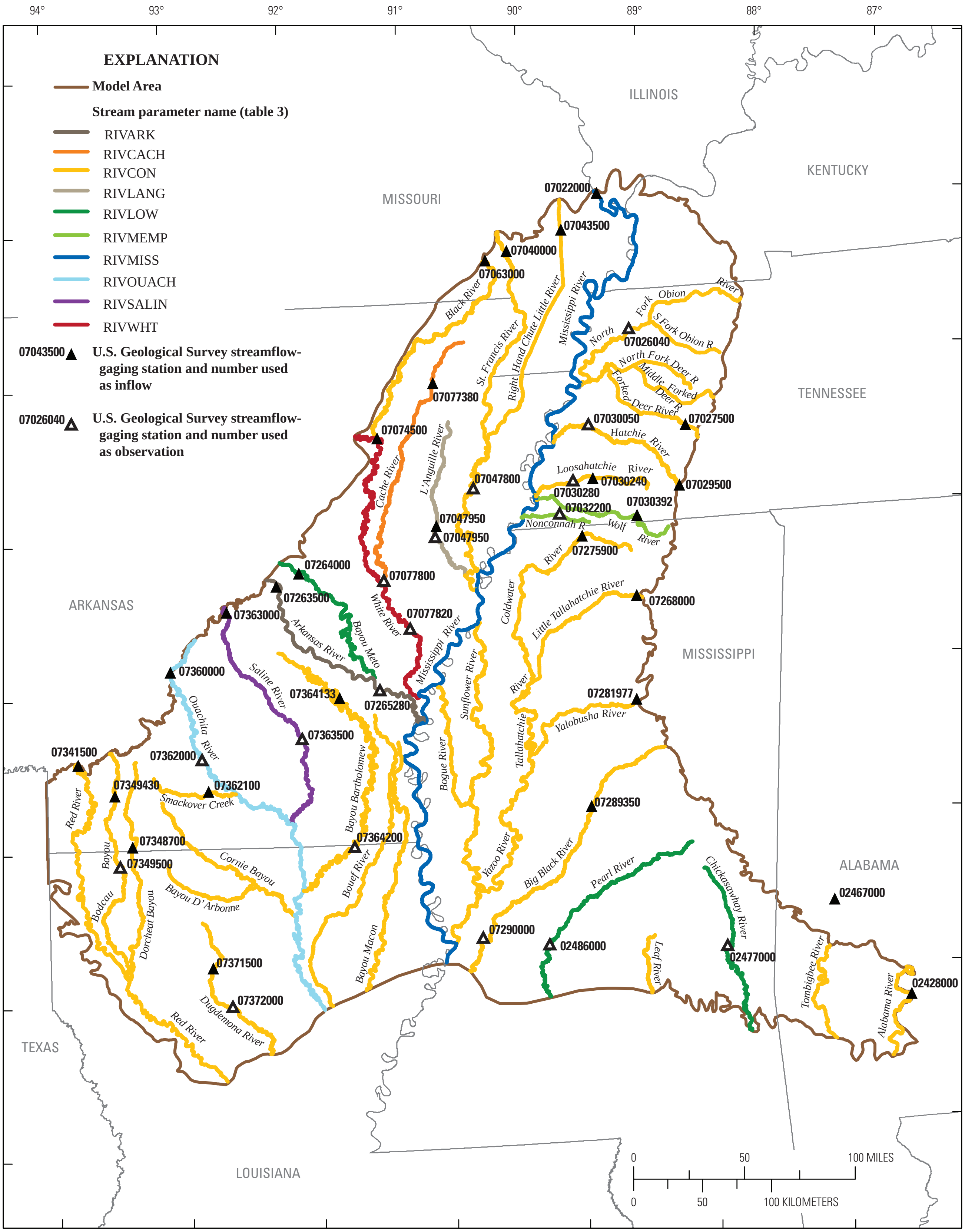


Figure 3. Streams simulated in the model area.

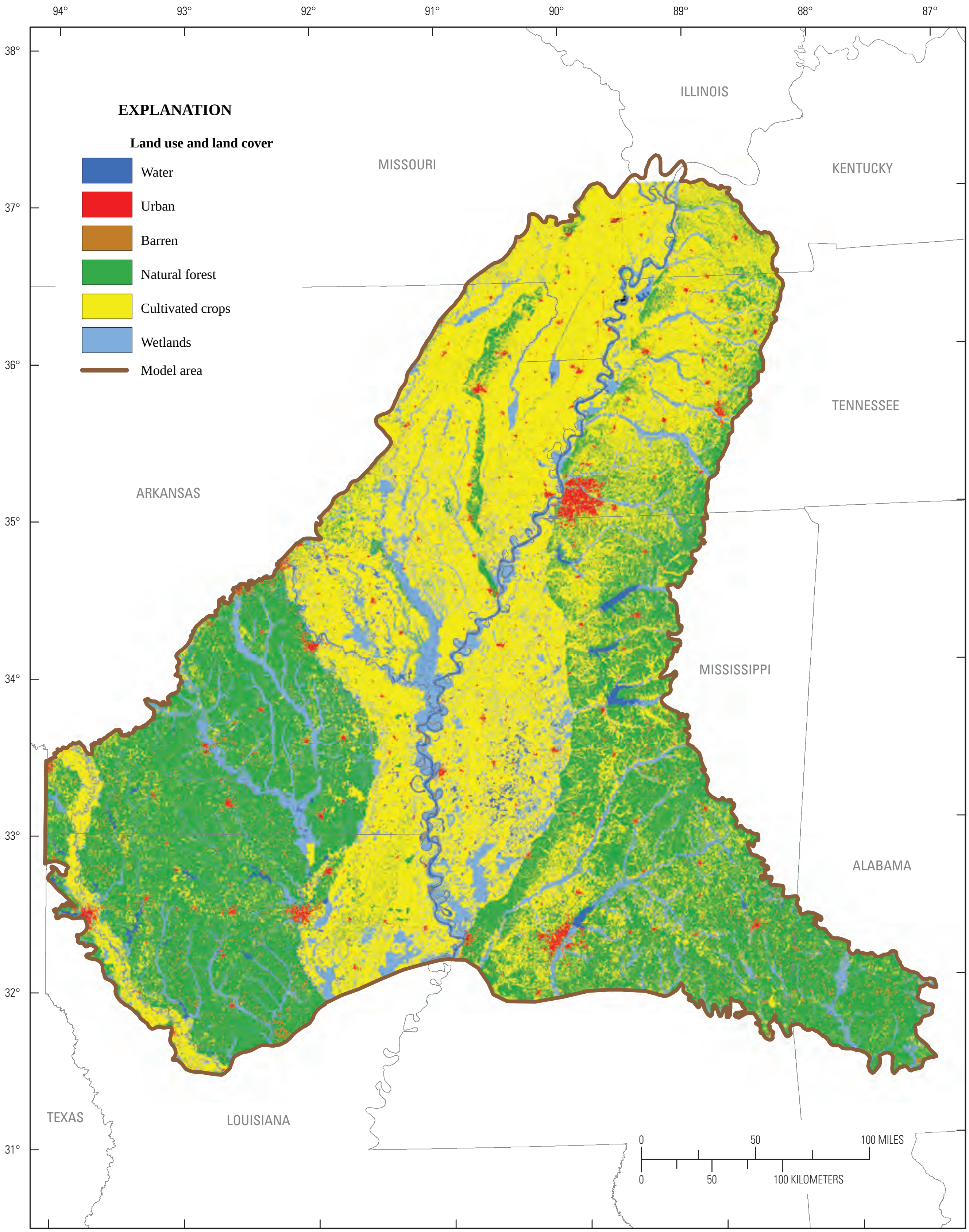


Figure 4. Typical land-use types within the Mississippi embayment.

MS SCT 002549

Table 1. Hydrogeologic and geologic units and their correlation across the States within the Mississippi Embayment Regional Aquifer Study.

ERATHEM	SYSTEM	EPOCH	GROUP	LOUISIANA	ARKANSAS Southern	ARKANSAS Northeastern	MISSOURI	KENTUCKY	TENNESSEE	MISSISSIPPI	ALABAMA	Hydrogeologic units	Model layer number
CENOZOIC	QUATERNARY	HOLOCENE / PLEISTOCENE		Alluvium and terrace deposits	Alluvium and terrace deposits	Alluvium and terrace deposits	Alluvium and terrace deposits	Alluvium and loess deposits	Alluvium and loess deposits	Alluvium, terrace, and loess deposits	Alluvium and terrace deposits	Mississippi River Valley alluvial aquifer	1
CENOZOIC	TERTIARY	OLIGOCENE	Vicksburg	Vicksburg Formation	Not present in study area	Not present in study area	Not present in study area	Not present in study area	Not present in study area	Vicksburg Formation	Vicksburg Formation	Vicksburg-Jackson confining unit	2
CENOZOIC	TERTIARY	EOCENE	Jackson	Jackson Formation	Jackson Formation	Jackson Formation	Jackson Formation	Jackson Formation	Jackson Formation	Jackson Formation	Jackson Formation	Vicksburg-Jackson confining unit	2
CENOZOIC	TERTIARY	EOCENE	Claiborne	Cockfield Formation	Cockfield Formation	Cockfield Formation	Cockfield Formation	Cockfield Formation	Cockfield Formation	Cockfield Formation	Gosport Sand	Upper Claiborne aquifer	3
CENOZOIC	TERTIARY	EOCENE	Claiborne	Cook Mountain Formation	Cook Mountain Formation	Cook Mountain Formation	Cook Mountain Formation	Cook Mountain Formation	Cook Mountain Formation	Cook Mountain Formation	Cook Mountain Formation	Middle Claiborne confining unit	4
CENOZOIC	TERTIARY	EOCENE	Claiborne	Sparta Sand	Sparta Sand	Memphis Sand	Memphis Sand	Sparta Sand	Memphis Sand	Sparta Sand	Lisbon Formation	Middle Claiborne aquifer[4]	5–7
CENOZOIC	TERTIARY	EOCENE	Claiborne	Cane River Formation	Cane River Formation	Memphis Sand	Memphis Sand	Tallahatta Formation	Memphis Sand	Zilpha Clay Winona Sand Tallahatta Formation	Tallahatta Formation	Lower Claiborne confining unit[2] / Middle Claiborne aquifer[4]	8–9
CENOZOIC	TERTIARY	EOCENE	Claiborne	Carrizo Sand	Carrizo Sand	Memphis Sand	Memphis Sand	Tallahatta Formation	Memphis Sand	Meridian Sand Member	Meridian Sand Member	Lower Claiborne aquifer[1] / Middle Claiborne aquifer[4]	10
CENOZOIC	TERTIARY	UPPER PALEOCENE	Wilcox	Dolet Hills Formation	Undifferentiated	Flour Island Formation	Flour Island Formation	Wilcox Formation	Flour Island Formation	Undifferentiated	Hatchetigbee Formation	Middle Wilcox aquifer	11
CENOZOIC	TERTIARY	UPPER PALEOCENE	Wilcox	Dolet Hills Formation	Undifferentiated	Fort Pillow Sand	Fort Pillow Sand	No Wilcox deposits identified as being of Paleocene age	Fort Pillow Sand	Undifferentiated	Bashi Formation Tuscahoma Sand / Nanafalia Formation	Lower Wilcox aquifer[3]	12–13
CENOZOIC	TERTIARY	UPPER PALEOCENE	Wilcox	Undifferentiated Naborton Formation	Undifferentiated	Old Breast-works Formation	Old Breast-works Formation	No Wilcox deposits identified as being of Paleocene age	Old Breast-works Formation	Undifferentiated	Nanafalia Formation	Lower Wilcox aquifer[3]	12–13
CENOZOIC	TERTIARY	UPPER PALEOCENE	Mid-way	Midway Group	Midway Group	Midway Group	Midway Group	Midway Group	Midway Group	Midway Group	Midway Group	Midway confining unit	Base of model

[1] Lower Claiborne aquifer includes the upper Wilcox aquifer in some parts of Mississippi.
[2] Winona-Tallahatta Formation is included with lower Claiborne confining unit in Hart and others (2008).
[3] Old Breastworks confining unit is included with middle Wilcox aquifer in Hart and others (2008).
[4] El Dorado confining unit and El Dorado Sand are included with middle Claiborne aquifer.

Modified from Hosman and Weiss, 1991

Four additional minor hydrogeologic units not described by Hart and others (2008) consist of the El Dorado confining unit, the El Dorado Sand, the Winona-Tallahatta aquifer, and the Old Breastworks confining unit, which will be more fully discussed here and shown in figures 5–7. These minor hydrogeologic units are included because of extensive use in local areas in southern Arkansas, northern Louisiana, and Mississippi. The El Dorado Sand is the lower part of the middle Claiborne aquifer in south-central Arkansas and north-central Louisiana. The El Dorado Sand is separated from the upper part of the middle Claiborne aquifer by a locally extensive confining unit termed the El Dorado confining unit in this report, which is as much as 155 ft thick (fig. 5). The Winona-Tallahatta aquifer is the lower part of the lower Claiborne confining unit throughout much of Mississippi and includes the Tallahatta Formation and the Winona Sand (fig. 6). The Tallahatta Formation consists of a greenish-gray, siliceous, sandy claystone, and the Winona Sand consists of glauconitic, fossiliferous, medium- to coarse-grained sandstone with a combined thickness up to 800 ft (Mancini and Tew, 1994; Spiers, 1977). Additionally, throughout most of Arkansas and Louisiana, the middle and lower Wilcox aquifers are undifferentiated; however, in areas of Tennessee and Mississippi, the lower Wilcox aquifer (Hart and others 2008, figs. 20 and 21) may be separated into two units, the lower Wilcox aquifer and the Old Breastworks confining unit (fig. 7). The lower Wilcox aquifer consists of the lower part of the Wilcox Formation and is the lowermost aquifer in Tertiary rocks within the Embayment (Lloyd and Lyke, 1995). This aquifer includes the Old Breastworks Formation in Missouri and Tennessee that consists of clay, silt, and lignite (Warwick and others, 1997).

Groundwater-Flow Model Construction

The following sections describe the spatial and temporal discretization, hydrologic boundaries, initial conditions, and hydraulic properties formulated for the MERAS model. In some instances, such as the temporal discretization, information from previous investigations was used as a basis (McKee and Clark, 2003; Stanton and Clark, 2003; Brahana and Broshears, 2001).

Spatial Discretization and Layering

The finite-difference grid is oriented north-south and consists of 414 rows, 397 columns, and 13 layers. Though a single model layer of the rectangular finite-difference grid contains over 164,000 cells, many cells are inactive because they fall outside of the active model area. Cells are a uniform 1 mi^2 (1 mile on a side) with varying thickness by cell and by layer. The northwestern corner of the grid is located at 37º 27' 28" north latitude and 93º 57' 19" west longitude. Vertically, the hydrogeologic units are discretized into 13 model layers (table 1). Layer 1 (fig. 8) represents primarily the alluvial aquifer where present, but also represents loess in Tennessee and Mississippi or other surficial units such as Pleistocene deposits on Crowleys Ridge or other sediments overlying the Vicksburg-Jackson confining unit in Louisiana, southern Mississippi, and Alabama. Layer 2 represents the Vicksburg-Jackson confining unit where present. Where the Vicksburg-Jackson confining unit is not present, the properties of layer 2 are modified to match that of the overlying surficial unit, such as the alluvial aquifer. The thickness of layer 2 also is modified to represent a partial thickness of the surficial unit, which in turn modifies the thickness of layer 1 to represent the remaining thickness of the surficial unit. The same technique of applying hydrologic properties and partial thickness of the surficial unit to layers that represent areas where formations pinch out or subcrop was applied to each layer below layer 1; therefore, the top layer of the model could be represented by characteristics of a single layer or combination of layers (1–13), depending on location. This was done to accommodate the requirement of continuous model layers throughout the finite-difference model grid. Layer 3 represents the upper Claiborne aquifer, where present, and the surficial unit beyond the upper Claiborne aquifer extent. Layer 4 represents the middle Claiborne confining unit where present, and the surficial unit beyond the middle Claiborne confining unit extent. The middle Claiborne aquifer begins in layer 5 and varies from 3 to 6 layers depending on spatial location. South of the facies transition zone (fig. 1), the middle Claiborne aquifer occupies layers 5 through 7, with a portion of layer 6 representing the El Dorado confining unit and layer 7 representing the El Dorado Sand. Layer 8 represents the lower Claiborne confining unit, layer 9 represents the Winona-Tallahata, and layer 10 represents the lower Claiborne aquifer. North of the transition zone, the middle Claiborne aquifer occupies layers 5 through 10. Layer 11 represents the middle Wilcox aquifer, and layer 12 represents the lower Wilcox aquifer. Layer 13 also represents the lower Wilcox aquifer or the Old Breastworks confining unit where present (fig. 8)

Temporal Discretization

The simulation period extends from January 1, 1870, to April 1, 2007, for a total of 137 years and 69 stress periods (table 2). The first stress period is simulated as steady state to represent predevelopment conditions. Stress periods 2 through 27 are variable length to reflect embayment-wide changes in groundwater withdrawals. These stress periods also mimic the temporal discretization used by McKee and Clark (2003), Stanton and Clark (2003), Reed (2003), Mahon and Poynter (1993), and Brahana and Broshears (2001). Stress periods 28 (beginning in 1986) through 69 are each 6 months in length to reflect spring–summer (April–September) and fall–winter (October–March) conditions related to irrigation.

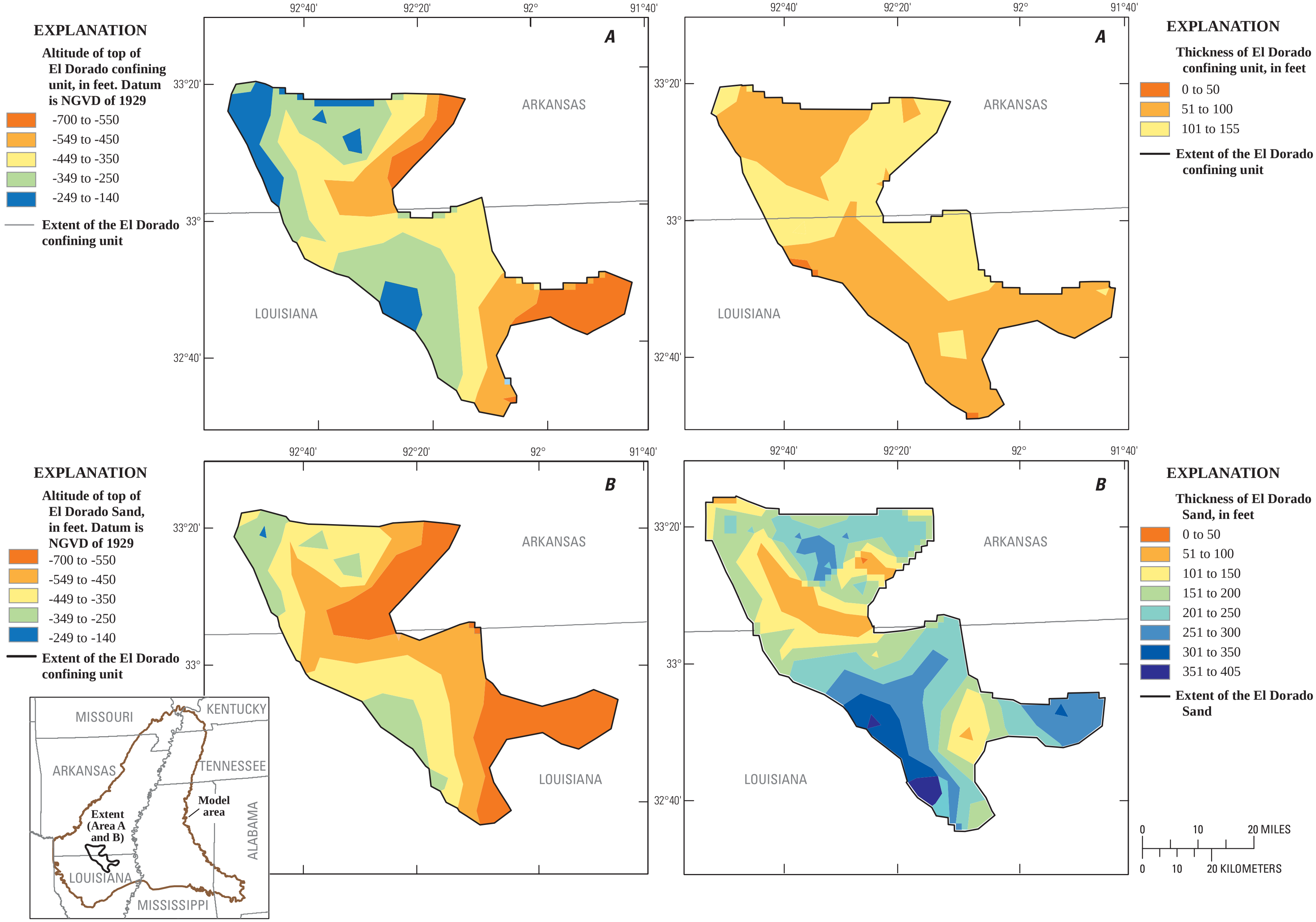


Figure 5. Top and thickness of (A) the El Dorado confining unit and (B) El Dorado Sand.

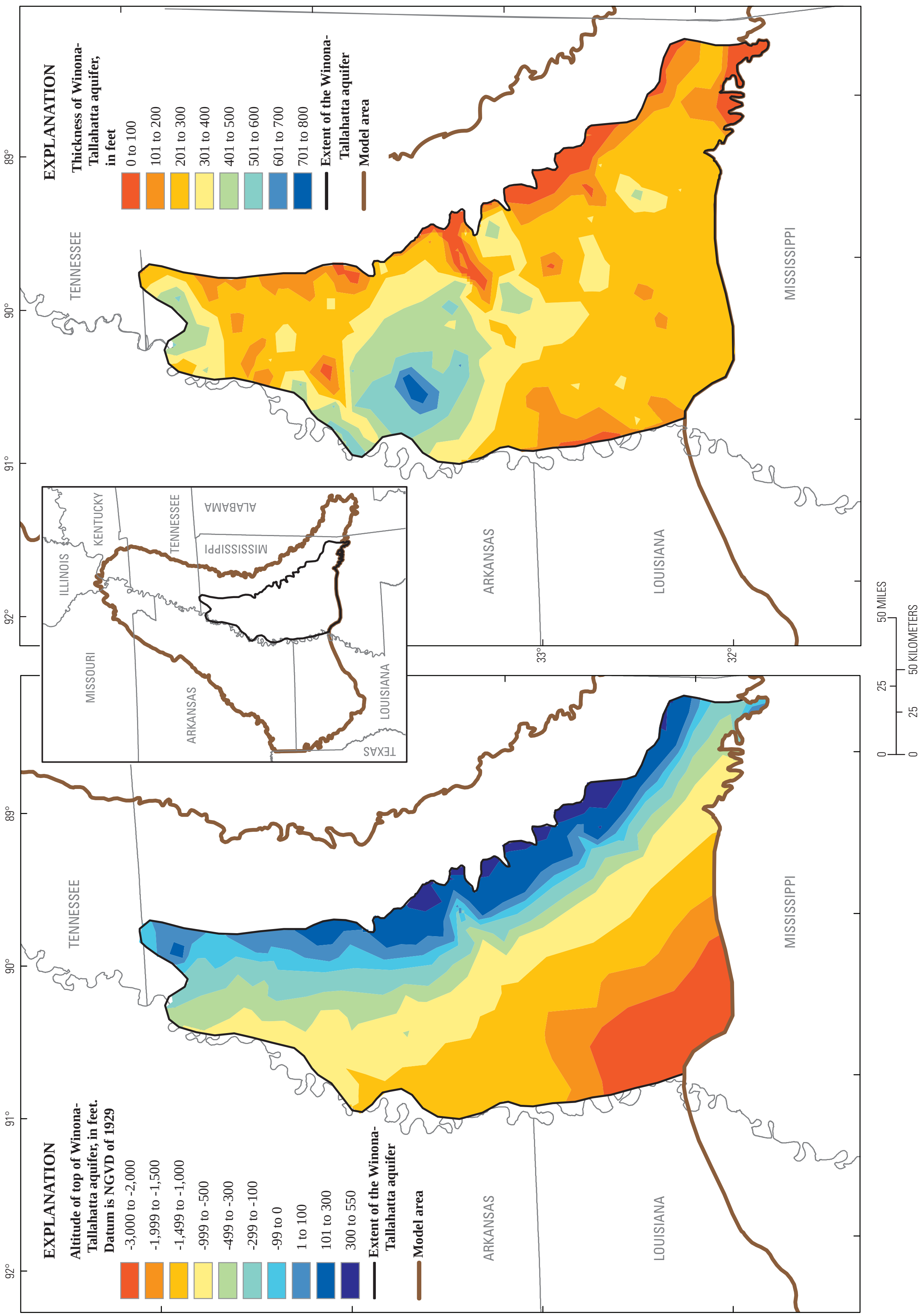


Figure 6. Top and thickness of the Winona-Tallahatta aquifer.

MS SCT 002553

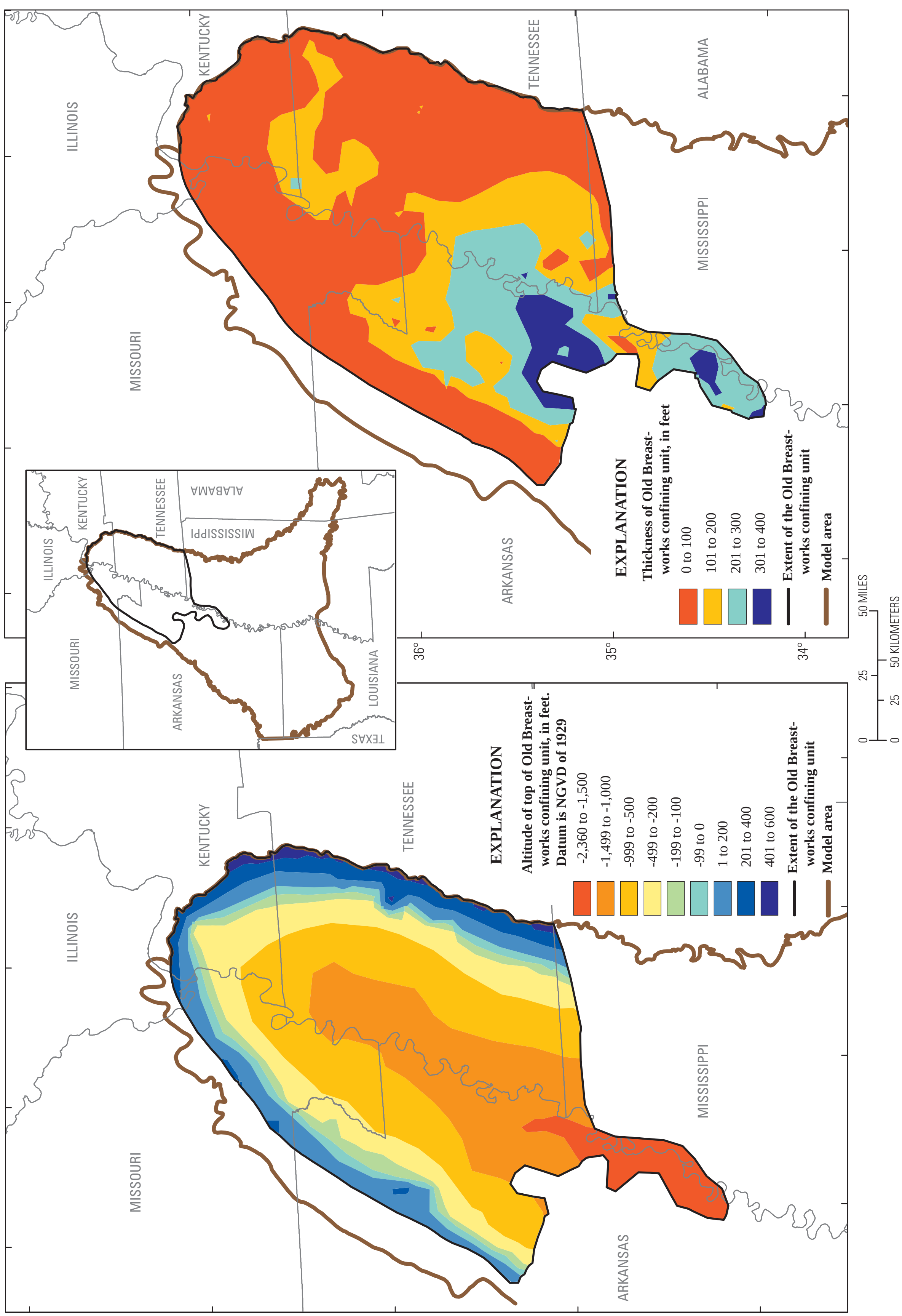


Figure 7. Top and thickness of the Old Breastworks confining unit.

MS SCT 002554

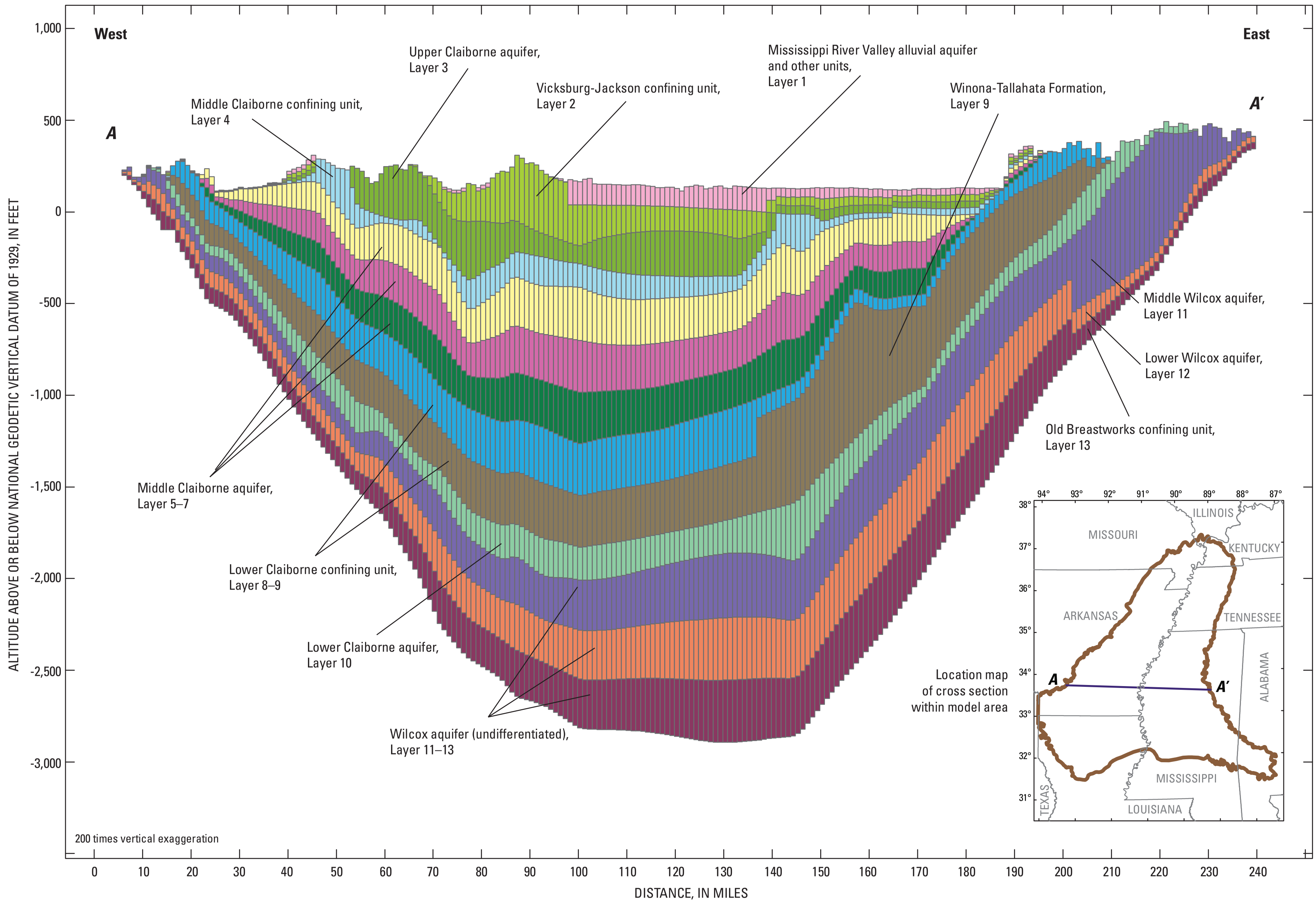


Figure 8. Cross section of model grid from west to east through row 258. Cross-section location is shown on inset map.

Table 2. Model simulation stress periods.

Beginning of stress period	Season	Stress period number	Days in stress period	Years in stress period	Cumulative year
01/01/1870	steady state	1	0	0	0
01/01/1870	multiyear	2	10,227	28.0	28.0
01/01/1898	multiyear	3	730	2.0	30.0
01/01/1900	multiyear	4	7,305	20.0	50.0
01/01/1920	multiyear	5	1,827	5.0	55.0
01/01/1925	multiyear	6	1,826	5.0	60.0
01/01/1930	full year	7	365	1.0	61.0
01/01/1931	multiyear	8	1,461	4.0	65.0
01/01/1935	multiyear	9	1,096	3.0	68.0
01/01/1938	multiyear	10	1,826	5.0	73.0
01/01/1943	full year	11	365	1.0	74.0
01/01/1944	multiyear	12	1,461	4.0	78.0
01/01/1948	multiyear	13	731	2.0	80.0
01/01/1950	multiyear	14	730	2.0	82.0
01/01/1952	multiyear	15	1,096	3.0	85.0
01/01/1955	multiyear	16	731	2.0	87.0
01/01/1957	full year	17	365	1.0	88.0
01/01/1958	multiyear	18	1,826	5.0	93.0
01/01/1963	multiyear	19	731	2.0	95.0
01/01/1965	multiyear	20	1,095	3.0	98.0
01/01/1968	multiyear	21	731	2.0	100.0
01/01/1970	full year	22	365	1.0	101.0
01/01/1971	multiyear	23	731	2.0	103.0
01/01/1973	multiyear	24	1,826	5.0	108.0
01/01/1978	multiyear	25	1,096	3.0	111.0
01/01/1981	multiyear	26	730	2.0	113.0
01/01/1983	multiyear	27	1,186	3.2	116.2
04/01/1986	spring-summer	28	183	0.5	116.7
10/01/1986	fall-winter	29	182	0.5	117.2
04/01/1987	spring-summer	30	183	0.5	117.7
10/01/1987	fall-winter	31	183	0.5	118.2
04/01/1988	spring-summer	32	183	0.5	118.7
10/01/1988	fall-winter	33	182	0.5	119.2
04/01/1989	spring-summer	34	183	0.5	119.7
10/01/1989	fall-winter	35	182	0.5	120.2
04/01/1990	spring-summer	36	183	0.5	120.7
10/01/1990	fall-winter	37	182	0.5	121.2
04/01/1991	spring-summer	38	183	0.5	121.7
10/01/1991	fall-winter	39	183	0.5	122.2
04/01/1992	spring-summer	40	183	0.5	122.7

Table 2. Model simulation stress periods.—Continued

Beginning of stress period	Season	Stress period number	Days in stress period	Years in stress period	Cumulative year
10/01/1992	fall-winter	41	182	0.5	123.2
04/01/1993	spring-summer	42	183	0.5	123.7
10/01/1993	fall-winter	43	182	0.5	124.2
04/01/1994	spring-summer	44	183	0.5	124.7
10/01/1994	fall-winter	45	182	0.5	125.2
04/01/1995	spring-summer	46	183	0.5	125.7
10/01/1995	fall-winter	47	183	0.5	126.2
04/01/1996	spring-summer	48	183	0.5	126.7
10/01/1996	fall-winter	49	182	0.5	127.2
04/01/1997	spring-summer	50	183	0.5	127.7
10/01/1997	fall-winter	51	182	0.5	128.2
04/01/1998	spring-summer	52	183	0.5	128.7
10/01/1998	fall-winter	53	182	0.5	129.2
04/01/1999	spring-summer	54	183	0.5	129.7
10/01/1999	fall-winter	55	183	0.5	130.2
04/01/2000	spring-summer	56	183	0.5	130.7
10/01/2000	fall-winter	57	182	0.5	131.2
04/01/2001	spring-summer	58	183	0.5	131.7
10/01/2001	fall-winter	59	182	0.5	132.2
04/01/2002	spring-summer	60	183	0.5	132.7
10/01/2002	fall-winter	61	182	0.5	133.2
04/01/2003	spring-summer	62	183	0.5	133.7
10/01/2003	fall-winter	63	183	0.5	134.2
04/01/2004	spring-summer	64	183	0.5	134.7
10/01/2004	fall-winter	65	182	0.5	135.2
04/01/2005	spring-summer	66	183	0.5	135.7
10/01/2005	fall-winter	67	182	0.5	136.2
04/01/2006	spring-summer	68	183	0.5	136.7
10/01/2006	fall-winter	69	182	0.5	137.2
04/01/2007	spring-summer		END DATE		

Hydrologic Boundaries

Hydrologic boundaries determine the locations and quantities of simulated flow into and out of the model; therefore, the selection of appropriate boundaries for the model is a major concern in a modeling effort. The selection of model boundaries for the aquifers in the current model is based on a conceptual interpretation of the flow system developed using information reported by Payne (1968), Hosman (1988), and Petersen and others (1985). Boundaries require the definition of model input variables, also called parameters.

Areal Recharge

Areal recharge is applied throughout the MERAS model area using the MODFLOW-2005 Recharge Package (Harbaugh, 2005). While many factors such as type and intensity of precipitation, land use, vegetation type, soil moisture, and slope determine recharge, the concept of parsimony (start simple, build complexity as needed) was used to develop a method of applying recharge in the MERAS model. This method consists of estimating recharge rates as a fraction (ranging from 1.25×10^{-4} to 7.06×10^{-2}) of precipitation based on typical literature values and soil type or geology and modified locally or regionally during calibration of the model into zones. Early attempts to use a land-use classification for recharge zones did not yield acceptable results. Therefore, 19 zones, based on soil type, geomorphology, or surficial geology, were assigned in the MERAS model (fig. 9). Alluvial recharge zones were classified based on soil type and geomorphology, and all other units' recharge zones were classified based on geology. The zone numbers on figure 9 are used for recharge distribution and hydraulic property parameters for surficial units defined later in the "Hydraulic Properties" section. Zone numbers for the alluvial aquifer are numbered 101 through 108. Recharge zone numbers of other units are generally sequential from the youngest to the oldest. Exceptions are zone number 61 for the eastern outcrop of the middle Claiborne aquifer and zone 10 representing surficial deposits other than the loess in Tennessee and Mississippi. Annual precipitation grids were downloaded from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) group for the period of 1895 to 2005 (Daly and others, 2000; PRISM Group, 2006). Annual precipitation grids were averaged together for stress periods that encompass multiple years. Precipitation amounts were divided evenly for stress periods representing 6-month periods of spring–summer and fall–winter. Each averaged or split precipitation grid then was multiplied by the recharge fraction assigned to each recharge zone. Recharge amounts to each respective recharge zone were a percentage of precipitation from the PRISM grids and, therefore, varied for each stress period. The precipitation percentage was determined from previous model simulations and adjustments were made during model calibration. While this method of recharge estimation neglects temporal increases in pumpage, the model fit described later in the "Model Fit and Model Error" section is considered reasonable given the scale and discretization of the model area, and reflects the concept of parsimony used during model construction.

Groundwater Pumpage

Pumpage from irrigation, municipal, and industrial wells is simulated using the Multi-Node Well (MNW) Package (Halford and Hanson, 2002). The MNW Package allows simulation of flow in wells that are completed in multiple aquifers or model layers. Flow through the well bore of a MNW is distributed dynamically based on transmissivity and hydraulic head differences between the respective layers. The MNW Package also allows the user to specify drawdown constraints for each well simulated. Flow into or out of the well bore can be affected by the contrast in transmissivity between the formation and the disrupted radius around the well bore, noted by a Skin coefficient. For all withdrawal wells, a final, calibrated Skin value of 4 was used, which results in a contrast of the transmissivity of the formation (T) to transmissivity of the disrupted radius (Tskin) value of 6.77 (T/Tskin). The contrast of T/Tskin allows variation in flow into and out of hydrogeologic units based on the different hydraulic properties of each unit. The final, calibrated Skin values are comparable to the values used by Clark and others (2008) and Hanson and others (2004), in which the Skin value was increased from 5 to 15 during calibration.

Pumpage from each MNW was input from site-specific data, 5-year water-use reports (Hall, 1989; Johnson, 1994; Sholar and Wood, 1995; Mooty and Richardson, 1998; Holland, 1999; Sargent, 2007), and trend analysis. Site-specific data were used to estimate the amount of pumpage per well for each aquifer to calculate a ratio of the number of wells to total pumpage. The ratio then could be used to estimate the number of wells required to pump a given amount of water. Site-specific pumpage information was averaged by stress period for each well and used as input to the model. Average annual pumpage from each aquifer and within each county contained by the model area was compiled from 5-year water-use reports generally from the period 1960–2005 or 1985–2005. For each county and aquifer, the number of wells used in a given stress period was estimated using the ratio of the number of wells to total pumpage amount. For most aquifers, the placement of wells within each county was selected from a list of known well locations in the USGS National Water Information System (NWIS) (http://waterdata.usgs.gov/nwis). The 5-year pumpage amount for each county and aquifer was distributed to the well locations for the given stress period. Thus, the number of wells increased through the simulation time as pumpage increased (fig. 10).

For wells in the middle Claiborne aquifer and the alluvial aquifer within Arkansas, the fraction of total pumpage from 2005 by county was calculated and assigned to the well. The 5-year pumpage amount then was partitioned to each well based on the pumpage fraction rather than evenly distributed to each well. This produced the desired effect of higher concentrations of pumpage in intensely agricultural or populated areas based on 2005 information, and also accounted for the jump in number of wells from stress period 17 to 18 (fig. 10). The trend analysis was based on a best fit exponential trend of water-use applications for the site-specific period of record, if available, and 5-year published data for each aquifer simulated by the model. The best fit exponential trend allows an estimation of pumpage for a given aquifer and stress period prior to 5-year water-use reporting. After the estimation of pumpage, well selection and pumpage distribution were assigned using a similar method described above for the 5-year pumpage amounts.

Streams

There are 43 streams included within the MERAS model (fig. 3). Each stream in the model area was represented using the Streamflow-Routing (SFR) package of MODFLOW (Prudic and others, 2004). The use of the SFR Package is considered an improvement over past simulations of the embayment because it "…uses the continuity equation to route surface-water flow through one or more simulated rivers, streams, canals, or ditches" (Prudic and others, 2004), rather than using a specified head boundary or river stage. The initial criterion

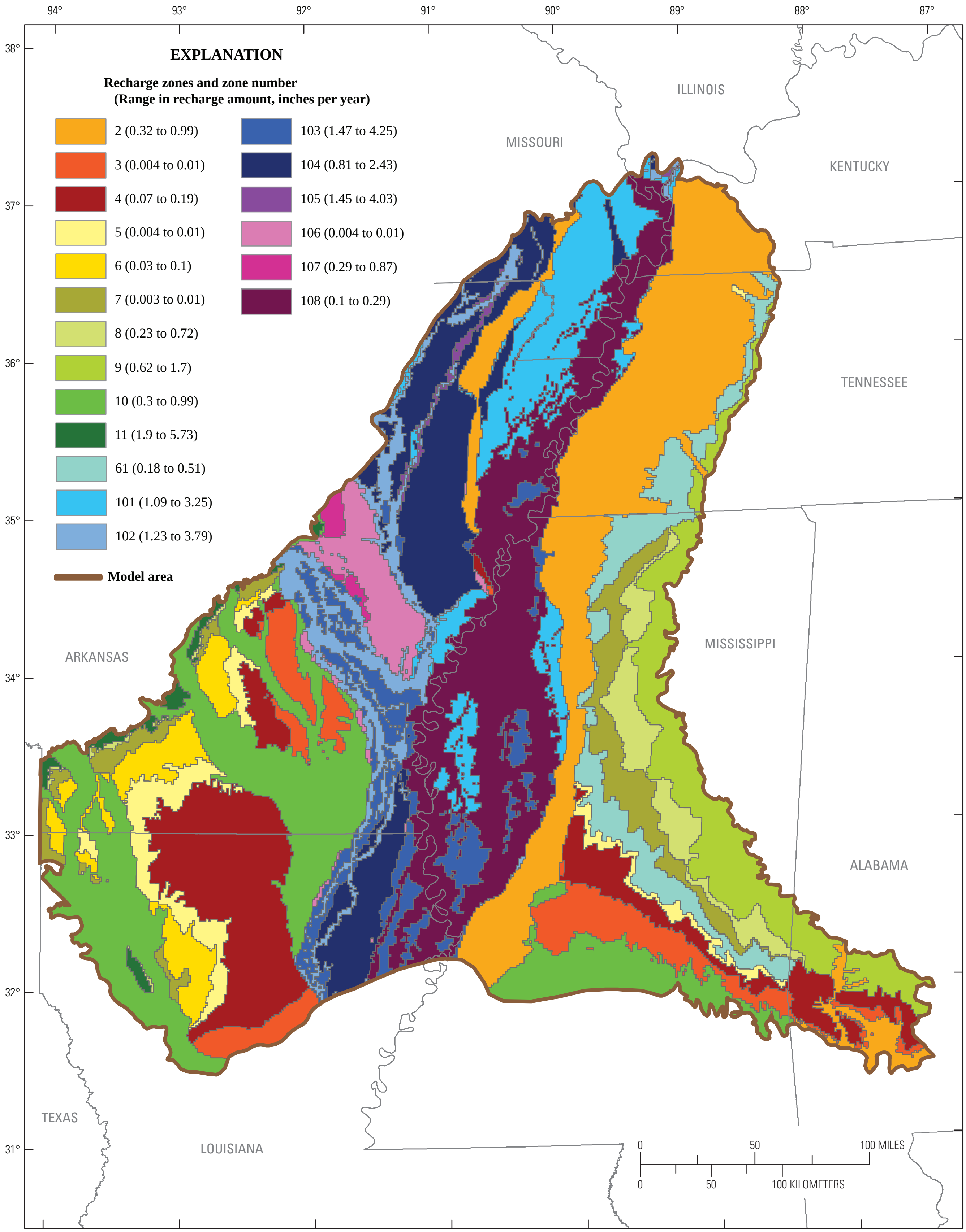


Figure 9. Zones used for both recharge and hydraulic property parameters in the model area.

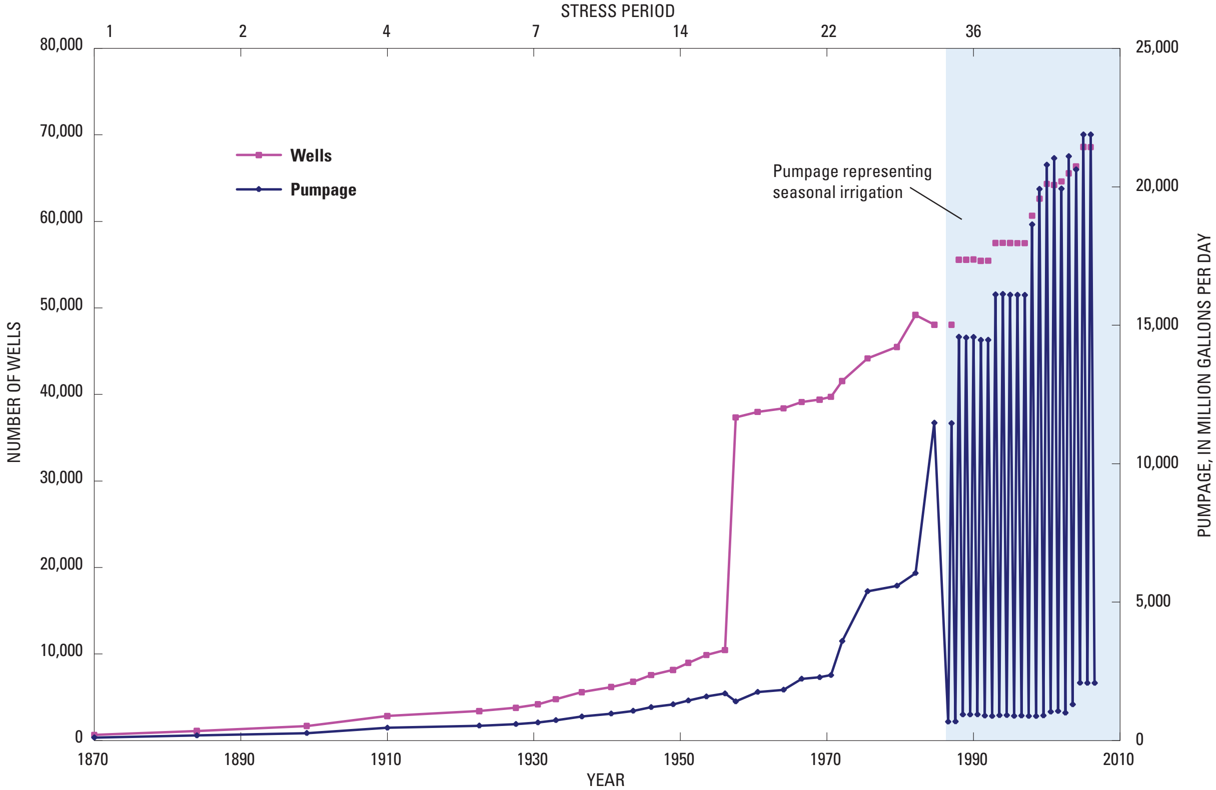


Figure 10. Number of wells and amount of pumpage in model simulation.

for the inclusion of streams in the model was a mean annual flow of 1,000 ft^3/s or more. Other streams were added based on inclusion by previous model studies that demonstrated the interaction of the streams with surficial aquifers (Reed, 2003; McKee and Clark, 2003; Stanton and Clark, 2003). Streams also were added in the Memphis, Tennessee, area where known interactions occur between the streams and the Memphis aquifer (Nyman, 1965). Streambed hydraulic conductivities were chosen as the stream parameters to be adjusted during simulations of the MERAS model. A streambed thickness of 10 ft was used, and an approximate stream width was measured from 1:24,000 topographic maps at the midpoint of the stream length for each simulated stream in the model area. The SFR package requires stream inflow at the model boundary or at the headwaters of the stream for each stress period of the simulation. Of the 43 streams simulated, 20 streams were assigned zero inflow because the headwaters started within the model area or near the model boundary; 12 streams with gages within 10 mi of the model boundary used the mean annual streamflow at the gage for model inflow (U.S. Geological Survey, 2008c); and inflows for 4 streams with gages that were further than 10 mi from the model boundary were corrected for the drainage area not gaged. For example, given a gage 15 mi upstream from the model boundary, the streamflow for the additional 15 mi of stream was calculated based on the drainage area from the model boundary to the upstream gage and the ratio of drainage area to streamflow at the gage. This streamflow then was added to the mean annual streamflow at the gage to approximate the streamflow at the model boundary.

The SFR package also allows input for overland runoff to streams. Runoff to simulated streams for each stress period was estimated from the 30-year average runoff (Williamson and others, 1990). The average runoff was divided by average precipitation for the same time period (1951-1980) to obtain a fraction for the average amount of precipitation that becomes runoff. The fraction of precipitation then could be multiplied by the precipitation for a given stress period to produce an estimate of runoff for each model cell and each stress period. The runoff estimates then were distributed to simulated streams by drainage basin.

No-Flow Boundaries

The perimeter of the model area and the base of the flow system are represented as no-flow boundaries. The perimeter of the model area represents an area where the hydrogeologic units do not exist or where flow into or out of the model area is assumed to be neglibible. The base of the flow system coincides with the top of the Midway confining unit. This unit is composed of thick marine clays; the effect of the thick marine clays allows for a small amount of flow leaking up through the Midway confining unit, which is considered to be minor compared to the volume of flow in the aquifers above it, and, therefore, chosen as the base of the model (Williamson and others, 1990). Brahana and Mesko (1988) delineated the Midway confining unit as a very low leakance unit except in the extreme northwestern part of the embayment where the Midway confining unit is absent and the alluvial aquifer directly overlies the Upper Cretaceous McNairy-Nacotoch aquifer.

Saltwater Interface

An increase in dissolved solids concentrations in milligrams per liter has been documented by Pettijohn and others (1988) in an area that extends from western Mississippi into Louisiana and Arkansas. Dissolved solids concentrations increase approximately 1,000 mg/L or more in a downdip direction over a distance of several miles (Pettijohn and others, 1988). Within the model area there are two large salt basins containing salt domes located in northern Louisiana and eastern Louisiana-central Mississippi. Salt domes have been noted to penetrate up through the base of the upper Claiborne aquifer (Beckman and Williamson, 1990). For the model simulation presented in this report, it is assumed that density of water remains constant with time. The downgradient limit of each model layer is a no-flow boundary, which approximates the extent of water with less than 10,000 mg/L dissolved solids. The downgradient limit of portions of layers 5 through 13 terminate north of the 10,000 mg/L dissolved solids line in an area that approximates the freshwater boundary delineated by Payne (1968). The assumption of a no-flow boundary at the freshwater-saltwater interface and constant density of water may not be entirely valid, but may be justified because most pumpage in each layer tends to be upgradient from the interface.

Initial Conditions

There are no known predevelopment potentiometric surfaces for the portion of the alluvial aquifer simulated by the MERAS model. Williams and Williamson (1989) calculated an average depth to water of 25.7 ft using the first nonpumping, pre-1960 hydraulic-head value in 6,825 wells less than 150 ft deep. Before the development of the groundwater resource in the early 1900s, hydraulic head in the alluvial aquifer is presumed to generally follow land surface and slope toward major rivers (Ackerman, 1989). Predevelopment potentiometric surfaces for the middle Claiborne aquifer also are scarce. Reed (1972) presents a potentiometric surface of the middle Claiborne for 1886 “based on measurements made prior to extensive development.”

Initial conditions are simulated using a steady-state stress period (representing conditions prior to January 1, 1870) at the beginning of the simulation. Stream inflows for this steady-state stress period were the mean annual flow average of the first 10 years of available flow data for each stream. While the potential exists that the first 10 years of available flow data could be affected by human actions, in many cases, data for streamflow began prior to the 1950’s. The average of the first 10 years of streamflow is thought to approximate early streamflow conditions in a way that is acceptable to create initial conditions from which to base the transient simulation. Recharge for the first stress period is the same as that used in the second stress period. There is no groundwater pumpage specified in the first stress period because it is designed to represent predevelopment conditions before pumping began.

Hydraulic Properties

In many groundwater-flow models, grid cells assumed to have similar hydraulic properties are grouped together as a zone and assigned a parameter value that can be adjusted during the calibration process (Hill and others, 2000). The MERAS model uses a total of 104 hydraulic parameters (table 3). These parameters include hydraulic properties of horizontal hydraulic conductivity, specific yield, specific storage, and vertical anisotropy. Parameter values of the aquifers and confining units also are affected by the amount (percent) of coarse (sand) or fine (clay) material within the unit. A discussion of the method used to assign the percent of sand within each unit is presented in the “Sand Percentage” section. In addition, selected faults present in some areas (Arkansas fault zone, Pickens-Gilbertown fault zone, fig. 2) are represented in the model, and the properties associated with faults were specified.

Hydraulic Conductivity

Horizontal hydraulic-conductivity parameters generally consist of a single zone for each aquifer and confining unit. The exceptions are the alluvial aquifer (or equivalent surficial unit), middle Claiborne confining unit, middle Claiborne aquifer, and Wilcox Group. Zone numbers generally coincide with model layers in multiples of 10. For example, layer 2 is 20, layer 3 is 30, layer 4 is 40, and so on. Using this design, 10 zone numbers per layer are available for use to define different areas within each layer. For example, there are four zones within layer 5; 50, 51, 52, and 53. Zone numbers may extend through multiple layers once they are defined for a hydrogeologic unit. Zone numbers for the alluvial aquifer are the same values used for recharge zones of the alluvial aquifer (fig. 9). Parameter zones for the alluvial aquifer are based on grouped classifications of geomorphology (Saucier, 1994) to create eight zones (zone 101 to 108, fig. 9). Equivalent surficial units are represented by two additional zones: one zone for the surficial unit covering Crowleys Ridge and loess in Tennessee and Mississippi or other equivalent units in the eastern half of the model area (zone 2, fig. 9), and one zone for other Quaternary age deposits in southeastern Arkansas (zone 10, fig. 9). There are three parameter zones to represent the middle Claiborne confining unit: one zone represents the majority of the confining unit (zone 40, fig. 11), a second zone represents areas where the middle Claiborne confining unit is absent in western Tennessee (Parks, 1990) (zone 30, fig. 11), and a third

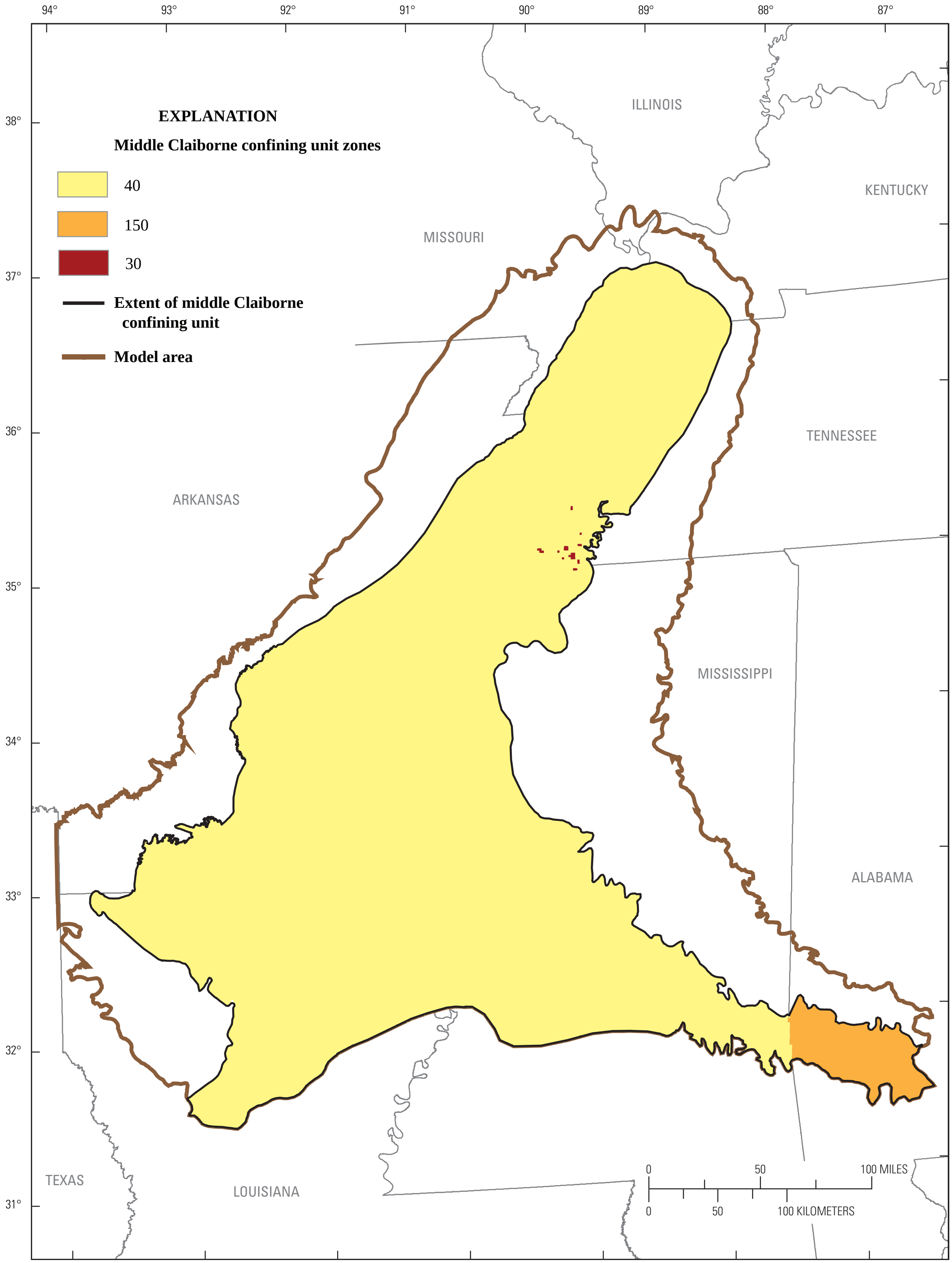


Figure 11. Parameter zones of the middle Claiborne confining unit.

zone represents the undifferentiated Claiborne Group in Alabama (zone 150, fig. 11). Zone 150 defines an area in Alabama that represents the undifferentiated Claiborne Group, which includes the upper Claiborne aquifer, middle Claiborne confining unit, middle Claiborne aquifer, lower Claiborne confining unit, and the lower Claiborne aquifer. Seven parameter zones define the properties of the middle Claiborne aquifer (fig. 12). Four zones, 50 through 53, were delineated based on hydraulic conductivity values estimated by Prudic (1991) and modified during the calibration procedure. Two zones, 60 and 70 (same area, different layers), were delineated based on a locally extensive clay layer within the middle Claiborne aquifer. Zone 60, which occurs only in layer 6, represents the finer material that confines the lower portion of the middle Claiborne aquifer (El Dorado confining unit). Zone 70, which occurs only in layer 7, represents the coarser material in the lower portion of the Middle Claiborne aquifer (El Dorado Sand), from which most wells are screened for municipal and industrial use. Four parameter zones define the properties of the Wilcox Group (fig. 13, 7). Zone 110 occurs in layer 11, 12, and 13 in areas where the Wilcox Group is undiffierentated. Zone 111 represents the middle Wilcox aquifer in layer 11, and zone 120 represents the lower Wilcox aquifer in layer 12. Zone 130 represents the Old Breastworks Formation in the northern part of the embayment as shown in figure 7 as the extent of the Old Breastworks confining unit.

Vertical Anisotropy and Storage

Zones used for vertical anisotropy, specific yield, and specific storage were identical to those used for horizontal hydraulic conductivity. Initial estimates of vertical anisotropy, specific yield, and specific storage were based on literature values (Fetter, 1994; Freeze and Cherry, 1979) and were adjusted during model calibration.

Sand Percentage

An analysis of sand percentage for each formation was conducted through the use of geophysical logs (Hart and others, 2008; Hart and Clark, 2008b). Sand percentage grids, created using automated interpolation methods, then were used as a multiplier array on model parameters, such as hydraulic conductivity, for select aquifers or confining units in the MERAS model.

Normal-resistivity and natural gamma logs for the sand percentage analysis were selected to maximize spatial distribution. A 25-percent subset of approximately 2,700 geophysical logs was digitized and exported to Log ASCII Standard (LAS) format. The short normal resistivity curve was digitized and the LAS data for each geophysical log were queried to determine percent coarse material and thickness of the coarse material for each hydrogeologic unit. Distinction between coarse and fine material for each individual geophysical log was determined by using 20 percent of the maximum resistivity as the division between coarse and fine material. Materials with resistivities greater than 20 percent of the maximum resistivities were considered coarse materials (sand) and materials with resistivities less than 20 percent of the maximum resistivities were considered fine materials (clay).

Sand thickness was calculated by summing the intervals of material with resistivity greater than 20 percent of the maximum resistivity. Sand percentage was determined by dividing sand thickness by total hydrogeologic unit thickness and multiplying by 100 for grid cells equal in size and shape of each model cell (fig. 14). Total thickness for each hydrogeologic unit was determined from Hart and Clark (2008a) to obtain the tops and bottoms of each unit from each geophysical log. The units selected for use with sand percentage grids were the alluvial aquifer (fig. 14 A), Vicksburg-Jackson confining unit (fig. 14 B), upper Claiborne aquifer (fig. 14 C), middle Claiborne confining unit (fig. 14 D), middle Claiborne aquifer (fig. 14 E-J), lower Claiborne confining unit (fig. 14 K), portions of the middle Wilcox aquifer (fig. 14 L), and portions of the lower Wilcox aquifer (fig. 14 M). The middle Claiborne aquifer is represented by three model layers south of the facies transition zone (fig. 1) and six model layers north of the transition zone. To accommodate multilayering of the middle Claiborne aquifer, sand percentage grids also were divided vertically into three to six layers depending on location. In general, sand percentages of each unit are higher in the north and east, and lower in the south and west, which correspond to the conceptual depositional environment of shallow, high energy environment in the north, and deep, low energy environment in the south.

Faults

The existence of faults in the model area is supported by multiple studies (Hosman, 1982; Petersen and others, 1985; Albin 1964, Kingsbury and Parks, 1993). McKee and Clark (2003) included inferred faults to improve hydraulic-head value matching in simulations of flow within the middle Claiborne aquifer.

Seven faults were represented in the model using the Horizontal Flow Barrier (HFB) package that allows a reduction in horizontal hydraulic conductivity between adjacent cells (fig. 12). All simulated faults extend from layer 5 (Tertiary age middle Claiborne aquifer) to the base of the model domain. For simplification, the width of the horizontal flow barrier is assumed to be 1.0 ft.

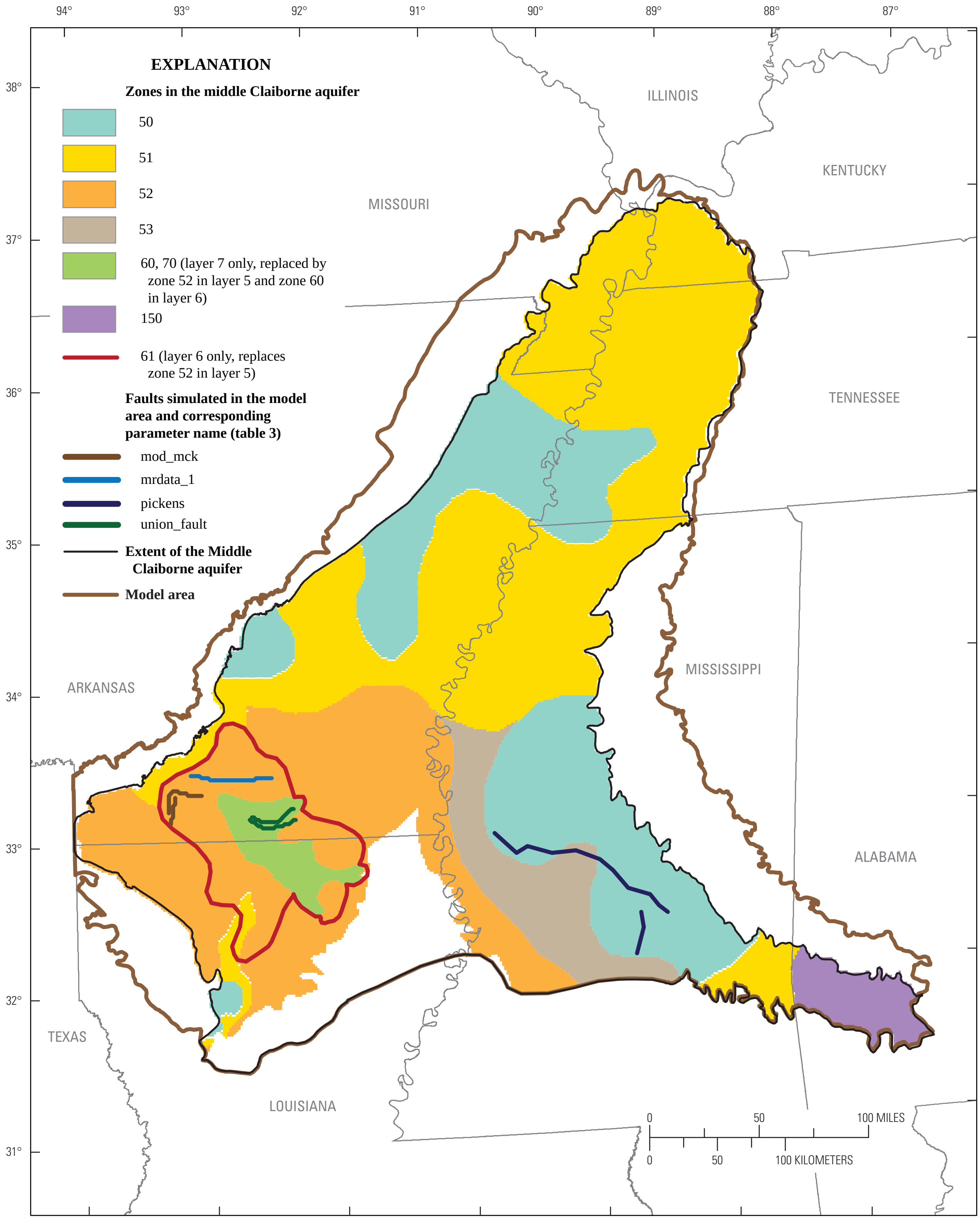


Figure 12. Parameter zones of the middle Claiborne aquifer and the location of faults simulated.

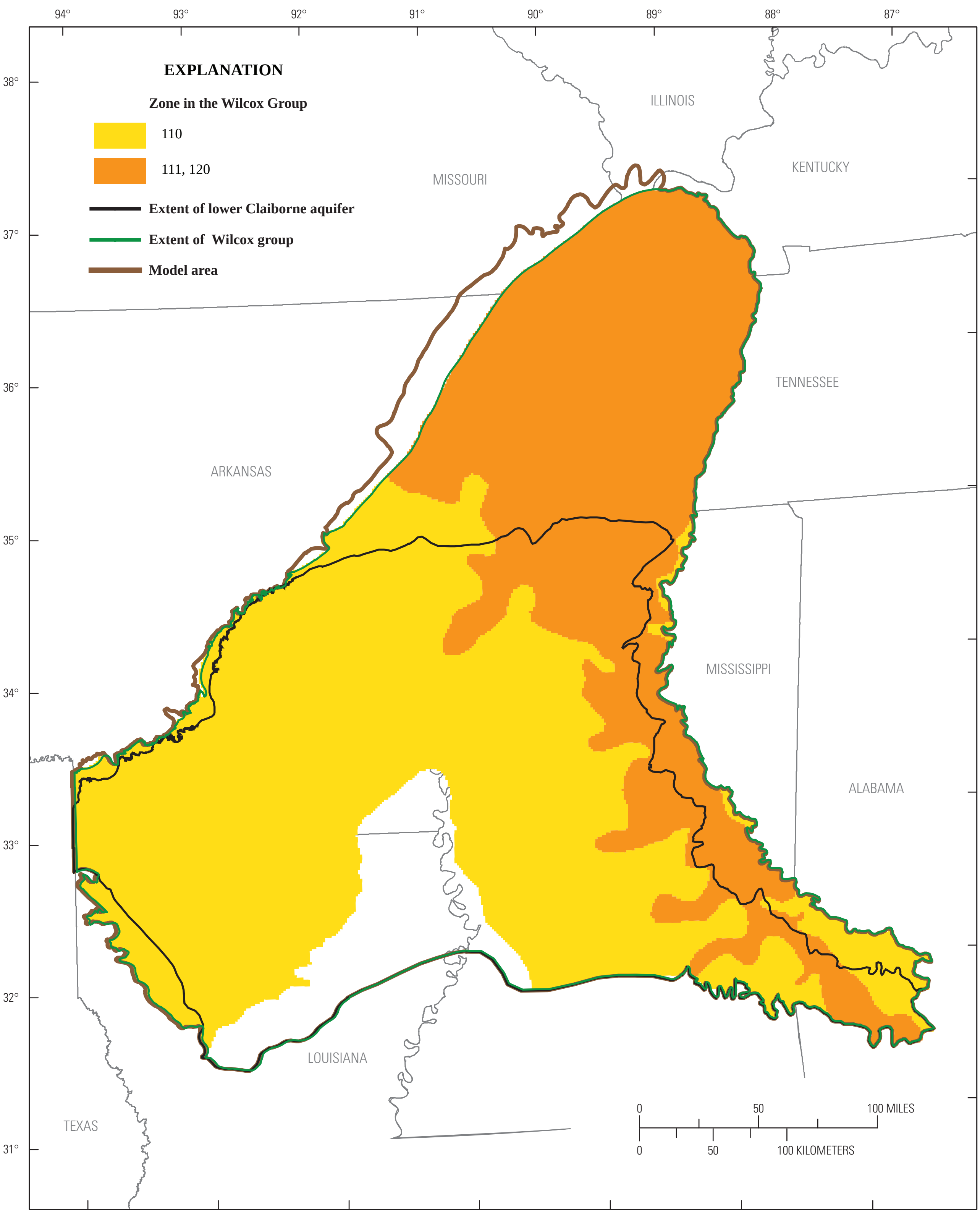


Figure 13. Parameter zones of the Wilcox Group and extent of the lower Claiborne aquifer.

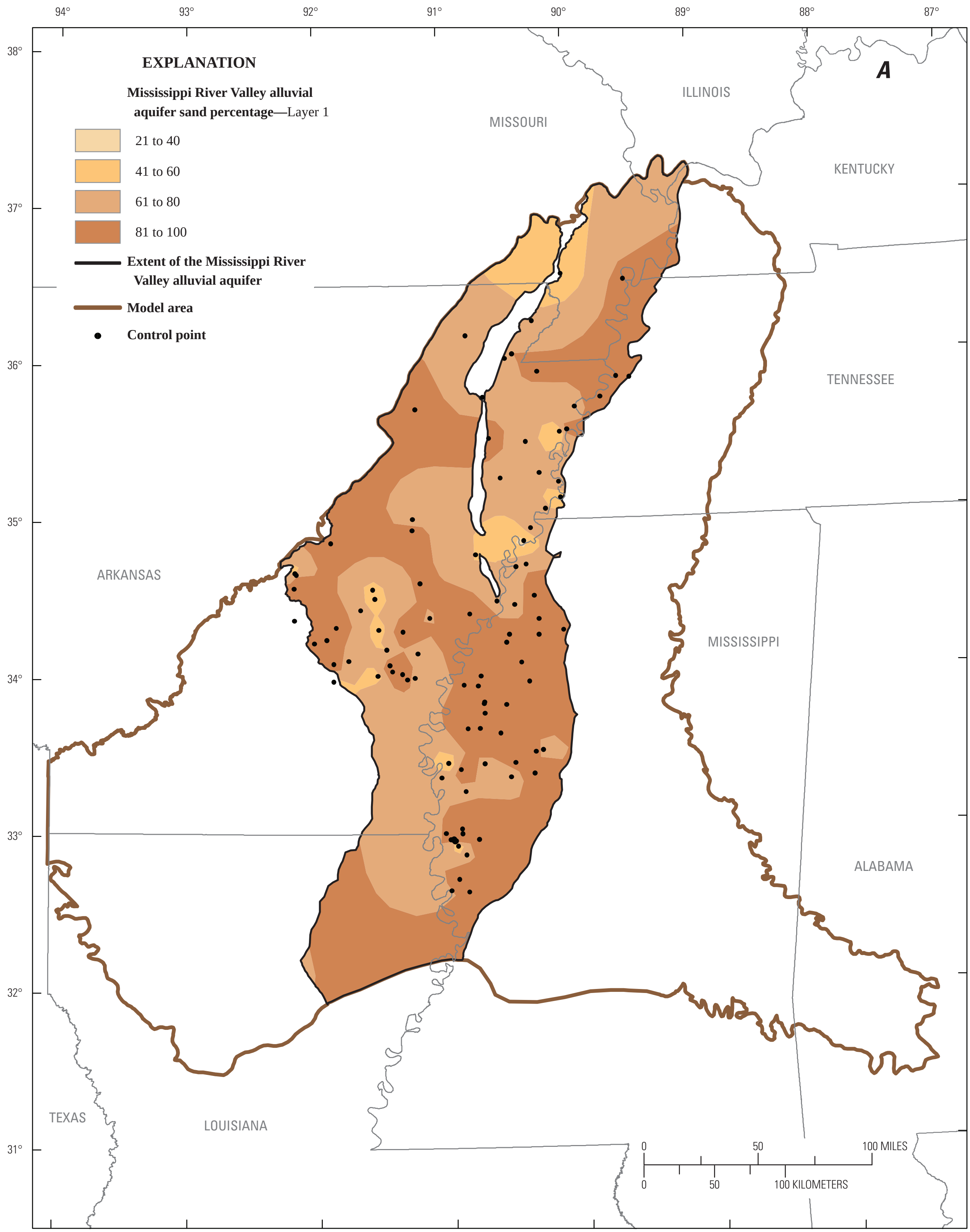


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.

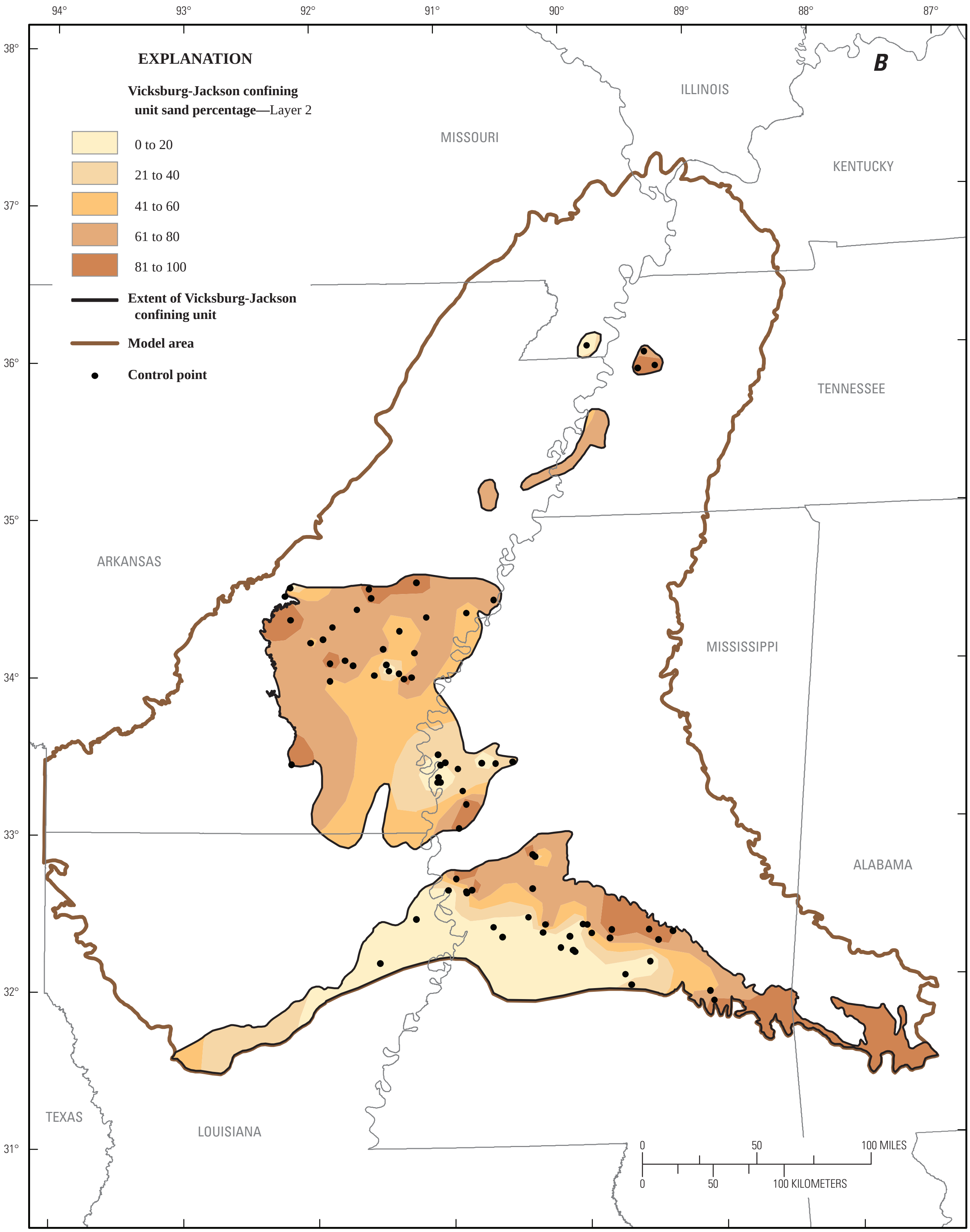


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

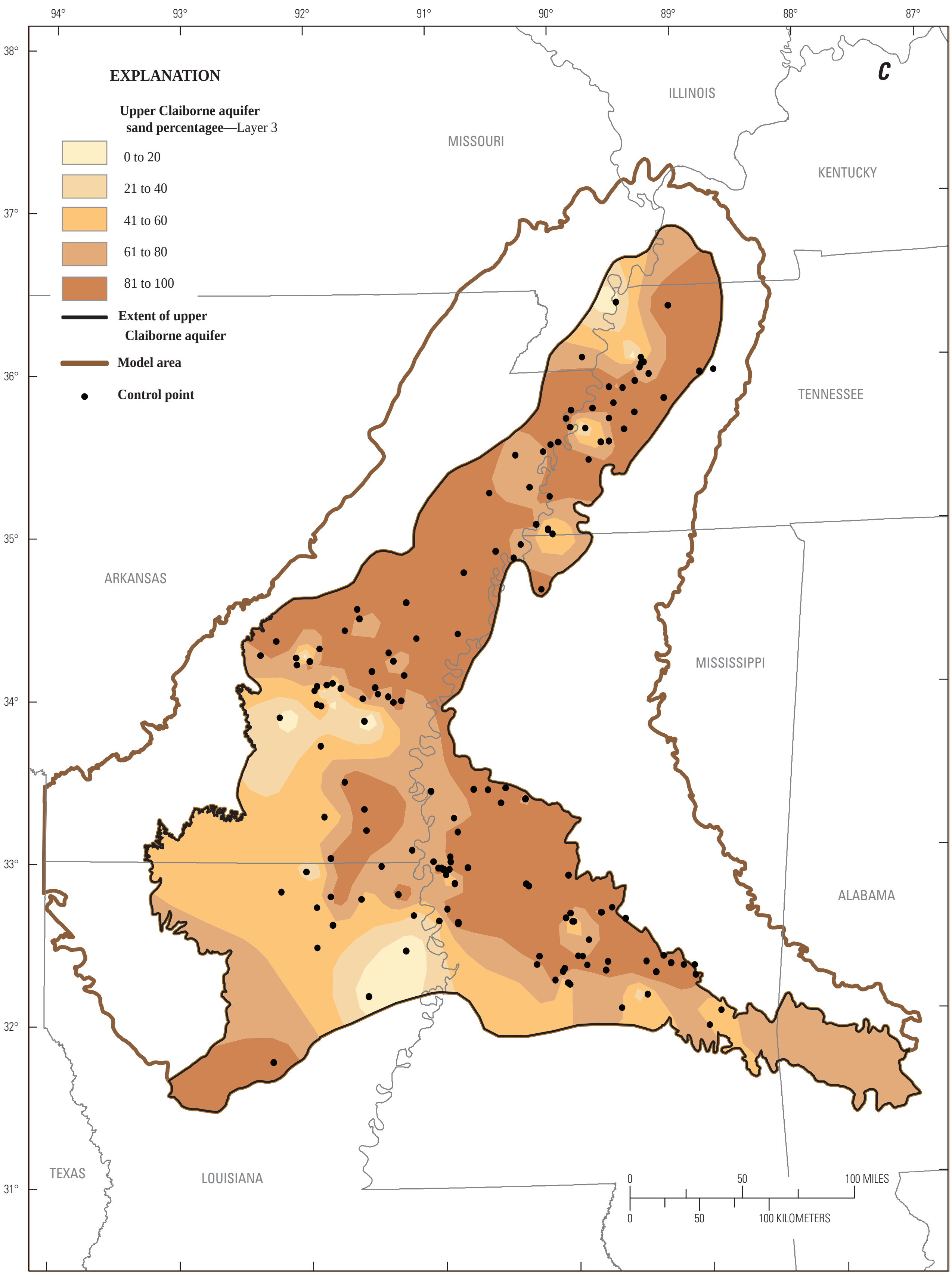


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

MS SCT 002568

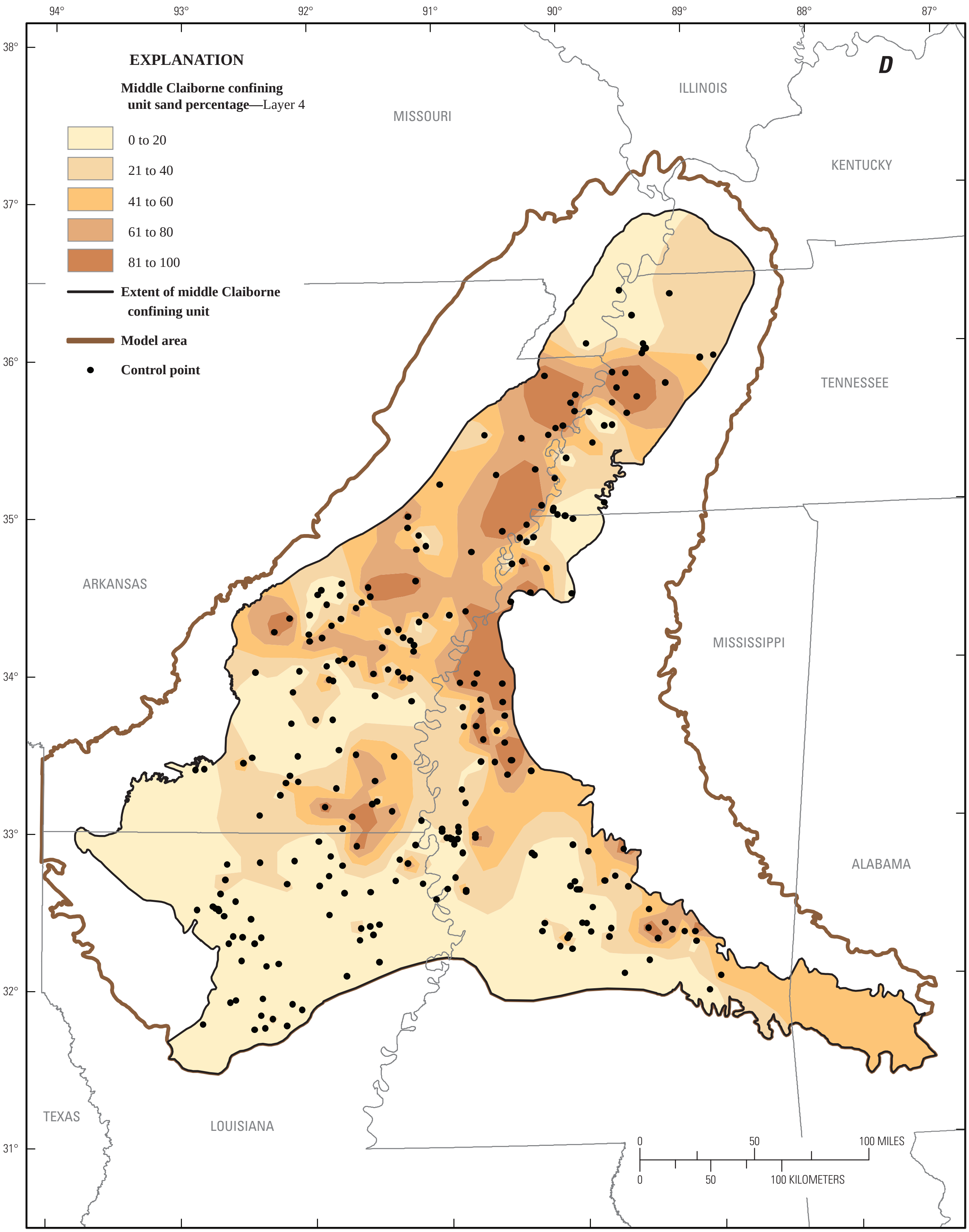


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

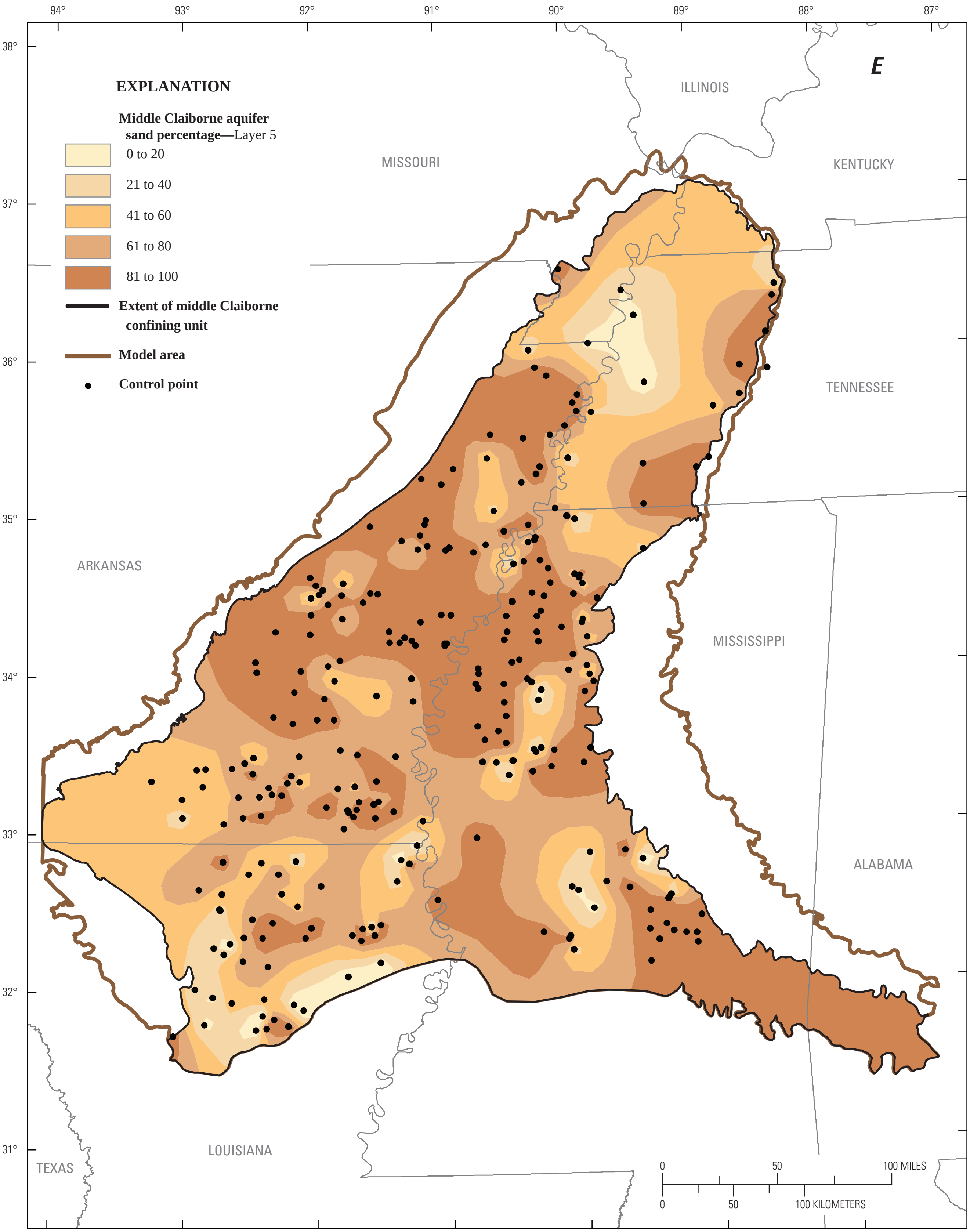


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

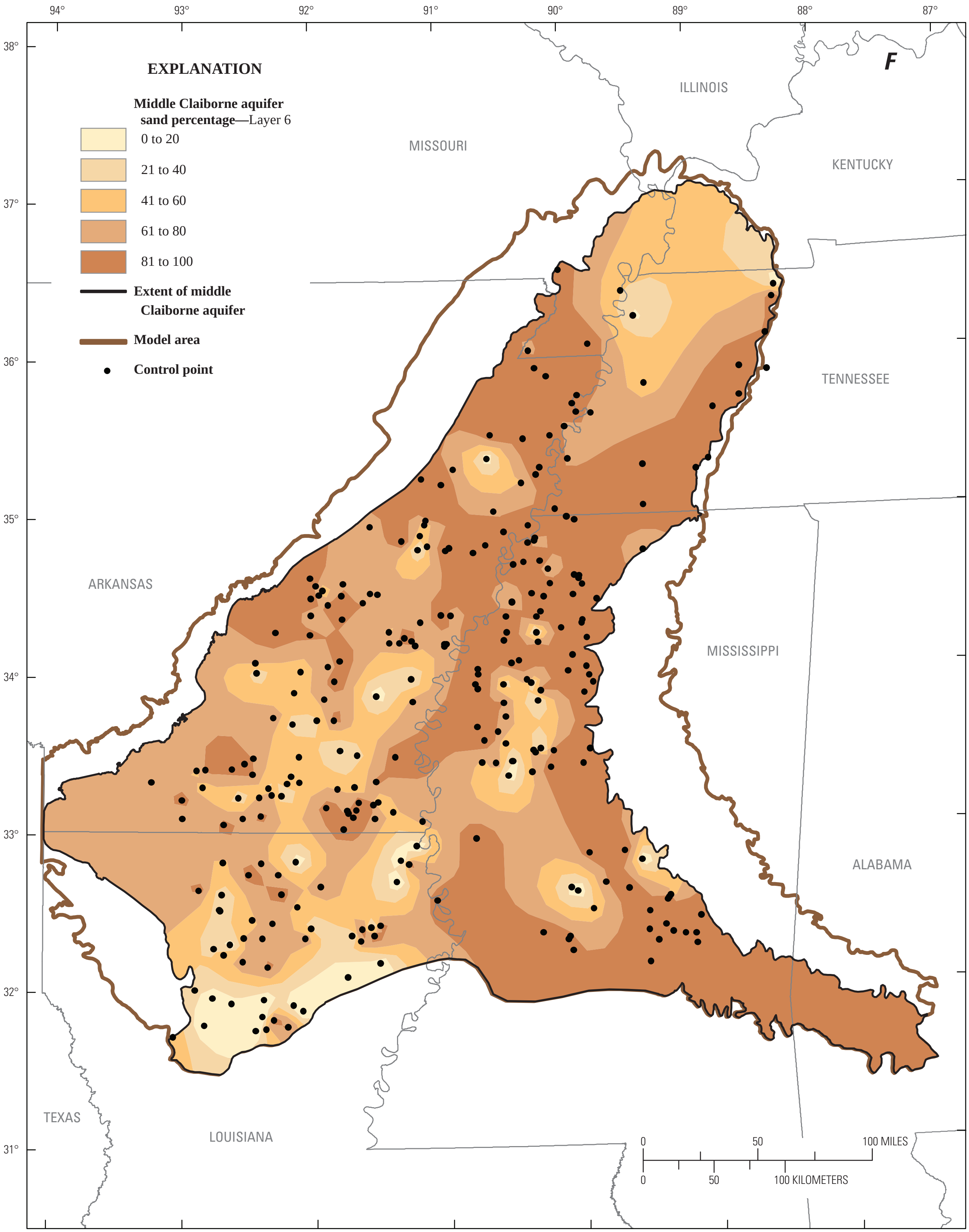


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

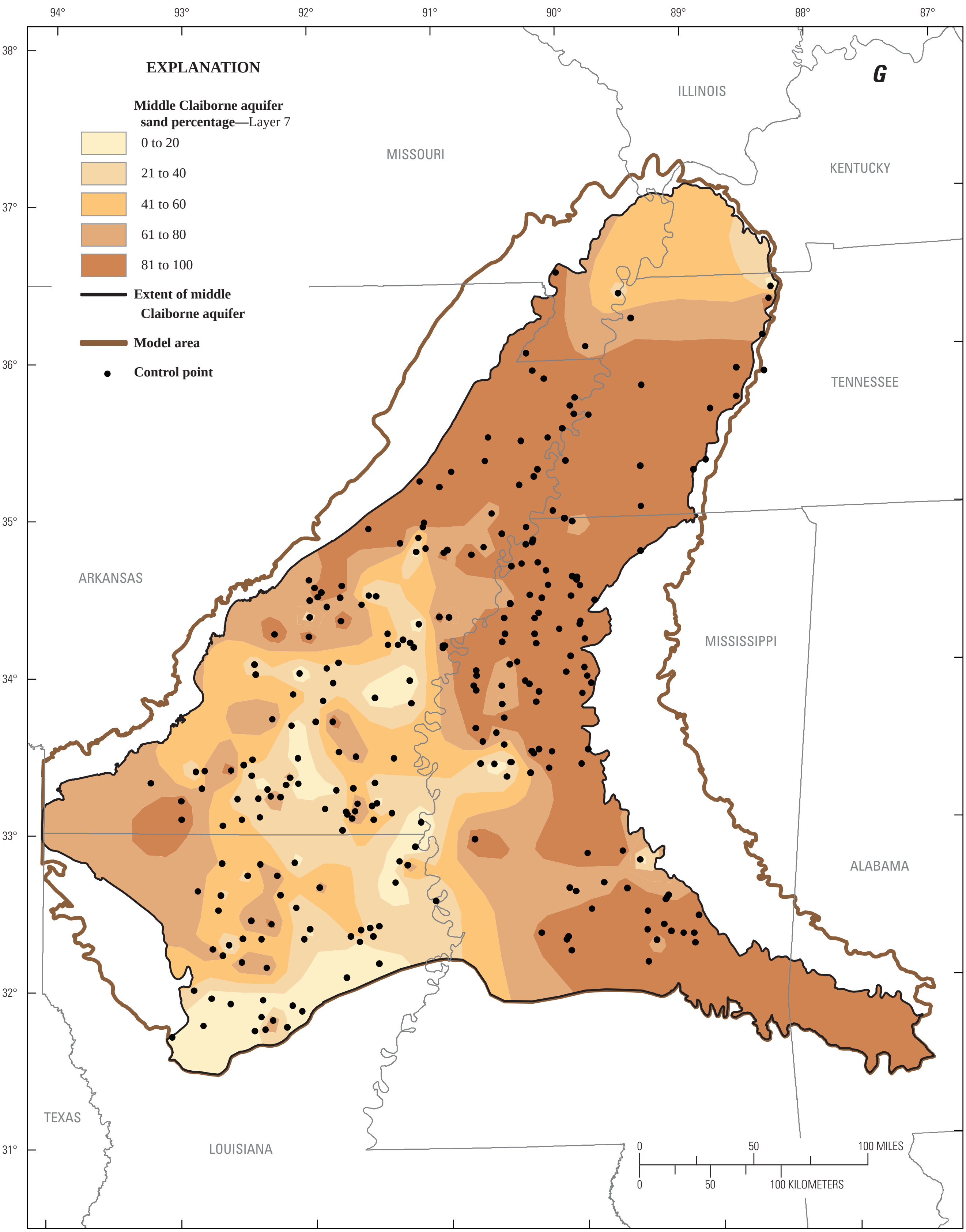


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

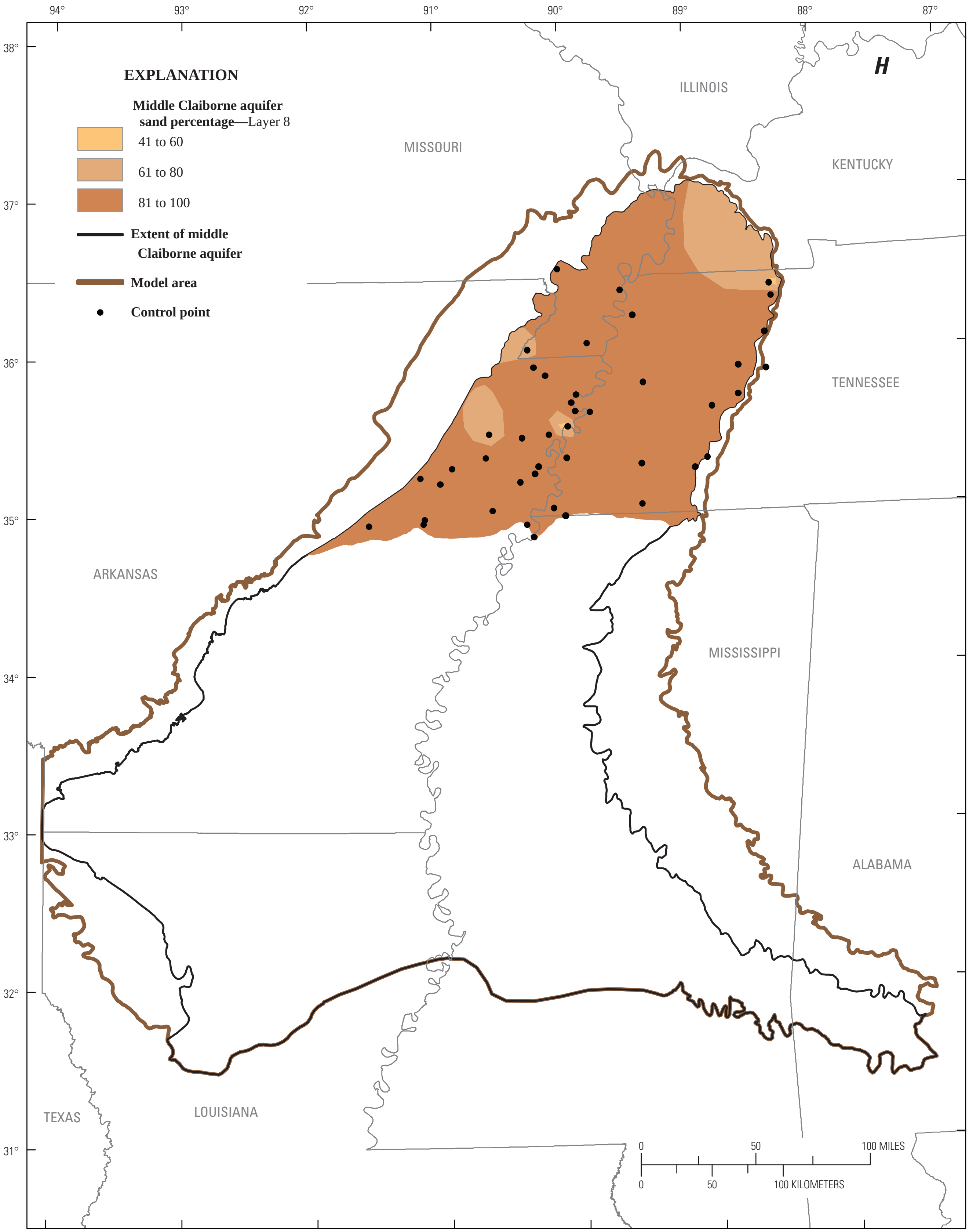


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

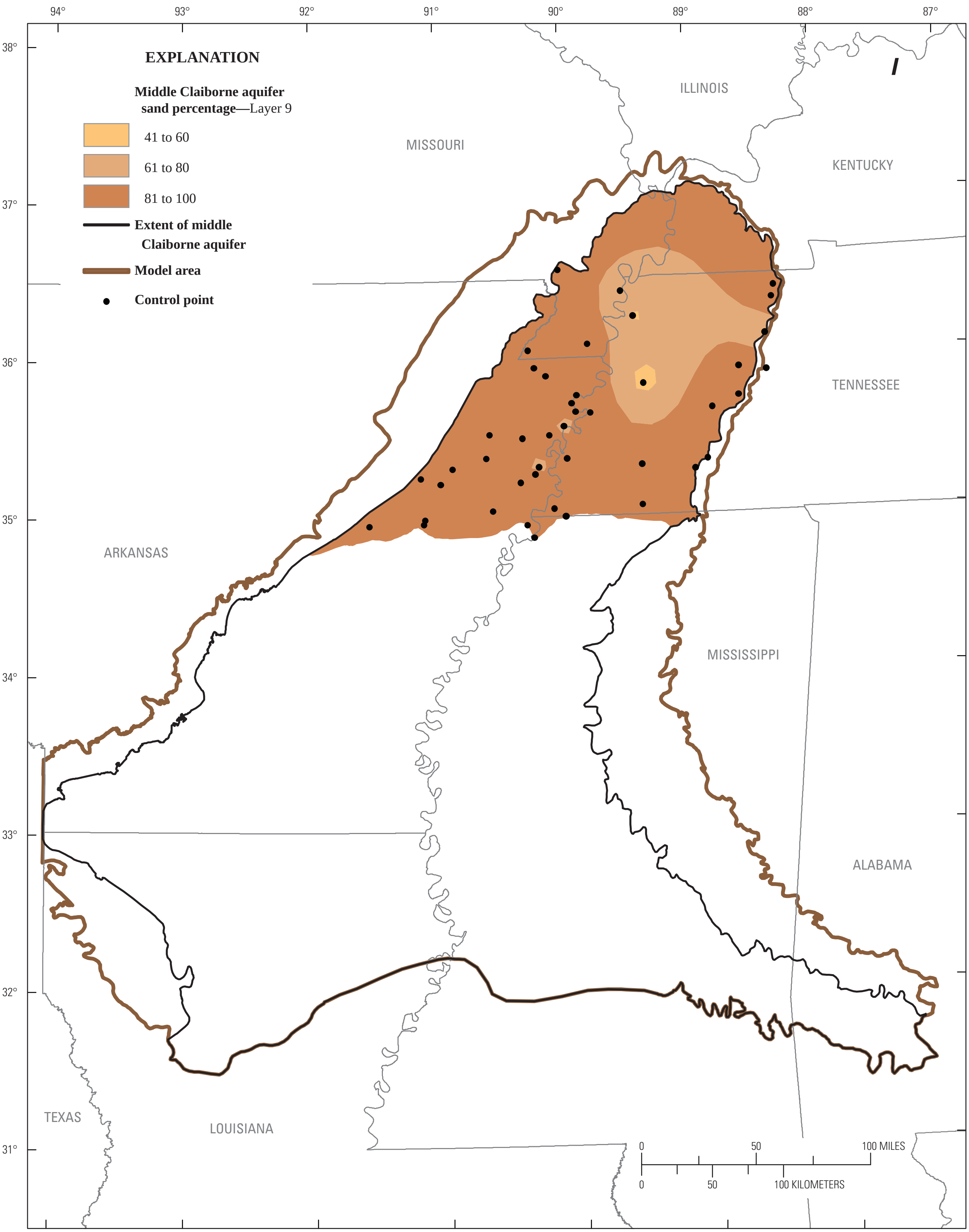


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

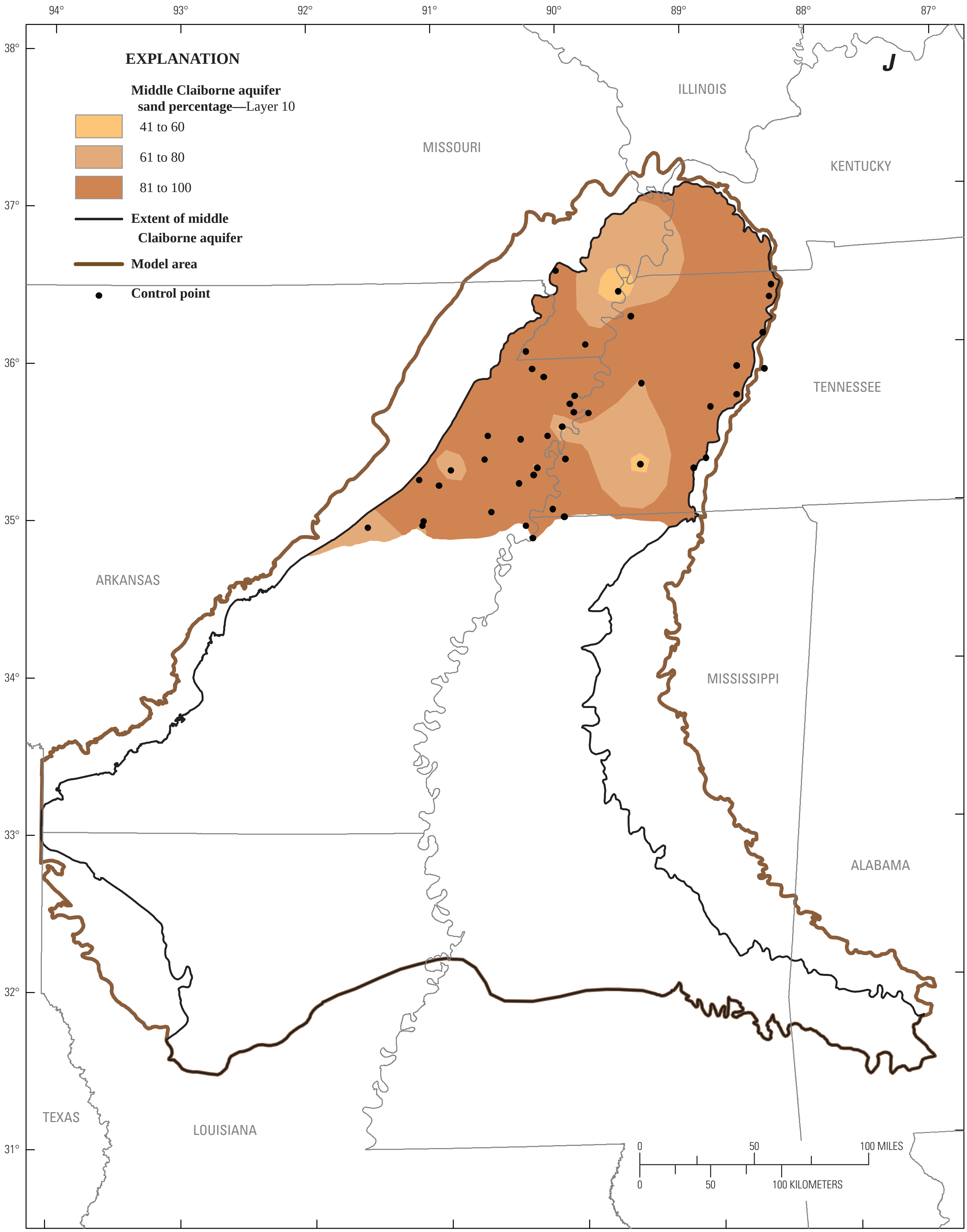


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

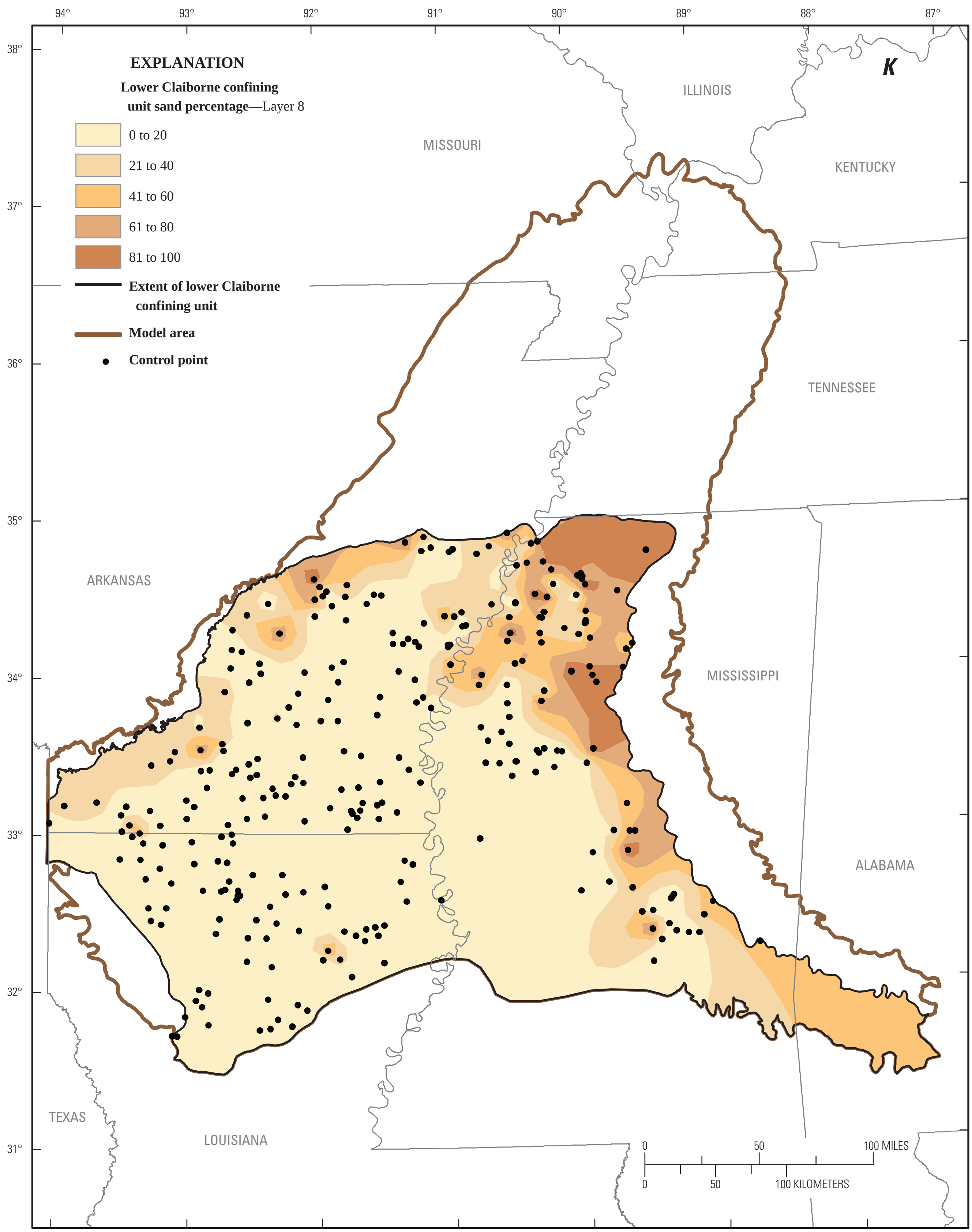


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

MS SCT 002576

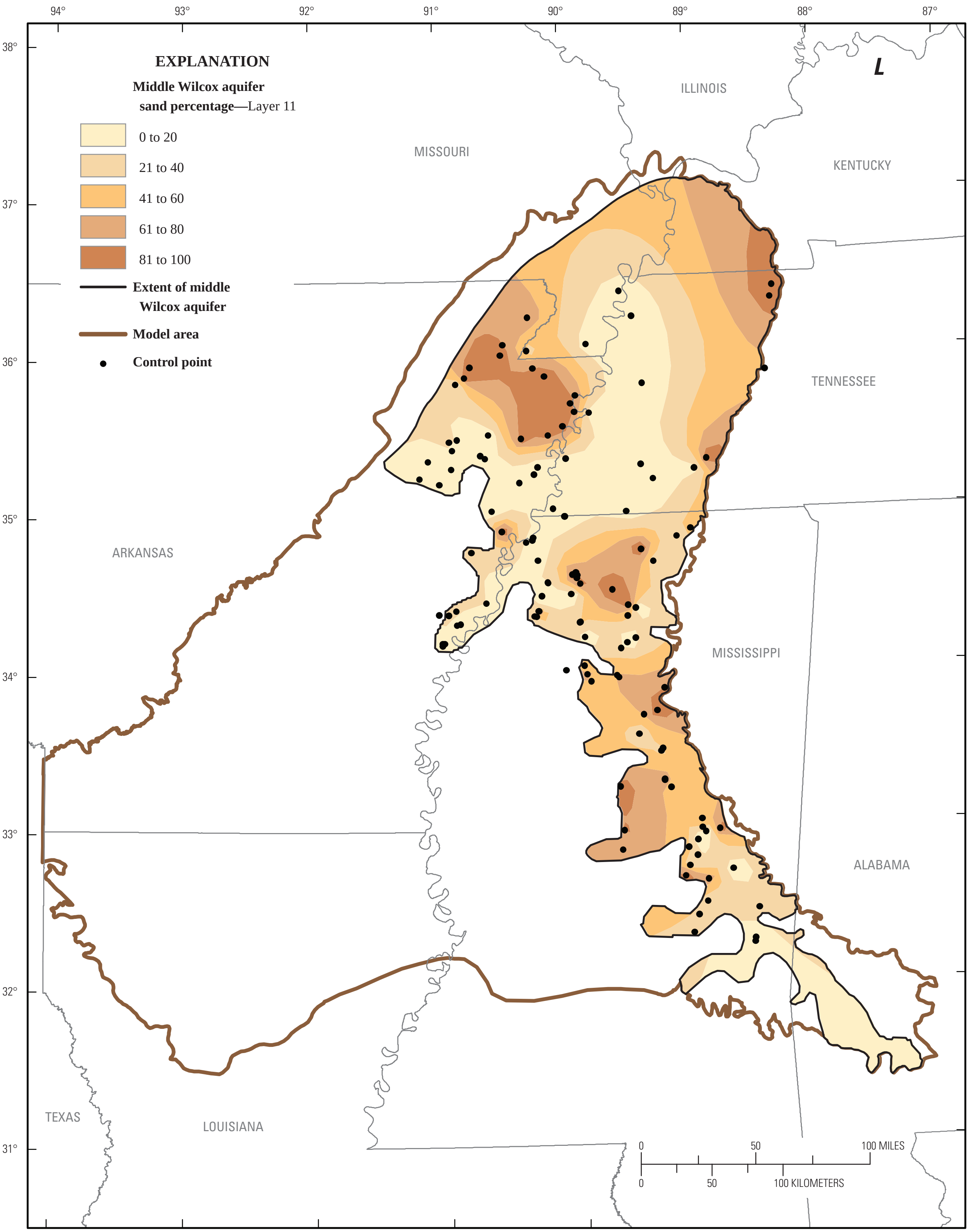


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

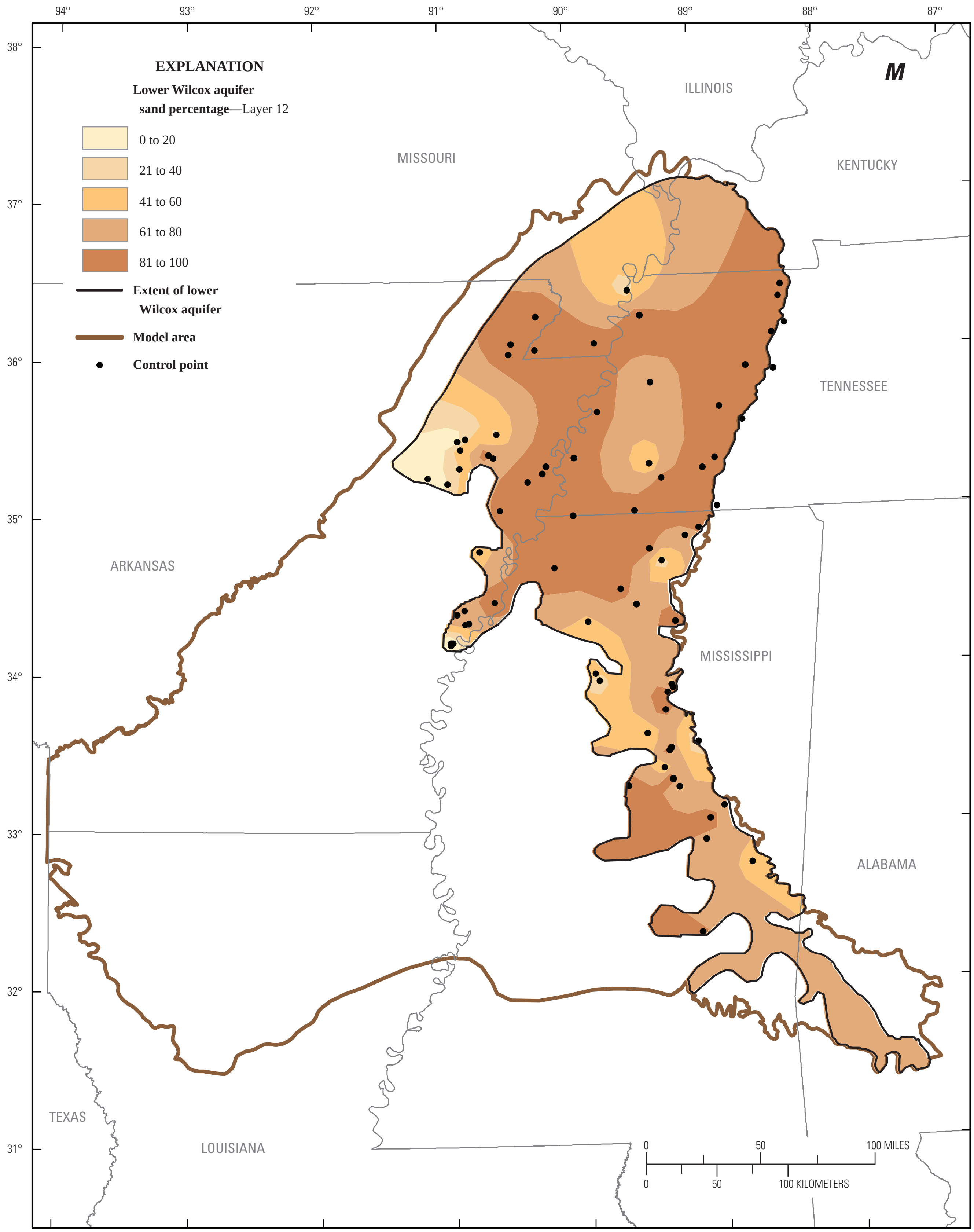


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

Model Calibration

The ability of the MERAS model to simulate measured conditions was accomplished by a combination of manual changes to parameter values and automated calibration methods. Automated parameter estimation was achieved through alternate use of UCODE-2005 (Poeter and others, 2005) and PEST (Doherty, 2008) for all 104 parameters. Simulations with UCODE-2005 were used primarily to examine the sensitivity of observations to various parameters during manual simulations. PEST automatically adjusted input parameters (hydraulic conductivity, vertical anisotropy, specific storage, specific yield, recharge, riverbed conductance, and hydraulic conductance of faults) in a series of model simulations. After each model simulation, simulated hydraulic-head values, total streamflow, and stream leakage were compared automatically to measured hydraulic-head values, total flow, and stream leakage. The simulations continued until a best fit between simulated hydraulic head and stream leakage with measured hydraulic head and stream leakage was attained. The calibration approach used here differs from traditional non-linear regression parameter estimation in two areas by using: (1) Tikhonov regularization (Tikhonov, 1963; Doherty, 2003; Fienen and others, 2009); and (2) hybrid singular value decomposition (Tonkin and Doherty, 2005; Hunt and others, 2007), also referred to as SVD-Assist (SVDA) in Doherty (2008). Additional information regarding the overview of the advantages of using these more sophisticated tools for parameter estimation are discussed by Hunt and others (2007); the tools were applied using the guidelines given by Doherty and Hunt (2009).

Weighted Hydraulic-Head Observations

Hydraulic-head observations were weighted to reduce the influence of hydraulic-head observations that are less accurate and to increase the influence of observations that are more accurate. Weights on observation data account for potential measurement error associated with the method of determining land surface, effects of recent pumpage, unknown screened intervals of wells, and other factors. In theory, weights of the observation values used in the regression procedure can be calculated from estimates of the variance or standard deviation of measurement error (Hill, 1998). The weights are calculated by dividing one by the square of the standard deviation (or variance) of the measurement errors for the observation. To estimate these standard deviations, the measurement errors can be assumed to have a normal distribution, and a 95-percent confidence interval for the measurement can be constructed. The 95-percent confidence interval spans a range equal to the measurement ±1.96 times the standard deviation (square root of the variance). Examples and detailed calculations of weights are given by Hill (1998).

For this report, standard deviations associated with land surface were calculated for hydraulic-head observations based on coordinate accuracy (how well the location of a well is known) and altitude accuracy (how well the land surface altitude of a measurement point of a well is known). The coordinate and altitude accuracy for wells are documented in the USGS National Water Inventory System (NWIS). Wells with coordinate accuracies better than ±5 seconds were included in the standard deviation calculation. Altitude accuracies other than those obtained from topographic maps were not included in the standard deviation because other methods generally were reasonably accurate. All wells that were not assigned a standard deviation based on the criteria above were assigned a standard deviation of one, which corresponds to a weight of one.

The standard deviation associated with coordinate accuracy was calculated by creating a radius around each well equal to the length of the well's coordinate accuracy value in degrees. The standard deviation of the land-surface altitude within the radius of each well was calculated. The standard deviation associated with the altitude accuracy was calculated by dividing half of the NWIS value of altitude accuracy (assuming the altitude accuracy equals the contour interval adjacent the well location) by 1.65 (where 1.65 is the critical value of a 90 percent confidence interval assuming that the error is normally distributed) (Hill and Tiedeman, 2007).

Each standard deviation was then converted to a variance (square root of standard deviation) so that the coordinate and altitude variances could be summed for each well. The final calculation converted the variance at each well back to a standard deviation. The resultant standard deviations of all wells range from 1 to 43.8 ft with an average of 1.9 ft.

Streamflow Measurements as Observations

Streamflow measurements, flow characteristics, and stream leakage estimates from previous studies were used as observations in the MERAS model. Flow characteristics were used for predevelopment observations and streamflow measurements were used for at least one additional observation late in the simulation period for each selected gage. Predevelopment observations were assumed to be the 50th percentile of daily streamflow (Wolock, 2003). Additional total streamflow measurement values were obtained from the USGS NWIS (U.S. Geological Survey, 2008c). Streamflow measurements used as observations were weighted using a method similar to that of weighting hydraulic head observations. Most predevelopment observations were assigned a standard deviation of 100,000 ft^3/d. The exception is the predevelopment observation on the White River, which was assigned a standard deviation of 1,000,000 ft^3/d because of the much greater difference in flow of the White River compared to most other streams. The standard deviation of postdevelopment observations was calculated by assuming a 90 percent probability that the streamflow measurements were within 5 percent of the true value. The standard deviation equals 5 percent of the streamflow value divided by 1.65 (see the "Weighted Hydraulic-Head

Observations" section) (Hill and Tiedeman, 2007). Stream leakage estimates were scarce in the model area as multiple factors (reservoir regulation, stream diversions, return flow from irrigation, etc.) combine to make true stream leakage estimates very difficult. Stream leakage estimates from Nyman (1965) were used to constrain the model in a local area on Nonconnah Creek in western Tennessee (fig. 3). Additionally, in 1998, streamflow measurements were made along a 40-mi segment of the White River in eastern Arkansas. The White River streamflow measurements indicated a 13 percent loss in streamflow from the upstream to downstream measurements (Jaysson E. Funkhouser, U.S. Geological Survey, written commun., 2006). The locations of the upstream and downstream measurements were used to extract information from the model to calculate the percent of streamflow that discharges to the aquifer through the use of UCODE-2005. Streamflow observation locations are shown in figure 3; total streamflow and stream leakage estimates and simulated values are presented in the "Streamflow Observations and Errors" section.

Model Evaluation

Optimal Parameter Estimates

The final parameter estimates of the model (table 3) are considered reasonable estimates for the type of material and conditions found in the Mississippi embayment aquifer system. For aquifers, horizontal hydraulic conductivity values of 3.7 to 600 ft/d are within the expected range of hydraulic conductivities for silty to clean sand (Freeze and Cherry, 1979), and also near the range of values used by McKee and Clark (2003), Stanton and Clark (2003), and Arthur (2001) for middle Claiborne and alluvial models. For confining units, horizontal hydraulic conductivity values of 0.00453 to 2.4 ft/d are within the expected range of hydraulic conductivities for marine clay to silt or loess (Freeze and Cherry, 1979). Generally, values for hydraulic conductivity are within the same order of magnitude for a given hydrogeologic unit and represent average values for large areas in the Mississippi embayment aquifer system. Horizontal hydraulic conductivities of horizontal flow barriers representing faults range from 0.0001 ft/d to 1.5536 ft/d. Specific yield values throughout the model range from 0.10 to 0.30. Specific storage values range from 2.59×10^{-7}/ft to 6.25×10^{-3}/ft. Final vertical anisotropy values range from 22.3 in surficial units to 2,297.1 in the El Dorado confining unit. Streambed conductances for each stream varied by stream reach, according to streambed hydraulic conductivity, streambed thickness, stream length, and stream width within each stream reach. The final values of streambed hydraulic conductivity range from 1.09×10^{-2} ft/d to 16.1 for streams simulated in the model. The fraction of precipitation (multiplier) that makes up recharge from infiltration ranges from 1.25×10^{-4} to 7.06×10^{-2} (table 4), which results in a range of recharge values of 0.003 to 5.73 in/yr. Comparatively, values of recharge in studies outside the embayment, range from 1.6 to 4.6 in/yr through a silt, clay, and sand confining unit over the Floridan aquifer system (Murray, 2007), and from 0.008 to 4.4 in/yr in the High Plains aquifer system (McMahon and others, 2006).

Model Fit and Model Error

Hydraulic Head Observations and Errors

Simulated heads were generally in good agreement with observed hydraulic-heads with 46,249 simulated values within ± 25 ft of the observed value. Simulated heads were compared to 55,786 observed hydraulic-head measurements from 3,245 wells in the MERAS model area. Values of mean, minimum, maximum, root mean square error (RMSE), and absolute mean error were computed for each year from residuals (table 5). RMSE in feet is determined using the equation:

$$\text{RMSE} = [\text{Sum of } (h_s - h_o)^2 / n]^{0.5}$$

where h_s is simulated hydraulic head, in feet,
h_o is observed hydraulic head, in feet, and
n is number of observations.

Values of RMSE between simulated and observed hydraulic heads of all observations ranged from 8.33 ft in 1919 to 47.65 ft in 1951, though only six annual RMSE values are greater than 40 ft for the entire simulation period (table 5). The six greatest RMSE values also occur in sequence from 1949 to 1954 and are attributed to the lack of pumping data for the pre-1960 time period. The RMSE for all observations in the model is 23.18 ft over a range in observed hydraulic head of 741.66 ft, where the range equals the difference between the highest and lowest observed hydraulic-head. The two principal aquifers, the alluvial aquifer and the middle Claiborne aquifer, are shown as individual statistics in table 5 because these aquifers make up the bulk of the information about the system. The RMSE for alluvial observations is 16.43 over a range in observed hydraulic head of 297.25 ft. The RMSE for the middle Claiborne aquifer is 35.78 over a range in observed hydraulic head of 634.94 ft. The mean of residuals indicates model bias depending on the magnitude and direction of the mean away from zero. The closer the mean is to zero, indicating a balance between positive and negative residuals, the less model bias occurs. A positive mean indicates the model tends to overpredict (simulated hydraulic heads greater than observed) water-level altitude, and a negative mean indicates underprediction (simulated hydraulic heads less than observed) of water levels. The mean residual approached zero with an absolute value less than 20 ft during 75 of the 88 years for which residuals were calculated. Out of 55,786 observations, 24,256 residuals were greater than or equal to

Table 3. Final calibrated hydraulic parameter values.

[* considered a confining unit within the parameter extent]

Parameter group	Parameter description	Parameter name	Final value	Units	Reference for parameter extent	Model layer	Composite-scaled sensitivity
Hydraulic conductivity in horizontal direction	Alluvial aquifer in zone 101	HK_alvm101	600	feet/day	fig. 9 zone 101	1 to 13	8.979×10^{-1}
	Alluvial aquifer in zones 102 and 108	HK_alvm102	166.7	feet/day	fig. 9 zones 102 and 108	1 to 13	2.744
	Alluvial aquifer in zone 103	HK_alvm103	135.4	feet/day	fig. 9 zone 103	1 to 13	1.382
	Alluvial aquifer in zone 104	HK_alvm104	458.5	feet/day	fig. 9 zone 104	1 to 13	1.078
	Alluvial aquifer in zone 105	HK_alvm105	425.4	feet/day	fig. 9 zone 105	1 to 13	1.554×10^{-1}
	Alluvial aquifer in zone 106	HK_alvm106	400	feet/day	fig. 9 zone 106	1 to 13	1.691
	Alluvial aquifer in zone 107	HK_alvm107	88.4	feet/day	fig. 9 zone 107	1 to 13	8.075×10^{-1}
	Loess undifferenitated	HK_loss	27.9	feet/day	fig. 9 zones 2 and 10	1 to 13	2.282
	Fluvial sediments undifferentiated	HK_fluv	200	feet/day	fig. 9 zone 2, where Vicksburg-Jackson confining unit (fig. 14 B) does not exist	2 to 10	8.797×10^{-1}
	Vicksburg-Jackson confining unit	HK_vkbg	1	feet/day	fig. 14 B	2	1.156
	Undifferientiated Claiborne Group	HK_clbr	48.7	feet/day	fig. 11, zone 150	3 to 10	5.070×10^{-1}
	Upper Claiborne aquifer	HK_cckf	26.3	feet/day	fig. 14 C; fig. 10, zone 30	3	2.690
	Middle Claiborne onfining unit	HK_ckmn	0.154	feet/day	fig. 11, zone 40	4	4.192
	Middle Claiborne aquifer in zone 50	HK_sprt1	146.1	feet/day	fig. 12, zone 50	5 to 7	4.867
	Middle Claiborne aquifer in zone 51	HK_sprt2	34.8	feet/day	fig. 12, zone 51	5 to 7	1.194
	Middle Claiborne aquifer in zone 52	HK_sprt3	27.2	feet/day	fig. 12, zone 52	5 to 7	1.782

Table 3. Final calibrated hydraulic parameter values.—Continued

[* considered a confining unit within the parameter extent]

Parameter group	Parameter description	Parameter name	Final value	Units	Reference for parameter extent	Model layer	Composite-scaled sensitivity
	Middle Claiborne aquifer in zone 61	HK_sprt3_5	3.7	feet/day	fig. 12, zone 61	6	2.096
	Middle Claiborne aquifer in zone 53	HK_sprt4	10.2	feet/day	fig. 12, zone 53	5 to 7	3.608
	El Dorado confining unit	HK_spcl	0.00453	feet/day	fig. 12, zone 61 (layer 6)	6	1.186
	El Dorado Sand	HK_spes	59	feet/day	fig. 12, zone 70 (layer 7)	7	7.397
	Lower Claiborne confining unit	HK_crvr	0.0883	feet/day	fig. 14 K	8	2.773
	Winona-Tallahatta aquifer	HK_wnth	26.9	feet/day	fig. 6	9	6.503×10^{-1}
	Lower Claiborne aquifer	HK_crrz	25	feet/day	fig. 13	10	9.737×10^{-1}
	Wilcox aquifer in zone 110	HK_wlcx	5.6	feet/day	fig. 13 zone 110	11 to 13	5.486
	Middle Wilcox aquifer*	HK_flid	2.4	feet/day	fig. 14 L	11	1.132
	Lower Wilcox aquifer	HK_lwaq	24.6	feet/day	fig. 14 M	12	1.714
	Old Breastworks confining unit	HK_odbx	1.4	feet/day	fig. 7	13	3.797×10^{-1}
Vertical anisotropy	Alluvial aquifer	VANI_alvm	100	dimension-less	fig. 9 zones 101-108	1 to 13	1.167×10^{-1}
	Loess undifferenitated	VANI_loss	22.3	dimension-less	fig. 9 zones 2 and 10	1 to 13	6.933×10^{-2}
	Vicksburg-Jackson confining unit	VANI_vkbg	1,475	dimension-less	fig. 14 B	2	1.127
	Undifferientiated Claiborne Group	VANI_clbr	23.4	dimension-less	fig. 11, zone 150	3 to 10	5.908×10^{-2}
	Upper Claiborne aquifer	VANI_cckf	612.8	dimension-less	fig. 14 C	3	2.938×10^{-1}
	Middle Claiborne confining unit	VANI_ckmn	564.6	dimension-less	fig. 14 D	4	4.194
	Middle Claiborne aquifer in zone 50	VANI_sprt1	243.4	dimension-less	fig. 12, zone 50	5 to 7	2.101×10^{-1}

Table 3. Final calibrated hydraulic parameter values.—Continued

[* considered a confining unit within the parameter extent]

Parameter group	Parameter description	Parameter name	Final value	Units	Reference for parameter extent	Model layer	Composite-scaled sensitivity
	Middle Claiborne aquifer in zones 51 and 53	VANI_sprt2	680	dimensionless	fig. 12 zones 51 and 53	5 to 7	1.339
	Middle Claiborne aquifer in zone 52	VANI_sprt3	798.8	dimensionless	fig. 12, zone 52	5 to 7	9.769×10^{-1}
	El Dorado confining unit	VANI_spcl	2,297.1	dimensionless	fig. 12, zone 61 (layer 6)	6	1.175
	El Dorado Sand	VANI_spes	254.2	dimensionless	fig. 12, zone 70 (layer 7)	7	8.046×10^{-2}
	Lower Claiborne confining unit	VANI_crvr	334.5	dimensionless	fig. 14 K	8	2.738
	Winona-Tallahatta aquifer	VANI_wnth	28	dimensionless	fig. 6	9	6.344×10^{-2}
	Lower Claiborne aquifer	VANI_crrz	23	dimensionless	fig. 13	10	6.958×10^{-2}
	Wilcox aquifer in zone 110	VANI_wlcx	402.8	dimensionless	fig. 13, zone 110	11 to 13	6.082×10^{-1}
	Middle Wilcox aquifer*	VANI_flid	617.8	dimensionless	fig. 14 L	11	9.910×10^{-1}
	Lower Wilcox aquifer	VANI_lwaq	27.7	dimensionless	fig. 14 M	12	6.780×10^{-2}
	Old Breastworks confining unit	VANI_odbx	478.4	dimensionless	fig. 7	13	1.274×10^{-1}
Specific storage	Alluvial aquifer in zone 101	SS_alvm101	3.50×10^{-3}	1/foot	fig. 9 zone 101	1 to 13	7.812×10^{-1}
	Alluvial aquifer in zones 102 and 108	SS_alvm102	4.03×10^{-3}	1/foot	fig. 9 zones 102 and 108	1 to 13	1.443
	Alluvial aquifer in zone 103	SS_alvm103	3.34×10^{-3}	1/foot	fig. 9 zone 103	1 to 13	5.152×10^{-1}
	Alluvial aquifer in zone 104	SS_alvm104	5.74×10^{-3}	1/foot	fig. 9 zone 104	1 to 13	2.839
	Alluvial aquifer in zone 105	SS_alvm105	2.85×10^{-3}	1/foot	fig. 9 zone 105	1 to 13	1.353×10^{-1}
	Alluvial aquifer in zone 106	SS_alvm106	4.33×10^{-3}	1/foot	fig. 9 zone 106	1 to 13	3.132
	Alluvial aquifer in zone 107	SS_alvm107	6.25×10^{-3}	1/foot	fig. 9 zone 107	1 to 13	8.637×10^{-1}
	Loess undifferenitated	SS_loss	1.36×10^{-3}	1/foot	fig. 9 zones 2 and 10	1 to 13	7.095×10^{-1}
	Vicksburg-Jackson confining unit	SS_vkbg	3.46×10^{-7}	1/foot	fig. 14 B	2	6.974×10^{-2}

Table 3. Final calibrated hydraulic parameter values.—Continued

[* considered a confining unit within the parameter extent]

Parameter group	Parameter description	Parameter name	Final value	Units	Reference for parameter extent	Model layer	Composite-scaled sensitivity
	Undifferientiated Claiborne Group	SS_clbr	3.68×10^{-7}	1/foot	fig. 11, zone 150	3 to 10	7.170×10^{-2}
	Upper Claiborne aquifer	SS_cckf	2.59×10^{-7}	1/foot	fig. 14 C	3	6.030×10^{-2}
	Middle Claiborne confining unit	SS_ckmn	2.88×10^{-7}	1/foot	fig. 14 D	4	8.166×10^{-2}
	Middle Claiborne aquifer in zone 50	SS_sprt1	8.51×10^{-6}	1/foot	fig. 12, zone 50	5 to 7	5.986×10^{-1}
	Middle Claiborne aquifer in zones 51 and 53	SS_sprt2	1.03×10^{-6}	1/foot	fig. 12 zones 51 and 53	5 to 7	5.312×10^{-1}
	Middle Claiborne aquifer in zone 52	SS_sprt3	9.92×10^{-7}	1/foot	fig. 12, zone 52	5 to 7	1.900
	El Dorado confining unit	SS_spcl	3.65×10^{-7}	1/foot	fig. 12, zone 61 (layer 6)	6	1.346×10^{-1}
	El Dorado Sand	SS_spes	2.44×10^{-6}	1/foot	fig. 12, zone 70 (layer 7)	7	1.341
	Lower Claiborne confining unit	SS_crvr	3.08×10^{-7}	1/foot	fig. 14 K	8	2.347×10^{-1}
	Winona-Tallahatta aquifer	SS_wnth	2.81×10^{-7}	1/foot	fig. 6	9	9.998×10^{-2}
	Lower Claiborne aquifer	SS_crrz	2.79×10^{-7}	1/foot	fig. 13	10	7.827×10^{-2}
	Wilcox aquifer in zone 110	SS_wlcx	3.65×10^{-7}	1/foot	fig. 13, zone 110	11 to 13	4.353×10^{-1}
	Middle Wilcox aquifer*	SS_flid	3.36×10^{-7}	1/foot	fig. 14 L	11	8.174×10^{-2}
	Lower Wilcox aquifer	SS_lwaq	3.39×10^{-7}	1/foot	fig. 14 M	12	5.892×10^{-2}
	Old Breastworks confining unit	SS_odbx	3.23×10^{-7}	1/foot	fig. 7	13	5.238×10^{-2}
Specific yield	Alluvial aquifer in zoness 101-105	SY_alvm	0.3	dimension-less	fig. 9 zones 101-105	1	4.310
	Alluvial aquifer in zone 106	SY_alvm106	0.1	dimension-less	fig. 9 zone 106	1	2.514
	Loess undifferenitated	SY_loss	0.3	dimension-less	fig. 9 zones 2 and 10	1 to 13	8.710×10^{-1}
Recharge multiplier	Alluvial aquifer in zone 101	RCHALM101	3.80×10^{-2}	dimension-less	fig. 9 zone 101	1 to 13	2.412

Table 3. Final calibrated hydraulic parameter values.—Continued

[* considered a confining unit within the parameter extent]

Parameter group	Parameter description	Parameter name	Final value	Units	Reference for parameter extent	Model layer	Composite-scaled sensitivity
	Alluvial aquifer in zone 102	RCHALM102	4.46×10^{-2}	dimension-less	fig. 9 zone 102	1 to 13	3.292
	Alluvial aquifer in zone 103	RCHALM103	5.10×10^{-2}	dimension-less	fig. 9 zone 103	1 to 13	4.482
	Alluvial aquifer in zone 104	RCHALM104	2.88×10^{-2}	dimension-less	fig. 9 zone 104	1 to 13	3.084
	Alluvial aquifer in zone 105	RCHALM105	5.11×10^{-2}	dimension-less	fig. 9 zone105	1 to 13	2.140×10^{-1}
	Alluvial aquifer in zone 106	RCHALM106	1.30×10^{-4}	dimension-less	fig. 9 zone 106	1 to 13	6.813×10^{-2}
	Alluvial aquifer in zone 107	RCHALM107	1.02×10^{-2}	dimension-less	fig. 9 zone 107	1 to 13	5.931×10^{-1}
	Alluvial aquifer in zone 108	RCHALM108	3.42×10^{-3}	dimension-less	fig. 9 zone 108	1 to 13	5.170×10^{-1}
	Various clay	RCHCLAY	1.25×10^{-4}	dimension-less	fig. 9 zones 3, 5, and 7	2, 4, and 8	1.299×10^{-1}
	Loess undifferenitated	RCHLOSS	1.23×10^{-2}	dimension-less	fig. 9 zone 2	multiple	3.542
	Upper Claiborne aquifer	RCHCCKF	2.35×10^{-3}	dimension-less	fig. 14 C	3	1.100
	Middle Claiborne aquifer in western part of model area	RCHSPTW	1.16×10^{-3}	dimension-less	fig. 9 zone 6	5	1.979×10^{-1}
	Middle Claiborne aquifer in eastern part of model area	RCHSPTE	6.38×10^{-3}	dimension-less	fig. 9 zone 61	5	4.439×10^{-1}
	Lower Claiborne aquifer	RCHCRRZ	8.60×10^{-3}	dimension-less	fig. 9, zone 8	10	1.053
	Wilcox aquifer undif-ferentiated in eastern part of model area	RCHWXE	7.02×10^{-3}	dimension-less	fig. 9, zone 9	11	1.527
	Wilcox aquifer undif-ferentiated in western part of model area	RCHWXW	7.06×10^{-2}	dimension-less	fig. 9, zone 11	11	5.226
	Terrace deposits undif-ferntiated	RCHTRRC	1.16×10^{-2}	dimension-less	fig. 9, zone 10	multiple	7.401
Streambed conductance	Selected rivers	RIVCON	1.458×10^{-1}	feet/day	fig. 4	multiple	1.495
	Arkansas River	RIVARK	0.09	feet/day	fig. 4	multiple	1.190
	Mississippi River	RIVMISS	15.4	feet/day	fig. 4	multiple	0.000
	Ouachita River	RIVOUACH	16.1	feet/day	fig. 4	multiple	7.891×10^{-2}
	White River	RIVWHT	13.8	feet/day	fig. 4	multiple	6.187×10^{-2}
	L'Anguille River	RIVLANG	0.99	feet/day	fig. 4	multiple	7.128×10^{-1}

Table 3. Final calibrated hydraulic parameter values.—Continued

[* considered a confining unit within the parameter extent]

Parameter group	Parameter description	Parameter name	Final value	Units	Reference for parameter extent	Model layer	Composite-scaled sensitivity
	Saline River	RIVSALIN	1.03	feet/day	fig. 4	multiple	8.998×10^{-2}
	Cache River	RIVCACH	1.14	feet/day	fig. 4	multiple	7.139×10^{-1}
	Selected rivers	RIVLOW	1.099×10^{-2}	feet/day	fig. 4	multiple	1.198
	Selected rivers	RIVMEMP	1	feet/day	fig. 4	multiple	5.116×10^{-1}
Horizontal flow barrier	Fault set in southeastern Arkansas	mod_mck	1.0×10^{-4}	feet/day	fig. 12	5 to 13	2.398
	Fault set in south-central Arkansas	mrdata_1	1.5536	feet/day	fig. 12	5 to 13	5.902×10^{-2}
	Fault set in south-central Arkansas	union_fault	5.928×10^{-3}	feet/day	fig. 12	5 to 13	1.098×10^{-1}
	Fault set in Mississippi	pickens	0.00504	feet/day	fig. 12	5 to 13	1.117×10^{-1}
Precipitation value	Predevelopment precipitation	predevrch	2.647×10^{-3}	feet/day	fig. 9 all zones	multiple	6.668

Table 4. Recharge parameter values and corresponding range of recharge.

Zone number	Parameter name (see table 3)	Range in precipitation (inches)	Fraction of recharge	Range in recharge amount (inches per year)
101	RCHALM101	29 to 85	3.80×10^{-2}	1.09 to 3.25
102	RCHALM102	27 to 85	4.46×10^{-2}	1.23 to 3.79
103	RCHALM103	29 to 83	5.10×10^{-2}	1.47 to 4.25
104	RCHALM104	28 to 84	2.88×10^{-2}	0.81 to 2.43
105	RCHALM105	28 to 79	5.11×10^{-2}	1.45 to 4.03
106	RCHALM106	27 to 85	1.30×10^{-4}	0 to 0.01
107	RCHALM107	28 to 86	1.02×10^{-2}	0.29 to 0.87
108	RCHALM108	28 to 85	3.42×10^{-3}	0.1 to 0.29
2	RCHLOSS	26 to 80	1.23×10^{-2}	0.32 to 0.99
10	RCHTRRC	26 to 85	1.16×10^{-2}	0.3 to 0.99
3	RCHCLAY	30 to 80	1.25×10^{-4}	0 to 0.01
4	RCHCCKF	30 to 83	2.35×10^{-3}	0.07 to 0.19
5	RCHCLAY	29 to 85	1.25×10^{-4}	0 to 0.01
6	RCHSPTW	27 to 85	1.16×10^{-3}	0.03 to 0.1
61	RCHSPTE	29 to 80	6.38×10^{-3}	0.18 to 0.51
7	RCHCLAY	27 to 83	1.25×10^{-4}	0 to 0.01
8	RCHCRRZ	27 to 84	8.60×10^{-3}	0.23 to 0.72
9	RCHWXE	31 to 84	7.02×10^{-3}	0.22 to 0.59
11	RCHWXW	27 to 81	7.06×10^{-2}	1.9 to 5.73

Table 5. Summary of weighted hydraulic-head residual statistics for model calibration for all observations, alluvial observations, and middle Claiborne aquifer observations.

[--, no value]

	All observations								Alluvial observations			Middle Claiborne observations		
Year	Mean (feet)	Minimum residual (feet)	Maximum residual (feet)	Root mean square error (RMSE) (feet)	Mean absolute error (feet)	Number of observa-tions	Range (feet)	Ratio of RMSE to range	Root mean square error (feet)	Number of observa-tions	Range (feet)	Root mean square error (feet)	Number of observa-tions	Range (feet)
1902	0.20	0.20	0.20	--	0.20	1	--	--	--	1	--	--	--	--
1911	7.44	7.44	7.44	--	7.44	1	--	--	--	--	--	--	--	--
1913	-72.37	-72.37	-72.37	--	72.37	1	--	--	--	--	--	--	--	--
1916	-25.87	-25.87	-25.87	--	25.87	1	--	--	--	--	--	--	1	--
1918	28.35	28.35	28.35	--	28.35	1	--	--	--	1	--	--	--	--
1919	1.88	-8.67	9.84	8.33	7.90	4	85.5	0.1	--	1	--	--	1	--
1925	-4.07	-4.07	-4.07	--	4.07	1	--	--	--	--	--	--	1	--
1927	-8.68	-17.19	-0.16	12.16	8.68	2	6.06	2.01	12.16	2	6.06	--	--	--
1928	3.56	-34.64	26.05	16.42	13.90	30	88.3	0.19	16.37	27	78.7	16.84	3	74.31
1929	2.12	-45.55	21.77	15.61	12.90	37	146.2	0.11	16.03	34	76.41	9.71	3	111.66
1930	2.21	-30.32	23.01	14.26	11.88	37	95.98	0.15	15.05	33	81.35	--	1	--
1931	3.85	-20.97	23.32	13.67	12.01	32	78.92	0.17	13.86	31	78.92	--	1	--
1932	3.69	-33.45	28.53	15.47	12.84	34	97.52	0.16	15.92	32	77.99	3.42	2	81.53
1933	3.91	-26.90	26.51	15.51	13.62	32	103.75	0.15	15.99	30	81.79	3.49	2	86.01
1934	5.30	-23.81	30.56	15.93	14.15	35	99.25	0.16	16.38	33	78.2	3.44	2	83.27
1935	9.91	-21.90	35.78	17.70	15.36	52	110.34	0.16	18.03	50	90.65	3.88	2	83.6
1936	10.59	-25.13	35.82	18.32	16.15	56	170.27	0.11	18.78	53	170.27	5.77	3	81.98
1937	8.46	-58.02	83.43	21.38	16.85	74	225.17	0.09	20.94	69	225.17	26.71	5	81.87
1938	9.64	-38.50	84.07	21.26	17.27	88	226.84	0.09	21.43	74	226.84	10.47	6	111.13
1939	11.45	-39.38	84.09	24.10	18.82	107	233.19	0.1	21.55	76	227.4	37.13	13	166.51
1940	9.11	-56.32	84.12	23.04	18.16	111	234.51	0.1	20.60	76	226.75	26.18	17	208.96
1941	10.05	-55.30	84.34	22.03	17.45	107	233.7	0.09	20.71	77	226.31	15.30	11	209.05
1942	9.97	-54.64	84.12	21.85	17.45	107	235.61	0.09	21.35	77	228.92	15.37	13	207.05
1943	10.34	-51.77	84.76	21.90	17.57	102	258.95	0.08	21.59	73	228.71	15.25	11	230.98

Table 5. Summary of weighted hydraulic-head residual statistics for model calibration for all observations, alluvial observations, and middle Claiborne aquifer observations.—Continued

[--, no value]

	All observations								Alluvial observations			Middle Claiborne observations		
Year	Mean (feet)	Minimum residual (feet)	Maximum residual (feet)	Root mean square error (RMSE) (feet)	Mean absolute error (feet)	Number of observa-tions	Range (feet)	Ratio of RMSE to range	Root mean square error (feet)	Number of observa-tions	Range (feet)	Root mean square error (feet)	Number of observa-tions	Range (feet)
1944	9.75	-52.08	85.54	22.53	18.43	110	228.64	0.1	22.30	79	228.64	17.20	14	198.43
1945	11.56	-52.26	85.99	24.04	19.03	66	201.56	0.12	23.75	37	147.13	17.51	12	166.95
1946	15.84	-50.50	206.21	37.96	22.93	85	398.5	0.1	21.79	48	231.23	72.54	16	369.58
1947	15.43	-50.20	226.49	38.50	23.27	111	390.33	0.1	21.78	73	151.62	76.00	20	390.33
1948	13.24	-53.92	227.10	36.51	23.13	131	390.86	0.09	21.49	82	181.28	66.86	27	390.86
1949	14.30	-54.03	224.87	41.56	24.61	166	415.52	0.1	21.30	96	180.51	71.40	44	415.52
1950	17.33	-51.53	224.70	45.17	26.60	156	417.06	0.11	21.85	87	229.17	75.14	46	416.72
1951	18.56	-54.84	210.66	47.65	27.80	148	404.17	0.12	21.74	85	181.41	79.87	44	404.17
1952	14.56	-51.83	196.12	40.37	23.74	152	390.37	0.1	21.16	88	176.78	67.59	42	390.37
1953	7.32	-144.11	233.67	47.17	26.34	247	543.97	0.09	18.19	172	228.36	83.36	43	428.38
1954	7.83	-152.77	216.43	40.56	22.80	336	518.11	0.08	18.82	252	235	75.70	44	398.84
1955	6.71	-145.51	229.54	34.13	18.54	483	539.54	0.06	16.84	389	247.41	76.95	48	424.81
1956	5.84	-154.95	229.69	32.03	17.33	548	548.36	0.06	16.15	440	236.93	69.54	59	426.2
1957	4.93	-77.03	225.27	25.96	14.36	657	649.65	0.04	15.59	543	256.72	68.11	60	422.46
1958	0.36	-131.78	229.46	26.92	15.57	742	627.6	0.04	17.61	606	254	61.87	72	428.26
1959	-1.12	-142.28	232.95	24.02	14.58	770	635.34	0.04	17.16	628	256.49	48.71	76	508.2
1960	-0.63	-143.97	234.68	23.70	14.34	774	532.46	0.04	16.76	634	255.27	49.72	73	438.33
1961	-0.40	-85.58	236.30	23.88	14.17	694	547.58	0.04	14.95	542	243.09	43.43	90	545.9
1962	-1.78	-90.73	230.30	22.79	13.92	696	637.97	0.04	15.29	545	247.28	46.44	87	455.59
1963	-0.44	-143.12	234.33	23.61	13.65	682	559.53	0.04	14.31	533	255.24	46.28	89	554.25
1964	0.73	-93.77	223.30	22.61	13.39	652	570.47	0.04	13.50	501	253.74	43.93	103	564.12
1965	1.40	-83.09	222.85	23.55	14.17	643	570.8	0.04	14.05	475	257.9	43.10	121	570.8
1966	2.27	-81.50	197.99	24.48	15.17	630	555.76	0.04	14.67	442	245.76	42.48	127	555.76
1967	2.93	-125.74	191.32	25.16	15.92	668	574.97	0.04	14.97	436	253.21	41.22	155	574.97
1968	1.95	-139.10	189.84	25.16	16.49	755	592.92	0.04	16.05	453	253.19	38.45	209	592.92

Table 5. Summary of weighted hydraulic-head residual statistics for model calibration for all observations, alluvial observations, and middle Claiborne aquifer observations.—Continued

[--, no value]

	All observations								Alluvial observations			Middle Claiborne observations		
Year	Mean (feet)	Minimum residual (feet)	Maximum residual (feet)	Root mean square error (RMSE) (feet)	Mean absolute error (feet)	Number of observa-tions	Range (feet)	Ratio of RMSE to range	Root mean square error (feet)	Number of observa-tions	Range (feet)	Root mean square error (feet)	Number of observa-tions	Range (feet)
1969	0.05	-80.33	137.15	23.62	16.20	887	712.15	0.03	16.32	575	251.89	36.22	216	599.25
1970	0.21	-82.93	130.91	23.04	15.88	889	567.24	0.04	16.33	563	252.67	34.67	219	567.24
1971	0.86	-81.05	129.78	21.50	14.59	929	558.63	0.04	14.97	593	245.75	32.66	229	558.63
1972	2.29	-80.98	131.49	21.26	14.30	846	560.56	0.04	14.70	505	254.68	29.83	227	560.56
1973	2.64	-89.71	133.78	23.17	16.20	788	552.26	0.04	16.35	426	253.1	30.20	239	552.26
1974	2.06	-92.86	168.09	24.15	16.75	809	550.26	0.04	17.00	443	254.15	31.63	251	550.26
1975	1.52	-94.96	189.05	23.59	16.76	882	613.19	0.04	17.33	493	276.03	29.58	265	543.14
1976	3.43	-89.82	157.20	23.10	15.96	887	633.45	0.04	15.88	469	279.83	30.31	264	549.21
1977	2.49	-143.18	161.85	26.01	17.42	891	633.64	0.04	17.81	455	282.01	31.79	267	547.14
1978	0.96	-146.27	176.66	26.22	17.26	987	637.76	0.04	17.01	535	281.35	33.06	280	553.92
1979	-1.93	-152.20	192.64	25.29	16.94	1053	663.75	0.04	17.42	565	280.05	29.24	294	580.4
1980	-1.47	-156.12	173.55	23.23	15.65	1204	630.89	0.04	16.45	760	254.28	26.54	289	558.11
1981	-0.33	-149.08	176.91	22.39	14.69	1274	659.58	0.03	14.76	804	256.8	27.27	280	552.35
1982	-0.17	-162.75	141.78	20.73	13.94	1300	658.53	0.03	14.92	864	254.26	26.52	264	560.17
1983	-2.04	-91.38	135.07	19.86	14.21	1401	662.79	0.03	15.85	936	273.93	24.72	291	564.44
1984	-0.94	-117.79	144.29	19.63	13.54	1643	678.65	0.03	14.79	1162	277.23	28.63	297	572.35
1985	-1.37	-117.74	142.11	20.00	13.85	1676	684.11	0.03	15.42	1197	282.45	28.53	303	580.76
1986	-0.47	-116.65	165.29	20.30	13.90	1700	669.82	0.03	15.35	1218	292.18	29.94	310	566.3
1987	-0.80	-128.37	164.25	20.27	14.00	1703	685.84	0.03	14.88	1227	275.73	30.05	298	585.98
1988	-0.54	-121.80	170.77	20.45	14.01	1610	689.15	0.03	14.71	1198	239.01	32.55	249	588.12
1989	-2.22	-124.29	181.39	20.53	13.66	1622	668.78	0.03	14.15	1160	246.95	30.61	302	567.71
1990	-3.02	-134.63	175.72	20.50	13.42	1561	672.85	0.03	14.60	1178	243.74	31.92	234	566.44
1991	-5.02	-139.39	68.75	18.37	12.49	1249	669.75	0.03	14.79	1048	231.73	31.24	57	565.53
1992	-4.97	-140.86	189.55	20.05	13.28	1360	711.91	0.03	15.54	1186	237.8	42.71	81	605.38
1993	-3.36	-141.81	197.39	20.68	13.43	1279	701.87	0.03	14.49	984	250.9	32.86	206	593.6

Table 5. Summary of weighted hydraulic-head residual statistics for model calibration for all observations, alluvial observations, and middle Claiborne aquifer observations.—Continued

[--, no value]

	All observations								Alluvial observations			Middle Claiborne observations		
Year	Mean (feet)	Minimum residual (feet)	Maximum residual (feet)	Root mean square error (RMSE) (feet)	Mean absolute error (feet)	Number of observa- tions	Range (feet)	Ratio of RMSE to range	Root mean square error (feet)	Number of observa- tions	Range (feet)	Root mean square error (feet)	Number of observa- tions	Range (feet)
1994	-5.49	-114.28	82.53	17.92	12.20	1198	707.32	0.03	16.35	1069	251.51	29.20	55	600.44
1995	-3.86	-93.32	183.95	19.57	13.33	1137	717.69	0.03	14.60	855	243.79	27.93	202	612.58
1996	-6.64	-122.67	111.77	21.30	14.18	1145	722.29	0.03	16.43	922	242.13	33.67	82	615.36
1997	-3.88	-137.83	84.07	20.61	14.27	953	623.85	0.03	15.66	659	243.15	30.14	231	623.85
1998	-6.37	-80.03	93.93	19.71	14.17	902	625.92	0.03	18.37	789	239.46	28.21	89	625.92
1999	-3.10	-93.59	89.16	20.40	14.45	919	626.11	0.03	15.76	668	241.32	29.89	223	626.11
2000	-5.81	-93.36	109.24	22.08	15.22	1083	631.29	0.03	18.35	851	245.28	31.26	130	631.29
2001	-3.19	-84.22	97.03	21.59	15.24	950	612.12	0.04	16.30	657	235.66	30.40	259	612.12
2002	-7.88	-89.04	100.45	21.33	14.99	887	627.24	0.03	20.06	777	235.85	30.34	73	627.24
2003	-5.84	-96.30	106.67	23.86	16.45	965	619.76	0.04	17.65	613	237.5	30.57	249	619.76
2004	-9.89	-91.53	112.45	23.20	16.32	854	625.54	0.04	21.37	732	237.19	35.46	84	625.54
2005	-7.88	-109.77	106.44	24.66	17.47	913	616.28	0.04	19.76	609	229.74	33.01	264	616.28
2006	-10.86	-98.92	110.53	25.23	17.78	904	627.42	0.04	22.11	722	228.24	36.60	83	627.42
2007	-8.61	-138.78	99.14	30.70	22.47	391	545.55	0.06	23.99	149	226.11	35.80	210	545.55
All	-1.15	-162.75	236.30	23.18	15.14	55786	741.66	0.03	16.43	39732	297.25	35.78	10265	634.94

zero (overprediction) and 31,530 residuals were less than zero (underprediction), resulting in a mean residual of -1.15 ft. The maximum and minimum residuals were 236.30 ft and -162.75 ft, respectively.

Streamflow Observations and Errors

Simulated streamflow generally is lower than measured streamflow for streams with streamflow less than 1,000 ft^3/s and greater than measured streamflow for streams with streamflow more than 1,000 ft^3/s (fig. 15). Simulated streamflow is underpredicted for 18 observations and overpredicted for 10 observations in the model. Four observations are not shown on figure 15—stream leakage for the White River and Nonconnah Creek and streamflow for the White River for pre- and post-development. The fraction of streamflow that is stream leakage for the White River was simulated as -0.042, which indicates by the negative value that flow is into the White River from the aquifer (4.2 percent of streamflow was gained from the groundwater system). The fraction of streamflow that is stream leakage for the White River was estimated by measurements to be 0.13 (13 percent of streamflow was lost to the aquifer). Stream leakage for Nonconnah Creek was simulated as 0.073 ft^3/s and the estimated stream leakage value for Nonconnah Creek was 0.100 ft^3/s (Nyman, 1965). While the simulated stream leakage for Nonconnah Creek closely matches the estimated value, the fraction of streamflow that is leakage for the White River is into the river (gaining) instead of out of the river (losing) as the estimated value indicates. One possible reason for the discrepancy includes pumping directly from the river. This pumping would remove water from the river resulting in a measured loss of streamflow that would appear to occur as leakage. Pre- and post-development streamflow for the White River was simulated as 4.02×10^4 ft^3/s and 2.47×10^4, respectively. Pre- and postdevelopment streamflow for the White River was measured as 1.85×10^4 and 1.27×10^4, respectively. Though the absolute differences between simulated and measured streamflow on the White River are great, the simulated values are considered a reasonable fit given the discretization of the simulated streams and other factors contributing to streamflow. These differences also illustrate the uncertainty in model inputs such as predevelopment recharge, overland flow, pumpage (from stream and aquifer), precipitation, and observation weights. Uncertainty in simulated streamflow values is compounded by the simulated hydraulic head in the surrounding aquifer. For example, if the simulated hydraulic head in the surrounding aquifer is slightly underpredicted, streamflow may simply be lost to the aquifer, instead of the stream gaining water from the aquifer. In these cases, a difference of a few feet may account for large differences in streamflow.

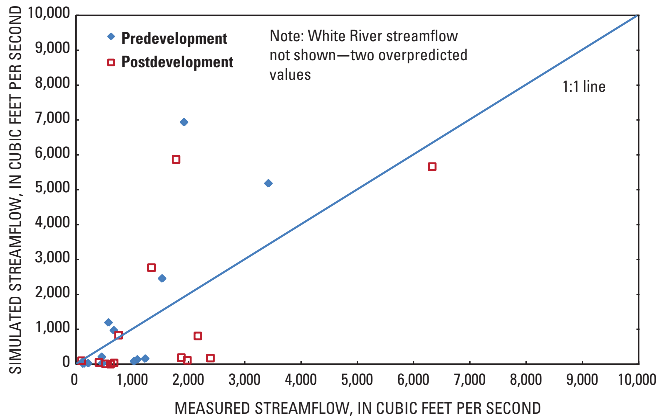


Figure 15. Simulated and measured streamflow.

Simulated and Observed Hydrographs

Simulated and observed hydrographs of hydraulic-head values completed in the alluvial aquifer and the middle Claiborne aquifer were used to examine the temporal trends of the model at selected wells in the model area (fig. 16). Hydrograph comparisons for the alluvial aquifer were based on wells used by Ackerman (1989). Most hydrograph comparisons for the middle Claiborne aquifer were based on wells used by Arthur and Taylor (1990). Though the simulated and observed hydrographs generally show declines in water levels, some hydrographs show slight increases in recent years (fig. 16 G, I, and J). Water-level increases can be attributed to various factors: water conservation, alternative water supplies, or the redistribution of well fields to pump from locations farther from the selected hydrograph wells (Freiwald and Johnson, 2007; Kingsbury, 1996).

The simulated and observed hydrographs show good agreement for most locations with relatively long periods of record (fig. 16). Some with a poorer fit to observed conditions (fig. 16 A and F) predict higher hydraulic heads throughout the period of measurement, or a steep decline in heads that observations do not reflect. Many of these differences are likely because of the placement and timing of pumping wells in the model, which are dependent on the accuracy of pumping data, as well as uncertainty in hydraulic property values.

Simulated and Observed Potentiometric Surfaces

Simulated potentiometric surfaces for 2007 generally agree with observed potentiometric surfaces (fig. 17). An embayment-wide potentiometric surface for the middle Claiborne aquifer was constructed representing the spring of 2007 (Schrader, 2007). The potentiometric surface was constructed using water-level measurements from 309 wells in Arkansas, 7 wells in Kentucky, 116 wells in Louisiana, 150 wells in Mississippi, 6 wells in Missouri, and 160 wells in Tennessee.

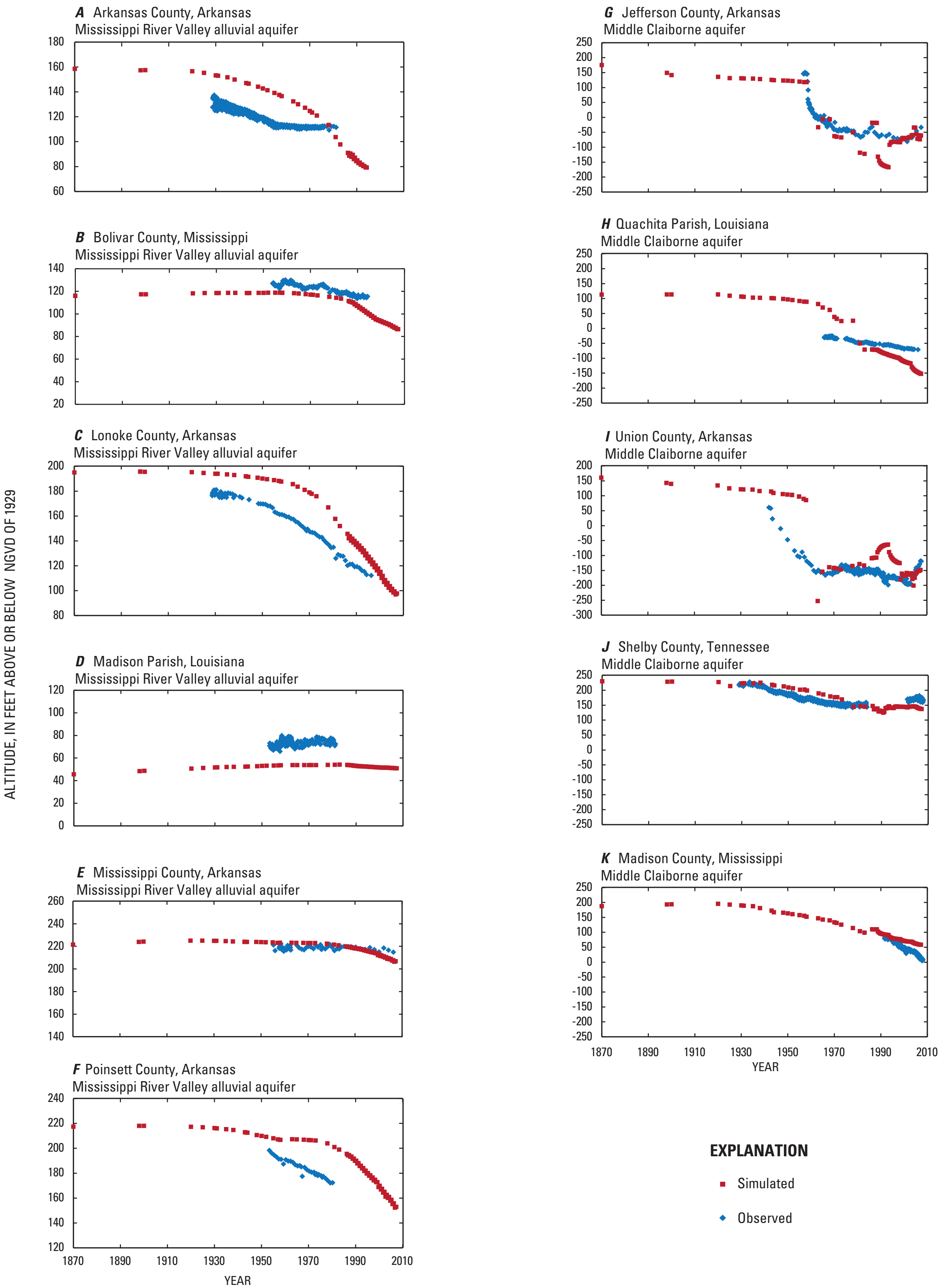
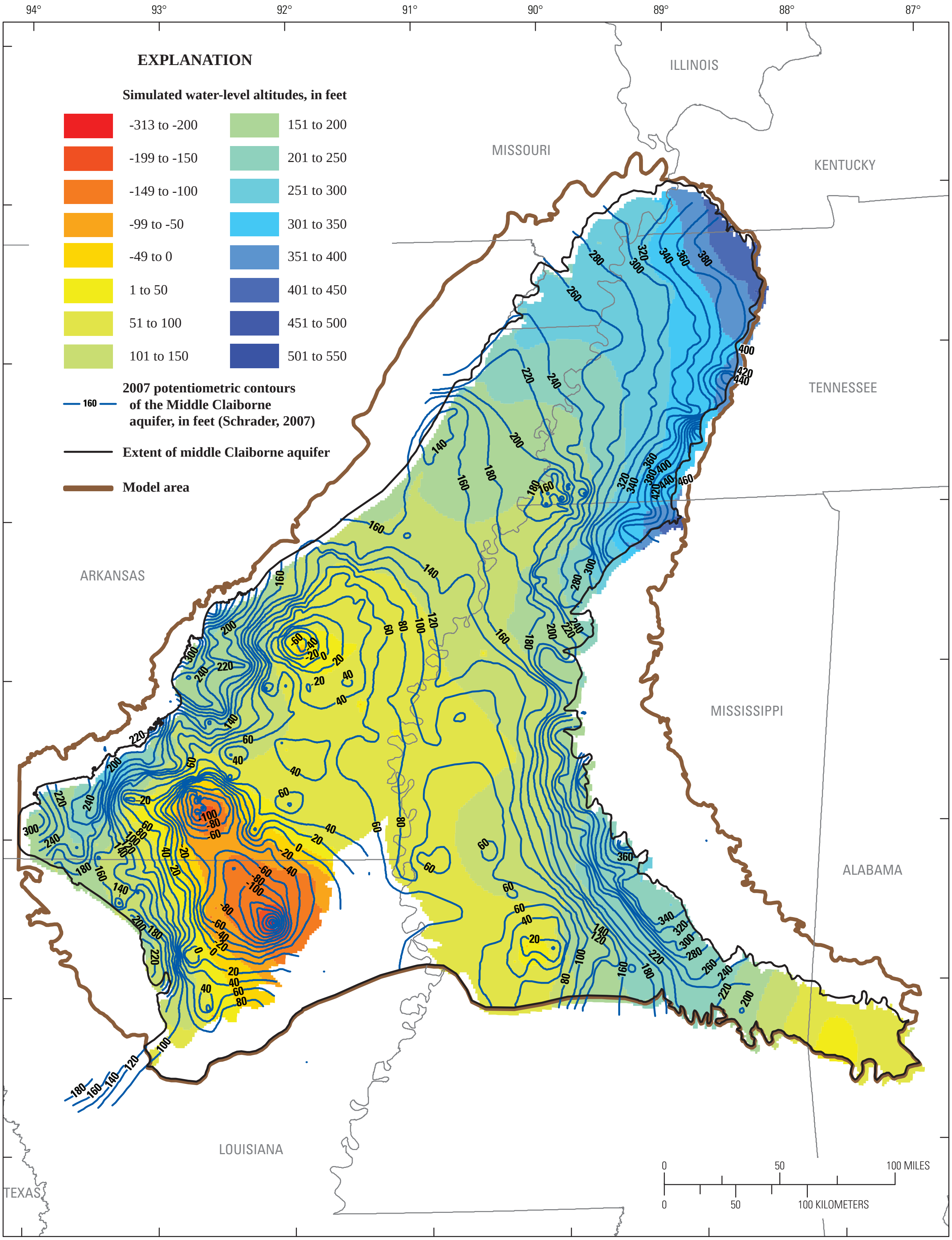


Figure 16. Simulated and observed hydrographs of hydraulic head in selected wells.



Potentiometric contours from Schrader (2007)

Figure 17. Potentiometric surface and simulated water levels for the middle Claiborne aquifer, 2007.

This potentiometric surface indicates a relief in water-level altitude of over 700 ft from the highest to lowest water level in the middle Claiborne aquifer. Potentiometric-surface contours for spring 2007, overlain on simulated hydraulic heads, give a reasonable qualitative match to cones of depression in central and southern Arkansas, northern Louisiana, and southern Mississippi (fig. 17). The simulated hydraulic heads also approximate large gradients in southern Arkansas, thought to be influenced by faulting in the area.

Sensitivity Analysis

The sensitivity of hydraulic heads to various model parameters was calculated using UCODE-2005 (Poeter and others, 2005). Composite scaled sensitivities (CSS) were calculated for all 104 parameters (table 3). CSS values aid in determining if there is adequate information in the calibration data to estimate a particular parameter. CSS values less than about 0.01 times the largest CSS indicate that the regression may not be able to estimate the parameter (Hill, 1998).

The CSS calculated using initial parameter values provided an indication of which model parameters were most important to estimate in the nonlinear-regression procedure and which should be set to fixed values. However, the CSS values are dependent on the parameter values because the sensitivities are a nonlinear function of the model parameters. Two of the defined parameters have CSS values greater than 10 (fig. 18): hydraulic conductivity of the middle Claiborne in the southwestern part of the model area (HK_sprt3) and hydraulic conductivity of the middle Claiborne aquifer primarily in the central part of the model area (HK_sprt2). The next highest parameters with a CSS over 6 are recharge to terrace deposits (RCHTRRC), hydraulic conductivity of the El Dorado Sand (HK_spes), and predevelopment precipitation (predevrch) (table 3).

Normality of Weighted Residuals

Normality of weighted residuals is a prerequisite for a valid regression. If the model accurately represents the system, the weighted residuals are expected to be random, independent, and normally distributed (Hill, 1998). The independence and normality of the weighted residuals can be assessed through use of (1) the summary statistic, R^2_N, which represents the correlation coefficient between the ordered weighted residuals and order statistics from the normal probability distribution function (Hill and others, 2000) and (2) a histogram of the weighted residuals. The weighted residuals are thought to be independent and normally distributed if the computed value of R^2_N for a calibration is higher than the tabulated critical value. The critical value of R^2_N is 0.987 for a set of 200 observations (maximum number of observations for which a value has been tabulated). The value of R^2_N for hydraulic heads in the model calibration is 0.95, which is smaller than the critical value; however Hill and Tiedeman (2007) state "correlations less than these critical values may

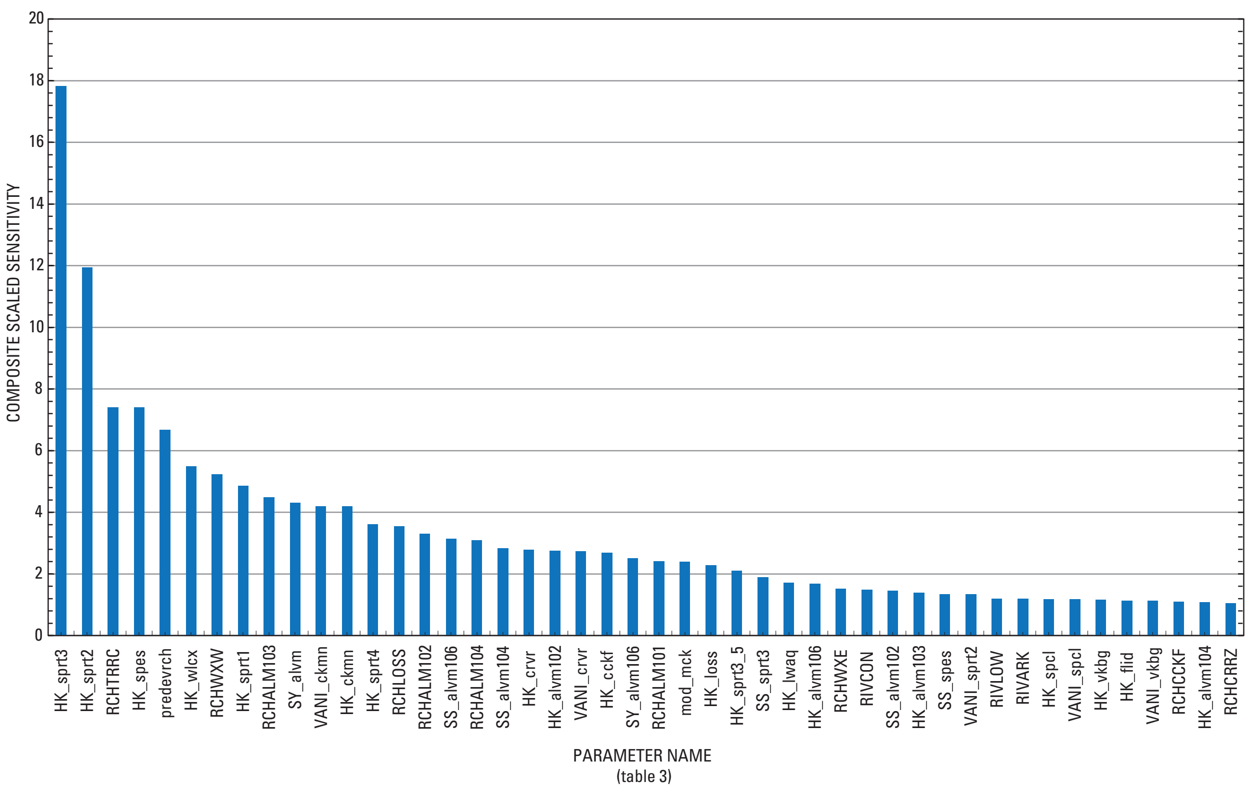


Figure 18. Composite scaled sensitivity values.

be acceptable…”. A histogram (fig. 19) of all 55,786 weighted residuals shows an approximately normal distribution with the mode occurring in the -25 ft to 25 ft interval.

Parameter correlations were computed using the approximate covariance matrix for the parameters, which is calculated as part of the nonlinear-regression method (Hill and others, 2000). If a pair of parameters has a correlation coefficient near 1.0 or -1.0, independent estimation of the two parameters is not possible given the calibration data set used in the regression. In the calibration, eight parameter pairs have correlations greater than 0.85.

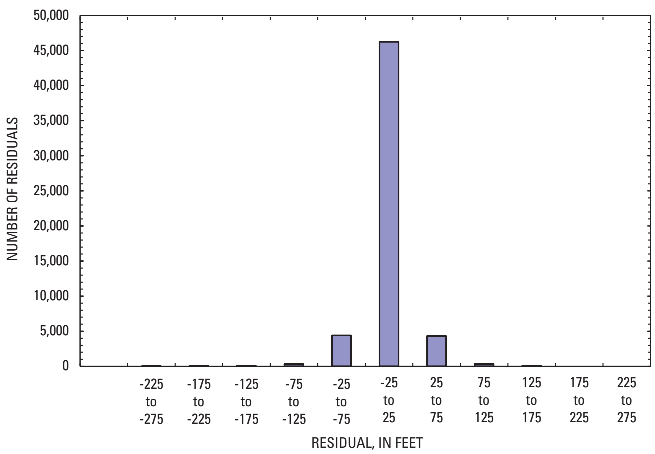


Figure 19. Histogram of weighted residuals.

Typically, correlations greater than 0.95 suggest problems with parameter nonuniqueness (Hill, 1998), and there were not enough observation data to independently estimate the model parameters. In these cases, the model may only be estimating the ratio or sum of the highly correlated parameters. HK_ckmn, VANI_ckmn, HK_crvr, and VANI_crvr (table 3) have the largest absolute correlations of any parameter pair at 1.0 each. However, through the use of SVDA during the calibration process of PEST, it was possible to estimate values for combinations of these parameters.

Graphical analyses of the weighted residuals facilitate assessment of model bias or error and of model fit to the calibration data. These analyses include plots of the weighted observed and weighted simulated values and of the spatial and temporal distribution of the weighted hydraulic-head residuals.

The plot of weighted observed and weighted simulated equivalents for an unbiased model ideally should show a random distribution of the weighted residuals above and below zero for all weighted simulated equivalents. In this case, the model fit is generally similar over the entire range of available hydraulic head values, and the calibration has, in general, the desired random distribution of weighted residuals (fig. 20).

Additional assessments of model error are accomplished through analysis of the spatial and temporal distribution of weighted residuals for years after 2000 (fig. 21). Different ranges in residuals are represented by a variety of geometric symbols for visual analysis of model bias. Residuals representing observation data following the year 2000 provide the best guide during model calibration because of (1) improved water-use data for later years and (2) the high number and uniform distribution of wells. Positive residuals, shown in blue, indicate simulated hydraulic heads that are higher than observed,

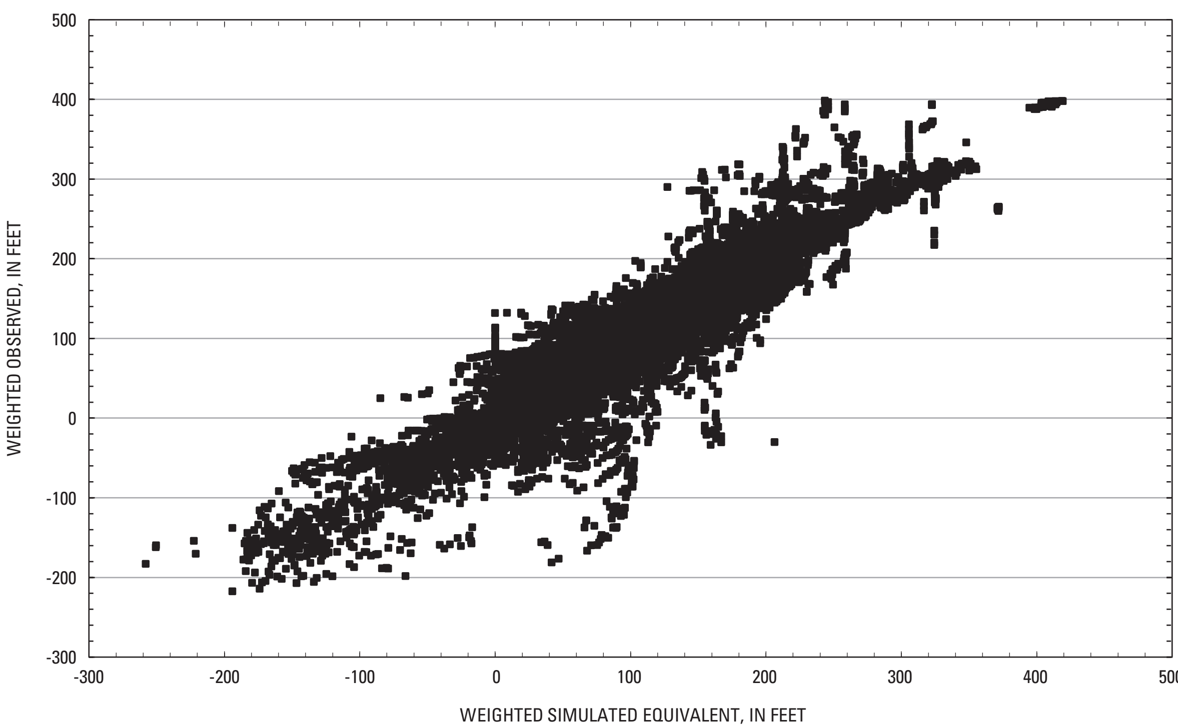


Figure 20. Weighted simulated equivalent plotted against weighted observed.

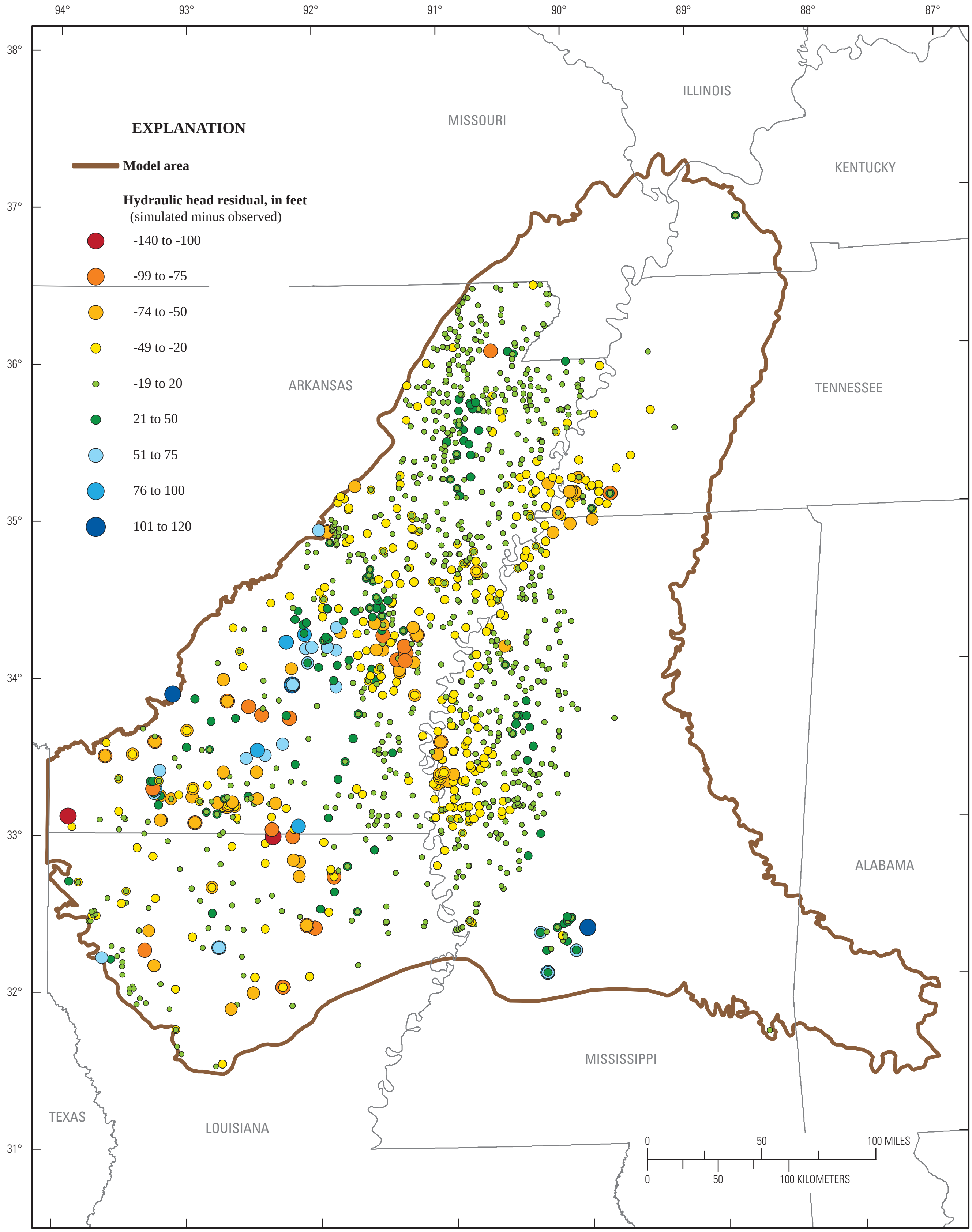


Figure 21. Spatial distribution of hydraulic-head residuals after 2000.

MS SCT 002596

while negative residuals indicate simulated hydraulic heads that are lower than observed.

Ideally, negative and positive weighted residuals should be small and randomly distributed in space. Clustering of residuals with similar magnitudes and signs is indicative of model bias. Overall, residuals (fig. 19) appear to be well distributed in both magnitude and sign (±). In many cases, insufficient reporting of well completion data makes it difficult to determine in which aquifer the well is screened or whether it is screened in both aquifers. The uncertainty of the aquifer assignment to a well may result in inaccurate assignment of the well within the model layers, which can affect the simulated water level and residual.

Geologic structure and averaging of pumpage data can affect model bias. A possible cause of model bias occurs in southern Arkansas where geologic studies suggest considerably more heterogeneity in geologic conditions and faulting than is presently mapped and represented by the simple zones and flow boundaries in the current model. In addition, model bias through time may be caused by the temporal averaging of groundwater withdrawals to obtain the mean annual pumpage used in each stress period and the spatial averaging of pumpage from several wells located in a single model cell.

The weighted residuals ideally should show no temporal bias and be balanced around zero. All of the weighted residuals are less than 250 ft in absolute value. Upward trends with time may occur because of some wells having hydraulic-head measurements only at later times in the simulation. For each year, the number of positive residuals is approximately equal to negative residuals, and there appears to be a slight trend through time from overprediction to underprediction as indicated by the mean for all observations (table 5).

Groundwater-Flow Budget

The groundwater-flow budget indicates changes in flow into (inflows) and out of (outflows) the model area from the predevelopment period (pre-1870) to 2007 (fig. 22). Negative rates indicate outflows from the groundwater system, and positive rates indicate inflows to the groundwater system. Total flow (sum of inflows or outflows) through the model ranged from about 600 Mgal/d in predevelopment to 18,197 Mgal/d near the end of the simulation. This increase in simulated flow through the model reflects increases in pumpage and inflow from the predevelopment condition. There are three inflows to the model listed from largest to smallest: withdrawal from storage, areal recharge, and stream leakage. There are three discharges or outflows listed from largest to smallest: pumpage from wells, addition to storage, and stream leakage. The pumpage from wells represents the largest outflow components with a net rate of 18,197 Mgal/d near the end of the model simulation in 2006. Groundwater outflows are offset primarily by inflow from aquifer storage.

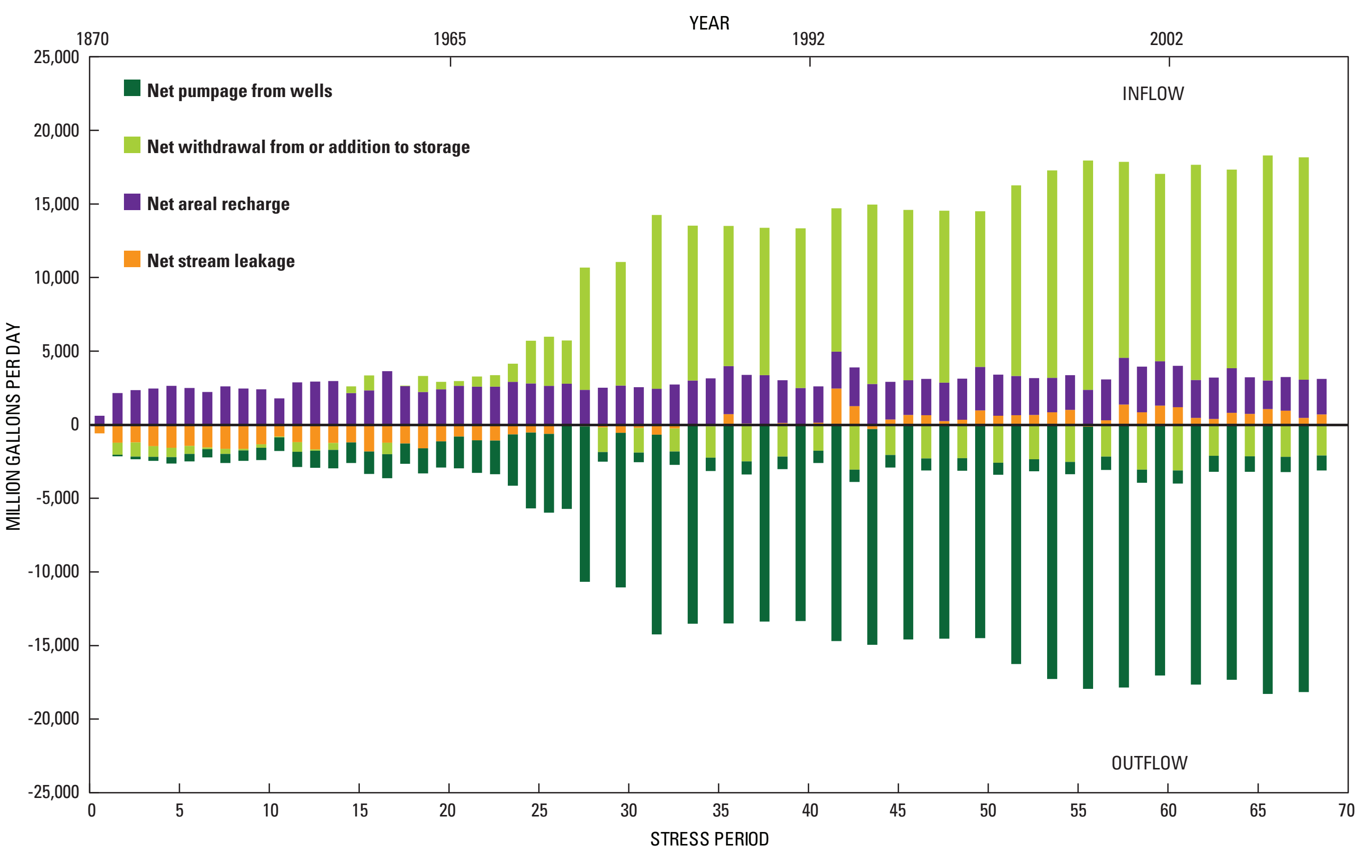


Figure 22. Groundwater-flow budget.

Limitation of Analyses

An understanding of model limitations is essential to effectively use flow and hydraulic head simulation results. The accuracy of a groundwater model is limited by simplification of complexities within the flow system (conceptual model), space and time discretization effects, and assumptions made in the formulation of the governing flow equations. Model accuracy also is affected by cell size, number of layers, accuracy of boundary conditions, accuracy and availability of hydraulic property data, accuracy of withdrawal and areal recharge estimates, historical data for calibration, parameter sensitivity, and the interpolations and extrapolations that are inherent in using data in a model. Although a model might be calibrated, the calibration parameter values are not unique in yielding acceptable distributions of hydraulic head.

Results of the MERAS model must be evaluated while taking into account the resolution of these limitations. The placement and timing of pumping wells in the model, which are dependent on the accuracy of pumping data, play a crucial role in the simulated hydraulic head and flow values. Much of the pumping data in the model is based on 5-year county totals and trend analysis from these 5-year totals. Very little site-specific pumping data are available relative to the temporal and spatial extent of the model area. Additionally, few data exist pertaining to wells that are screened through multiple hydrogeologic units. Though the model is capable of simulating multi-screened wells, assumptions were made regarding the number and location of these wells and number of hydrogeologic units through which they are screened. Data regarding predevelopment conditions for streamflow and hydraulic head are sparse to nonexistent, therefore model calibration to predevelopment conditions are not well constrained. The temporal disrectization of the model is determined, in part, by data resolution and, therefore, varies from 6 months to 28 years in stress period length. Each stress period incorporates average input values for pumpage, streamflow, and precipitation for the given time interval. Groundwater flow from underlying or adjacent systems is not well defined, though the contribution from such systems is considered negligible compared to the overall flow within the Mississippi embayment aquifer system. Model framework, which includes the altitude and thickness of hydrogeologic units, are based on available geophysical information, which varies spatially and vertically throughout the model area. Areas of sparse geophysical information may affect model results through assumptions in the altitude and thickness of these hydrogeologic units, and the lack of definition of structural controls that may affect groundwater movement. The horizontal hydraulic conductivity values assigned to many hydrogeologic units also are modified based on an assumption of sand percentage evaluated through the use of geophysical logs. The assumption of a no-flow boundary at the freshwater-saltwater interface and constant density of water may not be entirely valid, thus the need for simulations including variable density may be warranted in local areas where high salinity water is problematic.

The goal of the MERAS model was to develop a model capable of suitable accuracy at regional scales. The intent was not to reproduce individual local-scale details, which are typically not possible given the uniform cell size of 1 mi^2. Although the MERAS model may not represent each local-scale detail, it is relevant for a better understanding of the regional flow system.

Summary

The Mississippi Embayment Regional Aquifer Study (MERAS) was conducted with support from the Groundwater Resources Program of the U.S. Geological Survey Office of Groundwater. This report documents the model construction and calibration for use as a tool to quantify groundwater availability within the Mississippi embayment. To approximate the differential equations governing three-dimensional groundwater flow, the MERAS model used the U.S. Geological Survey's modular three-dimensional finite-difference code, MODFLOW-2005; the preconditioned conjugate gradient solver was used for the numerical solution technique. The model area boundary is approximately 78,000 mi^2 and includes eight States with approximately 6,900 mi of simulated streams, 70,000 well locations, and 10 primary hydrogeologic units. The finite-difference grid consists of 414 rows, 397 columns, and 13 layers. Each model cell is 1 mi^2 with varying thickness by cell and by layer. The simulation period extends from January 1, 1870, to April 1, 2007, for a total of 137 years and 69 stress periods. The first stress period is simulated as steady state to represent predevelopment conditions.

Areal recharge is applied throughout the MERAS model area using the MODFLOW-2005 Recharge Package. Recharge rates were estimated as a fraction (ranging from 1.25×10^{-4} to 7.06×10^{-2}) of precipitation based on typical literature values and soil type and modified during calibration of the regional model. Irrigation, municipal, and industrial wells are simulated using the Multi-Node Well Package. Pumpage from each multi-node well was input from site-specific data, 5-year water-use reports, and trend analysis. There are 43 streams simulated by the MERAS model. Each stream or river in the model area was simulated using the Streamflow-Routing Package of MODFLOW-2005. The base of the flow system is represented in the MERAS model as a no-flow boundary, which coincides with the top of the Midway confining unit. The downgradient limit of each model layer is a no-flow boundary, which approximates the extent of water with less than 10,000 mg/L dissolved solids. Initial conditions are simulated with a steady-state stress period (representing conditions prior to January 1, 1870) at the beginning of the simulation.

The MERAS model was calibrated by making manual changes to parameter values and examining residuals for hydraulic heads and streamflow. Additional calibration was achieved through alternate use of UCODE-2005 and PEST. Simulated heads were compared to 55,786 hydraulic-head measurements from 3,245 wells in the MERAS model area. Values of root mean square error between simulated and observed hydraulic heads ranged from 8.33 in 1919 to 47.65 in 1951, though only six annual root mean square error values are greater than 40 feet for the entire simulation period. The root mean square error for all observations in the model was 23.18 ft with a range in hydraulic-head altitudes of 741.66 ft. Simulated streamflow generally is lower than measured streamflow for streams with streamflow less than 1,000 ft^3/s, and greater than measured the streamflow for streams with streamflow more than 1,000 ft^3/s. Simulated streamflow is underpredicted for 18 observations and overpredicted for 10 observations in the model. These differences in streamflow illustrate the large uncertainty in model inputs such as predevelopment recharge, overland flow, pumpage (both from stream and aquifer), and precipitation, and observation weights.

The groundwater-flow budget indicates changes in flow into (inflows) and out of (outflows) the model area during the pregroundwater-irrigation period (pre-1870) to 2007. Total flow (sum of inflows or outflows) through the model ranged from about 600 million gallons per day in predevelopment to 18,197 million gallons per day near the end of the simulation. This increase in simulated flow through the model reflects increases in withdrawals and inflow from the pre-groundwater irrigation condition. The multi-node wells represent the largest outflow components with a net rate of 18,197 million gallons per day near the end of the model simulation in 2006. Groundwater outflows are offset primarily by inflow from aquifer storage and recharge.

Acknowledgments

The compilation of data for thousands of pumping and observations wells, miles of simulated rivers, streamflow, and the hydrogeologic framework for an area of this size in a relatively short period of time into a manageable model was not a trivial task. The authors would like to thank those who have given their time and expertise in model simulations and construction: Arlen Harbaugh, Tom Reilly, Connor Haugh, and Randy Hunt, as well as many others who have contributed to this investigation.

References Cited

Ackerman, D.J., 1989, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States – A preliminary assessment of the regional flow system: U.S. Geological Survey Water-Resources Investigations Report 88-4028, 80 p.

Ackerman, D.J., 1996, Hydrology of the Mississippi River Valley alluvial aquifer, South-Central United States: U.S. Geological Survey Professional Paper, 1416-D, 56 p.

Albin, D.R., 1964, Geology and ground-water resources of Bradley, Calhoun, and Ouachita Counties, Arkansas: U.S. Geological Survey Water Supply Paper 1779-G, 32 p.

Arthur, J.K., and Taylor, R.E., 1998, Ground-water flow analysis of the Mississippi embayment aquifer system, south-central United States: U.S. Geological Survey Professional Paper, 1416-I, 148 p.

Arthur, J.K., and Taylor, R.E., 1990, Definition of the geohydrologic framework and preliminary simulation of ground-water flow in the Mississippi embayment aquifer system, Gulf Coastal Plain, United States: U.S. Geological Survey Water Resources Investigations Report, 86-4364, 97 p.

Arthur, J.K., 2001, Hydrogeology, model description, and flow analysis of the Mississippi River alluvial aquifer in northwestern Mississippi: U.S. Geological Survey Water-Resources Investigations Report, 2001-4035, 47 p.

Beckman, J.D., and Williamson, A.K., 1990, Salt-dome locations in the Gulf Coastal Plain, South-Central United States: U.S. Geological Survey Water-Resources Investigations Report 90-4060, 44 p.

Brahana, J.V., and Broshears, R.E., 2001, Hydrogeology and ground-water flow in the Memphis and Fort Pillow aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 89-4131, 56 p.

Brahana, J.V., and Mesko, T.O., 1988, Hydrogeology and preliminary assessment of regional flow in the upper Cretaceous and adjacent aquifers in the northern Mississippi embayment: U.S. Geological Survey Water-Resources Investigations Report, 87-4000, 65 p.

Clark, B.R., Landon, M.K., Kauffman, L.J., and Hornberger, G.Z., 2008, Simulations of ground-water flow, transport, age, and particle tracking near York, Nebraska, for a study of transport of anthropogenic and natural contaminants (TANC) to public supply wells: U.S. Geological Survey Scientific Investigations Report 2007–5068, 48 p.

Cushing, E.M., Boswell, E.H., Speer, P.R., and Hosman, R.L., 1970, Availability of water in the Mississippi embayment: U.S. Geological Survey Professional Paper, 448-A, 11 p.

Daly, C., Taylor, G.H., Gibson, W.P., Parzybok, T.W., Johnson, G.L, Pasteris, P., 2000, High-quality spatial climate data sets for the United States and beyond: Transactions of the American Society of Agricultural Engineers, V. 43, p. 1957-1962.

Doherty, John, 2008, PEST model-independent parameter estimation user manual: 5th ed., Watermark Numerical Computing, accessed October 28, 2008 at http://www.grac.org/pest.html

Doherty, John, 2003, Ground water model calibration using pilot points and regularization: Ground Water v. 41, no. 2, p. 170-177.

Doherty, J., and Hunt, R.J., 2009, Two statistics for evaluating parameter identifiability and error reduction. Journal of Hydrology v. 366, p. 119-127.

Fenneman, N.M., and Johnson, D.W., 1946, Physical divisions of the United States (Map): Washington, D.C., U.S. Geological Survey.

Fetter, C.W., 1994, Applied hydrogeology, (3d ed.): New York, MacMillan College Publishing Co., Inc., 691 p.

Fienen, M.N., Muffles, C.T., and Hunt, R.J., 2009, On constraining pilot point calibration with regularization in PEST: Ground Water, 2009, accessed September 29, 2009, at http://www3.interscience.wiley.com/cgi-bin/fulltext/122343976/HTMLSTART

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

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

Freiwald, D.A., and Johnson, S.F., 2007, Monitoring of Sparta aquifer recovery in southern Arkansas and northern Louisiana, 2003-07: U.S. Geological Survey Fact Sheet 2007-3102, 4 p.

Halford, K.J. and Hanson, R.T., 2002, User guide for the drawdown-limited, multi-node well (MNW) package for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, versions MODFLOW-96 and MODFLOW-2000: U.S. Geological Survey Open-File Report 02-293, 33 p.

Hall, D.H., 1989, Estimated use of water in Missouri during 1985: U.S. Geological Survey Water-Resources Investigations Report 89-4038, 1 sheet.

Hanson, R.T, Li, Zhen, and Faunt, C.C., 2004, Documentation of the Santa Clara Valley regional ground-water/surface-water flow model, Santa Clara County, California: U.S. Geological Survey Scientific Investigations Report 2004-5231, 75 p.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model—The ground-water flow process: U.S. Geological Survey Techniques and Methods 6-A16, variously paged.

Hart, R.M., Clark, B.R., and Bolyard, S.E., 2008, Digital hydrogeologic surface and thickness for the hydrogeologic units of the Mississippi Embayment Regional Aquifer Study (MERAS): U.S. Geological Survey Scientific Investigations Report 2008-5098, 33 p., accessed December 4, 2008, at http://pubs.usgs.gov/sir/2008/5098/pdf/SIR2008-5098.pdf

Hart, R.M., and Clark, B.R., 2008a, Geophysical well-log database for the Mississippi Embayment Regional Aquifer Study (MERAS): U.S. Geological Survey Scientific Investigations Report 2008-5192, 8 p., accessed December 4, 2008, http://pubs.usgs.gov/sir/2008/5192/pdf/SIR2008-5192.pdf

Hart, R.M. and Clark, B.R., 2008b, Automated method using geophysical logs to determine hydrogeologic unit sand percent for ground-water model development: *in* Poeter, E.P., Zheng, C., Hill, M.C., eds. Proceedings, Modflow and more 2008, Ground Water and Public Policy: Golden, CO, Colorado School of Mines, May 19-21, 2008, p. 138-142.

Hays, P.D, Lovelace, J.K., and Reed, T.B., 1998, Simulated response to pumping stress in the Sparta aquifer of southeastern Arkansas and north-central Louisiana, 1998-2027: U.S. Geological Survey Water-Resources Investigations Report 98-4121, 25 p.

Hill, M.C., 1990, Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90-4048, 43 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration: U.S. Geological Survey Water-Resources Investigations Report 98-4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., Anderman, E.R., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model-user guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 209 p.

Hill, M.C., and Tiedeman, C.R., 2007, Effective groundwater model calibration: Hoboken, New Jersey, John Wiley & Sons, Inc., , 455 p.

Holland, T.W., 1999, Water use in Arkansas, 1995: U.S. Geological Survey Open-File Report 99-188, 1 sheet.

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

Hosman, R.L., 1988, Geohydrologic framework of the Gulf Coastal Plain: U.S. Geological Survey Hydrologic Investigations Atlas 695, scale 1:2,500,000, 2 sheets.

Hosman, R.L., 1996, Regional stratigraphy and subsurface geology of Cenozoic deposits, Gulf Coastal Plain, South-Central United States: U.S. Geological Survey Professional Paper 1416-G, 35 p.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas Coastal Uplands aquifer systems, South-Central Unites States: U.S. Geological Survey Professional Paper 1416-B, 19 p.

Hunt, R.J., Doherty, J., and Tonkin, M.J., 2007, Are models too simple? Arguments for increased parameterization: Ground Water, v. 45, no. 3, 254-262.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004, Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

Johnson, P.M., 1994, Estimated water withdrawals in Mississippi during 1990: U.S. Geological Survey Fact Sheet 94-060, 2 p.

Kingsbury, J.A., 1996, Altitude of the potentiometric surfaces, September 1995, and historical water-level changes in the Memphis and Fort Pillow aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 96-4278, 1 sheet.

Kingsbury, J.A., and Parks, W.S., 1993, Hydrogeology of the principal aquifers and relation of faults to interaquifer leakage in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93-4075, 22 p.

Kleiss, B.A., Coupe, R.H., Gonthier, G.J., and Justus, B.J., 2000, Water quality in the Mississippi embayment, Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky, 1995–98: U.S. Geological Survey Circular 1208, 36 p., online at http://pubs.water.usgs.gov/circ1208/

Lloyd, O.B., Jr., and Lyke, W.L., 1995, Ground water atlas of the United States: Segment 10, Illinois, Indiana, Kentucky, Ohio, Tennessee: U.S. Geological Survey Hydrologic Atlas 730-K.

Mahon, G.L., and Ludwig, A.H., 1990, Simulation of ground-water flow in the Mississippi River alluvial aquifer in eastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 89-4145, 57 p.

Mahon, G.L., and Poynter, D.T., 1993, Development, calibration, and testing of ground-water flow models for the Mississippi River Valley alluvial aquifer in eastern Arkansas using one-square-mile cells: U.S. Geological Survey Water-Resources Investigations Report 92-4106, 33.

Mancini, E.A., and Tew, B.H., 1994, Claiborne-Jackson Group contact (Eocene) in Alabama and Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 431-439.

McKee, P.W., and Clark, B.R., 2003, Development and calibration of a ground-water flow model for the Sparta aquifer of southeastern Arkansas and north-central Louisiana and simulated response to withdrawals, 1998-2027: U.S. Geological Survey Water-Resources Investigations Report 03-4132, 71 p.

McMahon, P.B., Dennehy, K.F., Bruce, B.W., Böhlke, J.K., Michel, R.L., Gurdak, J.J., and Hurlbut, D.B., 2006, Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, United States: Water Resources Research, v. 42, no. 3, p. 1-18.

Mehl, S.W., and Hill, M.C., 2007, MODFLOW-2005, The U.S. Geological Survey modular ground-water model—Documentation of the multiple-refined-areas capability of Local Grid Refinement (LGR) and the Boundary Flow and Head (BFH) Package: U.S. Geological Survey Techniques and Methods 6-A21, 13 p.

Mooty, W.S., and Richardson, J.R., 1998, Water use in Alabama, 1995: U.S. Geological Survey Water-Resources Investigations Report 98-4154, 92 p.

Murray, L.C. Jr., 2007, Analysis of water-level differentials and variations in recharge between the surficial and Upper Floridan aquifers in east-central and northeast Florida: U.S. Geological Survey Scientific Investigations Report, 2007-5081, 58 p.

National Oceanic and Atmospheric Administration, 2009, NOAA Southern Regional Climate Center, accessed January 13, 2009 at http://www.srcc.lsu.edu/southernClimate/atlas/

Nyman, D.J., 1965, Predicted hydrologic effects of pumping from the Lichterman well field in the Memphis area, Tennessee: U.S. Geological Survey Water Supply Paper 1819-B, 26 p.

Parks, W.S., 1990, Hydrogeology and preliminary assessment of the potential for contamination of the Memphis aquifer in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 90-4092, 39 p.

Parks, W.S. and Lounsbury, R.W., 1976, Summary of some current and possible future environmental problems related to geology and hydrology at Memphis, Tennessee: U.S. Geological Survey Water-Resource Investigations, 4-76, 34 p.

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

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

Pettijohn, R.A., Weiss, J.S., and Williamson, A.K., 1988, Distribution of dissolved-solids concentrations and temperature in ground water of the Gulf Coast aquifer systems, South-Central United States: U.S. Geological Survey Water-Resources Investigations Report 88-4082, scale 1:3,500,000, 5 sheets.

Poeter, E.P., Hill, M.C., Banta, E.R., Mehl, Steffen, and Christensen, Steen, 2005, UCODE_2005 and six other computer codes for universal sensitivity analysis, calibration, and uncertainty evaluation: U.S. Geological Survey Techniques and Methods 6-A11, 283 p.

PRISM Group, 2006, PRISM Group, accessed September 12, 2006, at www.ocs.orst.edu/prism/.

Prudic, D.E., Konikow, L.F., and Banta, E.R., 2004, A new streamflow-routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open-File Report 2004-1042, p. 95.

Prudic, D.E., 1991, Estimates of hydraulic conductivity from aquifer-test analyses and specific capacity data, Gulf Coast Regional Aquifer Systems, South-Central United States: U.S. Geological Survey Water-Resources Investigations Report 90-4121, 38 p.

Reed, T.B., 2003, Recalibration of a ground-water flow model of the Mississippi River Valley alluvial aquifer of northeastern Arkansas, 1918-1998, with simulations of water levels caused by projected ground-water withdrawals through 2049: U.S. Geological Survey Water-Resources Investigations Report 2003-4109, 58 p.

Reed, J.E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geological Survey Hydrologic Atlas, HA 434, 5 maps.

Sargent, B.P., 2007, Water use in Louisiana, 2005: Louisiana Department of Transportation and Development Water Resources Special Report no. 16, 133 p.

Saucier, R.T., 1994, Geomorphology and Quaternary geologic history of the Lower Mississippi Valley, Volume I: U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, 400 p.

Scheiderer, R.M. and Freiwald, D.A., 2006, Monitoring the recovery of the Sparta aquifer in southern Arkansas and northern Louisiana: U.S. Geological Survey Fact Sheet 2006-3090, 4 p.

Schrader, T.P., 2007, Potentiometric surface in the Sparta-Memphis aquifer of the Mississippi Embayment, spring 2007: U.S. Geological Survey Scientific Investigations Map 3014, 1 sheet.

Schrader, T.P., 2001, Status of water levels and selected water-quality conditions in the Mississippi River valley alluvial aquifer in eastern Arkansas, 2000: U.S. Geological Survey Water-Resources Investigations Report, 2001-4124, 52 p.

Sholar, C.J., and Wood, P.A., 1995, Water use in Kentucky, 1990: U.S. Geological Survey Water-Resources Investigations Report 95-4032, 51 p.

Spiers, C.A., 1977, The Winona-Tallahatta aquifer in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 77-125, 1 map.

Stanton, G.P., and Clark, B.R., 2003, Recalibration of a ground-water flow model of the Mississippi River Valley alluvial aquifer in southeastern Arkansas, 1918-1998, with simulations of hydraulic heads caused by projected ground-water withdrawals through 2049: U.S. Geological Survey Water-Resources Investigations Report 03-4232, 48 p.

Stephenson, L.W., Logan, W.N., Waring, G.A., and Howard, C.S., 1928, The ground-water resources of Mississippi, with discussions of the chemical character of the waters: U.S. Geological Survey Water Supply Paper 576, 515 p.

Stuart, M., Klotz, C., and Kascak, C., 1996, Agricultural resources and environmental indicators: U.S. Department of Agriculture Economic Research Service Number 17, 4 p.

Sumner, D.M., and Wasson, B.E., 1990, Geohydrology and simulated effects of large ground-water withdrawals on the Mississippi River alluvial aquifer in northwestern Mississippi: U.S. Geological Survey Water Supply Paper 2292, 60 p.

Tikhonov, A.N., 1963, Solution of incorrectly formulated problems and the regularization method: Soviet Mathematics, Doklady, v. 4, p. 1035–1038.

Tonkin, M. J., and Doherty, J., 2005, A hybrid regularized inversion methodology for highly parameterized environmental models, Water Resources Research, v. 41, no. 10, p. 1-16.

U.S. Geological Survey, 2008a, Office of Ground Water (OGW), accessed October 15, 2008, at http://water.usgs.gov/cgi/rasabiblio/?category=11&form=introduction.

U.S. Geological Survey, 2008b, The USGS Land Cover Institute (LCI), accessed October 15, 2008, at http://landcover.usgs.gov/natllandcover.php.

U.S. Geological Survey, 2008c, USGS water data for the Nation, accessed February 6, 2007, at http://waterdata.usgs.gov/nwis

Veach, A.C., 1906, Geology and underground water resources of northern Louisiana and southern Arkansas: U.S. Geological Survey Professional Paper 46, 422 p.

Warwick, P.D., SanFilipo, J.R., Crowley, S.S., Thomas, R.E., Freid, J., and Tulley, J.K., 1997, Map showing outcrop of the coal-bearing units and land use in the Gulf Coast Region: U.S. Geological Survey Open-File Report 97-172, 1 sheet.

Williamson, A.K., Grubb, H.F., and Weiss, J.S., 1990, Ground-water flow in the Gulf Coast aquifer systems, South-Central United States – A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 89-4071, 134 p.

Williams, T.A., and Williamson, A.K., 1989, Estimating water-table altitudes for regional ground-water flow modeling, U.S. Gulf Coast: Ground Water v. 27, no. 3, p. 333-340.

Wolock, D., 2003, Flow characteristics at U.S. Geological Survey streamgages in the conterminous United States: U.S. Geological Survey Open-File Report 2003-146, vector digital data.

Publishing support provided by:
Lafayette and Rolla Publishing Service Centers

For more information concerning the research
described in the report:

U.S. Geological Survey
Arkansas Water Science Center
401 Hardin Road
Little Rock, AR 72211-3528
(501) 228-3600

http://ar.water.usgs.gov

USGS

Clark and Hart—**The Mississippi Embayment Regional Aquifer Study (MERAS)**—Scientific Investigations Report 2009–5172

EXHIBIT 11

R.L. Hosman, A.T. Long, T.W.Lambert, H.G. Jeffery
Water Resources of the Mississippi Embayment:
Tertiary Aquifers in the Mississippi Embayment
USGS Professional Paper 448-D

USGS Publications Warehouse

Web Page Hardcopy

Wednesday, August 15, 2007 8:56:46 AM

Publications Warehouse

Search USGS bibliographic citations and obtain USGS products

Printed From: http://pubs.er.usgs.gov/usgspubs/pp/pp448D

This print version of the page is optimized to print only the content portions of the web page your were viewing and is not intended to have the same formatting as the original page.

Publications Warehouse

Publication Citation

Previous Citation ● Viewing Record #17 ● ***Next Citation***

USGS Series	Professional Paper
Report Number	448-D
Title	Water resources of the Mississippi embayment; Tertiary aquifers in the Mississippi embayment, with discussions of quality of the water
Edition	-
Language	ENGLISH
Author(s)	Hosman, R. L.; Long, A. T.; Lambert, T. W.; Jeffery, H. G.; and others
Year	1968
Originating office	
USGS Library Call Number	-
Physical description	p. D1-D29
ISBN	

Online Document Versions

-
    - *View Report as .DJVU* *Requires plug-in*
    - *View Plate as .DJVU* *Requires plug-in*

    Download free Lizardtech plug-in now. Plug-in provides searchable text, section 508 compliant accessibility, advanced navigation , and print controls.

    - *View Report as group of images* (No plug-in required)
    - *View Plate as group of images* (No plug-in required)

In Stock at the USGS Store

Tertiary Aquifers in the Mississippi Embayment

By R. L. HOSMAN, A. T. LONG, T. W. LAMBERT, *and others*

With discussions of QUALITY OF THE WATER

By H. G. JEFFERY

WATER RESOURCES OF THE MISSISSIPPI EMBAYMENT

GEOLOGICAL SURVEY PROFESSIONAL PAPER 448–D

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1968

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

[Plates are in separate volume]

TABLES

WATER RESOURCES OF THE MISSISSIPPI EMBAYMENT

TERTIARY AQUIFERS IN THE MISSISSIPPI EMBAYMENT

By R. L. Hosman, A. T. Long, T. W. Lambert, and others

ABSTRACT

The aquifers of Tertiary age contain water having less than 1,000 parts per million dissolved solids in an area of about 75,000 square miles and are used as sources of water supply in almost all this area. The total withdrawal from Tertiary aquifers is about 500 million gallons per day. In much of the area, two or more Tertiary aquifers are available for development, although generally only the shallowest aquifer is used. Most of the Tertiary aquifers are areally extensive, and some contain fresh water at depths in excess of 2,000 feet.

The aquifers are recharged by precipitation on the outcrop and by downward percolation of water from overlying alluvium where the outcrops are covered by Quaternary deposits.

Although analysis of test data shows that the hydraulic characteristics of the Tertiary aquifers differ from aquifer to aquifer and vary within any given aquifer, the permeabilities of the lower Wilcox aquifer are generally more consistent and higher than for other Tertiary aquifers. However, a hydrologic unit of the Claiborne Group, the Memphis aquifer–Sparta Sand, is the most productive.

The temperature of the water from the Tertiary aquifers ranges from about 62°F to 97°F. All the Tertiary aquifers contain water of good quality, but the quality generally deteriorates with depth as mineralization increases. Excessive mineralization occurs at depths of a few hundred feet to more than 3,000 feet. Generally, water in the Tertiary aquifers at shallow depths or where recharge occurs from overlying Quaternary alluvium is a calcium bicarbonate type with varying amounts of magnesium and iron; downdip, the water changes to a sodium bicarbonate–sodium chloride type with varying amounts of magnesium and sulfate. Iron is the most troublesome chemical constituent; the content generally decreases with depth. Locally, saline water occurs in aquifers that are shallower than other aquifers containing fresh water. The Sparta Sand contains mineralized water at shallow depths in an area both updip and downdip from fresh water.

Flowing wells can be obtained from Tertiary aquifers in a few low-lying areas associated with major streams. Although unrestricted flow from wells has contributed to water-level declines, most declines are the result of pumping, and no regional overdevelopment is indicated. Only one aquifer, the Sparta Sand, shows signs of pending or possible local overdevelopment. Collectively, the Tertiary aquifers are capable of sustaining more extensive development, and some aquifers are untapped by wells in large areas where they contain fresh water.

INTRODUCTION

This report is one of a series describing the aquifers in the Mississippi embayment (fig. 1). The aquifers are grouped according to geologic age into pre-Cretaceous, Cretaceous, Tertiary, and Quaternary. The Tertiary aquifers are defined and described in this chapter.

Sediments of the Tertiary System occur on the surface (fig. 2) or in the subsurface of about 75 percent of the Mississippi embayment and have a maximum aggregate thickness of about 7,000 feet. Much of the Tertiary outcrop, especially that west of the Mississippi River and north of the Arkansas River, is covered by Quaternary deposits. Many of the Tertiary sands are thick and extensive and contain fresh (less than 1,000 parts per million dissolved solids) water in areas of many thousands of square miles and form regional aquifers. Other sands that are not extensive or contain fresh water in limited areas are, nevertheless, locally productive aquifers. The principal Teritary aquifers are in the Wilcox Group (Formation) and the Claiborne Group; most are in the Claiborne.

The Tertiary System contains the most extensive aquifers in the Mississippi embayment, and most of the water is under artesian pressure. Areas of use, where producing wells tap the aquifers, are shown on plates 3–8, as are areas of potential use, where the aquifers contain fresh water but wells have not been drilled into the aquifer. The areas of use can also be considered as areas of potential use because the aquifers in these areas are generally capable of supporting much heavier withdrawals.

Stratigraphic relations of the Tertiary units are shown by nine geologic sections (pls. 1, 2), and table 1 lists the oil tests and wells used in the sections. Table 2 shows the geologic columns used by the U.S. Geological Survey and the units that are or include aquifers.

Temperature of the water from the Tertiary aquifers ranges from about 62°F to about 97°F (fig. 3).

Data used in the preparation of the maps showing top of unit, thickness, percentage of sand, and areal extent of fresh water were obtained from the interpretation of electric logs of water wells and oil-test wells. Chemical analyses were used to verify the areas of fresh and mineralized water. Drillers' logs were used in areas where electric logs were not available, and

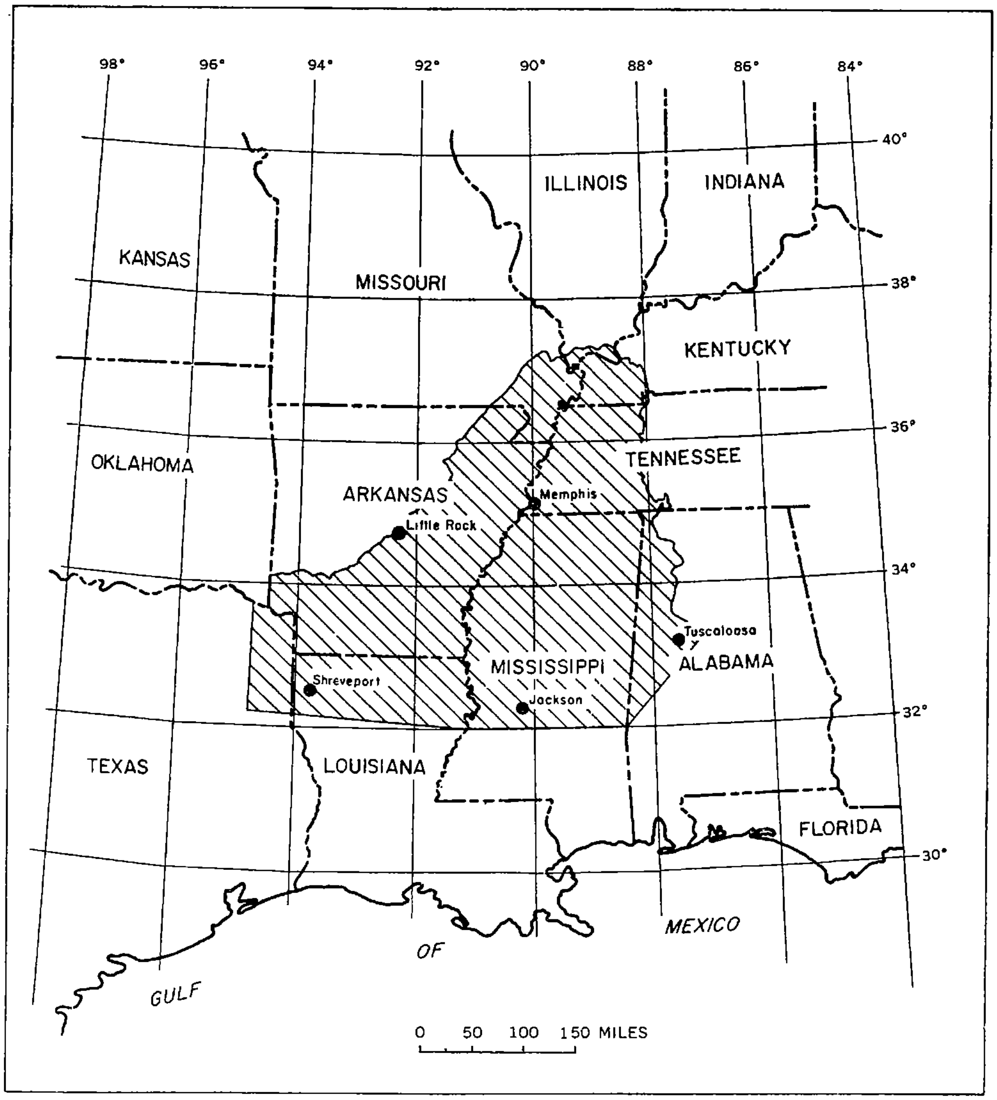


FIGURE 1.—Area of embayment study.

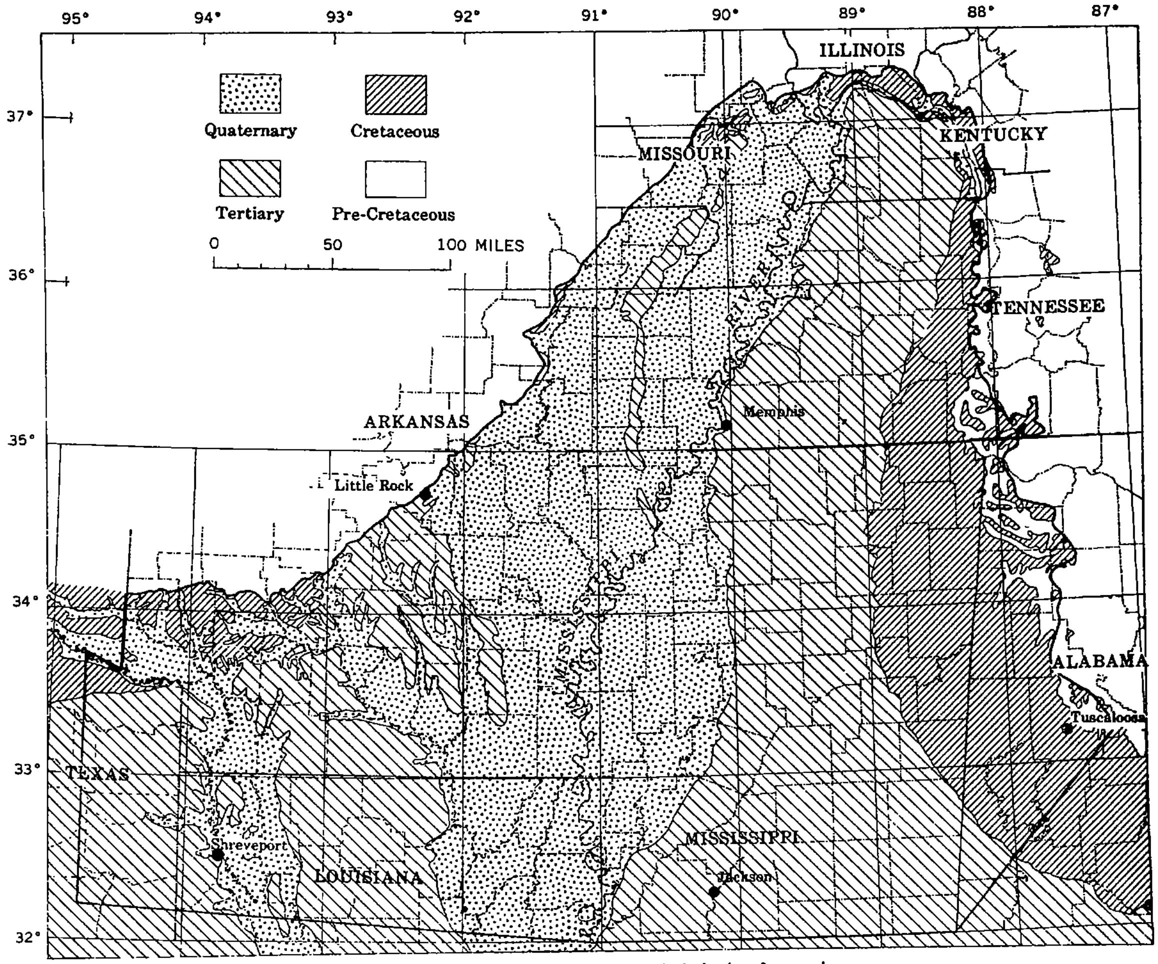


FIGURE 2.—Generalized geology of the Mississippi embayment.

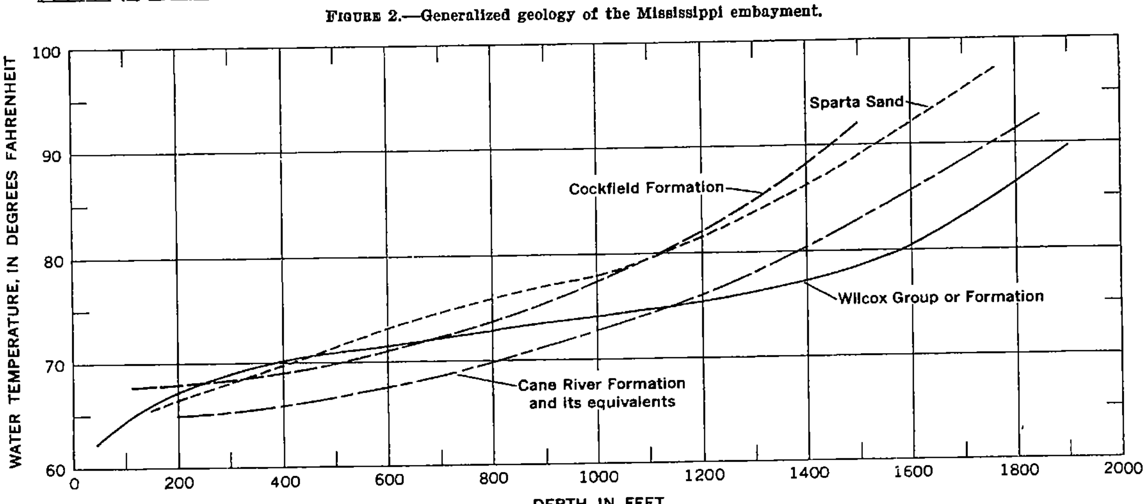


FIGURE 3.—Average temperature gradients of water from Tertiary aquifers.

some microscopic and micropaleontologic examinations of well cuttings were made to verify the geologic interpretations. Maps showing the percentage of sand generally indicate the water-bearing potential of each unit; the higher percentages are associated with the more favorable areas.

This investigation and the preparation of this report were under the direction of E. M. Cushing. Fieldwork and data synthesis and analysis for the report were done by J. G. Newton for Alabama, R. L. Hosman for Arkansas, T. W. Lambert and L. M. MacCary for Kentucky, Illinois, and Missouri, E. H. Boswell for Mississippi, G. K. Moore for Tennessee, and A. T. Long for Texas and Louisiana. Interpretation of quality-of-water data was done by H. G. Jeffery. Lithologic and micropaleontologic studies were done by S. M. Herrick.

TABLE 1.—*Oil tests and wells shown on geologic sections*

State and county or parish	Well	Company or driller	Name
Arkansas			
Calhoun	28	Lion Oil Co	Core hole C-4.
Do	49	Garland Anthony	Brazil 1.
Cleveland	48	G F G Oil Co	C. E. Young 1.
Do	45	Frank and George Frankel.	Ulna Edwards 1.
Do	46	Carter Oil Co	Foster-Grayson B-1.
Craighead	16	Tennark, Inc	Ruby Martin 1.
Crittenden	70	M. E. Davis	De Mange 1.
Do	71	Stanley Oil Corp	Danner 1.
Cross	14	Cross Oil Co	Newman Bros. 1.
Do	15	Seaboard Oil Co	F. S. Tilley 1.
Do	69	Ramsey Petroleum Co.	Singer 1.
Dallas	6	H. M. Mills	Sparkman Lumber Co. Horne 1.
Do	7	I. F. Stone	Herbert E. Walsh 1.
Desba	63	Hunt Oil Co	J. B. Thornton 1.
Do	64	Honolulu Oil Corp	Anderson Tully 1.
Do	65	Delta Caribbean Oil Corp.	Grief Brothers 1.
Do	90	W. Shannon	S. A. Banks 1.
Grant	8	Connelly and Froderman.	Ashcraft 1.
Do	47	Stratton Drilling Co	J. Stupka 1.
Jefferson	9	F. R. Jackson, and others.	David N. Ford 1.
Lafayette	3	Barnsdall Oil Co	Bond S-1.
Lee	1	U.S. Geological Survey.	U.S. Forest Service 1.
Do	3	City of Marianna, Ark.	Water well.
Do	97	Cockburn Oil Co	L. W. Robinson 1.
Do	54	Curtis Kinard	Payne Estate 1.
Lonoke	10	Seaboard Oil Co	S.A. Hovis 1.
Miller	1	Barnsdale Oil Co	Nichols 1.
Do	2	Carter Oil Co	H. B. Carroll 3.
Monroe	2	Seaboard Oil Co	E. L. Medford 1.
Do	12	Sohio Products Co	D. Gann 1.
Nevada	4	Barney Dunlap	Ervin Hart 1.
Ouachita	5	Hunt Oil Co	Mollie Purifoy 1.
Phillips	3	Ambassador Oil Corp.	Thompson Unit 1.
Do	61	McAlester Fuel Co	Welch 1.
Do	62	Plymouth Oil Co	J. R. Bush 1.
Prairie	2	M. W. Martin	Steward 1
Do	11	Victory Development Co.	Clayton 1.
Do	73	R. E. Smith	Stewart 1.
St. Francis	13	Barnwell Drilling Co	Thombaugh 1.
Union	50	R. T. Adams	Winn 1.
Woodruff	68	Magnolia Petroleum Co.	Roy Sturgis 1.
Kentucky			
Fulton	S946. 1- 92. 3	Mt. Carmel Drilling Co.	Florence Smith 1.
Do	S988. 3-105. 7	Layne-Central Co	City of Hickman.
Do	S1038. 0- 96. 9	Clemens Exploration Co.	Floyd R. Naylor.
Do	S1081. 5- 78. 2	Illinois Central	Illinois Central Railroad.
Graves	S1127. 8- 82. 2	Clemens Exploration Co.	Jess Walker.
Hickman	S1021. 1-170. 3	U.S. Geological Survey.	Jack Roberts 2.

TABLE 1.—*Oil tests and wells shown on geologic sections*—Con.

State and county or parish	Well	Company or driller	Name
Louisiana			
Bienville	36	Atlantic Refining Co	H. C. Cook 1.
Do	37	Hurley, Cummins, & Lohman.	Longbell Lumber Co. 1.
Do	38	Pierce & Crow	E. W. Merritt 2.
Bossier	10	A. J. Hodges Industries, Inc.	Skannal C-3.
Caddo	6	Arkansas-Louisiana Gas Co.	Bell A-1.
Do	32	C. P. Porter & Naro Oil Co.	Turner 1.
Jackson	42	The Texas Co	Tremont Lumber Co. 1.
Do	43	Shell Oil Co., Inc	Tremont 2.
Do	44	Brown Paper Mill Co.	Fee 3.
Lincoln	39	Arkansas-Louisiana Gas Co.	Hays 1.
Madison	29	V. S. Parham	Kathan-Johnson 1.
Do	46	Victor P. Grage	W. R. Gilfoil 1.
Ouachita	21	The California Co	Walter Maxey 1.
Do	45	Stanolind Oil Co	Tina S. Parker 1.
Richland	27	Atlantic Refining Co	Mrs. Birdie S. Franklin 1.
Union	19	H. J. Heartwell	Griffin 1.
Do	40	Phillips Petroleum Co.	Hamilton 1.
Do	41	Pan American Petroleum Corp.	T. L. James Co., Inc.
Webster	12	Hunt Oil Co	Jacinta Sales 1.
Do	33	Kin Ark Oil Co	M. Braswell 1.
Do	34	George Belchic, Jr., and others.	Prather 1.
Do	35	Sunray-Midcontinent Oil Co.	Gleason 1.
Mississippi			
Bolivar	8	Seaboard Oil Co	Chicago Mill and Lbr. Co. 1.
Calhoun	22	Layne-Central Co	Slate Springs Water Assn.
De Soto	1	Union Producing Co	Withers Estate 1.
Grenada	11	Adams Oil & Gas	J. K. Avent 1.
Hinds	28	Pure Oil Co	Gaddis Farms 1.
Do	41	Kingwood Oil Co. and George E. Shaw.	Lewis 1.
Do	48	Plains Production Co.	J. S. Taylor 1.
Do	1206	Leonard Jones	La Rue 1.
Issaquena	38	Pres Cochrane	Anderson-Tully 1.
Lauderdale	16	C. L. Higgason and L. L. Chapman.	Malone-Thigpen 1.
Do	18	American Liberty Oil Co.	Flintkote Corp. 1.
Marshall	6	Shell Oil Co	Paul F. Johnson, and others.
Newton	6	Sun Oil Co	Hilma Wall 1.
Do	7	Fred Mellen, James Hattox, and others.	Gordon Holroyd 1.
Rankin	11	Monsanto Chemical Co.	Leon 1.
Do	85	Layne-Central Co	City of Brandon.
Scott	31	Honolulu Oil Corp	Board of Supervisors 1.
Do	1009	Pan American Producing Co.	School Land 1.
Sharkey	10	Harold K. Boysen	A. Y. Keith 1.
Sunflower	2	J. L. Ryan and T. J. Townsend.	J. R. Cooper 1.
Tallahatchie	12	Gulf Refining Co	T. P. Cason et al. 1.
Tate	2	Johnson-Perry Co	Prichard Estate 1.
Tunica	2	Layne-Central Co	Tunica County Vocational High School.
Warren	43	Frontier Oil Ref. Corp.	F. C. Martin 1.
Do	58	Union Producing Co	C. J. Harlen 1.
Washington	1	Roeser & Pendleton, Inc.	Conn. Gen. Life Ins. Co. 1.
Do	9	Lee Raines	R. N. Aldrich 1.
Yazoo	40	E. P. Thomas and J. A. Morgan.	Callie Smith 1.
Do	92	Sells Petroleum Co	Faulkner 1.
Missouri			
Dunklin	1	Thomas C. Knight	John Stewart 1.
New Madrid	6809	Cordova-Union Oil Corp.	E. Phillips 1.
Do	8882	U.S. Bureau of Mines.	R. B. Oliver, Jr. 1.
Tennessee			
Fayette	Fa: J-1	Lazarov-Robillio Oil Co.	Beasley 1.
Do	Fa: 0-32	Barnwell Drilling Co	Shinault 1.
Do	Fa: S-7	Texas Gas Trans. Corp.	Matthews 7003.

TABLE 1.—*Oil tests and wells shown on geologic sections*—Con.

State and county or parish	Well	Company or driller	Name
Tennessee—Con.			
Fayette	Fa: W-1	Layne-Central Co	U.S. Geol. Survey and Tennessee Div. Geology.
Lake	Lk: E-17	Jack W. Frazier & Carl Benz.	Sam Hays 1.
Lauderdale	Ld: F-4	U.S. Geological Survey.	Sullivan 1.
Shelby	Sh: U-12	Lion Oil and Refining Co.	L. Bateman 1.
Texas			
Cass	DB-1664404	Arkla Oil Co	Brooks Brothers 1.
Do	DB-3505502	Max Agress	Clark and Boise Lumber Co. 1.
Do	DB-3506303	Joe G. Strahan	Mrs. Sloan Taylor 1.
Harrison	LK-3511802	Grelling and Ellison	H. P. McGaughey 1.
Do	LK-3535203	The Texas Co	R. E. Latham 1.
Do	LK-3536204	Paul Scott and R. E. Kennedy.	C. A. Bell 1.
Do	LK-3537103	H. J. Strief	A. White 1.
Do	LK-3538403	Stanolind Oil & Gas Co.	Hattie Cole 1.
Do	LK-3540403	Bert Fields	E. Vance 1.
Marion	SX-3512102	Magnolia Petroleum Co.	S. L. Orr 1.

TABLE 2.—*Stratigraphic columns of the Tertiary System in the Mississippi embayment*

NORTHEASTERN TEXAS

[Bowie, Cass, Marion, and Harrison Counties]

- Eocene Series
  - Claiborne Group
    - Sparta Sand[1]
    - Weches Greensand
    - Queen City Sand[1]
    - Reklaw Formation[1]
    - Carrizo Sand[1]
    - Wilcox Formation[1]
- Paleocene Series
  - Midway Group
    - Wills Point Formation
    - Kincaid Formation

NORTHERN LOUISIANA

[North of 32d parallel]

- Oligocene Series
  - Vicksburg Formation
- Eocene Series
  - Jackson Group
    - Yazoo Clay
    - Moodys Branch Formation
  - Claiborne Group
    - Cockfield Formation[1]
    - Cook Mountain Formation
    - Sparta Sand[1]
    - Cane River Formation[1]
    - Carrizo Sand[1]
- Eocene and Paleocene Series
  - Wilcox Group[1,2]
    - Dolet Hills Formation[1]
    - Naborton Formation[1]
- Paleocene Series
  - Midway Group
    - Porters Creek Clay
    - Clayton Formation

ARKANSAS

- Pliocene(?) deposits[1]
- Eocene Series
  - Jackson Group undifferentiated[1]
  - Claiborne Group
    - Cockfield Formation[1]
    - Cook Mountain Formation
    - Sparta Sand[1]
    - Cane River Formation[1]
    - Carrizo Sand[1]
    - Wilcox Group undifferentiated[1,3]

See footnote at end of table.

TABLE 2.—*Stratigraphic columns of the Tertiary System in the Mississippi embayment*—Continued

- Paleocene Series
  - Midway Group[4]
    - Porters Creek Clay
    - Clayton Formation[1]

MISSOURI

- Pliocene(?) deposits[1]
- Eocene Series
  - Claiborne Group undifferentiated[1]
  - Wilcox Formation[1]
- Paleocene Series
  - Midway Group
    - Porters Creek Clay[1]
    - Clayton Formation

ILLINOIS

- Pliocene(?) deposits[1]
- Eocene Series
  - Wilcox Group undifferentiated[1]
- Paleocene Series
  - Midway Group
    - Porters Creek Clay
    - Clayton Formation

KENTUCKY

- Pliocene(?) deposits[1]
- Eocene Series
  - Claiborne Group undifferentiated[1]
  - Wilcox Group undifferentiated[1]
- Paleocene Series
  - Midway Group
    - Porters Creek Clay
    - Clayton Formation[1]

TENNESSEE

- Pliocene(?) deposits[1]
- Eocene Series
  - Jackson(?) Formation
  - Claiborne Group undifferentiated[1]
  - Wilcox Group undifferentiated[1]
- Paleocene Series
  - Midway Group
    - Porters Creek Clay[1]
    - Clayton Formation[1]

NORTHERN MISSISSIPPI

Northern Part

- Pliocene(?) deposits[1]
- Eocene Series
  - Jackson Group undifferentiated
  - Claiborne Group
    - Cockfield Formation[1]
    - Cook Mountain Formation
    - Sparta Sand[1]
    - Zilpha Clay
    - Winona Sand[1]
    - Tallahatta Formation[1]
  - Wilcox Formation[1]
- Paleocene Series
  - Midway Group
    - Porters Creek Clay
      - Tippah Sand Lentil[1]
    - Clayton Formation[1]

Southern Part

- Pliocene(?) deposits[1]
- Eocene Series
  - Jackson Group undifferentiated
  - Claiborne Group
    - Cockfield Formation[1]
    - Cook Mountain Formation
    - Sparta Sand[1]
    - Zilpha Clay
    - Winona Sand[1]
    - Tallahatta Formation[1]
  - Wilcox Formation[1]
- Paleocene Series
  - Midway Group
    - Naheola Formation[1]
    - Porters Creek Clay
    - Clayton Formation[1]

TABLE 2.—*Stratigraphic columns of the Tertiary System in the Mississippi embayment*—Continued

CENTRAL MISSISSIPPI

- Pliocene(?) deposits[1]
- Oligocene Series
  - Forest Hill Sand[1]
- Eocene Series
  - Jackson Group
    - Yazoo Clay
      - Shubuta Member
      - Pachuta Marl Member
      - Cocoa Sand Member
      - North Twistwood Creek Member
    - Moodys Branch Formation
  - Claiborne Group
    - Cockfield Formation[1]
    - Cook Mountain Formation
      - Gordon Creek Shale Member
      - Potterchitto Sand Member
      - Archusa Marl Member
    - Sparta Sand[1]
    - Zilpha Clay
    - Winona Sand[1]
    - Tallahatta Formation
      - Neshoba Sand Member[1]
      - Basic City Shale Member
      - Meridian Sand Member[1]
    - Wilcox Formation[1]
      - Bashi Marl Member
      - Fern Springs Member
- Paleocene Series
  - Midway Group
    - Naheola Formation[1]
    - Porters Creek Clay
      - Matthews Landing Marl Member
    - Clayton Formation[1]

WESTERN ALABAMA

- Eocene Series
  - Claiborne Group
    - Tallahatta Formation
      - Meridian Sand Member[1]
  - Wilcox Group[1]
    - Hatchetigbee Formation[1]
      - Bashi Marl Member
    - Tuscahoma Sand[1]
      - Bells Landing Marl Member
      - Greggs Landing Marl Member
    - Nanafalia Formation[1]
      - Grampian Hills Member
      - Middle member
      - Gravel Creek Sand Member[1]
- Paleocene Series
  - Midway Group
    - Naheola Formation[1]
      - Coal Bluff Marl Member
      - Oak Hill Member
    - Porters Creek Formation
      - Matthews Landing Marl Member
    - Clayton Formation
      - McBryde Limestone Member
      - Pine Barren Member

[1] Unit is fresh-water aquifer or contains fresh-water aquifer(s).

[2] Wilcox Group (Eocene Series) undifferentiated. Wilcox Group (Paleocene Series): upper part is undifferentiated; Dolet Hills and Naborton Formations are lower two units.

[3] In ascending order Wilcox Group in Arkansas bauxite area composed of Berger Formation, Saline Formation, and Detonti Sand.

[4] In ascending order Midway Group in Arkansas bauxite area composed of Kincaid Formation and Wills Point Formation.

The cooperation of the following State officials and members of their staffs is gratefully appreciated: Philip E. LaMoreaux, State Geologist, Geological Survey of Alabama; Norman F. Williams, State Geologist, Arkansas Geological Commission; Wallace W. Hagan, Director and State Geologist, Kentucky Geological Survey; Jack W. Pepper, Engineer, Mississippi Board of Water Commissioners; Thomas R. Beveridge, former Director and State Geologist, and William C. Hayes, Jr., Director and State Geologist, Missouri Geological Survey; William D. Hardeman, State Geologist, Tennessee Division of Geology; Joe D. Carter, Chairman, Texas Water Commission; James H. Gill, Commissioner, Louisiana Department of Conservation; Leo W. Hough, State Geologist, Louisiana Geological Survey; and Claude Kirkpatrick, Director, Louisiana Department of Public Works. These officials furnished geologic and hydrologic information, many electric logs, and sets of well cuttings for this study. The pumping and water-level information supplied by well drillers in the area is appreciated.

TERTIARY AQUIFERS

MIDWAY GROUP

By R. L. HOSMAN, T. W. LAMBERT, and G. K. MOORE

The Midway Group of the Paleocene Series overlies the rocks of the Cretaceous System. In most of the embayment the group is predominantly made up of dark clay. It includes, however, three locally used aquifers: the Clayton Formation (Kincaid Formation in bauxite area of Arkansas), the subordinate sand beds of limited extent including the Tippah Sand Lentil of the Porters Creek Clay in extreme northern Mississippi, and the Naheola Formation in Mississippi and Alabama.

The Clayton Formation, basal unit of Paleocene age, is mostly composed of limestone, calcareous sand, and sandstone, all of marine origin. The formation is generally about 35 feet thick in the subsurface, but in some places in the outcrop area it is much thinner.

The Porters Creek Clay overlies the Clayton and ranges in thickness from about 180 feet to about 1,000 feet. It is a dark clay in most of the embayment but locally contains sand beds that are water bearing in western Kentucky, western Tennessee, and extreme northern Mississippi.

The Naheola Formation is the upper unit of the Midway Group in western Alabama and eastern Mississippi. The thickness generally ranges from 100 feet in Mississippi to about 200 feet in Alabama. Sandy beds in the Naheola Formation are water bearing in western Alabama and the adjacent areas of Mississippi. In this report these beds are considered as part of the lower Wilcox aquifer.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

Aquifers in the Midway Group receive recharge from precipitation in the outcrop area. The aquifers probably receive additional recharge locally where underlying Cretaceous rocks are permeable. The limited extent of the sand beds generally impedes ground-water movement except near the outcrop areas, and local conditions determine the direction of this movement.

The use of ground water from the Midway Group is generally confined to the outcrop areas of the aquifers in Arkansas, Kentucky, Tennessee, Mississippi, and Alabama. The aquifers crop out in a narrow belt on the east side of the embayment along the Tertiary-Cretaceous contact shown in figure 2. On the west side of the embayment the aquifers crop out and are used where the Tertiary outcrop area is adjacent to the periphery of the embayment. Wells tapping these aquifers are designed for small capacity, and the yields are adequate only for domestic and stock use. Some wells, tapping the Clayton Formation near the outcrop area in Arkansas, flow, but their yields are small and the hydrostatic pressure is low. The withdrawal of water from the Clayton is probably less than 0.1 mgd (million gallons per day).

AQUIFER CHARACTERISTICS

Data pertaining to aquifer characteristics of the Midway aquifers are not available, but well yields are generally small.

QUALITY OF THE WATER

Utilization of water is governed to a large extent by the chemical and physical properties of the water. The source and significance of many of these properties are given in table 3. Water from wells drilled near the outcrop of the Clayton Formation in Arkansas is moderately mineralized. The dissolved-solids content of six samples ranges from 184 to 437 ppm (parts per million) and averages 256 ppm. Calcium, magnesium, and bicarbonate generally are the predominant constituents where the dissolved-solids content is low; increases in dissolved solids are caused primarily by increases in sodium, bicarbonate, and chloride.

TABLE 3.—*Source and significance of dissolved mineral constituents and physical properties of natural waters*

Constituent or physical property	Source or cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, commonly less than 30 ppm. Higher concentrations, as much as 100 ppm, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam from high-pressure boilers to form deposits on blades of turbines. Inhibits deterioration of zeolite-type water softeners.
Iron (Fe)	Dissolved from practically all rocks and soils. Waters having a low pH tend to be corrosive and may dissolve iron in objectionable quantities from pipe, pumps, and other equipment. More than 1 or 2 ppm of soluble iron in surface waters generally indicates acid wastes from mine drainage or other sources.	More than about 0.3 ppm stains laundry and utensils reddish brown. Objectionable for food processing, beverages, dyeing, bleaching, ice manufacturing, brewing, and other processes. Large quantities cause unpleasant taste and favor the growth of iron bacteria. On exposure to air, iron in ground water usually is oxidized and forms a reddish-brown precipitate. "Public Health Service Drinking Water Standards" (1962) [1] recommend that iron in water supplies not exceed 0.3 ppm.
Manganese (Mn)	Dissolved from some rocks and soils. Not as common as iron. Large quantities often associated with high iron content and with acid waters.	Same objectionable features as iron. Causes dark-brown or black stain. Maximum concentration recommended by the drinking-water standards is 0.05 ppm.
Calcium (Ca) and magnesium (Mg).	Dissolved from practically all rocks and soils, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the bardness and scale-forming properties of water; soap consuming. (See ' Hardness.") Waters low in calcium and magnesium are desired in electroplating, tanning, and dyeing, and in textile manufacturing.
Sodium (Na) and potassium (K).	Dissolved from practically all rocks and soils. Found also in ancient brines, sea water, some industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers, and a high sodium content may limit the use of water for irrigation.
Bicarbonate (HCO_3) and carbonate (CO_3).	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot-water facilities to form scale and release corrosive carhon-dioxide gas. In combination with calcium and magnesium tbey cause carbonate hardness.
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in mine waters and in some industrial wastes.	Large amounts have a laxative effect on some people and, in combination with other ions, give a bittar taste. Sulfate in water containing calcium forms a hard scale in steam boilers. The drinking-water standards recommend that sulfate in water supplies not exceed 250 ppm.
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in ancient brines, sea water, and industrial wastes.	Large quantities increase the corrosiveness of water and, in combination with sodium, give a salty taste. The drinking-water standards recommend that chloride in water supplies not exceed 250 ppm.
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the teeth, depending on the concentration of fluoride, the age of the child, the amount of drinking water consumed, and the susceptibility of the individual. The maximum concentration of fluoride recommended by the drinking-water standards varies with the annual average maximum daily air temperatures and ranges downward from 1.7 ppm for an average maximum daily temperature of 50.0°F to 0.8 ppm for an average maximum daily temperature of 90.5°F. Optimum concentrations for these ranges are from 1.2 to 0.7 ppm.
Nitrate (NO_3)	Decaying organic matter, legume plants, sewage, nitrate fertilizers, and nitrates in soil.	Nitrate encourages growth of algae and other organisms that cause undesirable tastes and odors. Concentration much greater than the local average may indicate pollution. The drinking-water standards recommend that the nitrate content not exceed 45 ppm, as there is evidence tbat higher concentrations may cause methemoglobinemia (an often fatal disease in infants).
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils. Include any organic matter and some water of crystallization.	The drinking-water standards recommend that the dissolved solids not exceed 500 ppm. Waters containing more than 1,000 ppm dissolved solids are unsuitable for many purposes.
Hardness as $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. All the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form, and deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called noncarbonate hardness. In general, waters of hardness as much as 60 ppm are considered soft; 61–120 ppm, moderately bard; 121–180 ppm, hard; more than 180 ppm, very hard.
Specific conductance (micromhos at 25°C).	Mineral content of the water	Indicates degree of mineralization and is a measure of the capacity of the water to conduct an electric current. This property varies with concentration and degree of ionization of the constituents, and with temperature (therefore reported at 25°C).
Hydrogen-ion concentration (pH):	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity. values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters may also attack metals.

[1] "Public Health Service Drinking Water Standards", revised 1962, apply to drinking water and water-supply systems used by carriers and others subject to Federal quarantine regulations.

TABLE 3.—*Source and significance of dissolved mineral constituents and physical properties of natural waters*—Continued

Constituent or physical property	Source or cause	Significance
Color	Usually caused by organic matter	Refers to the appearance of water that is free of suspended matter. Color of 10 units or less usually goes unnoticed. The drinking-water standards recommend that color not exceed 15 units. Color in water is objectionable in food and beverage processing and in many manufacturing processes.
Temperature		Affects usefulness of water for many purposes. Most users desire water of uniformly low temperature. In general, temperatures of shallow ground waters show some seasonal fluctuation, whereas temperatures of ground waters from moderate depths remain near the mean annual air temperature of the area. In deep wells the water temperature generally increases 1°F for each 60–80 feet of depth.

The dissolved-solids content of water from five wells in the Clayton Formation in Tennessee ranges from 86 to 2,550 ppm; the dissolved-solids content of water from two of these wells is 1,060 and 2,550 ppm, and that of water from the other three wells ranges from 86 to 156 ppm. The water with the highest dissolved-solids content is a calcium magnesium sulfate type and may be representative of water from the Clayton where the Owl Creek Formation of Cretaceous age acts as an aquiclude between the Clayton and the McNairy Sand Member of the Ripley Formation.

Water from sandy zones in the outcrop of the Porters Creek Clay in Tennessee is generally low in dissolved solids. The analyses of water from eight wells show that the dissolved-solids content ranges from 80 to 533 ppm. Calcium, magnesium, and sulfate are generally the predominant constituents. In Missouri, the dissolved-solids content of water from sandy zones in the Porters Creek Clay is higher than it is in Tennessee. The range in dissolved solids of water from five wells in Missouri ranges from 200 to 1,080 ppm. However, two higher values, 797 and 1,080 ppm, may not be representative of water in these sands; these values include 268 and 200 ppm of nitrate, which indicate that the waters are probably polluted.

Analyses of water from three wells in Mississippi indicate that water from the Naheola Formation is generally of good chemical quality. The water is a sodium bicarbonate type, and the dissolved-solids content ranges from 128 to 418 ppm.

POTENTIAL USE

The interpretation of electric logs indicates that the Clayton Formation and local sand beds in the Porters Creek Clay contain fresh water in an area of about 2,800 square miles in Tennessee. Fresh water in these aquifers is generally restricted to the outcrop areas in Arkansas, Missouri, and Kentucky. The sand beds are thin and of small areal extent; therefore, only small yields of water may be expected. These sands are not extensively developed, however, because larger supplies of water of good quality are available from other aquifers in most of the region. Additional small supplies for domestic and stock use can be developed from the Midway.

CONCLUSIONS

Subordinate sand beds in the Clayton Formation and Porters Creek Clay contain fresh water near their outcrop areas in Arkansas, Missouri, Kentucky, Tennessee, and Mississippi. The aquifers yield small quantities of water and are the source of domestic and stock supplies. The water in the outcrop area is generally of good quality.

LOWER WILCOX AQUIFER

By E. H. BOSWELL, R. L. HOSMAN, and G. K. MOORE

The Wilcox Group (Formation) crops out in an area about 100 miles wide in the southwest corner of the embayment, and in belts 10–25 miles wide in the eastern part of the embayment (pl. 3). The outcrop area narrows in the northern part of the embayment, because the Wilcox thins and may be overlapped by the Claiborne Group in places. The Wilcox dips about 20 feet per mile toward the axis of the embayment in the northern part; the dip increases to more than 50 feet per mile in the southern part of the embayment. The unit is more than 3,000 feet thick in the southeastern part of the embayment (pl. 3).

The Wilcox contains thick extensive sands in the subsurface of northeastern Arkansas, southeastern Missouri, southwestern Kentucky, western Tennessee, and northwestern and central Mississippi. Although the exact stratigraphic and hydrologic relations of the sands cannot be determined by interpretation of available data, correlation of electric logs suggests that the Wilcox may contain as many as three major sand units in the northern and eastern parts of the embayment. These sands, which include the aquifer known in the Memphis area as the "1,400-foot" sand, are collectively referred to as the lower Wilcox aquifer in this report and are treated as one aquifer on the maps (pl. 4). The sands occupy similar stratigraphic positions within the Wilcox in that they are generally in the lower part, in some places forming the basal unit. In much of the area the base of the lower Wilcox aquifer is also the base of fresh water.

The maximum thickness of the lower Wilcox aquifer, where it contains fresh water, is 300 feet in Arkansas, 340 feet in Tennessee, 400 feet in Missouri, and 450 feet in Mississippi (pl. 4).

In most of the northern half of the embayment, more than 80 percent of the lower Wilcox aquifer is composed of sand (pl. 4). The aquifer is generally composed of fine to medium sand, but it is composed of coarse sand in places in Tennessee and Kentucky and of coarse sand and fine gravel in places in Mississippi.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

The main source of recharge is precipitation in the outcrop area. Leakage from overlying sandy beds may be a major source of recharge in the northern part of the embayment, where the lower Wilcox aquifer is overlain by outcropping sands of the Claiborne Group and the water is under water-table conditions.

The regional movement of ground water is toward the axis of the embayment. Large withdrawals of ground water, mainly for municipal and industrial use, result in large cones of depression in the piezometric surface near Memphis and Jackson, Tenn. (pl. 4). The ground-water withdrawals for municipal and industrial use are 15 mgd in Mississippi, 23 mgd in Tennessee (13 mgd in Memphis and 7 mgd in Jackson), 9 mgd in northeastern Arkansas, and 1 mgd in Missouri.

The area of use is small in Kentucky, Illinois, and Missouri; but in Tennessee it is about 1,500 square miles, mostly in a belt 8–16 miles wide adjacent to the outcrop and in the Memphis area. The aquifer is utilized in a large part of northeastern Arkansas and northwestern Mississippi, but the withdrawal is small.

Additional withdrawals of ground water result from uncontrolled flowing wells in northwestern Mississippi and in western Alabama. The piezometric surface in these areas shows changes imposed on the aquifer by the flowing wells. The amount of water wasted by flowing wells is not known. The piezometric surface is below land surface in the area of use in Tennessee, but it is probably above the land surface in a few of the major stream valleys where flowing wells may be drilled. The piezometric surface is below land surface in Missouri and Arkansas.

AQUIFER CHARACTERISTICS

Moderate yields from wells tapping the lower Wilcox aquifer are generally obtainable. Wells yielding from 500 gpm (gallons per minute) to more than 2,000 gpm can be constructed at many locations underlain by the aquifer. The results of pumping tests and aquifer tests using wells in the lower Wilcox aquifer are summarized (averages by county) in the following table:

[Number in parenthesis denotes number of tests used to compute average

County	State	Coefficient			Specific capacity [4] (gpm per ft of drawdown)
		Transmissibility [1] (gpd per ft)	Storage [2]	Permeability [3] (gpd per sq ft)	
Mississippi	Arkansas	(1) 160,000	(1) 0.0002	(1) 1,300	(3) 30
Ballard	Kentucky	----	----	----	(2) 12
Lauderdale	Mississippi	(3) 122,000	(2) .0001	(3) 1,250	(2) 14
Winston	do	(1) 80,000	(1) .0001	(1) 890	(1) 39
Madison	Tennessee	(4) 75,000	(3) .0015	(2) 510	(1) 12
Shelby	do	(20) 98,000	(20) .0002	----	----

[1] The worth of an aquifer as a fully developed source of water depends largely on two hydraulic characteristics—the capacity of the aquifer to transmit water (the coefficient of transmissibility) and the capacity of the aquifer to store water (the coefficient of storage).

The coefficient of transmissibility (T) is the rate of flow of water, in gallons per day, at the prevailing temperature, through a vertical strip of an aquifer 1 foot wide extending the full saturated height of the aquifer, under a hydraulic gradient of 100 percent. (A hyrdaulic gradient of 100 percent means a 1-foot drop in water level or head in a 1-foot flow distance.) For example, an aquifer has a coefficient of transmissibility of 26,400 gpd per ft. If the hydraulic gradient were 100 percent, 26,400 gallons of water would move through each vertical strip of the aquifer 1 foot wide in each 24-hour period. Assuming a line 100 feet in length perpendicular to the direction of flow in the aquifer, 26,400 gpd per ft multiplied by 100 feet, or 2,640,000 gpd, would move past the line. If the hydraulic gradient were only 10 feet per mile, then only 5,000 gpd $(26{,}400 \times \frac{10}{5{,}280} \times 100)$ would move past the line in a day.

[2] The coefficient of storage (S) is the volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The coefficient can be expressed as the quantity of water, in cubic feet, that is discharged from each vertical prism of the aquifer having a basal area of 1 square foot and a height equal to that of the aquifer, when the water level falls 1 foot. For an artesian aquifer, the water released from or taken into storage in response to a change in water level is attributed to the compressibility of the aquifer material and of the water. The volume of water thus released or stored, divided by the product of the water-level change and the area of the aquifer surface over which it is effective, is the coefficient of storage of the aquifer. For artesian aquifers the storage coefficients range from about 0.00001 to about 0.001, and for water-table aquifers they range from about 0.05 to 0.3.

When the coefficients of transmissibility and storage are known, the theoretical drawdown for any time at any point in an area of pumping for any given rate and distribution of pumping from wells can be computed (fig. 4).

[3] The coefficient of permeability is the rate of flow of water, in gallons per day, at the prevailing temperature through a cross section of 1 square foot of an aquifer under a hydraulic gradient of 100 percent. It is equal to the coefficient of transmissibility divided by the saturated thickness (in ft) of the aquifer.

[4] Specific capacity defines the capacity of a well to yield water. It is defined as the yield per unit of drawdown for a given period of pumping and is generally expressed as gallons of water discharged in 1 minute for each foot of decline in the water level in the well. If it were not for many extraneous factors—the size of well, the depth of penetration of the well into the aquifer, the length of screen, the size of screen openings and the relation of the size of these openings to size and assortment of aquifer materials, and the amount of development of the well—specific capacity would be a measure of the capacity of the aquifer in the vicinity of the well to transmit water.

Specific capacity is used to compare the yields of wells and as a means of determining how deep in the well the pump bowls (turbine) should be set. For example, if a well has a specific capacity of 5 gpm per ft and is capable of yielding 500 gpm, then the drawdown for this discharge will be about 100 feet $(\frac{500}{5})$, and the pump bowls must be set at least 100 feet below the static water level in the well in order to pump 500 gpm.

QUALITY OF THE WATER

Water in the lower Wilcox aquifer is generally a sodium bicarbonate type and has a low, fairly uniform dissolved-solids content. At a few places in the outcrop area, the water is a calcium bicarbonate type; and in extreme downdip areas it is a sodium bicarbonate chloride type. The dissolved-solids content of the water is lower in the outcrop areas, and it increases gradually as the water moves west and southwest from these areas (pl. 4). Calcium, magnesium, and sulfate are generally low, but at some locations they compose a large part of the dissolved solids. The chloride content of the water varies with the dissolved solids, and when the dissolved solids are less than about 500 ppm, the chloride content is generally low. Increases in dissolved solids in excess of about 500 ppm are mainly sodium, bicarbonate, and chloride. At many places, when dissolved solids are about 1,200 ppm, chloride and bicarbonate are present in about equal amounts. Small amounts of fluoride and nitrate are present in the water. Larger amounts of fluoride are present in extreme downdip areas. The larger amounts of nitrate are in water from shallow wells in the outcrop area and are probably the result of contamination. The iron content of the water generally decreases with depth. The ranges in concentration of the various constituents are shown in table 4. The median values in this table are representative of the quality of water over a large part of the area. The maximum values for most constituents are for water in downdip areas.

TABLE 4.—*Summary of chemical analyses of water from the lower Wilcox aquifer*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	44	0.0	11
Iron (Fe)	15	.00	.58
Calcium (Ca)	34	.0	2.9
Magnesium (Mg)	8.4	.0	.9
Sodium (Na)	704	1.5	36
Potassium (K)	16	.3	2.1
Carbonate plus bicarbonate (CO_3+HCO_3)	661	6	110
Sulfate (SO_4)	37	.0	3.0
Chloride (Cl)	725	.0	3.7
Fluoride (F)	1.8	.0	.1
Nitrate (NO_3)	13	.0	.3
Dissolved solids	1,810	13	120
Hardness as $CaCO_3$	112	1	11
Specific conductance (micromhos at 25°C)	3,520	19	176
pH	8.6	5.2	7.5
Color	90	0	8

POTENTIAL USE

Interpretation of electric logs indicates that the area of potential use of water from the lower Wilcox aquifer is large in Arkansas, Missouri, Tennessee, and Mississippi (pl. 4), where overlying aquifers contain adequate supplies of water. The area of potential use (about 8,000 sq mi) in Tennessee is more than five times the area of use (about 1,500 sq mi). The area of potential use also includes all or parts of several counties in Kentucky, where only a small quantity of water is withdrawn from the aquifer, and a small area in Illinois near Cairo. Areas where the contours in the piezometric surface are closely spaced (pl. 4) are probably unfavorable areas for potential largescale ground-water development of this aquifer.

CONCLUSIONS

The lower Wilcox aquifer is one of the largest sources of ground water in the Mississippi embayment. Wells yielding 500 gpm or more are possible in many places. Moderate yields are generally obtainable, and yields exceeding 2,000 gpm are possible in some places. The water is generally a sodium bicarbonate type and contains a fairly uniform amount of dissolved solids. Wells tapping the sand yield about 48 mgd. The area of potential use is larger than the area of use. A detailed study of the geohydrology of the thick extensive sands in the lower part of the Wilcox may be needed to provide information for future development.

MINOR WILCOX AQUIFERS

By R. L. HOSMAN, A. T. LONG AND E. H. BOSWELL

In addition to the thick sands, the Wilcox deposits contain aquifers consisting of thin sand beds interbedded with clay. The individual sands are not areally extensive but are locally used aquifers, which are collectively used in an area of several thousand square miles. These minor aquifers are in the upper part of the Wilcox in the northern part and in the southeastern part of the embayment and occur throughout the Wilcox in the southwestern part.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

Overlying clay confines the water in the minor sand beds a few miles downdip from the outcrop of the beds. In the southwestern part of the embayment the Wilcox receives recharge from precipitation on the outcrop and from overlying sandy Quaternary beds. The natural discharge is in the major stream valleys or toward points of heavy withdrawals in this area. Downdip, the water probably moves toward the axis of the embayment.

Withdrawal of ground water from the minor Wilcox aquifers is about 5 mgd in Mississippi, about 5 mgd in Louisiana and Texas, and about 2 mgd in southwestern Arkansas. More than half of the withdrawals is for municipal supply, and the rest is for industrial use and supplemental irrigation. Cones of depression in the piezometric surface show the effect of the withdrawals, and significant declines in the water level have accompanied the development of public supplies from the minor sand beds in the Wilcox.

AQUIFER CHARACTERISTICS

The aquifer characteristics of the minor Wilcox aquifers are shown (averages by county or parish) in the following table:

[Number in parenthesis denotes number of tests used to compute average]

County or parish	State	Coefficient			Specific capacity (gpm per ft of drawdown)
		Transmissibility (gpd per ft)	Storage	Permeability (gpd per sq ft)	
Hot Spring	Arkansas	(1) 18,000	(1) 0.00002	(1) 450	
Bossier	Louisiana	(2) 6,800	(1) .0005	(2) 95	
Webster	do	(2) 9,000	(1) .0002	(2) 100	
Lauderdale	Mississippi	(1) 26,000		(1) 200	(1) 11
Cass	Texas	(2) 7,200		(2) 100	(2) 4
Harrison	do	(3) 3,300		(3) 65	(3) 2
Marion	do	(1) 10,000		(1) 140	(1) 4

QUALITY OF THE WATER

Water in the area of use of the minor Wilcox aquifers in southwestern Arkansas, northwestern Louisiana, and northeastern Texas is generally a sodium bicarbonate type when dissolved solids are low and a sodium bicarbonate chloride type when they are high. The ranges in concentrations of the various constituents and the median values are given in table 5. The median values indicate that sodium, bicarbonate, and chloride are the principal constituents in the water. Maximum amounts of calcium and magnesium occur in the water locally but are not representative of any area. The maximum amount of sulfate is in water from an area in the central part of Caddo Parish, La., and Harrison County, Tex. (pl. 4). The maximum amount of nitrate is in water from a shallow well, and the nitrate is probably a result of contamination.

TABLE 5.—*Summary of chemical analyses of water from the minor Wilcox aquifers in Arkansas, Louisiana, and Texas*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	66	7.9	17
Iron (Fe)	55	.00	.24
Calcium (Ca)	134	.0	7.4
Magnesium (Mg)	155	.0	3.4
Sodium (Na)	849	1.0	110
Potassium (K)	13	.5	2.2
Carbonate plus bicarbonate (CO_3+HCO_3)	910	0	256
Sulfate (SO_4)	300	.0	3.7
Chloride (Cl)	985	1.0	50
Fluoride (F)	4.8	.0	.2
Nitrate (NO_3)	156	.0	.5
Dissolved solids	2,120	17	347
Hardness as $CaCO_3$	956	3	38
Specific conductance (micromhos at 25°C)	2,470	16	588
pH	8.6	4.8	7.6
Color	1,000	0	8

The patterns of chemical analyses of water from the minor Wilcox aquifers (pl. 4) show the variations in the chemical characteristics of the water. The patterns show that along the outcrop area in Arkansas the water is low in dissolved solids. Comparison of these patterns with the one for Ouachita County, Ark., indicates that the water farther downdip rapidly increases in dissolved-solids content and changes to a sodium chloride type.

In Louisiana and Texas, the chemical characteristics of the water vary more when the dissolved-solids content is low, and as the dissolved-solids content increases, sodium, bicarbonate, and chloride become the principal constituents. The general distribution of dissolved solids in this area (pl. 4) is related to the geologic structure. Locally, the distribution of dissolved solids is irregular; an extreme example of the irregularity is shown by the two patterns (pl. 4) for water from wells in Marion County, Tex. The two wells, at about the same location and depth (925 and 950 ft), yield water containing 80 and 909 ppm dissolved solids. These local variations in dissolved solids are probably related to variations in the physical character of the deposits.

Water in minor Wilcox aquifers in Mississippi is generally a sodium bicarbonate type in the northern part of the area of use and a calcium bicarbonate type in the southern part of the area of use ,pl. 4). The dissolved-solids content of the water ranges from 56 to 436 ppm (table 6). The iron content of the water is generally lower in areas where sodium and bicarbonate are the principal constituents. In areas where the water is a calcium bicarbonate type, the calcium content of the water in most instances will exceed the median value shown; and in areas where the water is a sodium bicarbonate type, the sodium content will exceed the median value for sodium.

TABLE 6.—*Summary of chemical analyses of water from the minor Wilcox aquifers in Mississippi*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	42	2.8	14
Iron (Fe)	15	.00	.25
Calcium (Ca)	48	2.5	13
Magnesium (Mg)	19	.4	2.5
Sodium (Na)	177	.8	18
Potassium (K)	4.0	1.0	1.5
Carbonate plus bicarbonate (CO_3+HCO_3)	364	9	137
Sulfate (SO_4)	36	.6	6.5
Chloride (Cl)	70	2.2	5.5
Fluoride (F)	.5	.0	.2
Nitrate (NO_3)	6.3	.0	.2
Dissolved solids	436	56	151
Hardness as $CaCO_3$	199	10	50
Specific conductance (micromhos at 25°C)	--------	73	-------
pH	8.7	5.5	7.3

POTENTIAL USE

Minor sand beds in the upper part of the Wilcox in Mississippi are of potential use locally, particularly in Grenada, Leflore, Holmes, and Madison Counties (pl. 3). Fresh water in the Wilcox is virtually untapped in a belt east of the Red River and underlying the Sparta Sand outcrop in Louisiana. In local areas in Texas, electric-log data indicate that sand beds of variable thickness and areal extent are potential aquifers. They are not used because water is available in overlying aquifers. The area of potential use in southwestern Arkansas is small, as the minor Wilcox aquifers are utilized in almost all the area where they contain fresh water. However, the total withdrawal is small and could be increased.

CONCLUSIONS

Discontinuous sands in the Wilcox are used as aquifers in many places in the embayment. The yields of wells and the chemical quality of the water differ widely. In the southwestern part of the embayment the iron content is commonly high, and the aquifers are chiefly used where other aquifers are not available or contain water of poorer chemical quality.

CARRIZO SAND AND MERIDIAN–UPPER WILCOX AQUIFERS

By R. L. HOSMAN, E. H. BOSWELL, and A. T. LONG

The Carrizo Sand is the basal unit of the Claiborne Group in Arkansas, Louisiana, and Texas, and unconformably overlies the Wilcox Group. It is overlain by the Cane River Formation in Arkansas and Louisiana. In Texas, where the Reklaw Formation, Queen City Sand, and Weches Greensand are equivalents of the Cane River Formation, the Carrizo is overlain by the Reklaw Formation. In northeastern Texas the Carrizo Sand crops out in two narrow bands, one on either side of the East Texas basin (pl. 5). The northern band extends northeastward into Arkansas, and the southern band extends southeastward into Louisiana.

In Arkansas and Louisiana, water in the Carrizo Sand is confined by the Cane River Formation above and the Wilcox below. The Cane River Formation becomes increasingly sandy updip near the outcrop, and, in places, sand in the Cane River apparently rests on and is hydraulically connected with the Carrizo. Interfingering middle Cane River sands in northwestern Louisiana and southwestern Arkansas merge to become the thick Queen City Sand in northwestern Texas and extreme southwestern Arkansas. The underlying Reklaw Formation is sandy in northeastern Texas. The Carrizo, Reklaw, and Queen City are apparently hydraulically connected, have similar hydrologic properties, and may be treated as a single hydrologic unit in this area. This sand unit ranges in thickness from about 200 feet to about 500 feet, the maximum thickness being in the trough of the East Texas basin. The beds dip southeast and northeast toward the axis of the basin and dip northeast to east in northwestern Louisiana. The dip ranges from about 15 to 50 feet per mile. The water-bearing sands underlie small parts of northern Caddo and Bossier Parishes, La., and about half (1,600 sq mi) of the northeast corner of Texas.

The Carrizo Sand is present in the subsurface of the Coastal Plain in south-central Arkansas south of about lat 35° N. North of this latitude the overlying Cane River Formation becomes sand, and the Carrizo becomes the basal part of a thick sand unit. The Carrizo dips southeastward from its outcrop in southwestern Arkansas at a rate of 20–40 feet per mile (pl. 5). The thickness in the subsurface ranges from about 60 feet near the outcrop to about 300 feet in south-central Arkansas (pl. 5).

In Mississippi the Meridian Sand Member of the Tallahatta Formation is equivalent to the Carrizo Sand and is the basal unit of the Claiborne Group. Generally, sands are present in the upper part of the Wilcox either in contact with the Meridian Sand or separated from it by discontinuous clay beds. Interpretation of piezometric data and chemical analyses of the water indicate that the Meridian Sand and the upper sands in the Wilcox are hydraulically connected and may be considered a single aquifer in much of the embayment in Mississippi.

The sands forming the Meridian–upper Wilcox aquifer are not represented by a continuous exposure on the outcrop; even the Meridian Sand, although it apparently overlaps the upper and middle parts of the

Wilcox in northern Mississippi, is irregular in thickness and is discontinuous. In extreme northern Mississippi, the entire Meridian–upper Wilcox aquifer and the lower part of the Claiborne form the major Memphis aquifer.

The Meridian–upper Wilcox aquifer ranges in thickness from 50 feet to about 400 feet (pl. 5) and contains fresh water in an area of about 17,500 square miles. It is one of the most widely used aquifers for municipal, industrial, domestic, and farm water supplies in Mississippi.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

Recharge to the Carrizo Sand and to the Meridian–upper Wilcox aquifer comes from rainfall on the outcrop, seepage from overlying Quaternary deposits in the northern part of the embayment, and underflow from the Memphis aquifer.

Withdrawals from the Carrizo Sand are extremely small, about 0.5 mgd, considering that the sand contains fresh water in an area of several thousand square miles. Most of the wells tapping the Carrizo are for domestic and stock supplies; only a few are for municipal, industrial, and irrigation supplies. The yields range from about 30 to 100 gpm. Flowing wells of low yield can be obtained in major stream valleys in southwestern Arkansas and possibly in northwestern Louisiana.

Withdrawals from the Meridian–upper Wilcox aquifer are distributed over the area of use (pl. 5) and are not large in any locality, although the total withdrawal is about 27 mgd. More water is probably wasted from flowing wells in the Meridian–upper Wilcox aquifer than is used at present (1965). The largest withdrawals are for municipal and industrial use in northeastern Leflore County, Miss. A large depression in the piezometric surface has formed in northwestern Mississippi (pl. 5) owing to discharge from uncontrolled flowing wells and, to a lesser extent, to withdrawals for use.

Water in the Carrizo Sand and in the Meridian–upper Wilcox aquifer moves downdip except in west-central Mississippi, where movement is toward an area of withdrawal delineated by the 150-foot contour (pl. 5). South of this area the water levels are higher, and wells drilled into the aquifer flow. The water level in wells in Yazoo County is about 125 feet above land surface.

AQUIFER CHARACTERISTICS

The aquifer characteristics of the Carrizo Sand and the Meridian–upper Wilcox aquifer are summarized (averages by county) in the following table:

[Number in parenthesis denotes number of tests used to compute average]

County	State	Coefficient: Transmissibility (gpd per ft)		Coefficient: Storage		Coefficient: Permeability (gpd per sq ft)		Specific capacity (gpm per ft of drawdown)	
Carrizo Sand									
Hot Springs	Arkansas	(1)	4, 100			(1)	100	(1)	2
Cass	Texas	(1)	2, 400			(1)	50	(1)	1
Harrison	do	(1)	1, 300			(1)	35		
Meridian–upper Wilcox aquifer									
Attala	Mississippi	(2)	32, 000	(1)	0. 0002			(2)	15
Holmes	do	(2)	54, 000	(2)	. 003	(2)	480		
Leflore	do	(2)	86, 000	(1)	. 0001	(2)	1, 000	(1)	20
Montgomery	do	(1)	56, 000	(1)	. 0002	(1)	910	(1)	24
Sunflower	do	(1)	18, 000	(1)	. 0001	(1)	200		
Tallahatchie	do	(1)	11, 000			(1)	200		

QUALITY OF THE WATER

Water from the Carrizo Sand is generally soft, low in iron, and a sodium bicarbonate type; but the type of water varies with the dissolved-solids content. The dissolved-solids content ranges from 90 to 2,820 ppm; the maximum amount is in water from a faulted zone. Where the dissolved-solids content is low (pl. 5), the water is either a calcium magnesium bicarbonate type or a sodium bicarbonate type. Increases in dissolved-solids content, up to about 400 ppm, are primarily due to increases in sodium and bicarbonate; increases in excess of about 400 ppm are due to increases in sodium, bicarbonate, and chloride. The sodium and chloride contents increase at a faster rate than the bicarbonate.

The dissolved solids increase as the water moves downdip, but this increase is probably small. For example, water from two wells that are 332 and 346 feet deep contains 90 and 178 ppm dissolved solids (pl. 5), and water from two downdip wells that are 1,406 and 2,050 feet deep contains 822 and 654 ppm dissolved solids.

279-873—67——3

Water from the Carrizo Sand is generally of good quality and is suitable for most uses, but in places treatment for iron removal would be desirable for some uses. In downdip areas, the chloride content makes the water unsuitable for some industrial uses.

Water in the Meridian–upper Wilcox aquifer in most of the area of use is soft and a sodium bicarbonate type and contains less than 500 ppm dissolved solids. The amounts of calcium, magnesium, and sulfate in the water are low; the larger amounts of these constituents are in water from wells in the outcrop area. The iron content of the water is usually low, but larger amounts occur locally throughout the area. The highly colored waters are generally found at considerable depths in the aquifer. The ranges in concentration and the median values of the various constituents and properties of the water are shown in table 7. The maximum amounts of most constituents are in water from wells in the extreme downdip area of use. The median values emphasize the sodium bicarbonate character of the water, and they are indicative of the quality of the water in a large part of the area of use.

TABLE 7.—*Summary of chemical analyses of water from the Meridian–upper Wilcox aquifer*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	41	0.0	13
Iron (Fe)	8.7	.00	.15
Calcium (Ca)	38	.0	2.5
Magnesium (Mg)	12	.0	.7
Sodium (Na)	1,060	2.0	82
Potassium (K)	15	.9	3.7
Carbonate plus bicarbonate (CO_3+HCO_3)	1,960	10	225
Sulfate (SO_4)	46	.0	4.2
Chloride (Cl)	860	.0	6.1
Fluoride (F)	7.0	.0	.1
Nitrate (NO_3)	17	.0	.7
Dissolved solids	2,680	24	238
Hardness as $CaCO_3$	134	0	11
Specific conductance (micromhos at 25°C)	4,490	48	------
pH	8.9	5.2	7.7
Color	90	0	11

Water in the outcrop of the Meridian–upper Wilcox aquifer contains smaller amounts of dissolved solids and has more variable chemical characteristics than water from downdip locations (pl. 5). As the water moves downdip from the outcrop, the dissolved-solids content gradually increases, up to about 500 ppm; most of the calcium and magnesium present in water in the outcrop is removed by base exchange, and sodium and bicarbonate become the principal constituents. Increases in dissolved solids up to about 600 ppm are principally an increase in sodium bicarbonate, and increases in excess of about 600 ppm are usually increases in sodium, bicarbonate, and chloride; the rate of increase of chloride varies from area to area.

Because of the fairly uniform character and low dissolved-solids content of the water, the Meridian–upper Wilcox aquifer is an excellent source of water supply for municipalities and industries. The type and degree of treatment required for water from this unit depends largely on the intended use. The water would be suitable for some uses, such as cooling, with little or no treatment; but for other uses it would require, depending upon the location, treatment for corrosion control and for the removal of iron and color.

POTENTIAL USE

The limit of the area of potential use of the Carrizo Sand and the Meridian–upper Wilcox aquifer is the downdip limit of fresh water (pl. 5). In much of the present area of use the full potential of the aquifers is not approached; in Mississippi, the Meridian–upper Wilcox aquifer contains fresh water in an area of about 17,500 square miles, some of the better parts of the aquifer are in the area of potential use. The data indicate that the yields of future wells drilled in the Carrizo in northeastern Texas and northwestern Louisiana will be within the range of yields of existing wells; yields exceeding about 100 gpm probably cannot be expected. Although the Carrizo Sand contains fresh water in an area of more than 5,000 square miles in Arkansas, it is largely unproven and unused as an aquifer. It is used in an area of less than 400 square miles in southwestern Arkansas where the hydrology and potential of the unit are virtually the same as in the northwestern Louisiana area. However, in south-central Arkansas, where the unit is much thicker, it is composed of slightly coarser sand than it is to the southwest and contains fresh water at depths exceeding 2,000 feet, and the potential appears large. As there are no wells tapping the Carrizo in this area (except for a deep exploratory test), the hydrostatic head is high, and large well yields can probably be expected.

CONCLUSIONS

The principal aspect of the Carrizo Sand and Meridian–upper Wilcox aquifer is that in their present undeveloped state they represent a huge reserve of ground water in nearly one-fourth of the Mississippi embayment. In Mississippi, where the withdrawal from the Meridian–upper Wilcox aquifer is about 27 mgd for all purposes, exclusive of the water lost from uncontrolled flowing wells, the potential of the aquifer is far greater than the present development. Large areas remain where the sands have not been tapped by water wells, although in some places the aquifer characteristics preclude large ground-water developments. In south-central Arkansas, where the hydrology of the Carrizo Sand is the most favorable for future development in that State, the unit is untapped. In the southwestern Arkansas–northeastern Texas–northwestern Louisiana area, data indicate that, although the aquifer yields water to only a few large-capacity wells, additional large withdrawals may overdevelop the aquifer unless the withdrawals cause increased recharge.

CANE RIVER FORMATION AND EQUIVALENTS

By R. L. HOSMAN, E. H. BOSWELL, and A. T. LONG

The Cane River Formation in Louisiana and Arkansas is equivalent to the Reklaw Formation, Queen City Sand, and Weches Greensand in Texas and to the Tallahatta Formation (exclusive of the Meridian Sand Member, which is equivalent to the Carrizo Sand), Winona Sand, and Zilpha Clay in Mississippi. Above the Meridian Sand Member, the Tallahatta Formation also includes the Basic City Shale and Neshoba Sand Members; north of lat 34° N., the upper part of the Tallahatta is undifferentiated.

The top of the Cane River Formation or its equivalents is defined in this report on the basis of a micropaleontologic and lithologic examination of drill cuttings from wells in Arkansas and Mississippi and a correlation of electric logs of these wells with electric logs of wells elsewhere in the embayment.

The Cane River Formation or its equivalents ranges from about 200 feet to about 500 feet in thickness (pl. 6), and the formation dips toward the axis of the embayment (pl. 6) at 5–40 feet per mile.

In the subsurface of Louisiana and Arkansas the Cane River Formation is a marine clay. However, in the updip section on the west side of the embayment the Cane River becomes increasingly sandy; the predominant and more persistent sands generally occur in the middle part of the formation. In northwestern Louisiana this middle part contains interfingering sands which merge updip in northeastern Texas to form the Queen City Sand. The sandy middle part of the Cane River extends a short distance northeastward into Arkansas, beyond which the Cane River generally contains from two to four principal sands. In northeastern Texas the Reklaw is also sand, and it and the underlying Carrizo Sand and the overlying Queen City Sand form an aquifer. In places in and near the outcrop area in southwestern Arkansas, the lower part of the Cane River Formation is sand or very sandy clay and provides hydraulic connection between the Carrizo and the overlying Cane River sands.

Sands of the Cane River Formation are sources of water for small domestic wells in an area of about 4,000 square miles in south-central and southwestern Arkansas. Only in about one-fourth of this area do wells tap the Cane River.

Updip the Cane River undergoes a facies change northward at about lat 35° N., and the marine clays become sand. The transitional zone of interfingering sands and clays is narrow. The northern sand facies of the Cane River is the middle part of the Memphis aquifer.

The Tallahatta Formation of Mississippi includes the Meridian Sand, Basic City Shale, and Neshoba Sand Members. North of lat 34° N., the upper part of the Tallahatta is undifferentiated. The Meridian Sand Member was discussed in this report with its equivalent, the Carrizo Sand. The Basic City Shale is not an aquifer in its type locality, but it does include water-bearing sands northward and is a locally used aquifer in some areas. The Neshoba Sand Member, apparently a facies of the Basic City Shale Member, and the overlying Winona Sand form an extensive aquifer in northwestern Mississippi. Although the Cane River in Arkansas is not subdivided, the Winona Sand and overlying Zilpha Clay are recognizable on electric logs in eastern Arkansas, chiefly in Lee and Phillips Counties. The marine clays in the Tallahatta and Zilpha Formations like those in the Cane River, change to a sand facies at approximately lat 35° N.

Several miles north of Memphis a clay reappears in the Claiborne section in the same stratigraphic position as that occupied by the Zilpha Clay and the corresponding part of the Cane River Formation to the south. Although this clay has not been identified as the Zilpha, its stratigraphic position and the overall thickness of the Claiborne section suggest that it probably is the Zilpha. If this clay is the Zilpha, its absence in many places at about the latitude of Memphis is possibly not due to a facies change but to removal by erosion and subsequent replacement by Sparta Sand. This replacement could have been accomplished by two or three major streams entering the embayment in this area, probably from the northeast.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

The outcrop is the principal recharge area for the Reklaw–Queen City aquifer and for sands of the Cane River Formation, and it forms uplands in the western part of the embayment. Wells in the outcrop area generally yield 5–10 gpm. Downdip, larger capacity wells tap the aquifer. Several industrial and irrigation wells in eastern Cass County, Tex., and a municipal well in Bossier Parish, La., yield 50–100 gpm and these pumpage figures are included with those for the Carrizo, as the Carrizo and the sands in the Cane River form one aquifer. Withdrawals from the Cane River in Arkansas are about 3 mgd in an area of about 1,000 square miles, mostly in the southwestern part of the State. In this area flowing wells of low yield can be obtained in major stream valleys.

The outcrop belt of the sands of the Tallahatta Formation is in an area of rugged topography, and recharge conditions are good. The water moves westward except in the central part of the Mississippi alluvial plain, where long-term withdrawals have caused a large cone of depression. This cone is a result of withdrawals beginning in 1896 (Brown, 1947, p. 27), when the first flowing artesian well in the alluvial plain was developed in the Winona–Tallahatta aquifer. Because this aquifer is shallow, is artesian, and yields water of good chemical quality, it has been the source of many flowing wells. As a result, the artesian pressure has declined, and the present trend in well drilling is to drill deeper and develop wells in the Meridian–upper Wilcox aquifer.

AQUIFER CHARACTERISTICS

Aquifer characteristics of the Cane River Formation and its equivalents are not known for most of the area. The results of one aquifer test in the Neshoba Sand in Carroll County, Miss. (pl. 6) show a coefficient of transmissibility of 4,800 gpd per ft, a coefficient of storage of 0.0005, and a coefficient of permeability of 60 gpd per sq ft. The specific capacity of the pumped well was 3 gpm per foot of drawdown.

QUALITY OF THE WATER

Water in the Reklaw–Queen City aquifer and in sands of the Cane River Formation is generally soft and has a fairly high iron content; the chemical characteristics generally vary with the dissolved-solids content. Where the dissolved-solids content of the water is low, calcium and sodium may both be present in about equal amounts or either may predominate. Bicarbonate is the principal anion. As the dissolved-solids content increases, sodium and bicarbonate become the principal constituents; a continued increase in dissolved solids results in the water changing to a sodium bicarbonate chloride type and then to a sodium chloride type.

The ranges in concentration and the median values of the various constituents are given in table 8. The maximum amounts of iron and nitrate are unusually high; but, excluding these anomalous amounts, the maximum amounts would be only 6.6 and 3.2 ppm, respectively. The dissolved-solids content of the water generally increases with depth, and most of the larger amounts are in water from wells deeper than 200 feet. The dissolved-solids content, however, does not necessarily increase because of an increase in depth. Some wells that are deeper than 200 feet yield water containing less than 350 ppm dissolved solids. The maximum amounts of dissolved solids are in water from a faulted zone in Arkansas.

TABLE 8.—*Summary of chemical analyses of water from the Reklaw–Queen City aquifer and the sands in the Cane River Formation*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Iron (Fe)	55	0.02	0.50
Calcium (Ca)	65	.8	7.5
Magnesium (Mg)	20	.0	2.8
Sodium (Na)	964	.8	119
Potassium (K)	16	.4	5.0
Carbonate plus bicarbonate (CO_3+HCO_3)	708	0	212
Sulfate (SO_4)	81	.0	1.8
Chloride (Cl)	1,410	1.8	59
Fluoride (F)	1.8	.0	.1
Nitrate (NO_3)	29	.0	1.0
Dissolved solids	2,720	29	306
Hardness as $CaCO_3$	236	2	31
Specific conductance (micromhos at 25°C)	4,610	43	500
pH	8.3	4.7	-------

Patterns of the variations in the chemical characteristics of water from several locations are shown in plate 6. Except for the patterns for the southernmost two Texas wells, the patterns are representative of the chemical characteristics of water at different locations in the formation. In Texas, the water containing 29 ppm nitrate and 96 ppm of dissolved solids is not representative of the formation. This water is from a 30-foot-deep well, and the high nitrate content probably results from surface contamination. The chemical characteristics shown by the pattern of the southernmost well (452 ppm dissolved solids) are neither similar to the chemical characteristics of water in other areas nor to those of water at shallower depths in the same area. The factors that caused these characteristics are not known.

Except in the faulted zone in Arkansas, the dissolved-solids content of water from sands in the Cane River Formation and its equivalents is less than 1,000 ppm. The median value for iron indicates that the iron content is generally high in much of the area; consequently, for many uses treatment for iron removal would be desirable. The silica content of the water ranges from 9.1 to 23 ppm, and the concentration of this constituent would need to be reduced if the water were to be used in high-pressure steam boilers.

Water from the Tallahatta Formation is generally soft and a sodium bicarbonate type (pl. 6). At a few locations, calcium and magnesium are in sufficient quantities to cause the water to be moderately hard or hard. The water commonly has a low iron content and is colored.

The dissolved-solids content ranges from 59 to 1,590 ppm (table 9). It is lowest in the water from the outcrop or recharge area, and increases with depth into the formation and with distance traveled by the water downdip. The increase in dissolved-solids content results mainly from an increase in the sodium and bicarbonate contents (pl. 6).

TABLE 9.—*Summary of chemical analyses of water from the Tallahatta Formation*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	51	0.4	19
Iron (Fe)	4.3	.00	.12
Calcium (Ca)	40	.0	1.9
Magnesium (Mg)	18	.0	.4
Sodium (Na)	651	7.4	152
Carbonate plus bicarbonate (CO_3+HCO_3).	1,710	52	332
Sulfate (SO_4)	42	.0	1.0
Chloride (Cl)	56	.0	5.6
Fluoride (F)	4.0	.0	.3
Dissolved solids	1,590	59	382
Hardness as $CaCO_3$	174	0	8
pH	8.6	7.0	-------
Color	120	5	-------

The median values in table 9 are indicative of the chemical characteristics of water in the Tallahatta Formation. The median concentrations of constituents other than silica, sodium, and bicarbonate rarely exceed 10 ppm. Calcium and magnesium ions are evidently either unavailable in the aquifer material or are removed from solution by ion exchange; near maximum amounts of calcium and magnesium ions are unusual and occur only locally in the water. The median value of 0.12 ppm for iron indicates that the iron content is usually low. Maximum and near maximum amounts of sulfate and chloride also are unusual and occur only locally in the water. The coloring material in the water is probably derived from organic material in the deposits, and the amount or degree of coloration generally increases with depth.

Water in the Tallahatta Formation is generally of good chemical quality, and in much of the area it is suitable for many uses without treatment. With treatment it can be made suitable for most uses. The particular treatment depends upon the area and the intended use of the water. It could include iron and color removal for domestic, municipal, and industrial supplies; reduction of alkalinity for some industrial uses; reduction of the silica content of water used in high-pressure steam boilers; and the addition of stabilizers or inhibitors for corrosion control.

Water in the Winona Sand is generally soft and a sodium bicarbonate type. At a few locations calcium is present in sufficient quantities to make the water moderately hard, but the percentage of calcium is not great enough to change the type of water. The available information on iron content of the water is inconclusive.

The dissolved-solids content of the water ranges from 33 to 977 ppm (table 10). It is less in water from wells in the outcrop area and increases with depth and the downdip movement of the water. The median values in table 10 and the patterns on plate 6 show that increases in dissolved solids are primarily in sodium and bicarbonate. A comparison of the median dissolved-solids values of water from the Winona Sand (619 ppm) with those from the Tallahatta Formation (382 ppm) and from the Sparta Sand (256 ppm) in Mississippi indicates that water in the Winona Sand is more mineralized than water from the underlying and overlying formations.

The maximum and minimum values in table 10 show the range in concentration of the various constituents; and the median values, except those for sodium and bicarbonate, are representative of the concentrations of these constituents in the water throughout the area of use. Near maximum amounts of calcium are unusual and occur only locally in the water. The calcium content of the water in 89 percent of the analyses was 11 ppm or less, and in 67 percent of the analyses it was 5 ppm or less. Sodium and bicarbonate increase with downdip movement of water. The maximum and minimum amounts of fluoride (table 10) are in water from the deepest (1,550 ft) and the shallowest (6 ft) wells, respectively. Fluoride generally is in water from wells deeper than 1,200 feet; the fluoride content of water at depths less than 1,200 feet is not known.

TABLE 10.—*Summary of chemical analyses of water from the Winona Sand*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	42	0.3	21
Iron (Fe)	1.5	.05	-------
Calcium (Ca)	33	.9	2.5
Magnesium (Mg)	3.0	.3	.9
Sodium (Na)	415	5.6	244
Potassium (K)	13	.4	3.5
Carbonate plus bicarbonate (CO_3+HCO_3)	1,110	15	650
Sulfate (SO_4)	11	.9	1.3
Chloride (Cl)	24	1.0	4.6
Fluoride (F)	2.7	.2	-------
Dissolved solids	977	33	619
Hardness as $CaCO_3$	92	4	8

Although water in the Winona Sand generally contains more dissolved solids than water in the Tallahatta Formation, the major chemical characteristics of water from both formations are similar. Thus, water from the Winona Sand would generally be suitable for the same uses, and subject to the same requirements of treatment, as water from the Tallahatta Formation.

POTENTIAL USE

The area of potential use of sands in the Cane River Formation (pl. 6) in Arkansas is about 3,000 square miles in the south-central and southwestern parts of the State. This area is about three times as large as the area of use. The area of potential use is limited by the downdip extent of the sands and the downdip limit of fresh water in them.

The present area of use of water from the Winona-Tallahatta aquifers is nearly the maximum potential area of development. However, the aquifers are sparsely developed, particularly in areas where they underlie the Sparta Sand. In other areas wells are drilled to the underlying Meridian–upper Wilcox aquifer to obtain higher water levels and greater artesian flows.

CONCLUSIONS

Aquifers of the Cane River Formation and its equivalents are underdeveloped. These aquifers are not used in large areas, and most wells provide small domestic supplies. A few large-capacity wells have been drilled in these aquifers in Mississippi, but the total withdrawal has been small, although the area in which fresh water occurs is large. The Winona equivalent is not tapped in eastern Arkansas.

As the sand beds in the Cane River Formation are updip sand facies of marine clays, water in them is confined not only by clays above and below, but also by the subsurface termination of the sand downdip. Thus, movement of water in these aquifers is naturally restricted to vertical leakage. Withdrawals by pumping would accordingly be the principal means of increasing the recharge in the outcrop.

Although not within the scope of this report, a detailed study of the stratigraphic relations, areal extent, and hydrologic nature of the sands of the Cane River Formation on the west side of the Mississippi embayment would be valuable to future development of the aquifers in this area.

SPARTA SAND

By R. L. Hosman, E. H. Boswell, and A. T. Long

The Sparta Sand overlies the Cane River Formation in most of the western part of the embayment, and the Zilpha Clay in the eastern part. It is correlative with the upper part of the Memphis aquifer. The Sparta crops out on both the west and east sides of the embayment and dips toward the axis of the embayment and southward toward the gulf (pl. 7). The thickness near the outcrop areas ranges from about 400 feet, in western Louisiana, to about 100 feet, in southeastern Mississippi; the maximum thickness in the subsurface is about 1,100 feet near the axis of the embayment at the south limit of the region (pl. 7).

The Sparta has been removed by erosion in places under the flood plain of the Mississippi River near the north boundary of Mississippi, and the truncated edge of the Sparta underlies the alluvium in other parts of the area. The Sparta occurs only as outliers in northeastern Texas.

The Sparta consists chiefly of beds of fine to medium sand in the lower half of the formation, and of beds of sand, clay, and lignite in the upper half. In parts of the embayment, clay beds separate the Sparta into two or more hydrologic units.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

The sources of recharge to the Sparta Sand are precipitation on the outcrop, leakage from overlying alluvium, and underflow from the Memphis aquifer. Recharge from streams is negligible except in areas where the streams are directly connected to the aquifer.

The areas of heavy withdrawals of water by wells, indicated by the depressions in the piezometric surface (pl. 7), are in south-central Arkansas, in north-central Louisiana, and at Jackson, Yazoo City, and Clarksdale, Miss. Withdrawals for industrial, irrigation, and municipal use are about 125 mgd in Arkansas, about 53 mgd in Louisiana, and about 37 mgd in Mississippi. The major withdrawals are for industrial use in Louisiana, for industrial and municipal use in Arkansas, and for municipal use in Mississippi. Larger capacity wells screened in the Sparta yield from a few hundred to more than 2,000 gpm. The piezometric surface has declined below the land surface everywhere in the lowlands, except in the southern part of the region in Mississippi, as a result of pumping and discharge from flowing wells. Water levels have declined more than 200 feet in south-central Arkansas and in north-central Louisiana and may be below the top of the Sparta Sand in parts of these areas.

The regional movement of ground water in the Sparta is toward the axis of the embayment. In the outcrop area the ground water discharges into streams or alluvium.

AQUIFER CHARACTERISTICS

The aquifer characteristics for the Sparta Sand are summarized (averages by county or parish) in the following table:

[Number in parenthesis denotes number of tests used to compute average]

County or parish	State	Coefficient			Specific capacity (gpm per ft of drawdown)
		Transmissibility (gpd per ft)	Storage	Permeability (gpd per sq ft)	
Arkansas	Arkansas	(2) 130,000			
Columbia	do	(8) 28,000	(3) 0.0008	(1) 830	(7) 9
Dallas	do	(1) 24,000	(1) .0003		
Desha	do	(1) 20,000	(1) .0024		
Drew	do	(1) 13,500		(1) 140	
Grant	do	(2) 38,000			(1) 12
Jefferson	do	(5) 100,000	(5) .0002		
Lafayette	do	(1) 49,000	(1) .0005		
Ouachita	do	(1) 29,000	(1) .0002	(1) 660	(1) 7
Prairie	do	(1) 55,000	(1) .0002		
Union	do	(6) 32,900	(2) .0004	(6) 80	(3) 14
Bienville	Louisiana	(2) 18,000	(1) .0012	(2) 170	
Claiborne	do	(2) 26,000		(2) 210	
Ouachita	do	(1) 24,000	(1) .0002	(1) 300	
Union	do	(2) 19,500	(2) .0004	(2) 270	
Webster	do	(1) 40,000	(1) .0001	(1) 400	
Coahoma	Mississippi	(1) 50,000	(1) .0005	(1) 850	
Hinds	do	(10) 43,000	(7) .0004	(10) 550	(5) 16
Humphreys	do	(1) 94,000	(1) .0002	(1) 1,000	
Leflore	do	(1) 140,000		(1) 1,300	

QUALITY OF THE WATER

Water in the Sparta Sand is generally soft and is a sodium bicarbonate type (pl. 7). The dissolved-solids content ranges from 20 to 1,510 ppm (table 11), but the median value of 218 ppm indicates that generally the water is moderately mineralized. The median values also indicate that concentrations of all constituents except sodium and bicarbonate are low. Greater amounts of calcium and magnesium occur in water in areas of Arkansas and Mississippi where recharge to the Sparta Sand is from overlying Quaternary deposits. Nearly maximum amounts of sulfate are unusual and occur only locally in the water in Madison County, Miss., and Jackson Parish, La. Larger amounts of fluoride are present in water from the downdip areas, and the higher iron content is generally in water in and near the areas of outcrop. Larger amounts of chloride occur in water in downdip areas and in parts of Monroe and Lee Counties, Ark.

The patterns of chemical analyses on plate 7 show that the dissolved-solids content of the water is less in the outcrop and that it increases as the water moves downdip; calcium, magnesium, and iron contents, however, generally decrease with the movement of water downdip. The downdip increase in dissolved solids is mainly due to increases in sodium and bicarbonate. In extreme downdip areas the increase in dissolved solids is mainly due to increases in sodium, bicarbonate, and chloride.

The median values indicate that water in the Sparta Sand is generally of good quality. Except in the area of highly mineralized water in Monroe and Lee Counties, Ark., and in the extreme downdip locations, the water is suitable for most uses; but some treatment, such as iron removal or softening, may be desirable in places.

TABLE 11.—*Summary of chemical analyses of water from the Sparta Sand*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	62	0.0	17
Iron (Fe)	23	.00	.21
Calcium (Ca)	79	.0	3.3
Magnesium (Mg)	29	.0	.9
Sodium (Na)	598	2.6	70
Potassium (K)	11	.6	3.0
Carbonate plus bicarbonate (CO_3+HCO_3)	991	0	193
Sulfate (SO_4)	216	.0	3.7
Chloride (Cl)	638	1.0	7.4
Fluoride (F)	5.4	.0	.2
Nitrate (NO_3)	14	.0	.8
Dissolved solids	1,510	20	218
Hardness as $CaCO_3$	288	0	13
Specific conductance (micromhos at 25°C).	2,710	42	338
pH	9.0	4.3	8.0
Color	240	0	14

The high dissolved-solids content and the sodium chloride type of water in parts of Monroe and Lee Counties, Ark., are uncommon. Water in the Memphis aquifer to the north of this area contains less dissolved solids and is generally a calcium magnesium bicarbonate type. Water in the Sparta Sand south of this area also contains less dissolved solids but is a calcium magnesium bicarbonate or a sodium bicarbonate type. This anomalous situation may be due to the upward movement of mineralized water from lower aquifers. The occurrence of mineralized water in the Sparta in this area coincides with the zone of transition (pl. 7) where the marine clays of the Cane River undergo a facies change to sand. In this zone the clays are sandy and are probably less confining than the marine clays. This apparent increase in vertical permeability and the facts that in this area the Carrizo Sand contains saline water and has about a 10-foot higher hydrostatic head than the Sparta could account for the mineralized water in the Sparta at shallow depths.

POTENTIAL USE

The Sparta Sand is extensively utilized in areas of south-central Arkansas and north-central Louisiana. Large depressions in the piezometric surface (pl. 7) in these areas indicate an overdraft from the aquifer, and the proximity of a deep cone of depression in northeastern Louisiana to the area in which the Sparta contains saline water indicates that this overdraft may eventually result in a deterioration of the quality of the water in the area of heavy withdrawals.

Increased withdrawal near the outcrop area in Arkansas and Louisiana may increase the recharge to the Sparta and increase the available supply. The Sparta is capable of sustaining increased withdrawals in much of Mississippi and in southeastern Arkansas.

CONCLUSIONS

The Sparta Sand is one of the major sources of water in much of the embayment and is generally capable of yielding at least a few hundred gallons per minute. It is extensively utilized in large areas of Arkansas and Louisiana, and heavy pumping in part of the area may result in deterioration of the quality of the water. The water from the Sparta is of good quality and is suitable for most uses, except in some areas near the axis of the embayment. The water has a high iron content and is hard near the outcrop. Potential areas for larger yields from the Sparta are near the outcrop in Louisiana, much of Mississippi, and southeastern Arkansas.

MEMPHIS AQUIFER

By R. L. Hosman, G. K. Moore, and T. W. Lambert

The Memphis aquifer is a major aquifer in western Tennessee, southwestern Kentucky, southeastern Missouri, and northeastern Arkansas north of about lat 35° N. It is known locally in the Memphis, Tenn., area as the "500-foot" sand, and is the principal aquifer from which Memphis obtains its water supply.

The sand rests unconformably upon clay of the Wilcox, and the top of the unit near the latitude of Memphis appears to correlate with the top of the Sparta. In this area marine clays of the lower part of the Claiborne are not present but are represented by sand facies, and the entire section of sand from the top of the Wilcox to the top of the Sparta constitutes a single aquifer several hundred feet thick. North of the Memphis area a clay is present in the upper part of the Memphis aquifer which divides it into two aquifers, the lower being several times thicker than the upper. This clay occupies approximately the same stratigraphic position as the Zilpha Clay of Mississippi. The zone of transition, or facies change, which marks the southern limit of the Memphis aquifer, is shown on plate 7. To the south in Arkansas the interval occupied by the Memphis aquifer farther north includes the Carrizo Sand, Cane River Formation, and Sparta Sand, and in Mississippi the Tallahatta Formation, Winona Sand, Zilpha Clay, and Sparta Sand.

The Memphis aquifer thickens southward and toward the axis of the Mississippi embayment, which is marked approximately by the present course of the Mississippi River. The thickness ranges from about 400 feet to about 870 feet (pl. 7). The unit crops out on both the east and west sides of the northern part of the embayment, but in Illinois and Missouri it is overlapped by younger beds. The top of the unit dips about 12 feet per mile toward the axis of the embayment (pl. 7).

The area of outcrop of the Memphis aquifer comprises about 2,000 square miles in Tennessee, about 600 square miles in Kentucky and Missouri, and about 2,000 square miles in Arkansas. The Memphis aquifer is covered by Quaternary deposits west of the Mississippi River except in parts of Craighead, Green, and Clay Counties, Ark., where a part of the aquifer crops out as a segment of Crowleys Ridge.

The Memphis aquifer is principally made up of sand, but contains some argillaceous, micaceous, and lignitic materials. The sand is thick bedded, very fine to gravelly, and generally well sorted. Clay layers constitute only a small part of the total thickness, but layers as much as 20 feet thick may be extensive enough locally to separate the sand hydraulically.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

The principal sources of recharge to the Memphis aquifer are precipitation on the outcrop area on the east side of the embayment and leakage from Quaternary alluvium and terrace deposits on the west side.

The major area of use of the Memphis aquifer is in the northeastern part of the embayment (pl. 7). Flowing wells can result from drilling in the major stream valleys east of the Mississippi River. The withdrawals from wells in 1960 were estimated to be about 160 mgd in Tennessee, 15 mgd in Arkansas, and 1 mgd in Missouri and Kentucky. The major part, about 140 mgd, was withdrawn in the Memphis area.

The regional movement of ground water in the Memphis aquifer is toward the axis of the embayment, and near the axis the movement has a southward component.

The large depression in the piezometric surface centered at Memphis results from the heavy withdrawal of ground water (pl. 7).

AQUIFER CHARACTERISTICS

The following table summarizes (averages by county) the aquifer characteristics for the Memphis aquifer:

[Number in parenthesis denotes number of tests used to compute average]

County	State	Coefficient			Specific capacity (gpm per ft of drawdown)
		Transmissibility (gpd per ft)	Storage	Permeability (gpd per sq ft)	
St. Francis	Arkansas	(1) 55,000	(1) 0.0009		
Graves	Kentucky	(1) 300,000	(1) .0002	(1) 2,000	(1) 54
Crockett	Tennessee	(1) 42,000	(1) .0005		(1) 11
Dyer	do	(3) 140,000	(3) .0004		
Fayette	do	(1) 20,000			
Gibson	do	(3) 89,000			
Haywood	do	(1) 200,000	(1) .0001		
Lake	do	(1) 130,000	(1) .0003		
Lauderdale	do	(2) 93,000	(1) .0003		(1) 4
Madison	do	(1) 150,000	(1) .011	(1) 600	
Obion	do	(4) 66,000	(3) .0006	(2) 265	(2) 23
Shelby	do	(60) 250,000	(52) .001		
Tipton	do	(1) 220,000			(1) 43
Weakley	do	(1) 54,000	(1) .0006		

QUALITY OF THE WATER

Water in the Memphis aquifer is generally a mixed type where the dissolved-solids content is low, and a calcium magnesium bicarbonate type when the dissolved-solids content is high (pl. 7). The maximum and minimum values in table 12 show a wide range in concentration for most constituents. The larger amounts of chloride, nitrate and dissolved solids and the higher values for specific conductance are in water from shallow wells and are not representative of water in the Memphis aquifer. The maximum values for calcium, magnesium, and bicarbonate are indicative of the concentrations of these constituents where recharge to the Memphis aquifer is from Quaternary deposits. The iron content of the water is generally low, but amounts in excess of 1 ppm are found locally.

TABLE 12.—*Summary of chemical analyses of water from the Memphis aquifer*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	43	3.3	13
Iron (Fe)	60	.00	.24
Calcium (Ca)	79	.5	7.0
Magnesium (Mg)	31	.3	2.6
Sodium (Na)	57	1.9	7.4
Potassium (K)	12	.0	.8
Carbonate plus bicarbonate (CO_3+HCO_3).	402	0	36
Sulfate (SO_4)	98	.0	3.1
Chloride (Cl)	174	.0	4.8
Fluoride (F)	2.0	.0	.1
Nitrate (NO_3)	439	.0	1.4
Dissolved solids	848	16	78
Hardness as $CaCO_3$	398	4	27
Specific conductance (micromhos at 25°C).	1,460	23	102
pH	8.5	4.7	6.3
Color	20	0	4

The patterns of chemical analyses (pl. 7) show that in the eastern part of the area of use, where the sand crops out, the water generally contains less than 100 ppm dissolved solids. Bicarbonate is the principal anion, and either calcium or sodium is the predominant cation. In a few places calcium, magnesium, and sodium are present in about equal amounts. In Missouri and parts of Arkansas and western Tennessee, where recharge to the Memphis aquifer is from Quaternary deposits, the water contains more dissolved solids and is a calcium magnesium bicarbonate type. Two exceptions are in southern Missouri, where the water contains less dissolved solids and is a sodium bicarbonate type. One of the samples from southern Missouri also contained an unusually high amount of iron.

Downdip from the area where a part of the sand forms a segment of Crowleys Ridge in northeastern Arkansas (pl. 7), the water is low in dissolved solids and is a sodium bicarbonate type. North and south of this segment of the ridge, where the outcrop of the aquifer is overlain by Quaternary deposits, the water has a higher dissolved-solids content and is a calcium magnesium bicarbonate type.

Water in the Memphis aquifer is generally of good quality and is suitable for most uses. However, in some places treatment for removal of iron and softening would be desirable for municipal and some industrial uses.

POTENTIAL USE

The Memphis aquifer is relatively undeveloped in the area of use except at Memphis. Large-capacity wells tap only the upper part of the aquifer. All the area of potential use where wells have not been drilled into the aquifer is in northeastern Arkansas and southeastern

Missouri. The Memphis aquifer is several hundred feet thick in this area and represents a large ground-water reserve.

CONCLUSIONS

The Memphis aquifer is a major aquifer in the northern part of the Mississippi embayment and is the principal source of water supply for Memphis. The aquifer is the sandy facies of the Claiborne Group below the top of the Sparta Sand. Large yields can be obtained from wells in most of the area of use, but the thickest sand is in the vicinity of Memphis, where the withdrawal of ground water is largest. The water from the sand is generally of good quality, but treatment for excessive iron and for hardness is desirable in places. Where the outcrop of the aquifer is overlain by Quaternary deposits, recharge from these deposits affects the chemical quality of the water, making it higher in dissolved-solids content and of a different chemical type. Most of the wells tap only the upper part of the aquifer. It offers excellent prospects for future development on the west side of the embayment, where it now is largely unused.

COCKFIELD FORMATION

By R. L. Hosman, A. T. Long, and E. H. Boswell

The Cockfield Formation crops out over large areas on both the east and west sides of the embayment. The truncated Cockfield underlies thick Quaternary alluvial deposits in the Mississippi River valley. The formation is missing in some areas of the western part of the valley in northern Louisiana. The Cockfield underlies the marine clay of the Jackson Group near the axis of the embayment at the extreme south limit. The lower part of the Jackson Group contains beds of fine sand in contact with the Cockfield in south-central Arkansas; these sands and the Cockfield together form one hydrologic unit. The thickness of the Cockfield near its outcrop area generally ranges from 100 feet to 400 feet; in the subsurface the thickness increases to about 700 feet (pl. 8). The Cockfield dips southward and toward the axis of the embayment (pl. 8).

The Cockfield Formation generally consists of fine to medium sand in the basal part, and silt, clay, and lignite in the upper part. The beds are discontinuous and contain carbonaceous material throughout.

Plate 8 does not show the Cockfield Formation north of lat 35° N., because positive identification of Cockfield deposits has not been established in this area. However, the Cockfield may be present in the northern part of the embayment east of the axis where the land surface is at a higher altitude.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

The recharge to the Cockfield Formation is from precipitation on the outcrop and seepage from the Quaternary alluvium. The excess or rejected recharge on the outcrop contributes to the base flow of streams.

The regional movement of water in the Cockfield as shown by contours on the piezometric surface (pl. 8) is westward in Mississippi, southward in Arkansas, and southwestward in Louisiana. The irregular shape of some of the contours may be partly due to the fact that the wells may be screened in different sands within the Cockfield. The degree of hydraulic connection between the sands is not known, but slightly different piezometric pressures apparently do exist where they are affected by pumping.

The Cockfield is used for water supply in an area of about 20,000 square miles in Mississippi, 10,000 square miles in Arkansas, and 3,000 square miles in Louisiana. Where the water is confined by the Jackson Group at the south limit of the region, the piezometric surface is above the land surface and wells flow. The water in the Cockfield is saline in much of the area where it is confined by the Jackson Group.

The withdrawal of water by wells for municipal and industrial use is about 10 mgd in Arkansas, 2 mgd in Louisiana, and 20 mgd in Mississippi. The largest local withdrawal, 10 mgd, is at Greenville, Miss. The withdrawal by wells is small compared with the natural discharge. Large withdrawals are confined to local areas where water cannot be obtained from deeper aquifers. The water in the Cockfield is withdrawn only for domestic and stock use in much of the area.

AQUIFER CHARACTERISTICS

The following table summarizes (averages by county or parish) the aquifer characteristics for the Cockfield Formation.

[Number in parenthesis denotes number of tests used to compute average]

County or parish	State	Coefficient			Specific capacity (gpm per ft of drawdown)
		Transmissibility (gpd per ft)	Storage	Permeability (gpd per sq ft)	
Chicot	Arkansas	(1) 51,000	(1) 0.0008	(1) 850	
Caldwell	Louisiana	(1) 29,000			
East Carroll	do	(1) 33,000	(1) .0003	(1) 330	(4) 7
West Carroll	do				(2) 8
Hinds	Mississippi	(2) 22,500	(2) .0001	(2) 230	(1) 4
Rankin	do	(3) 25,000	(1) .0008	(2) 370	(2) 8
Scott	do	(2) 63,000	(1) .0004	(2) 480	(2) 16
Washington	do	(3) 72,000	(3) .0004	(3) 910	(1) 28

QUALITY OF THE WATER

Water in the Cockfield Formation is generally soft and a sodium bicarbonate type (pl. 8). The dissolved-solids content ranges from 25 to 4,870 ppm (table 13), but the median value of 303 ppm indicates that in most of the area the water is moderately mineralized. The median values also indicate that the concentration of all the constituents except sodium and bicarbonate is low. Larger amounts of calcium and magnesium are present in water in parts of Arkansas and in Louisiana where the Cockfield Formation is recharged from Quarternary deposits. Larger amounts of sulfate occur in water from wells in Jefferson County and from a few wells in Drew County, Ark., where the aquifer is continuous with sand in the overlying Jackson Group. Higher-than-normal sulfate contents also occur in water in most of Madison, Rankin, and Hinds Counties, Miss. The iron values are irregularly distributed over the area but generally the larger amounts are in water in or near areas of outcrop. Large amounts of fluoride are in water from deep wells in the downdip part of the area of use. The maximum amount of chloride is in water from a deep well in the extreme downdip area. Most of the larger amounts of chloride are in water from wells in an east-west belt extending from southern Ashley County, Ark., across central Chicot County, Ark., and into Washington County, Miss. The amount of coloration is probably related to the amount of carbonaceous material in the formation. The more highly colored water is in wells in the downdip areas.

TABLE 13.—*Summary of chemical analyses of water from the Cockfield Formation*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	53	2.0	13
Iron (Fe)	62	.00	.21
Calcium (Ca)	125	.0	3.2
Magnesium (Mg)	36	.0	1.1
Sodium (Na)	1,910	1.2	105
Potassium (K)	13	.2	3.2
Carbonate plus bicarbonate (CO_3+HCO_3)	1,590	8	249
Sulfate (SO_4)	464	.0	2.4
Chloride (Cl)	2,380	2.0	16
Fluoride (F)	4.4	.0	.3
Nitrate (NO_3)	10	.0	1.0
Dissolved solids	4,870	25	303
Hardness as $CaCO_3$	440	0	13
Specific conductance (micromhos at 25°C)	8,430	25	455
pH	8.9	5.8	8.2
Color	1,200	0	11

The patterns of chemical analyses (pl. 8) are representative of areal variations in the chemical characteristics of water in the Cockfield Formation. These patterns show that the dissolved-solids content increases, principally in sodium and bicarbonate, with the downdip movement of water. These patterns also indicate that as water moves downdip, the concentrations of calcium, magnesium, and sulfate decrease.

Water in the Cockfield Formation is generally of good chemical quality and is suitable for most uses. In places, however, softening and iron and color removal would be desirable for municipal and many industrial uses.

POTENTIAL USE

The area of use coincides with the area of potential use in the southern part of the embayment, but in much of the area the aquifer has not been fully developed. An increase in withdrawals will eventually result in a decrease in the base flow of streams in the area and available water in the overlying Quaternary alluvium. In Arkansas, few wells tap the Cockfield north of the Arkansas River. In much of the area of potential use, yields will be adequate only for domestic and stock use.

CONCLUSIONS

The sandy basal part of the Cockfield Formation is a major aquifer locally. It contains fresh water in about 33,000 square miles, generally where the Quaternary alluvium directly overlies the sand of the Cockfield. The Cockfield contains saline water in some areas near the axis of the embayment. The Cockfield yields small to moderate quantities of water and is the source of domestic and several public and industrial water supplies. The water is generally of good quality, but treatment for iron and color removal and softening may be desirable in places.

Withdrawals from the Cockfield Formation can be increased in much of the area, but use will generally be limited by small yields. The present withdrawal is about 30 mgd.

FOREST HILL SAND

By E. H. Boswell

In Mississippi, south of the Cockfield outcrop (pl. 8) and near the south limit of the embayment, the Forest Hill Sand of Oligocene age crops out in a narrow band. This outcrop extends southeastward from just west of Jackson to about the 89th meridian of longitude. Although the Forest Hill Sand does not supply water in a large enough area to be of regional importance as an aquifer, it is used locally. Thus, some information about the sand is included in this report. However, because the area within the embayment is small, maps like those prepared for the other aquifers were not made.

The Forest Hill Sand is composed of gray clay and thin-bedded very fine sand and averages about 100 feet in thickness. The formation generally contains less than 40 percent sand, although in a few places it is predominantly sand. The Forest Hill is underlain by the Yazoo Clay and overlain by the Vicksburg Group; large areas of the outcrop are covered by surficial sand, gravel, and clay, which are terrace deposits or remnants of the Citronelle Formation.

RECHARGE, WITHDRAWAL, AND MOVEMENT OF GROUND WATER

The Forest Hill Sand is recharged by precipitation on the outcrop. Ground water in the sand moves southwestward.

Withdrawals of water from the Forest Hill Sand for all purposes are estimated to total about 1 mgd. Most of this water is for domestic and farm use.

AQUIFER CHARACTERISTICS

Results of an aquifer test in the Forest Hill Sand in Rankin County, Miss., show a coefficient of transmissibility of 900 gpd per ft, a coefficient of storage of 0.0001, and a coefficient of permeability of 26.

QUALITY OF THE WATER

Water in the Forest Hill Sand is slightly alkaline; generally it is soft, has a low iron content, and is a sodium bicarbonate type. The dissolved-solids content (table 14) ranges from 270 to 791 ppm; generally, it is lower in the outcrop and increases downdip, but large amounts occur throughout the area. Most constituents have a fairly wide range in concentration, but near maximum concentrations of most constituents are unusual and occur only locally. The large amounts of calcium and magnesium, and usually sulfate and chloride, are in water from the shallower wells in the area. This indicates that water in the upper part of the formation has chemical characteristics different from those in the lower part, or that part of the water pumped from these shallower wells is derived from an overlying formation. The larger amounts of fluoride and the greater coloration generally occur in water from deeper wells in the downdip part of the area.

The median values in table 14 indicate that water in the Forest Hill Sand is generally of good chemical quality and is suitable for most uses. However, in areas where the hardness of the water is high, softening treatment would be desirable. In the downdip area the fluoride content and color of the water may be high enough to make the water undesirable as a municipal or domestic supply.

Table 14.—*Summary of chemical analyses of water from the Forest Hill Sand*

[Constituents in parts per million]

Constituent or property	Maximum	Minimum	Median
Silica (SiO_2)	35	5.5	8.9
Iron (Fe)	9.0	.03	.16
Calcium (Ca)	74	.6	2.8
Magnesium (Mg)	24	.3	3.0
Sodium (Na)	289	47	142
Potassium (K)	11	2.6	4.6
Carbonate plus bicarbonate (CO_3+HCO_3)	724	154	386
Sulfate (SO_4)	214	.0	17
Chloride (Cl)	109	3.5	9.2
Fluoride (F)	4.0	.0	.4
Nitrate (NO_3)	4.8	.0	2.2
Dissolved solids	791	270	443
Hardness as $CaCO_3$	226	2	21
Specific conductance (micromhos at 25°C)	1,130	297	698
pH	8.7	7.0	8.3
Color	320	0	35

POTENTIAL USE

The Forest Hill Sand is, in general, used for domestic and farm water supplies in the area of outcrop and for about 20 miles downdip. The total withdrawal is small, and the aquifer is capable of sustaining further development by low-yield wells.

CONCLUSIONS

The Forest Hill is a locally used aquifer because the next source of water is at least 600 feet deeper, in the Cockfield Formation. Farther downdip and southeastward along the strike the sand percentage decreases, and hydrologic conditions are not conducive to the development of ground-water supplies. Although the Forest Hill aquifer will be used for some small public and industrial water supplies, it will be used mostly for domestic and farm supplies.

PLIOCENE(?) DEPOSITS

Scattered deposits of gravel of Pliocene(?) age occur in the embayment, generally underlying loess in prominent ridges and bluffs along the Mississippi River. These isolated gravels are generally water bearing and are of only local value as aquifers. Thickness of the gravels ranges from a few feet to about 50 feet. Yields of as much as 400 gpm have been reported, but most wells are used for domestic and farm water supplies.

SIGNIFICANCE OF RESULTS

By R. L. Hosman and E. M. Cushing

This report defines and describes the Tertiary aquifers within the embayment only where they contain water having a dissolved-solids content of less than 1,000 ppm. Determination of the manner in which these aquifers will behave when manmade changes are imposed upon them is beyond the scope of this investigation and the adequacy of available data. More information is needed to provide definitive answers to meet the needs of regional water management. However, some aspects of the areal relations, characteristics, and utilization of the aquifers are now known:

1. The water-bearing units in the Tertiary System that contain fresh water underlie an area of about 75,000 square miles (about three-fourths of the Mississippi embayment), and they are used as sources of supply in almost all this area. In most of the embayment two or more aquifers are available for use. Individually, the areas of use and of potential use of the aquifers are, in square miles:

Aquifer	*Area of use*	*Area of potential use*	*Total*
Wilcox Group or Formation	23, 000	19, 000	42, 000
Carrizo Sand and Meridian–upper Wilcox aquifer	17, 000	9, 000	26, 000
Cane River Formation and its equivalents	17, 000	3, 000	20, 000
Sparta Sand	37, 000	0	37, 000
Memphis aquifer	12, 000	6, 500	18, 500
Cockfield Formation	[1] 23, 000	[1] 5, 500	[1] 28, 500

[1] Possibly more, pending positive identification and mapping of Cockfield in northern part of embayment.

2. Parts of all Tertiary aquifers underlie the States in the embayment. The total withdrawal from those units is about 500 mgd. Most of this amount is withdrawn in the southern half of the embayment, and the largest areas of potential use are in the northern half. The largest single local withdrawal, about 140 mgd, is at Memphis, Tenn. In most areas where they are utilized, the aquifers are capable of sustaining much larger withdrawals.
3. Water from the Tertiary aquifers is generally of good chemical quality and is suitable for many uses without treatment. For some industrial and municipal uses treatment may be desirable. Iron is the most common troublesome chemical constituent.
4. In east-central Arkansas, mineralized water occurs at shallow depths in the Sparta Sand. This condition is anomalous and seems to coincide with a zone of transition (pl. 7) where the underlying Cane River Formation changes from clay to sand. The increasing amount of sand in the Cane River in this area causes an increase in vertical permeability, and thus reduces the effectiveness of the Cane River as a confining bed for mineralized water in the underlying Carrizo Sand. Water in the Carrizo in this area has about a 10-foot higher hydrostatic head than does water in the Sparta, and this head provides the pressure differential necessary to induce the upward movement of water from the Carrizo into the Sparta.

   North of this zone of transition where the Cane River Formation is predominantly sand, the water in the Sparta section, as well as in the Carrizo and Cane River (Memphis aquifer), is fresh.

   Towns in the vicinity of this zone of transition have difficulty in obtaining water supplies that do not require expensive treatment. A comprehensive report of the hydrology and geology in this area could give suggested solutions to the quality problems and provide knowledge of the principles of the movement of water through these zones of transition which would be applicable to hydrologically and geologically similar areas.
5. Chemical-quality changes in water from the Memphis aquifer on the west side of the embayment indicate the effects of recharge. In this area the Memphis aquifer crops out in a segment of Crowleys Ridge and receives recharge. Downdip from this segment of the ridge (pl. 7), water in the Memphis aquifer is low in dissolved solids and is a sodium bicarbonate type. However, north and south of this area Quaternary alluvium overlies and recharges the Memphis aquifer. Downdip from these areas water in the Memphis aquifer has a higher dissolved-solids content and is a calcium magnesium bicarbonate type.
6. Although flowing wells can be developed in some low-lying areas, chiefly stream valleys, water levels in the Tertiary aquifers are generally too low to produce natural flow from wells on a regional basis.
7. Most general water-level declines in the Tertiary aquifers are the result of pumping and are not indicative of overdevelopment. Only one aquifer, the Sparta Sand, shows water-level declines that are becoming regional (pl. 7); the cones of depression in the piezometric surface in some local areas have coalesced, and the coalescence of others is impending. Although the Sparta is capable of sustaining more development on a regional basis, local overdevelopment may be imminent.

8. Most wells tapping Tertiary aquifers are small-capacity domestic wells, but most withdrawal is by municipal, industrial, and irrigation wells. Wells yielding as much as 200 gpm can probably be developed in the Tertiary aquifers throughout the area where the aquifers contain fresh water, and in many areas wells yielding as much as 2,000 gpm have been and can be developed.
9. The lower Wilcox aquifer is widely used in the northern and eastern parts of the embayment. Electric logs indicate the aquifer is probably composed of two, or possibly three, major sands. These sands are areally extensive, occur in the lower to middle parts of the Wilcox, and seem to be interconnected so that, in effect, they constitute one aquifer. More data and study are needed to determine the extent, relations, and hydraulic characteristics of these sands.
10. The stratigraphic relations of the massive Claiborne sand section north of lat 35° N., the Memphis aquifer, can now be tentatively assigned as a result of electric log correlations and drill-cutting analyses. The top of the Memphis aquifer seems to correlate with the top of the Sparta, and the Memphis aquifer makes up the entire Claiborne section between the top of the Wilcox and the top of the Sparta.
11. Although the Cockfield Formation has not been definitely recognized in the northern part of the embayment, observations made while mapping the top of the Memphis aquifer indicate that it may occur in areas of higher land-surface altitude near the axis of the embayment, where the Tertiary section is thicker.

APPLICATION OF RESULTS

By E. M. Cushing and R. L. Hosman

On the basis of the data in this report, the water-bearing units that are sources of water supply anywhere in the Tertiary area can be determined, and the following approximations can be made: (1) The range in depth of the wells, (2) the water-bearing potential of each unit, (3) the water level, (4) the direction of flow of the water, (5) the yield and specific capacity of the well, and (6) the temperature and quality of the water. In some areas the amount of lowering of the water level due to the pumping of wells in that area (time-distance-drawdown) can be estimated.

To show how this information is used, we will pose a hypothetical question and then, in subsequent paragraphs, apply the information to answer the question. The problem is: What are the alternatives in developing a water supply of at least 300 gpm from an artesian aquifer in the southeast corner of Dallas County, Ark.?

From the contour maps showing the configuration of the tops of the aquifers within the embayment (pls. 3–8), one sees that four aquifers are available—the Carrizo, Cane River, Sparta, and Cockfield. A topographic map shows that the land-surface altitude of the southeast corner of Dallas County is about 250 feet above mean sea level.

The Cockfield Formation crops out in the area and is the shallowest aquifer. As the southeast corner of Dallas County lies near the outer edge of the outcrop (pl. 8), the Cockfield will be thin and will probably be suitable only for supplying small amounts of water to shallow wells. Consequently, the Cockfield is not a possible source of water in the amount of 300 gpm.

The top of the next aquifer, the Sparta Sand (pl. 7), is about 100 feet below sea level, or about 350 feet below the land surface. The Sparta is about 500 feet thick and should be 61–80 percent sand (pl. 7). To penetrate the entire Sparta a well should be drilled about 850 feet deep. The water level should be about 160 feet above sea level, or about 90 feet below land surface; the direction of movement of the water is south (pl. 7). The quality of the water (pl. 7) would probably be:

Constituent	*Epm*	*Ppm*
Ca	0.8	16
Mg	.4	5
Na+K	1.0	23
Fe	----------	Trace
HCO_3+CO_3	1.3	80
SO_4	.3	15
Cl	.5	18
$F+NO_3$	----------	Trace
Dissolved solids (sum)	----------	About 120

The temperature of the water should be 68°–76°F (fig. 3). Analysis of an aquifer test made in the same general area gives values of about 24,000 gpd per ft for the coefficient of transmissibility and 0.0003 for the coefficient of storage. A yield of about 300 gpm should be easily obtainable. The time-distance-drawdown relation for a discharge of 300 gpm is shown in figure 4.

The top of the Cane River Formation (pl. 6) is about 600 feet below sea level, or about 850 feet below land surface. It is about 450 feet thick and should be about 21–40 percent sand (pl. 6). To penetrate all the sands in the Cane River a well should be drilled about 1,300 feet deep. Quantitative hydrologic information such as water levels or aquifer characteristics pertaining to the sands of the Cane River in this area is not available. However, water levels should be high, probably slightly higher than those in the Sparta. Most wells tapping the sands of the Cane River are small-capacity domestic wells, and the maximum yield of

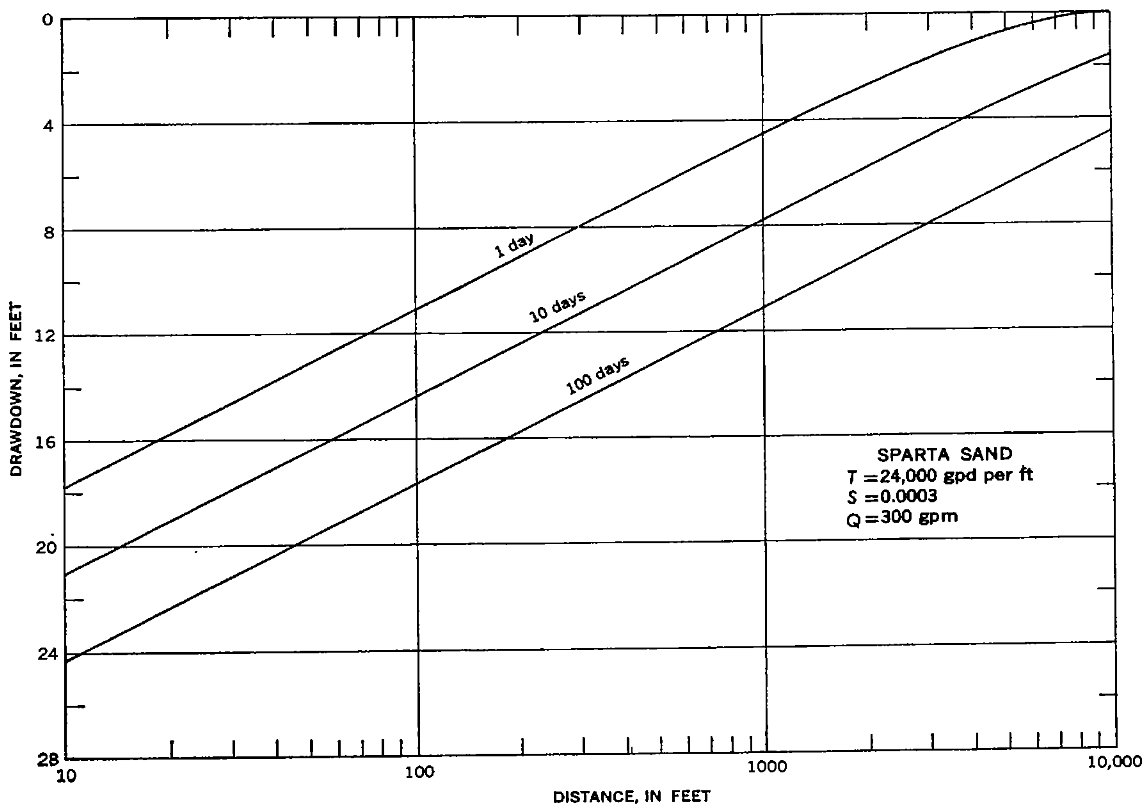


FIGURE 4.—Hypothetical relation between time, distance, and drawdown for a discharge of 300 gpm from the Sparta Sand in the southeast corner of Dallas County, Ark.

wells screened in these sands is not known. Because sand percentage of the Cane River is small in the southeast corner of Dallas County, the possibility of obtaining a well that will yield 300 gpm is remote. The chemical quality of the water (pl. 6) should be:

Constituent	*Epm*	*Ppm*
Ca	0.5	10
Mg	.1	1
Na+K	14.0	322
Fe	----------	Trace
HCO_3+CO_3	4.2	256
SO_4	.1	5
Cl	10.6	160
$F+NO_3$	----------	Trace
Dissolved solids (sum)	----------	About 620

The temperature of the water should be about 70°–78°F (fig. 3).

The deepest aquifer in the southeast corner of Dallas County is the Carrizo Sand. The top of the unit (pl. 5) is about 1,050 feet below sea level, or about 1,300 feet below land surface. The Carrizo is about 100 feet thick and 81–100 percent sand (pl. 5). To completely penetrate the Carrizo a well should be drilled about 1,400 feet deep. As water wells have not been drilled into this unit near the southeast corner of Dallas County, information regarding the aquifer is chiefly based on analysis of electric logs in the area.

The dissolved-solids content of the water from the Carrizo Sand will probably be between 900 and 1,000 ppm, and the principal constituents will be sodium, bicarbonate, and chloride. The temperature of the water should be about 78°F. Water levels should be higher than those in the Sparta Sand, and wells should yield at least 300 gpm.

The reader should remember that the above determinations are estimates based upon the available information. By drilling and testing a particular site, more exact data can be obtained.

SELECTED BIBLIOGRAPHY

Alabama Geological Survey, 1926, Geological Map of Alabama.

Arkansas Geological Survey, 1929, Geologic Map of Arkansas.

Albin, D. R., 1964, Geology and ground-water resources of Bradley, Calhoun, and Ouachita Counties, Arkansas: U.S. Geol. Survey Water-Supply Paper 1779–G, 32 p.

Baker, R. C., 1955, Arkansas' ground-water resources: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 1, 16 p.

Baker, R. C., Hewitt, F. A., and Billingsley, G. A., 1948, Ground-water resources of the El Dorado area, Union County, Arkansas: Arkansas Univ. Bur. Research, Research Ser. 14, 39 p.

Bedinger, M. S., and Reed, J. E., 1960, Geology and ground-water resources of Desha and Lincoln Counties, Arkansas: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 6, 129 p.

Brown, G. F., 1947, Geology and artesian water of the alluvial plain in northwestern Mississippi: Mississippi Geol. Survey Bull. 65, 424 p.

Caplan, W. M., 1954, Subsurface geology and related oil and gas possibilities of northeastern Arkansas: Arkansas Resources and Devel. Comm., Div. Geology Bull. 20, 124 p.

Conrad, T. A., 1848, Observations on the Eocene formation and description of 105 new fossils of that period, from the vicinity of Vicksburg, Miss.: Philadelphia Acad. Nat. Sci. Proc. 1847, 1st ser., v. 3, p. 280–299.

———1856, Observations on the Eocene deposits of Jackson, Miss., with descriptions of 34 new species of shells and corals: Philadelphia Acad. Nat. Sci. Proc. 1855, 1st ser., v. 7, p. 257–258.

Cooke, C. W., 1918, Correlation of the deposits of Vicksburg and Jackson ages in Mississippi and Alabama: Washington Acad. Sci. Jour., v. 8, p. 186–189.

Counts, H. B., 1957, Ground-water resources of parts of Lonoke, Prairie, and White Counties, Arkansas: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 5, 65 p.

Counts, H. B., and others, 1955, Ground-water resources in a part of southwestern Arkansas: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 2, 35 p.

Crider, A. F., and Johnson, L. C., 1906, Summary of the underground-water resources of Mississippi: U.S. Geol. Survey Water-Supply Paper 159, 86 p.

Criner, J. H., Sun, P–C. P., and Nyman, D. J., 1964, Hydrology of aquifer systems in the Memphis area, Tennessee: U.S. Geol. Survey Water-Supply Paper 1779–O, 54 p.

Darton, N. H., and others, 1937, Geologic map of Texas: U.S. Geol. Survey Geol. Atlas.

Ellisor, A. C., 1929, Correlation of the Claiborne of east Texas with the Claiborne of Louisiana: Am Assoc. Petroleum Geologists Bull., v. 13, no. 10, p. 1335–1346.

Fisk, H. N., 1944, Gelogical investigation of the alluvial valley of the lower Mississippi River: U.S. Dept. Army, Mississippi River Comm., 78 p.

Gardner, J. A., 1933a, The Midway group of Texas: Texas Univ. Bull. 3301, 403 p.

———1933b, Kincaid formation, name proposed for lower Midway of Texas: Am Assoc. Petroleum Geologists Bull., v. 17, no. 6, p. 744–747.

Glenn, L. C., 1906, Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geol. Survey Water-Supply Paper 164, 173 p.

Gordon, C. H., 1911, Geology and underground waters of northeastern Texas: U.S. Geol. Survey Water-Supply Paper 276, 78 p.

Gordon, Mackenzie, Jr., Tracey, J. I., Jr., and Ellis, M. W., 1958, Geology of the Arkansas bauxite region: U.S. Geol. Survey Prof. Paper 299, 268 p.

Grim, R. E., 1936, The Eocene sediments of Mississippi: Mississippi Geol. Survey Bull. 30, 240 p.

Grohskopf, J. G., 1955, Subsurface geology of the Mississippi embayment of southeast Missouri: Missouri Div. Geol. Survey and Water Resources, 2d ser., v. 37, 133 p.

Halberg, H. N., and Reed, J. E., 1964, Ground-water resources of eastern Arkansas in the vicinity of U.S. Highway 70: U.S. Geol. Water-Supply Paper 1779–V, 38 p.

Hewitt, F. A., Baker, R. C., and Billingsley, G. A., 1949, Ground-water resources of Ashley County, Arkansas: Arkansas Univ. Inst. Sci. and Technology Research Ser. 16, 35 p.

Hosman, R. L., 1962, Correlation of the Carrizo Sand in Arkansas and adjacent states: Geol. Soc. America Bull., v. 73, no. 3, p. 389–393.

——— 1964, The Carrizo Sand, a potential aquifer in south-central Arkansas, *in* Short papers in geology, hydrology, and topography: U.S. Geol. Survey Prof. Paper 501–D, p. D158–D160.

Klaer, F. H., Jr., 1942, Memphis, *in* Meinzer, O. E., Wenzel, L. K., and others, Water levels and artesian pressure in observation wells in the United States in 1940, pt. 2, Southeastern States: U.S. Geol. Survey Water-Supply Paper 907, p. 92–101.

Klein, Howard, Baker, R. C., and Billingsley, G. A., 1950, Ground-water resources of Jefferson County, Arkansas: Arkansas Univ. Inst. Sci. and Technology Research Ser. 19, 44 p.

Mississippi Geological Society, 1945, Geologic may of Mississippi.

Missouri Div. Geological Survey and Water Resources, 1961, Geologic map of Missouri.

Moore, Gerald K., 1965, Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geol. Survey Water-Supply Paper 1809–F, 44 p.

Murray, G. E., 1947, Cenozoic deposits of central Gulf Coastal Plain: Am. Assoc. Petroleum Geologists Bull., v. 31, no. 10, p. 1835–1850.

——— 1948, Geology of Red River and De Soto Parishes: Louisiana Dept. Conserv. Geol. Bull. 25, 312 p.

Murray, G. E., and Thomas, E. P., 1945, Midway-Wilcox surface stratigraphy of Sabine uplift, Louisiana and Texas: Am. Assoc. Petroleum Geologists Bull., v. 22, no. 1, p. 45–70.

Nyman, Dale J., 1965, Predicted hydrologic effects of pumping from the Lichterman well field in the Memphis area, Tennessee: U.S. Geol. Survey Water-Supply Paper 1819–B, 26 p.

Onellion, F. E., 1956, Geology and ground-water resources of Drew County, Arkansas: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 4, 43 p.

Onellion, F. E., and Criner, J. H., 1955, Ground-water resources of Chicot County, Arkansas: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 3, 32 p.

Page, Leland V., and May, Harold G., 1964, Water resources of Bossier and Caddo Parishes, Louisiana: Louisiana Dept. Conserv., Geol. Survey, and Louisiana Dept. Public Works, Bull. 5, 105 p.

Plebuch, R. O., 1961, Fresh-water aquifers of Crittenden County, Arkansas: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 8, 65 p.

Plummer, F. B., 1932, The Cenozoic systems in Texas, *in* Sellards, E. H., Adkins, W. S., and Plummer, F. B., The geology of Texas, v. 1, Stratigraphy: Texas Univ. Bull. 3232, p. 519–818.

Renfroe, C. A., 1949, Petroleum exploration in eastern Arkansas with selected well logs: Arkansas Resources and Devel. Comm., Div. Geology Bull. 14, 159 p.

Roberts, J. K., and Gildersleeve, Benjamin, 1945, Geology and mineral resources of the Jackson Purchase Region, Kentucky, with a section on Paleozoic geology, by Louise Barton Freeman: Kentucky Geol. Survey, ser. 8, Bull. 8, 126 p.

Rollo, J. R., 1960, Ground water in Louisiana: Louisiana Dept. Conserv., Geol. Survey, and Louisiana Dept. Public Works, 84 p.

Ryling, R. W., 1960, Nature and extent of the ground-water supply of Mississippi County, Arkansas: Arkansas Geol. and Conserv. Comm. Water Resources Circ. 7, 87 p.

Schneider, Robert, and Blankenship, R. R., 1950, Subsurface geologic cross section from Claybrook, Madison County, to Memphis, Shelby County, Tennessee: Tennessee Div. Geology Ground-Water Inv. Prelim. Chart 1.

Smith, C. R., 1958, Queen City-Sparta relationships in Caddo Parish, Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 42, no. 10, p. 2517–2522.

Smith, E. A., 1888, Geographic map of Alabama, *in* Alabama Geol. Survey Prog. Rept.

Stearns, R. G., 1957, Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi embayment: Geol. Soc. America Bull., v. 68, p. 1077–1100.

Stearns, R. G., and Armstrong, C. A., 1955, Post-Paleozoic stratigraphy of western Tennessee and adjacent portions of the upper Mississippi embayment: Tennessee Div. Geology Rept. Inv. 2, 29 p.

Stephenson, L. W., and Crider, A. F., 1916, Geology and ground waters of northeastern Arkansas: U.S. Geol. Survey Water-Supply Paper 399, 315 p.

Stephenson, L. W., Logan, W. N., and Waring, G. A., 1928, Ground-water resources of Mississippi: U.S. Geol. Survey Water-Supply Paper 576, 515 p.

Tait, D. B., Baker, R. C., and Billingsley, G. A., 1953, The ground-water resources of Columbia County, Arkansas, a reconnaissance: U.S. Geol. Survey Circ. 241, 25 p.

Tennessee Div, Geology, 1963, Geologic map of Tennessee.

Thomas, E. P., 1942, The Claiborne: Mississippi Geol. Survey Bull. 48, 96 p.

U.S. Geological Survey, 1932, Geologic map of the United States.

U.S. Public Health Service, 1962, Drinking water standards, revised 1962: Public Health Service Pub. 956, 61 p.

Veatch, A. C., 1905, Louisiana and southern Arkansas, *in* Fuller, M. L., Underground waters of eastern United States: U.S. Geol. Survey Water-Supply Paper 114, p. 179–187.

——— 1906, Geology and underground water resources of northern Louisiana and southern Arkansas: U.S. Geol. Survey Prof. Paper 46, 422 p.

Wilbert, L. J., Jr., 1953, The Jacksonian stage in southeastern Arkansas: Arkansas Resources and Devel. Comm., Div. Geology Bull. 19, 125 p .

Williams, N. F., and Plummer, Norman, 1951, Clay resources of the Wilcox group in Arkansas: Arkansas Resources and Devel. Comm., Div. Geology Inf. Circ. 15, 98 p.

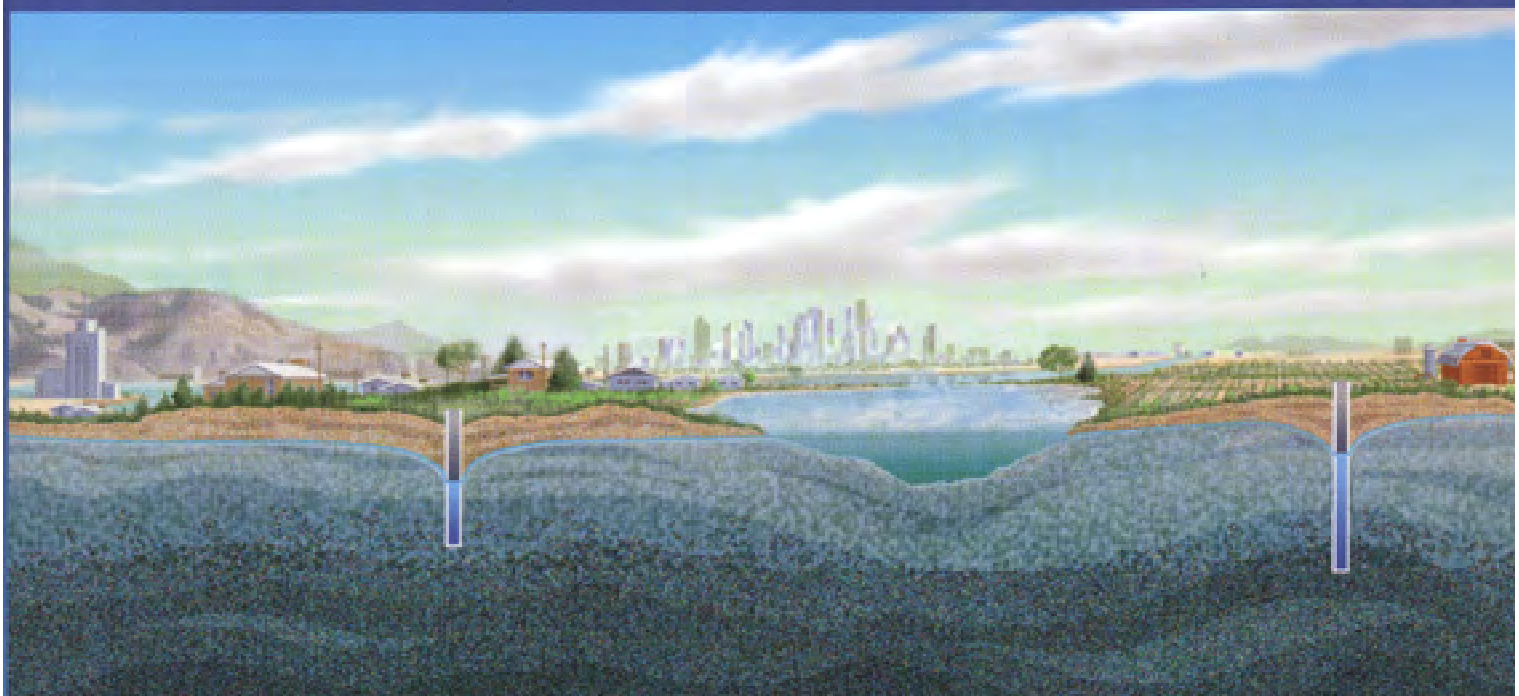
U.S. GOVERNMENT PRINTING OFFICE: 1968

EXHIBIT 12

W.M. Alley, T.E. Reilly, O.L. Franke
Sustainability of Ground-Water Resources
USGS Circular 1186
(Excerpts)

USGS
science for a changing world

Sustainability of Ground-Water Resources



U.S. Geological Survey Circular 1186

- **Velocities of ground-water flow generally are low and are orders of magnitude less than velocities of streamflow**. The movement of ground water normally occurs as slow seepage through the pore spaces between particles of unconsolidated earth materials or through networks of fractures and solution openings in consolidated rocks. A velocity of 1 foot per day or greater is a high rate of movement for ground water, and ground-water velocities can be as low as 1 foot per year or 1 foot per decade. In contrast, velocities of streamflow generally are measured in feet per second. A velocity of 1 foot per second equals about 16 miles per day. The low velocities of ground-water flow can have important implications, particularly in relation to the movement of contaminants.

- **Under natural conditions, ground water moves along flow paths from areas of recharge to areas of discharge at springs or along streams, lakes, and wetlands**. Discharge also occurs as seepage to bays or the ocean in coastal areas, and as transpiration by plants whose roots extend to near the water table. The three-dimensional body of earth material saturated with moving ground water that extends from areas of recharge to areas of discharge is referred to as a ground-water-flow system (Figure 5).

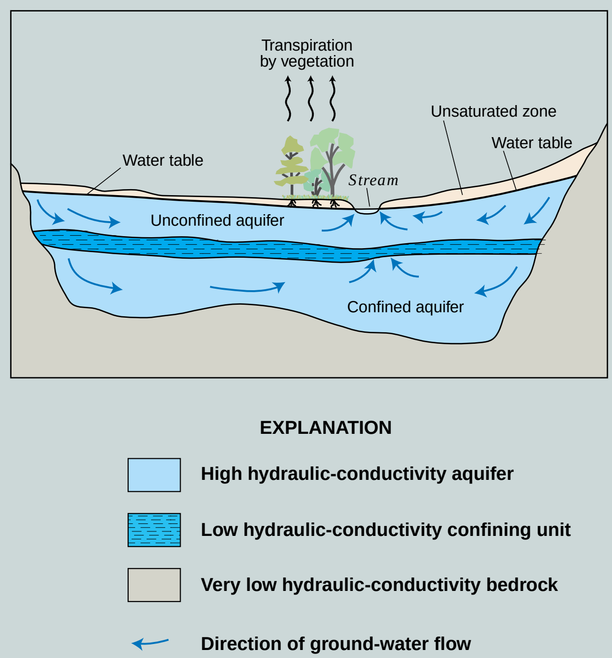


Figure 5. *A local scale ground-water-flow system.*

In this local scale ground-water-flow system, inflow of water from areal recharge occurs at the water table. Outflow of water occurs as (1) discharge to the atmosphere as ground-water evapotranspiration (transpiration by vegetation rooted at or near the water table or direct evaporation from the water table when it is at or close to the land surface) and (2) discharge of ground water directly through the streambed. Short, shallow flow paths originate at the water table near the stream. As distance from the stream increases, flow paths to the stream are longer and deeper. For long-term average conditions, inflow to this natural ground-water system must equal outflow.

EXHIBIT 13

Deposition of John Van Brahana
November 5, 2007
(Excerpts)

IN THE UNITED STATES DISTRICT COURT
FOR THE NORTHERN DISTRICT OF Mississippi
DELTA DIVISION

JIM HOOD, Attorney General, ex rel,
THE STATE OF MISSISSIPPI, Acting
for itself and Parens Patriae for
and on behalf of the People of the
State of Mississsippi,

Plaintiff,

Vs. Case No. CIVIL ACTION 2:05CV32D-B
(And Related Cases)

THE CITY OF MEMPHIS, TENNESSEE and
MEMPHIS LIGHT, GAS & WATER DIVISION,

Defendants.

THE DEPOSITION OF JOHN VAN BRAHANA

November 5th, 2007

BRIAN F. DOMINSKI, RPR, RMR
ALPHA REPORTING CORP.
COURT REPORTERS
LOBBY LEVEL, 100 NORTH MAIN BUILDING
Memphis, Tennessee 38103
(901) 523-9874

systems are -- the water is moving continuously. They probably never truly reach a rigorous, pristine steady state.
Q. Absent pumping, though, it would reach as close as you could get, I guess, to a steady-state equilibrium?
A. It depends on the climatic conditions.
Q. But once you impose a pumping stress on the aquifer, does that intensify or increase the dynamic condition of the aquifer?
A. Not necessarily. If you are changing the pumping amount, it will continue to -- it will modify it. But in terms of the dynamics -- I don't understand -- if I can -- if you could restate -- restate your question, sir.
Q. What do you mean it would "modify" if you --
A. It would create a cone of drawdown.
Q. Let's talk about that. The "cone of depression" I think is the term you used.
A. Yes.

Q. Define that for the jury, if you would, please, sir.
A. It is the -- it is created by constructing a well and taking the well -- the well itself is connected. It is open to the sand layers. Speaking specifically for the Memphis Aquifer, you pull water out of storage in the well, in the actual well itself. So you have lowered the water level in the well, and you are creating a point around which water is flowing in in all directions.
The cone of depression, if we evaluate this, we can see down to the top of that water-level surface, it will go down to a sharp cone shape, a three-dimensional shape. It gets steeper near the well. As you move out further, it is much more general. It is not a linear pattern at all. That cone of depression is what pulls the water. It drives the water into the well. You do that by taking the water out of the well bore.
Q. What causes -- did I hear you say

correctly that water flows in from every direction around a cone of depression?
A. Yes, under general terms under steady-state flow, and this is making assumptions that you don't have low permeability zones in some locations. In extreme examples you can pull it in only from a couple of locations.
Q. Is that just a function of gravity and pressure?
A. Gravity and pressure drive the flow of groundwater, that's correct.
Q. So any water that surrounds the cone will inexorably flow into the cone?
A. Yes.
Q. Or be drawn into the cone?
A. Yes, it will be drawn. Water above will also move down. Water from below will also move up because there is a pressure difference, and the water is a -- it moves from high to low energy.
Q. Is there such thing as a regional cone of depression?
A. I can't think of examples. I've not

heard that general term applied. Do you have another --
Q. Are you familiar with the fact that there is a regional cone of depression centered in Memphis that extends outward across the Tennessee-Mississippi border?
A. I'm aware that in areas where there is pumping there is going to be a drawdown. The term "regional" is -- that needs to be defined. I haven't heard the term. It needs to be defined.
Q. Are you familiar with the fact that there is a cone of depression that extends -- that centers in Memphis and extends outward into Shelby County and DeSoto County, Mississippi?
A. The drawdown from Memphis, yes, yes.
Q. Does the drawdown from Memphis result in groundwater moving from Mississippi into Shelby County, into the Memphis service area?
A. It gets into if you have a lower elevation, there will be waters coming from 360 degrees, yes.

EXHIBIT 14

David Wiley Rebuttal Expert Report
Addendum #1
July 31, 2017

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE ADDENDUM # 1

Prepared For:

Jim Hood, Attorney General of the State of Mississippi

July 31, 2017

Prepared By:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Groundwater and Environmental Engineering Consultants
10014 North Dale Mabry Highway, Suite 205
Tampa, FL 33618

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

This report was prepared by David, A. Wiley, Professional Geologist and Sr. Vice President of Leggette, Brashears & Graham, Inc. (LBG) at the request of the Attorney General of the State of Mississippi. It amends the report dated June 30, 2017 that updated and confirmed previous work performed for the Attorney General to determine the effect of Memphis Light, Gas & Water's (MLGW's) consistent, significant expansion of the commercial water well pumping operations between 1965 and our previous report dated April 14, 2014 on Mississippi's natural groundwater flow and storage. This report addendum focuses solely on the review of and critique of the June 27, 2017 Expert Report on the Interstate Nature of the Memphis/Sparta Sand Aquifer prepared by Gradient Corporation Gradient) for City of Memphis, Tennessee and Memphis Light, Gas & Water Division (MLGW). Our review is presented in a concise manner addressing each section of the Gradient report in order as appropriate.

SUMMARY OF EVALUATION OF GRADIENT REPORT

Section 1 Introduction

1.2 Opinion Summary:

1. The Memphis Sand/Sparta Aquifer (MSSA) lies beneath several states and is a shared resource among all the states that overlie it, including Mississippi and Tennessee.

MLGW is not sharing water. They pump the amounts that they want without approval/permission from Mississippi for the amount diverted from Mississippi due to the cone of depression created.

4. In pre-development times (before pumping began), groundwater in the MSSA naturally flowed across multiple state lines, including the Mississippi-Tennessee border.

Only some water flows slowly from Mississippi to Tennessee.

6. Pumping from the MSSA in one state can impact the flow direction and potentiometric head in another state.

Agreed that pumping by MLGW impacts flow direction and potentiometric head in Mississippi.

8. Water flow patterns in the MSSA were not influenced by state lines under pre-development conditions and are not influenced by state lines under current conditions.

Agreed, however pumping by MLGW has altered flow patterns in Mississippi by diverting groundwater flow to Tennessee.

9. Under pre-development conditions, all groundwater that entered the MSSA in Mississippi would eventually leave Mississippi.

Under pre-development conditions Sparta aquifer water resides in Mississippi for approximately 4,000 years to 22,000 years (**Figure 1**) and moves at a rate of approximately 13 to 53 feet per year based on USGS model used by Gradient. From the same model, in 2007, water velocity was increased due to MLGW pumpage to a rate of approximately 8 to 214 feet/year.

Section 2 Scientific Principles and Physical Setting

2.2 MSSA and Mississippi Embayment Overview:

Page 9, last paragraph – "Other interstate aquifers" is referred to by Gradient. The phrase "interstate aquifer" has no known technical reference in USGS literature or from other scientific professional organizations.

2.3 The Sparta Sand Aquifer in Mississippi and the upper Memphis Sand Aquifer in Tennessee are different names for the same aquifer:

Page 10, 1st sentence - There is no known historical and recent scientific literature that calls the MSSA an interstate aquifer. Also, the MSSA is not a shared resource. MLGW pumps the amounts that they want without approval from Mississippi.

Page 12, 5th bullet, Reed (1972) – Gradient refers to "interstate significance in such places as Memphis." This significance is the result of the cone of depression created by MLGW and the resulting groundwater flow diversions.

Page 12, 8th bullet, Arthur and Taylor (1990) – Arthur and Taylor do not refer to MSSA as being interstate.

Page 13, 2nd bullet, Arthur and Taylor (1998) – Gradient states that Arthur and Taylor describe the "historical shared nature of MSSA." Arthur and Taylor do not state that and just because one entity in one state pumps from an aquifer and another entity in another state pumps from the same aquifer does not mean they are not sharing. MLGW pumps the amount of water that they want with no permission from Mississippi for the amount being diverted.

2.4 The United States Geological Survey's MERAS Model

Page 14, 4th paragraph – Gradient states that particle tracking allows for tracking of water movement over a period of time but nowhere in their report do they address specific groundwater flow travel times.

Section 3 Statement of Opinion

3.1 The MSSA is physically located beneath several states, including Mississippi and Tennessee, and is a resource that is shared by and common to the states that overlie it.

Page 15, 1st paragraph – We concur that the aquifer is physically located beneath several states. There is no known technical reference for interstate aquifer by the USGS or other technical professional organizations.

Page 16, 1st paragraph – Gradient states there are no lateral barriers. Not true. Flow paths under natural pre-development conditions create a flow boundary. In most of the northwest Mississippi, ground water flows from east to west/southwest below the state line. Small portion of pre-development flow is northwest from Mississippi to Tennessee. Due to MLGW pumpage this natural east to west flow path in Mississippi has been altered to a northwesterly direction into Tennessee (see **Figures 2, 3, 4 and 5**). **Figures 2 and 3** are from the Gradient report, but are completed with additional flow lines in northern Mississippi. **Figures 4 and 5** are from the previous LBG report dated June 30, 2017.

3.2 In pre-development times (before pumping began), groundwater and surface water originating in Mississippi naturally flowed into and supplied the MSSA beneath Tennessee.

Page 16, 1st paragraph – Section 2.3 of the Gradient report does not discuss natural flow across state lines. Statements in paragraph 3.2 implies that a large volume of groundwater flowed from the Sparta sands in Desoto, Marshall and Benton Counties, Mississippi to Tennessee during pre-development times. In reality the MERAS model used by Gradient indicates that there was a net flow from Mississippi to Tennessee within the entire MSSA of less than 6 mgd; which is only 2.6 percent of the simulated areal recharge to the state of Mississippi. Furthermore, the MERAS indicated that there is a net flow from Tennessee into Desoto County, Mississippi of 2.3 mgd during pre-development times (see **Figure 6**).

Gradient is implying that there is a connection between the potentiometric heads and the bottom of the MSSA where no connection should exist between the bottom of the confined aquifer and the potentiometric heads. Shape of potentiometric contours is dependent on formations above the confined aquifer, recharge and discharge areas.

3.2.1 Pre-development flow from Mississippi to Tennessee in the MSSA has been confirmed by analysis of report data

LBG is in agreement that some water flows from the northeastern portion of Mississippi into Tennessee, however, as indicated above this is a small percentage of the simulated pre-development areal recharge to the state. In Gradient's Figure 3.2.1a, only a small portion of flow from Mississippi to Tennessee near northeast Desoto County and Marshall Counties occurs near state line. The figure only addresses flows in the Memphis area and not regional flows. The Waldron Map, Figure 3.2.1b in the Gradient report is not based on actual water-level measurements. Most well locations in this map are in the outcrop area, which is not representative of confined aquifer conditions due to topography and/or river discharge. Waldron also estimated well locations. Waldron did not look at regional water-level conditions as Arthur and Taylor did. Waldron did not consider model pre-development conditions as Arthur and Taylor did. The Arthur Taylor (1990) map shows regional pre-development potentiometric surface map including the Tennessee and Mississippi area, which is Figure 3.3.3 in the Gradient report and our revised **Figure 3** in this addendum. This map is based on calibrated flow model. This map shows flow in an east to west/ southwest orientation in northern Mississippi. Also in the Gradient report, figures 3.3.1a and 3.3.1b show their modeled pre-development map using the USGS model. Gradient shows only one flow line on 3.3.1b ignoring the majority of flow in northwest Mississippi, which is east to west/southwest, similar to Arthur and Taylor. Most of that water flows within Mississippi. Both Arthur and Taylor and Gradient show a small flow component from Mississippi to Tennessee near the outcrop. It should be noted that potentiometric contours shown in outcrops should be used carefully because those water levels are in unconfined conditions and not truly representative of the confined aquifer.

3.2.2 Pre-development flow from Mississippi to Tennessee in the MSSA has been confirmed by the USGS MERAS model particle tracking.

Page 17, 3.2.2.1 – Gradient's Fig 3.2.2 does not show flow paths that occur in only Mississippi from east to west/southwest, selective particle releasing was employed here. The flow amounts and residence times were not provided by Gradient, which was included by definition for using particle tracking earlier in their report. We used the USGS model presented by Gradient and calculated travel time, velocities and volumes. Results show the following travel times, velocities and volumes discharged are shown in Figures 1 and 6 in this addendum.

The flow path analysis completed by Gradient focuses primarily on the eastern portion of the Sparta sand outcrop (Benton and Marshall Counties) were the flow paths and direction are controlled primarily by surface water bodies. LBG completed a flow analysis along the western portion of the Sparta sand outcrop that shows that the groundwater would remain in the state of Mississippi (**Figure 1**). In addition, data derived for the USGS MERAS model shows that during the pre-development period approximately 84 percent of the simulated recharge to Mississippi would flow across the state for a period of time ranging from approximately 4,000 to 22,000 years.

Page 18, 3.2.2.2 - No Volumes, travel times, and velocities were provided with Gradient Figure 3.2.2.

Page 18, 3.2.2.3 – Gradient Fig 3.2.4a is misleading. Very little if any water that initiated in northeast Mississippi would flow around and discharge at the Mississippi river in Coahoma County, Mississippi. The USGS model used by Gradient shows that very little water follows the entire flow path in Gradient Figure 3.2.4a and on to the Mississippi River.

3.3 The interstate pre-development flow of groundwater in the MSSA from Mississippi to Tennessee is a component of and consistent with the larger, regional interstate groundwater flow patterns in the northern MSSA.

Page19, 3.3 – Gradient Figures 3.3.1a and 1b are selective, ignoring the majority of flow paths in northwest Mississippi. Initiating flow paths based on potentiometric surface contours must be done where the aquifer is continued or at edge of outcrop. Water levels in outcrop areas are under unconfined conditions, they discharge to rivers and not representative of the confined aquifer. Our **Figure 2** in this addendum revises the Gradient Figure 3.3.1b to show additional flow paths across northwestern Mississippi. The east to west/northwest flow paths are shown in **Figure 2**.

Gradient Figures 3.3.2a and 2b – These 2 figures show potentiometric contours and flow paths that under pre-development water flowed east to west/southwest in northwest Mississippi within 4 miles of the Mississippi/Tennessee state line. Gradient again used selective flow lines in Fig 3.3.3 (from Arthur and Taylor). We revised that Figure to add the northwest Mississippi flow lines shown on **Figure 3** of this addendum. Drawdown from MLGW extends more than 4 miles in Mississippi.

3.4 The interstate nature of the MSSA is demonstrated by the fact that pumping from the MSSA in one state can and does affect groundwater in the MSSA in other States.

Section 3.4 pages 20 - 22 – as shown in Gradient Figures 3.4.1 and 3.4.2a, a cone of depression has been created by MLGW pumpage that diverts Mississippi water from its natural east to west/southwest flow path as shown on **Figures 2, 3, 4 and 5** in this addendum. Many other USGS publications over the decades have shown and confirmed the cone of depression created by MLGW due to the large volumes of groundwater pumped from the aquifer.

LBG concurs that pumping in Tennessee impacts groundwater levels in Mississippi. LBG completed a flow budget analysis utilizing pre-development and 2007 output data from the USGS MERAS model. Pre-development showed that there is a net flow from

Tennessee into Desoto County of 2.3 mgd during pre-development conditions and a net flow out of Desoto County into Tennessee of 20.3 mgd under the 2007 pumping condition. Thus, withdrawal from Tennessee resulted in a net pumping related impact to the net flow out of Desoto County of 22.6 mgd as shown on **Figure 6** of this addendum. This value from the MERAS model is very comparable to the 2007 groundwater diversion (flux) LBG estimated at 22.3 mgd from using the Brahana model, to be taken from Mississippi due to MLGW Pumping. Additional modeling using the USGS MERAS shows that if Desoto County were to pump the same amount of water as MLGW, water levels would drop below the top of the aquifer, primarily in Mississippi, damaging the aquifer (see **Figure 7**). The red contours in **Figure 7** show areas where water levels drop below the top of the aquifer. This also infers that the MSSA is not a shared aquifer.

3.5 The MSSA has been and is a dynamic natural system. Groundwater flow in the MSSA was not influenced by state lines under pre-development conditions and is not influenced by state lines under current conditions.

Due to the cone of depression created by MLGW pumpage, recharge and discharge to and from Desoto County has change and reversed in some cases (see **Figure 6**). Reversal from discharge to recharge can effect water chemistry. From the USGS MERAS model used by Gradient, groundwater flow is calculated to be very slow. Under pre-development conditions, the model shows a flow velocity of approximately 14 to 53 feet/year across northwestern Mississippi. The residence time of water in northwest Mississippi is approximately 4,000 years to 22,000 years. Therefore, all water entering the aquifer during our lifetime or before the county was formed and before Moses time, stays in Mississippi.

3.6 Before and after pumping began, all groundwater entering the MSSA in Mississippi eventually leaves Mississippi.

See response to 3.5 above. This is misleading. As, stated previously, data derived from the USGS MERAS model shows that during the pre-development period approximately 84 percent of the simulated recharge to Mississippi would remain in the state. Gradient's statement is only true if you count pumped groundwater and groundwater that discharges to surface water bodies in Mississippi as water leaving the state. Also, due to the cone of depression, the groundwater direction of flow in Mississippi is altered, flow velocities increase and the water balance altered with discharge components changed to recharge. Geology is a key factor helping to control groundwater flow conditions as shown on **Figure 4** of this addendum. **Figure 4** is a combination of Mississippi Embayment Geology with pre-development potentiometric surface levels for the MSSA as presented by Arthur and Taylor 1990. As discussed in the LBG June 30, 2017 Update Report, potentiometric surface levels of the MSSA are controlled by the eastern boundary of Mississippi Alluvial Plain aquifer in western Mississippi which overlies the Middle Claiborne aquifer and runs north-south in northwest Mississippi and receives discharge from the Middle Claiborne aquifer. This causes potentiometric surface levels to equilibrate in a north-south direction through northwest Mississippi forcing groundwater to flow east to west from the recharge area on the east side of Mississippi Embayment in northwestern Mississippi under pre-development conditions. As a result, structural geology in northwest Mississippi influences the shape of potentiometric surface contours and direction of groundwater flow, which is westward.

REFRENCES

Arthur, J.K. and Taylor, R.E. 1990. Definition of the geohydrologic framework and preliminary simulation of ground-water flow in the Mississippi Embayment aquifer system, Gulf Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 86-4364, 97 p.

Arthur, J.K. and Taylor, R.E. Taylor1998 Ground –Water Flow Analysis of the Mississippi Embayment Aquifer System, South-Central United States, Regional Aquifer-System Analysis-Gulf Coastal Plan, USGS Professional Paper 14

Brahana, J.V. 1981. Ground Water Supply, Chapter 3 – Final Report Metropolitan Area Urban Water Resources Study: U.S. Geological Survey.

Brahana, J.V. 1982a. Digital Ground Water Model of the Memphis Sand and Equivalent Units, Tennessee, Arkansas, Mississippi: U.S. Geological Survey Open-File Report 82-99, 55 p.

Brahana, J.V., and Broshears, R.E., 2001. Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee, Water-Resources Investigations Report 89-4131, 56 p.

Criner, J.H., Sun, P-C.P., and Nyman, D.J. 1964. Hydrology of the aquifer systems in the Memphis Area, Tennessee: U.S. Geological Survey Professional Paper 1779-O, 54 p.

Criner, J.H., and Parks, William S., 1976. Historical Water-Level Changes and Pumpage From the Principal Aquifers of the Memphis Area: U.S. Geological Survey Water Resources Investigations 76-67

C.W. Fetter, Applied Hydrogeology, 1988.

E.M. Gushing, E.H. Boswell, and R.L. Hosman, General Geology of the Mississippi Embayment, Water Resources of the Mississippi Embayment, (1964) Department of the Interior, Geological Survey Professional Paper 448-B

Environmental Simulations Incorporated (ESI), 2006. Groundwater Vistas a pre-and post-processors.

Feldman, D. L., Ph.D., and Elmendorf, J. O., J.D., Final Report – Water Supply Challenges Facing Tennessee: Case Study Analyses and the Need for Long-Term Planning (June 2000).

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

Graham, D.D., and Parks, W.S., 1986. Potential for leakage among principal aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 85-4295, 46 p.

Hosman, R.L., Long, A.T., and Lambert, T.W., and others. 1968. Tertiary aquifers in the Mississippi embayment, *with discussions* of Quality of the water by H.G. Jeffrey: U.S. Geological Survey Professional Paper 448-D, 29 p.

Ivey, S.S., 1999. Ground Water Institute analysis of the proposed south wellfield area, September 16.

LBG, May 2007 Report On Diversion Of Ground Water From Northern Mississippi Due To Memphis Area Well Fields.

LBG, April 2014, Update Report On Diversion And Withdrawal Of Groundwater From Northern Mississippi Into The State Of Mississippi.

McDonald, M.G. and Harbaugh, A.W. 1988. A modular three-dimensional finite difference ground-water flow model, USGS Techniques of Water-Resources Investigations, Book 6.

Mississippi Embayment Regional Ground Water Study, EPA 600R/-10/130, 1 January 2011

Moore, 1965. Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geological Survey Water-Supply Paper 1809-F, 44 p.

Outlaw, J.E., 1994. A ground water flow analysis of the Memphis sand aquifer in the Memphis, Tennessee Area.

Parks, W.S., and Carmichael, J.K. 1989a. Geology and ground-water resources of the Memphis Sand in western Tennessee: U.S. Geological Survey Water Resources Investigations Report 88-4182. 30 p.

T.P. Schrader, Potentiometric Surface in the Sparta-Memphis Aquifer of The Mississippi Embayment, Spring 2007, Scientific Investigations Map 3014, 2008

Wells, F.G., 1933. Ground-water resources of western Tennessee, *With a discussion of* Chemical character of the water by F.G. Wells and M.D. Foster: U.S. Geological Survey Water-Supply Paper 656, 319 p.

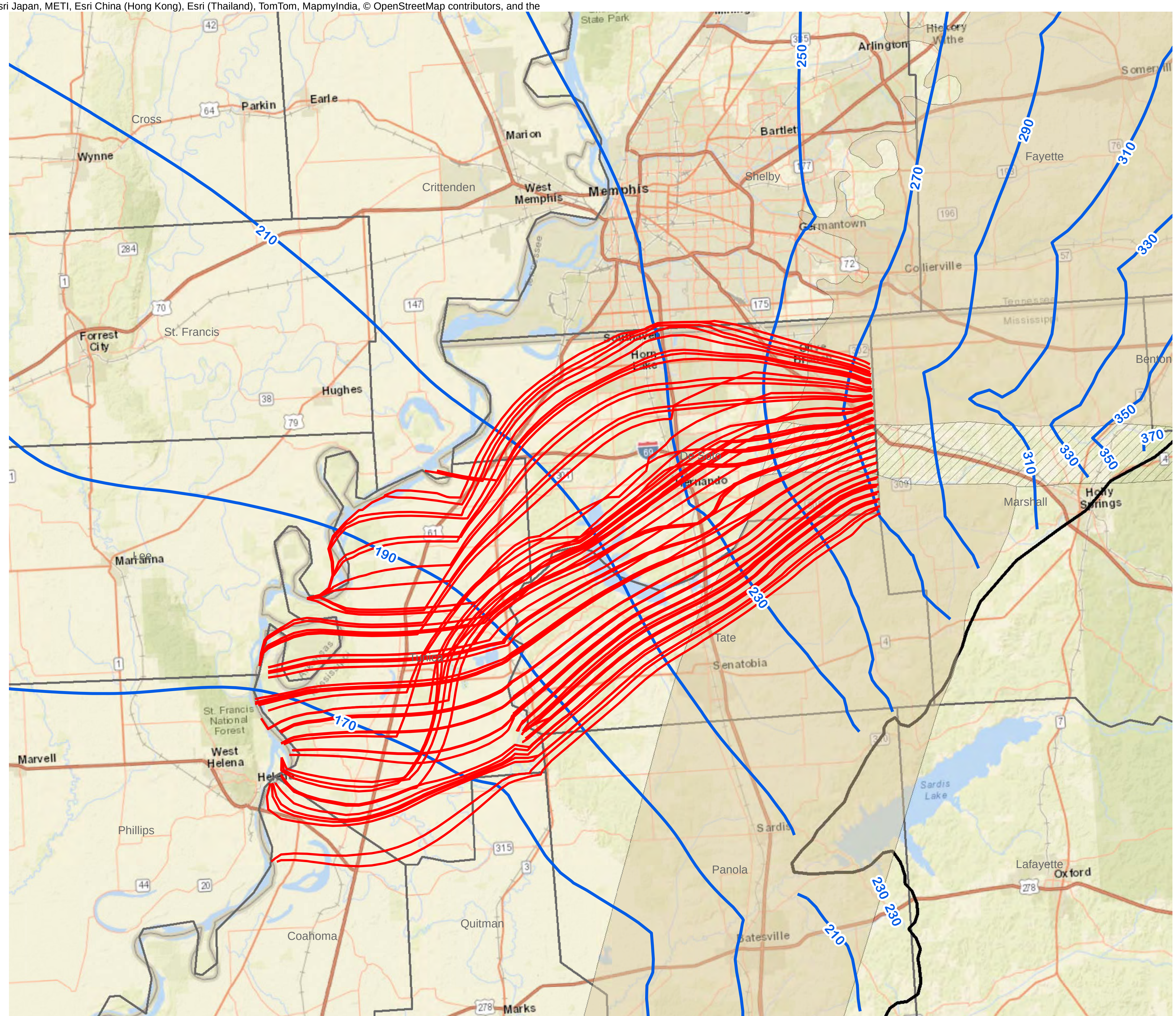
W. S. Parks and J. K. Carmichael, Altitude of Potentiometric Surface, FUN 1985, and Historic Water-Level Changes in the Memphis Aquifer in Western Tennessee, U.S. Geological Survey Water-Resources Investigations Report 88-4180 (1990a).

FIGURES

Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, MapmyIndia, © OpenStreetMap contributors, and the

N

0 5 10 Miles



Particle Tracking Analysis			
Simulated Velocity to Particle Discharge Location			
Average (feet/Year)	**Median (ft/year)**	**Maximum (ft/year)**	**Minimum (ft/year)**
40.61	44.71	52.76	13.75
Average (feet/day)	**Median (ft/day)**	**Maximum (ft/day)**	**Minimum (ft/day)**
0.11	0.12	0.14	0.04

Simulated Travel Time		
	Days	**Years**
Minimum	1,416,080	3,877
Maximum	8,104,420	22,189
Average	2,754,800	7,542

Legend

- Sparta Sands Flow Paths
- Pre-Development Heads
- Memphis Aquifer Outcrop (unconfined) Approximate Limits
- Transition Zone
- Middle Claiborne Aquifer Extent

C:\Graphics\GISDATA\0215.MISMEM\July 2017 - Supreme Court Case\Figure01.mxd

DRAWN BY: TDH
CHECKED BY: DAW
DATE: Aug. 2017
FIGURE NO.: 1

PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Groundwater and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

UPDATED REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

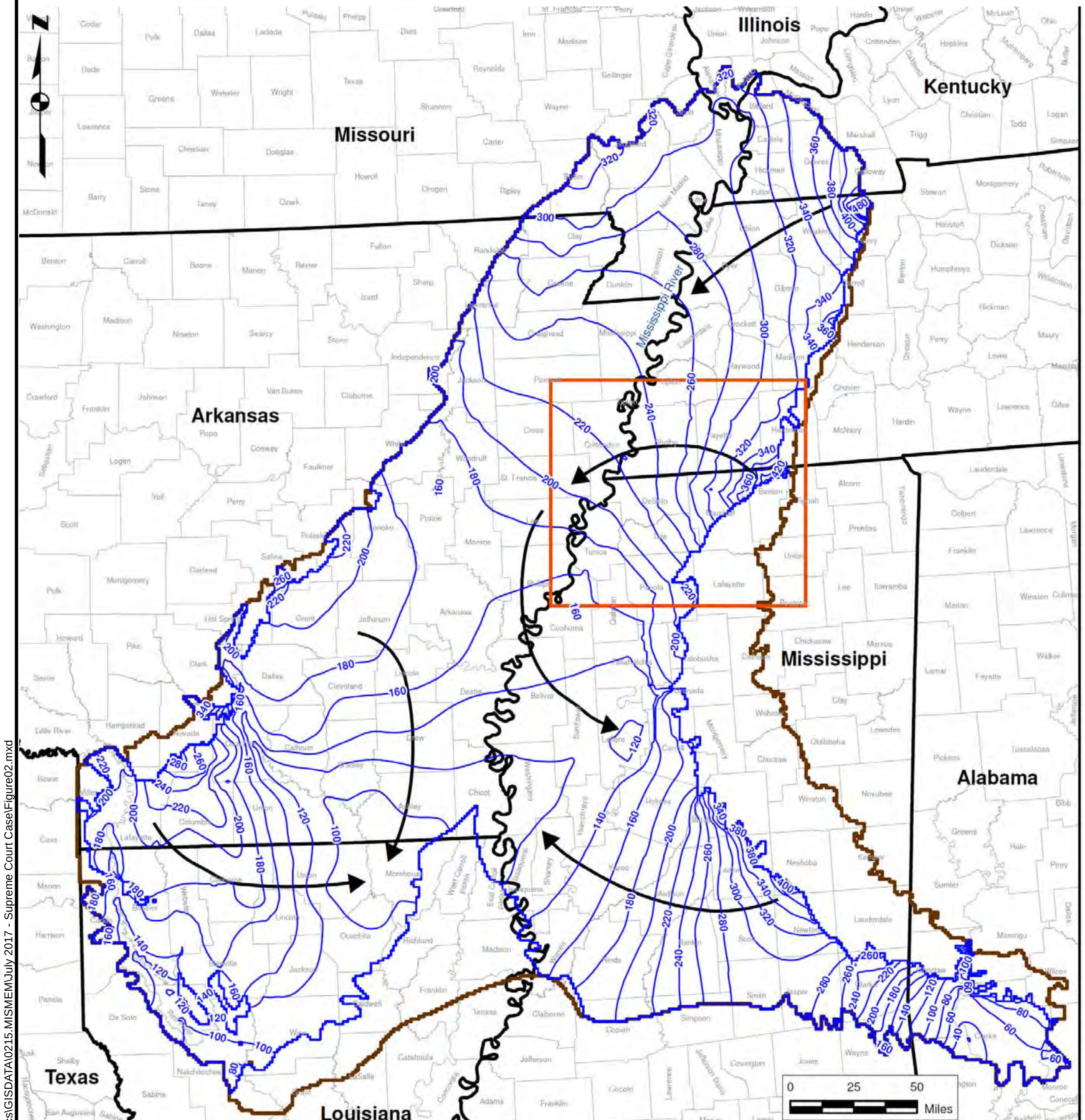
PRE-DEVELOPMENT FLOW PATHS IN NORTHWESTERN MISSISSIPPI

Acad GIS Corel

REVISED

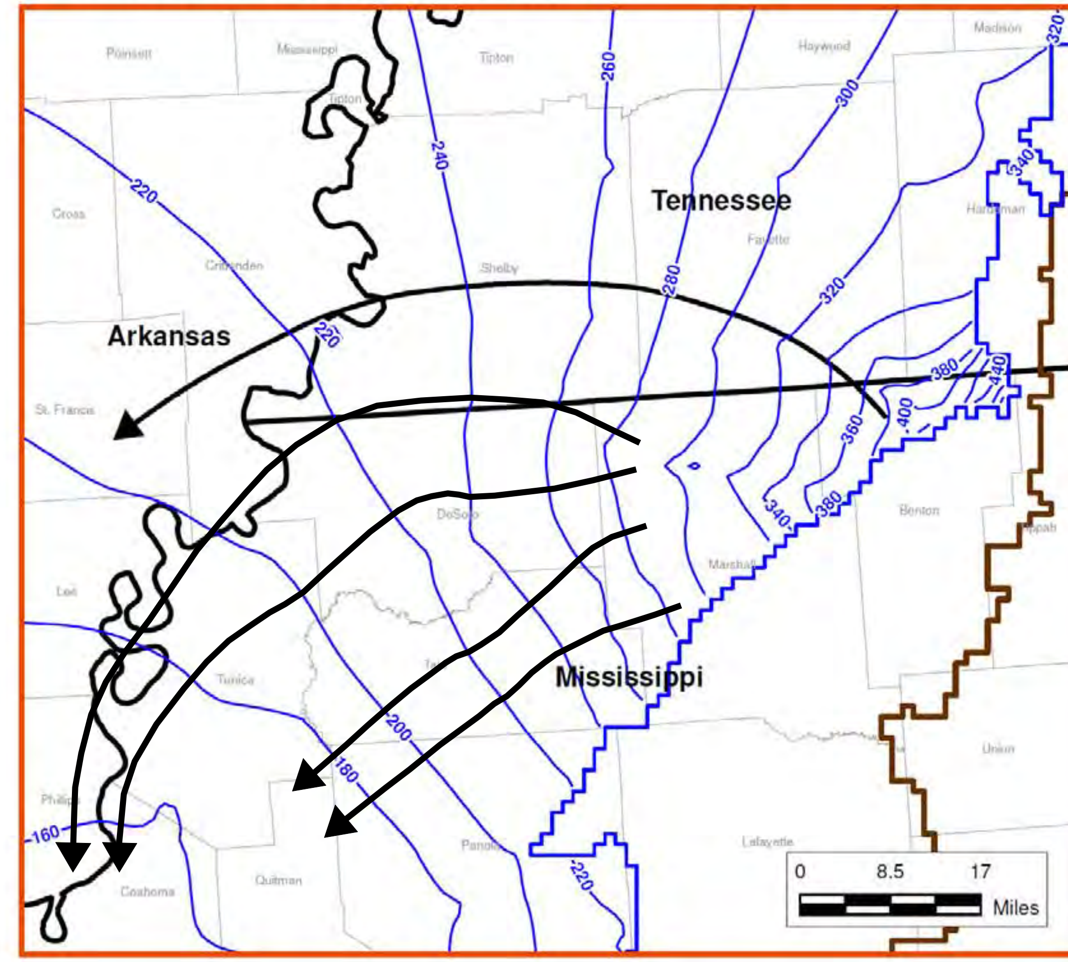
DATE

FILE NAME: FIGURE01.MXD



Source: Gradient, 2017 USGS MERAS Model Pre-development Surface with Generalized Flow Directions-Figure 3.3.1b

Inset – Mississippi-Tennessee Border Area



LEGEND

- Pre-development MSSA Potentiometric Surface
- Generalized Flow Direction
- Edge of the Top of the MSSA
- Edge of the USGS MERAS Model Domain
- State Boundaries
- County Boundaries

NOTES:
1) Potentiometric surfaces were created by contouring the USGS MERAS model hydraulic head results for layer 5 under pre-development conditions.
2) Generalized flow direction added by Gradient.
3) All site features and locations are approximate.
4) The original figure was produced in color. Significant information will be lost if copied in black and white.

SOURCES:
1) US Census Bureau, 2016a,b.
2) MODFLOW files associated with Clark *et al.*, 2013.

DRAWN BY: TDH
CHECKED BY: DAW
DATE: Aug. 2017
FIGURE NO.: 2

PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Groundwater and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

UPDATED REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

USGS MERAS MODEL PRE-DEVELOPMENT MSSA POTENTIOMETRIC SURFACE WITH GENERALIZED FLOW DIRECTIONS

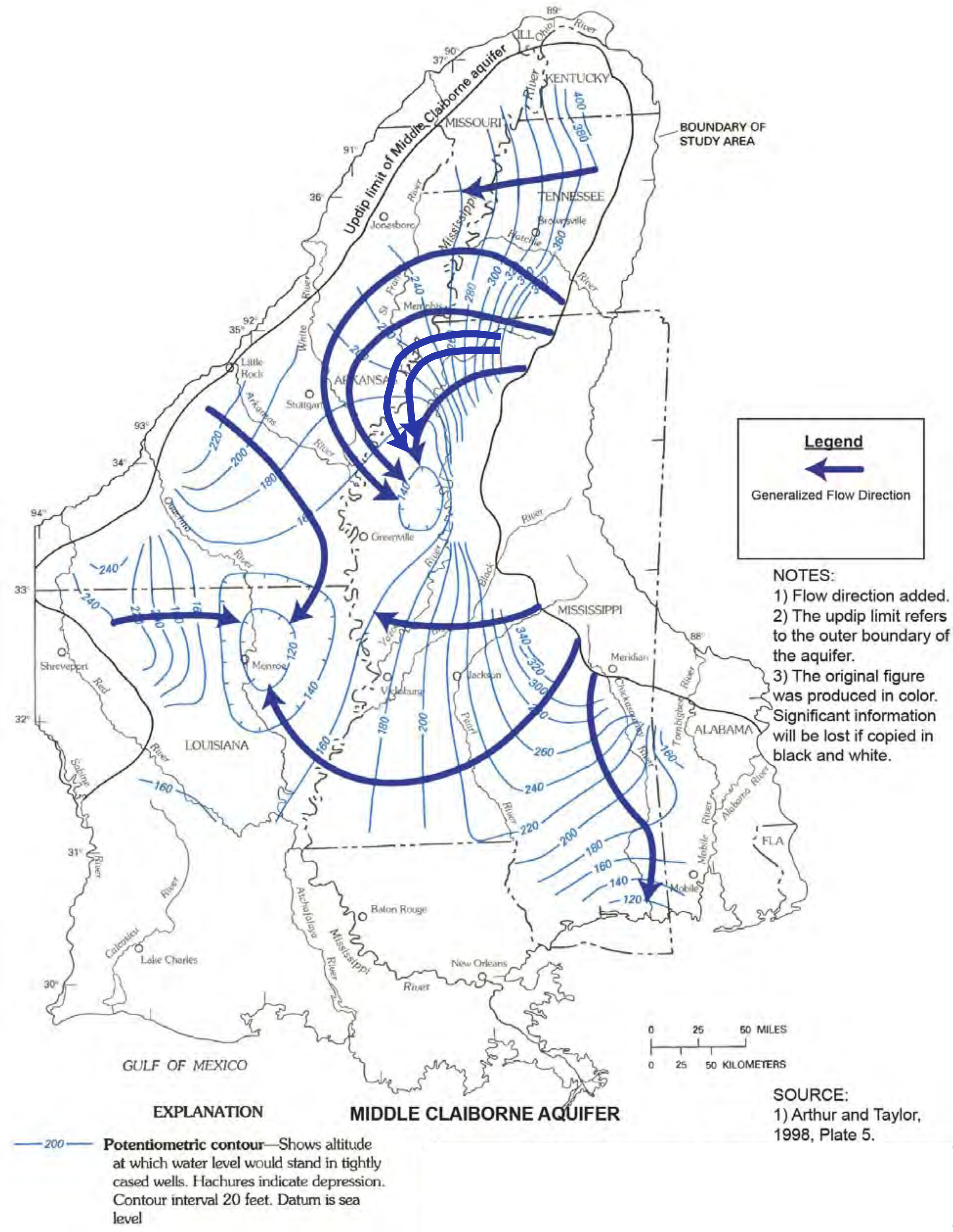
Acad GIS Corel

REVISED

DATE

FILE NAME: FIGURE02.MXD

C:\Graphics\GISDATA\0215.MISMEM\July 2017 - Supreme Court Case\Figure02.mxd



Source: Gradient, 2017; Model-Simulated Pre-development Potentiometric Head Contours for the Middle Claiborne Aquifer (Upper MSSA)-Figure 3.3.3

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

MODEL SIMULATED PRE-DEVELOPMENT POTENTIOMETRIC HEAD CONTOURS FOR THE MIDDLE CLAIBORNE AQUIFER

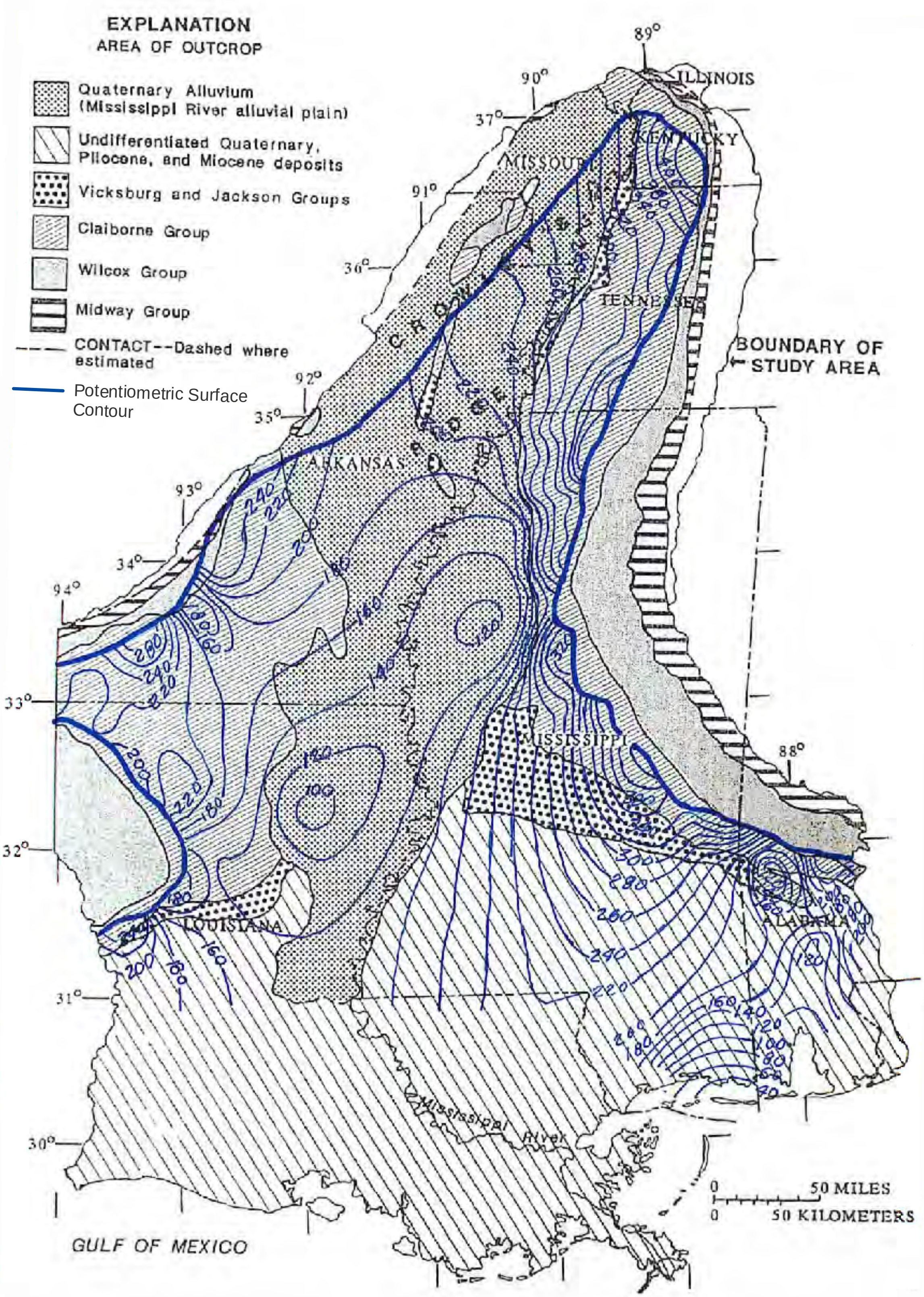
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

☐ Acad
☑ GIS
☐ Corel

DRAWN BY:	TDH
CHECKED BY:	DAW
DATE:	Aug. 2017
FILE NAME:	Figure03.MXD
FIGURE NO.:	3

C:\Graphics\GISDATA\0215.MISMEM\July 2017 - Supreme Court Case\Figure03.mxd



Source: Arthur & Taylor, 1990

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

GENERALIZED GEOLOGY OF ENBAYMENT AND PRE-DEVELOPMENT POTENTIOMETRIC SURFACE OF MIDDLE CLAIBORNE AQUIFER

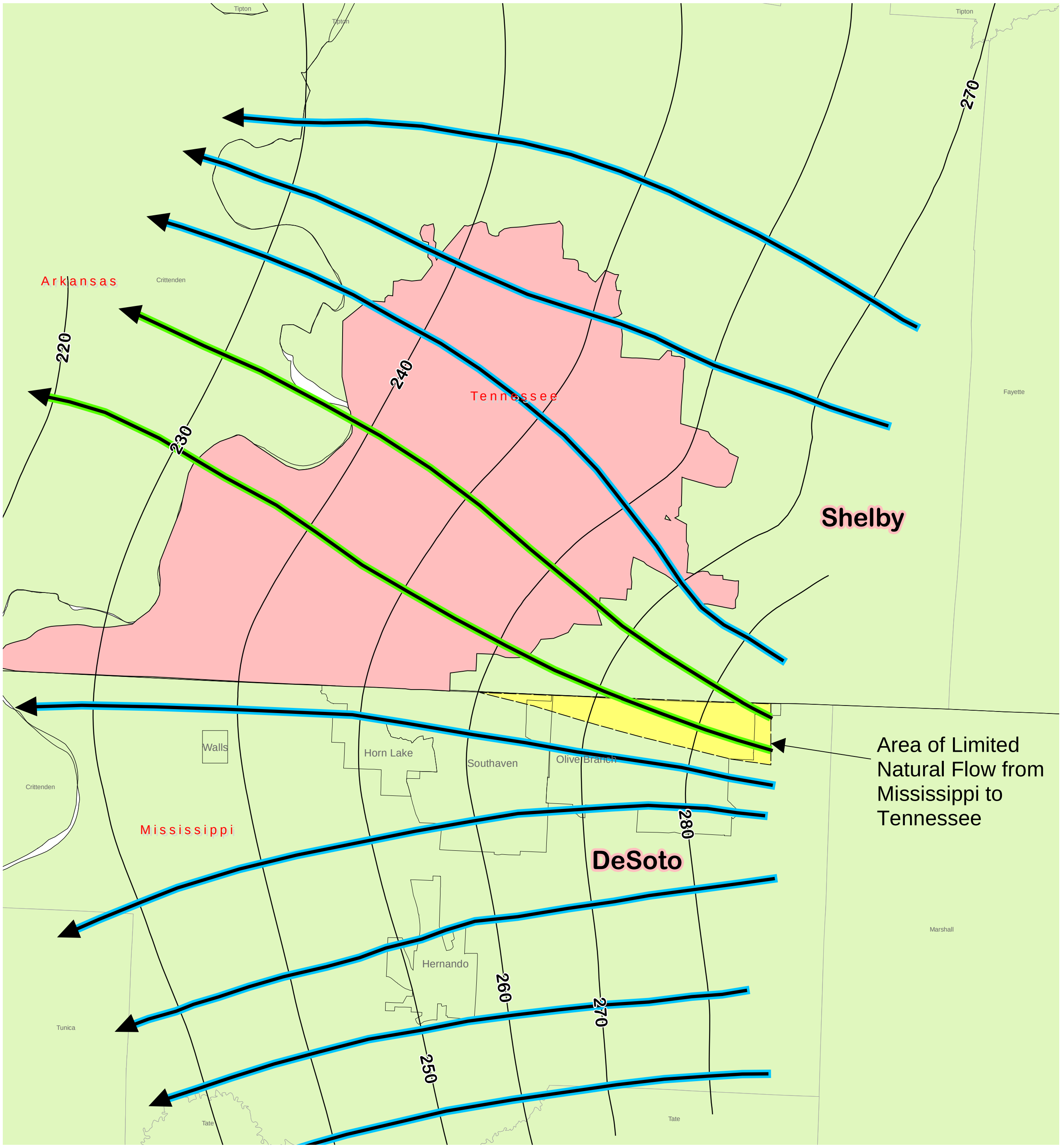
PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

☐ Acad
☑ GIS
☐ Corel

DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*Aug. 2017*
FILE NAME:	*Figure04.MXD*
FIGURE NO.:	*4*

C:\Graphics\GISDATA\0215.MISMEM\July 2017 - Supreme Court Case\Figure04.mxd



SOURCE: BRAHANA WRI 89-4131

N

0 3 6 Miles

Flow Lines Showing Pre-Development Groundwater Flow Direction

Flow Across State Line

Flow Within State

Potentiometric Surface Contour Lines

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

1886 ESTIMATED POTENTIOMETRIC SURFACE MAP FOR PREDEVELOPMENT CONDITIONS

PREPARED BY: **LEGGETTE, BRASHEARS & GRAHAM, INC.**

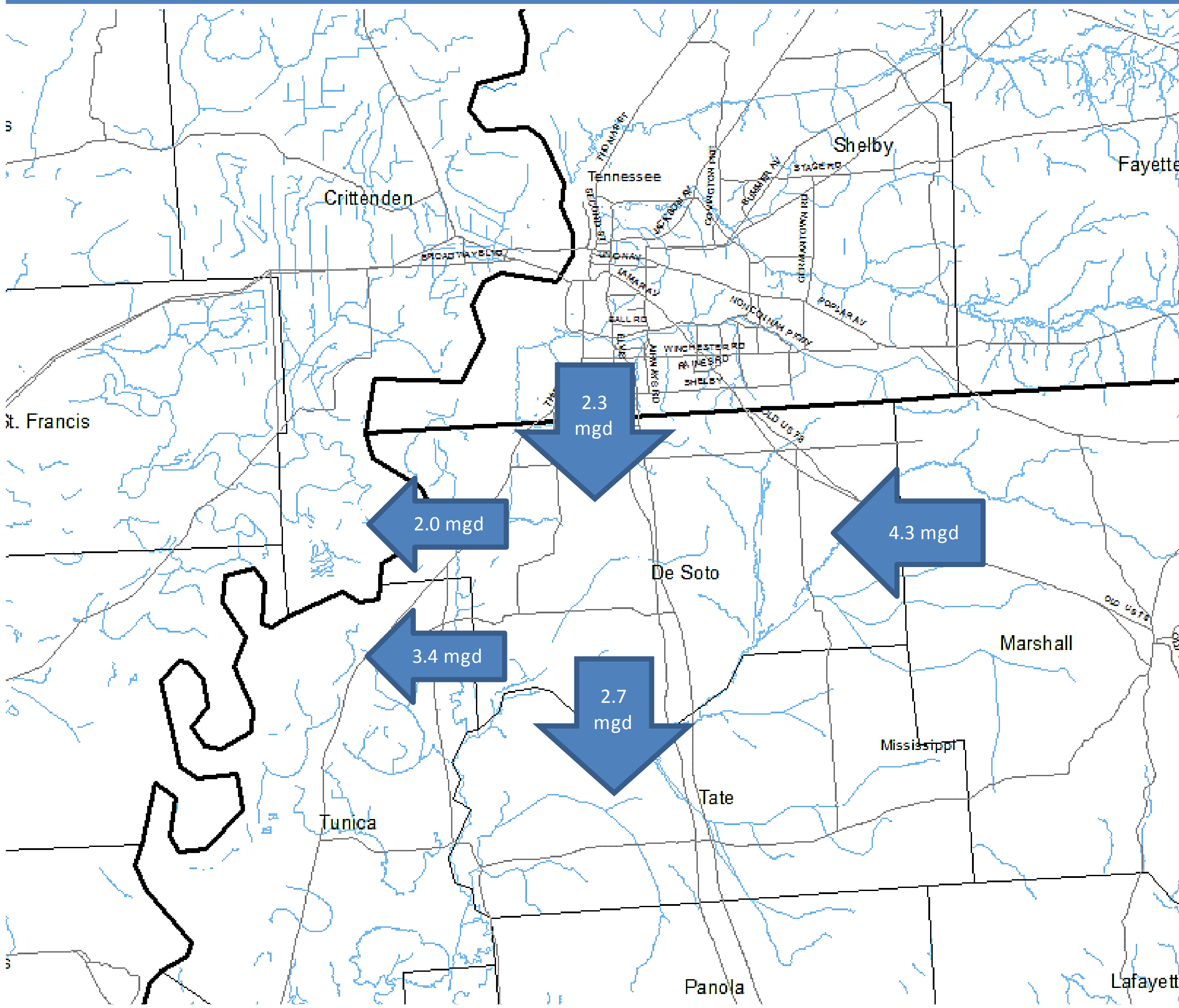
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

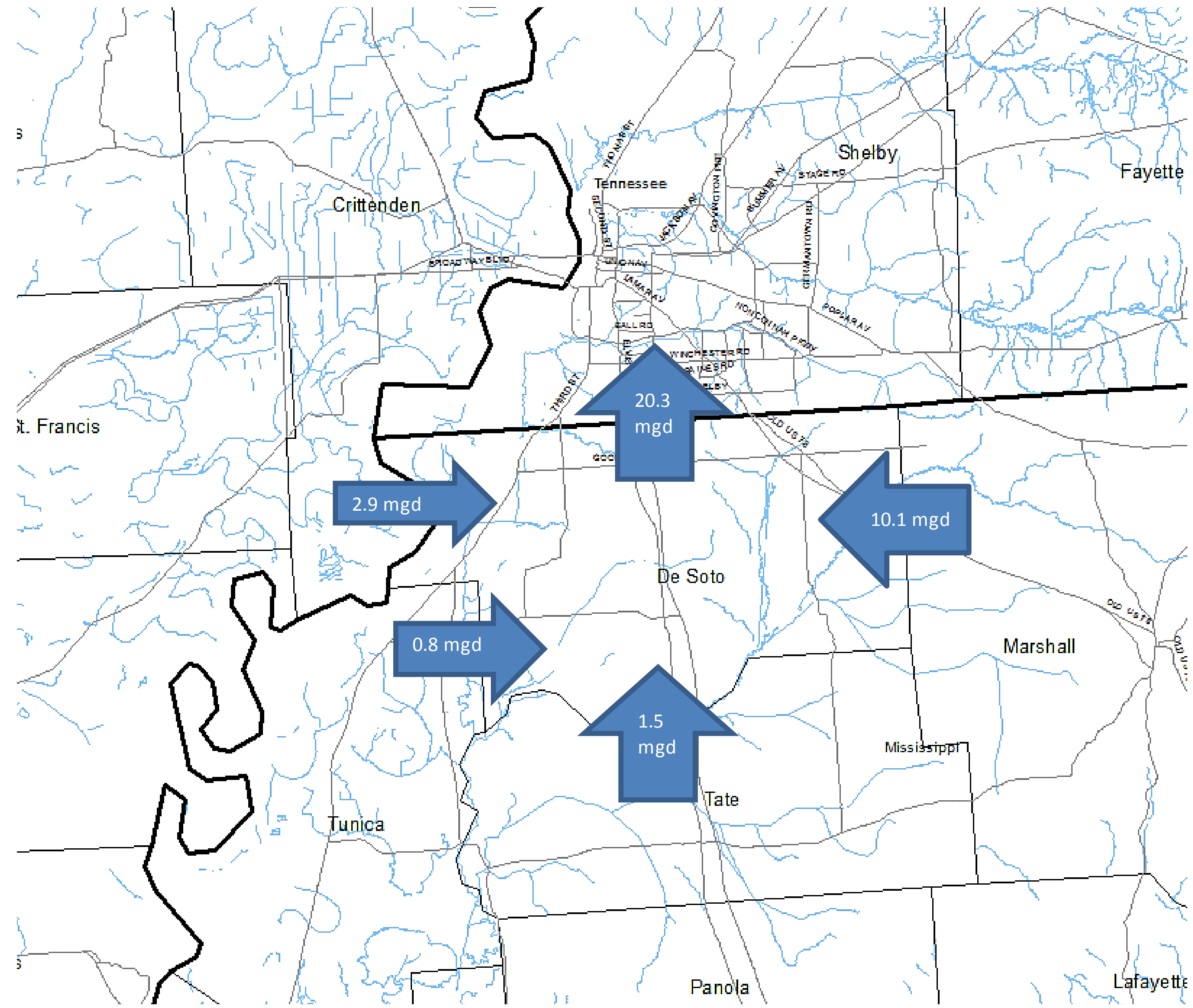
DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*Aug. 2017*
FILE NAME:	*Figure05.MXD*
FIGURE NO.:	*5*

C:\Graphics\GISDATA\0215.MISMEM\July 2017 - Supreme Court Case\Figure05.mxd

Pre - Development Memphis Sand Sparta Aquifer Model Layers 5 Through 10 (Desoto County)



2007 Memphis Sand Sparta Aquifer Model Layers 5 Through 10 (Desoto County)



Simulated Flow in Memphis Sand Sparta Aquifer

Simulation Period	Flux (million gallons per day)
Pre-Development Flow from Tennessee To Mississippi	2.3
2007 Flow from Mississippi To Tennessee	20.3
Net Pumping Related Impact (Diversion)	22.6

DRAWN BY: TDH
CHECKED BY: DAW
DATE: Aug. 2017
FIGURE NO.: 6

PREPARED BY:

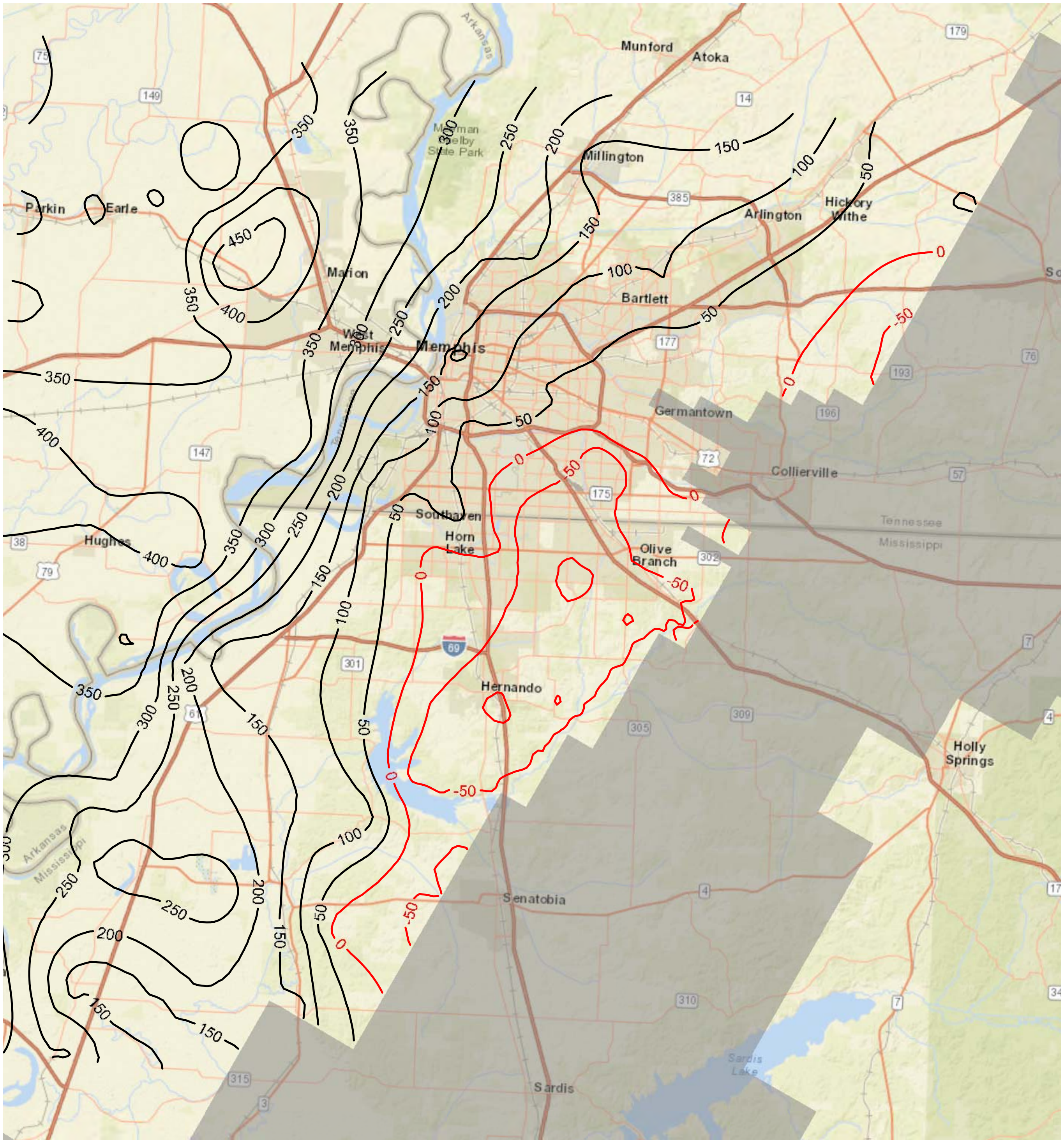
LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Groundwater and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

UPDATED REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

PRE-DEVELOPMENT AND 2007 WATER BUDGET IN DESOTO COUNTY MISSISSIPPI FROM USGS MERAS MODEL

REVISED
DATE
FILE NAME: FIGURE06.MXD

C:\Graphics\GISDATA\0215.MISMEM\July 2017 - Supreme Court Case\Figure06.mxd



N

0 5 10 Miles

Legend

Water Level in Feet Above or Below the Top of Memphis Sand Sparta Aquifer

Black - Above

Red - Below

Constant Head

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

HEADS ABOVE AND BELOW THE TOP OF MSSA AQUIFER FROM EQUAL AMOUNTS OF PUMPAGE OCCURING IN MISSISSIPPI AND TENNESSEE (BASED ON 2016 MLGW AND DESOTO COUNTY ESTIMATES)

PREPARED BY:

LEGGETTE, BRASHEARS & GRAHAM, INC.
Professional Ground-Water and Environmental Engineering Services
Cypress Point Office Park
10014 North Dale Mabry Highway, Suite 205
Tampa, FLorida 33618
(813) 968-5882

Acad
GIS
Corel

DRAWN BY:	*TDH*
CHECKED BY:	*DAW*
DATE:	*Aug. 2017*
FILE NAME:	*Figure07.MXD*
FIGURE NO.:	*7*

C:\Graphics\GISDATA\0215.MISMEM\July 2017 - Supreme Court Case\Figure07.mxd

EXHIBIT 15

C. J. Taylor, W.M. Alley
Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data,
USGS Circular 1217 (2001)
(Excerpts)

Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data

U.S. Geological Survey Circular 1217

by Charles J. Taylor
William M. Alley

Denver, Colorado
2001

location during the late winter and spring. As seen on the hydrograph, water levels in well GW–11 fluctuate slightly from November to June in response to individual precipitation events, but exhibit an overall seasonal increase of less than 2 feet. In contrast, the more permeable sand and gravel in the deeper aquifer zone transmits water very easily, and the deeper aquifer zone exhibits a much greater response to the seasonal increase in recharge. On the hydrograph for well MW–1, water levels increase gradually at first from November through January, then more sharply from February to June, and exhibit an overall seasonal increase of more than 12 feet.

Superimposed on natural, climate-related fluctuations in ground-water levels are the effects of human activities that alter the natural rates of ground-water recharge or discharge. For example, urban development, deforestation, and draining of wetlands can expedite surface runoff and thus reduce ground-water recharge. Agricultural tillage, the impoundment of streams, and creation of artificial wetlands can increase ground-water recharge. Long-term water-level monitoring during periods of significant land-use change is important to the protection of aquifers. The effects of such human-induced changes on ground-water recharge and storage are often incremental, and the cumulative effects may not become evident for many years.

The withdrawal of ground water by pumping is the most significant human activity that alters the amount of ground water in storage and the rate of discharge from an aquifer. The removal of water stored in geologic materials near the well sets up hydraulic gradients that induce flow from more distant parts of the aquifer. As ground-water storage is depleted within the radius of influence of pumping, water levels in the aquifer decline. The area of water-level decline is called the cone of depression, and its size is controlled by the rate and duration of pumping, the storage characteristics of the aquifer, and the ease with which water is transmitted through the geologic materials to the well. The development of a cone of depression can result in an overall decline in water levels over a large geographic area, change the direction of ground-water flow within an aquifer, reduce the amount of base flow to streams, and capture water from a stream or from adjacent aquifers. Within areas having a high density of pumped wells, multiple cones of depression can develop within an aquifer.

As the reader examines the case studies discussed in this report, it is instructive to identify the natural and human-induced stresses on the aquifers described and the relative and combined effects of each on ground-water levels. This will illustrate the primary point of emphasis—that ground-water-level data must be collected accurately and over periods of sufficient time to enable the proper development, management, and protection of the Nation’s ground-water resources.

Measuring water level in dewatering well near Yuma, Arizona. Photograph by Sandra J. Owen-Joyce, U.S. Geological Survey.

EXHIBIT 16

Deposition of Randy Gentry
August 7, 2006
(Excerpts)

DEPOSITION OF RANDALL W. GENTRY, PH.D., P.E.

August 7, 2006

IN THE UNITED STATES DISTRICT COURT
FOR THE NORTHERN DISTRICT OF MISSISSIPPI
DELTA DIVISION

JIM HOOD, ATTORNEY GENERAL, EX REL., THE STATE OF MISSISSIPPI, ACTING FOR ITSELF AND PARENS PATRIAE FOR AND ON BEHALF OF THE PEOPLE OF THE STATE OF MISSISSIPPI	
Plaintiff,	CIVIL ACTION NO. 2:05CV32-D-B Consolidated
vs.	
THE CITY OF MEMPHIS, TENNESSEE, AND MEMPHIS LIGHT, GAS & WATER DIVISION,	
Defendants.	
DESOTO COUNTY, MISSISSIPPI,	
Plaintiff,	
vs.	CIVIL ACTION NO. 2:05CV85-D-B
THE CITY OF MEMPHIS, TENNESSEE, AND MEMPHIS LIGHT, GAS & WATER DIVISION,	
Defendants.	
NESBIT WATER ASSOCIATION, INC., NORTH MISSISSIPPI UTILITY COMPANY, INC., AND BILL J. ROBERSON, ON BEHALF OF THEMSELVES AND ALL OTHER ENTITIES AND PERSONS SIMILARLY SITUATED,	CIVIL ACTION NO. 2:05CV108-D-B
Plaintiffs,	
vs.	

Gibson Court Reporting
865-546-7477

If you need to stop and refer to any of the documents that you brought with you or any of the potential exhibits that we may use in the course of the examination, please let me know if you need to do that in order to refresh your recollection about any of the matters that are the subject of the examination.

Would you please state your full name for the record, Dr. Gentry?

A. **Randall Wilson Gentry.**

Q. Where do you reside?

A. **At 5405 Green Valley Drive, Knoxville, Tennessee.**

Q. How long have you lived in Knoxville?

A. **Four years now.**

Q. So you moved here when?

A. **July 2002.**

Q. Where did you reside prior to moving to Knoxville?

A. **I lived on Linden Avenue in Memphis, Tennessee.**

Q. How long did you live in Memphis?

A. **I lived in Memphis most of my life, since the age of, I think, five roughly.**

Q. By whom are you currently employed?

A. **University of Tennessee.**

Q. What is your position with the University of Tennessee?

A. **I'm an associate professor of civil and environmental engineering.**

Q. What are your duties and responsibilities as an associate professor?

A. **Most of the duties are related to teaching and research. I teach several courses in civil and environmental engineering at the undergraduate and graduate level, and also perform research in my area of competency, which is water resources, generally ground-water hydrology.**

Q. Is there a water resources program with which you are associated?

A. **Well, we do have a water resources program. It's more interdisciplinary. We have two faculty members in the civil and environmental engineering and several faculty members across campus, some in earth and planetary sciences and some on the ag campus.**

Q. What is your relationship to the program? What is your position?

A. **Well, there is the academic program, and then the research program which is the -- a newly-formed institute on campus. It's the Institute**

For a Secure and Sustainable Environment which brought together two entities, the EERC which was the Energy and Environment Resources Center, and JIE, the Joint Institute For Energy and Environment, and then a third arm which was the Waste Management Research and Education Institute. So I am over the water resources program for that new institute.

Q. When you say you are over that, are you program leader?

A. **I'm program leader for that group.**

Q. What is the Southeastern Water Resources Institute?

A. **Well, underneath that water resources program, which is considered an umbrella organization where we attempt to bring all of the water resources research together on campus and with our partners, we have a couple of different entities which are more formal. One is the Southeast Water Resources Institute, which used to be more affiliated with the JIEE arm that we brought in, and then the Tennessee Water Resources Research Center, which was under the EERC arm.**

So prior to those being merged, I functioned as director for the Southeast Water Resources Institute.

Q. And briefly, what is the objective of the institute?

A. **The objective of the institute is really to provide better tools to communities to manage their water resources, but also to do what we consider to be novel research using, for instance, age dating tracers, geochemistry, to better define interactions between water resource units. So some of it might be more novel science, and then some it is just better tools for managing, whether it's aquifer systems or surface water system reservoirs.**

Q. Thank you. Would you provide us with a brief synopsis of your educational and your employment background? You can do that separately, or if in your case those timeframes overlap, you can do it together. But in giving us that synopsis, please break it down in terms of years and that sort of thing, specific years.

A. **Okay. Well, in 1991, I graduated with a Bachelor's of Science in Civil Engineering from the University of Memphis. It was Memphis State University at that time. I went to work for a company that was a division of Velsicol Chemical. It was called Memphis Environmental Center. That was the environmental arm of Velsicol Chemical, primarily doing management and some engineering-related services.**

Q. Would you spell Velsicol for the record?
A. V-E-L-S-I-C-O-L, I believe.
Q. Thank you. Please continue.
A. I worked for that outfit for approximately three years and decided to go back to graduate school. So I went back to graduate school and completed my Master's in 1996, Master's of Science in Civil Engineering, and then continued on to work on my Ph.D. at that time period under the same major professor, Dr. John Smith, and completed my Ph.D. in 1998 at the University of Memphis.
After that time period, I was hired as a sort of research associate, and then shortly thereafter, maybe a six-month period or so, a research assistant professor. And then that transitioned into a regular assistant professor position, and took on the position of associate director of the Ground-Water Institute at the University of Memphis. I was there for three years and then moved -- well, let's see. That would have been '99. Basically four years and then moved on to the University of Tennessee in 2002.
Q. What were your duties and responsibilities as associate director of the Ground-Water Institute?
A. I taught a couple of classes for the

civil engineering department as part of my responsibilities, ground-water-related courses, but also was primarily involved in research. The position was almost a hundred percent research. So I would have helped with any administrative duties by providing support to Dr. Jerry Anderson, attending planning meetings, strategic meetings, and also interfacing with any of who we consider to be our supporters who had issues or needs.
Q. What do you mean by supporters?
A. There were several groups who provided funding to the Ground-Water Institute. It was completely soft funded with some funds matched in kind by the University, giving us space and, you know, providing some teaching monies, that kind of thing. But most of the municipalities in Shelby County provided some form of support.
Memphis Light, Gas & Water was one; City of Germantown; City of Millington; Town of Collierville. City of Bartlett, I think, had stopped providing support. It was more in-kind support in later years. Primarily, that was it.
Q. What about industrial participants?
A. Early on, there were quite a few industrial participants. They still maintained

connections with the Ground-Water Institute, but it wasn't an active funding role by the time I came on. So, for instance, Dupont, I think, in the past had given some amount of funding to the Ground-Water Institute. But in later years, that had trailed off.
Q. What about Coors Brewing? Did they fund the institute?
A. Coors did. They provided -- I forgot that one. Coors provided some funding on sort of an on-again, off-again-type relationship.
Q. Did any of these entities participate in any research projects or have the Ground-Water Institute provide any research projects for their particular applications?
A. Not particularly. I think what they were more interested in was us being able to pull data together from the community into a cohesive package. We were rarely approached for individual research projects from the industrial groups. On occasion, we might involve them if we wanted to have access to their wells to collect data and information.
For instance, the Coors Brewery wells, we had collected samples for geochemistry and tritium at some point in time in an attempt to better understand what might be happening in that area of the aquifer.

Q. Would the information obtained from Coors relative to their wells, and I gather those wells are separate and distinct from the wells of other entities like MLGW; is that correct?
A. Correct.
Q. Would that well data be maintained at the Ground-Water Institute?
A. Yes.
Q. Are there any other entities other than Coors from whom the Ground-Water Institute obtained data?
A. There were quite a few well logs from companies like Buckeye Cellulose, Cargill. Velsicol, in fact, had several wells. I don't think they used them anymore, but that data was available. And any that would have been kept either by MLGW or other entities, we would have tried to collect that and put into our database.
Q. Now, wait a minute. When you say kept by MLGW, are you saying that MLGW also collected data from these other industrials?
A. No, no. They wouldn't --
Q. I'm sorry. I misunderstood.
A. Yeah. If they had it in a -- possibly had a record, we would have gotten it. I don't know

that they did keep any from the other industrial groups. Typically, the -- there was the same company that did all of the drilling in Memphis. It was Layne Central. And if you had difficulty finding a well log, if you could get permission from the owner of that well, Layne Central had a copy and would provide it. But in general, all the entities kept their own records.
Q. Did Dupont or Mapco provide any data?
A. **Not that I recall.**
Q. Did either of those entities provide any funding for the institute?
A. **Dupont may have at one point in time. Mapco, I do not recall whether they actually provided funding or not.**
Q. What was the level of funding, if you recall, provided by Memphis Light, Gas & Water?
A. **In the early years, they would have provided -- for the first two years, I believe, would have been around $500,000 a year. Thereafter, it would have dropped to somewhere around 225 to 250,000 a year.**
Q. Can you tell me generally what the annual budget of the institute would have been during the time you were there?
A. **It was highly variable, but it -- we**

would have been somewhere around 500 to $600,000 a year.
Q. So is it fair to say that at some point in time MLGW provided almost all of the funding for the Ground-Water Institute?
A. **I think that's close to being accurate. I think MLGW was the source of the managing those funds. And a lot of it came through MLGW mainly because they ran the meter feed component of what was going on in Memphis. So every water user paid a certain amount to a water fee and MLGW collected that. And part of that funding went to the Shelby County Health Department for maintaining well permits and a large portion of it then came to us for funding.**
Q. Okay. Dr. Gentry, I'm going to hand you what purports to be your most recent resume or curriculum vitae and ask you if you can identify that document for the record, please, sir?
A. **Yes. This is the most recent copy.**
Q. And in reviewing that, does this document, which we will have marked as Exhibit 1 to your deposition, reflect accurately the various research and scholarly activities, conference manuscripts and other contributions you have made, along with professional associations and honors, and

the courses you have taught, committees you have served on, and that sort of information?
A. **Yes.**
MR. CAMERON: Okay. We would like to have this document marked as Exhibit 1 to Dr. Gentry's deposition.
(**Exhibit 1** - Dr. Gentry's Curriculum Vitae.)
BY MR. CAMERON:
Q. Dr. Gentry, while at the Ground-Water Institute, did you personally have any experience in the study or analysis of the Memphis Sands aquifer associated ground-water systems?
A. **Most of my research was focused on the Memphis Sands aquifer primarily looking at water quality issues and also attempting to determine a little bit more information about leakage rates between the shallow aquifer and the Memphis Sands aquifer.**
Q. Did you do any quantitative analyses relative to the Memphis Sands aquifer?
A. **On various occasions we would have calculated perhaps, or attempted to calculate, leakage rates between the aquifer units and also flows from different areas.**
Q. What do you mean flows from different areas?

A. **We may have attempted to calculate -- for instance, a considerable amount of my work was done in the Shelby Farms area. We would have looked at flows that were approaching that study site on each boundary. We also later on would have looked at possibly this particular question between Shelby County and northern Mississippi and what potential flows may have been occurring across that boundary.**
Q. Could you expound on that and tell us what you mean by this particular question between Memphis and Mississippi?
A. **Well, there was a -- from 1998 to 2000, there was a lot of interest in what the state was doing with respect to water policy. And it was viewed as a potential hot topic, I guess, for lack of a better terminology -- well, there were two. There was one that was the Tennessee River and the potential water shortages in Atlanta, and then the other one was potential problems between northern Mississippi and Memphis with respect to ground-water usage.**
Q. What are those problems specifically?
A. **Some might argue it's never been completely elucidated, but I believe the problem is that Memphis is a large scale ground-water user. Northern Mississippi is developing and has purportedly**

run into problems with using water resources in northern Mississippi.

Q. So are you saying that Memphis -- the pumping of Memphis Light, Gas & Water is drawing water from -- ground-water from the -- in the Memphis Sands or Sparta aquifer from northwest Mississippi into the Memphis area?

A. **Well, Memphis is a very localized area of pumping, and it will pull in water from all directions. So it's going to pull water from the north, it's going to pull water from the west, east, and then some will come from the south, from Mississippi.**

Q. Why will it pull water from these other directions? What is the cause of that?

A. **Well, as you begin to remove water in the aquifers, it's a mass balance system, and so water begins to flow in along directions that it can flow in to fill that void in the potentiometric surface.**

Q. Tell the jury, please, what a potentiometric surface is.

A. **A potentiometric surface for a confined aquifer is an imaginary surface. Let's take a confined aquifer example. If I have a confined aquifer -- which means I have a clay layer, then I have the aquifer, and I have another clay layer -- if I punch a hole into**

that confined aquifer, the water level is going to come up above the confined layer. The surface that that forms, if I were to punch many holes throughout the aquifer, that surface becomes a potentiometric surface.

Q. What specifically -- what phenomenon occurs that causes the water to flow from these other areas into the Memphis area?

A. **Well, that's -- it's an energy and mass balance system, so if -- you know, think of it -- although you can't see it in the bathtub, if I begin removing water from one portion of the bathtub, water is going to flow from other areas to that area. So, basically, as you begin pumping, you begin removing water from voids, you lower that potentiometric surface level.**

So think of it in terms of energy. Energy is going to go from higher to a lower potential. So out in the surrounding areas, you now have a higher energy potential which is going to flow toward that lower potential to try and reach equilibrium.

Q. Is the lowering of the potentiometric surface, is that what is called a cone of depression?

A. **Yes. That would be called a cone of depression.**

Q. Could you explain for the jury what a

cone of depression is?

A. **A cone of depression is a predictable surface or pattern that forms when a pumping well pumps from an aquifer, in this case, a confined aquifer. It begins to form sort of an exponential surface in the potentiometric surface that forms a cone. In 3-D, it actually looks like a cone, and that's called a cone of depression.**

Q. You know, I notice, Dr. Gentry, that you brought some documents here with you today. Generally, what are these materials?

A. **Most of these are reports from USGS. These would have been reports either produced by Parks, Parks and Kingsbury, Criner and Parks, several individuals who were working with the Tennessee district of USGS at the time. One report from Kerry Arthur who was affiliated with the Mississippi district, and then two newspaper articles that sort of highlighted what was going on at the time in terms of this debate in the water policy area in Tennessee, particularly in the Memphis area.**

Q. And the USGS stands for what?

A. **United States Geological Survey.**

Q. What is the purpose of the United States Geological Survey, if you know?

A. **USGS is primarily responsible for collecting and helping interpret scientific data, in this particular case relating to water resources of the region. It could be surface water, could be ground-water. They also have a new division which does biological assessments and aids with that as well. But it's primarily a scientific organization.**

Q. Did the Ground-Water Institute interact with USGS on these studies?

A. **No. These predated a lot of the work that was done at the Ground-Water Institute. Many of these ranged from 1976 to the early nineties. The Ground-Water Institute came along in the later nineties. There was some collaboration. There is a report here which revisited Dr. Brahana's modeling efforts. We did interact a little bit on that report, but it was primarily just a USGS effort.**

Q. What is the relationship between the Ground-Water Institute and MLGW?

A. **We acted as a data warehouse for MLGW. Where we could, we also provided technical information and opinions on issues as they might arise.**

Q. When you say data warehouse, what do you mean? Are you suggesting that the data maintained at the Ground-Water Institute was the --

MR. DAVID BEARMAN: Objection. Leading.
BY MR. CAMERON:
Q. Well, I'm asking, why would you have functioned -- why would Ground-Water Institute have functioned as a data warehouse for the -- for MLGW?
A. Well -- and it wasn't just for MLGW. It was actually for the entire region. But the purpose was all of this data was available in multiple reports, in multiple locations. It was being maintained in different levels of quality, and we were attempting to develop a format that everybody could use as a common format to put this data together and manage and interpret for whatever reason they might want to. And we chose to do it in a GIS framework. So we used ARC/INFO, ARC GIS, and tried to get everything into that format so that these multiple data sets could be used together.
Q. Okay. Well, we are going to need to go over a few terms now. First of all, would you tell the jury what you mean by a confined aquifer?
A. A confined aquifer means that the aquifer is for the most part separated, meaning confined, from upper and lower strata, meaning it's slightly under pressure. So if we think of these aquifer systems as sort of a bowl, and we have alternating layers of clay,

sand and clay, typically they will outcrop at a certain area, and recharge will enter that outcrop area and then flow down depending upon what the sources and sinks are.
So if I tap into that confined layer, the potentiometric surface will rise up to a specific level, depending upon the flow and energy conditions in the aquifer. So that's a confined aquifer.
Q. You used two other terms I would like to ask you about. What is GIS?
A. GIS stands for geographic information systems. It's a broad-based term that means spatial data, taking spatial data and putting that into a cohesive database.
Q. And then you also referred to ARC?
A. That's a tradename, software name. It's ESRI, Environmental Systems Research Institute, I think, which is a primary seller of GIS software.
Q. These documents that you have brought with you today, did you bring them in response to the subpoena that was served on you?
A. Yes.
Q. Do these documents represent all of the materials within your possession or custody that would relate to the Memphis Sands or Sparta aquifer?

A. Well, I have other information regarding the Memphis aquifer and the Sparta Sands. I have other reports that are regional. These represent what I would say is the information that best represents the interactions between Memphis aquifer, surficial aquifer; Sparta Sand, Memphis area, and any policy issues that were going on at the time.
Q. And when you say policy issues, what do you mean?
A. Well, how is the aquifer being used? Is there potential problems, transboundary issues between Tennessee, Mississippi, or Arkansas, Tennessee, those kind of things.
Q. I notice that one of the documents you brought with you is a copy -- actually, it's an original of the Commercial Appeal for Monday, November 16, 1968. I want to refer to an article --
A. '98.
Q. '98, excuse me. And I want to refer to -- bi-focals. I want to refer to an article entitled "Memphis taps into DeSoto County's well Levels." Do you see that?
A. Yes.
Q. And who wrote that article?
A. It was written by Tom Charlier.

Q. Okay. Did you read -- have you reviewed this article before?
A. Yes.
Q. Did you review it contemporaneous with the date this paper was published?
A. Yes.
Q. I notice it states in the second -- third full paragraph actually of this article that, and I'm quoting, "Memphis each day sucks 20 million to 40 million gallons from under the feet of its neighbors in DeSoto County where wells already are straining to meet demand from rapid growth." Do you see that?
A. Yes.
Q. Do you know what Mr. Charlier based those comments on?
MR. DAVID BEARMAN: Objection. Speculation.
BY MR. CAMERON:
Q. You may answer.
A. Actually, I don't. I don't know what information he would have used to come up with that number.
Q. Have you made any studies of your own of such -- that are similar to this in terms of quantifying the amount of northward transboundary flow

from Mississippi into Memphis?
A. **A little later on, we did attempt to estimate based upon the potentiometric surface lines that were published by USGS what that flow could possibly be.**
Q. When you say "we," you mean the Ground-Water Institute?
A. **Yeah. It was primarily my job, but it was the Ground-Water Institute.**
Q. Is this what you would have referred to earlier as boundary issues?
A. **Yes.**
Q. To your knowledge, was this the first instance, and I'm referring to the Commercial Appeal article, was this the first instance at which you would have learned or heard of the boundary issue between Mississippi and Memphis?
A. **There were more informal discussions that things were beginning to be problematic between northern Mississippi and Memphis, but this is the first formal probably written statement of that concern.**
MR. CAMERON: Before we continue, we would like to have this document marked as Exhibit 2. And actually, if it's okay with you, Gentlemen, I would really prefer -- I guess we

could copy the whole front page, but -- so we can identify the Commercial Appeal edition, and then the article itself, which continues beyond the bottom of the front page of the newspaper to Page A9. And so we would like to have a copy of the complete article with the style of the newspaper and everything as the exhibit, if that's okay, as opposed to this entire newspaper. Is that acceptable?
MR. DAVID BEARMAN: Fine.
(**Exhibit 2** - Newspaper article from the Commercial Appeal, November 16, 1998, entitled "Memphis taps into DeSoto County's well levels," By Tom Charlier, RWG 000311.)
BY MR. CAMERON:
Q. Now, you say there were some informal discussions regarding these boundary issues. Do you recall any of those informal discussions?
A. **My memory is really hazy about that. You know, we had -- through conversations with Dr. John Smith, he had several colleagues in northern Mississippi; he had brought that to my attention. There were people affiliated with USGS who had heard these comments, but didn't really know the source, some of which may have been also from the State of**

Tennessee. We were hearing that through their counterparts in Mississippi that there were concerns.
Q. You don't know the specific timeframe?
A. **No. It would have all been in this general timeframe, but I don't know the specific dates.**
Q. Were these boundary issues discussed internally at the Ground-Water Institute?
A. **Not robustly. We would have -- we would have been interested in a factor figure like this 20 to 40 millions of gallons per day, where that would have come from. But I wouldn't say that we had intense meetings or anything over the subject.**
Q. There is a statement here by a Charles Branch. Do you know Mr. Branch?
A. **I do.**
Q. How do you know Mr. Branch?
A. **We met at the onset of a group that had gotten together to try and formalize interactions between Mississippi, Tennessee, and Arkansas called MATRAS, which stands for Mississippi, Arkansas, Tennessee Regional Aquifer Study, and Charles Branch attended that first meeting.**
Q. Mr. Branch is quoted in this newspaper article which is Exhibit 2 to your deposition stating, "There is a lot of concern about the cumulative use in

the Memphis area, Branch said. They, parenthetically the City, are the largest user of ground-water from the State of Mississippi. Significant volumes are flowing from DeSoto County northward into their pumping centers." Did you ever do any analysis to verify the statements of Mr. Branch?
A. **Other than just the calculation that I mentioned earlier, we didn't do any other calculations to try to verify that.**
Q. Okay. And the calculations you mentioned earlier were calculations to verify this directional flow from Mississippi into Memphis; is that correct?
MR. DAVID BEARMAN: Objection. Leading.
BY MR. CAMERON:
Q. Is that correct?
A. **Yes.**
Q. And did you independently attempt to quantify the amount of ground-water flowing from north Mississippi into Memphis?
A. **No. Just basically attempting -- looking at the potentiometric surface map, looking at the borehole data and trying to estimate what the true northward flux was. That was the extent of what I attempted to do to come up with that number.**
Q. Well, perhaps I confused you with my

question. When I say quantify, did you attempt to estimate -- when you say the northward flux, is that the northward flow? Is that what you mean?
A. Yes. I'm sorry.
Q. So is that estimation, was that in some particular volumetric quantity or percentage or --
A. It was. It was in a -- let's say a million gallon per day quantity. And as I recall, I do not remember the exact number, but given the annual pumpage at the time, it would have been reasonable for it to be a quarter to upwards of a third of the flow.
Q. What do you mean when you say a quarter to upwards of a third of the flow? I'm not following you.
A. Of the total annual pumpage that would have been occurring in Shelby County at the time.
Q. By pumpage, do you mean the water that is used to supply the City of Memphis?
A. Yes. And other municipalities as well.
Q. So are you saying that a quarter or a third of the --
MR. DAVID BEARMAN: Objection. Leading.
BY MR. CAMERON:
Q. I'm asking you, what do you mean when you say a quarter to a third of the pumpage flowed from

Mississippi into Memphis? I'm not following you.
A. Well, it would not have been unreasonable for this 20 to 40 million gallons per day to be within a range that would have been reasonable in terms of the estimate.
Q. Do you know the total pumpage, or would you have known the total pumpage in the Memphis area in -- around 2000?
A. Yes. I would have at that time. It would have been somewhere between 160 and 200 million gallons per day.
Q. So, are you saying it's a third to a quarter -- a quarter to a third of 160 to 200 million?
MR. DAVID BEARMAN: Objection. Leading.
THE WITNESS: Could have been. Again, I don't remember the exact numbers, but it could have been a third to a quarter of that number.
BY MR. CAMERON:
Q. Okay. Would that flux have represented normal conditions of the flow of the -- for the flow of the Memphis Sands aquifer?
A. It would have represented conditions based upon the data that we had, which would have been late eighties, early nineties flow.
Q. Okay. I'm going to hand you another

newspaper article that you have brought with you which is an article from the Commercial Appeal on Friday, May 12, 2000, entitled "Issue of Water Quantity Hits Home in Region." Would you please identify that for the record?
MR. LEO BEARMAN: I didn't hear the date. I'm sorry.
MR. CAMERON: Friday, May 12, 2000.
THE WITNESS: Yes. This was an editorial that was written by Dr. Dave Feldman of the University of Tennessee to the Commercial Appeal. And I would have read that the morning that it came out.
BY MR. CAMERON:
Q. Generally, what was Dr. Feldman's article about?
A. Well, Dave was at the time working with the water supply policy panel for the State of Tennessee, and he is very active in water policy issues. And he was basically writing an editorial to the City saying that we need to think about water resources in a new way, that it's not an infinite supply, and we need to work together in a regional collaboration, but don't think that this water is going to be here forever. Let's treat it as a resource that

we have that needs to be managed.
MR. CAMERON: We would like to have this article, and just the article itself actually, made an exhibit to Dr. Gentry's deposition, Exhibit No. 3.
(**Exhibit 3** - Newspaper article from the Commercial Appeal on Friday, May 12, 2000, entitled "Issue of Water Quantity Hits Home in Region," By David L. Feldman, RWG 000312.)
MR. CAMERON: But in copying the article, we would like it copied so that the date and the identification of the newspaper and so forth appear on the copy.
BY MR. CAMERON:
Q. Did Dr. Feldman do any other work to your knowledge relative to this boundary issue?
A. Well, he was publishing a report in and around the same time that was focused on all of Tennessee and Tennessee's potential water supply problems. And that -- I don't remember the title of the report right now, but that would have been the other major publication that came out.
Q. I hand you what purports to be a paper prepared by Dr. Lewis -- David Lewis Feldman and others entitled "Final Report - Water Supply Challenges Facing

Tennessee, Case Study Analyses and The Need for Long-term Planning," dated June 2000, and ask you if you can identify that document?

A. **Yes. This would have been the report I was referring to.**

Q. Have you read that report before?

A. **Pieces of it, yes.**

Q. Which pieces would you have read?

A. **Particularly those that were pertinent to the Memphis aquifer. I believe it was Chapter 5.**

Q. Would you please turn to Page 54 of this document, Dr. Gentry?

A. **Okay.**

Q. Would you review Pages 54 and following, and determine whether this was the part of the paper that you read?

A. **This is the portion of the report.**

Q. Did you do any analysis or critique of Dr. Feldman's work?

A. **We would have reviewed it and offered comments back. I do recall doing that. I did not do any technical review of the information that he had in the document. It would have been more from a policy standpoint, and then if we felt he got any technical information incorrect in terms of sizes and that kind**

of thing, I would have not have done any other calculations to verify anything though.

Q. When you said offered comments, what do you mean, offered comments to who?

A. **Directly back to Dr. Feldman.**

Q. Okay. Did you have any discussions with anyone else regarding Dr. Feldman's report?

A. **I may have discussed it with Jerry Anderson a bit at the Ground-Water Institute.**

Q. By the way, who is Dr. Anderson? Please identify him for the record.

A. **Dr. Anderson is director of the Ground-Water Institute at the University of Memphis. He was my direct supervisor while I was at the University of Memphis.**

Q. So did you say -- I'm sorry. I interrupted you. You discussed the Feldman report with Dr. Anderson?

A. **Yes. And we would have also discussed it with MLGW and others who were interested in the community as well.**

MR. CAMERON: We would like to have the Feldman report marked as Exhibit 4 to Dr. Gentry's deposition.

(**Exhibit 4** - Paper prepared by Dr. David Lewis

Feldman and others entitled "Final Report - Water Supply Challenges Facing Tennessee, Case Study Analyses and The Need for Long-term Planning," dated June 2000.)

BY MR. CAMERON:

Q. What discussions did you have with MLGW?

A. **Well, at the time, we had a meeting to discuss sort of the broader water policy issues going on in Tennessee. MLGW was very concerned that Tennessee would begin sort of an over-arching management of resources in the state. And we felt that in west Tennessee we were managing the resource fairly well and preferred to have it done at a local level. So we would have been looking at issues as they arose, particularly this with Dr. Feldman's report as a potential concern for a direction in terms of state regulatory practices with what could happen.**

Q. When you say "we," who is we?

A. **That would have been myself and Jerry Anderson at the Ground-Water Institute.**

Q. Did you attend any meetings where the Feldman report or this boundary issue was discussed?

A. **There was a concern, particularly when this editorial came out, at MLGW about sort of these broader issues. And we did have a meeting at MLGW to**

discuss this.

Q. When you say this editorial came out, are you referring to the May 12, 2000 article of Dr. Feldman in what has been marked as Exhibit 3 to your deposition?

A. **Yes.**

Q. Okay. When was that meeting held?

A. **I don't recall the exact date, but it would have been in and around the same time as the Feldman report and this editorial were coming out, so it would have been in 2000, and may have been in May of 2000.**

Q. Who attended the meeting, if you recall?

A. **Quite a few MLGW executives. I think Larry Thompson, Alonzo Weaver, Williams --**

Q. Max Williams?

A. **Max Williams. Jerry Anderson, myself, and attorneys that they had present as well.**

Q. Who were the attorneys?

A. **I'm trying to recall his name now. I think it was Weaver.**

Q. James Weaver?

A. **James Weaver.**

Q. Were there any other attorneys?

A. **There was one other one, a colleague of**

his, but I don't recall his name.

Q. Were there other MLGW representatives there?

A. **There were, but I don't remember specifically who they were.**

Q. For example, was Charlie Pickle in attendance?

A. **Charlie Pickle, I don't recall, but I -- he would have normally been at a meeting like that.**

Q. Why do you say that?

A. **He generally had a great deal of information about the water system and a great deal of information about the aquifer itself. He had over 40 years of experience in the business and was a very good source of information.**

Q. Who is Mr. Pickle?

A. **Mr. Pickle was an engineer with MLGW who basically ran or managed the water and gas side of operations. And particularly water was one that he had a great deal of interest in, and we interacted with him quite a bit.**

Q. And you had personally worked with Mr. Pickle before on projects relative to the Memphis Sands aquifer?

A. **Yes.**

Q. What about Mike Biscoe or Chris Beavers or any other individuals within MLGW? Did they attend the meeting?

A. **I can't remember.**

Q. Do you know whether or not Herman Morris attended the meeting?

A. **I don't recall.**

Q. And what was the overall substance of the discussion at the meeting?

A. **Well, there was this issue of this concern about water policy in Tennessee and potentially what could be occurring in the future in terms of management. And then a central issue came up regarding Shelby County and northern Mississippi and the concern for -- and potential of where that could go in the future.**

Q. What was the concern?

A. **Just that the groups were not working well together at this point, and there is this concern that a potential lawsuit could occur over water usage, and we should be working to avoid that.**

Q. So MLGW was concerned that Mississippi was going to sue Memphis?

MR. DAVID BEARMAN: Objection. Leading.

THE WITNESS: I don't know that for sure,

but that could have been one of the central concerns.

BY MR. CAMERON:

Q. Well, what was the lawsuit about which some concern was expressed?

A. **Well, the Feldman report had alluded to the fact that certainly there could be Supreme Court case issues if it got down to a case between Tennessee and Mississippi over ground-water related usage. So that concern would have been present.**

Q. All right. You had stated earlier that you actually performed some study of this boundary issue; did you not?

A. **Yes.**

Q. Okay. When did you perform that analysis?

A. **It would have been in and around the same time in 2000.**

Q. Did you report your findings to MLGW?

A. **Not in a quantitative form. I believe I may have mentioned that it would not be unreasonable to come up with the number that was reported in the paper.**

Q. The number -- what do you mean, what number?

A. **The 20 to 40 million gallons per day that**

was reported in the Commercial Appeal.

Q. As flowing from Mississippi into Memphis?

A. **Yes.**

Q. All right. For what purpose did you perform your analysis?

A. **It was primarily curiosity, and I felt I would be asked that question. Where did the number come from? Is it reasonable in terms of its value? I did not provide that number to Tom Charlier, so where would he have gotten it from, who would he have been talking to, and how would they have performed that estimate? So it was more out of curiosity that if you took a very basic data set, could you come up with something that would be in that range?**

Q. Who was involved in the analysis other than yourself?

A. **It was primarily me, but I had asked a student who was working for us and Brian Waldron to help with those calculations.**

Q. Who is Brian Waldron?

A. **He is now assistant professor at the University of Memphis in civil engineering and worked with the Ground-Water Institute as a research assistant professor for some time while I was there.**

Q. And who was the student?

level data?

A. **The water level data would be the same.**

Q. That's right. Okay. That's what I'm asking. What was the source of your -- values for hydraulic conductivity when you performed your approximation of the quantity of northward boundary -- transboundary flow from Mississippi into Memphis?

A. **They would have been values that we had in our database at the time. They would have come from USGS or from information we had from specific wells.**

Q. How is that database maintained?

A. **It's maintained at the Ground-Water Institute. As new information is available, it's updated. A graduate student back in the early nineties began piecing it together. Some of these reports have rather long lists of wells with information associated with those wells. That would have been pulled together into the database, and then any other information that we may have had would have been put in there as well.**

Q. If I wanted to get a copy of this database, who do I ask and what do I ask for?

A. **I would just ask the Ground-Water Institute, Dr. Jerry Anderson, for a copy of the borehole database that represents all of the Shelby County, Mississippi, Arkansas, spatial extent.**

Q. Is that what is known as a geo-spatial database?

A. **Yes.**

Q. Was that database in part compiled by a student named Clay Brown?

A. **There were a couple of students. Clay worked on it at one point, and then I don't remember his first name, but a fellow by the name of Braun.**

Q. How is that spelled?

A. **B-R-A-U-N, I believe. Both of those would have worked on a data set of wells and compiled that information together.**

Q. Is that data maintained in a paper format, or is it all computer maintained and generated?

A. **Computer maintained.**

Q. So if we were to ask Dr. Anderson for the borehole database, this geo-spatial database, how would that be produced to us?

A. **Probably very much like the CD I gave you. He will give you a copy of it in electronic format. It will be of the same format that I have here, ESRE ARC/INFO-type accessible.**

Q. So you have to have the ARC/INFO software or something in order to access what's on this?

A. **Yes.**

Q. So David is not going to be able to go home and read this?

A. **If he has ARC/INFO at home.**

Q. Is there a way to get -- how do you get the ARC/INFO GIS information?

A. **Well, they do have a reader, I think, that may be freeware or low cost. But, basically, this is like a Word document that you would pull up in Microsoft Word. You just pull this up in ESRE. It contains features. That's one of the things that's special about these GIS data sets is you can put a lot of information associated with a spatial feature. So if I were to click on this dot and I was in the software, information that had been put in about that location, transmissivity, thickness, that kind of thing, would be there.**

Q. When you say this dot, you are referring to a well bore?

A. **Yes.**

Q. Would that give you well construction data, location, all of that type of thing?

A. **It would give limited. It's not going to give you the date that it was probably put in. It would have been the information that was put in at the time. We were much more interested in sort of the**

physical contacts between aquifer units. So we would have been looking at that.

In fact, the color coding on here, by the way, the white dots really only have probably surficial aquifer information, and the colored dots have Memphis aquifer or other information at depth.

Q. And in performing your flow net analysis, what conclusions did you reach relative to the boundary issue you were studying?

A. **You know, there were no real conclusions. I think what I walked away with was a sense that whoever had given that number to Tom Charlier, it was at least a reasonable number to have estimated. I don't know where it came from. I don't know who did it, but if you were to do a flow net analysis, you could come up with a value like that, based upon the aquifer conditions.**

In terms of conclusions, again, no real conclusions. We just -- we always knew, you know, that water is flowing concentrically in from all areas. So it's -- it would not have been a surprise to anyone in the scientific community that someone said, okay, water is flowing from Mississippi to Tennessee. The more scientific questions we are interested in, you know, how is that affecting the regional picture, and can we

get a good picture over time of how that's occurring.

MR. CAMERON: We are going to take a short break. We will continue in, say, 10 minutes.

VIDEOGRAPHER: Off the record.

(The deposition was in recess.)

VIDEOGRAPHER: We are now back on the record.

BY MR. CAMERON:

Q. I may have asked you this, but let me make sure. Where did you obtain your hydro-conductivity values when you performed your sort of flow net quantitative analysis?

A. **I believe it would have been from the same data source. We had information in this data set that would have included transmissivity. It would have also included the thickness of the aquifer, so you could resolve that into two different values, the hydraulic conductivity or you could just use the transmissivity.**

Q. And you anticipated my next question. I I wanted to ask you about where you obtained your values for the saturated thickness. So if we wanted to get a copy of the basic data set that you had available to you at the time you performed your analysis, we

would ask Dr. Anderson to provide us with the borehole database?

A. **Yes. In particular, I would ask for the Braun database. You could always compare -- I think there was a great deal of similarity between Brown and Braun's data sets, but I would have probably used the Braun data set.**

Q. During this timeframe that we are talking about, I mean from 1998 to 2001 when you were aware of and looking at this boundary issue, was there ever any question in anybody's mind about whether there was transboundary flow from Mississippi into Memphis?

A. **Was there any concern?**

Q. No. Was there any question? Did anybody doubt that that was the case?

A. **No. No one would have doubted that there was flow moving from south to north.**

Q. To your knowledge, is there still today flow moving from south to north?

A. **Yes.**

Q. And it has been consistently moving south to north since you conducted your independent analysis, to your knowledge?

MR. DAVID BEARMAN: Objection. Lack of foundation.

THE WITNESS: There is no reason to believe it wouldn't.

BY MR. CAMERON:

Q. Have you reviewed any materials that would indicate that there is not a continuing south to north transboundary flow from Mississippi into Memphis?

A. **No.**

Q. I'm going to hand you a document entitled "Methodologies for Estimating a Directional Component of Ground-Water Flow" and ask you to please identify this document for the record, Dr. Gentry.

A. **Yes. This is a document that I prepared basically in providing you a methodology of how this flow component could be calculated. And I described two methodologies. One was this approximation method using the broad-based assumptions which I have been describing in this potentiometric surface and the boreholes.**

Q. Is that the flow net method?

A. **Yes. Sort of a modified localized flow net, yes.**

Q. Okay.

A. **Then the second aspect of this was to say that really where I think it would need to go is a comprehensive study looking at the changes over time**

using a consensus approach to come up with a management model that both Tennessee, Mississippi and Arkansas could agree upon.

Q. Right. And that would be more for prospective management of the aquifer?

A. **Prospective, and making sure that in terms of historical accuracy, that that's in place as well.**

Q. And could the latter that you referred to, the latter-type study be performed by, for example, updating the Brahana and Arthur models that you alluded to earlier?

A. **I think that's a good first step, yes.**

Q. So, basically, you would take the models that --

MR. DAVID BEARMAN: Objection. Leading.

BY MR. CAMERON:

Q. Would you take the models that had been --

MR. DAVID BEARMAN: Objection. Leading.

BY MR. CAMERON:

Q. -- developed by Mr. Brahana and Mr. Arthur as a starting point?

A. **If I were tasked to begin looking at this problem, I would begin with probably both models and**

possibly also storativity.

Q. I don't know if we have talked about storativity. Please tell the jury what storativity refers to.

A. **When you stress an aquifer, and we have been describing these cones of depression, as the head begins to change laterally outward, that's flow coming into the cone of depression. There is also another source of water called aquifer storage. And aquifer storage is defined based upon the compressibility of water which is extremely small, but also the compressibility of the mineral structure in the aquifer.**

So, if I had a series of spheres, and I stack them, and I have a small box I put them in, I can actually rearrange those spheres and change the amount of open space in that box. So when you begin pumping on an aquifer, think of sand grains as those small spheres, sometimes they will reorient themselves and produce where I had a higher porosity, it may be a lower porosity and generate a water flux. That's called water from storage. And its effect is to keep the head in the aquifer or the cone of depression from moving out at any faster rate.

Q. What potentially may happen if the cone

of depression is through pumping-induced stresses moved outward?

A. **Most of the water from storage has probably been captured at that point, and it's beginning to go outward and try and capture water from outlying areas to feed the cone of depression.**

Q. Is that what is essentially happening in the border issue involving Mississippi and Memphis?

MR. DAVID BEARMAN: Objection. Leading.

THE WITNESS: It could be one interpretation, yes. Cone of depression is moving outward.

BY MR. CAMERON:

Q. So the -- what is desaturation in the context of a ground-water act?

A. **Desaturation, in particularly these cases where you have confined aquifers, as long as the water level is above the confining layer or the top of the aquifer, you have a completely saturated media. Once the water level begins to drop below the confining layer and into the top of the aquifer, you begin to desaturate the aquifer. And when that happens, you get very rapid readjustment of those grains and the change in storage.**

Typically, an effect that can be seen in

those cases is a consolidation, subsidence issue of the aquifer. So you will actually see land surface changes, very localized land surface changes where the ground elevation has changed because of this pumping.

Now, this has happened in some very dramatic examples globally. One is the San Joaquin Valley in California has had very localized extreme subsidence. And then Mexico City has had the same. Basically their aquifer was an old lake bed, and as they began to pump it in very soft sediments, it began to reorganize itself and lowered in elevation so such now that you can go back now and you can see fire hydrants sticking out of the ground. And that's a subsidence issue.

Q. Are you familiar with the terms "mining" or "overdrafting" of an aquifer?

A. **Yes.**

Q. What do those terms mean?

A. **Mining and overdrafting can be used in several different ways. If you are using water out of an aquifer faster than it can replenish it, that's generally called overdrafting or mining. It's not sustainable, in other words.**

Q. What's not sustainable?

A. **The use is not sustainable.**

Q. Use of the aquifer?

A. **Yes.**

Q. As a source of supply?

A. **Yes.**

Q. So back to the technical brief. When Mr. Outlaw refers to aquifer parameters were estimated from pump test results, what is a pump test?

A. **Well, basically, you pump from a well, and they have very predictable ways that they behave. And so as you begin pumping them, you -- say it's a 24-hour pump test, you pump at different levels of intensity. And based upon the conceptual model of how these wells typically perform, you can fit that data and determine the hydraulic conductivity or transmissivity, and due to that changing head, possibly also if you are using an adjacent well, the storativity as well.**

Q. It also states that, "There are pump test results in the GWI files." If I wanted to get copies of the pump test results from the GWI files, what would we ask for?

A. **I would ask for specific well information associated with all of these boreholes that are shown on the map, where it exists, any pump test records or values obtained from those pump test records.**

interested in why we would be having a deposition, why would I be here, and may not have been aware of my history with the Ground-Water Institute.

Q. Okay. What did you tell him?

A. **I told him that I had worked with the Ground-Water Institute, had been involved in some of the work occurring during the time period when the interest was active with Dave Feldman's report, and the water policy panel, and also had attended this meeting at MLGW where we had discussed possible flow quantities.**

Q. Did he ask you any specific questions about the involvement of his client, MLGW or the City of Memphis?

A. **I don't recall any specifics there. Asked if I thought they were good managers, and I do, and I did at the time. They managed well within the capabilities of what they were doing.**

Q. Tell me more about the discussions that you had with MLGW in 2000. Where were those discussions had?

A. **Well, we would have always had those -- we had informal meetings at the Ground-Water Institute, Charlie Pickle and/or others would have come to the institute. For this particular meeting that I'm**

discussing, we would have gone to MLGW headquarters in downtown Memphis and had the meeting.

Q. Was this the only meeting that you recall having about the boundary issue that you described today and discussed today in your testimony?

A. **Yeah. Everything aside from that was always just informal discussions in the community. I don't recall any other meeting.**

Q. But I'm asking you, as far as MLGW was concerned, was that the only meeting that you attended where the boundary issue between Mississippi and Memphis was discussed?

A. **Yes.**

Q. And again, do you recall the specific substance of those discussions?

A. **Really, the focus was just this water policy issue that was being discussed in Tennessee. And then this potential -- what they viewed as potential litigation between Mississippi and Tennessee.**

Q. Who chaired the meeting?

A. **I don't recall a very specific chair. I think in terms of who it was being led by, it would have been James Weaver was most active.**

Q. Counsel for MLGW?

A. **Yes. And then Max Williams and maybe**

Larry Thompson would have invited us to attend as well.

Q. Did the discussion of the Feldman report come up in that meeting?

A. **It was discussed briefly.**

Q. Was there any request of you to critique or comment on Feldman's conclusions?

A. **I don't know of any direct comments asking us to critique. I think we -- I think what was asked was is this reasonable scientifically and, you know, what was the source of his information.**

Q. What was your -- what did you tell him in response to the question of is this reasonable scientifically?

A. **Well, I told him that it would not be unheard of for such a quantity to be coming from Mississippi.**

Q. And what quantity are you referring to?

A. **The 20 to 40 million gallons per day mentioned in the news article.**

Q. That were mentioned as having -- being flowing from Mississippi into the City of Memphis?

A. **Yes.**

Q. As a result of MLGW pumping stresses --

MR. DAVID BEARMAN: Objection to leading.

THE WITNESS: Well, it just would have

been northward flow from all the stresses that were occurring in Shelby County.

BY MR. CAMERON:

Q. What is the primary source of the northward flow?

A. **Most of it is pumping induced, MLGW having the largest pumping capacity in Shelby County.**

MR. CAMERON: Could we take a short break?

VIDEOGRAPHER: Off the record.

(The deposition was in recess.)

VIDEOGRAPHER: We are now back on the record.

MR. CAMERON: We have no further questions of Dr. Gentry at this time.

EXAMINATION BY MR. DAVID BEARMAN:

Q. Dr. Gentry, my name is David Bearman, and with me is Leo Bearman, Jr., and we represent the City of Memphis and Memphis Light, Gas & Water. I'm going to ask you some questions. If I ask you something you don't understand, let me know. Is that okay?

A. **That's fine. Thank you.**

Q. I want to clear up a couple of things real quick that you just talked about. In Technical Brief Number 7, which is Exhibit 15, do you have that

EXHIBIT 2 Dr. Gentry

THE COMMERCIAL APPEAL

159th Year, No. 320, 4 Sections | Memphis, Tennessee, Monday, November 16, 1998 | FINAL 50¢

Memphis taps into DeSoto County's well levels

By Tom Charlier
The Commercial Appeal

In getting their public water supplies, Memphis and neighboring communities in Mississippi are like a group of people drinking out of the same glass at a soda fountain.

Only Memphis has the bigger straw.

In fact, though its wells lie entirely in Tennessee, the Bluff City is the largest user of Mississippi's ground water, according to that state's regulators. Memphis each day sucks 20 million to 40 million gallons from under the feet of its neighbors in DeSoto County, where wells already are straining to meet demand from rapid growth.

At a time when conflicts over surface water are escalating across other parts of Tennessee and the Southeast, the Memphis-area withdrawals show that ground water, too, can become an interstate issue.

"It's all the same pool of water," said John W. Smith, former director of the Ground Water Institute at the University of Memphis.

With that in mind, many regulators and researchers are calling for a more regional look at the aquifer system supplying the Memphis area. It's an indication that the deep, rich beds of saturated sands on which the area depends are perhaps more complex, interconnected and vulnerable than previously thought.

The issue of the cross-state withdrawals has taken on new significance in the wake of a recent meeting in which Mississippi regulators warned DeSoto County officials about the potential consequences of declining water levels.

Charles Branch, head of the office of land and water resources with the Mississippi Department of Environmental Quality, said his agency has turned more of its attention to the DeSoto County ground water issue in recent years.

"There's a lot of concern about the cumulative use in the Memphis area," Branch said.

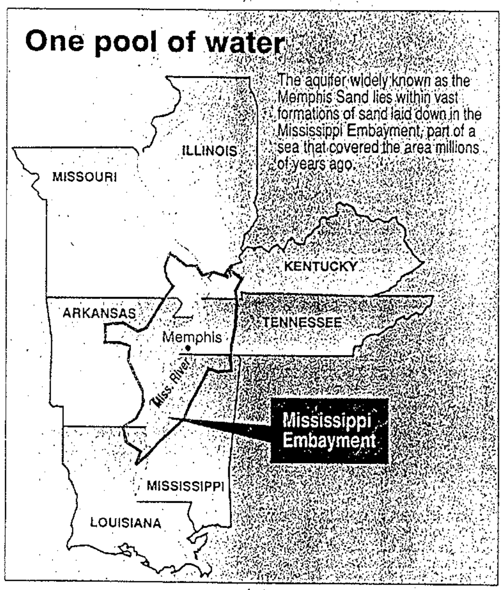
"They (the city) are the largest user of ground water from the state of Mississippi. Significant volumes are flowing from DeSoto County northward into their pumping centers."

DeSoto County is hardly the only part of Mississippi dependent on ground water.

According to the U.S. Geological Survey, Mississippians use some 3.3 billion gallons of water a day, with 80 percent, or 2.6 billion gallons, coming from underground sources. Much of that water is used for irrigating crops or in catfish-farming operations, which soak up 400 million gallons a day.

In DeSoto County, soaring demands for water have been

Please see WATER, Page A9



By Deborah D. Young

From Page A1

Water

driven mostly by rapid development in Memphis suburbs. As in Memphis, public water is drawn from an aquifer widely known as the Memphis Sand.

DeSoto County well water levels have been declining at rates of a foot or more a year, though similar drops have been recorded in some Memphis Light, Gas & Water Division well fields.

Mississippi officials acknowledge that DeSoto's growth is responsible for much of the decline. And they say the well levels don't necessarily portend disaster.

But with Memphis siphoning away tens of millions of gallons daily, a comprehensive study is needed to ensure that all users will have enough water in the future, Branch said.

He urges the development of a three-dimensional computer model showing how water flows within the aquifer and how growth and increased pumping could affect it.

The aquifer is among the sand formations laid down across the bottom of the Mississippi Embayment, part of a sea that covered the area 60 million years ago. The embayment stretches from southeastern Missouri to Louisiana and from central Arkansas to near the Tennessee River.

In the Memphis area, the layer of saturated sands comprising the aquifer is up to 900 feet thick and lies 500 or so feet below ground. Further south, the Memphis Sand splits into what is known as the Sparta Sand, an aquifer that extends across North Mississippi and even dips under the Mississippi River into Arkansas.

"The formation we call the Memphis Sand occurs throughout the Mississippi Embayment," said Mike Bradley, assistant district chief for the USGS in Nashville.

In West Tennessee and North Mississippi, the natural flow of water in the aquifer is to the west and southwest, said Kerry Arthur, hydrologist and civil engineer with the USGS in Pearl, Miss. But the heavy pumping of municipal wells in Memphis, he said, has diverted that flow, creating "cones of depression" that pull water from the south.

Three of the well fields serving LG&W's 10 water-pumping stations extend to within $2^1/_2$ miles of the Mississippi line.

Arthur said preliminary analyses suggest that as much as 20 percent to 30 percent of the water pumped by LG&W could be coming from Mississippi. The Memphis utility pumps about 145 million gallons daily.

Smith, who, as institute director, led studies on behalf of LG&W, said there's no dispute that some of that water comes from Mississippi.

"As we've increased our pumping rates, we've forced more water to come north from Mississippi into Shelby County," Smith said.

But while the aquifer crosses state lines, studies of it generally have not.

"As a regional resource, the Memphis Sand in Tennessee has been studied since the 1920s," said Bradley.

Interstate studies haven't been as common in the water-rich East as they are in the West, where "they divide up almost every raindrop," Bradley said.

More recently, studies have centered on Shelby County and concerns about contamination. The worries helped inspire the formation a decade ago of the city-county Groundwater Quality Control Board, a group charged with protecting aquifers.

Representatives of the board said they welcome more regional involvement in overseeing the aquifer.

"If you're trying to protect a resource that has as its boundaries a multistate area, then you need the cooperation to protect all that resource," said Carter Gray, technical secretary for the board.

Gray said cooperation across state lines also could help identify contamination threats to the aquifer, such as polluting industries, that might plan on locating in DeSoto or neighboring counties.

Smith said the involvement of Mississippi officials in monitoring the aquifer could bring about better water management in DeSoto County.

"DeSoto County doesn't have an (LG&W). They have 10 to 20 individual water utilities," Smith said.

It's important, Branch said, for all the groups having a stake in the aquifer to participate in efforts to protect it.

"Whatever happens in one area affects people in another" he said. "We need to have a more in-depth understanding of how this system works."

It's obvious, Branch said, that pumping ever more water from the ground eventually could cause shortages.

"There will come a time that you'll have more pronounced effects on these water levels, not just in DeSoto County, but in Shelby County."

> *Mississippi officials acknowledge that DeSoto's growth is responsible for much of the decline. And they say the well levels don't necessarily portend disaster.*

EXHIBIT
3
Dr. Gentry

VIEWPOINT

Issue of water quantity hits home in region

■ City, state must rethink notion of an inexhaustible supply.

By David L. Feldman

MEMPHIS ought to be one of the last places on the planet to worry about water. The city perches on a bluff overlooking one of the world's great river systems and sits atop the vast Memphis Sand Aquifer.

The aquifer, a thick layer of sand hundreds of feet below the surface, collects rain that falls on West Tennessee, north Mississippi, east Arkansas and southwest Kentucky. It has provided a reliable source of municipal water supplies for parts of these four states since 1886.

Because of the aquifer, Memphis remains one of the largest municipalities in the world to rely almost exclusively on groundwater. But this hydrologic resource is under threat and lies at the center of an interstate debate over water rights.

A sizable portion of the water drawn from the aquifer to serve Memphis is taken from beneath DeSoto County. As water has been pumped out more rapidly than it can be replenished, what hydrologists call a cone of depression may have developed in the region. Patterns of suburban growth in southeast Shelby County and northwest Mississippi may have disrupted the recharge areas where rainwater seeps into the deep layer of sand.

The decline in water levels in the aquifer is significant. The aquifer's level dropped by 77 feet between 1928 and 1985. Municipal wells in Memphis and north Mississippi are showing a foot-per-year drop in the water table.

Because the aquifer underlies parts of four states, its depletion raises possible legal issues. Mississippi has voiced concern about declining water levels and implicated Memphis — and by extension, Tennessee — as part of the cause.

Although there is little Tennessee case law addressing rights to the use of an aquifer, one court decision restricts the use of groundwater to a reasonable withdrawal from a source held in common.

Despite the absence of ready-made legal remedies, it is to the benefit of residents of both states — working through their communities and public officials — to find cooperative methods to protect, sustain and manage the aquifer equitably.

David L. Feldman

Experts at the University of Tennessee are looking at the legal and policy implications of these concerns and how they might be addressed. Experts on groundwater hydrology and water quality at other state universities are also exploring these issues and studying possible solutions. It is time for our state to draw on these institutions to help formulate a comprehensive state water plan.

Interstate concerns over water quantity may be relatively new to Tennessee, but potentially contentious situations are emerging elsewhere in the Southeast. Georgia is in a water war with Alabama and Florida over water allocations from two basins: the Alabama-Coosa-Tallapoosa and the Apalachicola-Chattahoochee-Flint.

The rapid growth of Atlanta and its increasing water needs, combined with competition among other water users, have fueled the dispute over these watersheds. If Georgia, Alabama and Florida can't reach a mutually satisfactory agreement, the issue will likely head to the U.S. Supreme Court.

The three states have a serious stake in keeping the issue away from the high court. In addition to the expense of litigation, any court-ordered solution would be a final, virtually inflexible decision, likely establishing a fixed water apportionment that won't take future needs into account.

One option that has been speculated on involves Atlanta's diversion of water from the Tennessee River. The primary concern is that waters from Tennessee streams that are dispatched to other states will not be returned to their original river basins, such as the Tennessee and Cumberland. This could deprive Tennesseans of their rights to use these waters.

These water supply conflicts involving communities in Tennessee, together with the possibility of increased sales of water outside the state, are driving a bill before the General Assembly. The Interbasin Water Transfer Act would make clear the rights of water users in Tennessee's river basins and articulate a legal framework that should limit both intrastate and interstate disputes in the future.

In shaping this policy, the state is positioning itself to anticipate and resolve water quantity problems before they become so contentious they cannot be addressed from a rational and detached perspective.

As cities such as Memphis and Atlanta continue to grow and the population of the Southeast rises, the competition for water resources is sure to become more contentious. State and regional leaders of government and industry are looking for ways to avoid costly litigation.

Officials from six states met in Atlanta last November and called for the creation of a Southeast water initiative. That effort would promote conservation, educate the public and political leaders about the potential shortage, collect data on water availability and consumption, and provide a setting where potential conflicts can be mediated before they reach the courtroom.

A regional water initiative, coupled with legislation that articulates a forward-looking water policy, will equip Tennessee and the Southeast with new tools to ensure equitable access to and adequate protection of the region's water supply.

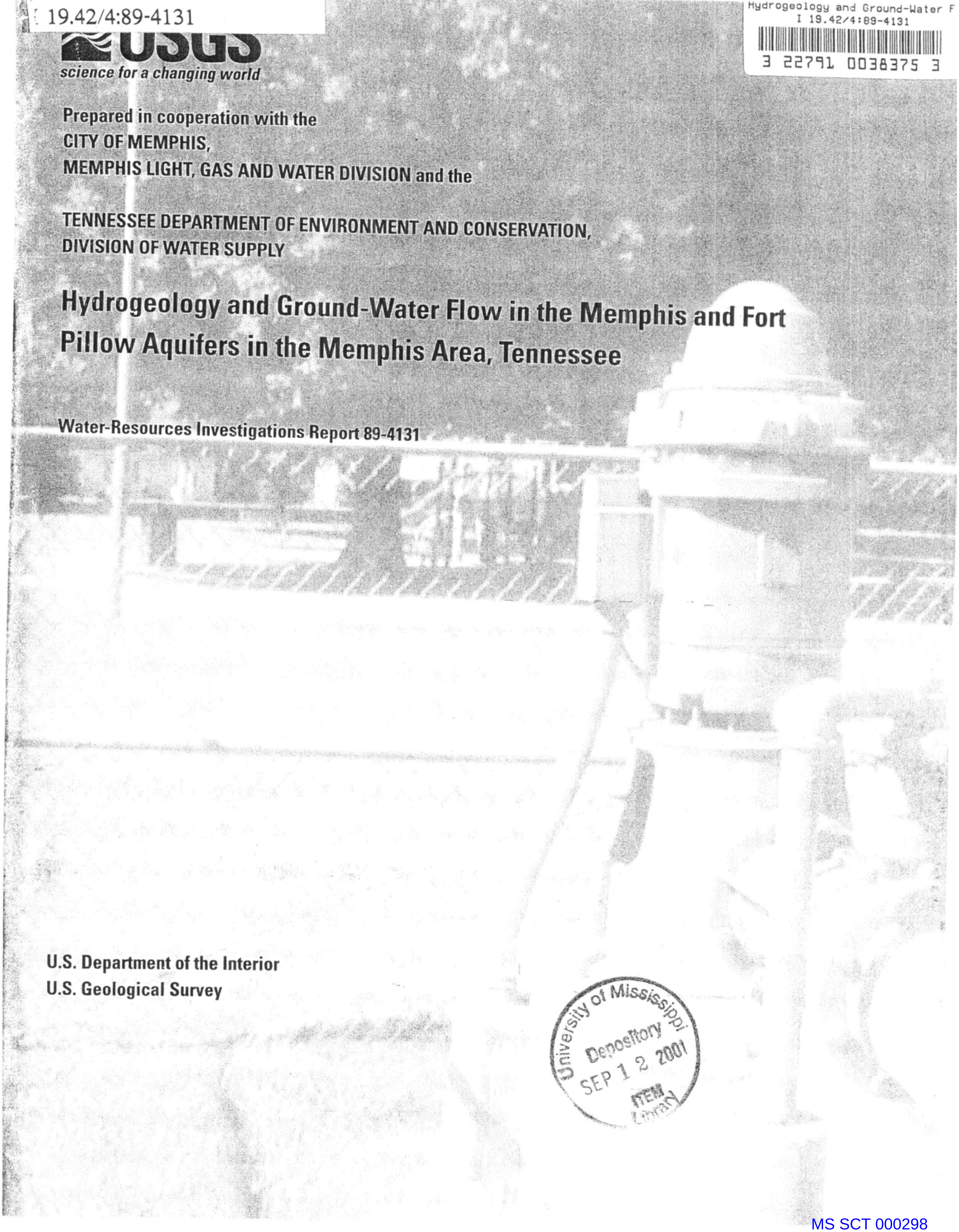
The people of Memphis and all other Tennesseans must discard the notion that our state's water supply is secure and inexhaustible.

As we do, we must carefully evaluate decisions about water use, and we must ensure that our laws, policies and use patterns protect this increasingly valuable resource.

David L. Feldman is a senior research scientist with the Energy, Environment and Resources Center at the University of Tennessee-Knoxville. He chaired the Southeast Water Supply Roundtable and is the author of a recent study of water problems in Tennessee.

EXHIBIT 17

J. V. Brahana and R.E. Broshears
Hydrogeology and Ground-Water Flow in the Memphis
and Fort Pillow Aquifers in the Memphis Area, Tennessee,
USGS 89-4131



USGS
science for a changing world

Prepared in cooperation with the
CITY OF MEMPHIS,
MEMPHIS LIGHT, GAS AND WATER DIVISION and the

TENNESSEE DEPARTMENT OF ENVIRONMENT AND CONSERVATION,
DIVISION OF WATER SUPPLY

Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee

Water-Resources Investigations Report 89-4131

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph: Public-supply well in Shelby County, Tennessee. Photograph taken by L.B. Thomas, U.S. Geological Survey.

Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee

By J.V. Brahana and R.E. Broshears

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 89-4131

Prepared in cooperation with the
CITY OF MEMPHIS,
MEMPHIS LIGHT, GAS AND WATER DIVISION and the

TENNESSEE DEPARTMENT OF ENVIRONMENT AND CONSERVATION,
DIVISION OF WATER SUPPLY

Nashville, Tennessee
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information write to:

District Chief
U.S. Geological Survey
640 Grassmere Park, Suite 100
Nashville, Tennessee 37211

Copies of this report may be purchased from:

U.S. Geological Survey
Branch of Information Services
Federal Center
Box 25286
Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	3.528×10^{-6}	meter per second (m/s)
square foot per second (ft^2/s)	0.0929	square meter per second (m^2/s)
cubic foot per second (ft^3/s)	2.83×10^{-2}	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per day (gal/d)	4.384×10^{-8}	cubic meter per second (m^3/s)
gallon per minute (gal/min)	6.309×10^{-5}	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	4.384×10^{-2}	cubic meter per second (m^3/s)
gallon per day per foot [(gal/d)/ft]	1.438×10^{-7}	square meter per second (m^2/s)
inch per year (in/yr)	0.0254	meter per year (m/a)

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.

Well-Numbering System: Wells are identified according to the numbering system used by the U.S. Geological Survey throughout Tennessee. The well number consists of three parts: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7-1/2-minute topographic quadrangle on which the well is plotted; and (3) a number generally indicating the numerical order in which the well was inventoried. The symbol Sh:U-2, for example, indicates that the well is located in Shelby County on the "U" quadrangle and is identified as well 2 in the numerical sequence. Quadrangles are lettered from left to right, beginning in the southwest corner of the county.

Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee

By J.V. Brahana *and* R.E. Broshears

ABSTRACT

On the basis of known hydrogeology of the Memphis and Fort Pillow aquifers in the Memphis area, a three-layer, finite-difference numerical model was constructed and calibrated as the primary tool to refine understanding of flow in the aquifers. The model was calibrated and tested for accuracy in simulating measured heads for nine periods of transient flow from 1886-1985. Testing and sensitivity analyses indicated that the model accurately simulated observed heads areally as well as through time.

The study indicates that the flow system is currently dominated by the distribution of pumping in relation to the distribution of areally variable confining units. Current withdrawal of about 200 million gallons per day has altered the prepumping flow paths, and effectively captured most of the water flowing through the aquifers. Ground-water flow is controlled by the altitude and location of sources of recharge and discharge, and by the hydraulic characteristics of the hydrogeologic units.

Leakage between the Fort Pillow aquifer and Memphis aquifer, and between the Memphis aquifer and the water-table aquifers (alluvium and fluvial deposits) is a major component of the hydrologic budget. The study indicates that more than 50 percent of the water withdrawn from the Memphis aquifer in 1980 is derived from vertical leakage across confining units, and the leakage from the shallow aquifer (potential source of contamination) is not uniformly distributed. Simulated leakage was concentrated along the upper reaches of the Wolf and Loosahatchie Rivers, along the upper reaches of Nonconnah Creek, and the surficial aquifer of the Mississippi River alluvial plain. These simulations are supported by the geologic and geophysical evidence suggesting relatively thin or sandy confining units in these general locations. Because water from surficial aquifers is inferior in quality and more susceptible to contamination than water in the deeper aquifers, high rates of leakage to the Memphis aquifer may be cause for concern.

A significant component of flow (12 percent) discharging from the Fort Pillow aquifer was calculated as upward leakage to the Memphis aquifer. This upward leakage was generally limited to areas near major pumping centers in the Memphis aquifer, where heads in the Memphis aquifer have been drawn significantly below heads in the Fort Pillow aquifer. Although the Fort Pillow aquifer is not capable of producing as much water as the Memphis aquifer for similar conditions, it is nonetheless a valuable resource throughout the area.

INTRODUCTION

The Memphis area has a plentiful supply of ground water suitable for most uses, but the resource may be vulnerable to pollution. Withdrawal of nearly 200 million gallons per day (Mgal/d) ranks Memphis second only to San Antonio, Texas, among the nation's cities that depend solely on ground water for municipal-water supply. For the past century, most of the city's ground water has been pumped from the Memphis aquifer, a Tertiary sand unit that is confined in most of the Memphis area. Industrial, public supply, and private withdrawals also have been made from the Fort Pillow aquifer, but these generally have amounted to less than 10 percent of the total pumping in the area.

There has been increasing concern that contaminated ground water in the area's surficial aquifers may leak downward to the Memphis aquifer (Parks and others, 1982; Graham and Parks, 1986; M.W. Bradley, U.S. Geological Survey, written commun., 1987). To assess the potential for such leakage, a cooperative investigation was initiated in 1978 between the City of Memphis, Memphis Light, Gas and Water Division (MLGW) and the U.S. Geological Survey. This investigation is part of a series of studies pursuing a more complete understanding of ground-water flow and chemistry in the area. The main tool of this investigation is a ground-water flow model of the major aquifers in the Memphis area. This flow model integrates all available information on the geology, hydrology, and ground-water chemistry of the region. The model has helped to quantify the potential for leakage between principal aquifers, and it may be a valuable predictive tool to assist water managers in managing ground-water resources.

Approach and Scope

The necessary approaches to this investigation were:

1. to describe the hydrogeologic framework of the Memphis area, with emphasis on the Memphis aquifer and Fort Pillow aquifer;
2. to develop a conceptual model of ground-water flow in the Memphis area;
3. to test the conceptual model through the application of a multilayer, finite-difference ground-water flow model.

As defined for this investigation, the Memphis area comprises a rectangular zone of roughly 1,500 square miles (mi^2), measuring about 45 miles from east to west by 35 miles from north to south. The Memphis area lies near the center of the northern part of the Mississippi embayment and includes all of Shelby County, Tennessee, and parts of Fayette and Tipton Counties, Tennessee, DeSoto and Marshall Counties, Mississippi, and Crittenden and Mississippi Counties, Arkansas (fig. 1).

The study area includes all of metropolitan Memphis, as well as undeveloped, outlying areas where ground water is affected by pumping from metropolitan well fields. Although the study focuses on the Memphis area, the aquifers and confining units are regional in occurrence, and extend far beyond the Memphis area boundaries. Descriptions and maps necessary to define the regional hydrogeology are included within this report only as an aid to understanding ground-water flow in the Memphis area. Readers interested in a full discussion of the regional hydrogeology of the Memphis and Fort Pillow aquifers in the northern Mississippi embayment are referred to Arthur and Taylor (1990).

Previous Investigations

A substantial body of literature exists on the hydrology and hydrogeology of aquifer systems in the Memphis area. The most recent, comprehensive studies include those of Graham and Parks (1986), who studied the potential for leakage in the Memphis area, and Parks and Carmichael (1989a, 1989b, 1989c), who described the geology and ground-water resources of three aquifers in West Tennessee. Extensive bibliographies of previous ground-water studies are included in Brahana (1982a, table 2 and p. 35-40) and in Graham and Parks (1986, p. 41-44). A series of potentiometric maps and a description of historic water-level changes and pumpage from the Memphis aquifer and Fort Pillow aquifer in the Memphis area are included in Criner and Parks (1976). Historic water levels in individual wells are also documented by the U.S. Geological Survey (1936-1973). The potentiometric surface in the Memphis aquifer for 1978 and 1980 in the Memphis area is shown in Graham (1979, 1982), and for 1985 for West Tennessee is shown in Parks and Carmichael (1989d). The potentiometric surface of the Fort Pillow aquifer for 1980 for the northern Mississippi embayment is shown in Brahana and Mesko (1988, fig. 11), and for 1985 for West Tennessee is shown in Parks and Carmichael (1989e, fig. 2).

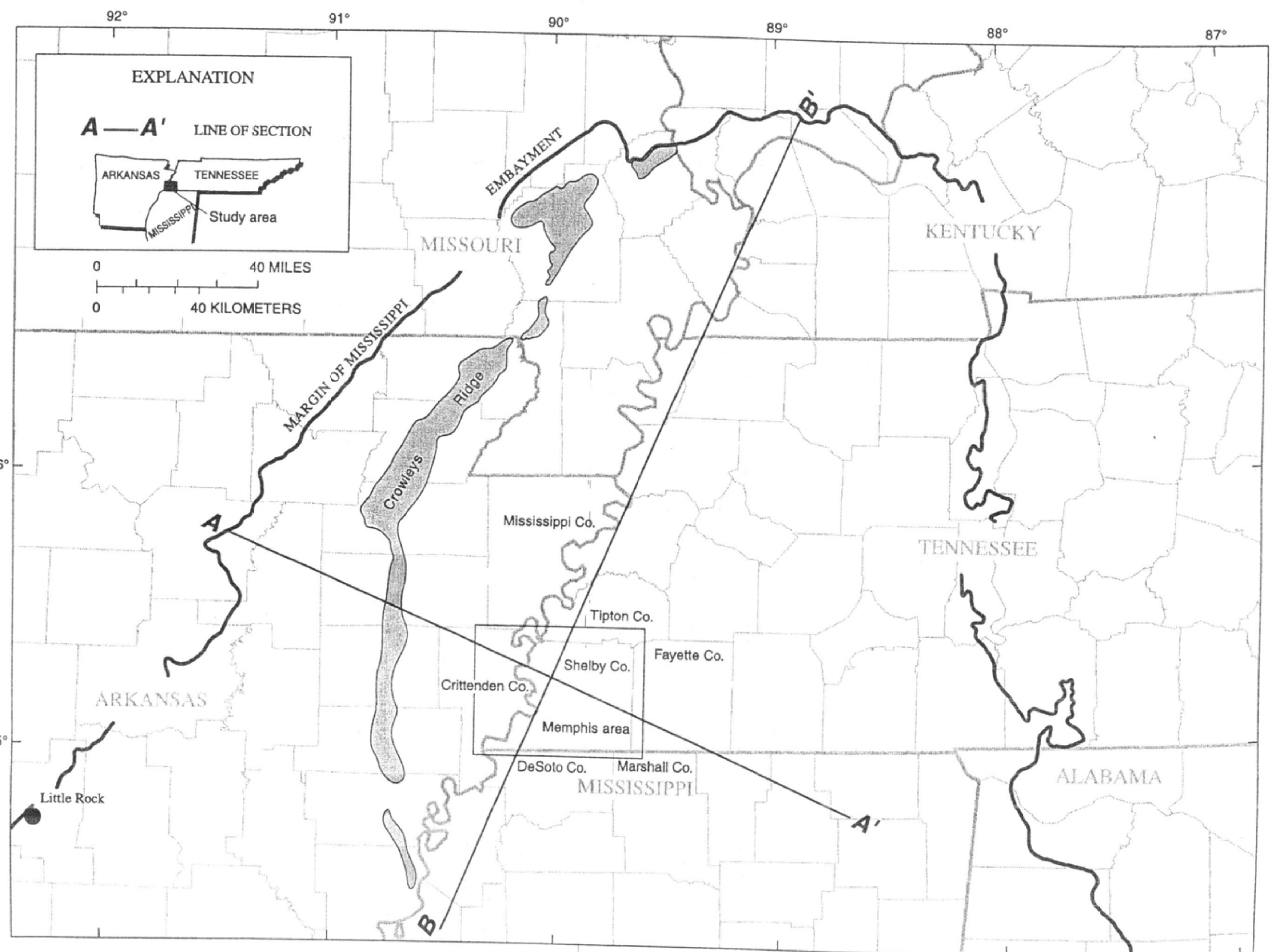


Figure 1. Location of the Memphis area and hydrogeologic sections along lines A-A′ and B-B′ in the Mississippi embayment.

Water quality in aquifers in the Memphis area has been summarized by Brahana and others (1987), and data describing selected water-quality parameters in the water-table aquifers in the Memphis area have been described by McMaster and Parks (1988). Parks (1973, 1974, 1975, 1977b, 1978, 1979a, 1979b) mapped the surface and shallow subsurface geology of the Memphis metropolitan area. A summary of some current and possible future environmental problems related to geology and hydrology in the Memphis area is given in a report by Parks and Lounsbury (1976). Parks and others (1982) described the installation and sampling of observation wells at selected waste-disposal sites.

Analog simulation of water-level declines in the Sparta aquifer (equivalent to the upper part of the Memphis aquifer) in the Mississippi embayment was summarized by Reed (1972). A two-dimensional digital flow model of the Memphis aquifer was described by Brahana (1982a). This model was used as a predictive tool to estimate aquifer response to various hypothetical pumpage projections (Brahana, 1982b). Arthur and Taylor (1990) evaluated the Memphis and Fort Pillow aquifers (as part of the Mississippi embayment aquifer system) in a regional study that encompassed the northern Mississippi embayment. Fitzpatrick and others (1989) described the geohydrologic characteristics and digital model-simulated response to pumping stresses in the Sparta aquifer (equivalent to upper part of Memphis aquifer) in east-central Arkansas.

Reports describing the general geology and ground-water hydrology of the Memphis area include Fisk (1944), Schneider and Blankenship (1950), Caplan (1954), Stearns and Armstrong (1955), Stearns (1957), Cushing and others (1964), Krinitzsky and Wire (1964), Moore (1965), Boswell and others (1965, 1968), Hosman and others (1968), and Cushing and others (1970).

In addition to published reports, there is a substantial body of unpublished hydrogeologic data for the Memphis area. These data include borehole geophysical logs, well-completion data, driller's records, geologic logs, summaries of pumping tests, inventories of pumpage, and individual well records and maps of water levels. Most of these records are located in the files of the U.S. Geological Survey, Water Resources Division; Tennessee Division of Geology; Tennessee Division of Water Resources; and City of Memphis, Memphis Light, Gas and Water Division.

HYDROLOGIC SETTING

Climate and Precipitation

The Memphis metropolitan area is characterized by a temperate climate, with a mean annual air temperature of about 62° F, and abundant precipitation. About 48 inches of precipitation per year is typical, although annual amounts recorded have ranged from 31 to 77 inches.

The distribution of rainfall is nonuniform in space and time. Mean annual precipitation increases approximately 4 inches per year from west to east across the Mississippi embayment (Cushing and others, 1970). The driest part of the year is late summer and fall, and the wettest is late winter.

Topography and Drainage

Land-surface altitudes in the Memphis area range from about 200 feet above sea level on the flat alluvial plain of the Mississippi River to about 400 feet above sea level in the upland hills of eastern Shelby County. A bluff 50 to 150 feet high separates the alluvial plain from the upland. Other than the bluff, local relief seldom exceeds 40 feet.

The Mississippi River dominates surface-water flow in the area. From the upland in the east, it receives drainage from three main tributary streams—Nonconnah Creek, Wolf River, and Loosahatchie River. Along most reaches, these three tributaries flow throughout the year. One notable exception is Nonconnah Creek upstream from the mouth of Johns Creek. Since the 1950's, Nonconnah Creek has been dry in its upstream reaches for short periods during the dry season from July to October (Criner and others, 1964).

Hydrogeologic Framework

The Memphis area is located near the axis of the Mississippi embayment, a regional downwarped trough of Paleozoic rock that has been filled with more than 3,000 feet of unconsolidated sediments (Criner and Parks, 1976). These sediments include uncemented sand, clay, silt, chalk, gravel, and lignite. On a regional scale, the sediments form a sequence of nearly parallel, sheetlike layers of similar lithology. The layers reflect the trough-like shape of the Paleozoic strata (fig. 2).

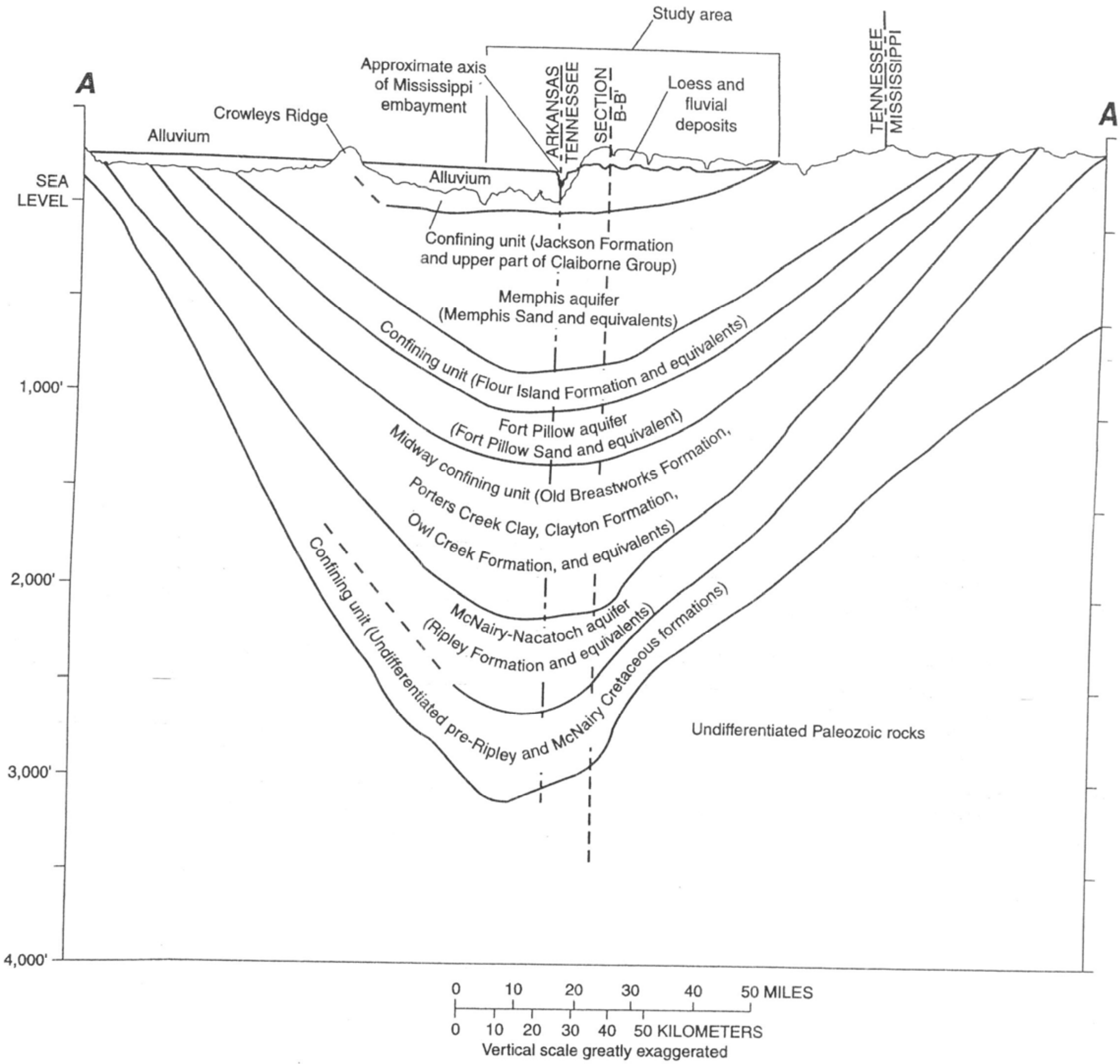


Figure 2. Hydrogeologic section showing principal aquifers and confining units, west to east, through the Mississippi embayment along line A-A'.

On a local scale, however, there are complex lateral and vertical gradations in the lithology of each layer. Of particular interest to this study are variations in thickness and sand percentage of the major clay layers. These confining clay units control the ground-water interchange between the sand layers that form the major aquifers. Zones where the confining clays are thin or sandy are potential sites of high leakage, and the most likely pathways for pollutant migration (Graham and Parks, 1986).

The structural axis of the northern Mississippi embayment is approximately coincident with the Mississippi River, passing south-southwest through the western part of the study area in eastern Crittenden County, Ark. (fig. 1). The sedimentary rock layers which comprise the embayment gently dip 10 to 35 feet per mile from both the west and east toward the axis of the embayment (fig. 2). These layers thicken to the south-southwest (fig. 3).

The thickness, lithology, and hydrologic significance of each stratigraphic unit in the Memphis area are described briefly in table 1. Five of these units represent major water-bearing zones: the alluvium, the surficial fluvial deposits, the Memphis Sand, the Fort Pillow Sand, and the Ripley Formation and McNairy Sand. With the exception of the alluvium and fluvial deposits, water-bearing zones are confined by clay layers over much of the Memphis area. Reported ground-water conditions and hydraulic characteristics of selected units that are the focus of this report have been generalized in table 2.

Water-Table Aquifers

Water-table aquifers in the Memphis area consist of the alluvium and fluvial deposits which are mostly unconfined (Graham and Parks, 1986, p. 5). These aquifers outcrop throughout the study area, and generally occur at shallow depths (table 2).

An interpretive water-table map of the alluvium and fluvial deposits was constructed for "average," steady-state conditions, designated 1980 (fig. 4). The map was based on the most complete set of water-level data available (Graham and Parks, 1986), supplemented by historic water-levels (Wells, 1933), stream stages, and where no other data were available, estimates based on topographic maps, land surface elevations, and extrapolated depths to water (Brahana and Mesko, 1988).

Alluvium

Alluvium occurs at land surface in the stream valleys of the study area. The alluvium is not a major ground-water source in the Memphis area, even though it is a major water-bearing zone and can supply large quantities of water to wells. This lack of use is related to its limited area of occurrence and to the hardness and high iron concentration of the water. West, north, and south of the study area, the alluvium of the Mississippi River alluvial plain is one of the most productive regional aquifers in the Mississippi embayment, supplying over a billion gallons per day to irrigation wells in Arkansas and Mississippi (Boswell and others, 1968; Ackerman, 1989).

The thickness of the alluvium may vary significantly over very short distances (Krinitzsky and Wire, 1964). In the Mississippi River alluvial plain, which lies west of the bluffs (fig. 4), the alluvium is commonly 100 to 175 feet thick (Boswell and others, 1968); along valleys of upland streams tributary to the Mississippi River east of the bluffs (fig. 4), thickness generally is less than 50 feet (Graham and Parks, 1986). Alluvium includes gravel, sand, silt, and clay; the latter is commonly rich in organic matter. Abrupt vertical and horizontal variations in lithology are common.

The alluvium is separated from the Memphis aquifer by a confining unit made up of clays and fine-grained sediments of the Jackson Formation and underlying upper part of the Claiborne Group, which has variable thickness and lithology. Where this confining unit is thin or sandy, leakage of ground water from one aquifer to the other may be substantial. The generalized thickness of this confining unit is shown in figure 5.

Rivers dominate the hydrology of the water-table aquifers. Local streams, as shown by figure 4, are in direct hydraulic connection with these aquifers, functioning as drains during much of the year. Seasonal variations of water level in the alluvium are typically less than 10 feet, although variations of as much as 15 feet have been reported (Plebuch, 1961; Broom and Lyford, 1981; Brahana and Mesko, 1988, fig. 13). During floods when stream stage is temporarily higher than the water table, some recharge to the alluvium occurs. No long-term declines in water level in the alluvium in the Memphis area are known.

Aquifer hydraulic characteristics of the Mississippi River alluvial aquifer in Arkansas and Missouri have been reported by Halberg and Reed (1964), Albin

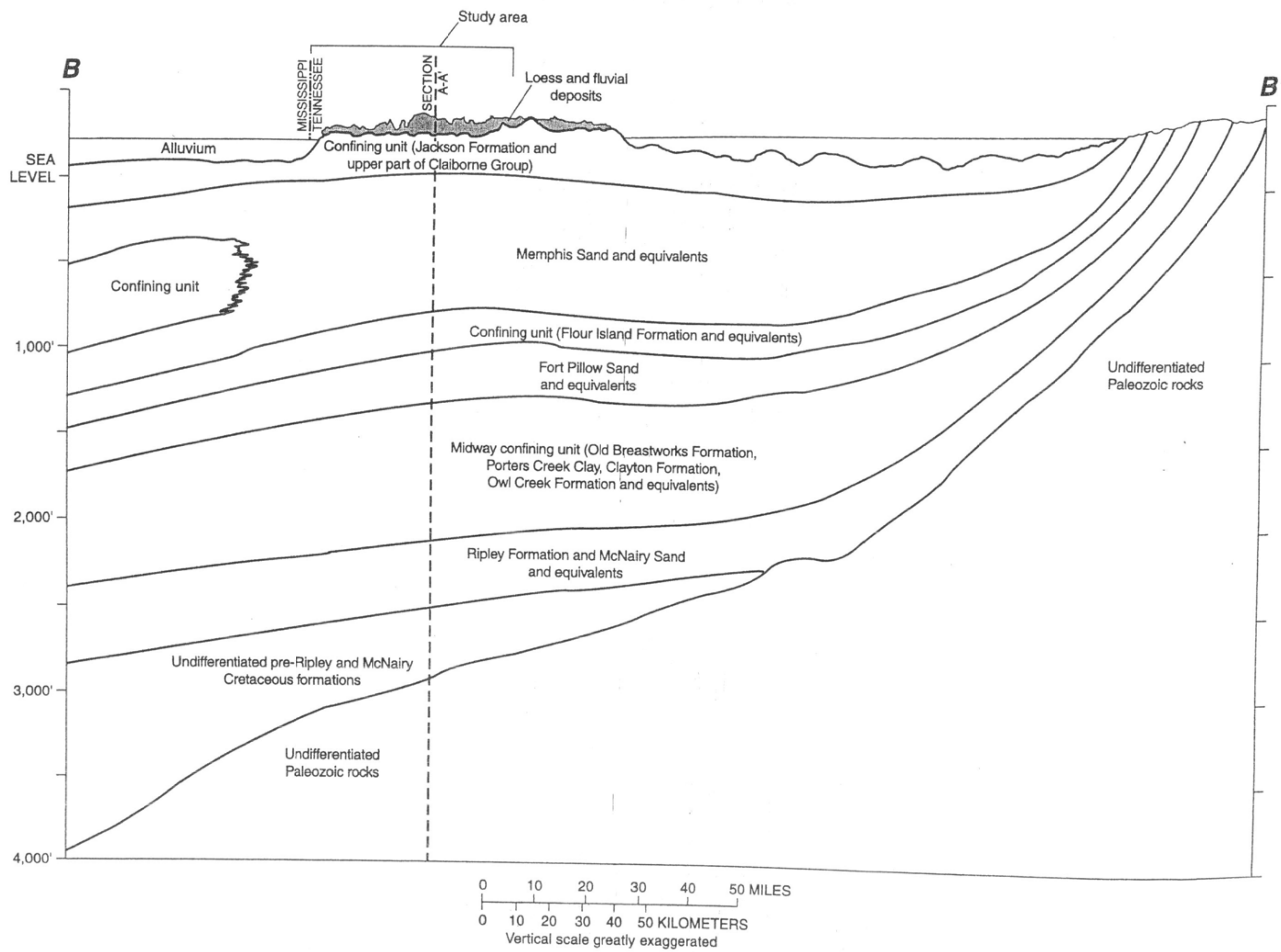


Figure 3. Hydrogeologic section showing principal aquifers and confining units, south to north, through the Mississippi embayment along line B-B′.

Table 1. Post-Paleozoic geologic units underlying the Memphis area and their hydrologic significance

[Modified frcm Criner and Parks, 1976; Moore and Brown, 1969; Plebuch, 1961; Schneider and Blankenship, 1950]

System	Series	Group	Stratigraphic unit	Thick-ness	Hydrologic unit	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Surficial Aquifer	Sand, gravel, silt, and clay. Underlies the Mississippi Alluvial Plain and alluvial plains of streams in the Gulf Coastal Plain. Thickest beneath the Alluvial Plain, where commonly between 100 and 150 feet thick; generally less than 50 feet thick elsewhere. Provides water to farm, industrial, and irrigation wells in the Mississippi Alluvial Plain.
Quaternary	Pleistocene		Loess	0-65	Surficial Aquifer	Silt, silty clay, and minor sand. Principal unit at the surface in upland areas of the Gulf Coastal Plain. Thickest on the bluffs that border the Mississippi Alluvial Plain; thinner eastward from the bluffs. Tends to retard downward movement of water-providing recharge to the fluvial deposits.
Quaternary and Tertiary(?)	Pleistocene and Pliocene (?)		Fluvial Deposits (terrace deposits)	0-100	Surficial Aquifer	Sand, gravel, minor clay and ferruginous sandstone. Generally underlies the loess in upland areas, but are locally absent. Thickness varies greatly because of erosional surfaces at top and base. Provides water to many domestic and farm wells in rural areas.
Tertiary	Eocene	? / Claiborne	Jackson Formation and upper part of Claiborne Group ("capping clay")	0-370	Confining Unit	Clay, silt, sand, and lignite. Because of similarities in lithology, the Jackson Formation and upper part the Claiborne Group cannot be reliably subdivided based on available information. Most of the preserved sequence is equivalent to the Cook Mountain and overlying Cockfleld Formations, but locally the Cockfield may be overlain by the Jackson Formation. Serves as the upper confining unit for the Memphis Sand.
Tertiary	Eocene	Claiborne	Memphis Sand ("500-foot" sand)	500-890	Memphis aquifer	Sand, clay, and minor lignite. Thick body of sand with lenses of clay at various stratigraphic horizons and minor lignite. Thickest in the southwestern part of the Memphis area; thinnest in the northeastern part. Principal aquifer providing water for municipal and industrial supplies east of the Mississippi River; primary source of water for the City of Memphis.
Tertiary	Eocene ?	Wilcox	Flour Island Formation	140-310	Confining unit	Clay, silt, sand, and lignite. Consists primarily of silty clays and sandy silts with lenses and interbeds of fine sand and lignite. Serves as the lower confing unit for the Memphis Sand and the upper confining unit for the Fort Pillow Sand.
Tertiary	Paleocene	Wilcox	Fort Pillow Sand ("1400-foot" sand)	92-305	Fort Pillow aquifer	Sand with minor clay and lignite. Sand is fine to medium. Thickest in the southwestern part of the Memphis area; thinnest in the northern and northeastern parts. Once the second principal aquifer supplying the City of Memphis; still used by an industry. Principal aquifer providing water for municipal and industrial supplies west of the Mississippi River.
Tertiary	Paleocene		Old Breastworks Formation	180-350	Midway confining unit	Clay, silt, sand, and lignite. Consists primarily of silty clays and clayey silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining unit for the Fort Pillow Sand, along with the underlying Porters Creek Clay, Clayton Formation, and Owl Creek Formation.

Table 1. Post-Paleozoic geologic units underlying the Memphis area and their hydrologic significance—Continued

System	Series	Group	Stratigraphic unit	Thick-ness	Hydrologic unit	Lithology and hydrologic significance
Tertiary	Paleocene	Midway	Porters Creek Clay ?	250-320	Midway confining unit	Clay and minor sand. Thick body of clay with local lenses of clayey, glauconitic sand. Principal confining unit separating the Fort Pillow Sand and the Ripley Formation and McNairy Sand.
			Clayton Formation ?	40-120		Clay, sand, and minor limestone. Calcareous clay and glauconitic sand with local lenses of limestone in basal part; fossiliferous. Because of lithologic similarities, upper boundary is difficult to recognize. Confining unit.
Cretaceous	Upper Cretaceous		Owl Creek Formation	40-90		Clay and sand. Calcareous clay and glauconitic sand; fossiliferous. Because of lithologic similarities, the Owl Creek Formation is difficult to distinguish from the overlying Clayton Formation without fossil verification. Confining unit.
			Ripley Formation and McNairy Sand	360-570	McNairy-Nacatoch aquifer	Sand and clay; minor sandstone, limestone, and lignite. Ripley changes facies northeast of Memphis to McNairy Sand. Ripley consists primarily of glauconitic sands and calcareous clays with minor interbeds of calcareous sandstone or sandy limestone; McNairy consists primarily of nonglauconitic sands and non-calcareous clays with local lenses of lignite. Aquifer with low potential for use in Memphis area because of lesser amounts of sand and poorer quality of water than aquifers above. Base of Ripley and McNairy is base of freshwater in the Memphis area.
			Coon Creek Formation	0-60	Confining unit	Clay and sand. Shaley clays with thin interbeds of fine sand; locally glauconitic and fossiliferous; locally contains some thin layers of rock. Probably present only in northeastern Shelby and northwestern Fayette Counties, Tenn. Confining unit.
			Demopolis Formation	270-390		Clay and chalk. Calcareous clays and chalks; glauconitic and fossiliferous. Some layers of chalk form indurated layers. Serves as the principal confining unit separating the Ripley Formation and McNary Sand and Coffee Sand.
			Coffee Sand	0-120	Coffee aquifer	Sand and minor clay. Sand is fine to medium; locally glauconitic or lignitic. Clay occurs as local lenses, particularly at the base. Absent locally in north-central Shelby County, Tenn., where the Demopolis Formation overlies igneous intrusive rock. Contains brackish or saline water; not considered a freshwater aquifer in the Memphis area. Underlain by Paleozoic dolomitic limestones of Ordovician age.

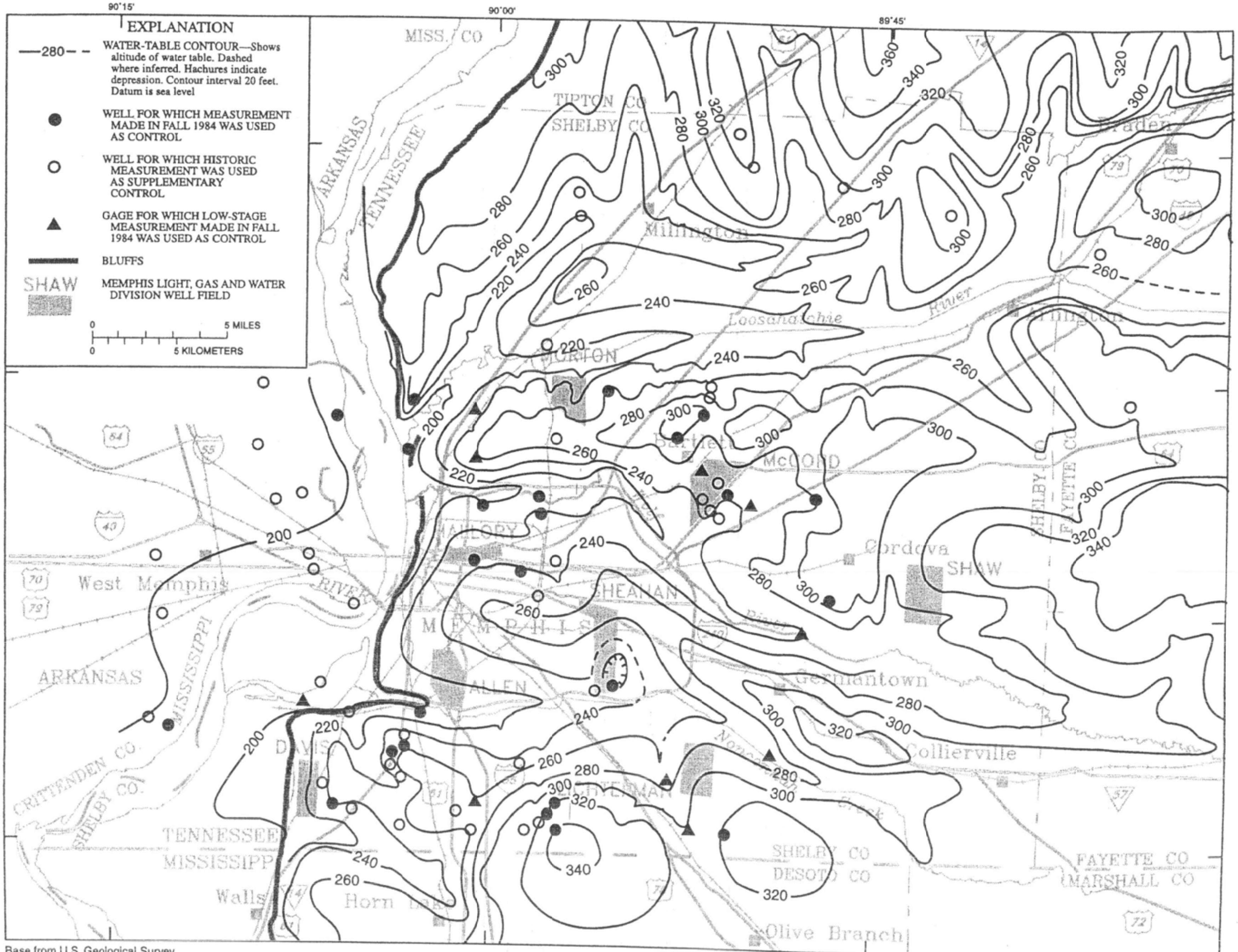
Table 2. Generalized ground-water characteristics and hydraulic properties of select hydrogeologic units in the Memphis area

Hydrogeologic unit	Generalized present-day flow directions	Depth commonly encountered (feet)	Thickness (feet)	Water-bearing character	Hydraulic properties of unit		
					T (ft^2/d)	S (unitless)	K′ (ft/d)
Alluvium	Toward major streams—downstream.	Surface	0-175	Unconfined aquifer Mississippi River alluvium confined in many places.	8,500-50,000 (a)	$1x10^{-4}$ to $4x10^{-2}$ (a)	--
Terrace (fluvial) deposits.	To valleys	Surface	0-100	Unconfined aquifer	No measurements	No measurements	--
Jackson Formation and upper part of Claibome Group (capping clay).	--	0-100	0-370	Confining layer	--	--	No measurements
Memphis Sand	Into pumping center	0-600 500 common	500-890	Confined aquifer in most of Memphis area; unconfined in southeast part of area.	2,700-45,000 (a) 6,700-54,000 (b)	$1x10^{-4}$ to $6x10^{-4}$ (a) $1x10^{-4}$ to $2x10^{-1}$ (b)	--
Flour Island Formation	--	1,000-1,400	140-310	Confining layer	--	--	$.8\text{-}4.4x10^{-11}$
Fort Pillow Sand	Into pumping center, primarily east to west.	1,200-1,500 1,400 common	92-305	Confined aquifer	2,700-21,000 (a) 12,000-19,000 (b)	$2x10^{-4}$ to $2x10^{-3}$ (a) $1.2x10^{-4}$ to $6.1\ x10^{-4}$ (b)	--
Porters Creek Clay, Clayton and Owl Creek Formations.	--	1,400-1,700	150-770	Confining layer	--	--	No measurements
McNairy Sand	Southeast to northwest	2,650	360-430	Confined aquifer	No measurements	No measurements	--

(a) Results from test conducted in the northern Mississippi Embayment, see table 3.

(b) Results for the Memphis area from Criner and others, 1964; Moore, 1965; Hosman and others, 1968; Brahana, 1982a; Arthur and Taylor, 1990; and Parks and Carmichael, 1989a.

MS SCT 000314



Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

Figure 4. Generalized altitude of the water table in the alluvium and fluvial deposits in the Memphis area, 1980.

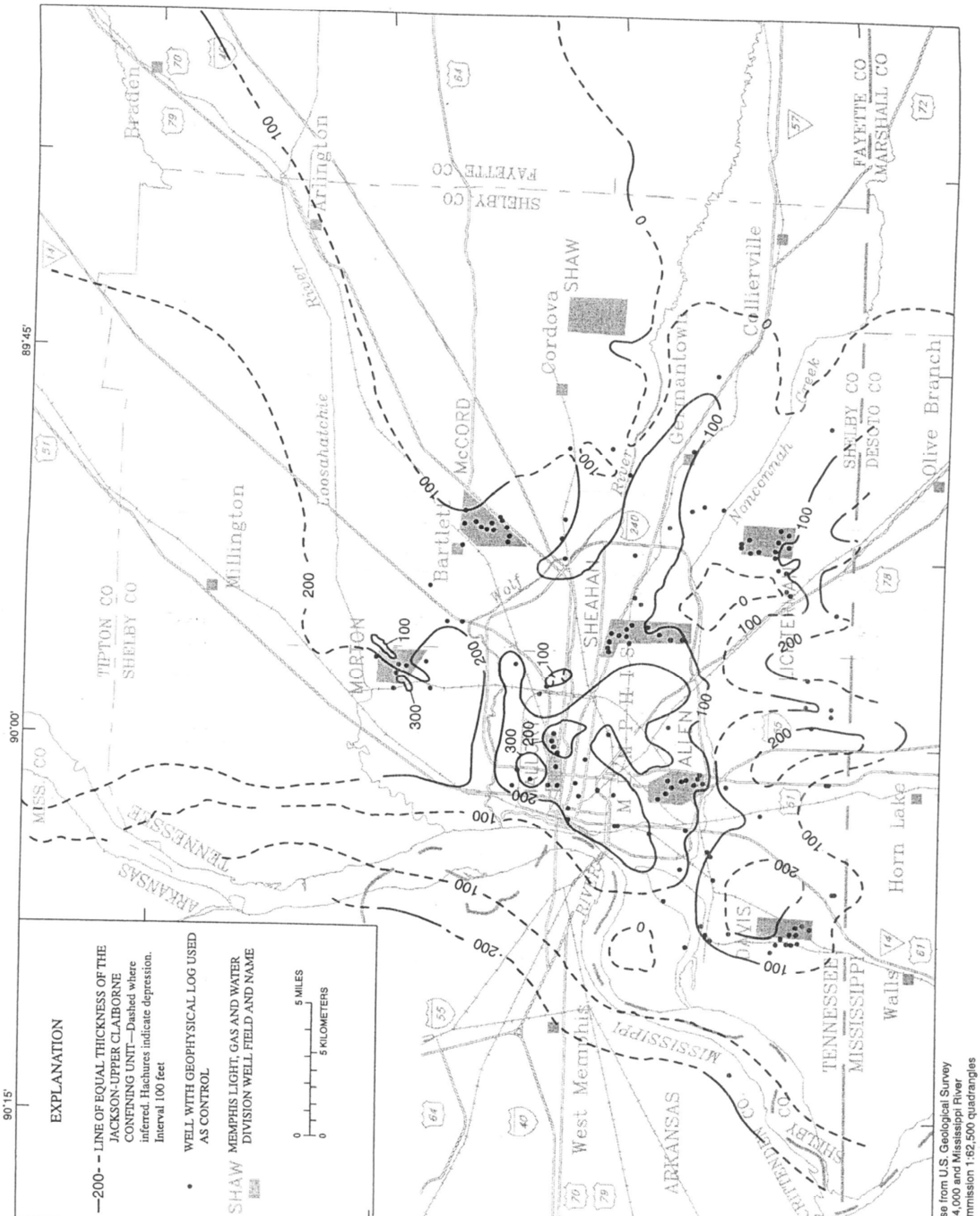


Figure 5. Generalized thickness of the Jackson-upper Claiborne confining unit in the Memphis area.

and Hines (1967), Broom and Lyford (1981), and Luckey (1985). Transmissivity ranges from 8,500 to 50,000 ft^2/d, and storage coefficient for the deeper, more confined part of the aquifer ranges from 1×10^{-4} to 4×10^{-2} (table 2). No values of aquifer hydraulic characteristics of alluvium at other locations in the Memphis area have been reported.

Water from the alluvium is hard and has relatively high concentrations of iron, dissolved solids, and barium (Brahana and others, 1987, tables 2 and 3). Lenses of clay rich in organic matter and associated geomicrobial activity are thought to be the source of high concentrations of hydrogen sulfide, carbon dioxide, and iron in this formation (Wells, 1933).

Fluvial Deposits

Fluvial deposits occur at land surface in the uplands east of the bluffs (fig. 4). Although at one time the fluvial deposits were an important source of domestic water, present pumpage from this formation is negligible. Since about 1950, when the city of Memphis expanded its municipal supplies to serve outlying areas, few wells have been drilled into the fluvial deposits. Many of the wells that existed in 1950 have not remained operational and have been abandoned, plugged, or destroyed. Wells in the fluvial deposits are capable of large yields, greater than 100 gal/min, signifying a potentially large source of water in the study area.

Fluvial deposits range in thickness from 0 to 100 feet (table 1). Thickness is highly variable, because of surfaces at both top and base (Graham and Parks, 1986). Locally, the fluvial deposits may be absent. The lithology of fluvial deposits is primarily sand and gravel, with minor layers of ferruginous sandstone.

Fluvial deposits are separated from the Memphis aquifer by sediments of the Jackson Formation and the upper part of the Claiborne Group (fig. 5). As with the alluvium, if the underlying confining unit is thin or sandy, leakage between water-table aquifers and the Memphis aquifer may be substantial.

Wells (1933), Graham (1982), and Graham and Parks (1986, fig. 8) reported seasonal water-level fluctuations in the fluvial deposits in the range of from 2 to 10 feet. Long-term declines of water levels within the fluvial deposits have not been documented, except in one location in the southern part of Sheahan well field (fig. 4). During the period 1943 to 1955, pumpage from the Memphis aquifer in the south Sheahan area dewatered the fluvial deposits around the southern part of the well field (Graham and Parks, 1986, figs. 7 and 8). Before pumping began in 1933 from the Sheahan well field, the fluvial deposits in the southern part of the well field supplied small domestic wells, but these wells were reported to be dry in 1985 (W.S. Parks, U.S. Geological Survey, written commun., 1985).

No measurements of aquifer hydraulic characteristics have been reported for the fluvial deposits in the Memphis area. Based on lithology, saturated thickness, and mode of occurrence, transmissivity probably is within the range of 5,000 to 10,000 ft^2/d, and storage coefficient probably is in the range of 0.1 to 0.2 (Freeze and Cherry, 1979).

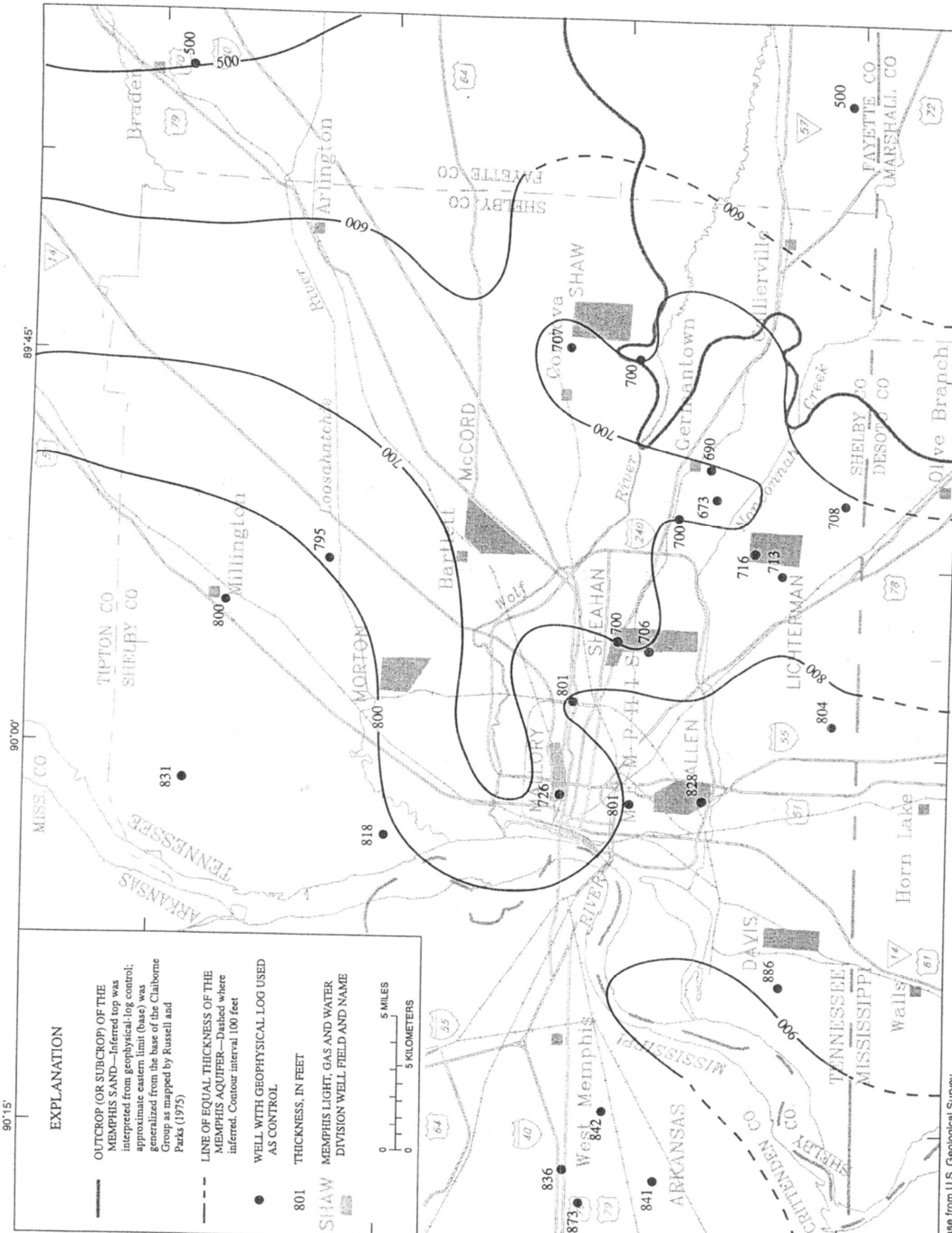
Water quality in the fluvial deposits is highly variable. The distribution of dissolved-solids concentrations, which ranges from 76 mg/L iron to 440 mg/L, shows more variation in these deposits than in any other aquifer in the area (Brahana and others, 1987, tables 2 and 3). Some of the variation may be related to the thickness of overlying loess, which may contribute much of the dissolved solids in the aquifer (Wells, 1933). Dissolved-solids concentrations are lowest in the east-central part of the Memphis area, between the Loosahatchie and Wolf Rivers (Brahana and others, 1987, fig. 5).

Memphis Aquifer

The Memphis aquifer is the most productive aquifer in the study area, providing approximately 98 percent of total pumpage (188 Mgal/d) to the city of Memphis in 1980 (Graham, 1982). Total pumpage since 1886 is calculated to be more than 3.2 trillion gallons, using published pumping values (Criner and Parks, 1976, fig. 2; Graham, 1982, table 2).

The Memphis aquifer is a fine- to coarse-grained sand interbedded with layers of clay and minor amounts of lignite. The formation occurs at depths ranging from 0 to 600 feet (table 2) and varies in thickness from 500 to 890 feet (table 1) based on interpretations of geophysical logs. Generalized thickness of the Memphis aquifer in the Memphis area, based on work by Parks and Carmichael (1989a), has been extrapolated to a slightly wider range from less than 500 to more than 900 feet (fig. 6).

The Memphis aquifer is separated from the underlying Fort Pillow aquifer by 140 to 310 feet of clay of the Flour Island Formation, and from the overlying alluvium and terrace deposits by 0 to 370 feet of clay and sandy clay of the Jackson Formation and



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Modified from W.S. Parks and J.K. Carmichael, 1989a

Figure 6. Generalized thickness of the Memphis aquifer in the Memphis area.

upper part of the Claiborne Group. The effectiveness of the Jackson Formation and upper part of the Claiborne Group as a confining unit appears to vary because of areal differences in sand content and layer thickness (Graham and Parks, 1986). Due to this variability, rates of leakage from surficial aquifers are spatially heterogeneous.

Water levels in the Memphis aquifer are strongly influenced by pumping (fig. 7). Water levels within the outcrop area, which occurs in the southeastern part of the Memphis area, range from about 280 to 290 feet above sea level (Graham, 1982, plate 1; Parks and Carmichael, 1989a, fig. 7). Recharge to the Memphis aquifer occurs primarily in the outcrop area (fig. 7). The deepest pumping cone of depression in the Memphis aquifer is less than 100 feet above sea level; the water levels at most other pumping centers are in the range of 120 to 170 feet above sea level (Graham, 1982, plate 1; Parks and Carmichael, 1989a, fig. 7). The widespread and irregular distribution of pumping centers in the Memphis aquifer in the Memphis area causes a complex flow pattern as ground water flows inward from all directions to several pumping centers (fig. 7).

Long-term water-level declines in the Memphis aquifer are greater than 120 feet in the area of maximum drawdown near the Mallory well field. East of the pumping centers near the areas of outcrop, long-term declines have not been detected (Parks and Carmichael, 1989a, fig. 10). Seasonal variations in water levels are commonly less than 2 feet in areas unaffected by pumping.

Data from 23 representative aquifer tests in the Memphis aquifer (table 3; fig. 8) from throughout the northern Mississippi embayment show transmissivity ranges from 2,700 to 45,000 ft^2/d, and storage coefficients range from 1×10^{-4} to 6×10^{-4}. Confined conditions are typical for the Memphis aquifer, except in areas of outcrop.

The Memphis aquifer in the Memphis area (table 2) is reported to have a range of transmissivity from 6,700 to 54,000 ft^2/d, and a range of storage coefficients from 1×10^{-4} to 2×10^{-1} (Criner and others, 1964; Moore, 1965; Hosman and others, 1968; Brahana, 1982a; Arthur and Taylor, 1990; Parks and Carmichael, 1989a, p. 27).

Ground water in the Memphis aquifer is a calcium-magnesium-sodium bicarbonate type (Hosman and others, 1968; Brahana and others, 1987, table 2). In the study area, water in the Memphis aquifer is characterized by a pH generally less than 7, and except for a limited area in the northwestern part of the study area, the dissolved-solids concentration is generally less than 100 mg/L.

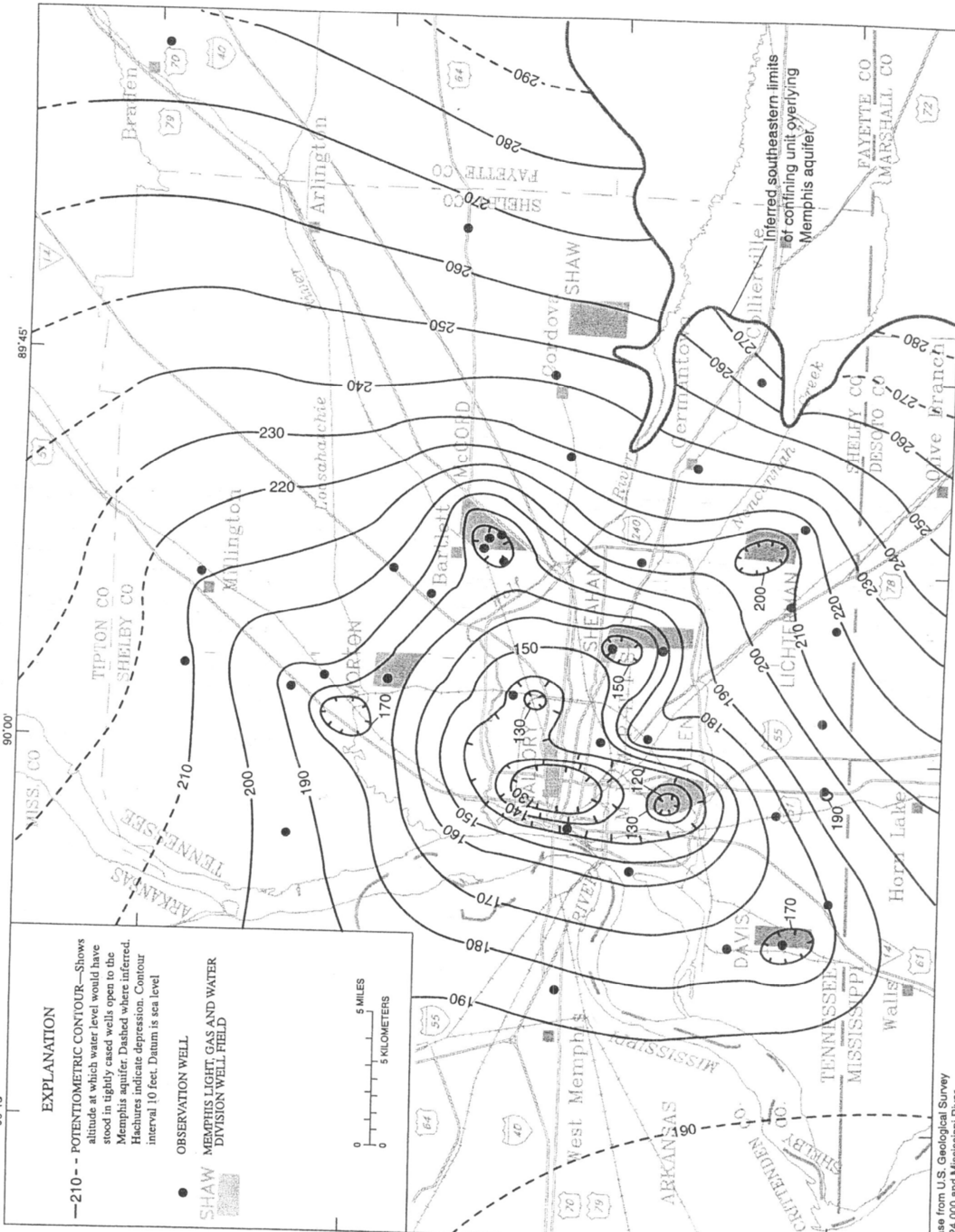
Fort Pillow Aquifer

The Fort Pillow aquifer is a major regional aquifer throughout much of the northern Mississippi embayment (Hosman and others, 1968; Arthur and Taylor, 1990; Parks and Carmichael, 1989b). In the Memphis study area, the Fort Pillow aquifer currently (1989) provides water to supplement supplies at Millington, Tenn., the U.S. Naval Air Station near Millington, one industrial user in Memphis, and the Shaw well field east of Memphis (fig. 9). The Fort Pillow aquifer is the sole source of water for West Memphis, Marion, and other small towns in eastern Arkansas, and for the town of Walls in Mississippi (fig. 9). In 1984, pumpage from the Fort Pillow aquifer averaged about 10 Mgal/d (Graham and Parks, 1986). Although the Fort Pillow aquifer is much deeper in the subsurface than the Memphis aquifer, the Fort Pillow is the preferred aquifer in eastern Arkansas for municipal and domestic supplies because it provides water that requires less treatment than water from the Memphis aquifer.

The Fort Pillow aquifer is characteristically a fine- to medium-grained sand containing clay lenses and minor amounts of lignite. Thickness of the aquifer is commonly about 250 feet and ranges from about 125 to 305 feet (table 1). The generalized thickness of the Fort Pillow aquifer in the Memphis area, based on work of Parks and Carmichael (1989b), is shown in figure 10.

The Fort Pillow aquifer is confined above by 140 to 310 feet of clay of the Flour Island Formation, as defined by interpretation of geophysical logs (table 1). The Flour Island Formation is thought to be a leaky confining unit. Generalized thickness of the Flour Island confining unit in the Memphis area is based on the work of Graham and Parks (1986, fig. 5) and E. Mahoney, Vanderbilt University (written commun., 1989) (fig. 11). Head differences between the Memphis aquifer and Fort Pillow aquifer (Graham and Parks, 1986) occur as a result of pumping and are affected by the vertical hydraulic characteristics and thickness of the Flour Island Formation.

Water levels in the Fort Pillow aquifer (fig. 9) in 1980 were from slightly less than 160 to more than 240 feet above sea level. Water levels are highest in



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Hydrology modified from D.D. Graham, 1982; Geology modified from J.H. Criner and W.S. Parks, 1976.

Figure 7. Altitude of the potentiometric surface of the Memphis aquifer in the Memphis area, 1980.

Table 3. Results of selected aquifer tests

[Data source: 1, Davis and others (1973); 2, Moore (1965); 3, Newcome (1971); 4, Hosman and others (1968); 5, Luckey (1985); 6, Broom and Lyford (1981); 7, Albin and Hines (1967); 8, Halberg and Reed (1964); --, not reported; ft^2/d, square feet per day; ft/d, feet per day]

Test no. (keyed to fig. 8)	Location	Transmissivities (T) (ft^2/d)	Hydraulic conductivity (K) (ft/d)	Storage coefficient (S)	Water-bearing formation	Data source
1	Mayfleld, Ky.	37,000-41,000	--	0.0001-0.0004	Memphis Sand	1
2	Union City, Tenn.	8,300	--	.0003	Memphis Sand	1
3	Tiptonville, Tenn.	18,000	--	.0003	Memphis Sand	2
4	Dresden, Tenn.	7,200	--	.0006	Memphis Sand	2
5	Kenton, Tenn.	15,000	--	--	Memphis Sand	2
6	Dyersburg, Tenn.	19,000	--	.0004	Memphis Sand	2
7	Milan, Tenn.	16,000	--	--	Memphis Sand	2
8	Ripley, Tenn.	22,000	--	--	Memphis Sand	2
9	Bells, Tenn.	5,600	--	.0005	Memphis Sand	2
10	Covington, Tenn.	29,000	--	--	Memphis Sand	2
11	Stanton, Tenn.	27,000	--	.0001	Memphis Sand	2
12	Arlington, Tenn.	21,000	--		Memphis Sand	2
13	Memphis, Tenn.	41,000	--	.0014	Memphis Sand	2
14	Somerville, Tenn.	2,700	--	--	Memphis Sand	2
15	Memphis (McCord), Tenn.	43,000	--	.0002	Memphis Sand	2
16	Memphis (Mallory), Tenn.	26,000	--		Memphis Sand	2
17	Memphis, Tenn.	45,000	--		Memphis Sand	2
18	Memphis (Sheahan), Tenn.	35,000	--		Memphis Sand	2
19	Memphis (Allen), Tenn.	31,000	--		Memphis Sand	2
20	Memphis (Lichterman), Tenn.	27,000	--		Memphis Sand	2
21	Germantown, Tenn.	23,000	--		Memphis Sand	2
22	Collierville, Tenn.	23,000	--		Memphis Sand	2
23	Clarksdale, Miss.	6,600	100	.0006	Memphis Sand	3
24	Blytheville, Ark.	21,000	--	.002	Fort Pillow Sand	4
25	Memphis (Mallory), Tenn.	17,000-19,000	--	.0002-.0006	Fort Pillow Sand	4
26	Madison Co., Tenn.	10,000	--	.0015	Fort Pillow Sand	4
27	Marks, Miss.	2,700	29	--	Fort Pillow Sand	3
28	Stoddard Co., Mo.	15,000	--	.002	Alluvium	5
29	Stoddard Co., Mo.	20,000	--	.001	Alluvium	5
30	Wayne Co., Mo.	47,000	--	.0009	Alluvium	5
31	Butler Co., Mo.	50,000	--	.001	Alluvium	5
32	Clay Co., Ark.	30,000	360	.0011	Alluvium	6
33	Jackson Co., Ark.	39,000	320	.022	Alluvium	7
34	Craighead Co., Ark.	37,000	380	.022	Alluvium	6
35	Jackson Co., Ark.	8,500	--	--	Alluvium	6
36	Jackson Co., Ark.	10,000	100	.007	Alluvium	6
37	Poinsett Co., Ark.	48,000	390	.001	Alluvium	6
38	St. Francis Co., Ark.	43,000	330	.04	Alluvium	8
39	Lee Co., Ark.	13,000-19,000	130	.00073	Alluvium	6
40	Monroe Co., Ark.	24,000	--	--	Alluvium	6
41	Monroe Co., Ark.	32,000	290	.0004	Alluvium	6
42	Phillips Co., Ark.	34,000	247	.0001	Alluvium	6

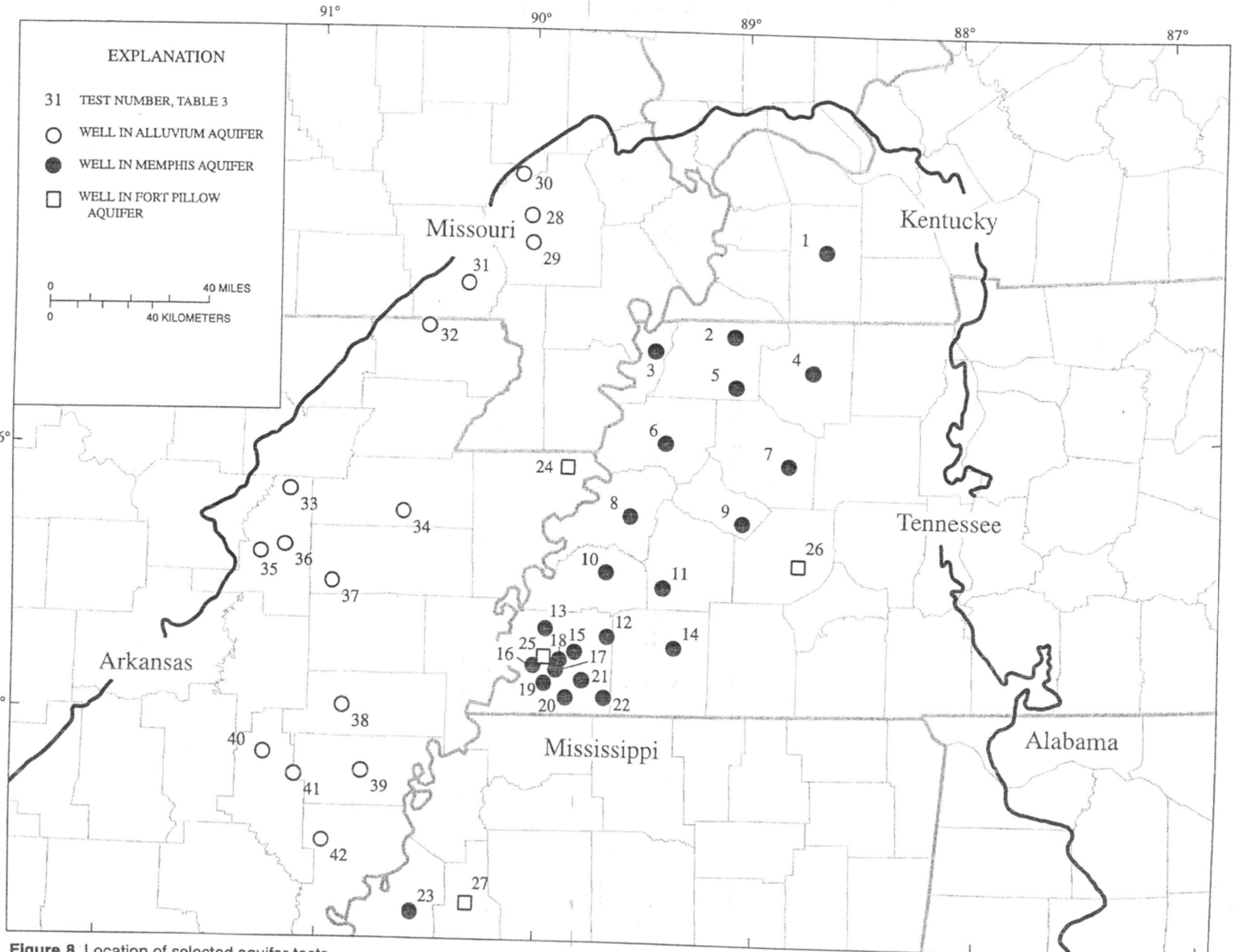


Figure 8. Location of selected aquifer tests.

MS SCT 000322

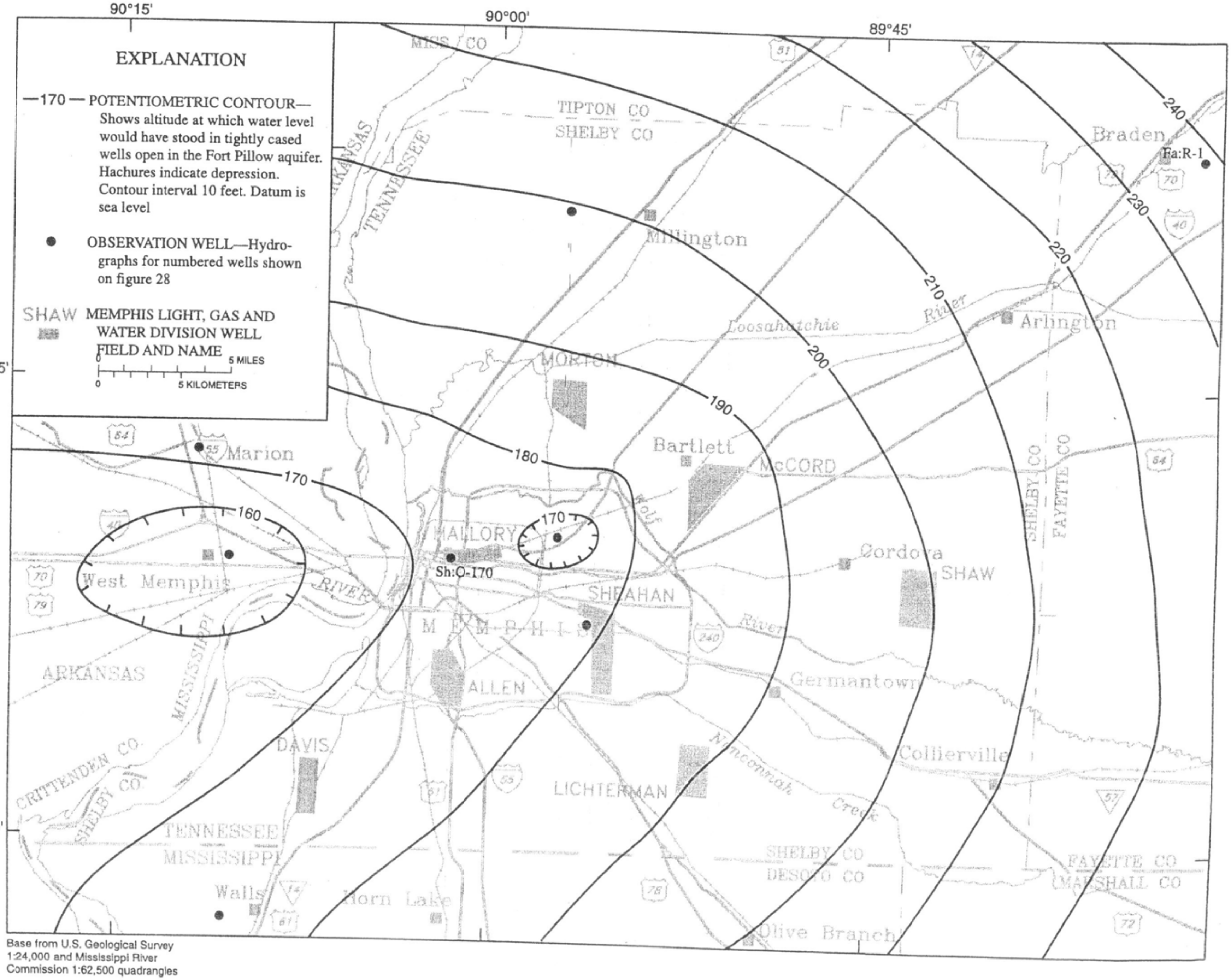
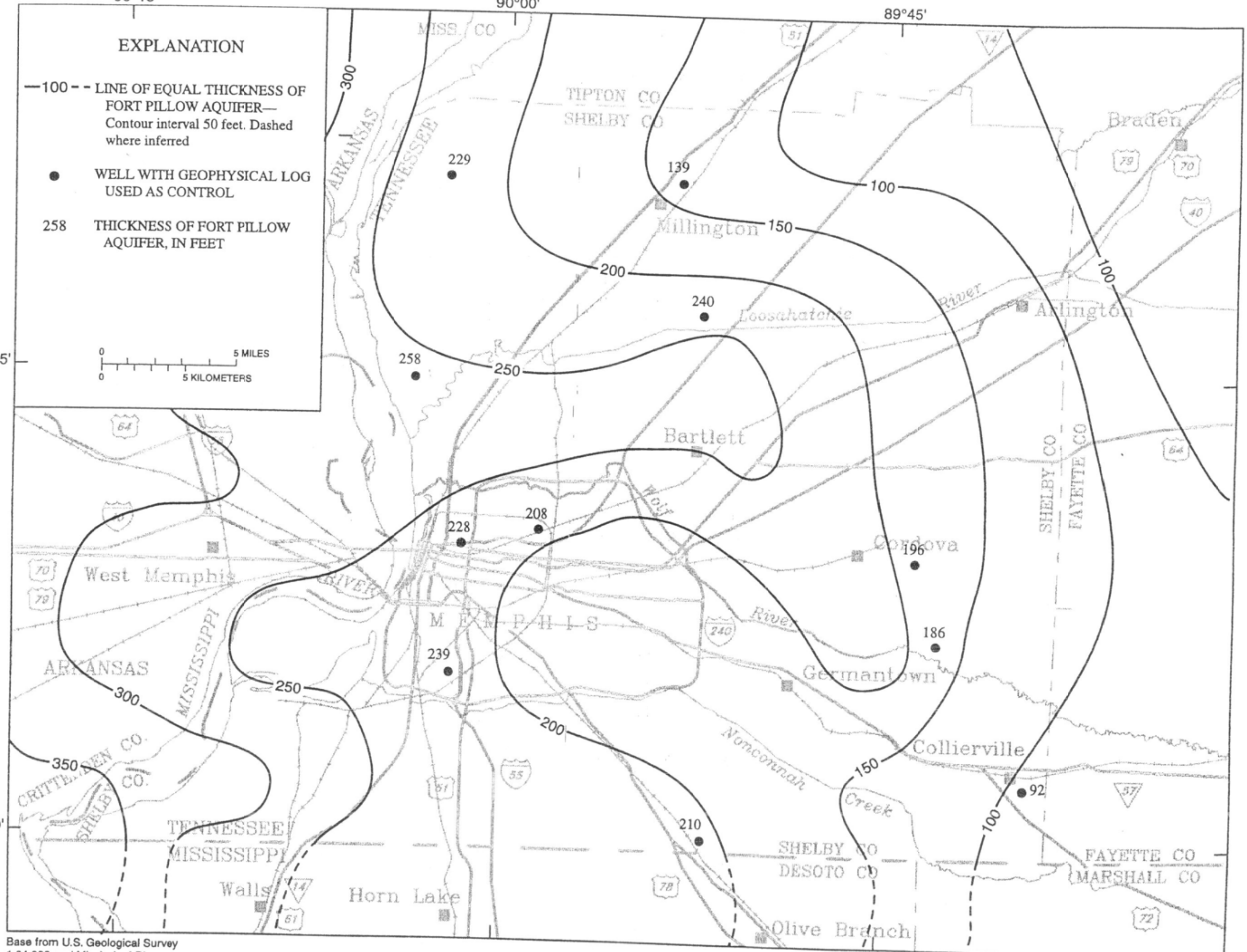


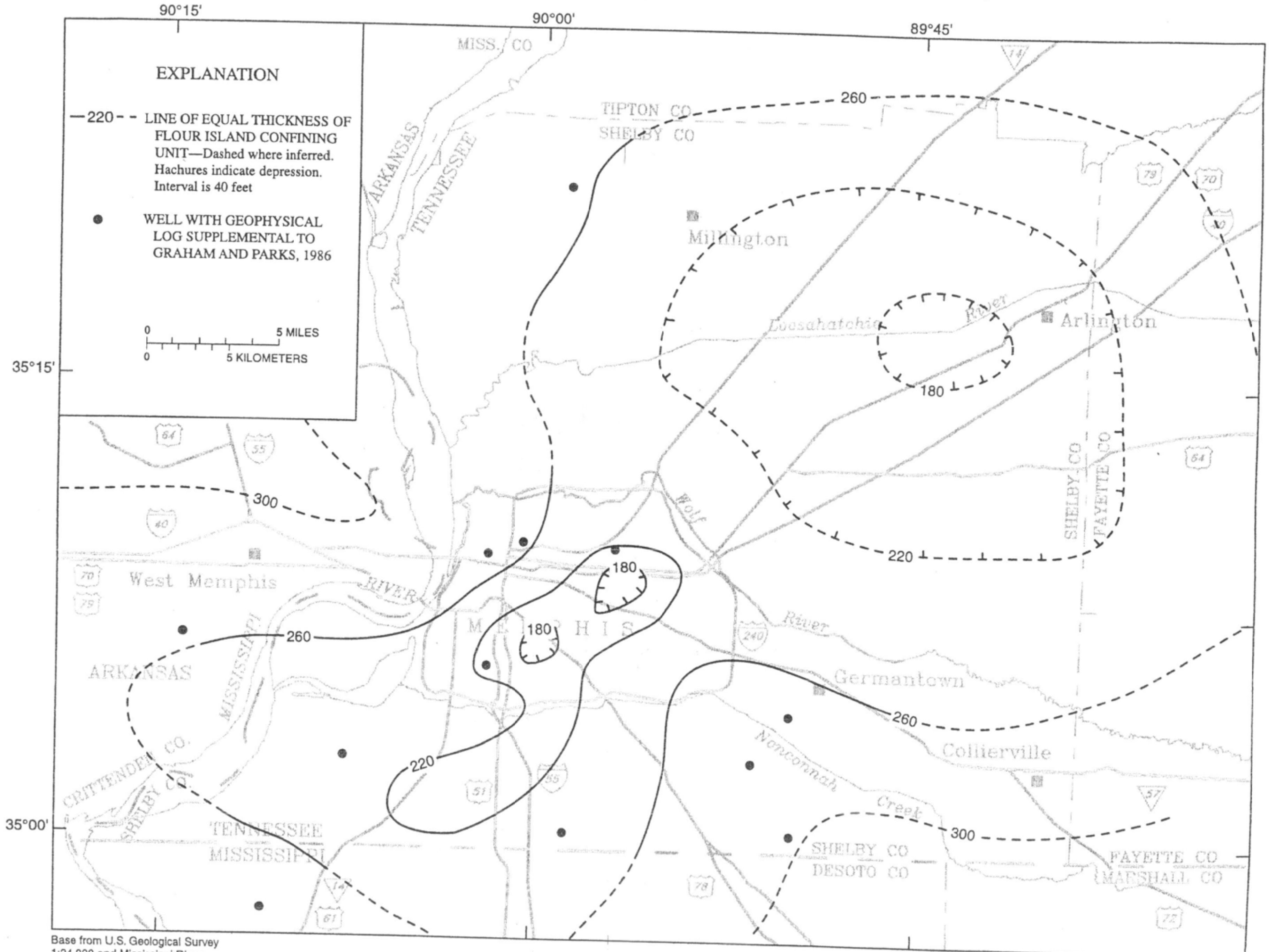
Figure 9. Altitude of the potentiometric surface of the Fort Pillow aquifer in the Memphis area, 1980.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Modified from W.S. Parks and J.K. Carmichael, 1989b, figure 2.

Figure 10. Generalized thickness of the Fort Pillow aquifer in the Memphis area.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Modified from D.D. Graham and W.S. Parks, 1986

Figure 11. Generalized thickness of the Flour Island confining unit in the Memphis area.

the eastern part of the area, nearest the outcrop, and lowest in the west near the centers of pumping. The regional movement of ground water in the Fort Pillow aquifer is toward the axis of the Mississippi embayment (Hosman and others, 1968).

The hydrograph for well Fa:R-1 (location on fig. 9), which taps the Fort Pillow aquifer about 27 miles east of the center of pumping at Memphis, shows a long-term decline of about 0.4 foot per year (ft/yr) (Graham, 1982). Regionally, declines of about 1 ft/yr are not uncommon (Hosman and others, 1968; Brahana and Mesko, 1988, fig. 13). Graham (1982) noted that the hydrograph of well Sh:O-170 (location on fig. 9) near the center of historic pumping in Memphis showed approximately 20 feet of recovery when all municipal (MLGW) pumpage from the Fort Pillow aquifer ceased in the early 1970's. Seasonal variations of nonstressed water levels are commonly less than 2 feet (Graham, 1982, fig. 4).

Hydraulic conductivity of the Fort Pillow aquifer throughout its area of occurrence in the northern Mississippi embayment is reported to range from 25 to 470 ft/d. This corresponds to a range of transmissivity from about 670 to 85,000 ft^2/d. Storage coefficient is reported to range from 2×10^{-4} to 1.5×10^{-2} (Hosman and others, 1968; Boswell, 1976; Parks and Carmichael, 1989b). Data from aquifer tests of the Fort Pillow aquifer (table 3, fig. 8) indicate that transmissivity ranges from 2,700 to 21,000 ft^2/d, and storage coefficients range from 2×10^{-4} to 2.0×10^{-3}.

Within the Memphis area, hydraulic characteristics have a narrower range (table 2) than described previously for the entire embayment. In the Memphis area, transmissivity of the Fort Pillow aquifer is reported to range from 12,000 to 19,000 ft^2/d, and storage coefficient is reported to range from 1.2×10^{-4} to 6.1×10^{-4} (Criner and others, 1964).

Water from the Fort Pillow aquifer is a soft, sodium bicarbonate type with a median dissolved-solids concentration of 116 mg/L (Brahana and others, 1987). Iron concentrations range from 170 to 1,900 micrograms per liter, and pH typically is about 7.4.

McNairy-Nacatoch Aquifer

The McNairy-Nacatoch aquifer, which encompasses sands of the Ripley Formation, McNairy Sand (table 1), and equivalent Upper Cretaceous Nacatoch Sand in Arkansas, is the basal freshwater aquifer in the study area. The McNairy-Nacatoch aquifer has not been used as a source of water supply in Memphis, but it has the potential for such use; north and east of the study area, it is a major regional aquifer (Brahana and Mesko, 1988).

The McNairy-Nacatoch aquifer ranges in thickness from 360 to 570 feet and is fine- to coarse-grained, glauconitic sand. The McNairy-Nacatoch aquifer occurs deeper than 2,500 feet below land surface at Memphis, and is confined and hydraulically separated from the overlying Fort Pillow Sand by about 750 feet of clays of the Midway and lower Wilcox Groups (table 1). These confining clays, herein called the Midway confining unit, are a major hydrologic boundary in the northern Mississippi embayment. Arthur and Taylor (1990) simulated the Midway confining unit as a lower no-flow boundary. Brahana and Mesko (1988) used flow modeling to evaluate leakage across the Midway confining unit; they found less than 0.5 ft^3/s moved across this confining unit in the study area.

Hydrogeologic evaluation of the McNairy-Nacatoch aquifer in the Memphis area is based on unpublished data from a single observation well in the Mallory well field and on extrapolation of regional data (Boswell and others, 1965; Davis and others, 1973; Luckey and Fuller, 1980; Edds, 1983; Brahana and Mesko, 1988). The static water level in this well is approximately 350 feet above sea level, which is about 100 feet above land surface (W.S. Parks, U.S. Geological Survey, written commun., 1985). Seasonal variation in water level is about 2 feet, and no long-term decline is evident. Head values in the McMairy-Nacatoch aquifer are approximately 180 feet higher than heads measured in the overlying Fort Pillow aquifer (Brahana and Mesko, 1988, figs. 10 and 11). Water-level declines in the McNairy-Nacatoch aquifer due to pumping in the overlying Fort Pillow aquifer have not been observed.

In addition to head differences, significant differences in water quality exist between the McNairy-Nacatoch aquifer and the Fort Pillow aquifer. Concentrations of dissolved solids, for example, are 10 times greater in the McNairy-Nacatoch aquifer than in the Fort Pillow aquifer.

Although the data from the McNairy-Nacatoch aquifer are sparse, they are consistent on both a local and regional scale. These differences in hydrology and water chemistry strongly support the contention that clays in the Midway confining unit (Porters Creek Clay, Clayton Formation, and Owl Creek Formation, table 2) act as an effective confining unit (figs. 2 and 3), and isolate the Fort Pillow aquifer from deeper aquifers.

CONCEPTUALIZATION OF THE GROUND-WATER FLOW SYSTEM

The hydrogeologic information presented in the previous section forms the basis for a conceptual model of ground-water flow in the Memphis area. This conceptualization accounts for the ability of each major unit to store and transmit water, as indicated by its lithology and stratigraphy, and by hydrologic data. Water-quality data are also used to lend credence to hypotheses regarding the hydrologic isolation or communication between aquifers. The conceptual model represents a simplification of reality but preserves and emphasizes the major elements controlling ground-water flow in the study area. This conceptual model can be tested quantitatively by depicting each of its elements mathematically in a digital model of ground-water flow. The relation between the hydrogeologic framework, the conceptual model, and the digital ground-water flow model is shown in figure 12.

The alluvium and fluvial deposits form the uppermost water-table aquifers in the conceptual model. Water levels respond seasonally to recharge, evapotranspiration, and minor pumping, but on the time scale of interest to this investigation, the water-table aquifers are at steady state. The one documented exception to steady state occurred about 1943 in the southern area of the Sheahan well field. Conceptually, the water-table aquifers serve the important function of providing a potentially large reservoir of vertical leakage to the underlying confined aquifers. Horizontal flow in the water-table aquifers are defined by the water-level map (fig. 4), but are of incidental interest in this investigation. Recharge to the aquifer is primarily from the infiltration of rainfall on the outcrop. Discharge from these aquifers is primarily to streams, as baseflow, and vertically to deeper aquifers as downward leakage.

The Jackson-upper Claiborne confining unit is conceptualized as a leaky confining unit with variable thickness (fig. 5) and lithology. Leakance values for this confining unit were poorly defined by aquifer test data (table 2), and much quantitative testing of alternative leakance parameters and distributions were undertaken. In general, pumping from the Memphis aquifer has induced flow from the shallow water-table aquifers downward to the Memphis aquifer through the Jackson-upper Claiborne confining unit. Leakage has increased with time as the head difference between the water-table aquifers and the Memphis aquifer has increased.

Flow in the Memphis aquifer has been transient since the onset of pumping in 1886. Recharge occurs in the outcrop area in the southeastern and eastern parts of the study area (fig. 13), and flow is predominantly into the centers of pumping from all directions (fig. 7). An increasing component of recharge is derived from leakage through time from the super and subjacent aquifers across nonhomogeneous confining units. Pumping represents the major source of discharge from the system, and the areal and temporal variation of pumping through time is the major reason this aquifer is not at steady state. Prior to pumping, discharge was westward to the subcrop of the Memphis aquifer beneath the alluvium, and upward beneath the Mississippi River alluvial plain. Up dip pinch out of the Memphis Sand defines the limit of occurrence of the Memphis aquifer, and no-flow boundaries around the eastern, northern, and western boundaries conceptually represent ground-water conditions where the pinch out occurs. A major effort of quantitative testing was focused on the Memphis aquifer and its related hydrogeology, including its transmissivity, storage, boundary configuration, and pumping.

The Flour Island confining unit is conceptualized as a confining unit that is less variable in thickness (fig. 11) and less leaky than the Jackson-upper Claiborne confining unit. Flow directions across the Flour Island confining unit are in response to dynamically changing heads in the overlying Memphis aquifer and underlying Fort Pillow aquifer. Quantitative testing of the vertical hydraulic conductivity of this unit was a specific focus of this investigation.

Flow in the Fort Pillow aquifer has been transient since about 1924, not only in response to pumping from this aquifer in the study area, but to major regional pumping in Arkansas. Recharge to the Fort Pillow aquifer occurs primarily in the outcrop areas east and north of the study area. Vertical leakage provides some recharge at locations where heads in the overlying Memphis aquifer are higher than heads in the Fort Pillow aquifer. Discharge from the system is primarily to a temporally and areally varying pumping distribution particularly in Arkansas (Arthur and Taylor, 1990). Some discharge from the Fort Pillow aquifer occurs as horizontal flow southward, and some

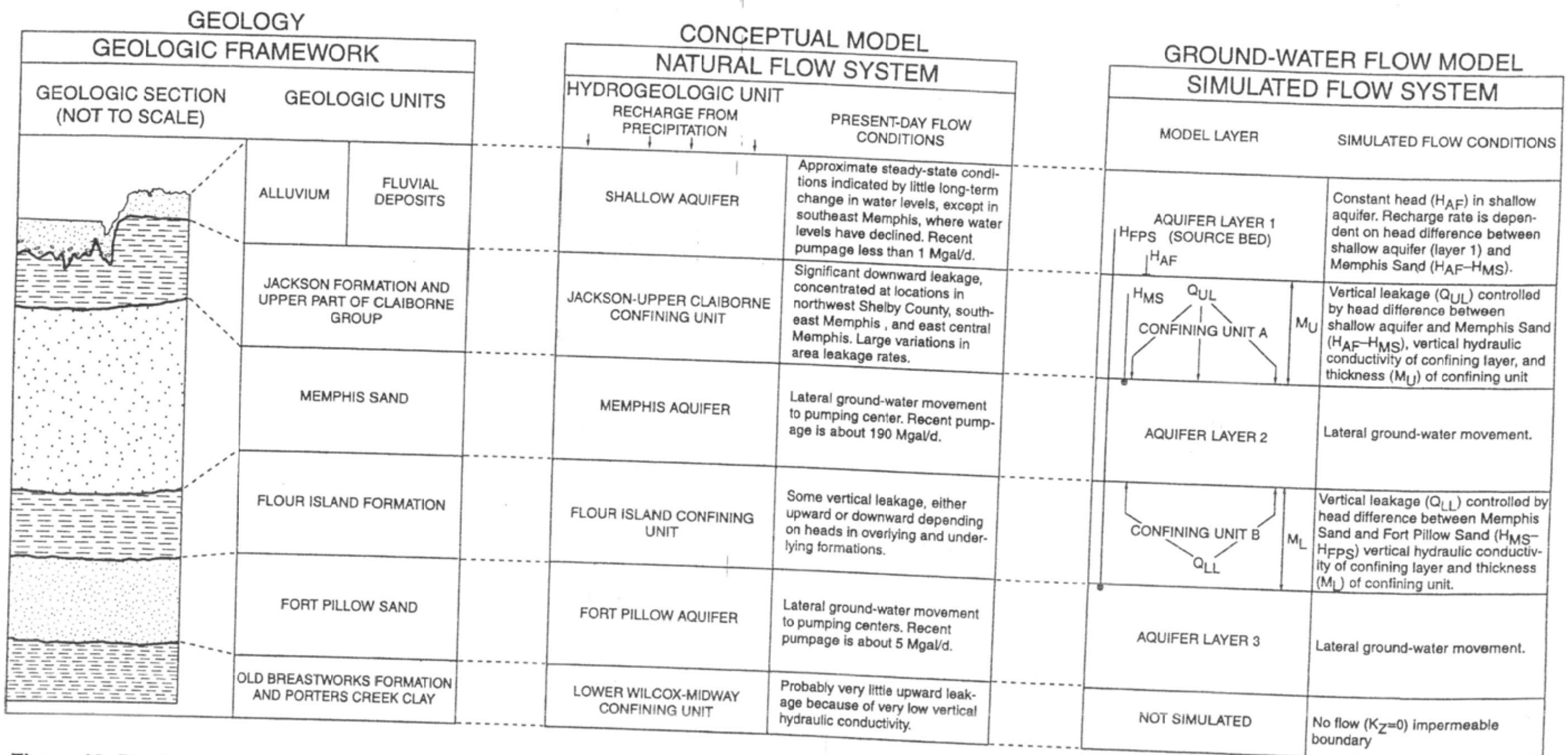
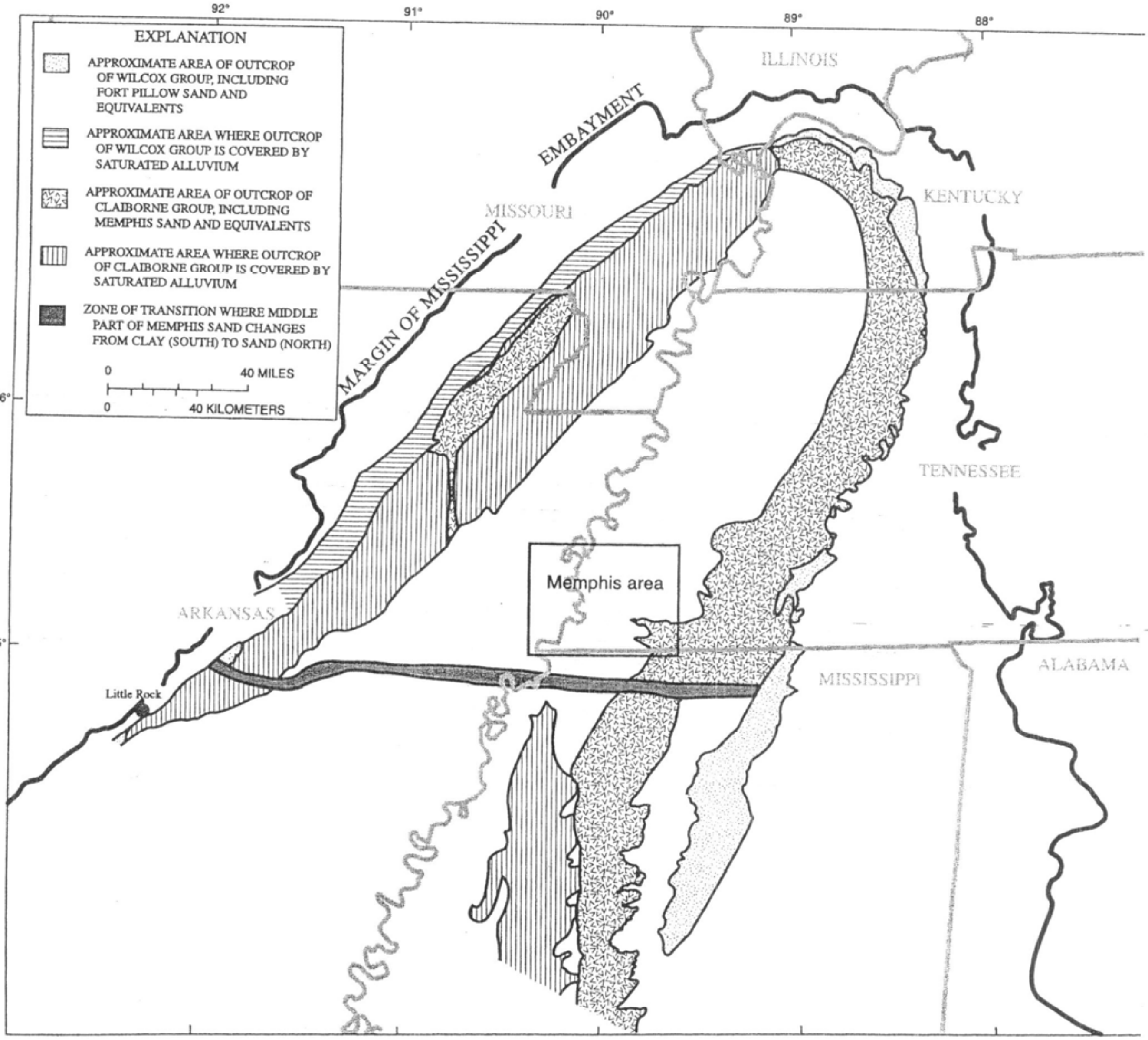


Figure 12. Relation between units of the geologic framework, the natural flow system of the conceptual model, and the simulated flow system of the ground-water flow model.



Geology modified from R.L. Hosman, and T.W. Lambert and others, 1968, F and J.H. Criner and W.S. Parks, 1976,

Figure 13. Areal geology of the northern Mississippi embayment.

occurs as vertical flow upward. No-flow boundaries define the up-dip limits of the Fort Pillow aquifer. Higher leakance through the overlying Flour Island confining unit simulates horizontal outflow to the south, more than 50 miles from the study area. Quantification of hydraulic parameters of the Fort Pillow aquifer (transmissivity, storage coefficient, boundary configuration, and pumping) was the focus of quantitative testing and verification.

The Midway confining unit was conceptualized as being a no-flow boundary. The concept was tested by Brahana and Mesko (1988) and found to be a valid assumption. Alternative testing was not undertaken in this study.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

The validity of the conceptual model can be assessed in part by constructing a digital model of the ground-water flow system. In the digital model, differential equations depicting the physical laws governing ground-water flow in porous media are solved to simulate the movement of water through the system. The digital model code used in this study was developed by McDonald and Harbaugh (1988) and has the following attributes:

1. Flow is simulated in a sequence of layered aquifers separated by confining units;
2. Flow within the confining units is not simulated, but the hydraulic effect of these units on leakage between adjacent aquifers is taken into account;
3. A modular design facilitates hydrologic simulation by several alternative methods; and
4. The model code has been documented and validated in hydrogeologic settings similar to those which occur in the study area.

For this model the study area is discretized in space and time, and finite-difference approximations of differential equations depicting ground-water flow are solved at each node. The solution algorithm employs an iterative numerical technique known as the strongly implicit procedure—SIP (Weinstein and others, 1969). The theory and use of the model is documented by McDonald and Harbaugh (1988).

A three-layer model (fig. 12) was constructed to simulate the regional flow system in the Memphis and Fort Pillow aquifers. The uppermost layer represents the shallow aquifer. Flow within the shallow aquifer was not simulated; rather, the layer consisted of an array of constant-head nodes representing water levels at steady state during any given stress period. This layer serves as the ultimate source of recharge to the aquifers, either by leakage, or where the Memphis and Fort Pillow aquifers outcrop, as a source of simulated direct recharge.

The second and third layers represent the Memphis and Fort Pillow aquifers, respectively. The areal extent of the formations that make up the Memphis and Fort Pillow aquifers are shown in figure 13.

Layers of the model are separated by leaky confining units. These units are depicted by arrays of leakance terms. Leakance is calculated by dividing the vertical hydraulic conductivity by the thickness of the confining unit (McDonald and Harbaugh, 1988, p. 5-11). Leakance values are high in areas where confining units are thin or absent, and are low where the units are thick and tight.

Finite-Difference Grid

The area simulated by the digital model (fig. 14) is much larger than the Memphis study area. Evaluation of the larger area allows simulation of regional flow in the aquifer using realistic representations of the natural boundaries of the Memphis and Fort Pillow aquifers on the western, northern, and eastern margins of the Mississippi embayment.

Approximately 10,000 mi^2 of the northern Mississippi embayment is divided by a variably-spaced, finite-difference grid of 58 rows, 44 columns, and 3 layers. The grid, in relation to the areas of outcrop and subcrop of the Memphis and Fort Pillow aquifers, is shown in figures 14 and 15 and is oriented to minimize the number of inactive nodes. Directional properties of transmissivity were not used to determine grid alignment, because on a regional scale there is no evidence of anisotropic transmissivity in the Mississippi embayment area (Hayes Grubb, U.S. Geological Survey, oral commun., 1986). An evaluation of an aquifer test of the Memphis aquifer in the Memphis area using tensor analysis (Randolph and others, 1985) was conducted after the grid was aligned. This evaluation indicated a slight anisotropy (2.3 to 1) with respect to principal axes oriented within 15° of the grid of this model (Morris Maslia, U.S. Geological Survey, written commun., 1985).

Geology modified from R.L. Hosman, A.T. Long, and T.W. Lambert and others, 1968, Plate 7; and J.H. Criner and W.S. Parks, 1976, figure 4.

Figure 14. Regional digital model representation of aquifer layer 2 (Memphis aquifer) in the northern Mississippi embayment.

Geology modified from R.L. Hosman, A.T. Long, and T.W. Lambert and others, 1968, Plate 7; and J.H. Criner and W.S. Parks, 1976, figure 4.

Figure 15. Regional digital model representation of aquifer layer 3 (Fort Pillow aquifer) in the northern Mississippi embayment.

The grid spacing varies from a minimum of 3,200 feet in the Memphis area to 100,000 feet at the western boundary of the model. This variable spacing provides computational efficiency while affording the highest node density within the Memphis study area. Grid block size within the Memphis study area varies from 0.45 mi^2 to slightly more than 8 mi^2 (see fig. 25). A grid block size of about 1 mi^2 is typical for the area of intense pumping in metropolitan Memphis. To reduce the potential for numerical instability during model simulation, block dimensions varied by no more than 1.5 times the dimensions of adjacent blocks.

Hydrologic Parameters

The flow model requires arrays of input data that define the distribution of "average" hydrologic parameters and conditions affecting ground-water flow within each grid block. These parameters include initial head distributions, boundary conditions, hydraulic properties of the aquifers and confining beds, and pumping stresses.

Initial Head Distributions

The initial head distributions used in the model are general estimates of pre-development, steady-state conditions. Data are sparse, and many data points were extrapolated. Initial water levels for the shallow aquifer (layer 1) in the Memphis area are estimated to be the same as water levels in 1980 (fig. 4), except that the cone of depression in the area of the south Sheahan well field was not present under initial conditions. Prior to pumping, water levels in the shallow aquifers in the south Sheahan area are estimated to be about 240 feet above sea level. Initial heads for the shallow aquifer (layer 1) in the Memphis area are based on data from Wells (1933), Boswell and others (1968, plate 1), Krinitzsky and Wire (1964), and Graham and Parks (1986, fig. 7).

Initial heads in the Memphis aquifer for the entire modeled area prior to development were derived from Arthur and Taylor (1990), Hosman and others (1968, plate 7), and Reed (1972). Within the Memphis area, estimated potentiometric surface of the Memphis aquifer prior to development in 1886 is shown in figure 16 (Criner and Parks, 1976, fig. 4).

Initial head data for the Fort Pillow aquifer in the modeled area are from Arthur and Taylor (1990), Criner and Parks (1976, fig. 4), Hosman and others (1968, plate 4), Plebuch (1961), and Schneider and Cushing (1948). The estimated potentiometric surface of the Fort Pillow aquifer within the Memphis area prior to development in 1924 is shown in figure 17.

Boundary Conditions

Boundary conditions include lateral no-flow boundaries for the Memphis and Fort Pillow aquifers, a no-flow condition beneath the Fort Pillow aquifer, and constant heads for the uppermost layer. To the north, east, and west for the Memphis and Fort Pillow aquifers, no-flow boundaries correspond with the updip extent of respective outcrop and subcrop areas (figs. 14 and 15). On the south, a no-flow boundary is specified that is roughly perpendicular to water-level contours (parallel to ground-water flow). This boundary is not truly "no flow"; however, the low aquifer transmissivity and distance from the area of interest are assumed to cause negligible effects on simulation in the area of interest.

Constant heads in the uppermost layer, which corresponds to the water-table aquifer, represent long-term, steady-state water-table altitudes. Head declines have been documented in only one isolated area in the shallow water-table aquifer. In this area of water-level decline, the water levels were decreased step-wise in sequential stress periods to reflect estimated declines in the local water table.

Simulated flow to and from the uppermost layer represents deep recharge and discharge from the system. Inasmuch as the focus of the study was on the deeper aquifers, a detailed evaluation of the hydrologic budget of the shallow aquifer was outside the scope of this report. However, the calculated value of regional recharge used in the model was hydrologically reasonable and compared favorably with values used in Arthur and Taylor (1990) and Brahana and Mesko (1988).

The Midway confining unit underlying the Fort Pillow aquifer is assumed to be impermeable, and its upper surface is specified as a "no-flow" boundary. This assumption is supported by lithologic, chemical, and hydrologic data (Brahana and Mesko, 1988, figs. 8, 10, and 11, and table 2).

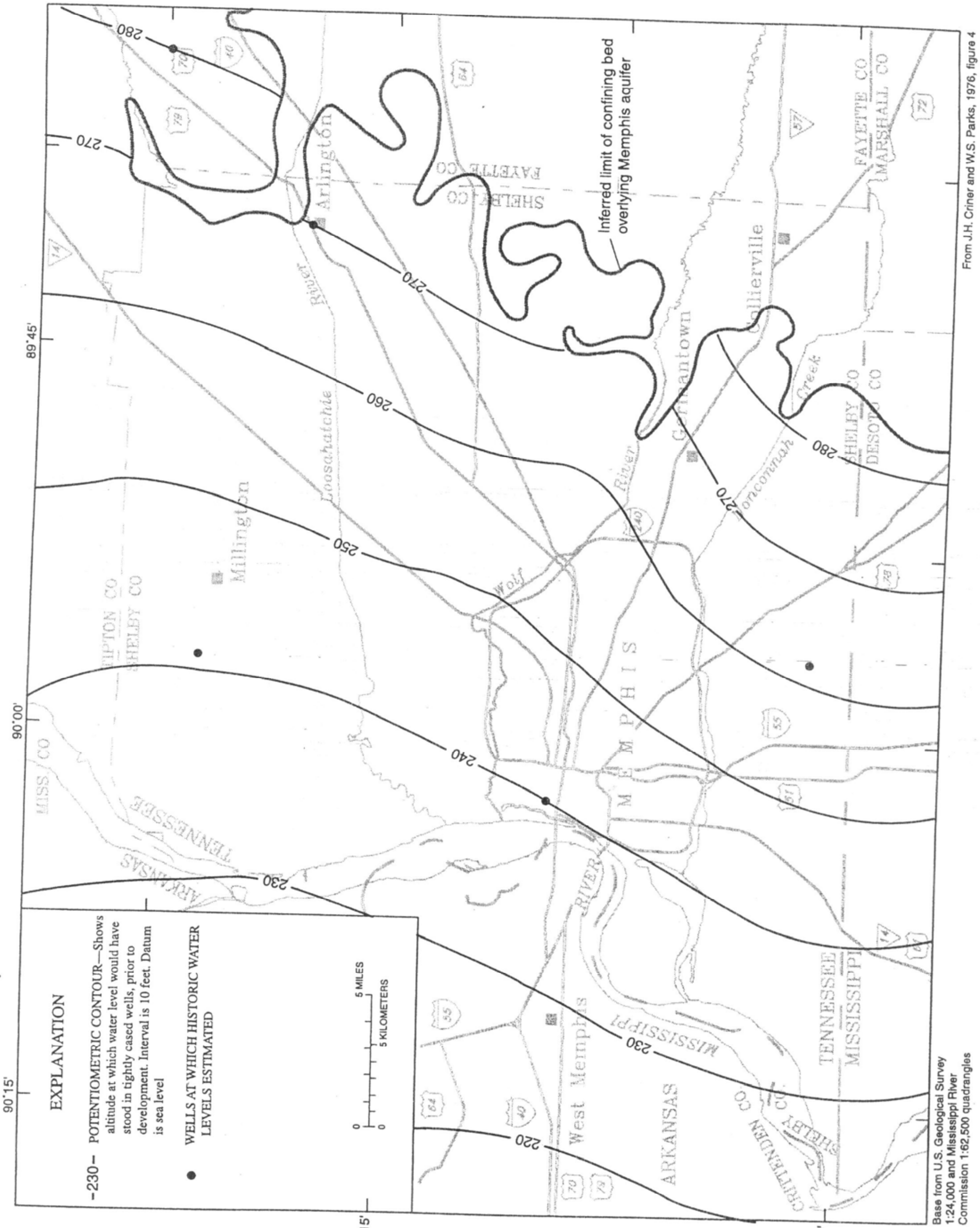
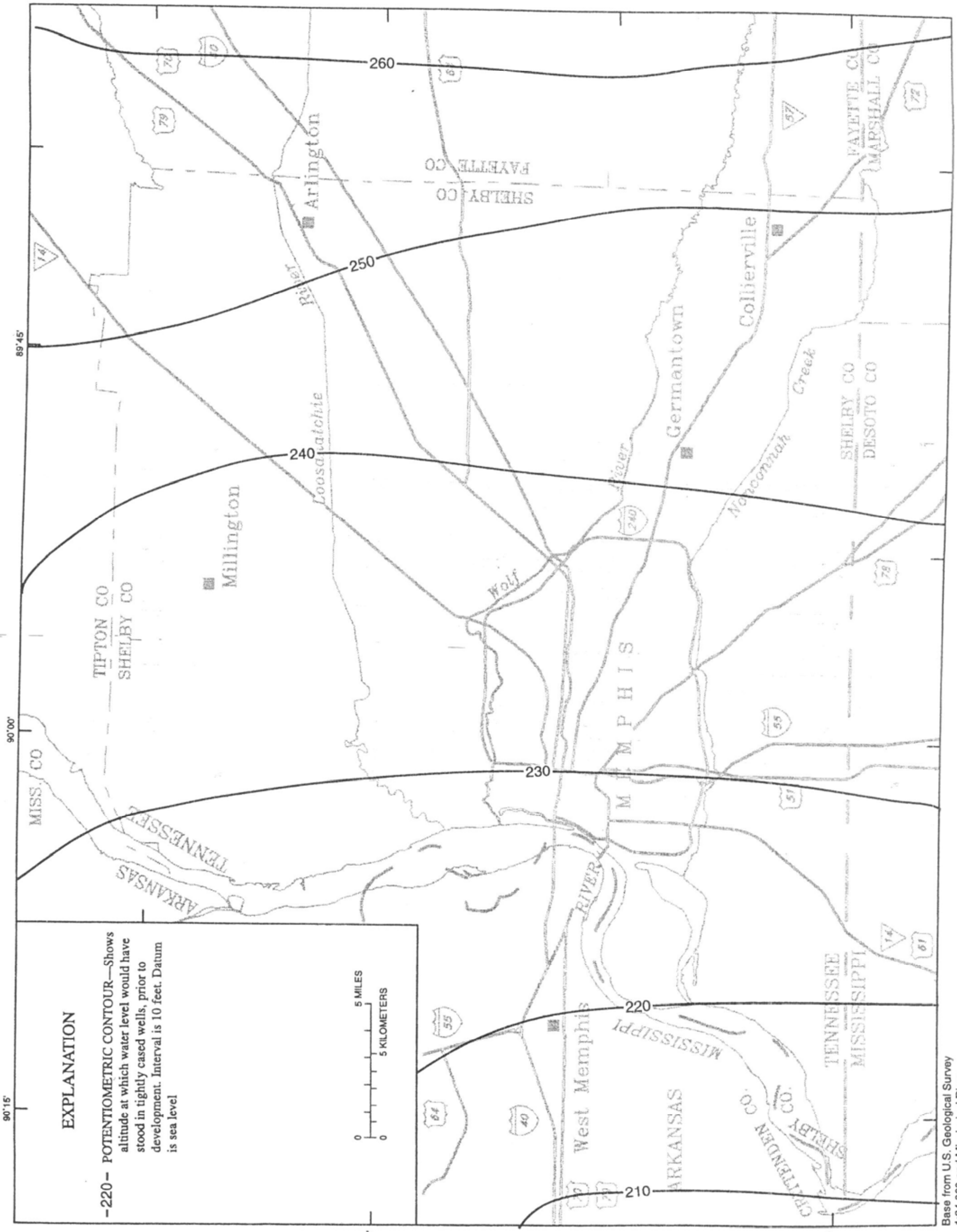


Figure 16. Estimated potentiometric surface of the Memphis aquifer prior to development in 1886.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 17. Estimated potentiometric surface of the Fort Pillow aquifer prior to development in 1924.

Aquifer Hydraulic Properties

Average storage coefficient and transmissivity for each grid block for each aquifer were required for model simulation. Initial estimates for these hydraulic properties were based on pumping tests, geologic data such as lithology and layer thickness, and estimates and calculations made by other investigators (Schneider and Cushing, 1948; Criner, Sun, and Nyman, 1964; Halberg and Reed, 1964; Bell and Nyman, 1968; Boswell and others, 1968; Hosman and others, 1968; Cushing and others, 1970; Newcome, 1971; Reed, 1972; Parks and Carmichael, 1989a and b). The model-derived storage coefficient and transmissivity for the Memphis aquifer represent the values that provided the best fit between calculated and observed potentiometric levels (heads) (table 2 and figs. 18 and 19).

Transmissivity values determined by calibration for the Memphis aquifer in the Memphis area ranged from less than 10,000 ft^2/d to 50,000 ft^2/d, with values commonly in the range from 20,000 ft^2/d to 50,000 ft^2/d (fig. 19). These values agree with the average transmissivity determined by flow-net analyses (U.S. Geological Survey, unpublished data, 1985), and are within the range of reported values (table 2). Transmissivity decreases south of Shelby County, which reflects the change to clay facies in the middle part of the Memphis Sand (Hosman and others, 1968). The best match of heads was simulated using values of transmissivity that more closely matched those of the Sparta aqufier (Fitzpatrick and others, 1989) than those of the entire clay and sand unit. The storage coefficients for the Memphis aquifer ranged from 2×10^{-4} to 2×10^{-1} (fig. 18).

Leakance values were initially determined by dividing estimates of the vertical hydraulic conductivity of reported lithologies (U.S. Geological Survey, unpublished data, 1984; Freeze and Cherry, 1979) by the generalized thickness of the confining units (Graham and Parks, 1986, figs. 3-6). These values were refined during the calibration process; areal distribution of leakance by calibration is shown in figure 20.

Leakance of the upper confining layer, the Jackson Formation and upper part of the Claiborne Group, was characterized by a wide range of values, from 1×10^{-8} feet per day per foot to 1×10^{-3} feet per day per foot. This range reflects the diverse lithology of the Jackson-upper Claiborne confining unit as well as variations in thickness of the unit (fig. 5).

Most transmissivity values determined by calibration for the Fort Pillow aquifer in the Memphis area ranged from 6,000 to 24,000 ft^2/d (fig. 21). The storage coefficients used in the calibrated model for the Fort Pillow aquifer in the Memphis area varied by less than a factor of 2, from 5×10^{-4} to 1×10^{-3} (fig. 22), sigifying uniformly confined conditions for the Fort Pillow aquifer. Leakance values for the lower confining unit, the Flour Island Formation, were from 1×10^{-12} feet per day per foot to 2×10^{-12} feet per day per foot (fig. 23), reflecting similar lithology and little variation in thickness (fig. 11) of the Flour Island confining unit within the Memphis area.

Pumping

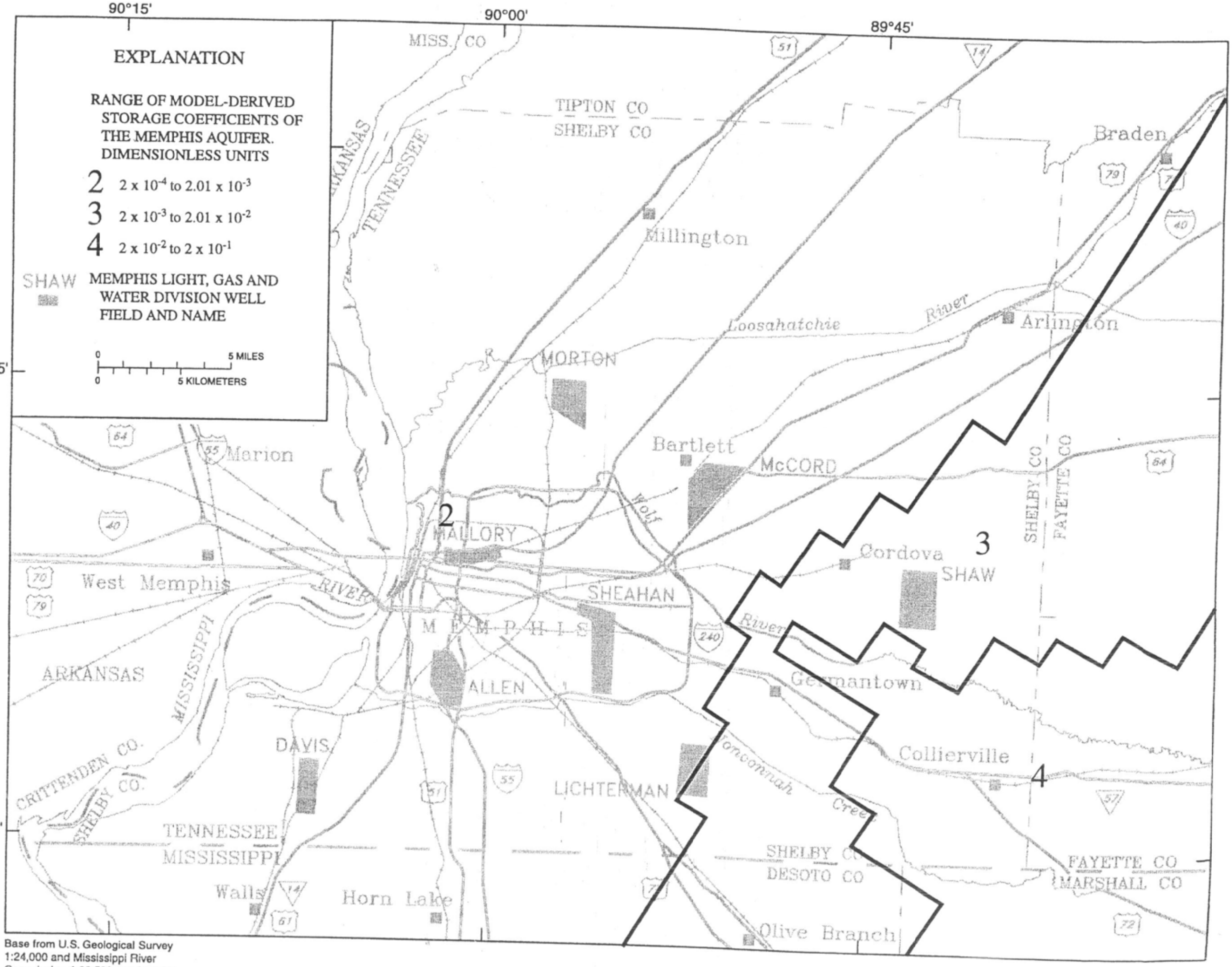
Pumping from the Memphis aquifer began in 1886, and pumping from the Fort Pillow aquifer began in 1924. Withdrawals from these two major aquifers have occurred at varying rates and with a changing areal distribution. Because of variation with time, pumping data were introduced in the model in nine discrete stress periods. The total modeled pumpage and the corresponding total reported pumpage for the nine periods are shown in figure 24. The length of the stress periods ranged from 5 to 39 years. Seasonal variations in pumping were not simulated. Mean annual pumping was used to calculate average stress at each node for each of the stress periods.

Delineation of stress periods was based on abrupt changes in pumpage rates, variations in the areal distribution of pumping centers, and on availability of water-level maps. The number of well nodes simulating pumping in the Memphis area increased from 18 in stress period 1 to 88 in stress period 9. Total pumping from the Memphis and Fort Pillow aquifers increased from 0 in 1885 to about 190 Mgal/d in 1985.

Pumpage data for the Memphis and Fort Pillow aquifers in the Memphis area are based on the published reports of Criner and Parks (1976) and Graham (1982). Areal distribution was assigned based on extensive unpublished documents of water use reported to the U.S. Geological Survey in Memphis (W.S. Parks, U.S. Geological Survey, written commun., 1984).

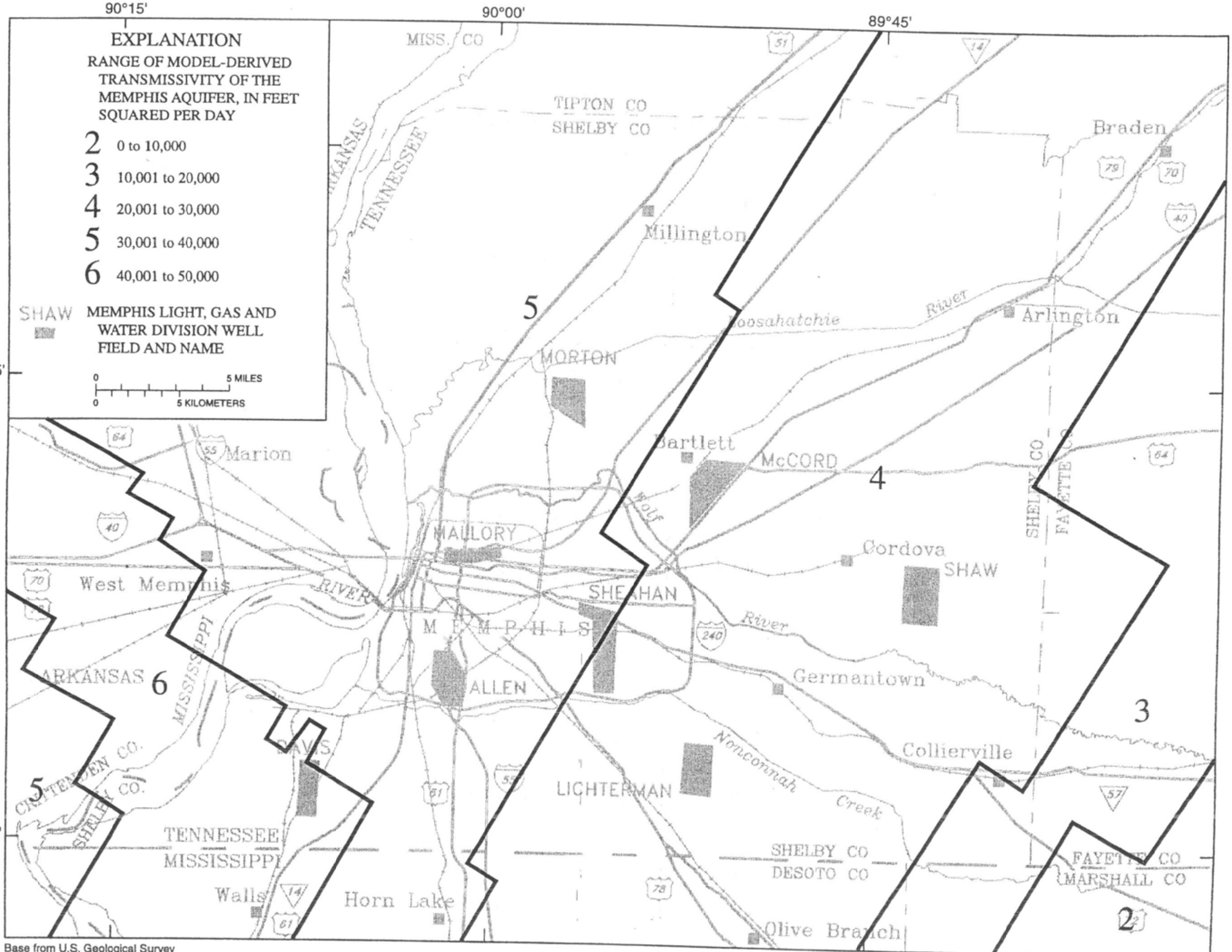
Model Calibration

Calibration of the flow model is the process of adjusting the input data to produce the best match between simulated and observed water levels. The



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 18. Model-derived storage coefficient of the Memphis aquifer.



Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

Figure 19. Model-derived transmissivity of the Memphis aquifer.

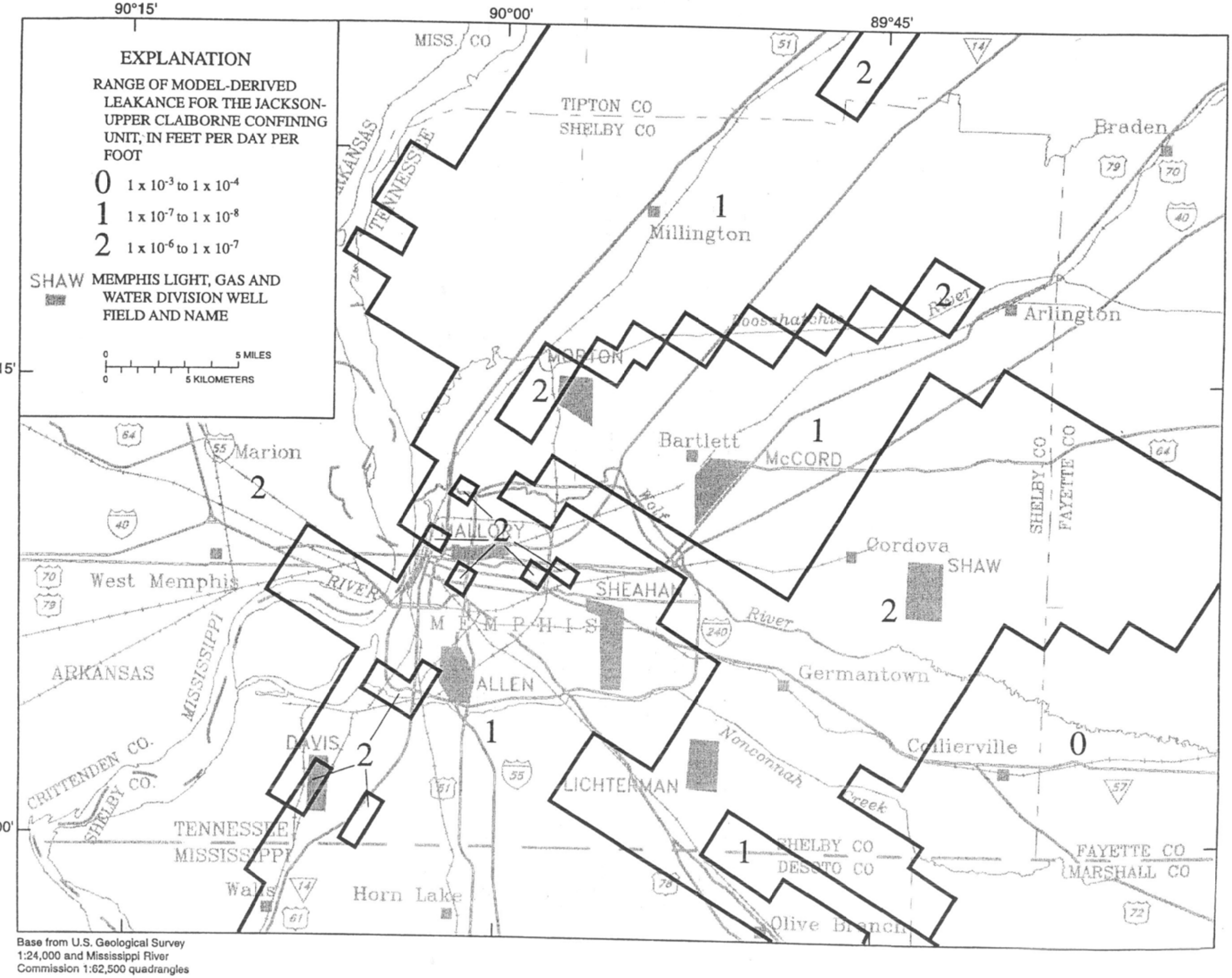


Figure 20. Model-derived leakance of the Jackson-upper Claiborne confining unit.

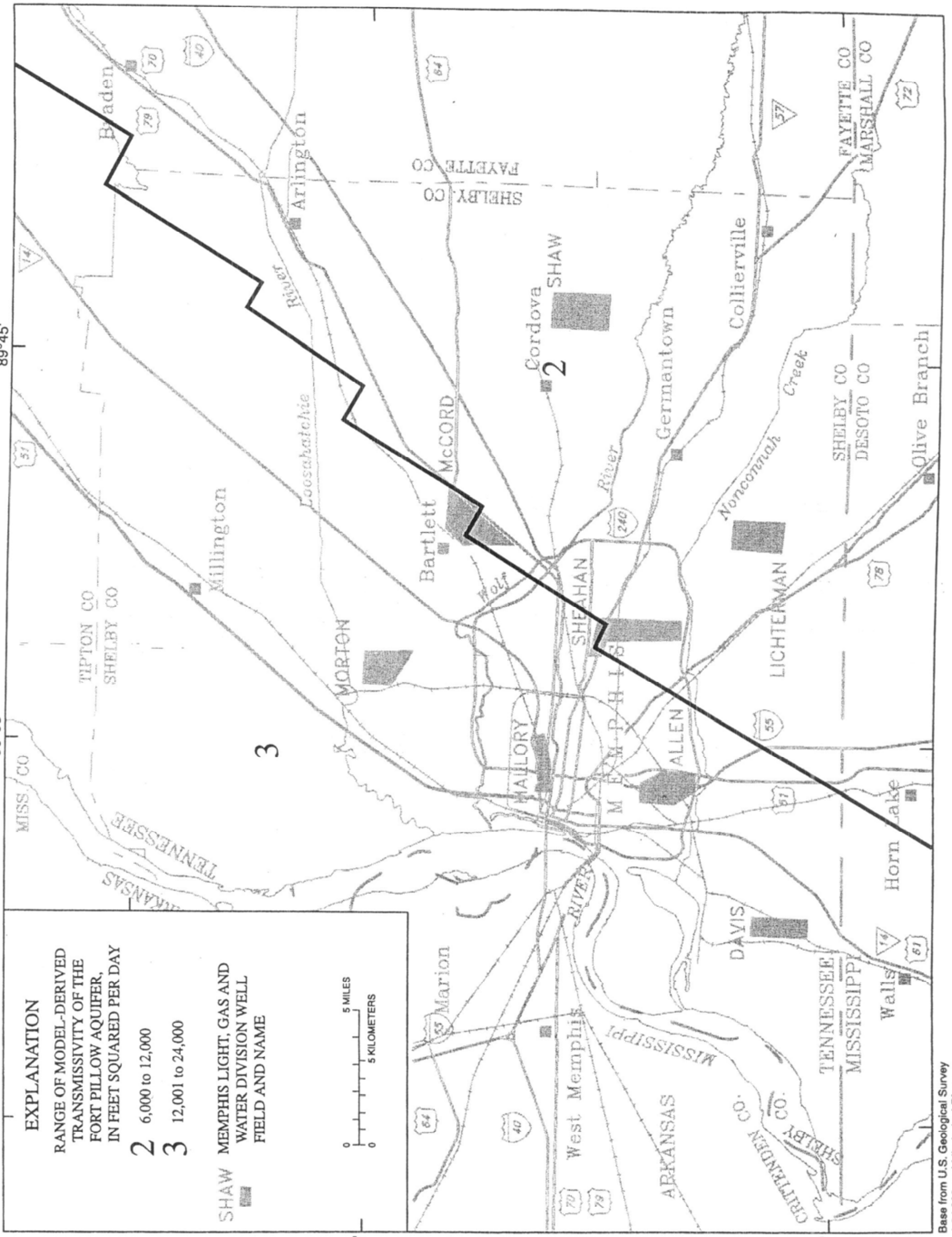
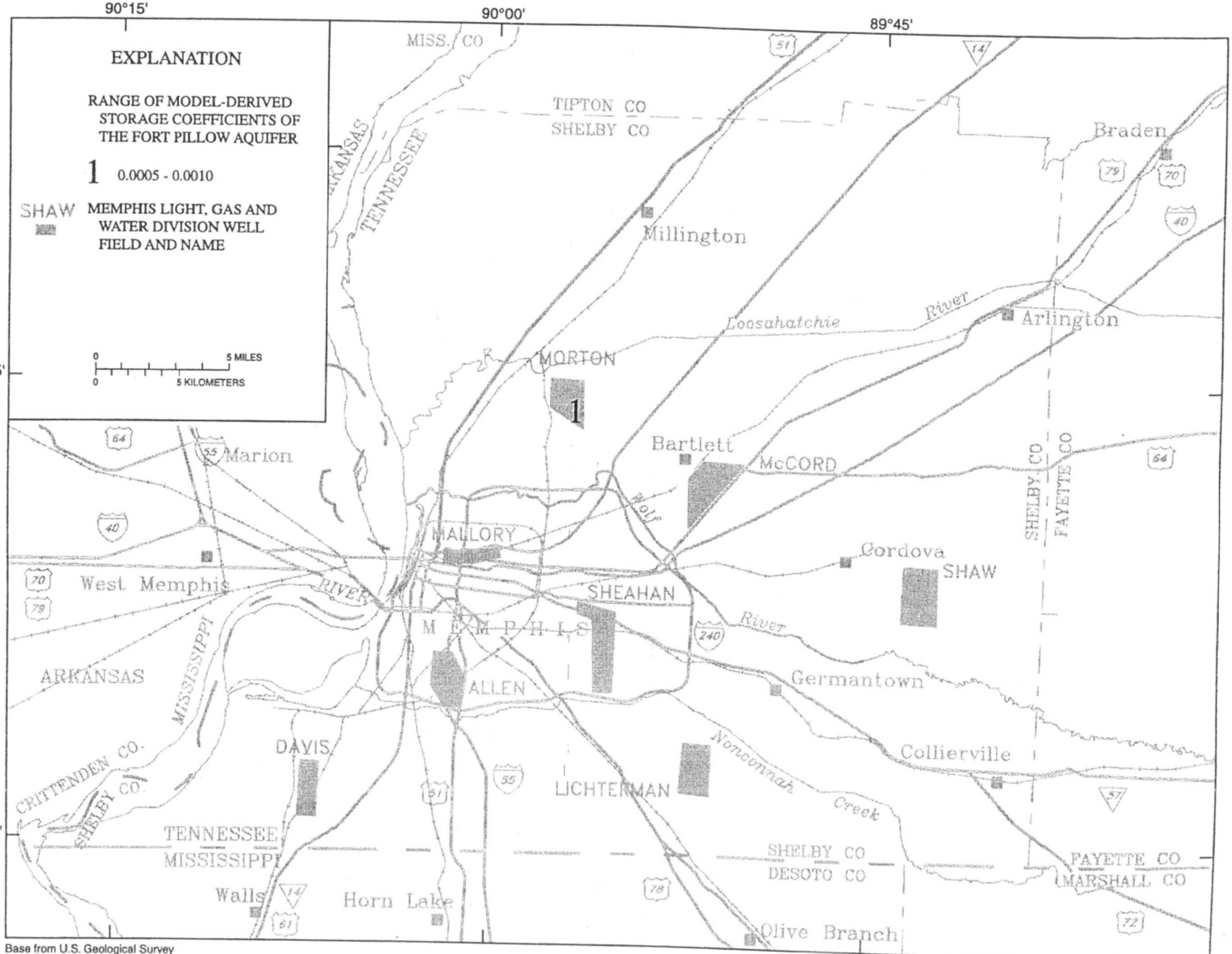
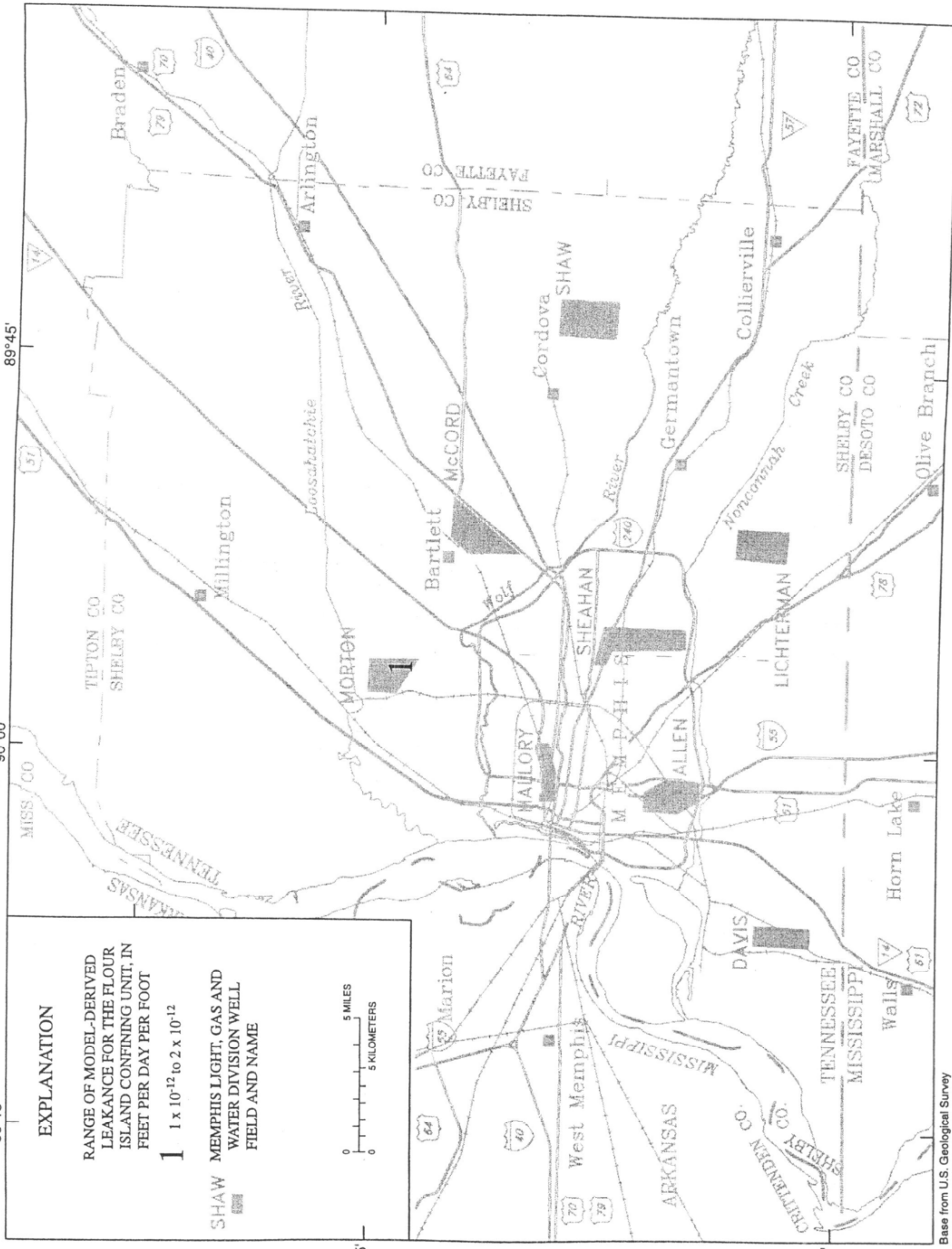


Figure 21. Model-derived transmissivity of the Fort Pillow aquifer.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 22. Model-derived storage coefficient of the Fort Pillow aquifer.



Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

Figure 23. Model-derived leakance of the Flour Island confining unit.

MS SCT 000342

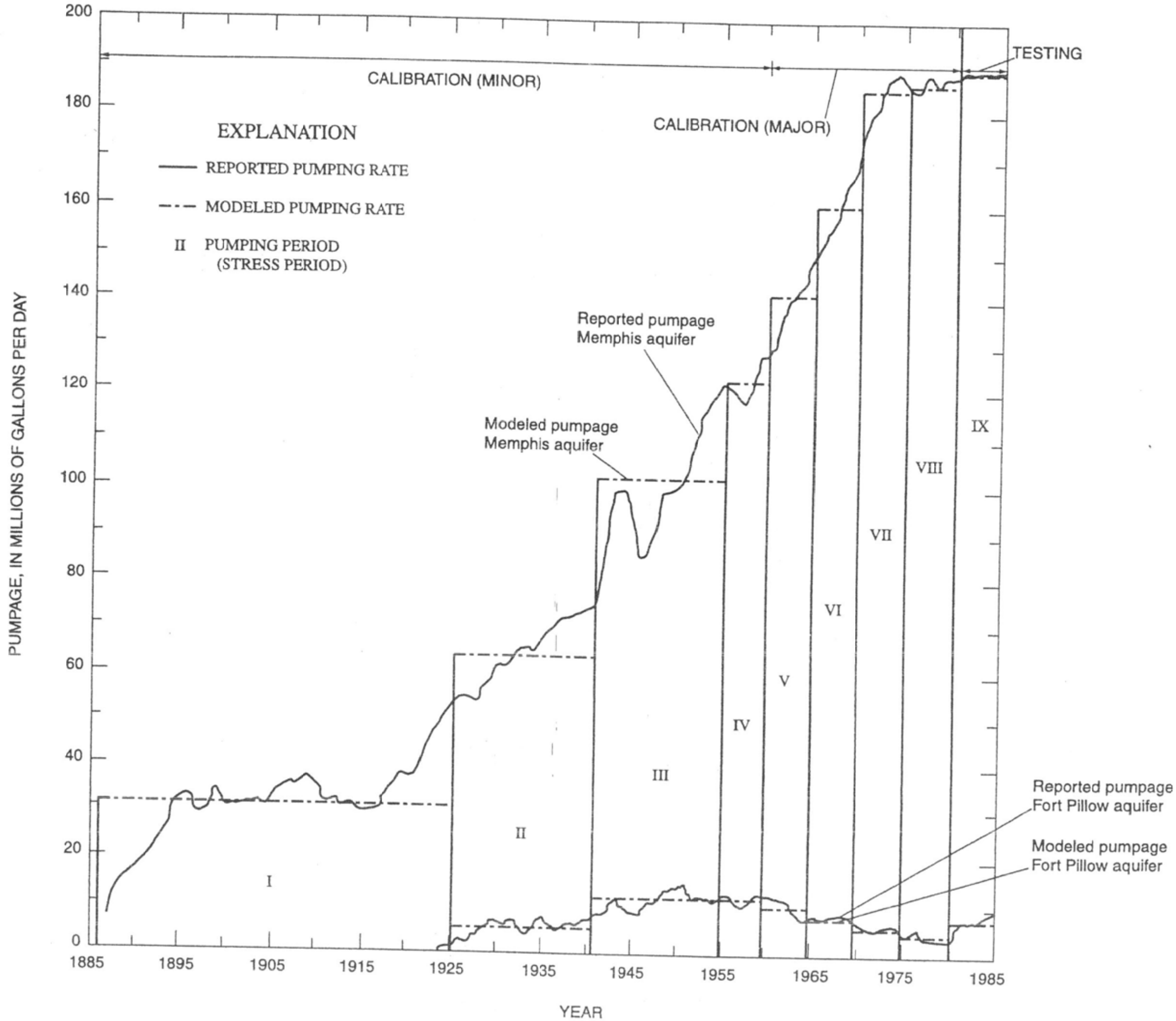


Figure 24. Actual and modeled pumpage from the Memphis aquifer and Fort Pillow aquifer in the Memphis area, 1886-1985.

model was calibrated by simulating the stress periods from 1886-1980, a time interval during which flow in both the Memphis and Fort Pillow aquifers was thought to be transient. Calibration was concentrated on stress periods from 1961 to 1980. Ground-water conditions were transient in both the Fort Pillow and the Memphis aquifers during the period 1961 to 1980, whereas conditions in the shallow aquifer were thought to be at steady state. It should be noted that water-level and pumping data exist for the entire period of development of the Memphis aquifers; the early data are sparse, however, and are less well documented than data collected after 1960.

An enlarged view of part of the model grid in the Memphis study area, including locations simulated as major centers of pumping, is shown in figure 25.

The strategy for calibration was dictated by the availability of data, and in partcular, by availability of detailed water levels and pumping information for specified wells. In general, there is a wealth of water-level and pumpage data for the Memphis and Fort Pillow aquifers since 1960. There are many records that are adequate for general interpretation for the period 1924 to 1960, but prior to 1924, there are few reliable records at all.

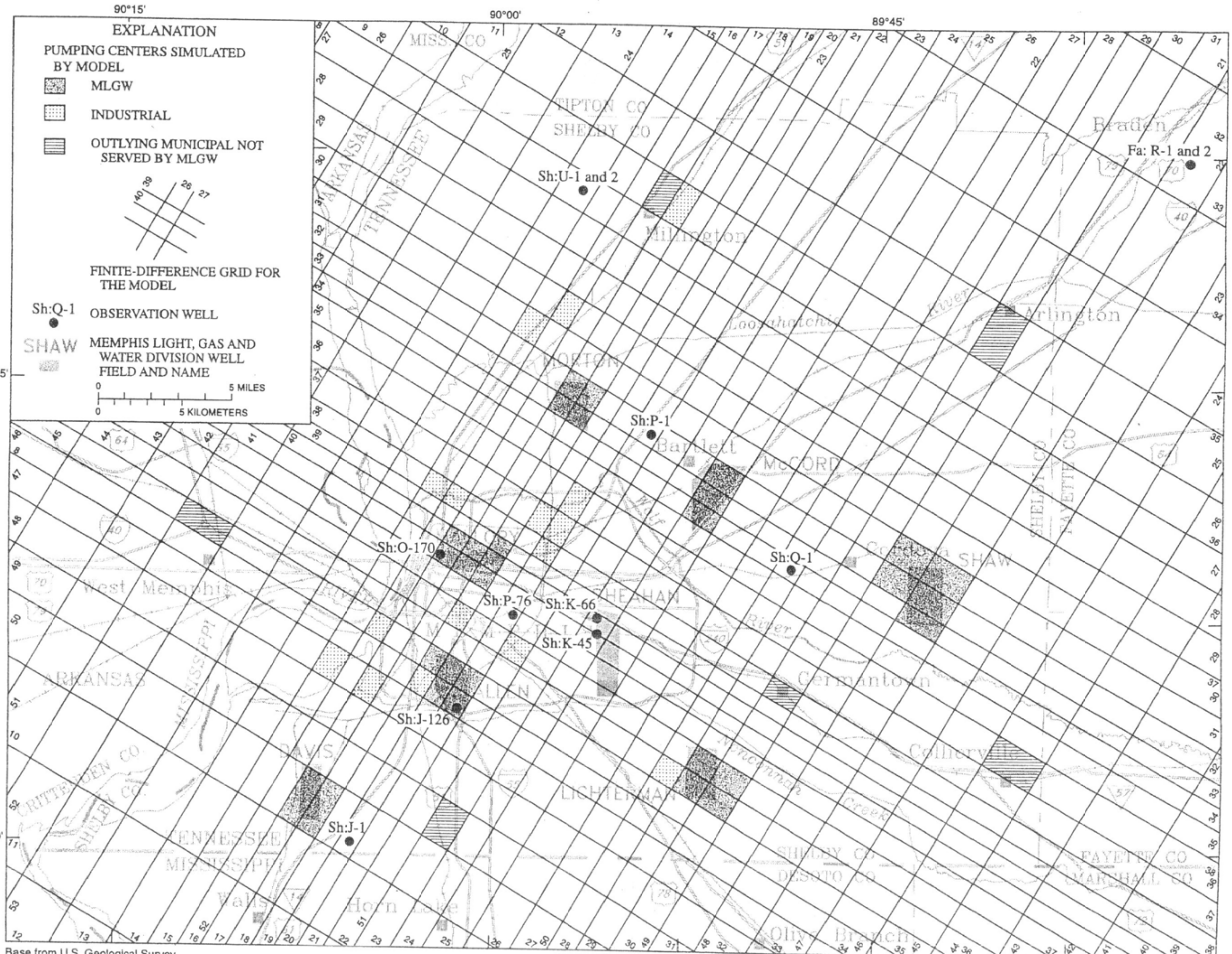
For example, the prepumping (1886) potentiometric surface of the Memphis aquifer is based on four data points (Criner and Parks, 1976), all of which were extrapolated (fig. 16). Data points for the Fort Pillow aquifer in the Memphis area likewise are lacking for this period. Because of this data, no formal steady-state calibration to these few prepumping data was attempted, although the match of prepumping conditions by removing pumping from the calibrated model (transient) provided a reasonable match with the estimated maps.

The completeness and documentation of the data base for conditions after 1960 justified using this data as the major tool of calibration. The transient simulation from 1961 to 1980 was completed using four 5-year pumping periods (fig. 24) of 10 time-steps each. Seasonal fluctuations in water levels were averaged to give a single annual value. The model was calibrated by minimizing the difference between model simulated heads and measured heads (Criner and Parks, 1976; Graham, 1982). In addition, differences between hydrographs of observed and simulated water levels at long-term observation wells were minimized.

Calibration was continued by adjusting the global multiplier of transmissivity, vertical conductance, and storage coefficients of the Memphis and Fort Pillow aquifers and their confining units until the sum of the squared differences between observed and calculated heads was minimized. Individual hydraulic data for nodes was adjusted only if geologic or hydrologic justification warranted such a change. Calibrated values for hydraulic properties were within the range determined by aquifer tests (table 2) and those estimated from published values of similar geologic materials (Schneider and Cushing, 1948; Criner, Sun, and Nyman, 1964; Halberg and Reed, 1964; Bell and Nyman, 1968; Boswell and others, 1968; Hosman and others, 1968; Cushing and others, 1970; Newcome, 1971; Reed, 1972; Parks and Carmichael, 1989a and b).

Data collected from the period 1886 to 1960 were used to make minor adjustments to parameters during calibration (fig. 24). These data were less well defined than post-1960 data, and in some instances, were essentially undocumented. As an example, major uncertainty exists about water levels and discharge from the Auction Avenue "tunnel," a major source of municipal supply that was used from about 1906 to about 1924. The Auction Avenue "tunnel" was a collector tunnel for some early wells screened in the Memphis aquifer (Criner and Parks, 1976, p. 13). According to Criner and Parks (1976): "...little is known about the tunnel (Auction Avenue "tunnel"), but it is reported to have been constructed in a clay layer, about 85 feet below land surface and below the potentiometric surface of the Memphis aquifer. The tunnel was reported to be brick-lined, about 5 feet in diameter, and about one-quarter mile in length. Several wells were completed along the tunnel and constructed so that water would flow into the tunnel through underground outlets. Water was pumped into the city supply system from a large well, 40 feet in diameter, at the end of the tunnel at Auction Avenue Station." Inasmuch as this and other dominant withdrawals during the period 1886-1924 were not well defined, little emphasis was given to calibrating the model using older data.

An important model calibration and testing criterion was an error analysis of simulated and observed water levels at the nodes representing the control points. The root mean square error (RMSE) was used to judge how closely the simulation matched "reality," which was defined by a network of observation wells (Criner and Parks, 1976, fig. 1). The root mean square error was calculated as a measure of the difference between model-calculated heads and observed heads.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 25. Finite-difference grid in the Memphis study area showing location of pumping nodes and selected observation wells.

The root mean square error is described by the equation:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\langle H_i^C - H_i^O \rangle^2}{n}} .$$

where

$RMSE$ is the root mean square error;
H^C is calculated head, in feet, at a model node;
H^O is observed head, in feet;
n is the number of comparison points;
i is a subscript that defines any specific comparison point, varying between 1 and n.

Another criterion was the comparison made between observed and simulated hydrographs. Records from four wells from the Memphis aquifer and two wells from the Fort Pillow aquifer were of sufficient duration to provide reasonable comparisons (fig. 28). Locations of the wells from which the comparisons were made are shown on figure 25. For the most part, the observed and simulated hydrographs agree closely.

The results of the calibration are shown in figures 26, 27, and 28. A comparison of observed data points and simulated potentiometric surface of the Memphis aquifer is shown in figure 26; a similar map for the Fort Pillow aquifer is shown in figure 27. Hydrographs of observed and simulated water levels for selected wells are compared in figure 28.

The simulated potentiometric surfaces match the observed data points reasonably well for both aquifers at the end of the calibration period, stress period 8 (figs. 26 and 27). Likewise, interpretive maps contoured from the observed data (figs. 7 and 9) are similar to simulated potentiometric surfaces. Stress periods 4 through 7 simulated observed water levels as well or better than stress period 8, but because of their similarities to one another, have not been included as figures.

In addition to the areal match of water-level data, simulated and observed water levels agree closely through time for selected hydrographs (fig. 28). Variations are thought to be due to errors in the amount and distribution of pumping, particularly prior to 1960, when pumping was not accurately monitored.

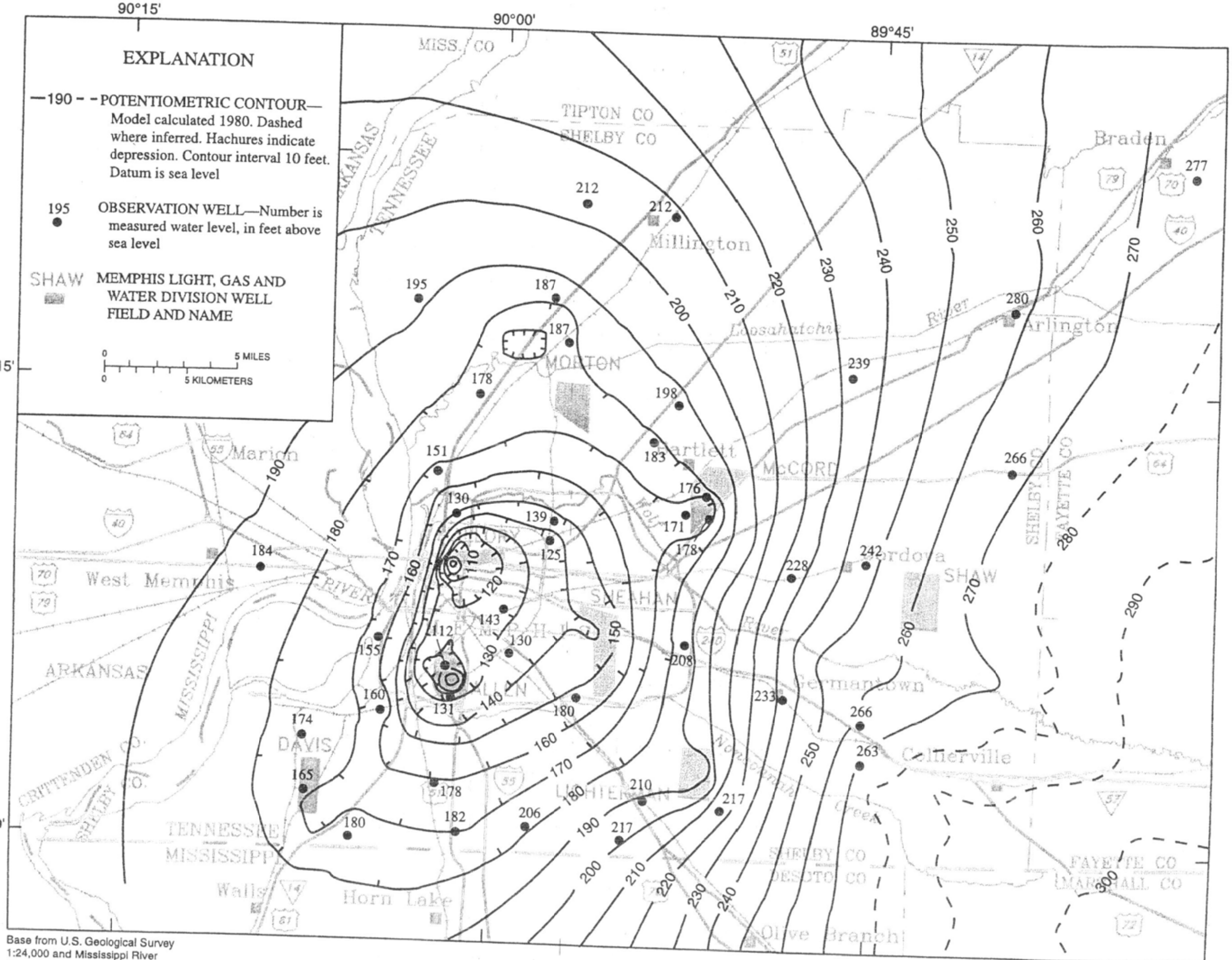
Although the overall simulation of heads in the Memphis aquifer is considered to be good, heads matched poorly in one subarea lying near Nonconnah Creek and the Tennessee-Mississippi border in south Memphis (figs. 26 and 7). Many alternative representations of transmissivity, leakage, and recharge were attempted, but their effect on heads outside the problem area created more problems with overall simulation than they solved with improved subarea simulation. Hydrogeologic data from this area suggest that the model does not contain all relevant hydraulic or boundary conditions; any model application to this subarea should be undertaken with extreme caution. There is no doubt that this subarea is a source of significant recharge to the Memphis aquifer. The quantity and location of the concentrated recharge in this area as indicated by the model may be subject to error and the descriptions of these factors in this report should be considered tentative at best.

It is common in reports documenting ground-water flow models to evaluate average ground-water discharge to streams with calculated flux from the model. Inasmuch as the Mississippi River and its tributaries dominated the ground-water flow, and inasmuch as simulation of the shallow aquifer was outside the scope of this report, no attempt was made to include this comparison. Discharge to streams was not undertaken in this study because:

1. Flow in the Mississippi River was four to five orders of magnitude greater than ground-water inflow rates to streams, thereby masking the inflow component;
2. Grid dimensions for the outcrop areas of the Memphis aquifer and Fort Pillow aquifer were large. Simulation of streams in these large blocks required estimations that were poorly quantified;
3. No aquifer hydraulic tests were reported for the fluvial deposits; and
4. Direct simulation of flow in the water-table aquifer was outside the scope of the investigation.

Model Testing

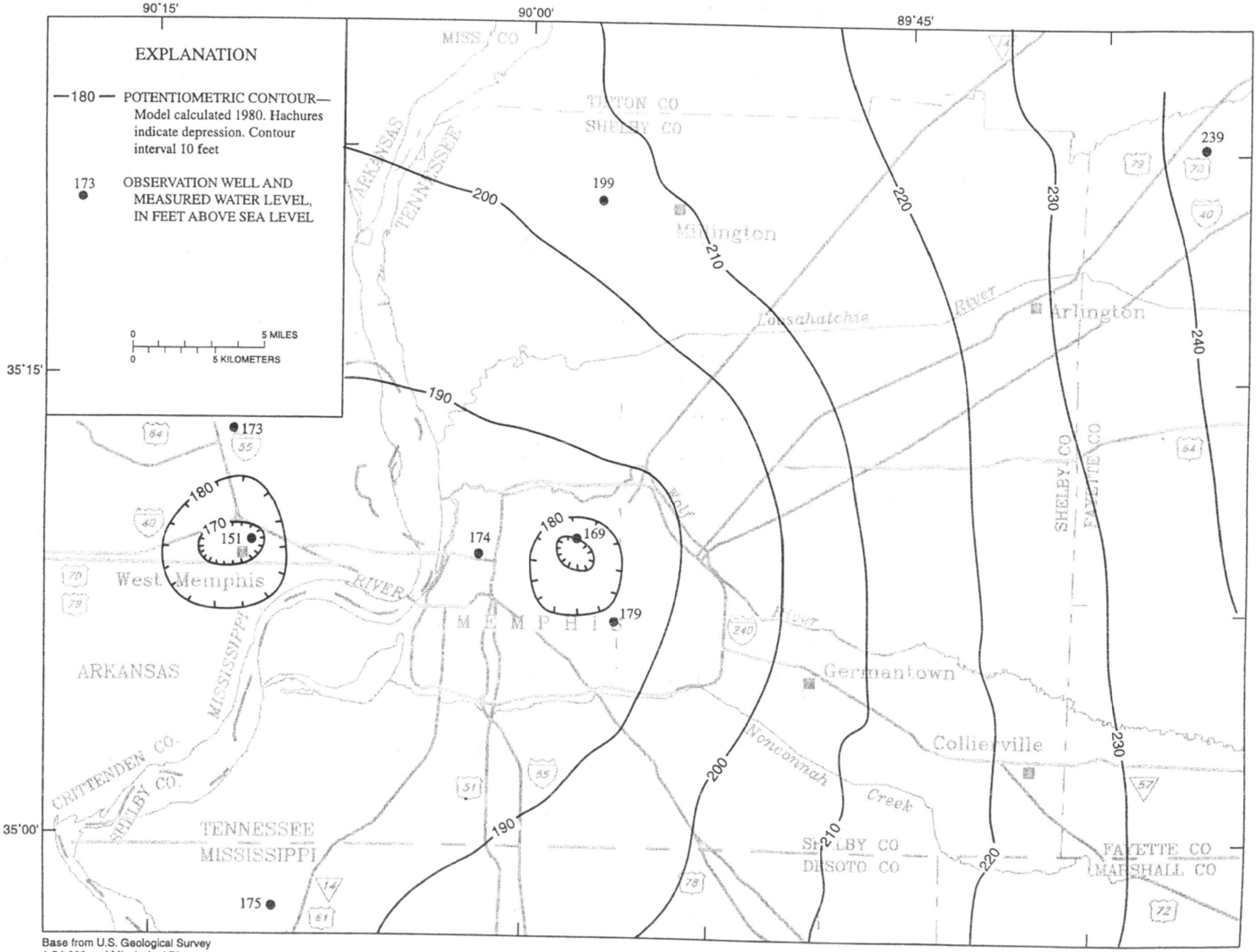
After calibration, the model was tested to determine its ability to simulate observed water levels for the period 1981-85 (fig. 24). For this testing phase, no modification of boundary conditions or calibrated data was made. In this testing phase, the flow model simulated heads in the Fort Pillow aquifer and Memphis aquifer within 5 feet of observed water levels for at least 75 percent of the observation wells (this comparison used interpolated values rather than root mean square error values). These results increase confidence that the model accurately simulates ground-water flow in the study area. The additional criteria used to evaluate the calibration phase also were used to judge the accuracy of the simulated results for this testing phase.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

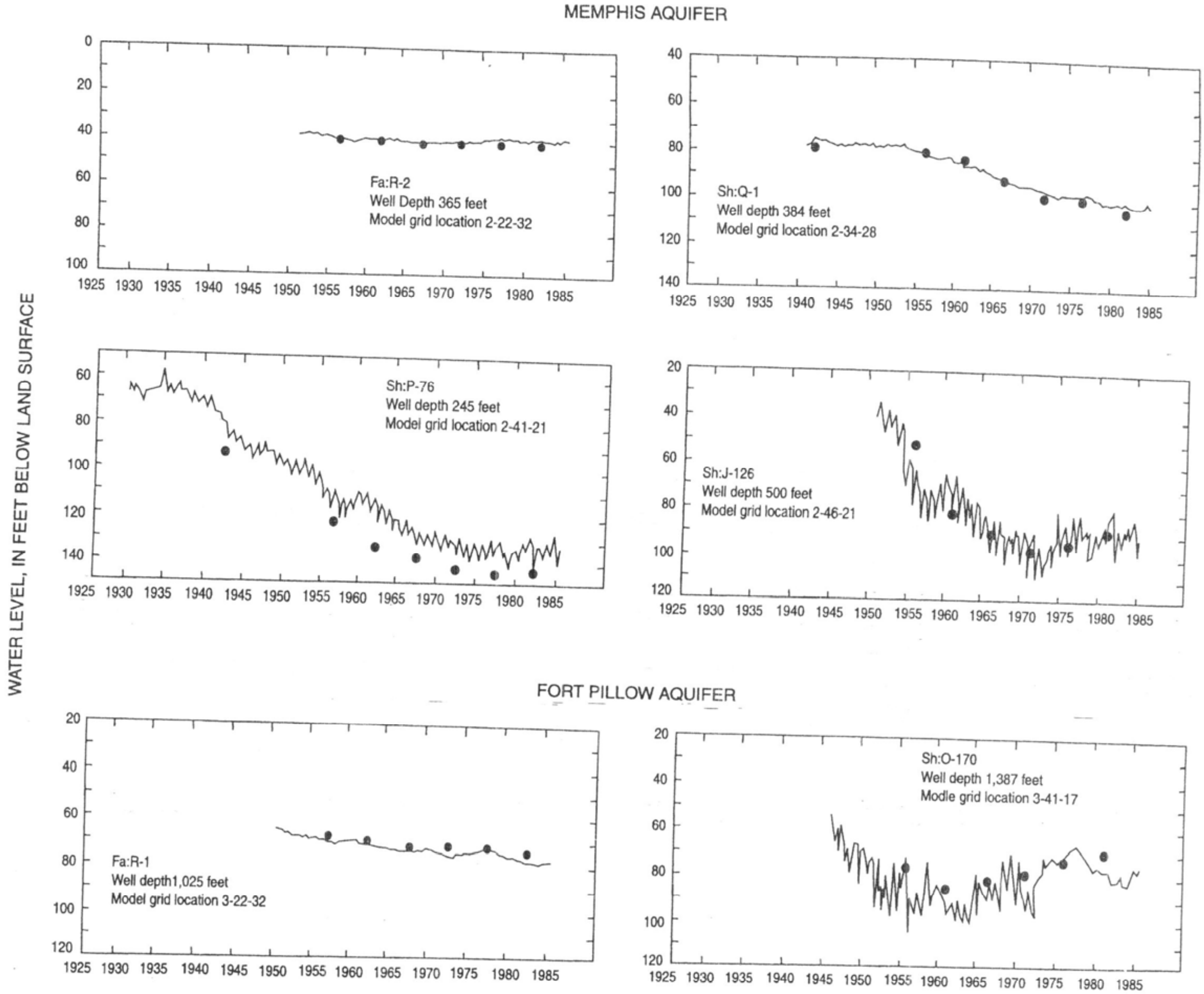
Figure 26. Comparison of observed water levels and model-computed potentiometric surface of the Memphis aquifer, Memphis area, 1980.

MS SCT 000347



Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

Figure 27. Comparison of observed water levels and model-computed potentiometric surface of the Fort Pillow aquifer, Memphis area, 1980.



EXPLANATION

OBSERVED WATER LEVEL, LOWEST WATER LEVEL FOR THE MONTH

MODEL-COMPUTED WATER LEVEL FOR THE GRID IN WHICH THE WELL IS LOCATED

3-22-32 MODEL GRID LOCATION: LAYER-ROW-COLUMN

Figure 28. Selected hydrographs of observed and model-computed water levels for wells in the Memphis and Fort Pillow aquifers in the Memphis area.

Sensitivity Analysis

The response of the calibrated model to variations in model parameters, pumping, and boundary conditions was evaluated by sensitivity analysis. Transmissivity and storage of the Memphis and Fort Pillow aquifers, and leakance for the Jackson-upper Claiborne and Flour Island confining units were each varied uniformly in the model while the other parameters were kept constant. The subsequent effects of these variations on calculated water levels in the Memphis and Fort Pillow aquifers were evaluated by root mean square error (*RMSE*) comparison of observed and simulated water levels for 1980. Results of the sensitivity analyses are illustrated in figures 29 and 30 for the Memphis aquifer and the Fort Pillow aquifer, respectively.

The *RMSE* was 14 feet for the Memphis aquifer and about 10 feet for the Fort Pillow aquifer. These values, on initial evaluation, appear to define very poor simulation of a system. The data set that was used to generate the *RMSE* value, however, was treated in a nontraditional manner, and the values generated should be considered relative rankings rather than absolute measures of goodness-of-fit.

The data set for *RMSE* comparisons included all known observed water levels for the period of interest. Typically, for pumping periods 4 through 9 (fig. 24) occurring after 1955, the data set included more than 100 points. For pumping period 8, on which figures 29 and 30 are based, 129 comparison points were used. Many of the observation wells did not occur at the center of a model node, but fell near boundaries of adjacent nodes. Rather than interpolate an observed value to the nearest nodal center, the actual measurement was compared to the simulated head at the surrounding nodes typically either the two nearest if on a boundary, or the four nearest if on a corner. Because of the steep gradients associated with pumping, a large difference in head frequently occurred for such comparisons (one typically higher, one typically lower), giving rise to a large *RMSE* when in fact an interpolation of simulated conditions matched observed conditions closely.

Results of the sensitivity analysis showed that calculated heads in the Memphis aquifer were most sensitive to variations in aquifer transmissivity and leakance of confining unit A, and least sensitive to storativity (fig. 29). Calculated heads in the Memphis aquifer were not responsive to changes in the aquifer characteristics of the Fort Pillow aquifer. Calculated heads in the Fort Pillow aquifer were most sensitive to transmissivity, and least sensitive to leakance of the Flour Island confining unit and storativity (fig. 30). As a general rule, calculated heads in the Fort Pillow aquifer were insensitive to general changes in aquifer characteristics of the Memphis aquifer. Because of the dominating effect of the pumping stress in the Memphis aquifer, calculated heads in the Fort Pillow aquifer were sensitive to factors affecting recharge and leakage to the Memphis aquifer. Although not shown in the figures, variations in simulated pumping caused large variations in calculated heads in the aquifers. Changes in simulating the southern boundary of the model 20 miles closer and 20 miles farther from Memphis caused only very slight changes in calculated heads from calibrated values.

These results suggest that the values used in the calibrated model are reasonable approximations of actual conditions within the aquifer, particularly in light of the constraints made by the well-defined pumping data and the well-defined potentiometric surfaces. The high sensitivity of leakance of the Jackson-upper Claiborne confining unit with respect to simulated heads in the Memphis aquifer gives confidence that an otherwise poorly defined parameter is well approximated in the model.

Interpretation of Model Results

The underlying objective of ground-water flow modeling was to develop a tool to quantitatively assess the hydrogeology of the Memphis area, and thereby improve understanding of the factors affecting ground-water flow. Digital simulation of ground-water flow permitted a quantitative evaluation of flux across hydrogeologic boundaries and calculation of a hydrologic budget. Interpretation of these results promotes a more complete understanding of the flow system and often has direct implications for resource management.

Hydrologic Budget

One of the principal products of the digital model is a hydrologic budget for each layer in which ground-water flow is simulated. For a given stress period, the model calculates the simulated volume of water that was added to or removed from the layer. Flow rates are also calculated. Because pumpage was variable in space and time throughout the simulation, components of the hydrologic budget were not

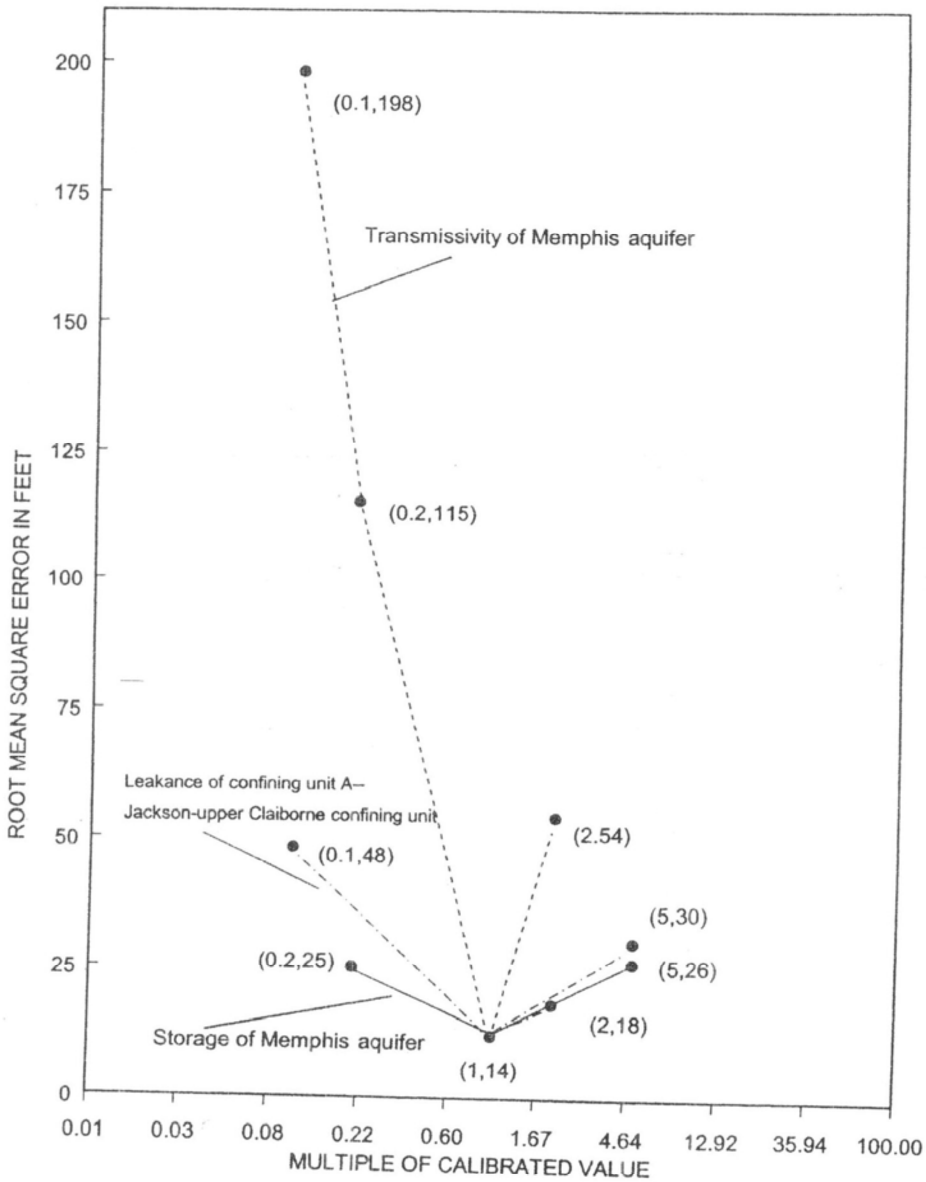


Figure 29. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Memphis aquifer.

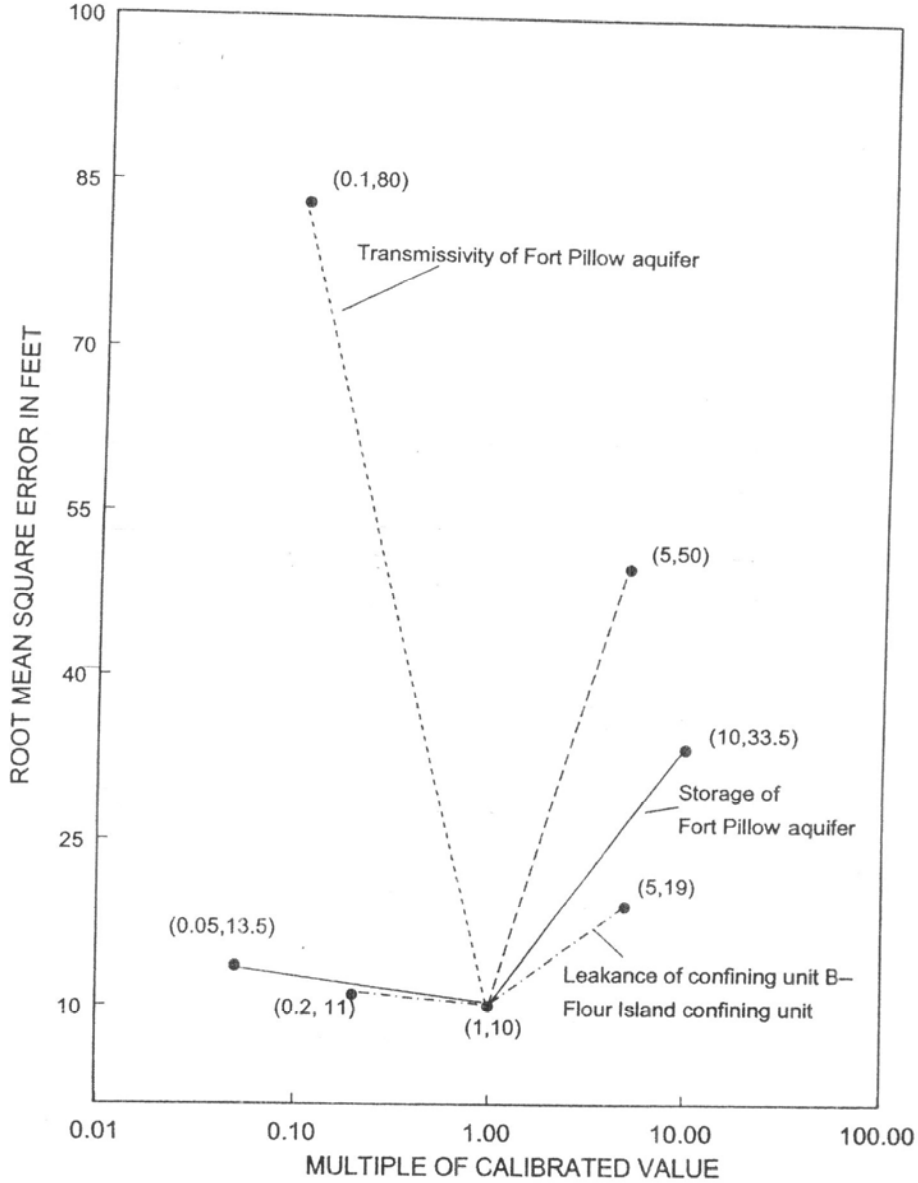


Figure 30. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Fort Pillow aquifer.

constant. The budget figures for 1980 are presented in table 4.

Pumpage accounted for almost all of the total discharge from the Memphis aquifer (table 4). Model simulations indicated pumped water was replaced from three sources: recharge and lateral inflow (42 percent), leakage from the shallow aquifer (54 percent), leakage from the deep aquifer (1 percent), and storage (3 percent). Lateral inflow refers to the essentially horizontal movement of water within the aquifer; the ultimate source of this water is recharge in the outcrop area.

Leakage to the Memphis aquifer occurred both from the surficial aquifers and the Fort Pillow aquifer. As water-levels in the Memphis aquifer declined in response to pumpage, hydraulic gradients favored the flow of water across the overlying and underlying confining units. Approximately 98 percent of the simulated leakage to the Memphis aquifer was attributable to flow across the Jackson-upper Claiborne confining unit. In 1980, this leakage from water-table aquifers contributed more than 50 percent of the water pumped from the Memphis aquifer. Because water in the water-table aquifers is inferior in quality and more susceptible to contamination than water in the Memphis aquifer, this substantial contribution may be cause for concern. The third source of water pumped from the Memphis aquifer was storage, which refers to water made available by compression of the aquifer and expansion of the water column. Storage contributes a minor part (3 percent) of the budget of the Memphis aquifer, based on simulation of 1980 conditions.

The hydrologic budget for the Fort Pillow aquifer in 1980 also is defined in table 4. Water was removed from this aquifer both by pumpage (88 percent) and leakage to the Memphis aquifer (12 percent). Most of the water removed from this aquifer was derived from recharge and lateral inflow (87 percent). About 13 percent of the water was derived from storage.

Areal Distribution of Leakage

Downward leakage from the water-table aquifer through the Jackson-upper Claiborne confining unit to the Memphis aquifer poses a potential threat to the quality of water used for public supply in the Memphis area. To facilitate management and protection of this resource, it is important to identify those areas where leakage is most significant.

In the flow simulation, a small amount of downward leakage to the Memphis aquifer occurred throughout the study area. In certain zones, however, leakage was more pronounced (fig. 31). In most places leakage did not exceed 0.01 cubic feet per second per square mile, which is equivalent to an infiltration velocity of 0.14 inch per year (in/yr). Near the outcrop area and around Lichterman well field in southeastern Memphis, there was a zone in which leakage was greater than other areas. Near the outcrop area, leakage rates varied from 0.01 to 0.1 cubic feet per second per square mile, which is equivalent to an infiltration velocity of 0.14 to 1.4 in/yr. In this zone the confining unit is known to be relatively thin (fig. 5).

Simulated leakage rates were substantially higher in several other locations, as well. These locations included: (1) Johns Creek, Nonconnah Creek, and the South Sheahan area (fig. 31, area 1); (2) the Wolf River between Sheahan and McCord well fields (fig. 31, area 2); (3) along the Mississippi River near Mallory well field (fig. 31, area 3); and (4) a zone east of Lichterman well field (fig. 31, area 4). The large leakage rates indicated by the simulation agree with other evidence supporting substantial flow between the surficial aquifers and the Memphis aquifer at these locations. Other evidence includes isotopic data, water-level measurements, and thermal anomalies (Graham and Parks, 1986).

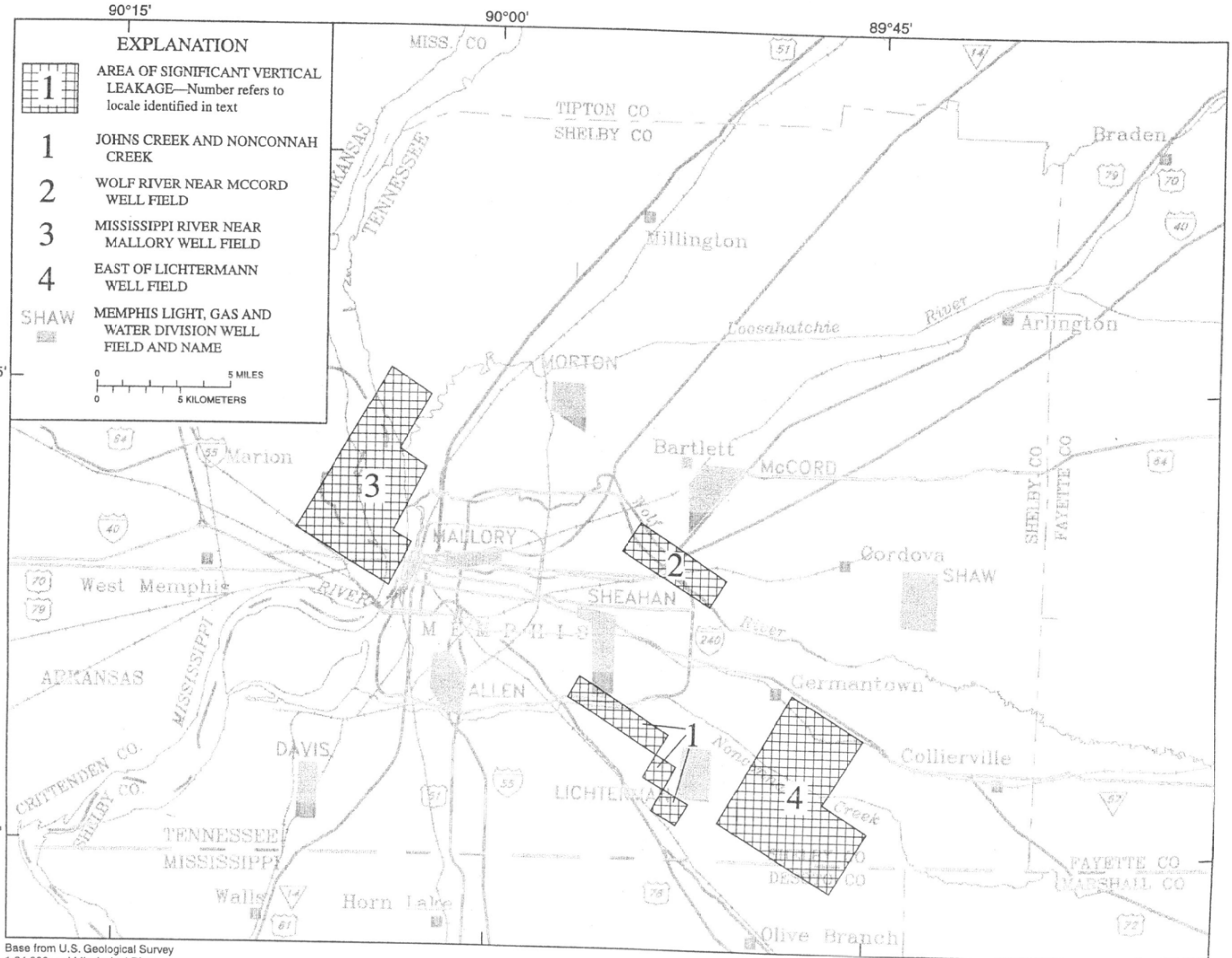
Model Limitations

Models by their very nature are only approximations, and are not exact replicas of natural systems. The success of a model in approximating the natural system is limited by such factors as scale, inaccuracies in estimating hydraulic characteristics and stresses, inaccurate or poorly defined boundary or initial conditions, and the degree of violation of flow-modeling assumptions (P. Tucci, U.S. Geological Survey, written commun., 1988).

For example, the minimum grid block size for this model is about 0.45 mi^2, an area much too large to simulate ground-water levels in individual wells. The model was neither designed for nor should it be used for site-specific applications. It was designed for intermediate to regional evaluation of "average" transient ground-water conditions within the Memphis area, and within this application, the model has been shown to simulate observed conditions to a reasonable degree of accuracy.

Table 4. Water budget calculated by the flow model, 1980, for the Memphis area

Sources and discharges	Flow, in cubic feet per second	Percentage of total
	Memphis Aquifer	
Sources:		
Recharge	106	36
Boundary flux	17	6
Leakage from shallow aquifer	157	54
Leakage from deep aquifer	2	1
Storage	10	3
Total	292	100
Discharge:		
Boundary flux out	3	1
Pumping	289	99
Leakage (net in)	0	0
Total	292	100
	Fort Pillow Aquifer	
Sources:		
Recharge	5	31
Boundary flux in	9	56
Leakage from Memphis aquifer	0	0
Storage	2	13
Total	16	100
Discharge:		
Boundary flux out	0	0
Pumping	14	88
Leakage to Memphis aquifer	2	12
Total	16	100



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 31. Areas of significant vertical leakage in the Memphis area as determined by model calculations.

MS SCT 000355

Selection of model boundary conditions can greatly influence model results. Model boundaries should closely correspond to natural hydrologic boundaries whenever possible (E. Weeks, U.S. Geological Survey, written commun., 1975), and, with the exception of the southern boundary, this concept was a guiding approach that was followed in this (figs. 14 and 15) and previous models of the area (Brahana, 1982a, fig. 5). The variable spacing of the grid, however, has the potential of introducing "average" approximations within the larger grid cells (the largest are about 8 mi^2) that are significantly different than actual conditions. For example, representation of hydrologic features such as divides or drains is difficult in large grid cells, because the feature represents only a small percentage of the total area of the cell. For this reason, any but regional interpretations regarding head and flow in grid cells larger than several square miles should be avoided, and, as with the actual development of the model, emphasis should be limited to the Memphis study area.

Continuing reassessment will be very important in the evolution of the model. As ongoing studies fill the gaps in the data base and improve understanding of this complex flow system, the model can be modified and recalibrated to include those changes. Newly developed techniques of aquifer parameter estimation would be particularly useful as an aid to understanding the system, as would an optimization model (Larson and others, 1977; Lefkoff and Gorelick, 1987). Though the USGS does not develop them, an optimization model might be useful to resource managers in evaluating placement of future well fields and pumping configurations.

Despite the limitations discussed in this section, the model provided useful insights into the workings of the hydrologic system of the study area. Model results support the conceptual model of the ground-water flow system that the Memphis aquifer and Fort Pillow aquifer are partially isolated by the Flour Island confining unit. Leakage between aquifer layers represents a large component of the hydrologic budget (table 4), and if the model is to be used for predictive purposes using pumping configurations with locations significantly different than those tested for the calibration and validation phases, simulated results may vary from measured results. Extreme caution is recommended in interpreting results in such simulations.

SUMMARY AND CONCLUSIONS

The Memphis area has a plentiful supply of ground water suitable for most uses, but the resource may be vulnerable to contamination. Current withdrawals totalling about 200 million gallons per day have caused water-level declines in the major aquifers, increasing the potential for contaminated ground water in the surficial aquifer downward into the major aquifers. This study describes the hydrologic framework, simplifies and conceptualizes the hydrogeologic system to preserve and emphasize the major elements controlling ground-water flow, and quantitatively tests each of the major elements. The main tool for the investigation is a digital ground-water flow model; the ultimate objective of the study is an improved understanding of the factors affecting ground-water flow in the Memphis area.

The hydrogeologic framework of the area consists of approximately 3,000 feet of unconsolidated sediments that fill a regional downwarped trough, the Mississippi embayment. For the most part, the sediments are interbedded clays and sands, with varying amounts of silt, gravel, chalk, and lignite present. On a regional scale, the sediments form a sequence of nearly parallel, sheetlike layers of similar lithology. On a local scale, complex lateral and vertical gradations in lithology are common.

Clays of the Owl Creek Formation, Clayton Formation, Porters Creek Clay, and Old Breastworks Formation effectively define the base of freshwater aquifers. Overlying this base, the hydrogeologic framework includes the Fort Pillow Sand, the Flour Island Formation, the Memphis Sand, the Jackson Formation and upper part of the Claiborne Group, and alluvial and fluvial deposits.

Ground-water flow in this framework of aquifers (sands and gravels) and confining units (clays) is controlled by the altitude and location of sources of recharge and discharge, and by the hydraulic characteristics of the hydrogeologic units. Leakage between the Fort Pillow aquifer (Fort Pillow Sand) and Memphis aquifer (Memphis Sand), and between the Memphis aquifer and the shallow aquifer (alluvium and fluvial deposits) is a major component of the hydrologic budget. Pumping from the Fort Pillow and Memphis aquifers has significantly affected flow in these aquifers in the study area. Net discharge to the Mississippi River alluvial plain from the subcropping Fort Pillow and Memphis aquifers has decreased or ceased since predevelopment time; pumpage has captured most of present-day flow by lowering potentiometric surfaces. The shallow surficial aquifer has not been pumped intensively (<1 Mgal/d), and with the exception of one limited area, is thought to have remained at steady state throughout the period of evaluation.

A three-layer finite-difference flow model was constructed to simulate the regional flow system in the Memphis area. The model area was much larger than the area of immediate concern, so that natural boundaries of the aquifers could be incorporated. Initial conditions, boundary conditions, hydraulic characteristics, and stresses were input values into 58 row by 44 column matrices. The model calculated heads and hydrologic budgets. In the model, the uppermost aquifer layer represents the shallow aquifer. Flow within the shallow aquifer was not simulated; rather, the layer consisted of an array of constant-head nodes representing water levels at steady state during any given stress period. The second and third layers represent the Memphis aquifer and Fort Pillow aquifer, respectively, where horizontal flow was simulated. Layers of the model are separated by leaky confining units. These units are depicted by arrays of leakance terms. Leakance values are high in areas where confining units are thin or absent, and are low in areas where the confining units are thick and hydraulically tight. The model was calibrated and tested using standard accepted practices of the U.S. Geological Survey.

This study has provided an improved understanding of the hydrogeology and ground-water flow in the Memphis and the Fort Pillow aquifers in the Memphis area. Calibration and validation of a multilayer finite-difference flow model indicated that leakage through the upper confining layer was a significant part of the hydrologic budget of the Memphis aquifer. The model attributes more than 50 percent of water withdrawn from this aquifer in 1980 to leakage. Although a significant portion of this leakage occurs near the outcrop area where the confining unit is thin, the implications for the Memphis aquifer remain the same. The potential exists for contamination of the Memphis aquifer in areas where surficial aquifers are contaminated and head gradients favor downward leakage.

Leakage was not uniformly distributed. The assumption of zones of high leakage along the upper reaches of the Wolf and Loosahatchie Rivers, the upper reaches of Nonconnah Creek, and in the area of the surficial aquifer in the Mississippi River alluvial plain was essential in simulating observed water levels in the Memphis aquifer. Geologic and geophysical data from these suspected zones of leakage suggest relatively thin or sandy confining units. On a regional basis, simulated vertical leakage through the upper confining unit was almost an order of magnitude greater than leakage through the lower confining unit.

A significant component of flow (12 percent) from the Fort Pillow aquifer was calculated to occur in the form of upward leakage to the Memphis aquifer. This upward leakage generally was limited to areas near major pumping centers in the Memphis aquifer, where heads in the Memphis aquifer have been drawn significantly below heads in the Fort Pillow aquifer. Although the Fort Pillow aquifer is not capable of producing as much water as the Memphis aquifer for similar conditions, it is nonetheless a valuable resource throughout the area.

The multilayer finite-difference flow model is a valuable tool for hydrogeological research and resource management in the Memphis area. The model integrates boundary conditions as suggested by available information on the geology, hydrology, and water chemistry of the area; it can be updated as new data are collected.

SELECTED REFERENCES

Ackerman, D.J., 1988, Generalized potentiometric surface of the Sparta-Memphis aquifer, eastern Arkansas, spring 1980: U.S. Geological Survey Water-Resources Investigations Report 87-4281, 1 sheet.

———1989, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States—a preliminary assessment of the regional flow system: U.S. Geological Survey Water Resources Investigations Report 88-4028, 74 p.

Albin, D.R. and Hines, M.S., 1967, Water resources of Jackson and Independence Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1838-G, 29 p.

Arthur, J.K. and Taylor, R.E., 1990, Definition of the geohydrologic framework and preliminary simulation of ground-water flow in the Mississippi Embayment aquifer system, Gulf Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 86-4364, 97 p.

Bell, E.A., and Nyman, D.J., 1968, Flow pattern and related chemical quality of ground water in the "500-foot" sand in the Memphis area, Tennessee: U.S. Geological Survey Water-Supply Paper 1853, 27 p.

Boswell, E.H., 1976, The lower Wilcox aquifer in Mississippi: U.S. Geological Survey Water-Resources Investigations 60-75, 3 sheets.

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

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

Brahana, J.V., 1982a, Two-dimensional digital groundwater model of the Memphis Sand and equivalent units, Tennessee, Arkansas, Mississippi: U.S. Geological Survey Open-File Report 82-99, 55 p.

Brahana, J.V., 1982b, Ground water supply, *in* Chapter 3—Final report Memphis metropolitan area urban water resources study: U.S. Army Corps of Engineers, Memphis, Tenn., 30 p.

Brahana, J.V., and Mesko, T.O., 1988, Hydrogeology and preliminary assessment of regional flow in the Upper Cretaceous and adjacent aquifers in the northern Mississippi embayment: U.S. Geological Survey Water-Resources Investigations Report 87-4000, 65 p.

Brahana, J.V., Parks, W.S., and Gaydos, M.W., 1987, Quality of water from freshwater aquifers and principal well fields in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 87-4052, 22 p.

Broom, M.E., and Lyford, F.P., 1981, Alluvial aquifer of the Cache and St. Francis River basins, northeastern Arkansas: U.S. Geological Survey Open-File Report 81-476, 48 p.

Caplan, W.M., 1954, Subsurface geology and related oil and gas possibilities of northeastern Arkansas: Arkansas Geological and Conservation Commission Information Circular 21, 17 p.

Criner, J.H., and Parks, W.S., 1976, Historic water-level changes and pumpage from the principal aquifers in the Memphis area, Tennessee: 1886-1975: U.S. Geological Survey Water-Resources Investigations Report 76-67, 45 p.

Criner, J.H., Sun, P-C.P., and Nyman, D.J., 1964, Hydrology of the aquifer systems in the Memphis Area, Tennessee: U.S. Geological Survey Professional Paper 1779-O, 54 p.

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

Cushing, E.M., Boswell, E.H., Speer, P.R., and Hosman, R.L., and others, 1970, Availability of water in the Mississippi embayment: U.S. Geological Survey Professional Paper 448-A, 13 p.

Dalsin, G.J., and Bettandorff, J.M., 1976, Water for industrial and agricultural development in Coahoma, DeSoto, Panola, Quitman, Tate, and Tunica Counties, Mississippi: Mississippi Research and Development Center Bulletin, 87 p.

Davis, R.W., Lambert, T.W., and Hansen, A.J., 1973, Subsurface geology of the ground-water resources of the Jackson Purchase region, Kentucky: U.S. Geological Survey Water-Supply Paper 1987, 66 p.

Edds, Joe, 1983, Ground-water levels in Arkansas, Spring 1983: U.S. Geological Survey Open-File Report 83-268, 49 p.

Edds, Joe, and Fitzpatrick, D.J., 1986, Maps showing altitude of the potentiometric surface and changes in water levels in the aquifer in the Sparta and Memphis Sand in eastern Arkansas, spring 1985: U.S. Geological Survey Water-Resources Investigations Report 86-4084, 1 sheet.

Fisk, H.N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: U.S. Department of the Army, Mississippi River Commission, 78 p.

Fitzpatrick, D.J., Kilpatrick, J.M., and McWreath, Harry, 1989, Geohydrologic characteristics and simulated response to pumping stresses in the Sparta aquifer in east-central Arkansas: U. S. Geological Survey Water-Resources Investigations Report 88-4201, 50 p.

Franke, O.L., Reilly, T.E., and Bennett, G.D., 1984, Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems—an introduction: U.S. Geological Survey Open-File Report 84-458, 26 p.

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

Graham, D.D., 1979, Potentiometric map of the Memphis Sand in the Memphis area, Tennessee, August 1978: U.S. Geological Survey Water-Resources Investigations Report 79-80, scale 1:125,000, 1 sheet.

———1982, Effects of urban development on the aquifers of the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 82-4024, 20 p.

Graham, D.D., and Parks, W.S., 1986, Potential for leakage among principal aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 85-4295, 46 p.

Halberg, H.N., and Reed, J.E., 1964, Ground-water resources of eastern Arkansas in the vicinity of U.S. Highway 70: U.S. Geological Survey Water-Supply Paper 1779-V, 39 p.

Hines, M.S., Plebuch, R.O., and Lamonds, A.G., 1972, Water resources of Clay, Greene, Craighead, and Poinsett Counties, Arkansas: U.S. Geological Survey Hydrologic Investigations Atlas HA-377, 2 sheets.

Hosman, R.L., Long, A.T., and Lambert, T.W., and others, 1968, Tertiary aquifers in the Mississippi embayment, *with discussions of* Quality of the water by H.G. Jeffrey: U.S. Geological Survey Professional Paper 448-D, 29 p.

Krinitzsky, E.L., and Wire, J.C., 1964, Ground water in alluvium of the Lower Mississippi Valley (upper and central areas): U.S. Army Engineer Waterways Experiment Station Technical Report 3-658, v. 1, 100 p.

Larson, S.P., Maddock, T., and Papadopulos, S.S., 1977, Optimization techniques applied to ground-water development: Memoirs of XIII Congress of International Association of Hydrogeologists, v. XIII, pt. 1, p. E-57 - E-66.

Lefkoff, L.J., and Gorelick, S.M., 1987, AQMAN: Linear and quadratic programming generator using two-dimensional ground-water flow simulation for aquifer management modeling: U.S. Geological Survey Water-Resources Investigations Report 87-4061, 164 p.

Luckey, R.R., 1985, Water resources of the southeast lowlands, Missouri, *with a section on* Water quality by Dale Fuller: U.S. Geological Survey Water-Resources Investigations Report 84-4277, 78 p.

Luckey, R.R., and Fuller, D.L., 1980, Hydrologic data for the Mississippi embayment of southeastern Missouri: U. S. Geological Survey Open-File Report 79-421, 199 p.

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

McKeown, F.A., and Pakiser, L.C., eds., 1982, Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236, 201 p.

McMaster, B.W., and Parks, W.S., 1988, Concentrations of selected trace inorganic constituents and synthetic organic compounds in the water-table aquifers in the Memphis area, Tennessee: U.S. Geological Survey Open-File Report 88-485, 23 p.

Moore, G.K., 1962, Downdip changes in chemical quality of water in the "500-foot" sand of western Tennessee: U.S. Geological Survey Professional Paper 450-C, p. C133-C134.

———1965, Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geological Survey Water-Supply Paper 1809-F, 44 p.

Moore, G.K., and Brown, D.L., 1969, Stratigraphy of the Fort Pillow test well, Lauderdale County, Tennessee: Tennessee Division of Geology Report of Investigations 26, 1 sheet.

Newcome, Roy, Jr., 1971, Results of aquifer tests in Mississippi: Mississippi Board Commission Bulletin 71-2, 44 p.

Newcome, Roy, Jr., 1976, The Sparta aquifer system in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 76-7, 3 sheets.

Nyman, D.J., 1965, Predicted hydrologic effects of pumping from the Lichterman well field in the Memphis area, Tennessee: U.S. Geological Survey Water-Supply Paper 1819-B, 26 p.

Parks, W.S., 1973, Geologic map of the Southwest Memphis quadrangle Tennessee: U.S. Geological Survey open-file report, scale 1:24,000.

———1974, Geologic map of the Southeast Memphis quadrangle, Tennessee: U.S. Geological Survey open-file report, scale 1:24,000.

———1975, Geologic map of the Germantown quadrangle, Tennessee: U.S. Geological Survey open-file report, scale 1:24,000.

———1977a, Geologic map of the Teague quadrangle, Tennessee: U.S. Geological Survey open-file report, scale 1:24,000.

———1977b, Geologic map of the Ellendale quadrangle, Tennessee: U.S. Geological Survey Open-File Report 77-752, scale 1:24,000.

———1978, Geologic map of the Tennessee portion of the Fletcher Lake quadrangle, Tennessee, (including portions of adjacent quadrangles to the north, west, and south): Tennessee Division of Geology Geologic Map 404-SW, scale 1:24,000.

———1979a, Geologic map of the Northeast Memphis quadrangle, Tennessee: U.S. Geological Survey Open-File Report 79-1268, scale 1:24,000.

———1979b, Geologic map of the Tennessee portion of the Northwest Memphis quadrangle, Tennessee: U.S. Geological Survey Open-File Report 79-1269, scale 1:24,000.

Parks, W.S., and Carmichael, J.K., 1989a, Geology and ground-water resources of the Memphis Sand in western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 88-4182, 30 p.

Parks, W.S., and Carmichael, J.K., 1989b, Geology and ground-water resources of the Fort Pillow Sand in western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 89-4120, 20 p.

Parks, W.S., and Carmichael, J.K., 1989c, Geology and ground-water resources of the Cockfield Formation in western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 88-4181, 17 p.

Parks, W.S., and Carmichael, J.K., 1989d, Altitude of potentiometric surface, fall 1985, and historic water-level changes in the Memphis aquifer in western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 88-4180, 8 p.

Parks, W.S., and Carmichael, J.K., 1989e, Altitude of potentiometric surface, fall 1985, and historic water-level changes in the Fort Pillow aquifer in western Tennessee: U.S. Geological Survey Water-Resources Investigations Report 89-4048, 8 p.

Parks, W.S., Carmichael, J.K., and Graham, D.D., 1985, Preliminary assessment of ground-water resources of Lauderdale County, Tennessee: U.S. Geological

Survey Water-Resources Investigations Report 84-4104, 35 p.

Parks, W.S., Graham, D.D., and Lowery, J.F., 1981, Chemical character of ground water in the shallow water-table aquifer at selected localities in the Memphis area, Tennessee: U.S. Geological Survey Open-File Report 81-223, 29 p.

———1982, Installation and sampling of observation wells and analysis of water from the shallow aquifer at selected waste disposal sites in the Memphis area, Tennessee: U.S. Geological Survey Open-File Report 82-266, 32 p.

Parks, W.S., and Lounsbury, R.W., 1976, Summary of some current and possible future environmental problems related to geology and hydrology at Memphis, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 4-76, 34 p.

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

Pernik, Maribeth, 1987, Sensitivity analysis of a multilayer, finite-difference model of the Southeastern Coastal Plain Regional Aquifer System: Mississippi, Alabama, Georgia, and South Carolina: U.S. Geological Survey Water-Resources Investigations Report 87-4108, 53 p.

Plebuch, R.O., 1961, Fresh-water aquifers of Crittenden County, Arkansas: Arkansas Geology and Conservation Commission Water Resources Circular no. 8, 65 p.

Randolph, R.B., Krause, R.E., and Maslia, M.L., 1985, Comparison of aquifer characteristics derived from local and regional aquifer tests: Ground Water, v. 23, no. 3, p. 309-316.

Reed, J.E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geological Survey Hydrologic Investigations Atlas HA-434, 1 sheet.

Russell, E.E., and Parks, W.S., 1975, Stratigraphy of the outcropping Upper Cretaceous, Paleocene, and Lower Eocene in western Tennessee (including descriptions of younger Fluvial deposits): Tennessee Division of Geology Bulletin 75, 118 p.

Ryling, R.W., 1960, Ground-water potential of Mississippi County, Arkansas: Arkansas Geology and Conservation Commission Water Resources Circular no. 7, 87 p.

Schneider, R.R., 1972, Distortion of the geothermal field in aquifers by pumping: U.S. Geological Survey Professional Paper 800-C, p. C267-C270.

Schneider, R.R., and Blankenship, R.R., 1950, Subsurface geologic cross section from Claybrook, Madison County, to Memphis, Shelby County, Tennessee: Tennessee Division of Geology Ground-Water Investigations, Preliminary Chart 1.

Schneider, R.R., and Cushing, E.M., 1948, Geology and water-bearing properties of the "1,400-foot" sand in the Memphis area: U.S. Geological Survey Circular 33, 13 p.

Sorrels, William, 1970, Memphis' Greatest Debate - A Question of Water: Memphis State University Press, 139 p.

Stearns, R.G., 1957, Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi embayment: Geologic Society of America Bulletin, v. 68, p. 1077-1100.

Stearns, R.G., and Armstrong, C.A., 1955, Post-Paleozoic statigraphy of western Tennessee and adjacent portions of the upper Mississippi embayment: Tennessee Division of Geology Report of Investigations no. 2, 29 p.

Stearns, R.G., and Zurawski, Ann, 1976, Post-Cretaceous faulting in the head of the Mississippi embayment: Southeastern Geology, v. 17, no. 4, p. 207-229.

Trescott, P.C., Pinder, F.G., and Larson, S.P., 1976, Finite difference model for aquifer simulation in two dimensions and results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

U.S. Geological Survey, 1936-73, Water levels and artesian pressures in observation wells in the United States: U.S. Geological Survey Water-Supply Papers 817, 840, 845, 886, 907, 937, 945, 987, 1017, 1024, 1072, 1097, 1127, 1157, 1166, 1192, 1222, 1266, 1322, 1405, 1538, 1803, 1978, and 2171.

Weinstein, H.C., Stone, H.L., Kwan, T.V., 1969, Iterative procedure for solution of systems of parabolic and elliptic equations in three dimensions: Industrial Engineering Chemistry Fundamentals, v. 8, no. 2, p. 281-287.

Wells, F.G., 1931, A preliminary report on the artesian water supply of Memphis, Tennessee: U.S. Geological Survey Water-Supply Paper 638-A, 34 p.

———1933, Ground-water resources of western Tennessee, *With a discussion of* Chemical character of the water by F.G. Wells and M.D. Foster: U.S. Geological Survey Water-Supply Paper 656, 319 p.

Brahana and Broshears—HYDROGEOLOGY AND GROUND-WATER FLOW IN THE MEMPHIS AND FORT PILLOW AQUIFERS IN THE MEMPHIS AREA, TENNESSEE—USGS/WRIR 89-4131

Printed on recycled paper

EXHIBIT 18

J.V. Brahana
Digital Ground-Water Model of the Memphis Sand and
Equivalent Units, Tennessee-Arkansas-Memphis

DIGITAL GROUND-WATER MODEL OF THE MEMPHIS SAND AND EQUIVALENT UNITS TENNESSEE-ARKANSAS-MISSISSIPPI

by

J. V. Brahana

Prepared by
U.S. Geological Survey
for
U.S. Army Corps of Engineers
Memphis District
May 1981

3-1.1

CONTENTS

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

Note # indicates that the associated figure will be found in the envelope at the back cover of this appendix.

TABLES

CONVERSION FACTORS

The following report uses the U.S. Customary units for consistency with U.S. Army Corps of Engineers requirements for this administrative report. The units are frequently abbreviated using the notations shown below. The Customary units can be converted to SI units by multiplying by the factors given in the following list.

U.S. Customary unit to convert	Multiply by	To obtain SI unit
Feet (ft)	0.3048	Meters (m)
Feet per second (ft/s)	0.3048	Meters per second (m/s)
Feet per day (ft/d)	3.528×10^{-6}	Meters per second (m/s)
Square feet per second (ft^2/s)	0.0929	Square meters per second (m /s)
Cubic feet per second (ft^3/s)	2.832×10^{-2}	Cubic meters per second (m /s)
Miles (mi)	1.609	Kilometers (km)
Square miles (mi^2)	2.59	Square kilometers (km^2)
Gallons per day (gal/d)	4.384×10^{-8}	Cubic meters per second
Million gallons per day (Mgal/d)	4.384×10^{-2}	Cubic meters per second (m^3/s)
Gallons per day per foot [(gal/d)/ft]	1.438×10^{-7}	Square meters per second (m^2/s)

DIGITAL GROUND-WATER MODEL OF THE MEMPHIS SAND
AND EQUIVALENT UNITS
TENNESSEE-ARKANSAS-MISSISSIPPI

ABSTRACT

A digital model simulating ground-water flow in the Memphis Sand and equipvalent units was constructed and tested for the Memphis metropolitan area and found to simulate historic water levels to at least within 5 feet of observed for 75 percent of the control points. Split-sample testing verified that the model could reproduce water levels for pumping configurations other than those for which it was developed.

Utilization of the model for predictive purposes requires pumping locations and pumping rates and duration. Output includes a tabled computation of water level for each grid node and a contoured map of water level for the area.

The modeling effort refined the concepts of flow in the aquifer. Zones of lower transmissivity were determined during the calibration phase to provide the best overall calculated response. These zones, which closely match the locations of fault zones hypothesized by previous researchers, appear to restrict flow between the aquifer in the Memphis area and to the west in Arkansas. Calibration also indicated that leakage was nonhomogeneous throughout the area. Zones of high leakage along the upper reaches of the Wolf and Loosahatchie Rivers; upper reaches of Nonconnah Creek, and the alluvial aquifer of the Mississippi River alluvial plain were essential in simulating observed water levels. Electric logs from these suspected zones of leakage commonly show thinner confining clays or sandier zones within the confining layer as compared with areas where leakage is low.

INTRODUCTION

The Memphis area has experienced a continuing increase in ground-water withdrawals with resulting water-level declines since 1886, when the first well was completed in the major aquifer, the Memphis Sand. Although the aquifer is capable of supplying the present requirements of almost 195 Mgal/d, its importance as an intensively utilized resource requires that it be effectively managed and protected, particularly in light of anticipated growth in the area.

In response to this requirement, a digital ground-water model that simulated two-dimensional flow in the leaky, artesian Memphis Sand and equivalent units was constructed by the U.S. Geological Survey at the request of the Memphis District, U.S. Corps of Engineers, as part of the Memphis Metropolitan Area Urban Study. This model, described herein, can be used to determine resource adequacy and to help establish a general management plan for usage of ground water from the aquifer.

Previous Studies

Memphis and the surrounding area have been intensively studied with respect to water resources. Some of the more notable works include Wells (1931 and 1933), Kazmann (1944), Schneider and Cushing (1948), Criner and Armstrong (1958), Criner and others (1964), Moore (1965), Nyman (1965), and Bell and Nyman (1968). Particularly helpful was the compilation by Criner and Parks (1976) which summarized pumpage and water-level data for the Memphis area, and the water-level map by Graham (1979). Records of water levels from 1936 through 1973 have been issued periodically in U.S. Geological Survey Water Supply Papers 817, 840, 845, 886, 907, 937, 945, 987, 1017, 1024, 1072, 1097, 1127, 1157, 1166, 1192, 1222, 1266, 1322, 1405, 1538, 1803, 1978, 2171.

Ryling (1960), Plebuch (1961), Halberg and Reed (1964), Halberg (1972) included data describing historic water levels and pumpage from Arkansas; Davis and others (1971) include the same for Kentucky; and Callahan (1973), Dalsin and Bettandorff (1976), and Newcome (1976) provide these data for Mississippi.

Regional and local studies relating to the geology of the Memphis area have been made by Fisk (1944), Caplan (1954), Stearns and Armstrong (1955), Stearns (1957), Cushing and others (1964 and 1970), Boswell and others (1968), Hosman and others (1968), Payne (1968), and Stearns and Zurawski (1976). Krinitzsky and Wire (1964) described the Mississippi River alluvium and its hydrology, and Reed (1972) summarized the results of an analog simulation of the Sparta Sand in the Mississippi Embayment. Parks (1973a, 1973b, 1974, 1975, 1977a, 1977b) has mapped the geology of selected quadrangles within the Memphis area.

Data used in this study that have not been published include electric logs, well completion data, driller's records, geologic logs, summaries of pumping tests, inventories of pumpage, and individual records and maps of historic water levels. These records are primarily in the files of the U.S. Geological Survey, Water Resources Division; Tennessee Division of Geology; Tennessee Division of Water Resources; and Memphis Light, Gas and Water Division (MLGW). Table 1 shows the addresses and phone numbers of these and other agencies which are the primary sources of ground-water and geologic information. Additional sources of unpublished information exist, but they are generally not the primary repository of the data. Table 2 contains a summary of the published reports of the area.

Table 1.--Primary Agencies that maintain ground-water information of the Memphis Area

U.S. Geological Survey - Water Resources Division
(ground water occurrence, water use and 2-dimensional ground water flow model)

Memphis Office
204 Federal Office Building
167 N. Main Street
Memphis, TN 38103
phone (901) 521-3229

Nashville Office
A-413 Federal Building
U.S. Courthouse
Nashville, TN 37203
phone (615) 251-5424

Little Rock Office
Room 2301 Federal Office Building
700 W. Capitol Avenue
Little Rock, AR 72201
phone (501) 378-6391

Jackson Office
Suite 710 Federal Building
100 West Capitol Street
Jackson, MS 39201
phone (601) 960-4600

Tennessee Department of Conservation - Division of Geology (geologic data)

Memphis Office
c/o Earthquake Information Center
Memphis State University
Memphis, TN 38152
phone (901) 454-2779

Nashville Office
G5 State Office Building
Nashville, TN 37219
phone (615) 741-2726

Tennessee Department of Conservation - Division of Water Resources
(well completion data, water use; ground water data)

Memphis Office
1109 A State Office Building
Memphis, TN 38103
phone (901) 529-7294

Nashville Office
4721 Trousdale Drive
Nashville, TN 37219
phone (615) 741-6860

Memphis Light, Gas, and Water Division
(drilling information, pumping, water level data)

P.O. Box 430
Memphis, TN 38101
phone (901) 528-4011

U.S. Army - Corps of Engineers
(well drilling information, stratigraphy, lithology - primarily concentrated in alluvial plain of Mississippi River - 2 dimensional ground-water flow model)

Memphis District
U.S. Army Engineer District, Memphis
Corps of Engineers
668 Clifford Davis Federal Building
Memphis, TN 38103
phone (901) 521-3635

Table 2.--A SUMMARY OF PUBLISHED GROUND-WATER AND GEOLOGIC REPORTS OF THE MEMPHIS AREA

Subject Area	General Hydrology	Water Levels	Pumpage	General Geology	Water Quality	Modeling Studies
Regional-Mississippi Embayment	Cushing & Others, 1970 Hosman & Others, 1968 Payne, 1968 Boswell & Others, 1968 Krinitsky & Wire, 1964	General Hydrology references contain water levels	General Hydrology references contain pumpage	Fisk, 1944 Stearns, 1957 Cushing & Others, 1964	General Hydrology references contain water quality	Reed, 1972 Brahana, 1978 Brahana, 1981
West Tennessee	Wells, 1933 Moore, 1965	General Hydrology references contain water levels	General Hydrology references contain pumpage	Stearns & Armstrong, 1955 Stearns & Zurawski, 1976	Wells, 1933 Moore, 1965	
Shelby County, Tennessee and Memphis	Wells, 1931 Kazmann, 1944 Schneider & Cushing, 1948 Criner & Armstrong, 1958 Criner, Sun & Nyman, 1964 Nyman, 1965 Bell & Nyman, 1968	USGS WSP 817, 840, 845, 886, 907, 937, 945, 987, 1017, 1024, 1072, 1097, 1127, 1157, 1166, 1192, 1222, 1266, 1322, 1405, 1538, 1803, 1978, 2171 Criner & Parks, 1976 Graham, 1978	Criner & Parks, 1976	Parks, 1973a; 1973b; 1974; 1975; 1977a; 1977b	Bell & Nyman, 1968 Criner, Sun & Nyman, 1964 Parks & Lounsbury, 1976 Waste Age, 1979 Parks, Graham & Lowery, 1981	Brahana, 1981
North Mississippi	Dalsin & Bettandorff, 1976 Newcome, 1976 Boswell, 1977 Dalsin, 1978	General Hydrology references contain water levels	Callahan, 1973		General Hydrology references contain water quality	
East Arkansas	Plebuch, 1961 Ryling, 1960 Halberg & Reed, 1964	General Hydrology references contain water levels	Halberg, 1972 Halberg, 1977			

Description of the Study Area

The study area is centered within the Memphis metropolitan area, and includes approximately 1,000 square miles in Shelby County, Tenn., and parts of adjacent counties. Figure 1 shows the general location of the study area; county boundaries and identification are given in figure 6. This area approximately coincides with the Corps of Engineers' metro study area. Although a much larger area simulating the natural boundaries of the regional aquifer system was incorporated in the model, it is described in this report only in its hydrologic relationship to the Memphis area.

Geologic Setting

The study area is near the center of the northern half of the Mississippi Embayment, a structural trough that has been filled by about 3,000 feet of unconsolidated gravel, sand, silt, and clay. The trough axis strikes 30° east of north, with the present course of the Mississippi River approximately marking the axis. Near Memphis, the axis of the embayment plunges southwestward at about 10 feet/mile.

Fisk (1944), Criner and others (1964), and Stearns and Zurawski (1976) are among researchers who feel there is evidence for faulting in the study area. However, abrupt facies changes, lack of marker beds, and vertical lithologic similarity of sediments make positive fault definition difficult.

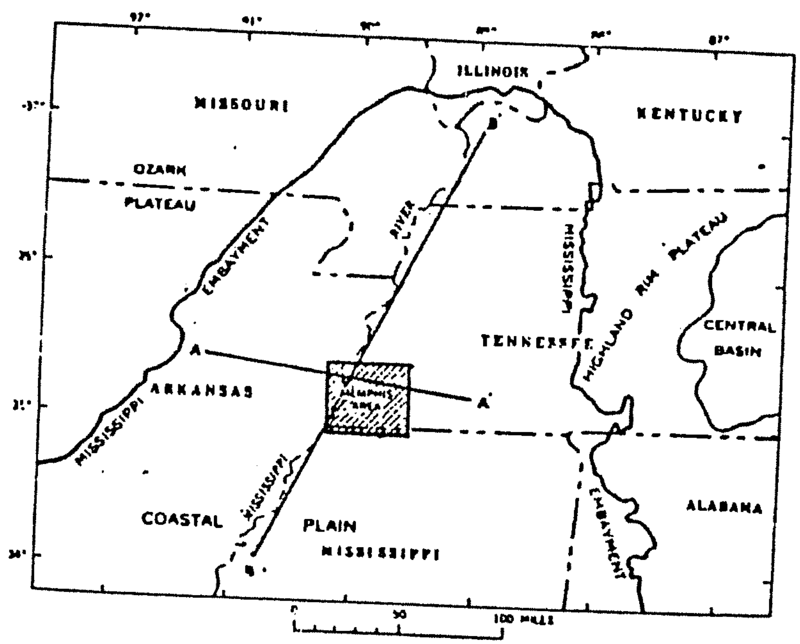


Figure 1.--Location of the study area showing generalized lines of section A-A' and B-B'.

Stratigraphically, the study is limited to the Memphis Sand, and to those geologic units that may have a direct hydrologic relationship to the Memphis Sand (table 3). This formation which ranges from 500 to 880 feet thick in the Memphis area (Criner and Parks, 1976), is made up of fine- to coarse-grained sand and subordinate lenses of clay and lignite. Geophysical logs of many wells indicate that the lower part of the Memphis Sand may contain some clay beds that are areally more extensive than those in the upper part of the formation. Even the thickest of the clay beds is discontinuous, however, and the Memphis Sand is considered a single hydrologic unit (Criner and others, 1964).

At most places in the study area, the Memphis Sand is overlain by beds of clay, sandy clay, fine-grained sand, and lignite that are assigned to the undifferentiated upper part of the Claiborne Group and the Jackson Formation. Within the Memphis area this sequence of beds forms a zone that varies in thickness from 350 feet at Mallory well field to a feather edge where it pinches out in southeastern Shelby County. Where present, these fine-grained sediments retard the downward movement of water from the overlying formations and form the upper confining bed for the Memphis Sand. Geophysical logs of wells throughout the area show that both the thickness and nature of the confining bed are variable.

Southward from the study area, the Memphis Sand and its equivalent units thicken along the axis of the Mississippi Embayment. The units crop out on the east side of the embayment; on the west side they have been extensively eroded and truncated, and younger Mississippi River alluvial sediments have been deposited on top of them. This contact is called a subcrop, and occurs throughout the subsurface in the Mississippi

Table 3.--Post-Midway geologic units underlying the Memphis area and their hydrologic significance.

SYSTEM	SERIES	GROUP	STRATIGRAPHIC UNIT	THICKNESS (feet)	LITHOLOGY AND HYDROLOGIC SIGNIFICANCE
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Sand, gravel, silt, and clay. Underlies the Mississippi River alluvial plain and the flood plains of other streams in the area. Supplies water to a few domestic and industrial wells. Could be an important source of water for irrigation and some industrial uses.
	Pleistocene		Loess	0-65	Wind-deposited silt; silty clay and minor sand. Forms a blanket over the fluvial deposits in upland areas; topographically higher than alluvium. Thickest on the bluffs that border the Mississippi River alluvial plain; generally thinner towards the east. Not a source of groundwater.
Quaternary and Tertiary	Pleistocene and Pliocene		Fluvial deposits (terrace deposits)	0-100	Sand and gravel; minor ferruginous sandstone. Underlies the upland areas in a broad, irregular belt east of the Mississippi River alluvial plain; may be locally absent. Supplies water to many shallow, small-capacity wells in suburban and county areas.
Tertiary	Eocene	? Claiborne	Jackson Formation and upper part of Claiborne Group ("capping clay")	0-350	Gray, bluish-gray, greenish-gray, and tan clay; subordinate beds of fine-grained sand and lignite. Supplies water to some small-capacity wells. Generally considered to be of low permeability and to confine water in Memphis Sand. Absent in southeastern part of Memphis area.
			Memphis Sand ("500-foot" sand)	500-880	Fine-to coarse-grained sand; subordinate lenses of clay and minor amounts of lignite. Thick clay bed locally in lower part; coarse sand lenses locally at base. Very good aquifer supplying 95 percent of water used in Memphis area.
		Wilcox	Flour Island Formation	160-350	Gray, greenish-gray, and brown carbonaceous clay. Locally contains fine-grained sand lenses and some lignite. Serves as lower confining bed for Memphis Sand and upper confining bed for Fort Pillow Sand.
	?		Fort Pillow Sand ("1,400-foot" sand)	210-280	Fine- to medium-grained sand; minor amounts of lignite and and some clay lenses. Second principal aquifer supplying about 3 percent of water used in Memphis area.
	Paleocene		Old Breastworks Formation	200-250	Gray, greenish-gray, and brown carbonaceous clay. Contains some lignite and is sandy near top. Lower confining bed for water in Fort Pillow Sand.

SOURCE: Parks, Graham, & Lowery, 1981

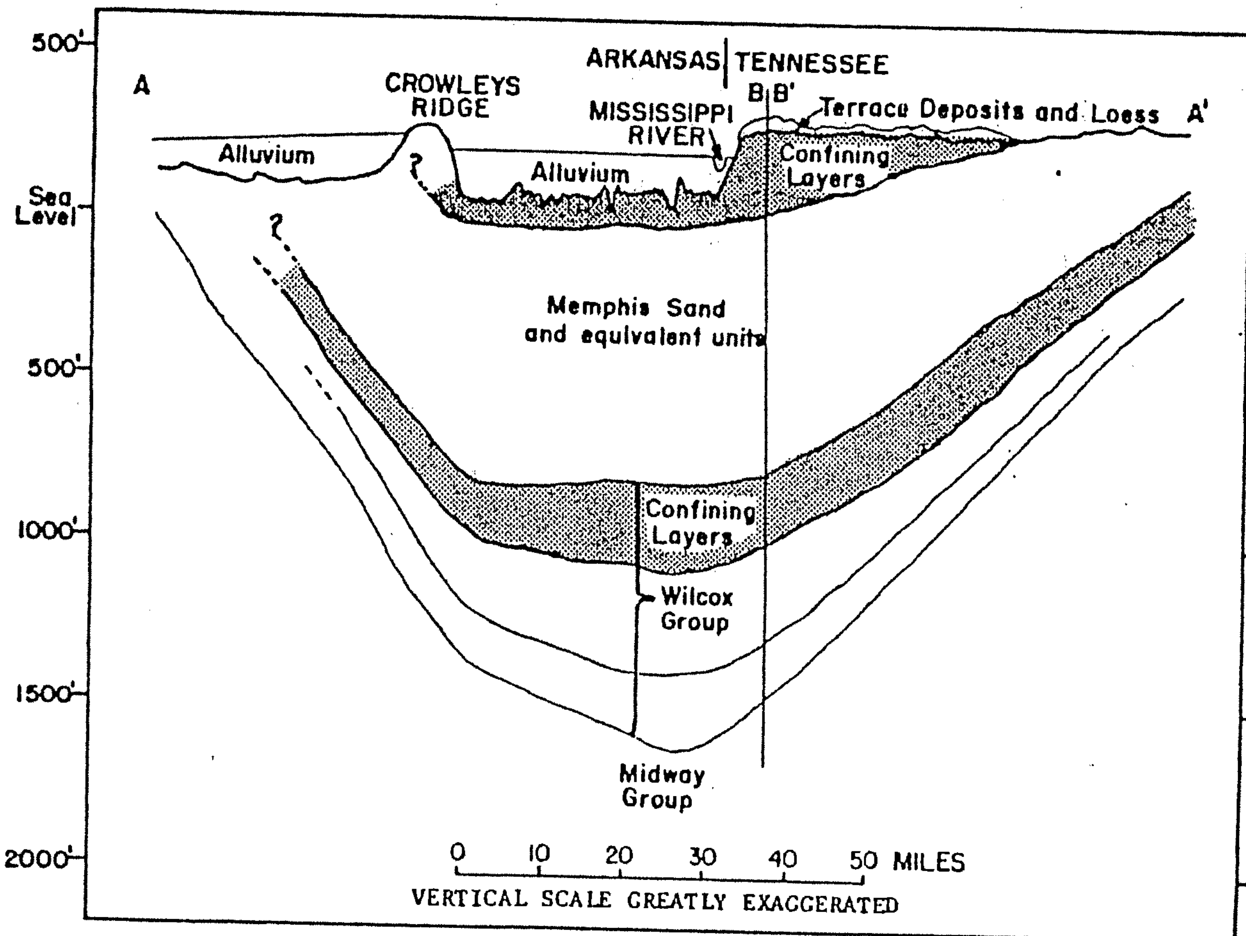


Figure 2.--Generalized cross-section from west to east along line A-A'.

River alluvial plain except where a segment crops out at the surface as part of Crowleys Ridge in Arkansas (Hosman and others, 1968). These generalized relationships are shown in figure 2.

South of Memphis, approximately along lat 35°N, a zone of transition (facies change) occurs in the Memphis Sand. The middle sand units become increasingly clayey, and effectively separate the top sand unit from the bottom sand unit. In Arkansas, the interval equivalent to the Memphis Sand includes the Carrizo Sand, the Cane River Formation, and the Sparta Sand; and in Mississippi, the Tallahtta Formation, Winona Sand, Zilpha Clay, and Sparts Sand (Hosman and others, 1968). For the purposes of this report, the Memphis Sand and its equivalent units in Arkansas and Mississippi are herein called the Memphis Sand. In the area of Memphis, the entire section of sand from the top of the Wilcox Group to the bottom of the "capping clay" of the Jackson Formation and upper part of the Claiborne Group constitutes a single aquifer hundreds of feet thick (Hosman and others, 1968). Figure 3 is a generalized geologic section along the SW-NE trending line B-B' (fig. 1) that illustrates the above-mentioned relationships.

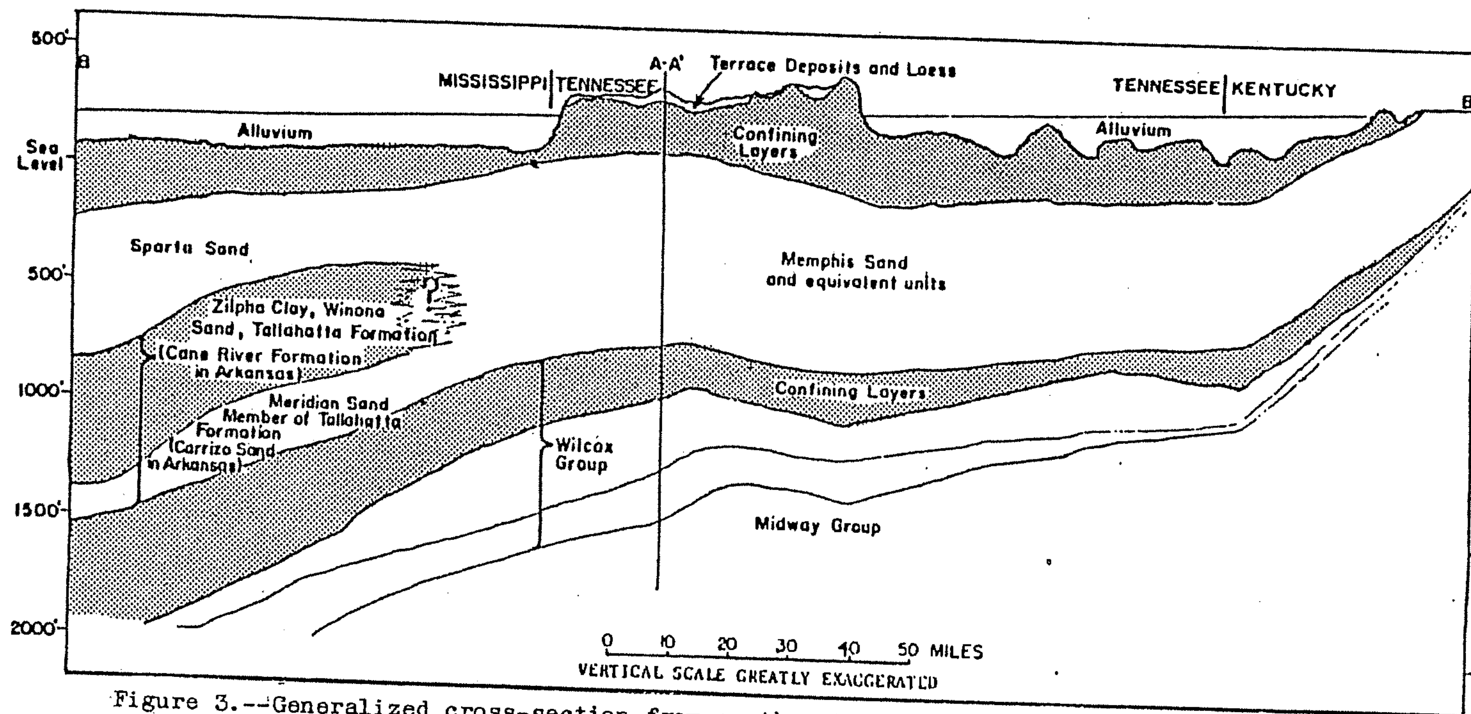


Figure 3.--Generalized cross-section from southwest to northeast along line B-B'.

Precipitation, Runoff, and Recharge

Precipitation serves as the ultimate source of recharge to the Memphis Sand. Mean annual precipitation is more than 48 inches/year in the Memphis area, and most occurs during the winter and spring. Droughts and low-flow conditions in streams are common during the late summer and fall. Low-flow studies in the area (Gold, 1978) have indicated that from 5 to 7 inches/year recharge the shallow aquifers where they outcrop north and east of the study area; most of this follows a fairly shallow ground-water path and reemerges as base flow of streams during the drier parts of the year. A small percentage of this recharge becomes part of the deep circulation pattern.

Hydrographs of wells tapping the Memphis Sand are characteristically sinusoidal: high during periods of recharge in the winter and spring, and low during the periods of greatest stress, during summer and fall. On a long-term basis, such as employed by the model, the effect of the seasonal variations cancel each other leaving the general water-level decline due to pumping as the dominant feature on the hydrograph.

Flow data from streams that drain the outcrop area of the Memphis Sand suggest that, during most of the year, the Wolf and Loosahatchie Rivers and Nonconnah Creek derive flow from ground-water discharge. Total discharge including storm runoff averages about 20 inches/year for these three streams. The upper Wolf, the upper Loosahatchie, and Nonconnah above the confluence with John's Creek, lose flow to the Memphis Sand during the dry season at points along their reaches where the confining beds are absent.

Shallow ground-water aquifers likewise interact with the Memphis Sand in the area where it is confined. The confining beds that separate the shallow aquifers from the Memphis Sand have a variable thickness and permeability (hydraulic conductivity). Where the confining beds are thinner and more permeable, and head conditions are favorable, a significant amount of water may leak into or out of the Memphis Sand.

Water levels and water quality in the alluvium and Memphis Sand directly west of Memphis in eastern Arkansas are consistent with water being transmitted from the alluvium into the Memphis Sand. Likewise in the Memphis metropolitan area, similar water-level responses in the shallow terrace aquifers and the Memphis Sand suggest that leakage is recharging the confined aquifer here as well.

Discharge from the Memphis Sand into the alluvium occurs when head is greater in the Memphis Sand than in the alluvium. The Memphis Sand is thought to be discharging into the alluvium along much of the area where the Memphis Sand subcrops beneath the alluvium in Arkansas and Missouri (fig. 2).

BASIC MODELING CONCEPTS

The model of the Memphis Sand described in this report is based on the numerical approximations of the two-dimensional differential equation describing ground-water flow. The boundaries, aquifer properties, initial conditions, and pumping are input to the equations, and resulting drawdowns and heads are calculated. Adjustment of the input parameters in the calibration phase of the study optimizes the response calculated by the model to the response actually observed in the field. Split sample testing and a sensitivity analysis of the model as a final step verified it as a tool capable of predicting water levels for pumping stresses different from those for which it was developed.

Because the model is an abstraction of a physical process, because it involves less than complete definition of the system, because it involves approximations and assumptions, and because the responses it gives are subject to misinterpretation, it is important to define each of the steps that go into its creation, and particularly, to point out its capabilities and limitations.

From Pinder and Bredehoeft (1968), the equation for transient two-dimensional flow of a homogeneous compressible fluid through a nonhomogeneous, anisotropic aquifer may be written as equation 1:

(Equation 1)

in which

Txx, Txy, Tyx, Tyy	are the components of the transmissivity tensor (L t-);
h	is hydraulic head (L);
S	is the storage coefficient (dimensionless);
W(x,y,t)	is the volumetric flux of recharge or withdrawal per unit surface area of the aquifer (Lt-).

Considering only fluxes of: (1) direct withdrawal of recharge, such as well pumpage, well injection, or evapotranspiration, and (2) steady leakage into or out of the aquifer through a confining layer or streambed, then W(x,y,t) may be expressed as:

$$W(x,y,t) = Q(x,y,t) - \frac{K_z}{m}(H_s - h)$$

where Q is the rate of withdrawal (positive sign) or recharge (negative sign), L/t;

K_z is the vertical hydraulic conductivity of the confining layer or streambed, L/t;

m is the thickness of the confining layer or streambed; L; and

H_s is the hydraulic head in the source bed or stream, L.

In the sinulation model, equation 1 is simplified by assuming that the Cartesian coordinate axes x and y are alined with the principal components of the transmissivity tensor, Txx and Tyy, giving

(Equation 2)

An exact solution to equation 1 is not possible mathematically because of the variable aquifer properties and variable boundary conditions, but a numerical solution of high accuracy offers an alternative that is practical for use on a digital computer. In this numerical method, the aquifer system parameters and boundaries, which are continuous in the field and as represented by equation 2, are replaced with a set of discrete values for each of the parameters and for the boundary. Determination of the values for these sets is accomplished by dividing the area into small rectangular subareas by means of a orthogonal grid, and taking the average value of each parameter in each block of the grid.

Equation 3 (Pinder and Bredehoeft, 1968) is the general form of the numerical method into which the appropriate discrete values are substituted and solved for each block in the grid. The equation yields head values calculated as finite-difference approximations to the continuous derivatives at a point (the node at the center of the block). Input values of appropriate hydrologic parameters represent average values for the entire block. Equation 2 may be approximated by equation 3, which is given as:

$$T_{xx[i-(1/2),j]}\left[\frac{h_{i-1,j,k} - h_{i,j,k}}{(\Delta x)^2}\right]$$

$$+ T_{xx[i+(1/2),j]}\left[\frac{h_{i+1,j,k} - h_{i,j,k}}{(\Delta x)^2}\right]$$

$$+ T_{yy[i,j-(1/2)]}\left[\frac{h_{i,j-1,k} - h_{i,j,k}}{(\Delta y)^2}\right]$$

$$+ T_{yy[i,j+(1/2)]}\left[\frac{h_{i,j+1,k} - h_{i,j,k}}{(\Delta y)^2}\right]$$

$$= S\left[\frac{h_{i,j,k} - h_{i,j,k-1}}{\Delta t}\right]$$

$$+ \frac{q_{\omega(i,j)}}{\Delta x \Delta y} - \frac{K_z}{m}\left[H_{s(i,j)} - h_{i,j,k-1}\right] \qquad \text{(Equation 3)}$$

where i,j,k are indices in the x-, y-, and time-dimensions, respectively;

$\Delta x, \Delta y, \Delta t$ are increments in the x-, y-, and time-dimensions, respectively; and

q_ω is the volumetric rate of withdrawal or recharge at the (i,j) node, L^3/t.

A modified version of a computer program written and documented by Trescott and others (1976) was used for the analysis of the Memphis Sand. The Trescott, Pinder, Larson model offers several solutional schemes to solve equation 3; the strongly implicit procedure (Stone, 1968) was used because of its computational efficiency.

DEVELOPMENT OF THE MEMPHIS SAND GROUND-WATER MODEL

Conceptual Model

A conceptual model serves as the basic framework for developing a digital ground-water model. The conceptual model possesses the significant hydrologic features essential to define accurately ground-water flow within an aquifer, yet at the same time it is much less complex than the real aquifer.

The conceptual model of regional flow prior to pumping in the Memphis Sand is shown in figure 4. Historical water-level maps were used to determine original flow directions and to locate sources of recharge and discharge (Hosman and others, 1968; Reed, 1972; Criner and Parks, 1976). The regional flow system was characterized by movement from the outcrop area of the aquifer in western Kentucky and Tennessee toward the axis of the embayment and from there to areas of discharge. The initial discharge areas were the area of the subcrop in Missouri and Arkansas, and upward leakage where the overlying confining beds as were thin and sandy. Some flow is presumed to have continued across the southwestern boundary of the model area.

Transient conditions associated with pumping are thought to have dominated the system since 1886, when the first wells were drilled and pumped. From 1886 to 1975 pumpage at Memphis had drawn down the original potentiometric surface by as much as 150 feet in the major pumping center and reversed the original gradient, which was to the west (Criner and Parks, 1976). Flow that moved through the area toward natural discharge points to the south and west before 1886 is now diverted and captured by pumpage at Memphis.

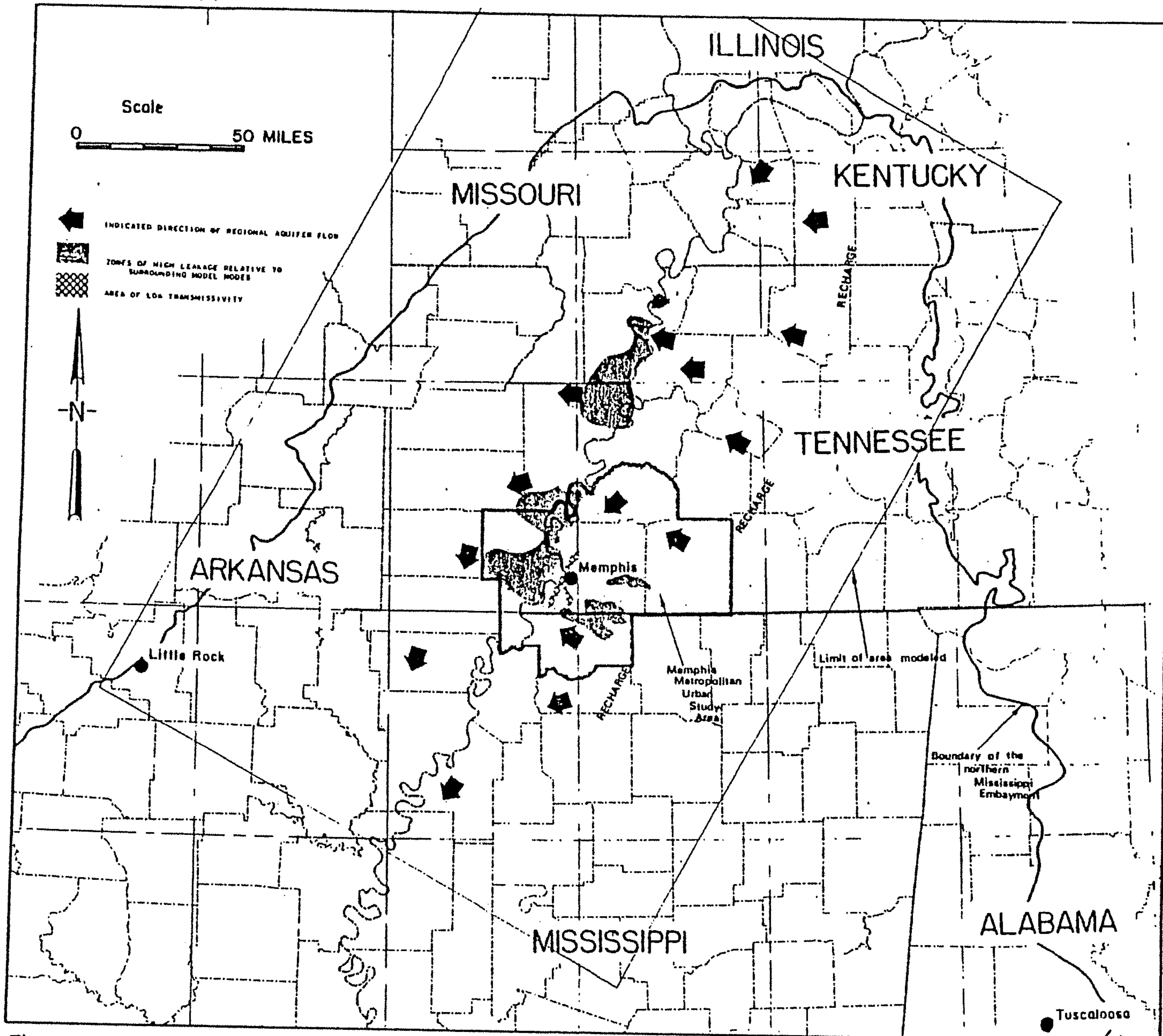


Figure 4 REGIONAL CONCEPTUAL FLOW MODEL OF THE MEMPHIS SAND

MEMPHIS METROPOLITAN URBAN AREA
DEPARTMENT OF THE ARMY
MEMPHIS DISTRICT, CORPS OF ENGINEERS, MEMPHIS, TENNESSEE
JULY 1981 Serial: 21724 File: 209A/58
PLATE Number 2 of 8

Leakage to and from the Memphis Sand is thought to occur at locations where head differences, confining bed thicknesses, and confining bed permeabilities (hydraulic conductivities) are favorable. Leakage is assumed to occur primarily through the upper confining layer (capping clay), and three-dimensional modeling has confirmed this assumption. No accommodation was made in this model for leakage through the Flour Island Formation, which is the lower confining layer to the Memphis Sand. Evidence for leakage includes greater than expected vertical hydraulic conductivity calculations from aquifer tests, observed water levels at altitudes higher than expected for known pumping rates and transmissivities, assymmetric water level response to pumping, and similarity of water levels and water chemistry between parts of the Memphis Sand and the alluvium (Ryling, 1960; Plebuch, 1961). Drilling records from exploration wells made by the Corps of Engineers in the Mississippi River alluvial valley and electric logs from water and oil wells indicate a highly variable thickness of the confining bed and note its complete absence in some places (Krinitsky and Wire, 1964).

Evidence from pumping tests and grain size analyses of core samples (Criner and others, 1964; Moore, 1965; Bell and Nyman, 1968) as well as drilling records and the combined drawdown-pumping history records from Memphis indicate that the aquifer has a large hydraulic conductivity, but is not homogeneous. Faulting, which is suspected (Fisk, 1944; Criner and others, 1964; Stearns and Zurawski, 1976), may contribute to the nonhomogeniety.

Digital Model

In the case of the Memphis Sand, the area was divided into discrete blocks and a form of equation 3 was solved at each block for specified boundaries, initial conditions, aquifer hydraulic properties, and pumping stresses.

Characteristics of the Model

The Model Grid

The rectangular grid which defines the arrangement of blocks in the model is alined parallel and perpendicular to the axis of the Mississippi embayment, and divides are area of almost 47,000 mi^2 into a 44 x 58 matrix (fig. 5). Spacing of the grid lines varies from 100,000 feet at the margins of the area to 3,200 feet within metropolitan Memphis.

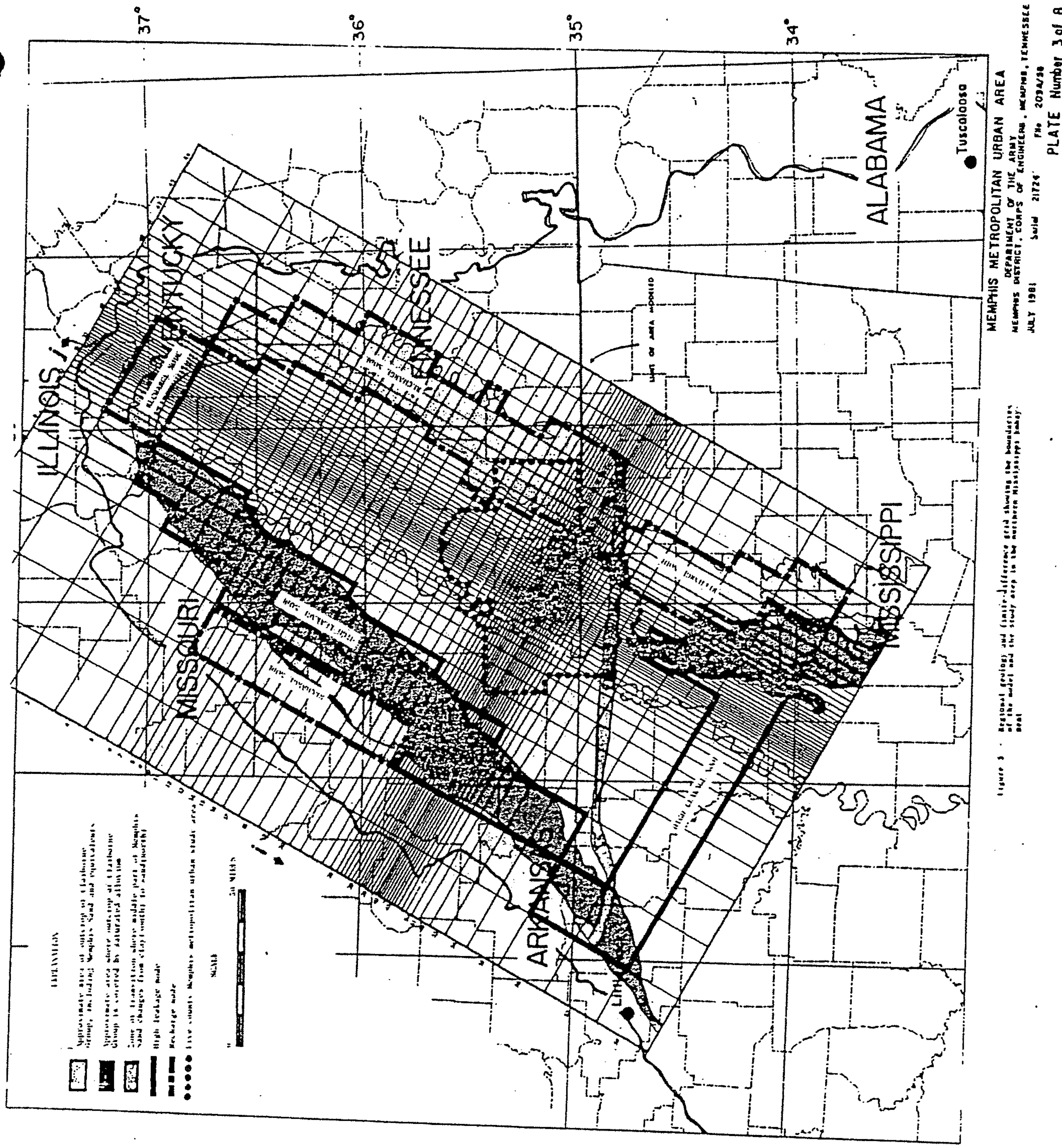
The grid is closely spaced throughout the primary area of interest and is shown in figure 6 along with the location of pumping centers and control wells. The closer spacing allows a more refined input of pumping stresses to be placed on the model as well as more precise prediction of the resulting water levels in the aquifer. The grid spacing is adequate to define the response of major pumping centers as required by this study, but it is not suitable for defining individual wells within a well field. Pumping is input as the total of all wells represented as a single well for the block, and it is centered in the middle of the block. By convention, centers of the blocks are called nodes. Any specific node may be located by designating its row (i) and column (j) location. For example, Davis well field (fig. 6) in southwest Memphis is located in node (50, 17).

All of the aquifer parameters and head values of each block represent an average value over the entire block. This approximation requires that precise well location be known, especially in the areas of steep water level gradients and intensive pumping.

Boundaries of the model

The model is bounded on the north, east, and west by a representation of the natural boundary between the Memphis Sand the overlying confining bed (figure 5). The boundary toward the south has no geologic significance; it was chosen for its hydrologic homogeniety, its distance from Memphis, and its lack of effect on the Memphis metropolitan area.

The boundary on the north and east is represented by recharging blocks with unconfined storage coefficients that correspond to the outcrop of the Memphis Sand. These recharge cells provide the deep circulation that is influx to the confined aquifer and they form a constant flux boundary in which head may vary with different pumping periods. Flow from these cells also contributes to the base flow of streams in the outcrop area. Major streams in the outcrop area are represented as constant head nodes. In locations near the outcrop area where the upper confining bed is discontinuous, there is a transitional zone of semi-confined conditions. Vertical leakage occurs where the confining bed is thin or absent in the area; otherwise, the aquifer is represented as confined.



See envelope at the back cover for oversize Figure 6.

The subcrop of the Memphis Sand beneath the alluvium to the west is modeled as a zone of high leakage. This simulates natural discharge from the aquifer for most nodes. The subcrop of the Memphis Sand is discontinuous in the nodes corresponding to Crowley's Ridge. At that location, the aquifer crops out and is recharged; these are modeled as constant flux.

The southern boundary of the Memphis Sand is modeled as a zone of high leakage in row 57 of the overlying confining bed to simulate under flow out of the system. While this does not reflect the geology closely, the hydrologic representation is valid.

Aquifer Characteristics Modeled

Data used in the model were derived from numerous published and unpublished investigations made in the area (table 4). Because parts of the area have been studied by different researchers, disagreement as to the validity of certain data and conclusions exists. After evaluation, these data were plotted and contoured on a base map of the study area. The grid was superimposed and values were assigned by interpolation and weighted mean methods for each grid block.

The following parameters were input to the model as individual values for each grid block:

(1) initial head - the altitude of the water level in the Memphis Sand prior to pumping (1886),

(2) the storage coefficient of the aquifer,

(3) the transmissivity of the aquifer,

(4) the vertical hydraulic conductivity of the confining bed,

(5) the head in the unconfined aquifers or rivers overlying the Memphis Sand,

(6) the thickness of the confining bed separating the unconfined alluvial aquifer from the Memphis Sand;

(7) the recharge to the aquifer from precipitation, simulated by constant flux cells and the discharge from the area, simulated by leakage out, and

(8) the discharge from pumping.

Table 4 defines the source of these input data and the range for each parameter used in the model.

Stresses on the System

Pumpage from the Memphis Sand began in 1886 when the Bohlen Huse Ice Company drilled a well in downtown Memphis. Since that time, pumpage from the aquifer has occurred at varying rates and with a changing areal distribution of pumping centers. Because of variation with time, pumpage data were introduced in the model in seven discrete pumping periods. The modeled pumpage and the corresponding amount actually pumped for the seven periods are shown in figure 7.

The pumping periods were based on abrupt changes in pumpage rates, or variations in the areal distribution of pumping centers, and on availability of water-level maps. Pumping period duration, the historic amount pumped, in millions of gallons per day, and the pumpage simulated in the model are given in table 5. Variations between historic amount pumped and modeled amount pumped are less than 1 percent of total pumpage prior to 1965. Differences are due to round-off errors of simulated pumpage for which the withdrawal location was not known.

Although the exact pumping location was not always known, the centers of pumping were fairly well defined. The unlocated pumpage was assigned to nodes that fell within those pumping centers.

TABLE 4.--DESCRIPTION OF INPUT PARAMETERS

PARAMETERS	RANGE OF PARAMETER	GENERALIZED SENSITIVITY OF MODEL TO RANGE OF PARAMETER	BASIS OF PARAMETER DEFINITION	SOURCE OF DATA	COMMENTS
Initial Head	125 to 400 (Feet above MSL)	Low (Drawdown) Highly Sensitive (W.L. Maps)	4 Points All Extrapolated	Criner & Parks, 1976 Reed, 1972 Chester & Fleming, 1920 Wells, 1931 & 1933	Maps are based on few data points, with none west of the Mississippi River in Arkansas. Water quality data and geology are used to reconstruct some flow directions.
Storage Coefficient	.00055 to .001	Low	Existing maps Unpublished pumping tests	Reed, 1972 Payne, 1968 Cushing, unpub. map Moore, 1965 Unpub. USGS records	Maps constructed by Cushing & Reed assumed to be proportional to thickness of the aquifer for confined areas.
Transmissivity	1300 to 60,000 (ft^2/d)	Moderately Sensitive	Existing maps Published and unpublished pumping tests	Reed, 1972 Reed, unpub. map Cushing, unpub. map Moore, 1965 Unpub. USGS records	Transmissivity maps based on thickness of sands and on scattered aquifer test results. Cushing's data used north of 35 N. lat.
Hydraulic Conuctivity of Confining Bed	8.6×10^{-5} to 2×10^{-2} (ft/d)	Highly Sensitive	Calibration Acceptable range from modeling literature No direct observation	Krinitzsky and Wire, 1964 Unpub. USGS records	This factor, as in most modeling studies, is poorly defined at best. Slight changes in input affect model results very markedly. With reasonable values input for the other parameters, this parameter can be obtained from the model.
Head in Overlying Aquifer	159 to 312 (feet)	Low	Maps - mean w. l. Published and unpublished water levels (100 points)	Krinitzsky and Wire, 1964 Unpub. USGS records	Based on mean water levels, these values are fairly well defined but are subject to natural variation of as much as tens of feet.
Thickness of Confining Bed	45 to 180 (feet)	Low	Bore hole records E-log records (100 points)	Krinitzsky and Wire, 1964 Unpub. USGS records	Original data from Corps of Engineers bore holes (in Mississippi River alluvial plain) and from unpublished USGS E-logs.
Boundary Flux	0.9×10^{-9} 1.0×10^{-6} (ft^3/sec)	Moderately sensitive	Calibration Extrapolated from water budget studies No direct observations	Unpub. USGS records	Most of the precipitation that falls and infiltrates on the outcrop area reemerges as base flow of the streams draining the area. This parameter represents deep infiltration for the node. All data are indirect.
Pumpage Rates	50,000 to 25,000,000 (gal/d)	Highly Sensitive	Empirical Water use inventories	Criner & Parks, 1976 Callahan, 1973 Unpub. USGS records	Data sources include ongoing inventories in Shelby County & Mississippi & Arkansas. Rural Tennessee based on an updated study in 1976. Historic data is variable, with better records for the most part in the area of study.

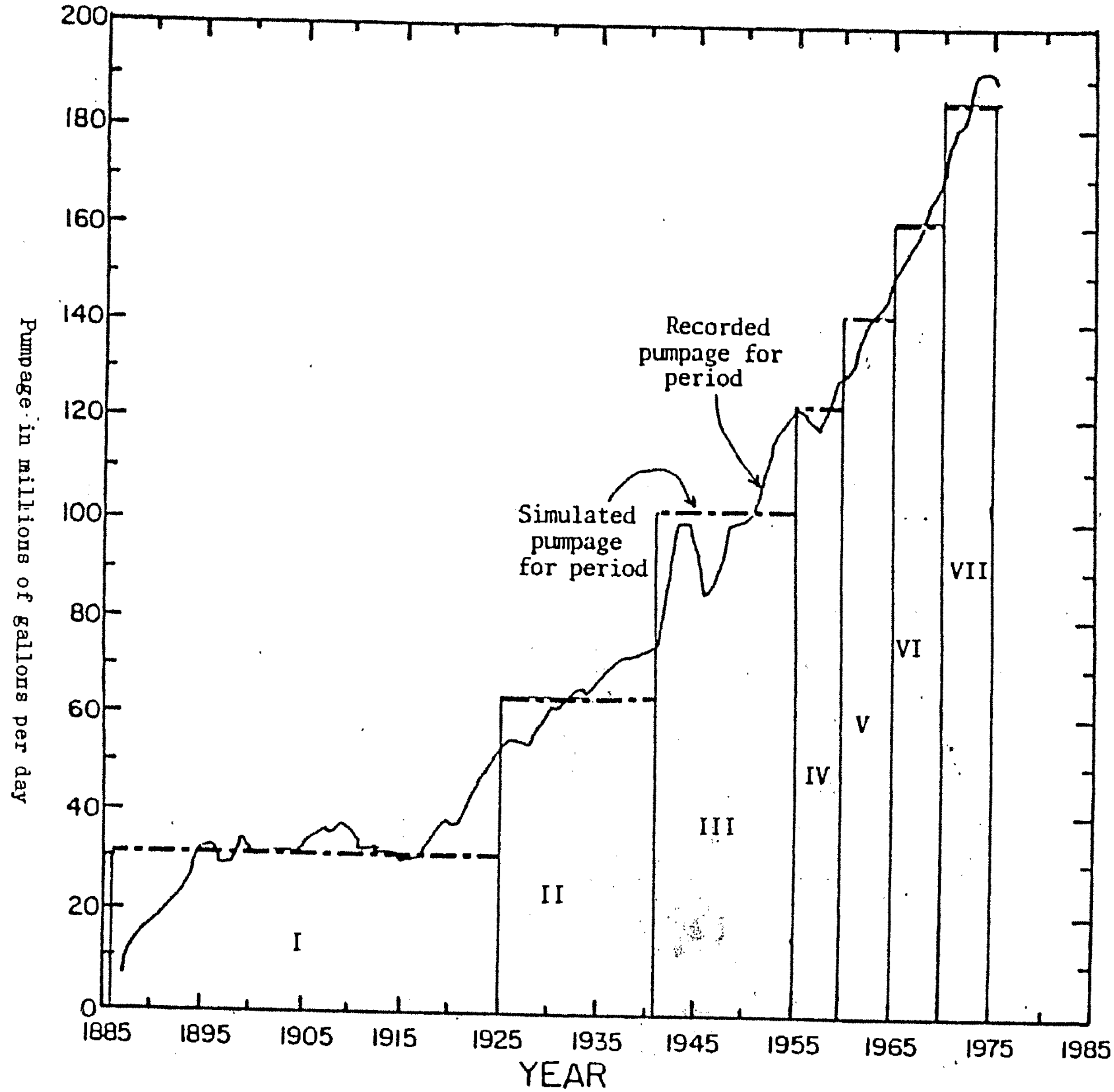


Figure 7.--Recorded and modeled pumpage for 7 pumping periods from 1886 to 1975.

Table 5.--Summary of historic and simulated pumpage used in the Memphis Sand ground-water model

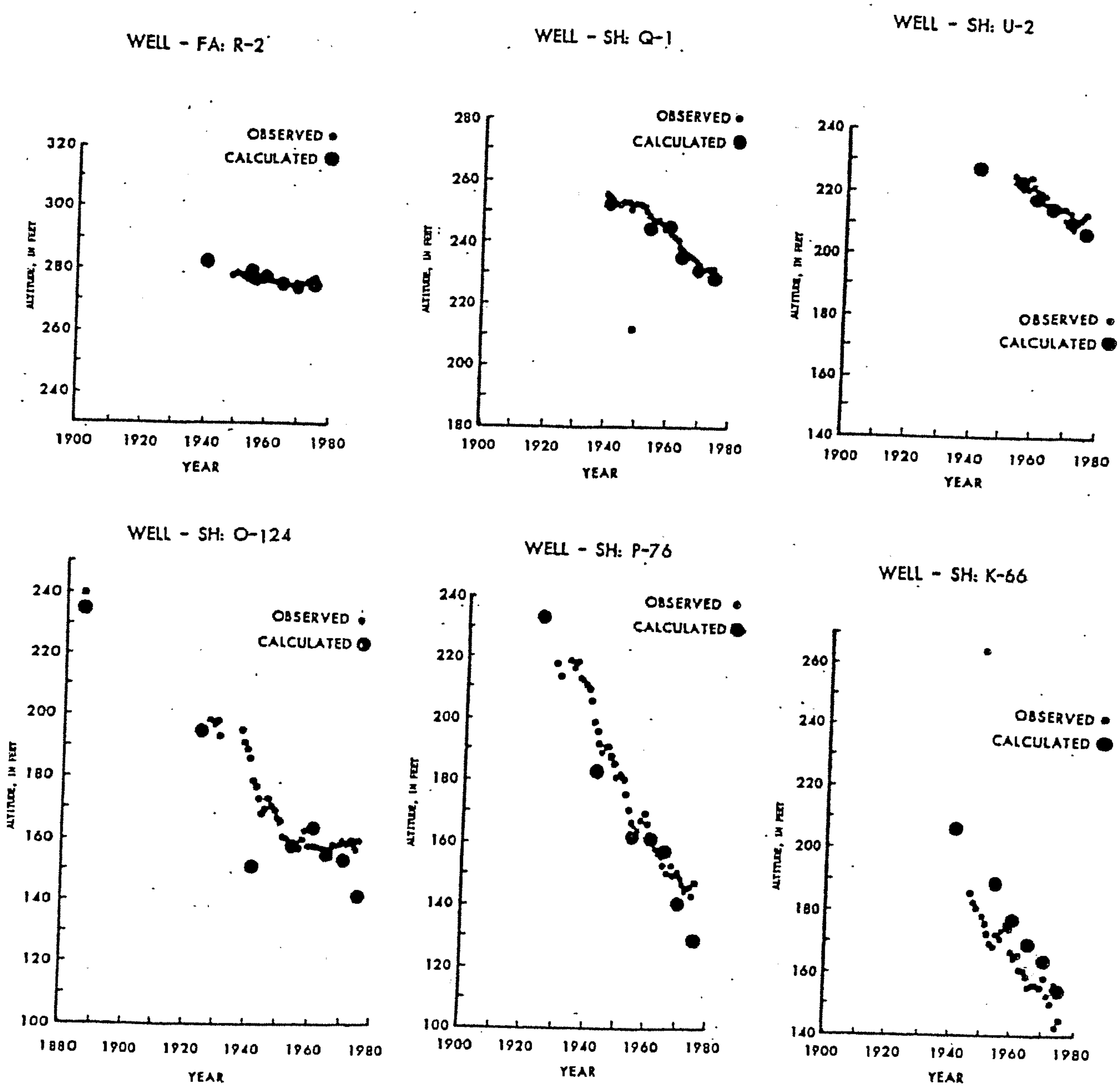
Pumping period	Dates of occurrence	Historic pumpage * (in Mgal/d)	Total simulated pumpage (in Mgal/d)	Volume of simulated pumpage for which with-drawal location was not known (in Mgal/d)
I	1886-1924	30.29	30.61	8.0
II	1925-1941	64.69	63.94	40.0
III	1942-1955	101.96	101.56	34.0
IV	1956-1960	122.50	122.15	17.8
V	1961-1965	141.26	141.59	14.9
VI	1966-1970	161.10	161.10	15.0
VII	1971-1975	184.80	184.80	0

* Criner and Parks, 1976.

Actual pumpage generally increases throughout a pumping period, whereas the model maintains a constant pumping rate throughout a pumping period (fig. 7). The effect of different pumping rates may be observed by plotting computed hydrographs showing all time steps with observed hydrographs for selected wells in the area; the computed hydrographs show the computed water-level trends as steeper than actually observed at the beginning of the pumping period, and flatter than actually observed at the end of the period. Because the pumping rate modeled represents an average pumped during the interval, the rate for the model is greater than actual at the start, and less than actual at the finish. The water levels, however, should be similar at the end of a pumping period. Also important is the fact that both the model and the actual hydrologic systems tend toward an equilibrium which is observed in a stabilization of water-level trends after the abrupt initial decline.

Figure 8 shows calculated water levels at the end of pumping periods superimposed on observed hydrographs of six selected observation wells (Criner and Parks, 1976).

Figure 8.--Selected hydrographs of observed and computed water levels within the Memphis Sand.



See Figure 6 (Plate 4) in the envelope at the back cover of this report for a location diagram of these well sites.

Calibration of the Model

Calibration of the model is the process whereby differences between the observed and computed potentiometric surfaces are minimized by estimating and adjusting aquifer properties, boundary conditions, and hydraulic stresses. As Konikow (1976) has pointed out, the large number of interrelated factors affecting ground-water flow makes calibration a highly subjective procedure, but one that can be simplified by evaluating the certainty of input parameters. Those values that are confidently known are not adjusted, thereby reducing the number of parameter combinations the modeler must evaluate. On parameters that are poorly defined, such as hydraulic conductivity of confining clay, various hydrologically reasonable values were assumed, generally over a range of several orders of magnitude.

Table 4 lists the input parameters and summarizes the significant features of each in the model. The parameter values used provide the "best fit" of the computed values of the model to the water levels observed in the field.

Initial calibration was conducted on a steady-state prepumping model using the input values and boundary conditions described previously. Water levels and ground-water discharge were computed and compared with observed data, and hydrologically reasonable adjustments were made to various parameters until an acceptable match of calculated and observed data occurred. The most significant adjustments were made on the hydraulic conductivity of the confining bed separating the shallow aquifers from the Memphis Sand and on the constant flux nodes that simulated the recharging boundaries.

The results of the steady-state calibration are shown along with the 1886 water level as envisioned by Criner and Parks (1976) in figure 9. Criner and Parks (1976) based their map on four control points, which are simulated by the model within 5 feet. Part of the difference between the water-level maps is ascribed to the fact that control in the area is areally and temporally incomplete for water-level and pumping history.

An important result of the initial steady-state calibration was the refinement of the conceptual model of flow in the aquifer. Initial runs utilizing constant-head boundaries and the best estimate of aquifer characteristics resulted in a calculated water level map similar to that presented by Criner and Parks (1976).

Calibration of the pumping periods I, II, V, and VI was undertaken to refine the model further and test its ability to reproduce the observed water-level configurations under transient conditions. Input data that most nearly simulated Criner and Parks (1976) steady-state map resulted in a poor simulation of transient conditions. Modifications to input data were made in the same manner as for the steady-stage calibration until a best fit for the transient periods and steady state was determined for one unique, specific set of input data. Inasmuch as data were sparse for the older pumping periods, more importance was attached to calibration of pumping periods V and VI.

Because calibration periods were split into several discrete intervals and not run as a continuous sequence, observed water level at the beginning of pumping period I and pumping period V were input. This had the effect of splitting the sample into four parts: a calibration (I-II) followed by a verification (III-IV); and another original calibration (V-VI), followed by a final verification (VII).

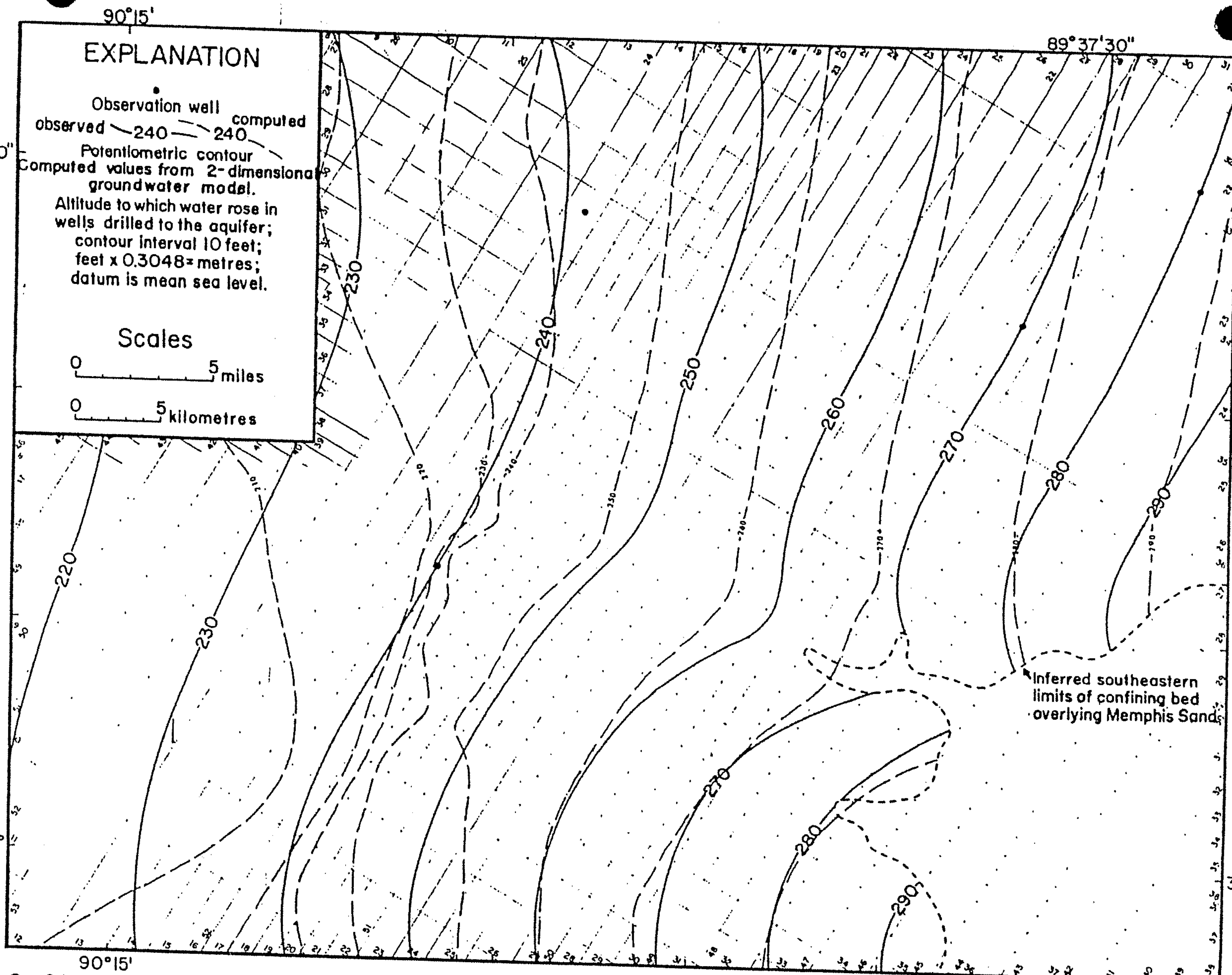


Figure 9 COMPUTED and OBSERVED STEADY-STATE WATER-LEVEL MAP OF THE MEMPHIS SAND, 1886

MEMPHIS METROPOLITAN URBAN AREA
DEPARTMENT OF THE ARMY
MEMPHIS DISTRICT, CORPS OF ENGINEERS, MEMPHIS, TENNESSEE
JULY 1981 Serial 21724 File: 209A/58
PLATE Number 5 of 8

The two zones of low transmissivity (fig. 4), whose presence is consistent with other hydrologic and geologic evidence, were located in the calibration phase, as was a refinement in definition of the leaky zones of the confining layer.

Figure 10 shows the results of pumping at the end of pumping period VI, the final calibration period. Major features of the water-level surface are generally well reproduced by the model, particularly the asymmetric shape of the cone of depression in Memphis, details in the cone at the major points of pumpage, the steep slope of the cone to the west and the fairly flat potentiometric surface underlying the alluvium. Table 6 shows the rates computed for major elements of the hydrologic budget for pumping period VI (1966-1970).

More than 100 hydrologically possible configurations of aquifer properties, pumpage, and recharge were run and evaluated. Calibration runs that did not include high-leakage zones from parts of the Mississippi alluvial aquifer and near the recharge areas east and south of Memphis and the low-transmissivity zones as shown in the conceptual model did not simulate the observed water-level measurements as well as those that included these features.

Removal of the low-transmissivity zones shifted the effect of simulated pumping to the west and tended to reduce the calculated drawdown and diffuse it over a larger area. Exclusion of high leakage zones in the alluvial plain to the west resulted in greater than observed drawdowns during transient calculations and poorly matched water-level configurations during both steady-state and transient simulation.

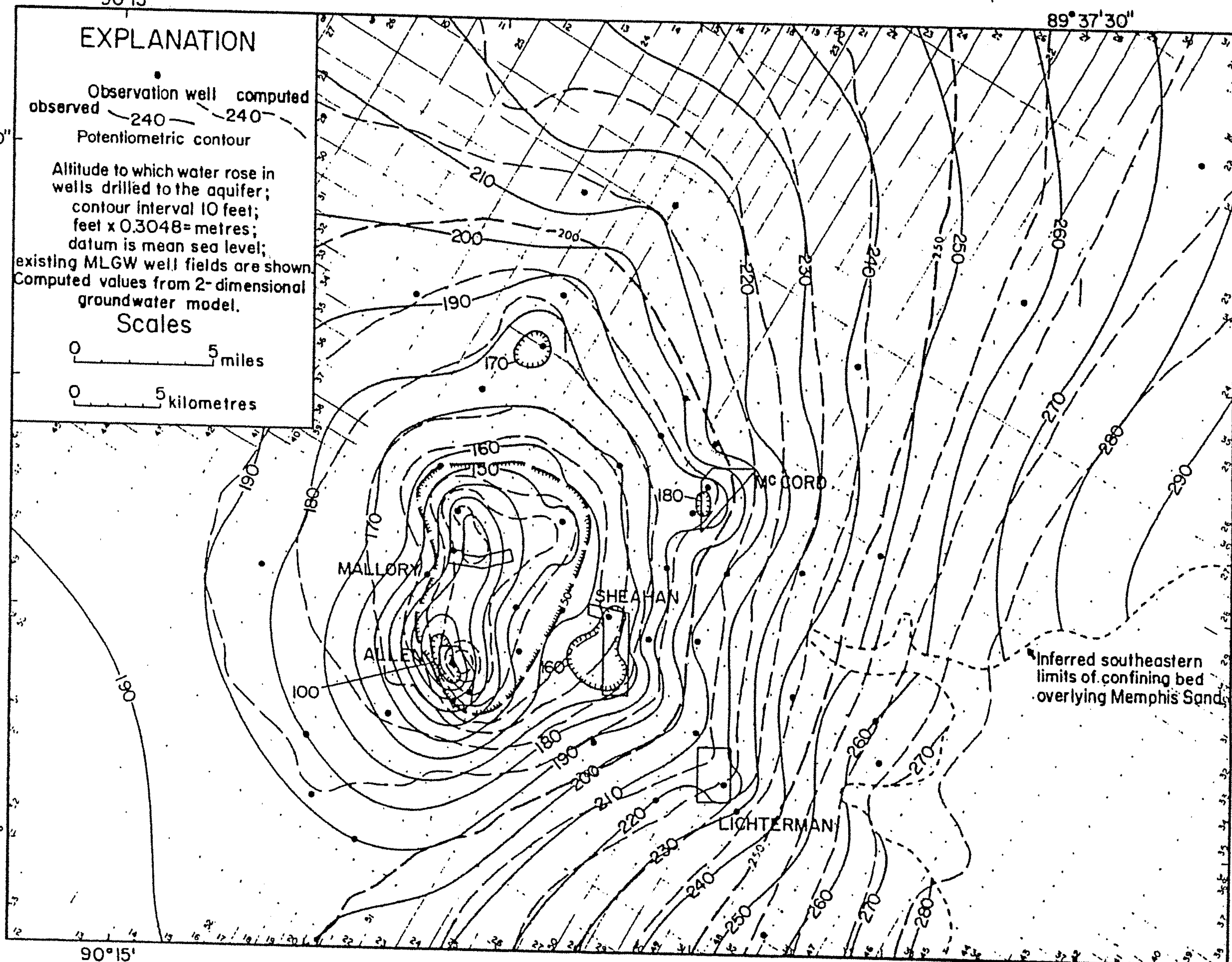


Figure 10 COMPUTED and OBSERVED TRANSIENT WATER-LEVEL MAP OF THE MEMPHIS SAND, 1970

MEMPHIS METROPOLITAN URBAN AREA
DEPARTMENT OF THE ARMY
MEMPHIS DISTRICT, CORPS OF ENGINEERS, MEMPHIS, TENNESSEE
JULY 1981 Serial: 21724 File: 209A/58
PLATE Number 6 of 8

Table 6.--Generalized hydrologic budget computed by model for pumping period VI (1966-1970)

	Mgal/day
Total pumpage from wells in Memphis metropolitan area	164.1
Recharge - simulated by recharge boundaries east and northeast of study area	91.6
Vertical leakage - primarily from near outcrop area, Mississippi River alluvium, and zones along upper reaches of Wolf and Loosahatchie Rivers and Nonconnah Creek	61.2
Storage	11.3

The calibration of this model involved matching calculated and observed water levels with as many as 48 observation wells for a given pumping period. Throughout the calibration phase, close simulation of the observation well data was highest priority. In addition to these discrete point matches, the general symmetry of the calculated water-level surface was matched qualitatively to interpretive water-level maps that were based on more extensive although unverified data.

Historic pumping and water-level data collected prior to 1960 were commonly incomplete, and in some cases, were inaccurate. Calculations based on these data made matching water levels from individual observation wells difficult. The overall "goodness-of-fit" of calculated water levels to observed water levels, however, gave confidence in the results calculated by the final model because it simulated varied conditions quite closely.

Verification of the Model

Model verification was accomplished by split-sample testing. With this method, pumpage data, which were not used during any aspect of the calibration phase, were run in the calibrated model. No aquifer parameter changes were made during the verification. Water levels calculated by the model were within the predetermined range of accuracy of the water level as measured, and the model was judged acceptable. The acceptable accuracy limit was simulation to within at least 5 feet for 75 percent of the observation wells.

The Memphis Sand model was verified using data from pumping periods III, IV, and VII. The computed results of a single run from pumping period VII are shown in figure 11.

The model was successful in reproducing the general water-level configurations for pumping periods III and IV, and for qualitatively simulating the major features and most of the details of pumping period VII. Variations between the observed and calculated values of pumping periods III and IV can be accounted for in part by the fact that exact pumping locations for about 33 percent of total pumping were not known and thus assigned to known well fields for period III, and about 15 percent were similarly assigned to period IV.

During pumping period VII the location of all pumpage was known, and new heavy pumping began during this period. Because the new pumping could not be considered in earlier calibration runs to help determine recharge, the verification runs for this period did not meet the accuracy standards. They were, however, close to those standards (71 percent).

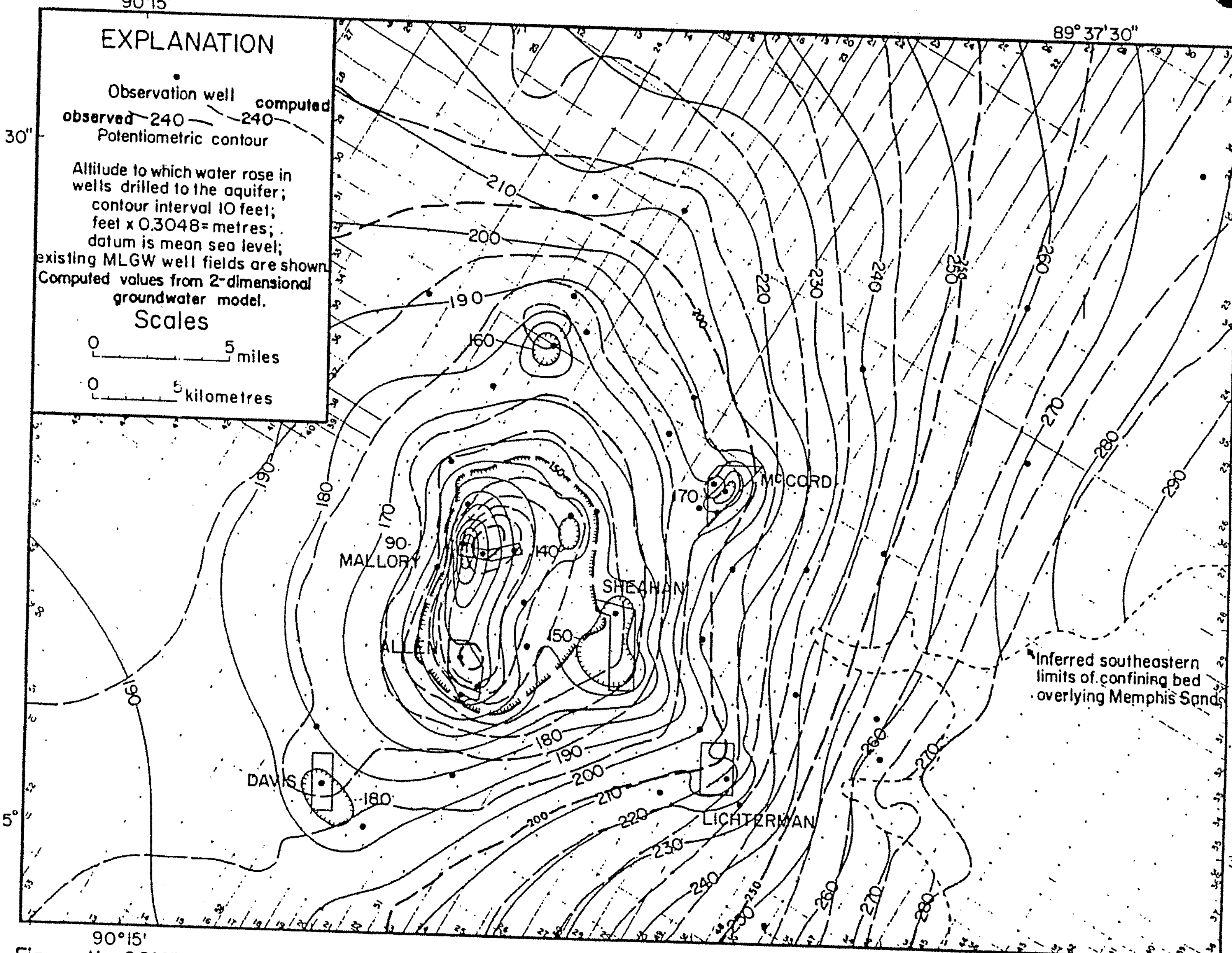


Figure 11 COMPUTED and OBSERVED TRANSIENT WATER-LEVEL MAP OF THE MEMPHIS SAND, 1975

MEMPHIS METROPOLITAN URBAN AREA
DEPARTMENT OF THE ARMY
MEMPHIS DISTRICT, CORPS OF ENGINEERS, MEMPHIS, TENNESSEE
JULY 1981 Serial: 21724 File: 209A/58
PLATE Number 7 of 8

The verification procedure addresses the question of model capabilities and prediction reliability insofar as data exist, but it does not specify the source or cause of error, defined as the difference between calculated and observed data. In the Memphis Sand model, a qualitative estimate of reliability has been assigned to the general sources of error described below, and estimates for specific parameters are provided in table 4.

Four general sources of error are common with models; these limit the effect of the model as a predictive tool, and if not evaluated carefully, commonly lead to misapplication of the model. The errors are:

(1) poor choice and application of a numerical scheme to approximate the flow equations;

and lack of accuracy or completeness in definition of:

(2) aquifer boundary simulation;

(3) aquifer hydraulic properties;

(4) historic records of stress (pumping) and response (water level).

The Memphis Sand model used the SIP solutional scheme, which has successfully been applied to studies in similar hydrologic terrains (Trescott and others, 1976). From the transferability of results from these similar studies, and from the evaluation of the mass balance error of .01 or less on the final runs of the Memphis Sand model, the numerical technique was not judged a major source of error.

The fact that this two-dimensional model represents a three-dimensional system probably accounts for error, but the magnitude is difficult to assess. Where initial assumptions concerning vertical flow are violated, errors will occur in the model. The three-dimensional model would provide the magnitude of this source of error.

Aquifer boundary simulation in the Memphis Sand model, while qualitatively correct, has not been defined by direct measurement. Indirect methods, which include water budget analyses, comparison of expected flow rates based on observed hydrologic characteristics and responses, and extreme examples of no-flow and constant-head configurations provide a range of possible flux across each boundary node. Recharge rates were chosen from within this range.

Confidence in aquifer hydraulic properties of the Memphis Sand model is variable areally for each of the different parameters. Table 2 contains a summary of the overall confidence of the data that comprise each parameter. All of the input data are constrained by the requirement of being hydrologically reasonable both with regard to absolute value and to total range of values for the parameter. Error in the model due to poor aquifer hydraulic property definition is not significant on a regional scale, but could cause predicted water levels to be more than 10 feet in error in small localized areas. A possible example would be a future large pumping center proximate to presently unknown zones of low transmissivity.

Model Capability and Reliability in Predicting

This study, which utilized a split-sample analysis for calibration and verification, suggests that the Memphis Sand model reliably simulated water levels to within ± 5 feet for 75 percent of the observation wells using a range of recharge values. The model is suitable for quantitative prediction within the limits established by the calibration and verification and within the range of maximum and minimum values of parameters listed in table 4. The variations between calculated and observed water-level changes are thought to result primarily from: (1) simplification of unknown aspects of a complex, nonhomogeneous hydrologic system, particularly variable transmissivity, recharge, and leakage; and (2) incomplete pumping records.

Continuing reassessment will be very important in the evolution of the model. As ongoing studies fill the gaps in the data base and improve our understanding of this complex flow system, the model should be modified to include these changes. Newly developed techniques of aquifer-parameter estimation would be particularly useful as an aid to understanding the system, as would development of a three-dimensional model, and an optimization model (Larson and others, 1977). The latter would be helpful in evaluating placement of future well fields and pumping configurations.

Historic records of pumping stress and water-level response in Memphis are more complete for the recent data. Unlocated pumping ranges from more than 60 percent for pumping period II to essentially zero percent for pumping period VII (table 5). Although ground-water withdrawal during the first four pumping periods was areally restricted to several specific pumping centers, the actual amount of pumping was generally not known and had to be estimated. For that reason, more emphasis was placed on the calibration of periods V and VI for which 90 percent or more of the pumpage locations were known.

The resulting response to pumpage may likewise be subject to error and misrepresentation. Prepumping conditions are based on extrapolations of early reported water levels: The maps presented are the best estimate based on all of the available data, but data from the older historic records was sparse until the 1940's, during pumping period III. This was used as further justification to attach more importance to calibration of periods V and VI.

Significant changes introduced by resource development may render the present model inaccurate. The study area should be monitored so that important changes to the aquifer system can be programmed into the model. Development of new stresses or changing boundary conditions caused by pumping, lignite or other mineral mining, or changing land use could have a considerable effect at Memphis.

Whereas these potential sources of error may appear significant in a conservative evaluation of limitations, in actual application their combined effect has been minor. The calibration phase, particularly pumping period VI, showed that the model simulated the major components of the flow system of the Memphis Sand. Likewise, more than 100 variations of the calibration exercise confirmed that alternative configurations were poorer than the final model in simulating not only pumping periods V and VI, but the entire pumping record.

Sensitivity of Input Parameters

By varying one parameter and holding all others constant, it is possible to observe the relative sensitivity of the model to different input parameters. A column summarizing the sensitivity of each input parameter is given in table 4, and cross sections showing Criner and Parks' (1976) interpretation of the observed water level, and water levels calculated using a range of selected input values for single parameters are shown in figure 12.

Hydraulic conductivity of the confining bed, pumpage, and transmissivity appear to be the most sensitive parameters; hydraulic conductivity of the confining bed, and boundary fluxes are the parameters for which the least data exist. The sensitivities of leakage and transmissivity provide a fairly narrow range of acceptable input values for the parameters, but boundary fluxes are relatively unconstrained because most of the observation wells are far removed from the recharge area. The total mass input must be equal to a specified amount, but this can be accommodated by innumerable recharge configurations. The choice of recharge from the input cells was determined to provide the best compromise between efficiency and accuracy.

FIGURE 12A SENSITIVITY ANALYSIS OF SELECTED INPUT PARAMETERS TO THE MEMPHIS SAND MODEL ON CALCULATED HEAD VARYING LEAKAGE ONE (1) ORDER OF MAGNITUDE.

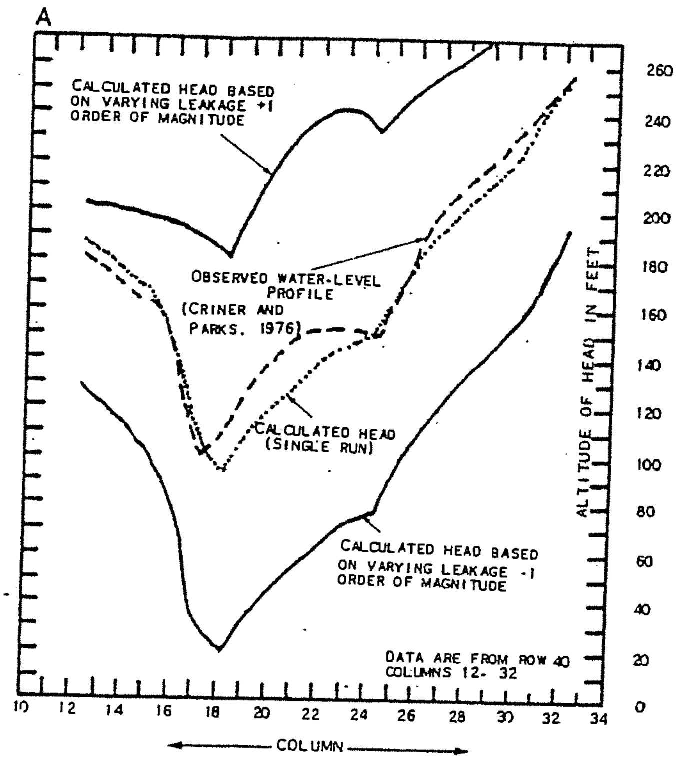


FIGURE 12C SENSITIVITY ANALYSIS OF SELECTED INPUT PARAMETERS TO THE MEMPHIS SAND MODEL ON CALCULATED HEAD VARYING TRANSMISSIVITY ONE (1) ORDER OF MAGNITUDE.

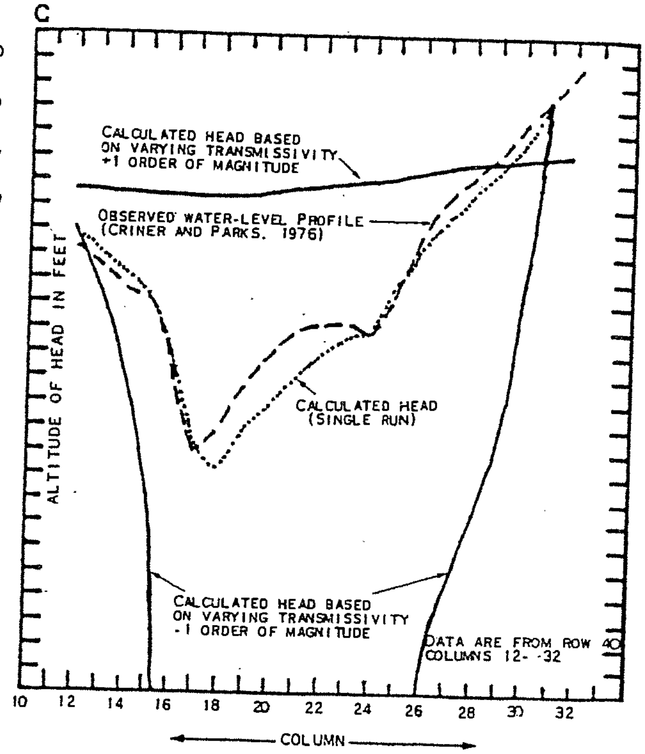
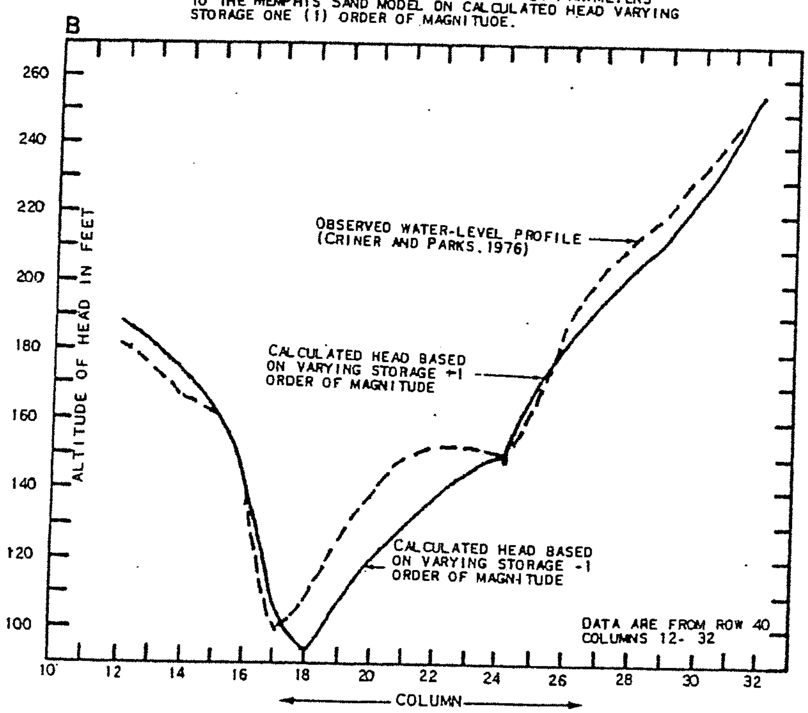


FIGURE 12B SENSITIVITY ANALYSIS OF SELECTED INPUT PARAMETERS TO THE MEMPHIS SAND MODEL ON CALCULATED HEAD VARYING STORAGE ONE (1) ORDER OF MAGNITUDE.



A
Variations in Leakage cause a wide range of calculated heads.

B
Variations in Storage cause a narrow range of calculated heads.

C
Variations in Transmissivity cause a wide range of calculated heads.

Figure 12 Sensitivity analysis of selected input parameters.

SUMMARY AND CONCLUSIONS

A digital model simulating ground-water flow in the Memphis Sand was constructed, tested, and found to simulate historic water levels for the Memphis metropolitan area and found to be at least within 5 feet of observed for 75 percent of the control points. The model is based on the two-dimensional Pinder-Trescott-Larson (1976) model using the SIP algorithm; the model has been used successfully in other areas of similar hydrologic setting. The two-dimensional version was chosen for initial evaluation because flow in the aquifer was thought to be primarily two dimensional.

Split-sample testing verified that the model could reproduce water levels for pumping configurations other than those for which it was developed. A sensitivity analysis of input parameters increased confidence that the model could predict water-level responses.

Use of the model for predictive purposes has been simplified to an essentially one-step process for the individual utilizing the model. Projected pumpage configurations and durations are located within the model grid, coded, and entered. The output from the model is a printed tabulation of water levels and flux calculations, and a contoured map showing the water-levels that would be expected from the specified pumping.

The construction of the model of the Memphis Sand provides not only a tool that will aid in evaluating the capabilities of the aquifer, and in predicting responses to management alternatives of this aquifer but also provides much insight into the flow system of the aquifer in the Memphis area.

Specifically, the regional homogeneity of transmissivity initially ascribed to the aquifer did not suitably simulate observed water levels. Several narrow zones of lower transmissivity, some as much as one order of magnitude less, were determined during the calibration phase to provide the best overall calculated response. These zones, which closely match the locations of fault zones hypothesized by Fisk (1944), Criner and others (1964), and A. Zurawski, U.S. Geological Survey (oral commun., 1978) appear to restrict flow between the aquifer in the Memphis area and to the west in Arkansas.

Placement of these zones of lowered transmissivity is also consistent with water quality differences observed in the aquifer (Plebuch, 1961; Criner and others, 1964; Halberg and Reed, 1964; Moore, 1965) and water-level variations (Halberg and Reed, 1964; Criner and Parks, 1976). Figures 9, 10, and 11 show water-levels in the areas of restricted flow. Observed geometries in these diagrams are consistent with restriction of flow in the aquifer between western Tennessee and eastern Arkansas.

Comparing observed with calculated water levels also indicated that the inclusion of leakage along the upper reaches of Wolf and Loosahatchie Rivers, Nonconnah Creek, and the Mississippi River alluvium provided the closest simulation of observed water levels. Electric logs from these suspected zones of leakage commonly show thinning confining clays or more sandy zones within the confining layer. Approximately 15 percent of the total leakage shown in the water budget in table 6 occurs near the subcrop area where the confining bed is thin, or in the western part of the study area where streams have breached the confining clay.

Resolving the intricacies of interaquifer movement of ground water between the Memphis Sand, the alluvium, and the Wilcox Group aquifers will require a three-dimensional model, as will any water-quality models, and any newly developed studies to evaluate total resource management alternatives. Parameter-estimation techniques (Cooley, 1977) should be helpful in quantitative studies of the hydrology of the area. An existing optimization model developed by Larson and others (1977) offers an attractive approach to evaluating placement of future well fields and pumping configurations.

SELECTED REFERENCES

Appel, C. A., and Bredehoeft, J. D., 1976, Status of ground-water modeling in the U.S. Geological Survey: U.S. Geological Survey Circular 737, 9. p.

Bear, Jacob, 1972, Dynamics of fluids in porous media: American Elsevier Publishing Company, 764 p.

Bedinger, M. S., Reed, J. E., and Griffin, J. D., 1973, Digital-computer programs for analysis of ground-water flow: U.S. Geological Survey open-file report, 85 p.

Bell, E. A., 1966, Water Resources of the Memphis area, Tennessee: Nashville, Tenn., U.S. Geological Survey open-file report, 4 p.

Bell, E. A., and Nyman, D. J., 1968, Flow pattern and related chemical quality of ground water in the "500-foot" sand in the Memphis area, Tennessee: U.S. Geological Survey Water-Supply Paper 1853, 27 p.

Black and Veatch Consulting Engineers, 1949, Report on the Water Supply--Memphis Light, Gas, and Water Division--City of Memphis, Tennessee: March 3, 1949, Kansas City, Mo., 130 p.

Boswell, E. H., Cushing, E. M., and Hosman, R. L., 1968, Quarternary aquifers in the Mississippi Embayment: U.S. Geological Survey Professional Paper 448-E, 15p.

Brahana, J. V., 1981, A multi-layered ground-water flow model of the Memphis area, Tennessee-Arkansas-Mississippi: U.S. Geological Survey Water Resources Investigation, 73 p.

Callahan, J. A., 1973, Public and industrial water supplies in northern Mississippi: Mississippi Board Water Commission Bulletin 73-1, 68 p.

Caplan, W. M., 1954, Subsurface geology and related oil and gas possibilities of northeastern Arkansas: Arkansas Resources and Development Commission, Division of Geology Bulletin 20, 124 p.

Chester and Fleming Consulting Engineers, 1920, Report on the Water Supply in Memphis, Tennessee: Memphis, Tennessee, 69 p.

Clark, Dietz and Associates - Allen and Hoshall, 1968, Water Supply and distribution, Memphis and Shelby County Planning Commission: Prepared for Memphis and Shelby County Planning Commission, Memphis, Tennessee, 54 p.

Cooley, R. L., 1977, A method of estimating parameters and assessing reliability for models of steady state ground-water flow: Water Resources Research, v. 13, no. 2, p. 318-324.

Criner, J. H., and Armstrong, C. A., 1958, Ground-water supply of the Memphis area: U.S. Geological Survey Circular 408, 20 p.

Criner, J. H., and Parks, W. S., 1976, Historic water-level changes and pumpage from the principal aquifers in the Memphis area, Tennessee: 1886-1975: Nashville, Tennessee, U.S. Geological Survey, Water Resources Investigations 76-67, 55 p.

Criner, J. H., Sun, P-C. P., and Nyman, D. J., 1964, Hydrology of the aquifer systems in the Memphis Area, Tennessee: U.S. Geological Survey Water Supply Paper 1779-O, 54 p.

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

Cushing, E. M., Boswell, E. H., Speer, P. R., and Hosman, R. L., 1970, Availability of water in the Mississippi Embayment: U.S. Geological Survey Professional Paper, 448-A, 13 p.

Dalsin, G. J., and Bettandorff, J. M., 1976, Water for industrial and agricultural development in Coahoma, DeSoto, Panola, Quitman, Tate, and Tunica Counties, Mississippi: Mississippi Research and Development Center Bulletin, 87 p.

Davis, R. W., Lambert, T. W., and Hansen A. J., Jr., 1971, Water in the economy of the Jackson Purchase region of Kentucky: Kentucky Geological Survey Special Publication 20, 32 p.

Fisk, H. N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: U.S. Department of the Army, Mississippi River Commission, 78 p.

Freeze, R. A., 1971, Three-dimensional, transient, saturated-unsaturated flow in a ground-water basin: Water Resources Research, v. 7, no. 2, p. 347-366.

Fuller and McClintock Consulting Engineers, 1922, Report on water supply of Memphis, Tennessee: March 1, 1922, Memphis, Tenneessee, 88 p.

Glenn, L. C., 1906, Underground water of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geological Survey Water-Supply Paper 164, 173 p.

Gold, R. L., 1978, Low-flow measurements of Tennessee streams: Tennessee Division of Resources, Water Resources Series no. 69, 580 p.

Graham, D. D., 1979, Potentiometric map of the Memphis Sand in the Memphis Area, Tennessee, August 1978: U.S. Geological Survey Water-Resources Investigation 79-80, scale 1:125,000, 1 sheet.

Grubb, H. F., 1974, Simulated drawdown for selected well fields in the Ohio River alluvial aquifer: U.S. Geological Survey, Water Resources Investigations 2-74, 38 p.

Halberg, H. N., 1972, Use of water in Arkansas, 1970: Arkansas Geological Commission Water Resources Summary no. 7, 17 p.

Halberg, H. N., and Reed, J. E., 1964, Ground-water resources of eastern Arkansas in the vicinity of U.S. Highway 70: U.S. Geological Survey Professional Paper 448-D, 28 p.

Hosman, R. L., Long, A. T., and Lambert, T. W., and others, 1968, Tertiary aquifers in the Mississippi Embayment: U.S. Geological Survey Professional Paper 448-D, 28 p.

Kazmann, R. G., 1944, The water supply of the Memphis area: Nashville, Tenn., U.S. Geological Survey Open-File Report, 66 p.

Kernodle, J. M., and Wilson, J. M., 1973, Water Use in Tennessee, 1970: Tennessee Division of Water Resources, Water Use Series no. 6, 102 p.

Konikow, L. F., 1976, Preliminary digital model of ground-water flow in the Madison group, Powder River Basin and adjacent areas, Wyoming, Montana, South Dakota, and Nebraska: U.S. Geological Survey Open-File Report, 44 p.

Krause, R. E., and Counts, H. B., 1975, Digital model analysis of the principal artesian aquifer, Glynn County, Georgia: U.S. Geological Survey Water Resources Investigations I-75, open file, 4 sheets.

Krintizsky, E. L.,, and Wire, J. C., 1964, Ground water in alluvium of the lower Mississippi Valley (upper and central areas): U.S. Army Engineer Waterways Experiment Station, Technical Report 3-658, v. 112, 501 p.

Larson, S. P., 1976, An appraisal of ground water for irrigation in the Appleton area, west-central Minnesota: U.S. Geological Survey Water-Supply Paper 2039 B, 34 p.

Larson, S. P., Maddock, T., III, and Papadopulos, S. S., 1977, Optimization techniques applied to ground-water development: Memoirs of XIII Congress of International Association of Hydrogeologists, v. XIII, pt. 1, p. E-57 - E-66.

Larson-Higdem, Dana, Larson, S. P., Norvitch, R. F., 1975, Configuration of the water table and distribution of downward leakage to the Prairie DuChien - Jordan aquifer in the Minneapolis - Saint Paul Metropolitan area, Minnesota: U.S. Geological Survey Open-File Report, 33 p.

Lundie, John, 1898, Report on the waterworks system of Memphis, Tennessee Memphis, Tennessee, 46 p.

Maddock, Thomas, III, 1972, A ground-water planning model - a basis for a data collection network: International Symposium on uncertainties in Hydrologic and Water Resources Systems Proceedings, p. 63.1 - 63.25.

Matalas, N. C., and Maddock, T. III, 1976, Hydrologic Semantics: Water Resources Research, v. 1, p. 123.

Moore, G. K., 1962, Downdip changes in chemical quality of water in the "500-foot" sand of western Tennessee: U.S. Geological Survey Professional Paper 450-C, p. 133-134.

______1965, Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geological Survey Water-Supply Paper 1809-F, 44p.

Newcome, Roy, Jr., 1971, Results of aquifer tests in Mississippi: Mississippi Board Commission Bulletin 71-2, 44 p.

______1976, The Sparta aquifer system in Mississippi: U.S. Geological Survey Water Resources Investigations 76-7, 3 sheets.

Nyman, D. J., 1965, Predicted hydrologic effects of pumping from the Lichterman well field in the Memphis area, Tennessee: U.S. Geological Survey Water-Supply Paper 1819-B, 26 p.

Parks, W. S., 1973a, Geologic map of the Fletcher Lake quadrangle, Tennessee: U.S. Geological Survey Open-File Report.

______1973b, Geologic map of the Southwest Memphis quadrangle Tennessee: U.S. Geological Survey Open-File Report.

______1974, Geologic map of the Southeast Memphis quadrangle, Tennessee: U.S. Geological Survey Open-File Report.

______1975, Geologic map of the Germantown quadrangle, Tennessee: U.S. Geological Survey Open-File Report.

______1977a, Geologic map of the Teague quadrangle, Tennessee: U.S. Geological Survey Open-File Report.

______1977b, Geologic map of the Ellendale quadrangle, Tennessee: U.S. Geological Survey Open-File Report no. 77-752.

Parks, W. S., Graham, D. D., and Lowery, J. F., 1981, Chemical character of ground water in the shallow water-table aquifer at selected localities in the Memphis area, Tennessee: U.S. Geological Survey Open-File Report 81-223, 29 p.

Parks, W. S., and Lounsbury, R. W., 1976, Summary of environmental geology and related problems at Memphis, Tennessee: U.S. Geological Survey Water Resources Investigations 4-76, 34 p.

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

Pinder, G. F., 1970, An iterative digital model for aquifer evaluation: U.S. Geological survey Open-File Report, 44 p.

Pinder, G. F., and Bredehoeft, J. D., 1968, Application of the digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

Plebuch, R. O., 1961, Fresh-water aquifers of Crittenden County, Arkansas: Arkansas Geology and Conservation Commision Water Resources Circular no. 8, 65 p.

Reed, J. E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi Embayment: U.S. Geological Survey Hydrol. Investigations Atlas HA 434

Remson, I., Hornberger, G. M., and Molz, F. J., 1971, Numerical methods in subsurface hydrology: New York, Wiley Interscience, 389 p.

Robson, S. G., 1974, Feasibility of digital water quality modeling illustrated by application at Barstow, California: U.S. Geological Survey Water Resources Inv. 46073, 56 p.

Russell, E. E., and Parks, W. S., 1975, Stratigraphy of the outcropping upper Cretaceous, Paleocene, and lower Eocene is western Tennessee (including descriptions of younger fluvial sediments): Tennessee Divison of Geology Bulletin 75, 118 p.

Ryling, R. W., 1960, Ground-water potential of Mississippi County, Arkansas: Arkansas Geology and Conservation Commission Water Resources Circular no. 7, 85 p.

Safford, J. M., 1890, The water supply of Memphis: Tennessee Board of Health Bulletin v. 5, 93 p.

Schneider, Robert, 1972, Distortion of the geothermal field in aquifers by pumping: U.S. Geological Survey Professional Paper 800-C, p. C267-C270.

Schneider, Robert, and Cushing, E. M., 1948, Geology and water bearing properties of the "1400-foot" sand in the Memphis area: U.S. Geological Survey Circular 33, 13 p.

Sorrels, William, 1970, Memphis Greatest Debate - A Question of Water: Memphis State University Press, 139 p.

Stearns, R. G., 1957, Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi Embayment: Geologic Society of America Bulletin, v. 68, p. 1077-1100.

Stearns, R. G., and Armstrong, C. A., 1955, Post-Paleozoic statigraphy of western Tennessee and adjacent portions of the upper Mississippi Embayment: Tennessee Division of Geology Report Investigations 2, 29 p.

Stearns, R. G., and Wilson, C. W., Jr., 1972, Relationships of earthquakes and geology in west Tennessee and adjacent states: Tennessee Valley Authority, 301 p.

Stearns, R. G., and Zurawski, Ann, 1976, Post-Cretaceous faulting in the head of the Mississippi Embayment: Southeastern Geology, v. 17, no. 4, p. 207-229.

Stone, H. K., 1968, Iterative solution of implicit approximations of multidimensional partial differential equations: SIAM Journal Numerical Analysis, v. 5, no. 3, 530-558.

Trescott, P. C., 1973, Iterative digital model for aquifer evaluation: U.S. Geological Survey Open-File Report, 18 p.

Trescott, P. C., Pinder, F. G., and Larson, S. P., 1976, Finite difference model for aquifer simulation in two dimensions and results of numerical experiments: U.S. Geological Survey, Techniques of Water Resources Investigations, Book 7, Chapter C1, 116 p.

Waste Age, 1979, Hit list, part two: v. 10, no. 8, p. 53, 54, 56, 58.

Wells, F. G., 1931, A preliminary report on the artesian water supply of Memphis, Tennessee: U.S. Geological Survey Water-Supply Paper 638-A, 34 p.

______1933, Ground-water resources of western Tennessee: U.S. Geological Survey Water-Supply Paper 656, 319 p.

Wolff, R. G., and Olsen, H. W., 1968, Piezometer for monitoring rapidly-changing pore pressures in saturated clays: Water Resources Research, v. 4, no. 4.

Attachment I

TECHNICAL DESCRIPTION OF GENERALIZED TWO-DIMENSIONAL DIGITAL MODEL FROM WHICH THE MODEL OF THE MEMPHIS SAND WAS DERIVED

The digital ground-water model presented in this report is based on the model developed by Trescott, Pinder, and Larson (1976) that has been used successfully to simulate a variety of aquifer systems in two dimensions. This report by Trescott, Pinder, and Larson (1976) provides a cogent description of the theory and capabilities of the generalized model, as well as giving detailed instruction in the general use and application of the model, and documentation of the model. Included in the documentation are flow charts, complete program listing, example simulations, and alternative data output techniques to the printout of calculations and contoured map generated by the Memphis Sand model.

Used in conjuction with Attachment II, the documentation in the Trescott, Pinder, Larson (1976) report will provide the practical basis for full utilization, including trouble-shooting, of the model of the Memphis Sand.

Attachment II

INSTRUCTIONS AND EXAMPLES FOR CARD INPUT - MEMPHIS SAND GROUND-WATER MODEL

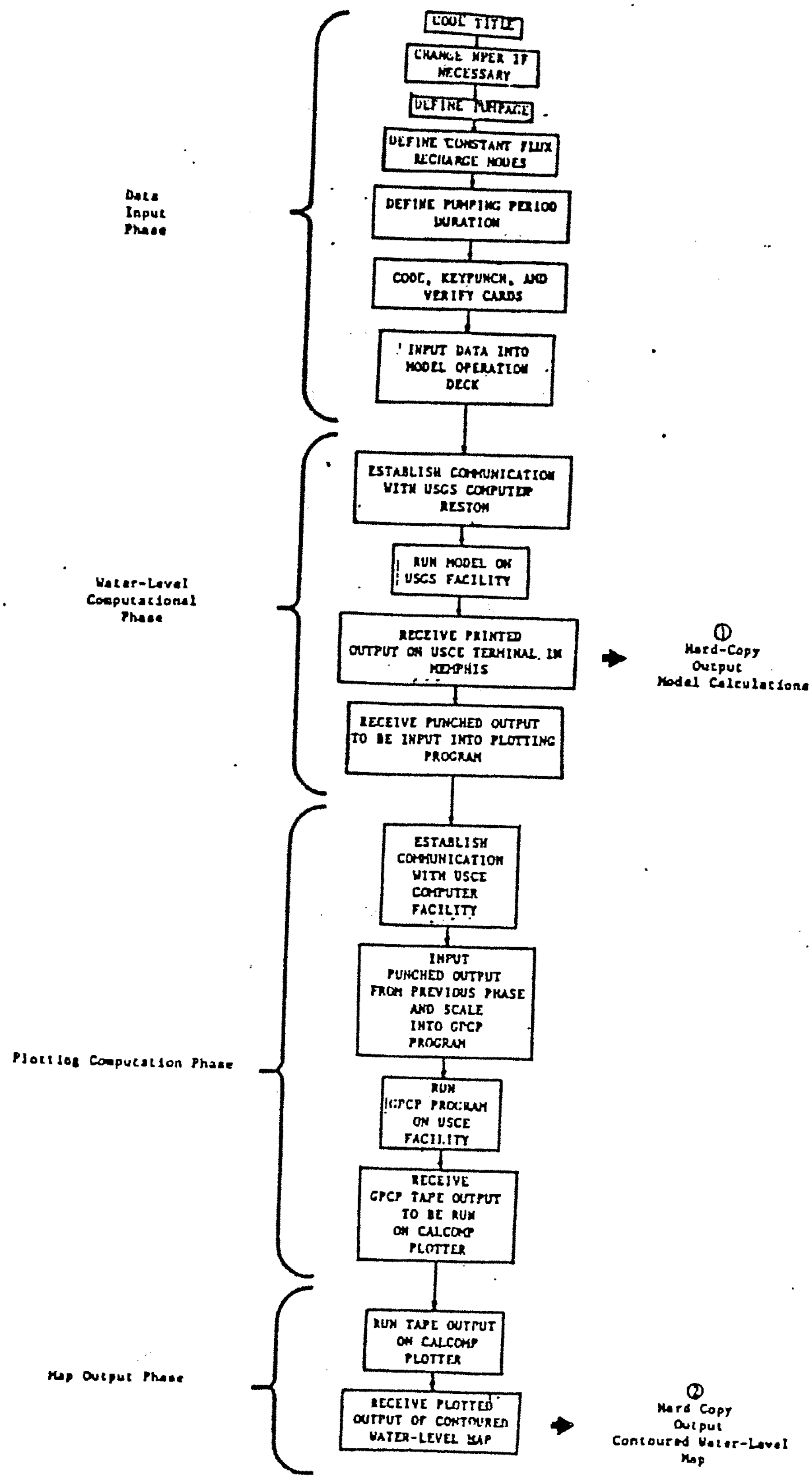
The digital model of the Memphis Sand has been simplified to facilitate use by personnel inexperienced in computer modeling. Although the Memphis Sand model follows the same format as described on pages 49-55 of Trescott, Pinder, and Larson (1976), most data are stored on the U.S. Geological Survey computer in Reston, Va., and do not need to be reentered.

Only the title, simulation options, problem dimensions and parameters that change with the pumping period will require encoding and entry into the general Memphis Sand ground-water model. Other JCL and parameter cards will not change, and these are described at the back of Attachment II.

A flow chart (fig. 13) shows the sequential steps necessary for running the model. The sequence is defined in greater detail below:

1. Code Title -- Code any title that identifies the individual run in 120 spaces or less; 80 spaces on the first card, 40 spaces on the second card. Always include 2 cards; leave the last 40 spaces on the second card blank.
2. If simulation of more than one pumping period is desired, change variable NPER (Group II, Card 2, Columns 9-10) to 7 + the number of pumping periods simulated. Otherwise, leave NPER = 8. Note that this number should match the highest number given for variable KP (Group IV, Card 1, column 9-10).

Figure 13.--Flow chart for operating the Memphis Sand digital ground-water model.



3. Define Pumpage -- Locate pumping centers on base map by alining grid overlay of same scale. Grid location should be given by row (down) in card space 9-10, by column (across) in card space 19-20, and pumpage, in negative (-) (feet/sec) in columns 21-30. Row and column are integer numbers, and pumpage is a decimal. All numbers should be right justified in their fields. Pumpage can be converted from Mgal/d to - (ft/sec) by multiplying the value in Mgal/d times (-1.547). If pumpage falls between 2 or more nodes, it should be divided proportionally between the nodes.

4. Define Pumping Period Duration -- The number of the pumping period should be coded in card space 9-10. Most simulations will use 8, because 7 were used in modeling through 1975. For simulations run with the model, the following pumping period designations were used. It is not necessary to conform to these, but other variations should be noted.

Pumping period	Interval
8	1976-1980
9	1981-1990
10	1991-2000
11	2001-2025

In card space 19-20 code one minus the value you have in columns 9-10. For example, if pumping period 8 was shown in card space 10, then (8-1) or 7 would be shown in space 20. In card spaces 28-30 show the total number of nodes in which pumping and recharge will occur during this period (count them on the grid). Right justify the number in the field. Right justified in card space 31-40, show the number of days the wells will be pumped. Days = 365 x number of years. Code 100 into spaces 48-50. Code 1.5 into spaces 58-60. Right justified into spaces 61-70, code the value = (no. of days in period x 24)/170. This completes the pumping header card. This card, when punched, goes in front of the group of pumpage and recharge cards completed in step 3. For each pumping period a new set of pumpage (step 4) data by nodes preceded by a pumping period duration card (step 5) is required. Multiple periods should be placed directly in back of the preceding pumping period.

5. Code, keypunch, list on printer, and verify, -- check input values carefully; errors here are magnified in the program.
6. After inserting these data in the deck described in the attached listing (p. 69), this deck is now ready to be run on the USGS 370-195 computer in Reston, Va.
7. Run the program.
8. Upon successful completion, a printed record of the calculations will be received.
9. In addition, the card punch at the terminal will receive punched output which will be used to draw the water-level contour map.
10. Initiate communications with USCE INFØNET computing facility.
11. Read punched output or tape of card images into file GRDO 2 on INFØNET.
12. Run SPLØT on INFØNET. This is an interactive program that asks

you questions about map scales, titles, and plotting information. A form included on page 70 of this section contains all the program needs. Page 71 shows a CRT print of a plotting run. Data input from plot request form on p. 71 are highlighted in yellow.

13. Output from SPLØT will be a plot tape.
14. Have the tape plotted on CALCØMP plotter.
15. Output is a contoured water-level map on paper or mylar to the scale of the specified base (generally 1:10416). This represents the resulting water level in the Memphis Sand from pumping the configuration previously input in step 3.

Attachment III

Observed and computed water levels for selected wells in the Memphis Sand under transient (pumping) conditions

(datum is mean sea level)

Well number	Grid location	Observed altitude of water level (feet)			Calculated altitude of water level (feet)		
		Aug 1960	Sept 1970	Aug 1975	1960	1970	1975
Fa:R-2	22-23	276	275	277	277	275	275
Sh:H-1	49-15/16	188	180	180	188		180
Sh:J-1	50-20	200	190	184	197	197	189
Sh:J-10	46-19/20	139			140		
Sh:J-25	44-17	159			158		
Sh:J-31	44/45-17	158			155		
Sh:J-36	43/44-19/20	144			145		
Sh:J-41	43/44-18/19	146			144		
Sh:J-47	47-17	173			171		
Sh:J-50	47/48-18/19		157			178	
Sh:J-62	46/47-18/19	163			158		
Sh:J-70	48-22			181			180
Sh:J-102	45-20	130	99	124	130	104	87
Sh:J-110	45/46-21	145	123	129	150	128	120
Sh:J-126	46-20/21	151	122	135	147	139	132
Sh:J-140	50-17		188	171		188	171
Sh:K-4	44/45-25/26	211	192		209	189	
Sh:K-13	43/44-22/23	171			172		
Sh:K-15	43/44-23/24	184			183		
Sh:K-20	43-22	170	153	155	171	148	135
Sh:K-23	39/40-25/26	190	186		197	186	
Sh:K-25	43-25/26	201			261		
Sh:K-28	48-25	211			213		
Sh:K-29	46/47-23/24	199			197		
Sh:K-31	45-28		220	215		212	203
Sh:K-66	39/40-24	166	159	145	175	164	154
Sh:K-74	42/43-25	178			184		
Sh:L-1	42/43-29	241			243		
Sh:L-10	38-30	253	243	239	253	235	231
Sh:L-13	42-28		208	200		207	198
Sh:L-15	37-32	266	260	258	264	260	261
Sh:L-20	39/40-27	230			228		
Sh:L-24	43/44-28/29	238			237		
Sh:L-39	43/44-30	245	216	208	248	221	218
Sh:L-43	44-30/31	249	230	222	251	232	227
Sh:L-54	38/39-32/33		264	263		266	268
Sh:L-64	38/39-26/27	225	212	211	222	201	195

Attachment III

Observed and computed water levels for selected wells in the Memphis Sand under transient (pumping) conditions--Continued

(datum is mean sea level)

Well number	Grid location	Observed altitude of water level (feet) Aug 1960	Sept 1970	Aug 1975	Calculated altitude of water level (feet) 1960	1970	1975
Sh:O-1	34/35-14/15	184	174	174	179	178	175
Sh:O-41	38/39-16/17	133	126	126	138	128	130
Sh:O-98	42/43-16/17		140	142		156	145
Sh:O-110	39/40-16/17	131			133		
Sh:O-115	37/38-14/15	161	157	157	162	159	152
Sh:O-124	41-16/17	158	159	160	165	154	142
Sh:O-153	40/41-18/19	130			134		
Sh:O-179	39/40-16/17	124	127	88	133	127	127
Sh:O-212	40/41-18			105			103
Sh:P-1	32-22/23	205	190	188	206	191	184
Sh:P-8	37-20/21	144	144	141	148	141	145
Sh:P-12	37/38-21	143			148		
Sh:P-37	36/37-21/22	162		157	165		153
Sh:P-50	38/39-18/19	145			144		
Sh:P-54	38/39-21	154			151		
Sh:P-61	40/41-22/23	168	157		168	153	
Sh:P-69	34/35-21/22		170			176	
Sh:P-74	36/37-25	202	190		203	191	
Sh:P-75	33/34-21/22	193			193		
Sh:P-76	41/42-21	163	149	148	162	141	129
Sh:P-85	34/35-24/25	200	183	182	201	188	184
Sh:P-96	30/31-22/23		201	198		201	193
Sh:P-97	39/40-19/20			131			116
Sh:Q-1	34-28/29	243	233	231	245	231	229
Sh:Q-3	31/32-30	257	249	249	255	247	246
Sh:Q-9	35/36-16		210	210		206	201
Sh:Q-21	32-25	217			219		
Sh:Q-23	33-24/25	209	184	188	212	190	180
Sh:Q-24	31-24	220	211		222	203	
Sh:Q-53	34-25			181			182
Sh:Q-59	33-25			168			178
Sh:R-15	27-32			271			273
Sh:T-17	32/33-12		192	192		195	193
Sh:U-2	27-14	221	214	214	219	211	207
Sh:U-11	26-17/18	223	213	212	223	214	21[illegible]
Sh:U-13	31/32-15/16			157			17[illegible]
Sh:U-15	31/32-15/16		168			178	
Sh:U-22	30-15/16	199			197		

Attachment III

Observed and computed water levels for selected wells in the Memphis Sand under transient (pumping) conditions--Continued

(datum is mean sea level)

Well number	Grid location	Observed altitude of water level (feet)			Calculated altitude of water level (feet)		
		Aug 1960	Sept 1970	Aug 1975	1960	1970	1975
Sh:U-23	30-15/16		186	187		188	179
Sh:U-25	30/31-16/17	187		183	187		180
Sh:V-1	26-26	246			244		
Sh:V-7	27/28-26/27	246	242	240	245	237	234
Sh:W̄-3	24/25-30	258	258	260	259	262	262
AR-1	45/46-12	186	183		188	188	
MS-1	47/48-32/33	263	256	254	262	258	256

ATTACHMENT IV

PROJECTIONS OF WATER USE

Future pumping demands are required input if the model is to be used for predictions of future water levels. Because water-use projection is affected by many variables, most of which are outside the range of expertise of the U.S. Geological Survey, it was decided to chose a range of values - maximum, intermediate, and minimum - that would bracket the probable pumpage and define its limits. These projected demands are summarized in table 7 by major use and figure 14 by major well field. The pumping demands are based on extrapolation of information provided by MLGW, and represent a "best estimate" at this time. They include the time period from 1980 to 2025.

Maximum conditions are based on the ultimate design capability of the MLGW distribution system for each municipal well field, as well as inclusion of all planned withdrawal demands for projects that have been proposed. Self-supplied industrial pumpage, industries that use their own wells, has remained relatively constant since about 1950, and on the basis of little variation during the last 30 years, it was assumed that all new industrial pumpage would be accommodated by MLGW. Pumping demands for existing self-supplied industries were projected as 20 percent greater than 1980 figures. Calculation of the maximum case yields a conservative pumping figure that is felt to be an extreme upper limit of ground-water use.

Table 7.--Projection of maximum, intermediate, and minimum pumpage for three intervals from 1981 to 2025

MLGW well field	Maximum pumpage (Mgal/d)	Intermediate pumpage (Mgal/d)	Minimum pumpage (Mgal/d)	Time period
Allen	25.49	22.08	15.00	1981-1990
	29.55	23.85	15.00	1991-2000
	33.80	25.34	15.00	2001-2025
Airport	10.97	6.49	3.80	1981-1990
	14.48	12.99	4.60	1991-2000
	15.0	14.74	5.00	2001-2025
Davis	22.20	17.32	10.00	1981-1990
	28.30	21.74	10.00	1991-2000
	30.00	27.35	10.00	2001-2025
Lichterman	27.46	25.91	19.52	1981-1990
	30.00	29.21	20.92	1991-20000
	30.00	30.00	22.48	2001-2025
Mallory	25.06	21.78	13.00	1981-1990
	29.72	23.94	13.00	1991-2000
	34.09	26.60	13.00	2001-2025
McCord	26.75	23.75	18.00	1981-1990
	28.00	26.79	18.00	1991-2000
	28.00	28.00	18.00	2001-2025
Morton	19.76	13.38	4.38	1981-1990
	28.26	21.27	9.99	1991-2000
	30.00	28.53	16.25	2001-2025
Sheahan	29.55	25.20	15.00	1981-1990
	34.10	28.99	15.00	1991-2000
	35.00	33.62	15.00	2001-2025
Municipal pumpage (Subtotal)	187.24	155.91	98.70	1981-1990
	222.41	188.78	106.51	1991-2000
	235.89	214.18	114.73	2001-2025
Industrial pumpage	75.00	74.00	72.5	1981-1990
	80.00	76.00	72.5	1991-2000
	87.00	80.00	72.5	2001-2025
Municipalities (outside MLGW) pumpage	10.00	9.00	8.21	1981-1990
	12.00	10.00	8.21	1991-2000
	15.00	12.00	8.21	2001-2025
Total pumpage	272.24	238.91	179.41	1981-1990
	314.41	274.78	187.22	1991-2000
	337.89	306.18	195.44	2001-2025

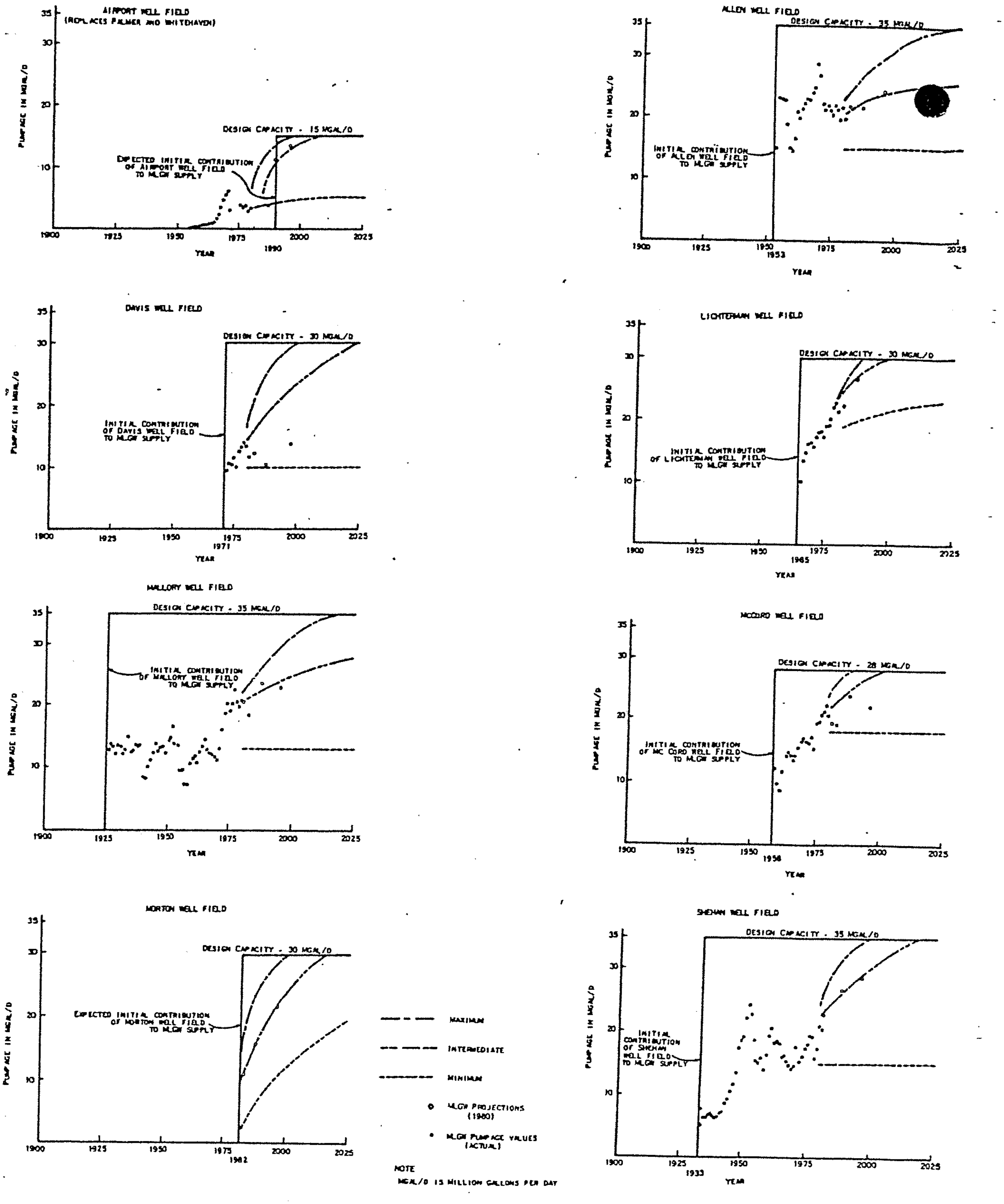


FIGURE 14. HISTORIC PUMPAGE AND THE RANGE OF EXPECTED PUMPAGE THROUGH 2025 FOR MAJOR MLGW WELL FIELDS

MEMPHIS METROPOLITAN URBAN AREA
DEPARTMENT OF THE ARMY
MEMPHIS DISTRICT, CORPS OF ENGINEERS, MEMPHIS, TENNESSEE
JULY 1981 Serial: 21724 File: 209A/58

The intermediate pumpage figures are based on extrapolations of MLGW projections. These values are taken as one hypothetical situation only and were determined to show water-level effects in the middle of the range between maximum and minimum. No increase was assumed in self-supplied industrial pumpage.

Minimum pumpage was arbitrarily selected as the smaller of (a) the minimum five year demand that stabilized for each well field during the last 30 years or (b) the projected MLGW pumpage reduced by a factor of 40 percent.

EXHIBIT 19

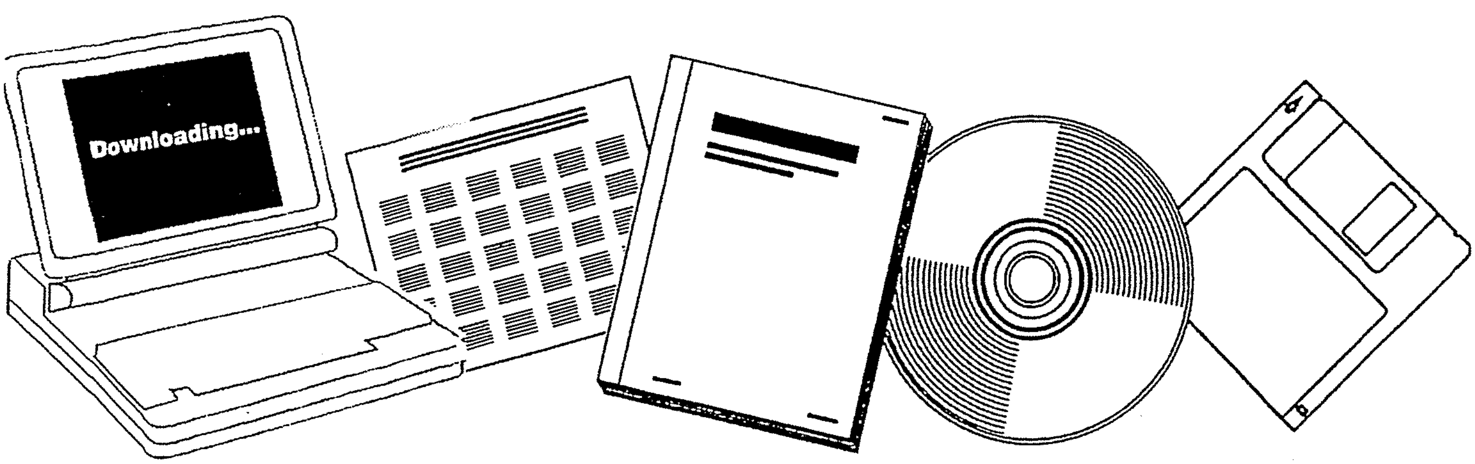
James H. Criner and William S. Parks
Historic Water-Level Changes and Pumpage from the Principal
Aquifers of the Memphis Area, Tennessee: 1886-1975
USGS WRI 76-67

PB264778

HISTORIC WATER-LEVEL CHANGES AND PUMPAGE FROM THE PRINCIPAL AQUIFERS OF THE MEMPHIS AREA, TENNESSEE: 1886-1975

GEOLOGICAL SURVEY, MEMPHIS, TENN. WATER
RESOURCES DIV

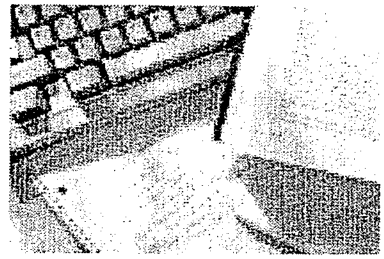
MAY 1976



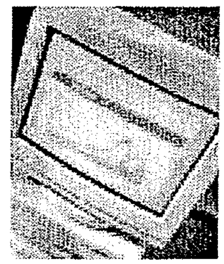
U.S. Department of Commerce
National Technical Information Service

One Source. One Search. One Solution.

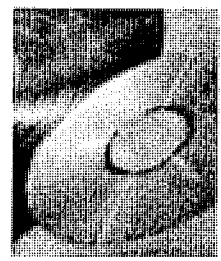
NTIS



Providing Permanent, Easy Access to U.S. Government Information



National Technical Information Service is the nation's largest repository and disseminator of government-initiated scientific, technical, engineering, and related business information. The NTIS collection includes almost 3,000,000 information products in a variety of formats: electronic download, online access, CD-ROM, magnetic tape, diskette, multimedia, microfiche and paper.



Search the NTIS Database from 1990 forward

NTIS has upgraded its bibliographic database system and has made all entries since 1990 searchable on **www.ntis.gov.** You now have access to information on more than 600,000 government research information products from this web site.

Link to Full Text Documents at Government Web Sites

Because many Government agencies have their most recent reports available on their own web site, we have added links directly to these reports. When available, you will see a link on the right side of the bibliographic screen.

Download Publications (1997 - Present)

NTIS can now provides the full text of reports as downloadable PDF files. This means that when an agency stops maintaining a report on the web, NTIS will offer a downloadable version. There is a nominal fee for each download for most publications.

For more information visit our website:

www.ntis.gov

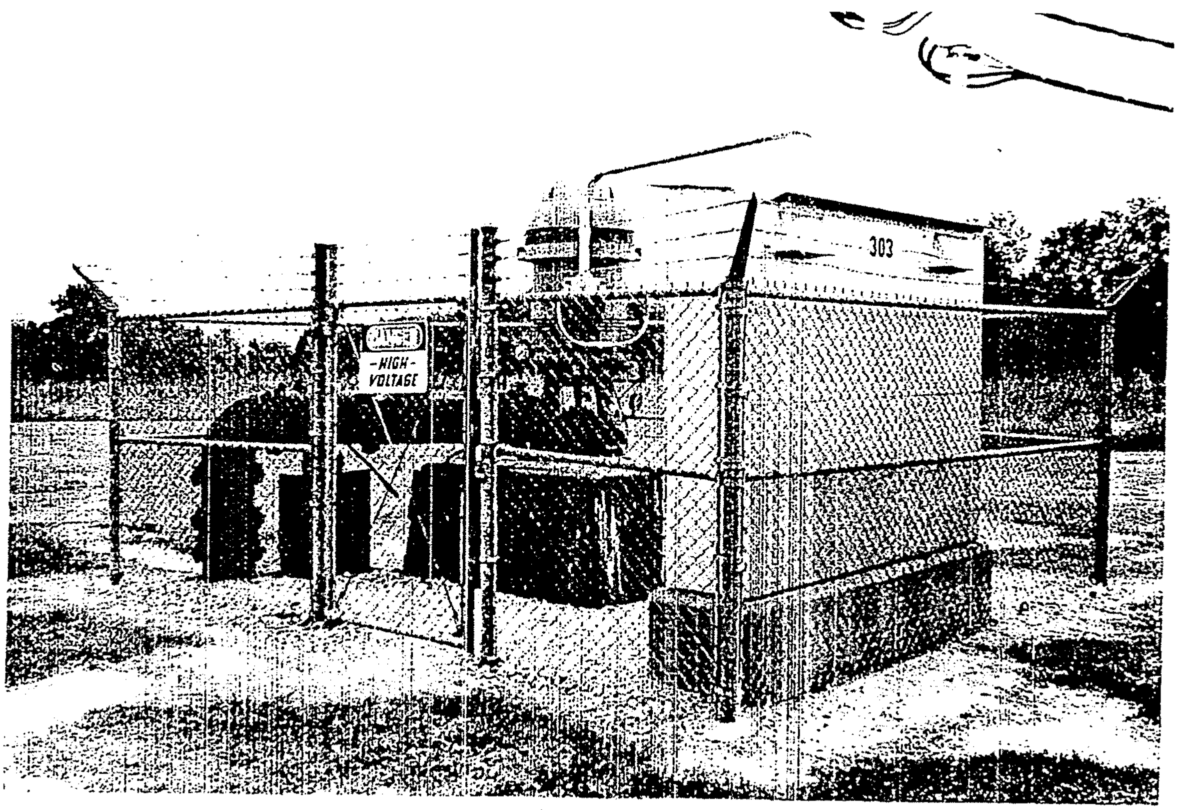
U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Technical Information Service
Springfield, VA 22161

PB 264 778

HISTORIC WATER-LEVEL CHANGES AND PUMPAGE FROM THE PRINCIPAL AQUIFERS OF THE MEMPHIS AREA, TENNESSEE: 1886-1975

U. S. GEOLOGICAL SURVEY

Water-Resources Investigation 76-67



Prepared in cooperation with the

CITY OF MEMPHIS,

MEMPHIS LIGHT, GAS AND WATER DIVISION

BIBLIOGRAPHIC DATA SHEET	1. Report No. USGS/WRD/WRI-77/019	2.	3. Recipient's Accession No.
4. Title and Subtitle HISTORIC WATER-LEVEL CHANGES AND PUMPAGE FROM THE PRINCIPAL AQUIFERS OF THE MEMPHIS AREA, TENNESSEE: 1886-1975 Text, tables, and illustrations indicating historic ground-water use and results.			5. Report Date May 1976
			6.
7. Author(s) James H. Criner and William S. Parks			8. Performing Organization Rept. No. USGS/WRI-76-67
9. Performing Organization Name and Address U.S. Geological Survey, Water Resources Division 826 Federal Office Bldg. Memphis, Tennessee 38103			10. Project/Task/Work Unit No.
			11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey, Water Resources Division 826 Federal Bldg. Memphis, Tennessee 38103			13. Type of Report & Period Covered Progress 1967-1975
			14.

15. Supplementary Notes

Prepared in cooperation with the Memphis Light, Gas and Water Division

16. Abstracts Annual pumpage for both the Memphis Sand ("500-foot" sand) and Fort Pillow Sand ("1400-foot" sand) from the time of initial pumping from these aquifers to 1975 is presented in both tabular and graphic forms. The Memphis Sand supplied 188 million gallons per day in 1975 or 95 percent of the total water used in the area. Pumpage from the Fort Pillow Sand has decreased in recent years and in 1975 was about 4 million gallons per day. Pumping increases from the Memphis Sand have caused an almost continual decline of water levels as shown by graphs, tables, and a series of potentiometric-surface maps. Water-level-change maps show the fluctuations in water levels for two' periods of high water use. Water levels in the Fort Pillow Sand are also shown by tables and graphs and a potentiometric-surface map. These graphs illustrate a rise of water levels since 1963, coincidental with pumping reductions. The data presented suggest that a constant pumping rate will cause little water-level decline and that the water levels can be altered for efficient resource management by areally varying the distribution of pumping. The references listed support the information presented in this report.

17. Key Words and Document Analysis. 17a. Descriptors

Water levels*, potentiometric level*, hydrographs*, water utilization*, withdrawal*, ground water*, water supply*, aquifers*, Tennessee, water management, geologic formations.

17b. Identifiers/Open-Ended Terms

Memphis area, ground-water resources, water-level change, pumpage.

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restriction on distribution.	UNCLASSIFIED	60
	20. Security Class (This Page)	22. Price MF
	UNCLASSIFIED	A04 - A01

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

PC

I

HISTORIC WATER-LEVEL CHANGES AND PUMPAGE FROM THE PRINCIPAL AQUIFERS OF THE MEMPHIS AREA, TENNESSEE: 1886-1975

U.S. GEOLOGICAL SURVEY

Water Resources Investigations 76-67

Prepared in cooperation with the

City of Memphis,

Memphis Light, Gas and Water Division

I (a)

HISTORIC WATER-LEVEL CHANGES AND PUMPAGE FROM THE PRINCIPAL AQUIFERS OF THE MEMPHIS AREA, TENNESSEE: 1886-1975

By James H. Criner and William S. Parks

U.S. GEOLOGICAL SURVEY

Water Resources Investigations 76-67

Prepared in cooperation with the

City of Memphis

Memphis Light, Gas and Water Division

May 1976

I (b)

UNITED STATES DEPARTMENT OF THE INTERIOR

Thomas S. Kleppe, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

For additional information write to:

U.S. Geological Survey, WRD
826 Federal Office Building
Memphis, Tennessee 38103

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Factors for converting English units to metric units are shown to four significant figures. In the text, however, the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	Multiply by	Metric
ft (feet)	3.048×10^{-1}	m (metres)
ft/mi (feet per mile)	1.894×10^{-1}	m/km (metres per kilometre)
ft^2/d (feet squared per day)	9.290×10^{-2}	m^2/d (metres squared per day)
gal (gallons)	3.785	l (litres)
gal/min (gallons per minute)	3.785	l/min (litres per minute)
gal/d (gallons per day)	3.785	l/d (litres per day)
Mgal/d (million gallons per day)	3.785	Ml/d (million litres per day)
mi (miles)	1.609	km (kilometres)
mi^2 (square miles)	2.590	km^2 (square kilometres)

HISTORIC WATER-LEVEL CHANGES AND PUMPAGE FROM THE PRINCIPAL AQUIFERS OF THE MEMPHIS AREA, TENNESSEE: 1886-1975

by

James H. Criner and William S. Parks

ABSTRACT

The Memphis Sand ("500-foot" sand) supplies about 95 percent of the water used in the Memphis area for municipal and industrial purposes. In general, pumpage has increased at an irregular rate since the completion of the first well to this aquifer in 1886. These withdrawals are responsible for an almost continuous decline of water levels in wells throughout the Memphis area. Water-level data indicate that over the years a broad, regional cone of depression has developed in the potentiometric surface of the Memphis Sand and is centered near downtown Memphis. Areally smaller, subsidiary cones are superimposed upon this regional cone in areas heavily pumped by municipal and industrial wells. Pumpage from the Memphis Sand in Shelby County, Tenn., was 188 Mgal/d (million gallons per day) or 712 Ml/d (million litres per day) in 1975, although a maximum of 190 Mgal/d (719 Ml/d) was reached in 1974.

Pumpage from the Fort Pillow Sand ("1,400-foot" sand) began in 1924 and increased at a yearly rate of about 0.6 Mgal/d (2.3 Ml/d) until 1942. From 1943 to 1962, pumpage averaged about 11.5 Mgal/d (43.5 Ml/d), then was reduced as MLGW (Memphis Light, Gas and Water Division) discontinued wells that became unserviceable. MLGW ceased pumping from the aquifer in 1974, and pumpage from the remaining industrial wells in Shelby County in 1975 was 4.4 Mgal/d (16.6 Ml/d). Water levels in the Fort Pillow Sand generally have risen since 1963.

Water levels in the aquifers in the Memphis area fluctuate inversely with changes in pumping. Analysis of observation-well and pumpage data indicates that local water levels can be altered by changing the pumping rates or by varying the areal distribution of pumping.

INTRODUCTION

The Memphis area, one of the major population and industrial centers of the Mississippi Valley, obtains most of its water supply from a complex artesian aquifer system that underlies a large part of the upper Mississippi embayment. Although water is pumped from both the Memphis Sand and Fort Pillow Sand, known locally as the "500-foot" sand and "1,400-foot" sand respectively, most of the current water supply is withdrawn from the Memphis Sand alone. Pumpage from this aquifer in 1975 was about 188 Mgal/d (712 Ml/d) which is about twice that in 1950, five times that in 1920, and ten times that in 1890. This escalating withdrawal from the Memphis Sand has resulted in a nearly uninterrupted lowering of its potentiometric surface, as indicated by the historic decline of water levels in wells throughout the area.

This report reviews the historic changes of water levels in the Memphis area with emphasis on the period after 1960. It also presents information on pumpage from the Memphis Sand since 1886 and from the Fort Pillow Sand since 1924 and discusses the relationship between pumping rate and water-level decline to 1975. The report is intended to provide basic data and interpretive information for use by water managers, planners, and other persons interested in the ground-water resource, and to update prior publications discussing the water-level changes in the Memphis area.

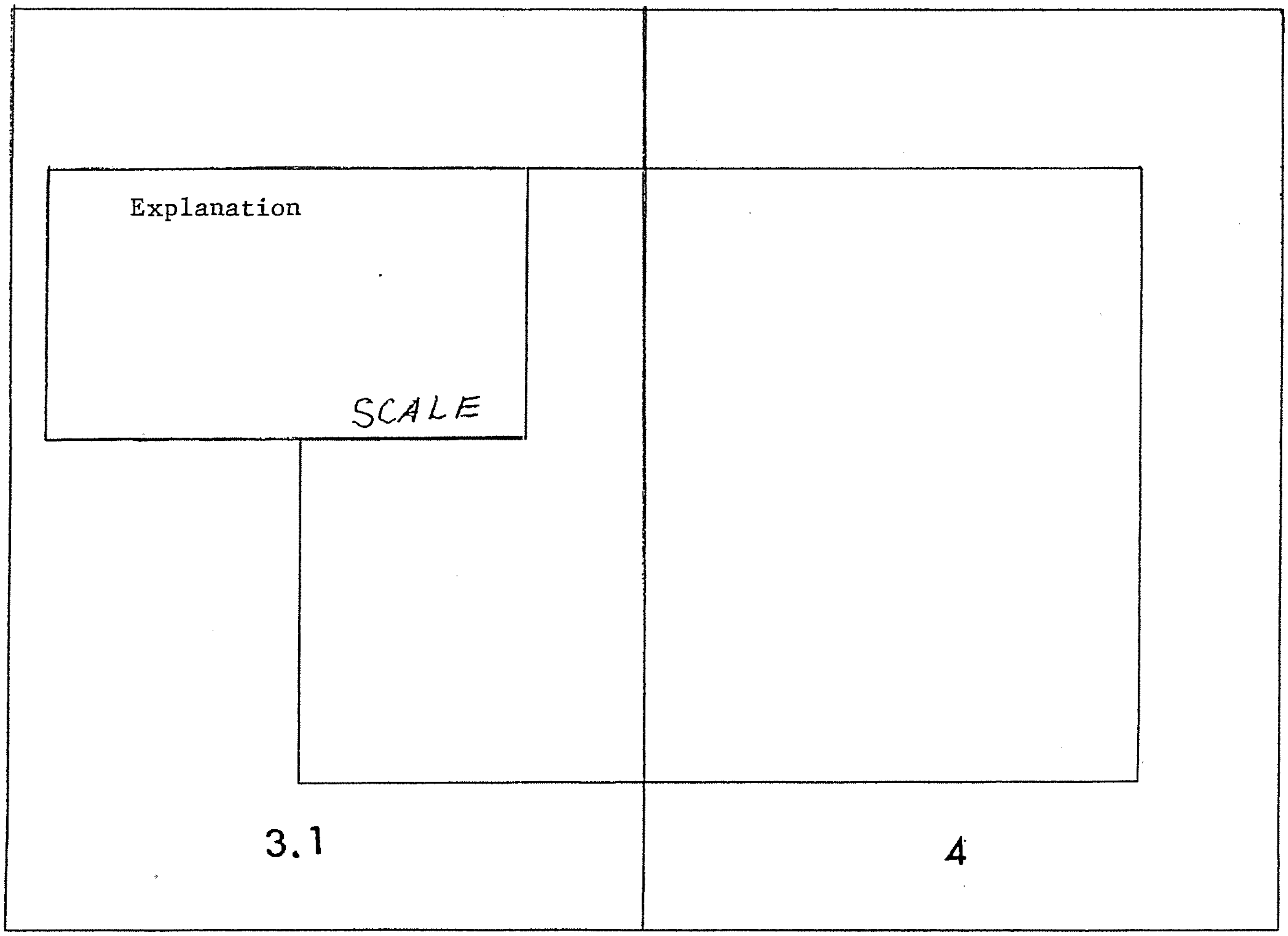
General aspects of the aquifer systems in the Memphis area are described or discussed in reports by Schneider and Cushing (1948), Criner and Armstrong (1958), Criner, Sun, and Nyman (1964), and Bell and Nyman (1968). Other reports which contain pertinent information about pumping rates and water levels for the principal aquifers are included in the selected references. Since 1935, the Geological Survey has published many water-supply papers that give data concerning ground-water levels in the United States. To provide easy reference for readers interested in low water levels on a monthly or 5-day basis, those water-supply papers that include data for the Memphis area are listed in the following table:

Numbers of U.S. Geological Survey Water-Supply Papers containing records of water levels in the Memphis area, Tennessee

Year	WSP	Year	WSP	Year	WSP	Year	WSP
1936	817	1942	945	1948	1127	1954	1322
1937	840	1943	987	1949	1157	1955	1405
1938	845	1944	1017	1950	1166	1956-58	1538
1939	886	1945	1024	1951	1192	1959-63	1803
1940	907	1946	1072	1952	1222	1964-68	1978
1941	937	1947	1097	1953	1266	1969-73	2171

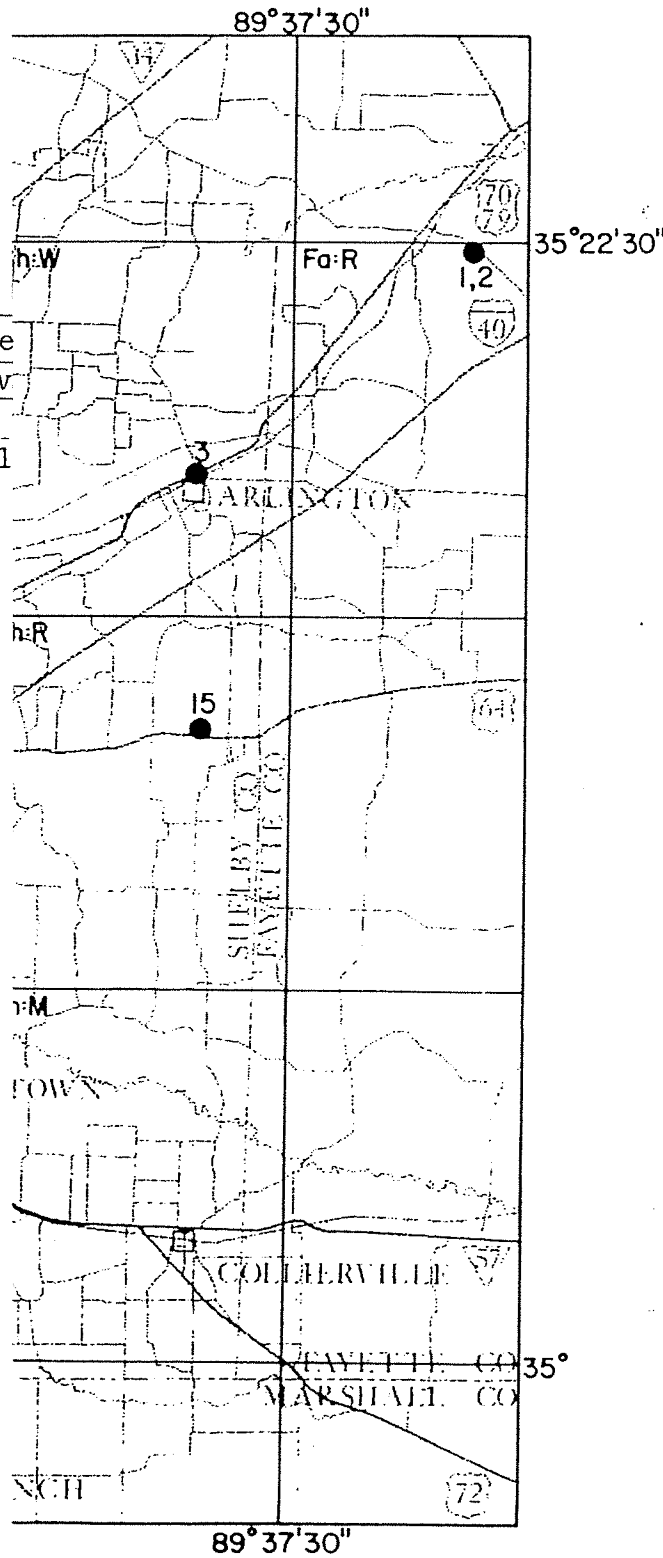
As used in this report, the term "Memphis area" refers to a 1,300 mi^2 (3,400 km^2) area comprising parts of three states. It includes Shelby County and parts of Fayette and Tipton Counties in Tennessee and adjacent counties in Mississippi and Arkansas. The boundaries of the Memphis area have been modified somewhat from the area as defined for previous reports. The present boundaries and the locations of observation wells used for diagrams and maps presented in this report are shown in figure 1.

FIGURE 1



Index map showing page numbers of each component of figure 1.

Figure 1.-- Memphis area, Te
locations of observ
and Memphis Light,
Water Division well



Well-Numbering System

Wells are identified according to the numbering system used by the U. S. Geological Survey throughout Tennessee. The well number consists of three parts: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7½-minute quadrangle, or 7½-minute quadrant of the 15-minute quadrangle, on which the well is plotted; and (3) a number generally indicating the numerical order in which the well was inventoried. The symbol Sh:U-2, for example, indicates that the well is located in Shelby County on the "U" quadrangle and is identified as well 2 in the numerical sequence. The quadrangles are lettered from left to right, beginning in the southwest corner os the county. Quadrangle "U", cited in the example, is the southwest quadrant of the Millington 15-minute quadrangle, now the Millington 7½-minute quadrangle.

For this report, wells in Arkansas and Mississippi are numbered consecutively in order of use in the preparation of illustrations and are assigned prefixes AR and MS, respectively.

AQUIFER SYSTEMS

About 3,000 ft (900 m) of sand, clay, silt, chalk, gravel, and lignite underlie the Memphis area above the Paleozoic bedrock. These deposits make up geologic units ranging in age from Late Cretaceous to Holocene. In this report, only the post-Midway formations (Wilcox and younger) will be considered. The stratigraphic relations of these units and their hydrologic significance are shown in table 1.

The principal water-bearing formations are the Memphis Sand and the Fort Pillow Sand. More than 95 percent of the ground water used in the Memphis area is supplied by the Memphis Sand. The Fort Pillow Sand is the source of supply for one industry in Tennessee and for a few municipal and industrial wells in Arkansas and Mississippi. The fluvial deposits and alluvium supply water to many domestic and farm wells and to a few industrial wells. Collectively, the shallow aquifers and the Fort Pillow Sand provide less than 5 percent of the water used in this area.

GROUND-WATER PUMPAGE

The early citizens of Memphis obtained their water supply from streams, cisterns, springs, and shallow wells. As the city grew, these sources became inadequate because of the small quantity or poor quality of the water. The search for a dependable source of good quality water ended in 1886 when the first artesian well was completed to the Memphis Sand. The successful completion of this flowing well encouraged the drilling of additional wells and a greater utilization of the ground-water resource. Within the year, two water companies began drilling to the Memphis Sand, and by 1888 each had completed eight wells and both were supplying water to the city.

Table 1.--Post-Midway geologic units underlying the

System	Series	Group	Stratigraphic unit	Thickness (feet)
Quaternary	Holocene and Pleistocene		Alluvium	0-175
	Pleistocene		Loess	0-65
Quaternary and Tertiary(?)	Pleistocene and Pliocene		Fluvial deposits (terrace deposits)	0-100
Tertiary	Eocene	?	Jackson Formation and upper part of Claiborne Group ("capping clay")	0-350
		Claiborne	Memphis Sand ("500-foot" sand)	500-880
		Wilcox	Flour Island Formation	160-350
	?		Fort Pillow Sand ("1,400-foot" sand)	210-280
	Paleocene		Old Breastworks Formation	200-250

Memphis area and their hydrologic significance.

Lithology and hydrologic significance
Sand, gravel, silt, and clay. Underlies the Mississippi River alluvial plain and the flood plains of other streams in the area. Supplies water to a few domestic and industrial wells. Could be an important source of water for irrigation and some industrial uses.
Wind-deposited silt; silty clay and minor sand. Forms a blanket over the fluvial deposits in upland areas; topographically higher than alluvium. Thickest on the bluffs that border the Mississippi River alluvial plain; generally thinner towards the east. Not a source of ground-water.
Sand and gravel; minor ferruginous sandstone. Underlies the upland areas in a broad, irregular belt east of the Mississippi River alluvial plain; may be locally absent. Supplies water to many shallow, small-capacity wells in suburban and county areas.
Gray, bluish-gray, greenish-gray, and tan clay; subordinate beds of fine-grained sand and lignite. Supplies water to some small-capacity wells. Generally considered to be of low permeability and to confine water in Memphis Sand. Absent in southeastern part of Memphis area.
Fine- to coarse-grained sand; subordinate lenses of clay and minor amounts of lignite. Thick clay bed locally in lower part; coarse sand lenses locally at base. Very good aquifer supplying 95 percent of water used in Memphis area.
Gray, greenish-gray, and brown carbonaceous clay. Locally contains fine-grained sand lenses and some lignite. Serves as lower confining bed for Memphis Sand and upper confining bed for Fort Pillow Sand.
Fine- to medium-grained sand; minor amounts of lignite and some clay lenses. Second principal aquifer supplying about 3 percent of water used in Memphis area.
Gray, greenish-gray, and brown carbonaceous clay. Contains some lignite and is sandy near top. Lower confining bed for water in Fort Pillow Sand.

Over the years the development of the ground water resource in the Memphis area has progressed at an accelerated rate with the addition of many wells in both the Memphis Sand and Fort Pillow Sand for municipal and industrial supplies. In 1975 the municipal system at Memphis consisted of about 140 wells, most of which are in six well fields - (1) Mallory (formerly Parkway), (2) Sheahan, (3) Allen, (4) McCord, (5) Lichterman, and (6) Davis (fig. 1). In addition to the Memphis supply, other municipal systems and industries have more than 200 wells scattered over the area, some of which are concentrated in well fields or towns or in industrial development sites.

Average-daily pumping rates from the major aquifers and by major users in Shelby County for the period from 1887 to 1975 are shown in figure 2. Specific information concerning annual withdrawals from the major aquifers are given in table 2 in the pumpage-data section of this report. Pumpage data for the Arkansas and Mississippi parts of the Memphis area are not included because the water-use surveys have not extended into these areas.

Since the discovery of the artesian water system in 1886, annual withdrawals from the Memphis Sand have continued to increase at an irregular rate (fig. 2). In the late 1880's and early 1890's, pumpage increased at a yearly rate of about 3.3 Mgal/d (12.5 Ml/d). From 1895 to 1920, however, the rate of increase was only about 0.2 Mgal/d (0.8 Ml/d), and annual withdrawals averaged about 33 Mgal/d (125 Ml/d). Beginning in 1920, pumpage shows a pronounced and sustained yearly rate of increase of about 2.3 Mgal/d (8.7 Ml/d). This rate of increase persisted until 1960 when withdrawal was about 127 Mgal/d (481 Ml/d). Between 1920 and 1960, short-term deviations from the long-term trend include a sharp increase in annual withdrawal from 1941 to 1943 and a sharp decrease from 1944 to 1946. These deviations were the result of increased water use by industry to meet production demands brought on by World War II and of a reduction in water use near the end of the war. Beginning in 1960, pumpage shows another sustained yearly rate of increase which is larger than that for the previous five decades. This increase has averaged about 4.5 Mgal/d (17 Ml/d) and persisted to 1974. In that year, withdrawal from the Memphis Sand in Shelby County was about 190 Mgal/d (719 Ml/d), which is the largest annual pumpage yet recorded. In 1975, pumpage was reduced to 188 Mgal/d (712 Ml/d) probably as a result of above-normal rainfall during the year.

The Fort Pillow Sand was first used at Memphis in 1924 to supplement supplies from the Memphis Sand. From the time of initial use until 1942, pumpage from the Fort Pillow Sand increased at an average yearly rate of about 0.6 Mgal/d (2.3 Ml/d). From 1943 to 1962, annual pumpage remained relatively constant and averaged about 11.5 Mgal/d (43.5 Ml/d). Peak withdrawal within this period was in 1951, when annual pumpage was about 14.3 Mgal/d (54.1 Ml/d). At that time, MLGW[1]/ had 20 wells pump-

1/ MLGW, throughout this report, refers to the present Memphis Light, Gas and Water Division since its orgainization in 1939 and to private and municipal predecessors supplying water to the City of Memphis before that time.

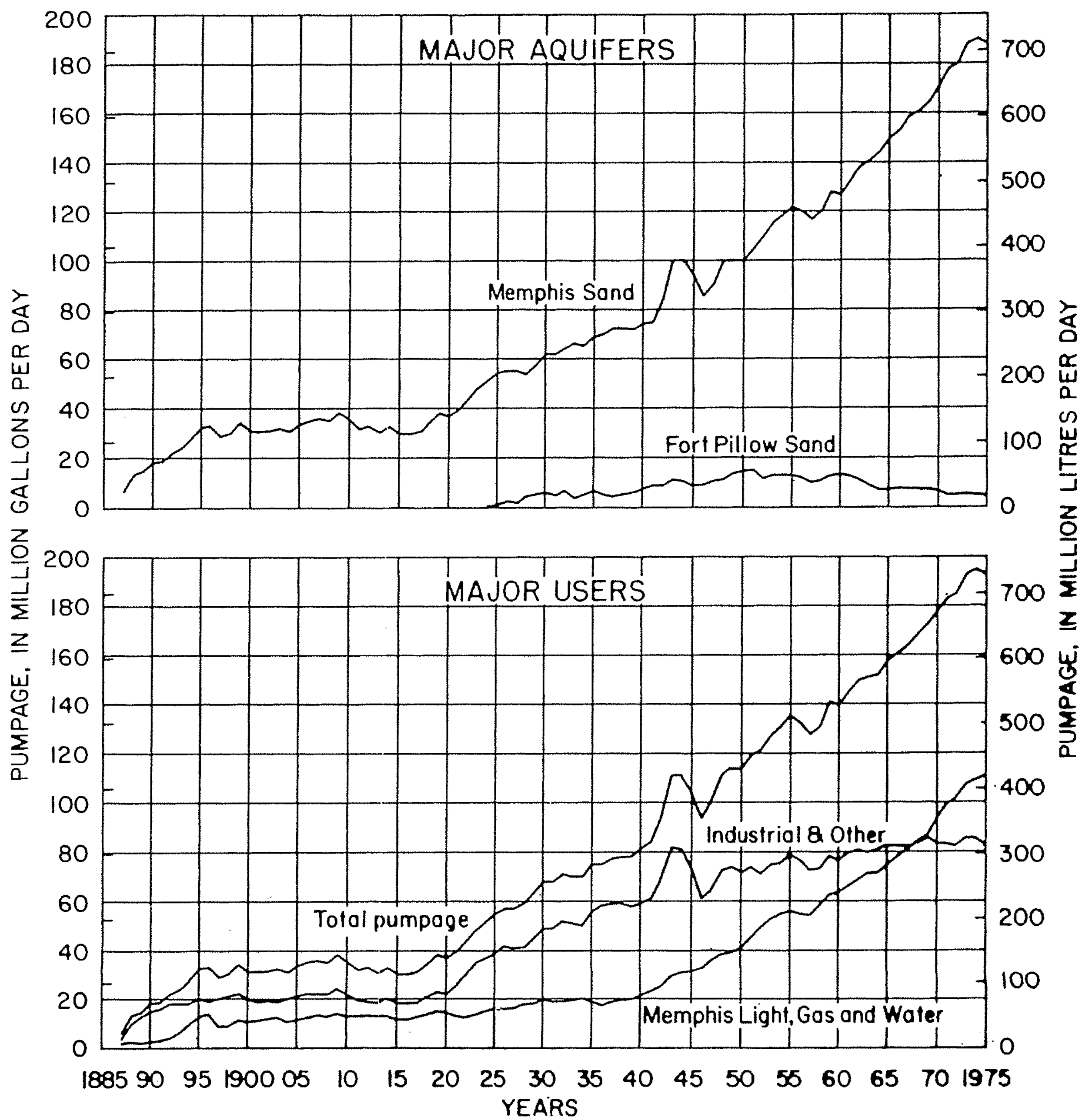


Figure 2.--Pumping rates from major aquifers by major users in Shelby County, Tennessee, 1887-1975.

ing from the Fort Pillow Sand in Mallory and Sheahan well fields, and industry had three wells. In 1962, however, MLGW began a reduction in their withdrawals by discontinuing wells as they became inefficient or unserviceable with age. These moderately deep, airlift wells in the Fort Pillow Sand were replaced by shallower, turbine-pumped wells in the Memphis Sand. In December 1971, MLGW discontinued pumping from the Fort Pillow Sand in the Mallory well field, and in January 1974 pumping was stopped in the Sheahan well field. This aquifer is now regarded by MLGW officials to be an auxiliary source of supply for future use. In 1975, industrial pumpage from the Fort Pillow Sand in Shelby County was about 4.4 Mgal/d (16.6 Ml/d).

Figure 2 shows separate plots for pumpage reported by MLGW, the largest single supplier of water in Shelby County, pumpage reported by or estimated for major industrial and other users, and total pumpage by major users from both aquifers. A comparison of these plots shows that in 1920 annual withdrawal by industrial and other users began to increase at a pronounced and sustained rate, whereas Memphis municipal pumpage continued to increase at a much smaller rate. In 1940, near the beginning of World War II, withdrawal by MLGW began to increase at an accelerated yearly rate, and by 1968 it had exceeded pumpage by industrial and other users.

In 1948 after World War II, the increase in pumpage by industrial and other users leveled off and has increased at a small yearly rate to the present. This leveling off in the annual withdrawal by industrial and other users is the result of the extension of MLGW's water-supply system into large areas annexed to Memphis that were once supplied by independent systems, an increase in the number of minor water-using industries and commercial establishments that are buying water from MLGW, and a reduction in the annual withdrawals by several major water-using industries that now have systems for recirculation of water for repeated use. Although several self-supplied, major water-using industries have located in Shelby County within the last few years, the general trends of annual withdrawal by MLGW and industry probably have been well established. MLGW supplies an increasing percentage of the total water used as it expands the municipal system into other areas of the county.

In 1974, a total of 195 Mgal/d (738 Ml/d) was pumped by major users from the major aquifers in Shelby County. Of this total, MLGW withdrew 109.5 Mgal/d (414 Ml/d) and major industrial and other users withdrew 85.5 Mgal/d (324 Ml/d). In 1975, pumpage by MLGW was increased by 1 Mgal/d (3.8 Ml/d) while withdrawals by industrial and other users was reduced by about 3 Mgal/d (11.4 Ml/d) for a total of 193 Mgal/d (730 Ml/d).

WATER LEVELS

Water levels have declined throughout the Memphis area as a result of the long-term escalation of pumping. The rates of water-level decline have not been uniform from place to place because of changes in pumping rates and distribution of wells and well fields, and also because of variations in annual rainfall. In some large well fields and adjacent areas, changes in pumping have caused substantial water-level fluctuations, but in outlying parts of the Memphis area, variations in annual rainfall may cause greater water-level changes than pumping. Nevertheless, historic decline of water levels and the concurrent increase in pumping indicate that water levels will continue to decline in the Memphis area in response to future increases in pumping.

Observation wells, located at various distances from well fields and away from the estimated center of pumping, provide information that can be used to determine the effects of pumping throughout the Memphis area. From water levels measured in these wells, hydrographs (fig. 3), potentiometric-surface maps (figs. 5-8), and water-level-change maps (figs. 9-10) were prepared to illustrate water-level changes in the major aquifers. These graphs and maps are useful in the analysis of the local and areal effects of pumping and long-term water-level trends. Water levels and water-level changes for the wells used in the preparation of this report are given in tables 3 through 6 in the section on water-level data.

Hydrographs

Hydrographs for six wells screened in the Memphis Sand and four in the Fort Pillow Sand are shown in figure 3. These wells were selected for their long-term record and their areal distribution. Collectively, the hydrographs show representative water-level trends and reflect the relationship of water levels to changes in pumping within the Memphis area. The hydrographs also are useful because they indicate water levels below land surface at each well and reflect changes in pumping rates for nearby well fields or show long-term water-level trends for localized areas.

Well Sh:P-76 in the Memphis Sand is near the estimated center of pumping for the Memphis area. The hydrograph for this well (fig. 3) reflects the total pumping in the area and indicates an almost continuous water-level decline. The few rises shown are attributed to reductions in pumpage. Fa:R-2 is the most remote well from the center of pumping. The water level in this well declined 2.6 ft (0.8 m) from 1949 to 1972. However, high rainfall during 1973 and 1975 caused a rise to within 1.1 ft (0.3 m) of the original water-level in this well. Wells Sh:U-2 and Sh:Q-1 are located at intermediate distances between the center of pumping and the outer limit of the influence of pumping. The hydrographs for these wells show the effect of pumping and the declining trend of water levels for their respective areas. Well Sh:K-66 is in Sheahan well field but it is far enough away from production wells that its water-level record is representative of water-level changes in the central part of the Memphis area.

The earliest, continuous, automatically-recorded water-level data collected in the Memphis area began in 1927 on Sh:O-124. This well is near the site of the first well completed to the Memphis Sand in 1886, and for this reason, its hydrograph was projected backward in time to illustrate the probable original water level with respect to the land surface (fig. 3). This projection to an estimated water level of 10 ft (3 m) above land surface or 240 ft (73 m) above sea level is

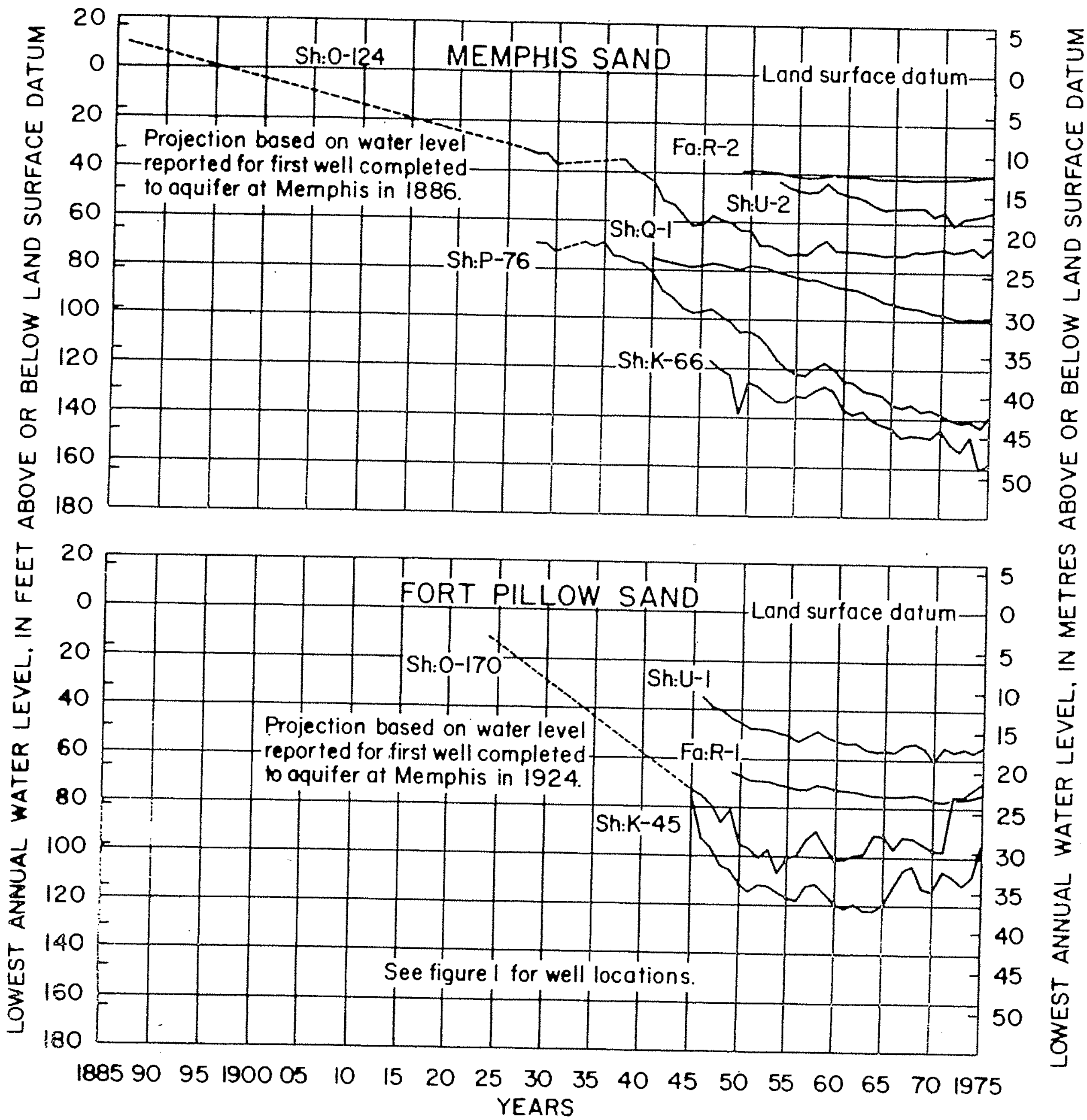


Figure 3. -- Water-level changes in observation wells screened in the major aquifers within the Memphis area, Tenn., 1886-1975.

figure 3 - - the plots of water levels for wells Sh:U-2 and Sh:U-1 are in error for the years 1968 through 1975 and should be changed slightly to conform with the new values given for these wells on page 41 (table 3) and page 42 (table 4)

based on a reported water level in the Bohlen-Huse Ice Company well drilled in 1886 and an estimated land surface altitude at the location of this first well.

It should be noted that well Sh:O-124 is an inspection shaft to an underground tunnel used in an early water-supply system as a collector for water which flowed from several wells screened in the Memphis Sand. Little is known about the tunnel, but it is reported to have been constructed in a clay layer, about 85 ft (26 m) below land surface and below the potentiometric surface of the Memphis Sand. Actual measurement to the bottom of the tunnel at Sh:O-124 in 1975 was 90.4 ft (27.5 m). The tunnel was reported to be brick lined, about 5 ft (1.5 m) in diameter, and about one-quarter mile (0.4 km) in length. Several wells were completed along the tunnel and were constructed so that water would flow into the tunnel through underground outlets. Water was pumped into the city supply system from a large well, 40 ft (12 m) in diameter, at the end of the tunnel at the Auction Avenue Station. The water-level record for well Sh:O-124 appeared responsive to annual pumpage in Memphis until about 1955 (fig. 3). Thereafter, the water level remained nearly constant except during years of high rainfall when it rose, as did the water level in other observation wells in the area.

The hydrograph (fig. 3) and potentiometric-surface maps indicate that the water level in Sh:O-124 is anomalously high and that the tunnel may have become a line of recharge to the Memphis Sand in about 1955. For this reason, the records for this well were not used in the preparation of the potentiometric-surface or water-level-change maps (figs. 5-7 and 9-10). The water level in Sh:O-124 fluctuates seasonally in unison with other wells located about the same distance from pumping centers. Nevertheless, the water level in this well may be affected by leakage from the Mississippi River, other nearby streams, the shallow aquifers, a storm sewer, or any combination of these.

The hydrographs for wells screened in the Fort Pillow Sand (fig. 3) are similar to those for the Memphis Sand, although water levels are more responsive to pumping. The center of pumping for the aquifer has remained near well Sh:O-170 since 1924, although pumping from the well field (Mallory) in which this well is located was stopped in 1971. The hydrograph shows a sharp rise in water level in 1971, reflecting the cessation of pumping. Well Fa:R-1 is the most remote observation well from the center of pumping for the Fort Pillow Sand. The hydrograph for this well shows greater water-level fluctuations than does the one for nearby Fa:R-2 in the Memphis Sand. These greater fluctuations reflect the lower transmissivity of the Fort Pillow Sand which responds to pumping more like an idealized artesian aquifer than the Memphis Sand. The hydrograph for well Sh:U-1, located about 18 mi (30 km) north of the center of pumping, reflects some local variations in pumping, but it is a good indicator of the areal water-level trend. Well Sh:K-45 is in Sheahan well field about 10 mi (16 km) east of the center of pumping. The hydrograph for this well also reflects the areal water-level trend, but the effect of local pumping is more pronounced.

The water level in the first well completed in the Fort Pillow Sand was recorded by MLGW as 11 ft (3.3 m) below land surface or at a potentiometric-surface altitude of 244 ft (74 m) above sea level in November 1924. This production well was about 1,000 ft (300 m) north of Sh:O-170, at about the same land-surface altitude, and therefore, the water level below land surface should have been nearly the same in both wells. Owing to the similarity in altitude, to the closeness of Sh:O-170 to the site of an original water-level measurement, and because this well has the longest water-level record, its hydrograph was projected backward in time to the probable original static level in the Fort Pillow Sand. This projection is shown in figure 3.

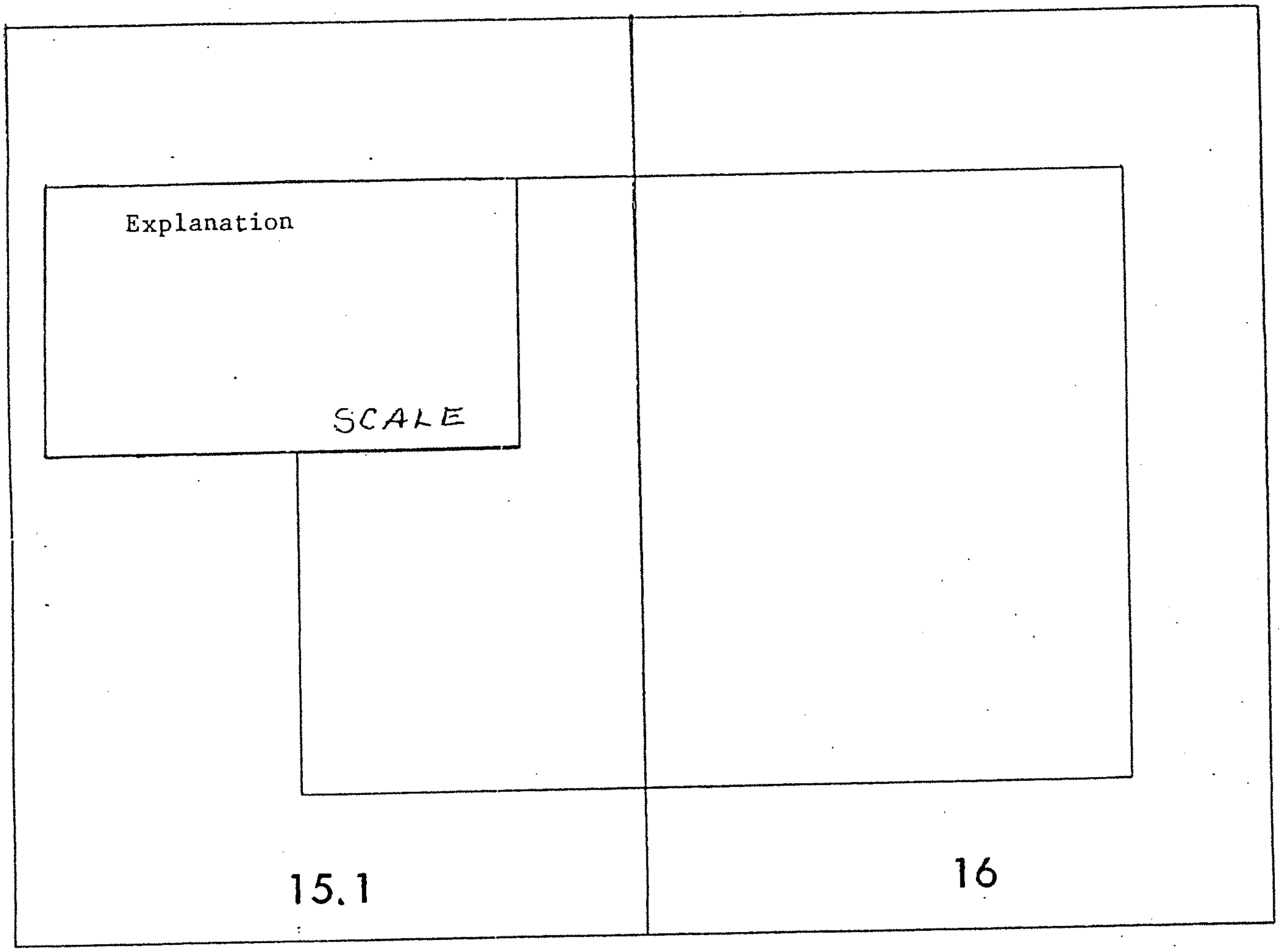
Potentiometric-Surface Maps

Contour maps made from water-level measurements in wells show the configuration of the potentiometric surface of an artesian aquifer at a particular time. The presumed shape of that surface for the Memphis Sand in 1886, prior to the development of wells in the aquifer, is shown in figure 4. The surface was generally flat, dipping northeasterly at a hydraulic gradient of from 1.5 to 2 ft/mi (0.28 to 0.38 m/km). Although the original altitude of the potentiometric surface is uncertain, it is estimated to have been about 240 ft (73 m) above sea level at the site of the first well on Court Avenue at Gayoso Bayou (Bohlen-Huse Ice Company). The control wells shown in figure 4 were selected for their locations away from pumping centers and for their long records which were used to estimate the probable original potentiometric surface.

The shape of the surface in August 1960, after 73 years of pumping from the Memphis Sand, is shown in figure 5. This contour map shows that one of the effects of escalating pumping has been the development of a broad cone of depression in the originally, nearly flat, potentiometric surface. This cone is centered beneath downtown Memphis. Within the major cone of depression were areally smaller, subsidiary cones at Allen, Mallory, and Sheahan well fields and two industrial sites. The two cones shown on figure 5 for Sheahan were centered on the two widely separated clusters of wells in that field. By 1960 only a slight distortion of the potentiometric surface was evident at the eastern edge of the Memphis area, illustrating the decreasing effect of pumping with distance from the pumping centers.

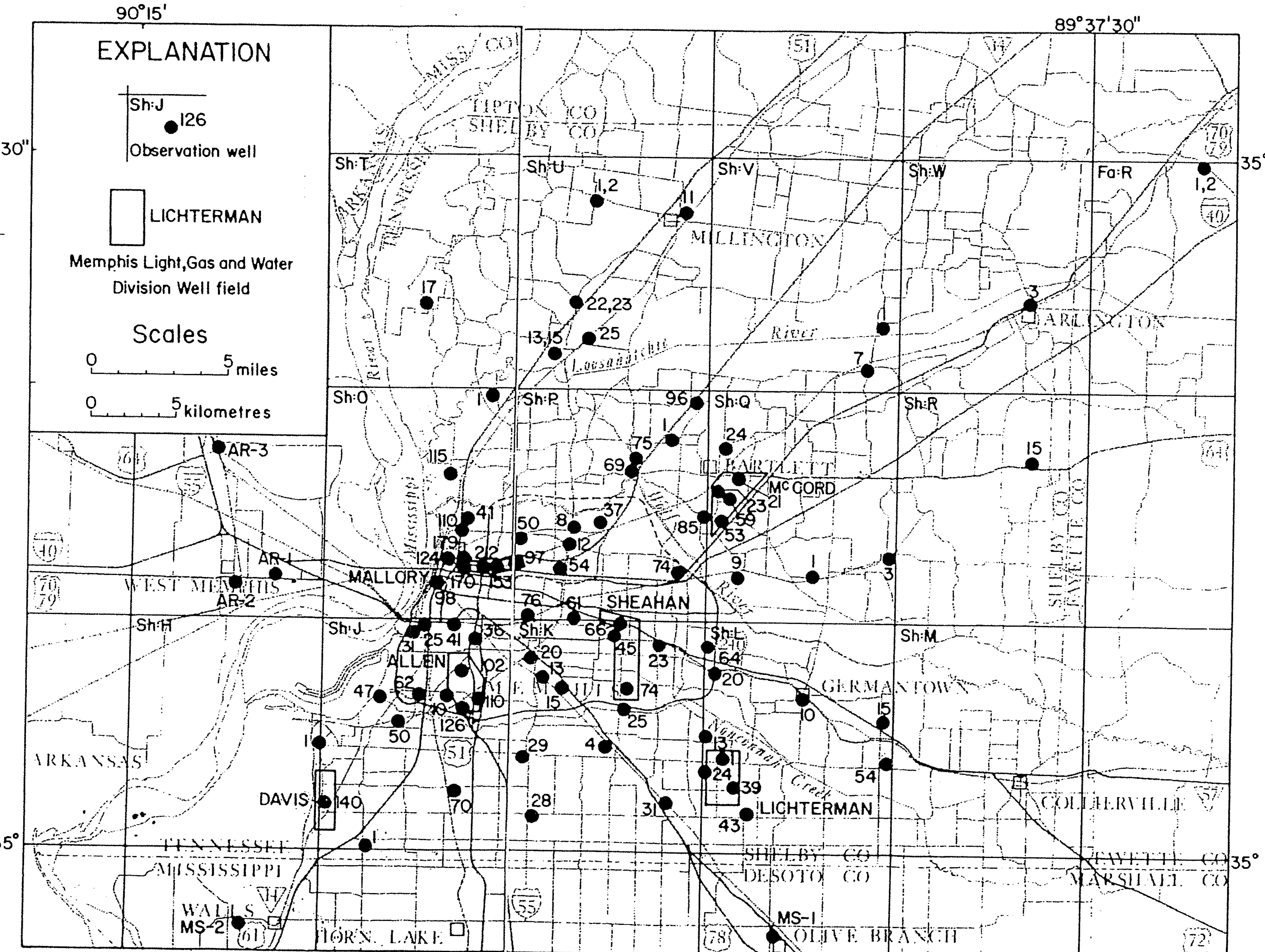
A similar potentiometric-surface map for September 1970 is shown in figure 6. By 1970 the increased pumpage of water from the Memphis Sand has caused the regional cone of depression to deepen and expand throughout the area with subsidiary cones becoming more or less pronounced in accordance with changes in pumping at these localities. The greatest decline of water levels or deepening of the cone was in Allen well field where the annual pumping rate doubled from 1960 to 1970. Also, by 1970 the hydraulic gradient had steepened throughout the area. This gradient was about 10 ft/mi (1.9 m/km) along a line from Olive Branch, Miss., to the Allen well field. The contour map for 1970 (fig. 6) shows that the subsidiary cones at well fields and industrial sites were somewhat deeper than in 1960 and that the two cones at Sheahan well field had been replaced by a single cone for that field.

FIGURE 4



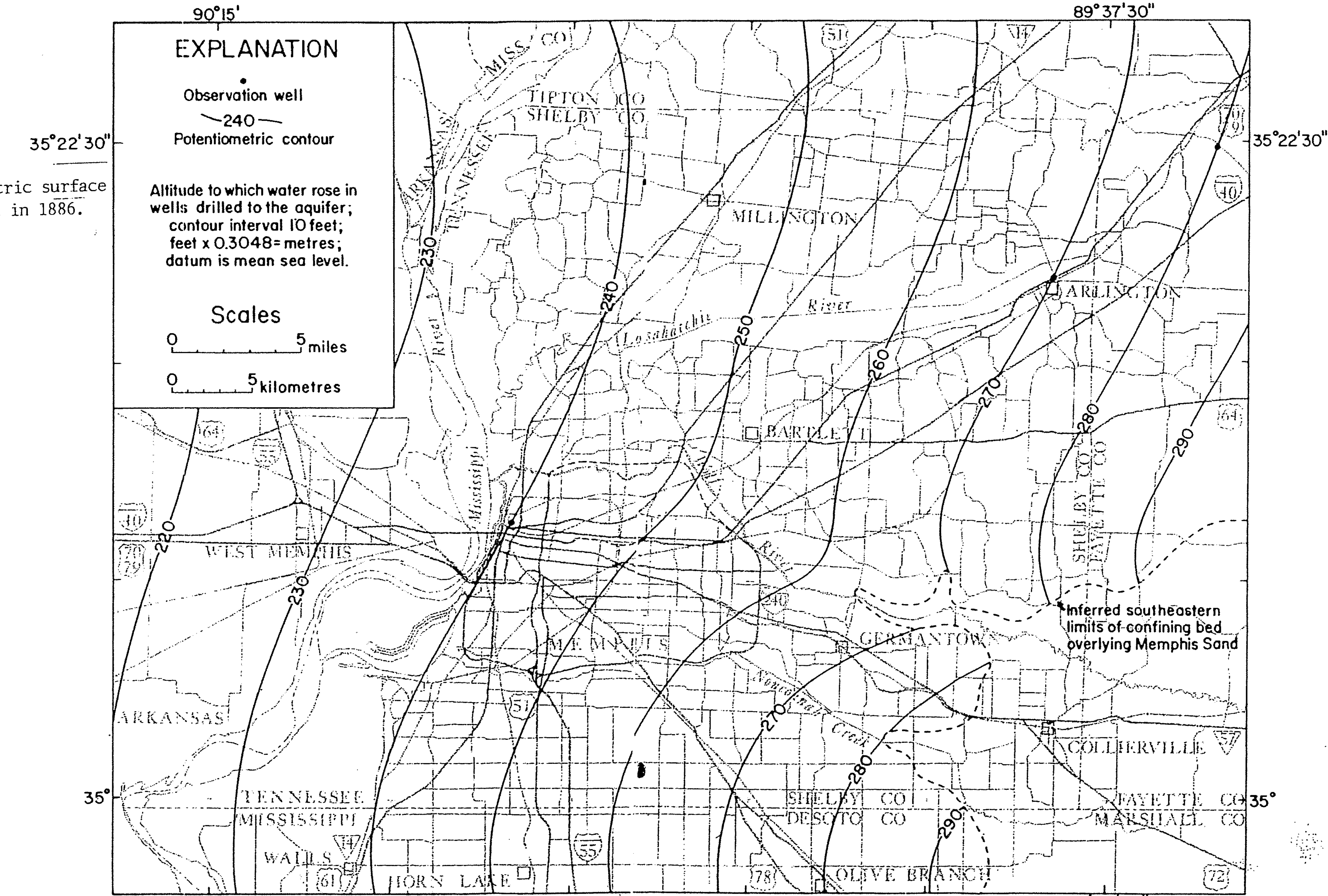
Index map showing page numbers of each component of figure 4.

Figure 1.-- Memphis area, Tenn., with locations of observation wells and Memphis Light, Gas and Water Division well fields.



Base from U. S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

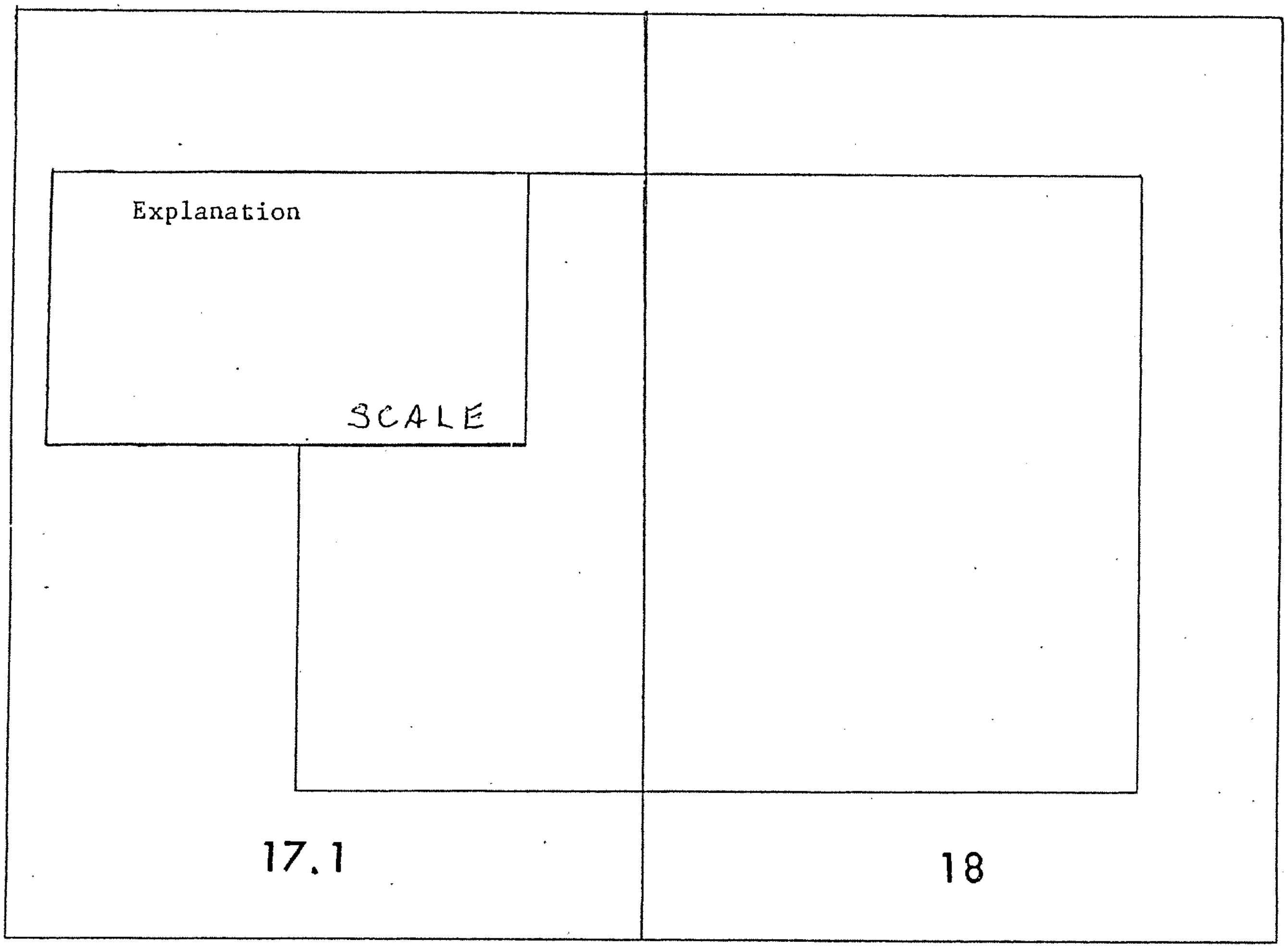
Figure 4.--Potentiometric surface of the Memphis Sand in 1886.



Base from U. S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

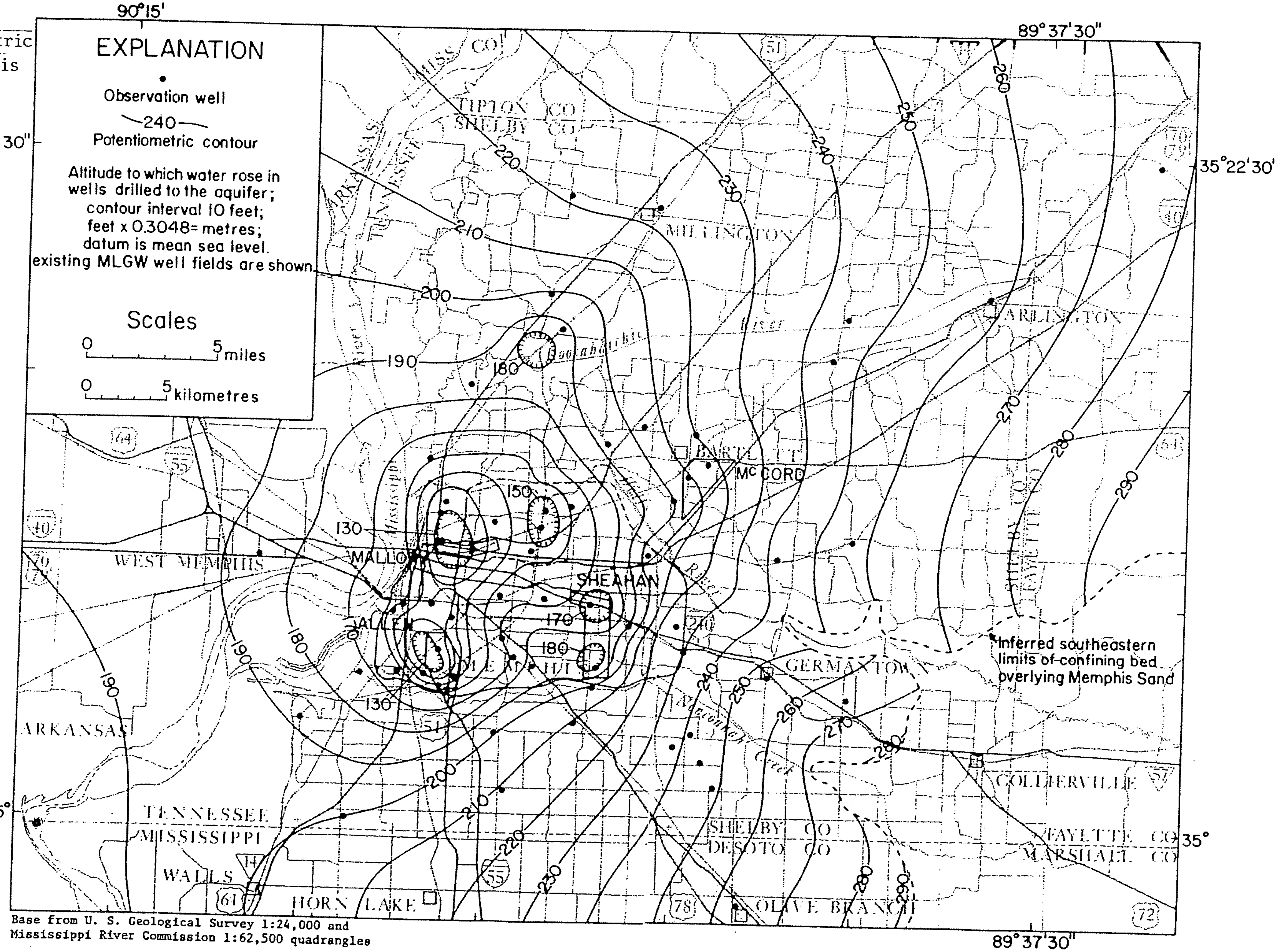
15.1

FIGURE 5



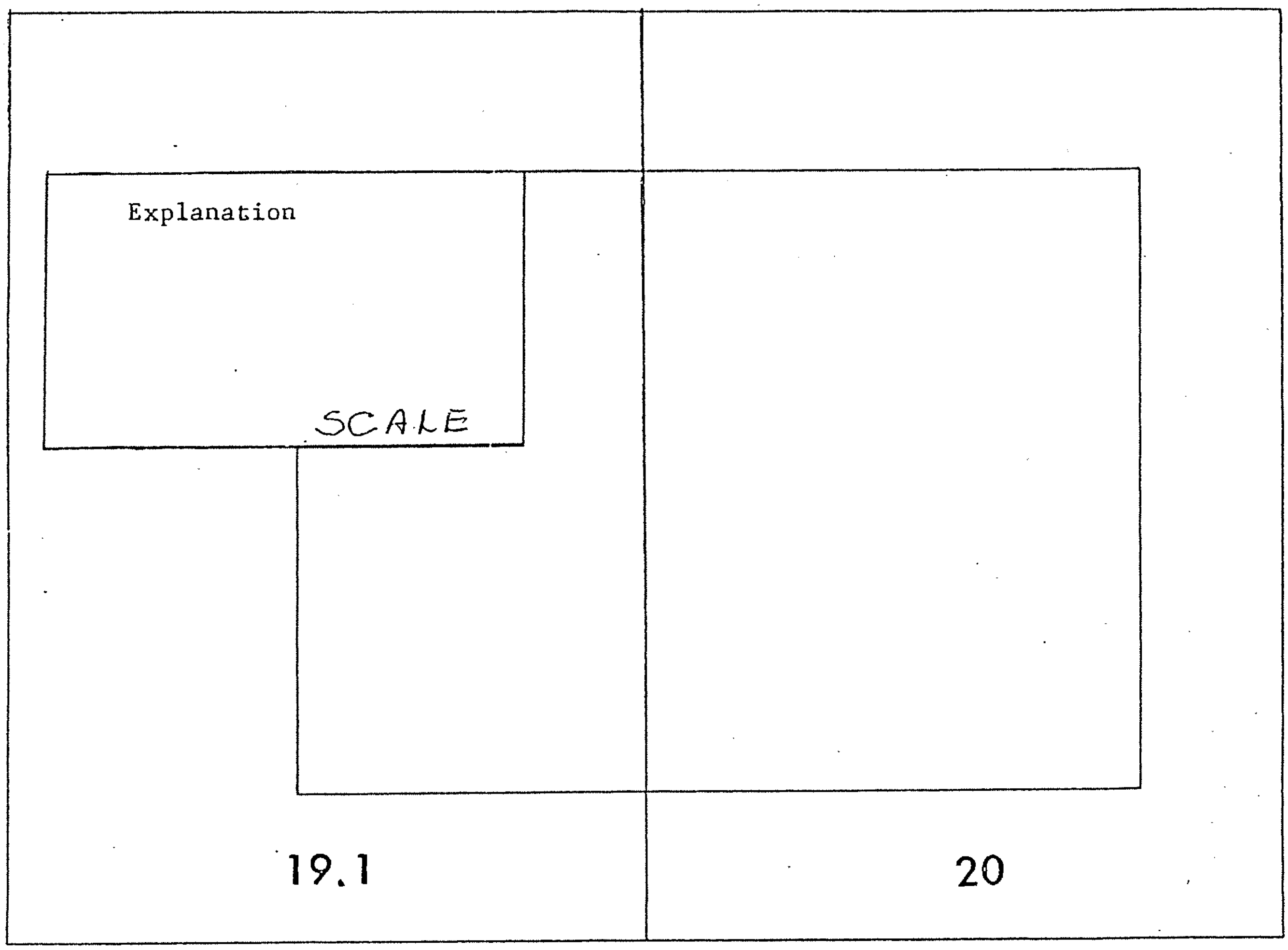
Index map showing page numbers of each component of figure 5.

Figure 5.--Potentiometric surface of the Memphis Sand in August 1960.



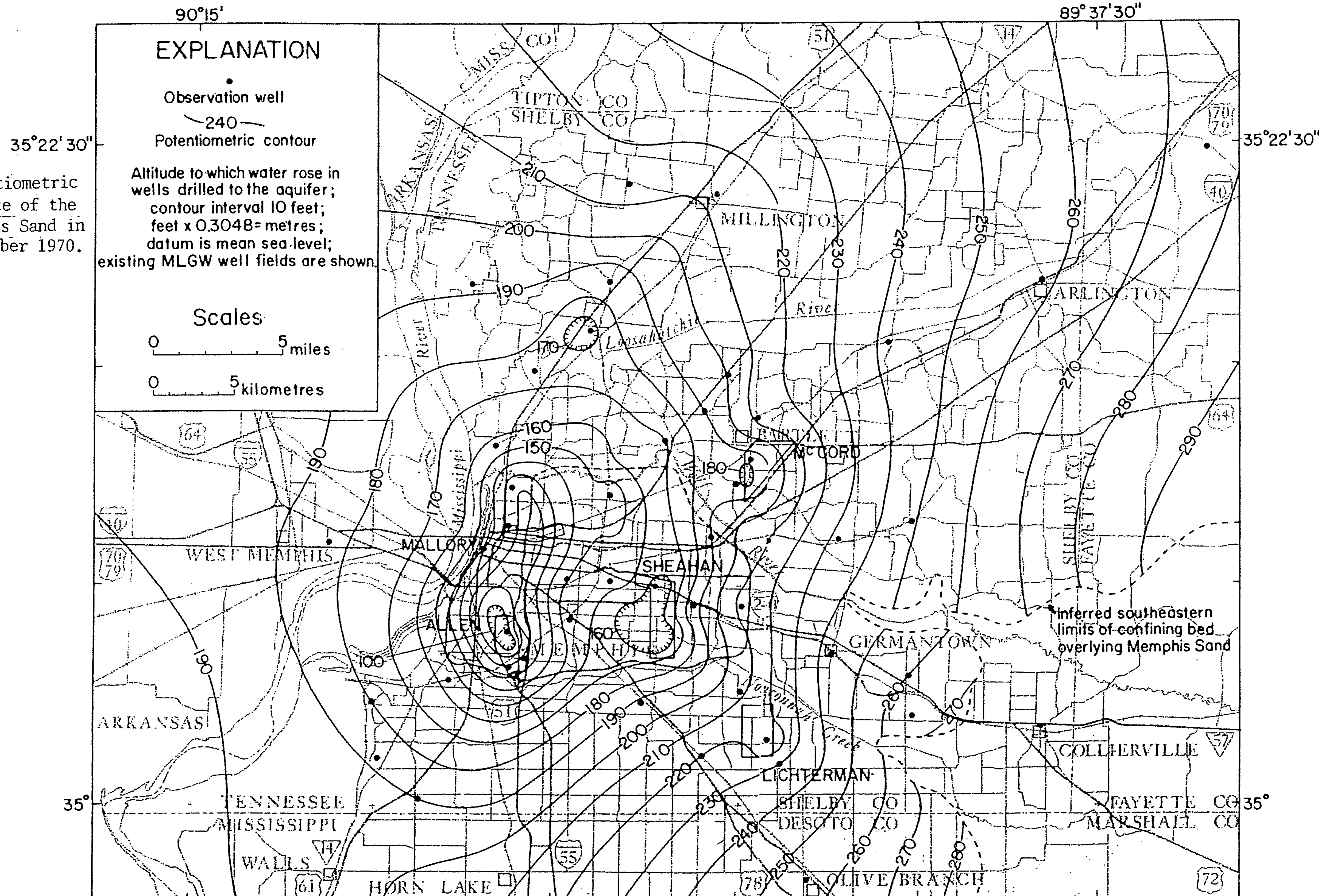
17.1

FIGURE 6



Index map showing page numbers of each component of figure 6.

Figure 6.--Potentiometric surface of the Memphis Sand in September 1970.



Base from U. S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

The cones at Mallory and Allen well fields had also overlapped, forming a single elongated cone, further indicating the interference of pumping between well fields. The apex of this cone was centered on Allen well field, which in 1970, produced about three times the amount of water produced by Mallory well field.

Other noticeable changes by 1970 included the development of new cones at McCord and Lichterman well fields. The McCord field, which is not shown as a distinct cone on the 1960 map, almost doubled its water production in the decade ending in 1970. Lichterman began operation in 1965 and averaged more than 16 Mgal/d (60 Ml/d) in 1970.

A potentiometric-surface map for August 1975 is shown in figure 7. This map shows a cone of depression at the Davis well field, which began operation in 1971 and in 1975 pumped about 12 Mgal/d (45 Ml/d). The map also shows a higher potentiometric surface at Allen well field than that of 1970, as a result of a reduction in pumping of about 10 Mgal/d (38 Ml/d). Pumping from Mallory increased about the same amount and the cone deepened in that field to about 90 ft (27 m) above sea level, as determined from the deepest water level recorded in the Memphis area in Sh:O-179. Although the cones at Mallory and Allen well fields remained overlapped in 1975, a large increase in pumpage from Mallory and continued industrial withdrawals in the vicinity, caused the apex of the combined cone to shift from Allen well field to Mallory well field. In 1975, pumpage was about 21 Mgal/d (79 Ml/d) from Allen field and about 28 Mgal/d (105 Ml/d) from Mallory field and nearby industrial wells.

A comparison of the 1960, 1970, and 1975 potentiometric-surface maps (fig. 5-7) shows a progressive steepening of the hydraulic gradient on the western side of the major cone of depression adjacent to the Mississippi River. The exceptionably steep hydraulic gradient west of Mallory well field evident on the 1975 map (fig. 7) indicates recharge to the Memphis Sand. This recharge may be the result of downward leakage from the Mississippi River alluvium, or perhaps, from the river itself.

The original potentiometric surface of the Fort Pillow Sand was probably similar to that of the Memphis Sand, but a few feet higher. Comparatively few observation or production wells are made in the Fort Pillow Sand, and therefore, only a limited number of water-level measurements are available for use in making potentiometric-surface maps. For this reason, the potentiometric surface for 1970, as shown in figure 8, was constructed by using miscellaneous water-level measurements for April, July, and August of that year. Although the resulting map does not show local pumping centers, it outlines the general shape of the major cone of depression. Since 1970, the cessation of pumping from this aquifer at Mallory and Sheahan well fields has caused water levels in Shelby County to recover several feet.

Water-Level-Change Maps

The net change of potentiometric-surface altitudes can be determined by deriving a water-level-change map from the potentiometric-surface maps and water levels in observation wells for any two years. Such a map, illustrating the water-level changes in the Memphis Sand from 1960 to 1970, is shown in figure 9. The contours generally outline the major municipal and industrial pumping centers and indicate a general water-level decline throughout most of the Memphis area. Those contours encompassing declines of 10 to 30 ft (3 to 9 m) or more form an irregular pattern in and around downtown Memphis. In the northern part of Memphis and outside the irregular band of large decline, are areas of decline from zero to less than 10 ft (3 m) where pumpage has remained nearly constant for more than 10 years.

A similar map, illustrating water-level changes in the Memphis Sand from 1970 to 1975, is shown in figure 10. This map shows a general rise in water levels for outlying areas away from the major cone of depression (fig. 7). This rise is attributed to the abnormally high rainfall for 1973 and 1975 and the associated increased recharge to the aquifer. The pronounced local rise in water levels in the area of Allen well field resulted from the reduction in pumping of about 10 Mgal/d (38 Ml/d) from 1970 to 1975. This reduction was offset by water supplied to the system from the new Davis well field, where the water level declined more than 10 ft (3 m).

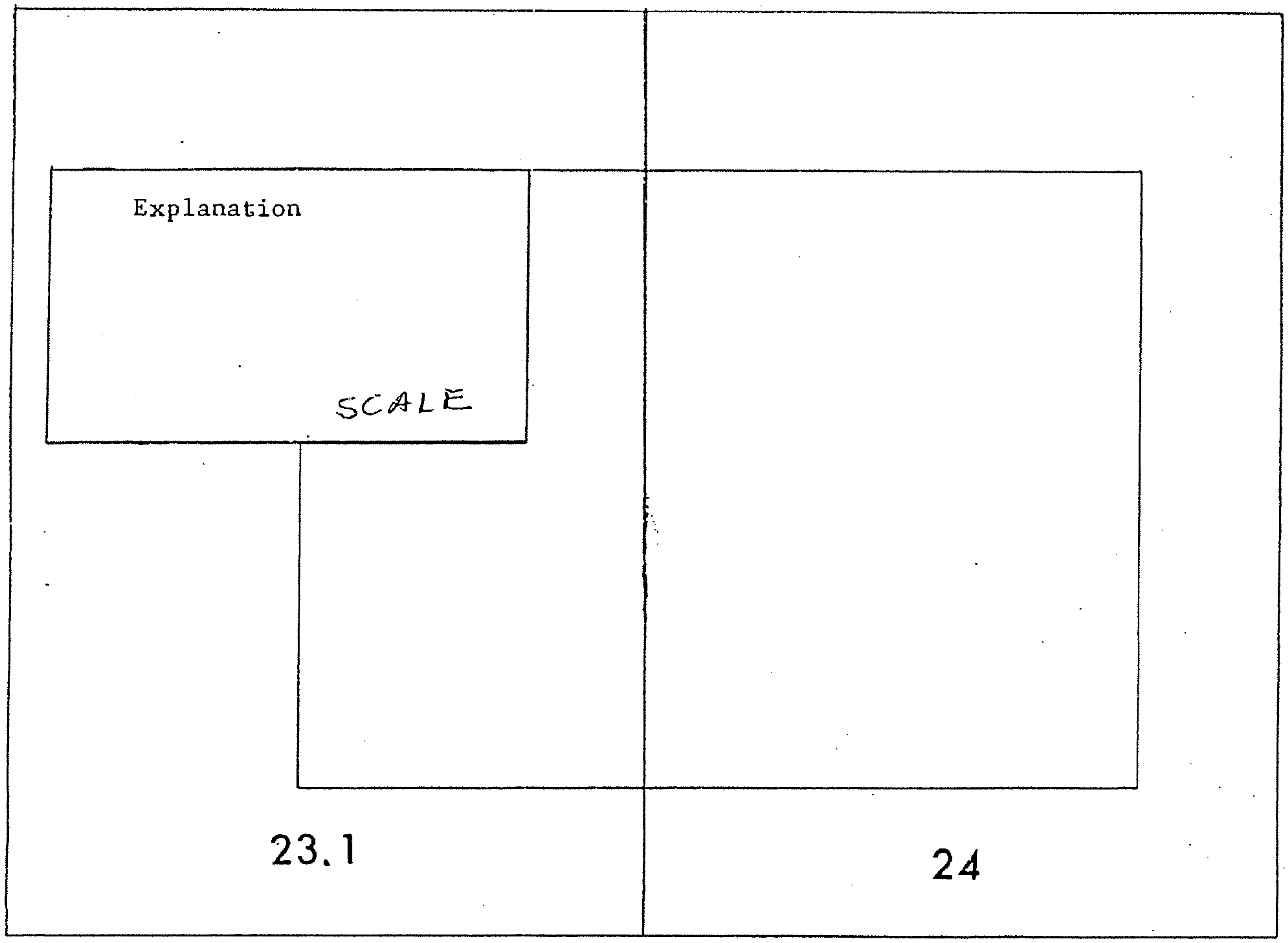
In the central part of the Memphis area, water levels continued to decline from 1970 to 1975 as a result of increased pumping from several well fields. Pronounced declines are evident in the areas of Mallory and McCord well fields where pumping was greatly increased. Nevertheless, water-level declines generally were less than would have been expected when comparisons are made with water-level declines for the previous decade (1960-70). The cause of the smaller decline rate in this area may be attributed to a more widespread distribution of pumping, a general increase in recharge to the aquifer during the periods of above-normal rainfall in 1973 and 1975, and an increase in leakage induced by a deepening of the major cone of depression.

SUMMARY AND CONCLUSIONS

The Memphis Sand supplies nearly all of the water used in the Memphis area. Since 1886, when the first well was completed to this aquifer, annual withdrawals generally have increased, but at an irregular rate. The annual pumpage has increased at a faster rate since 1960 than during any previous decade, reaching a maximum of 190 Mgal/d (719 Ml/d) in 1974. Pumpage in Shelby County in 1975 was reduced to about 188 Mgal/d (712 Ml/d).

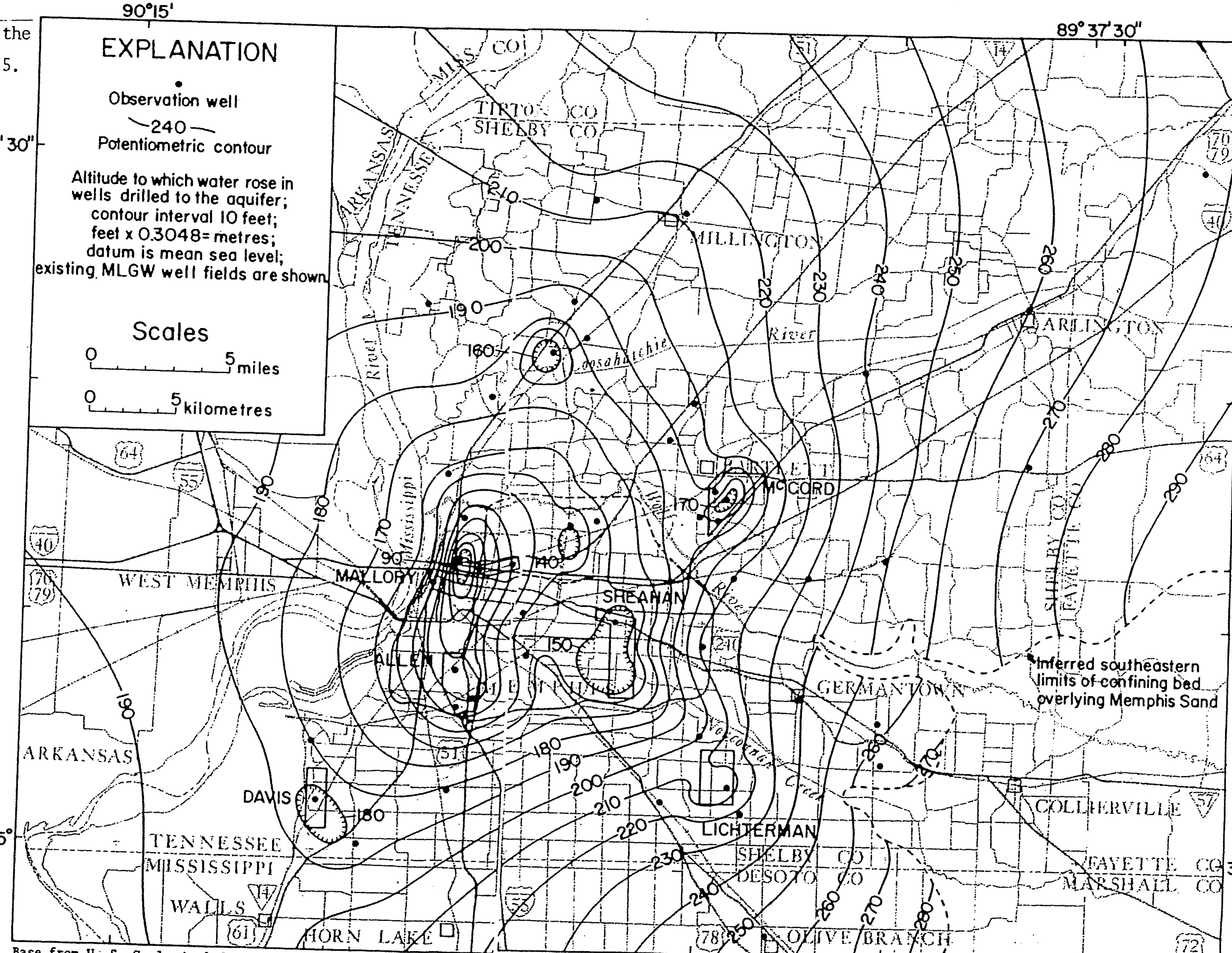
Long-term escalation of ground-water withdrawals has caused a general decline of water levels throughout the 1,300 mi^2 (3,400 km^2) Memphis area. The water-level decline in the central part of the regional cone of depression has been about 105 ft (32 m), or about 1.1 ft (0.33 m) per year since 1886. The lowest water level ever recorded in Memphis was about 170 ft (52 m) below land surface in Mallory well field in 1975, which represents an overall decline of more than 150 ft (46 m). About 30 mi (48 km) east of the center of pumping, the rate of decline has been less than 0.1 ft (0.03 m) per year since 1949.

FIGURE 7



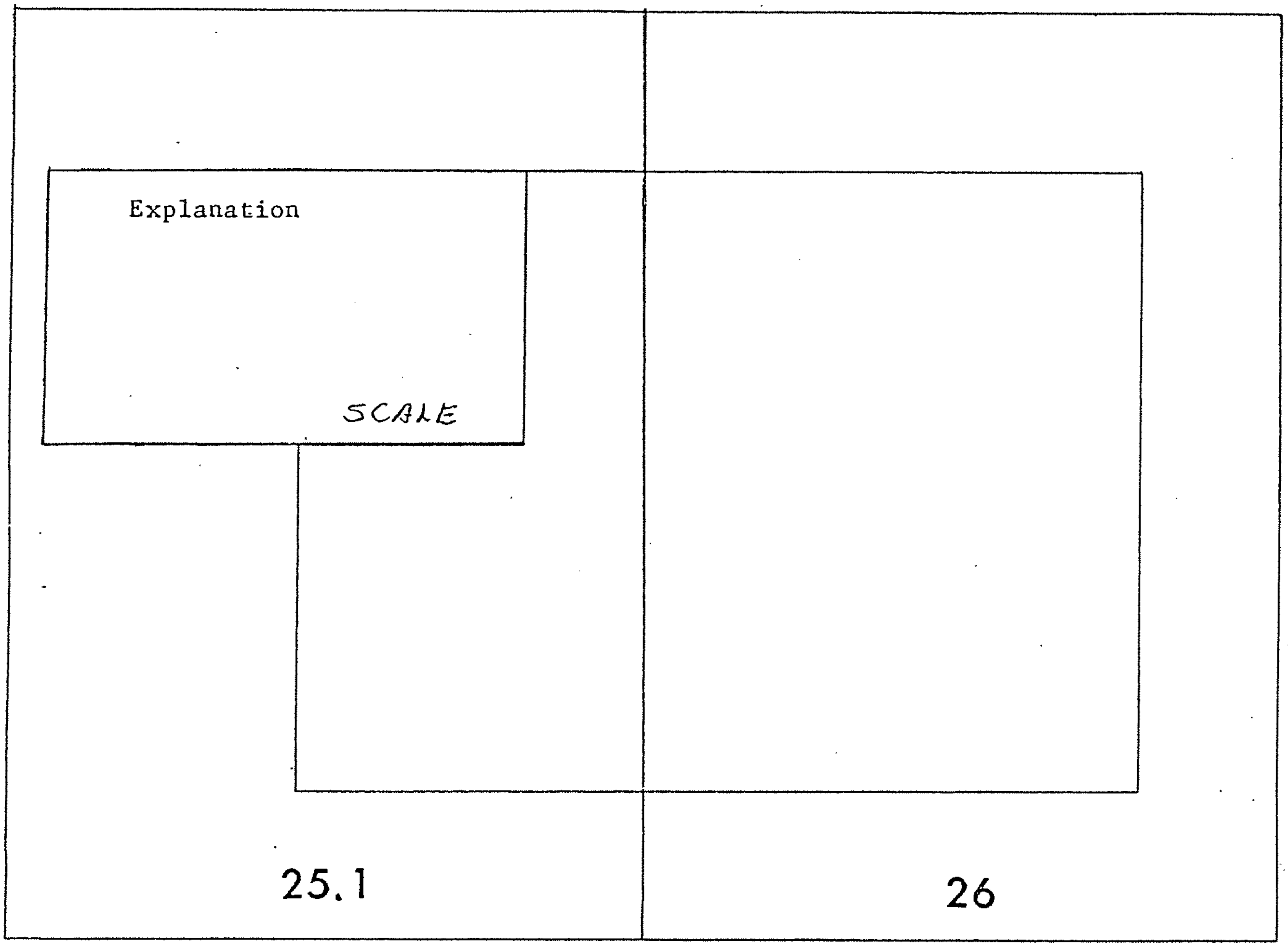
Index map showing page numbers of each component of figure 7.

Figure 7.-- Potentiometric surface of the Memphis Sand in August 1975.



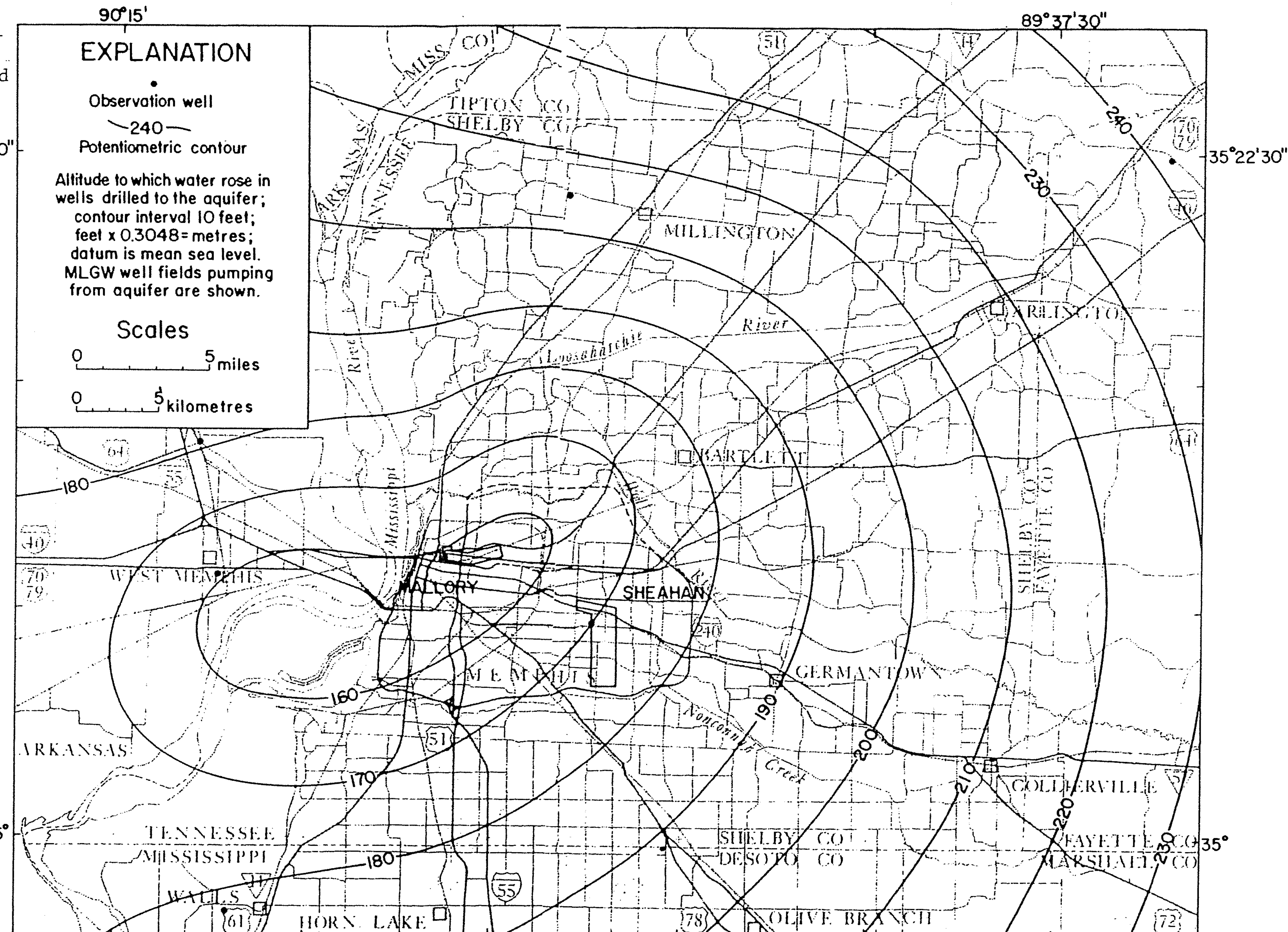
Base from U. S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

FIGURE 8



Index map showing page numbers of each component of figure 8.

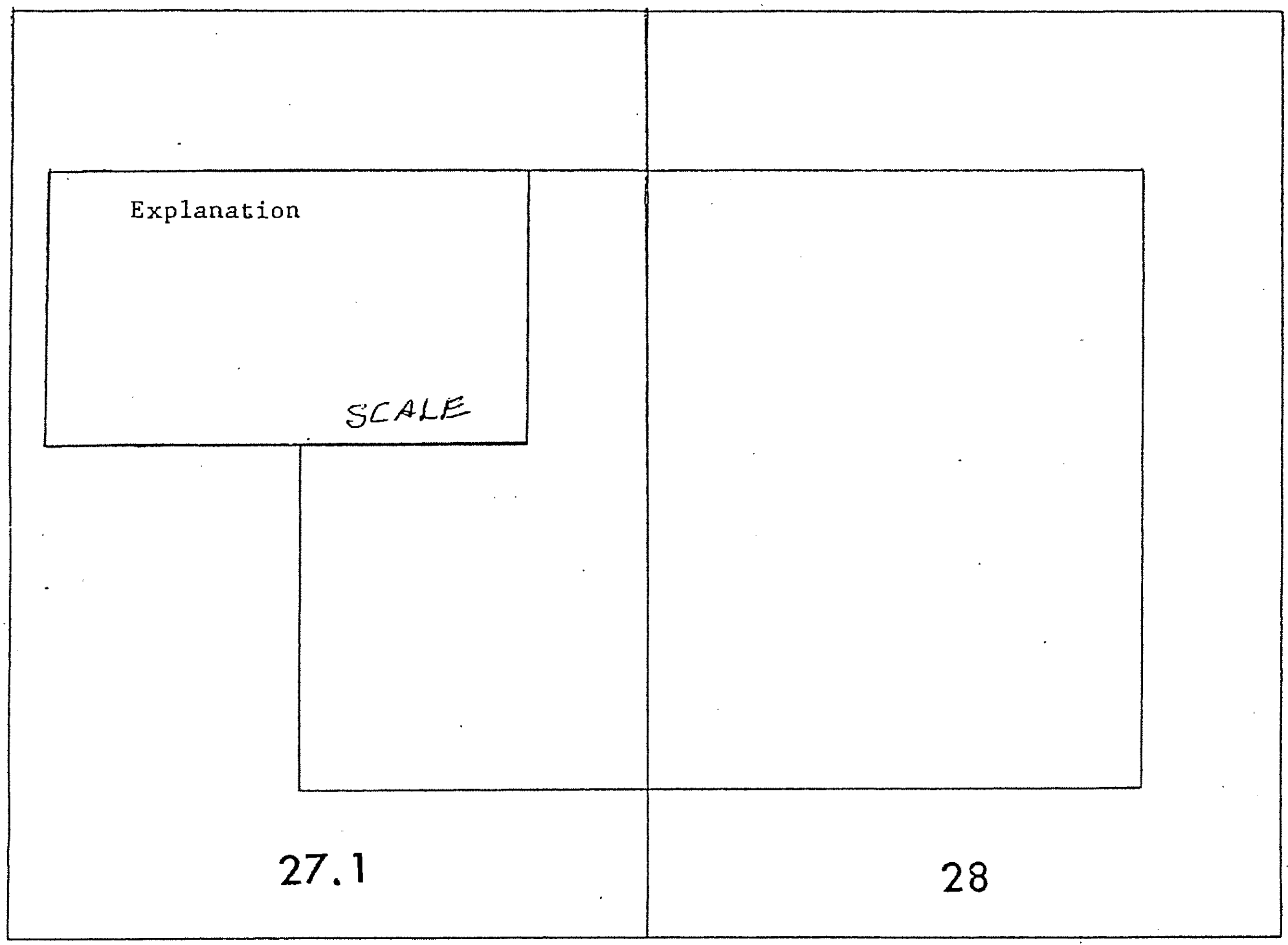
Figure 8.--Potentiometric surface of the Fort Pillow Sand in April-August 1970.



Base from U. S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

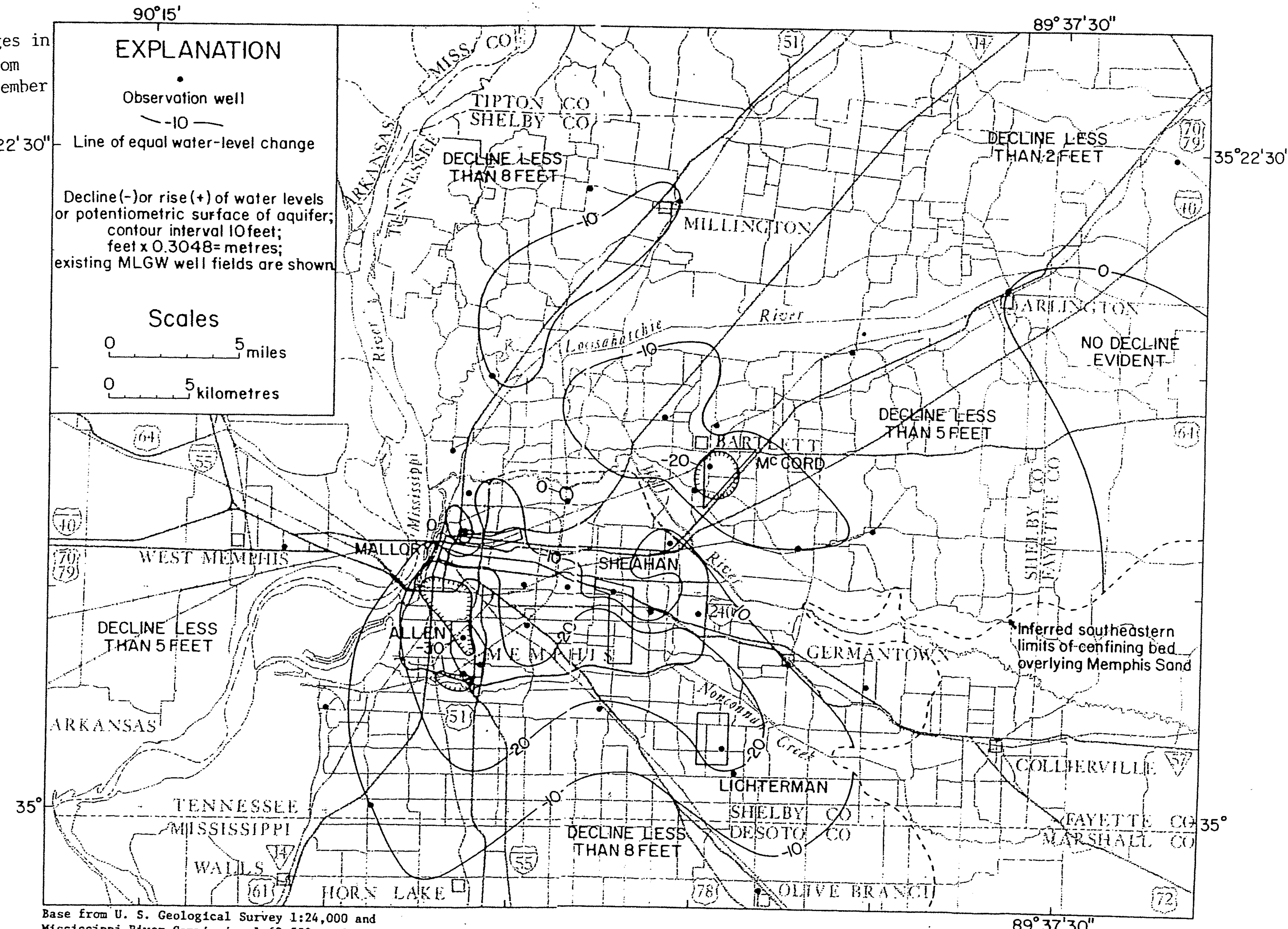
25.1

FIGURE 9



Index map showing page numbers of each component of figure 9.

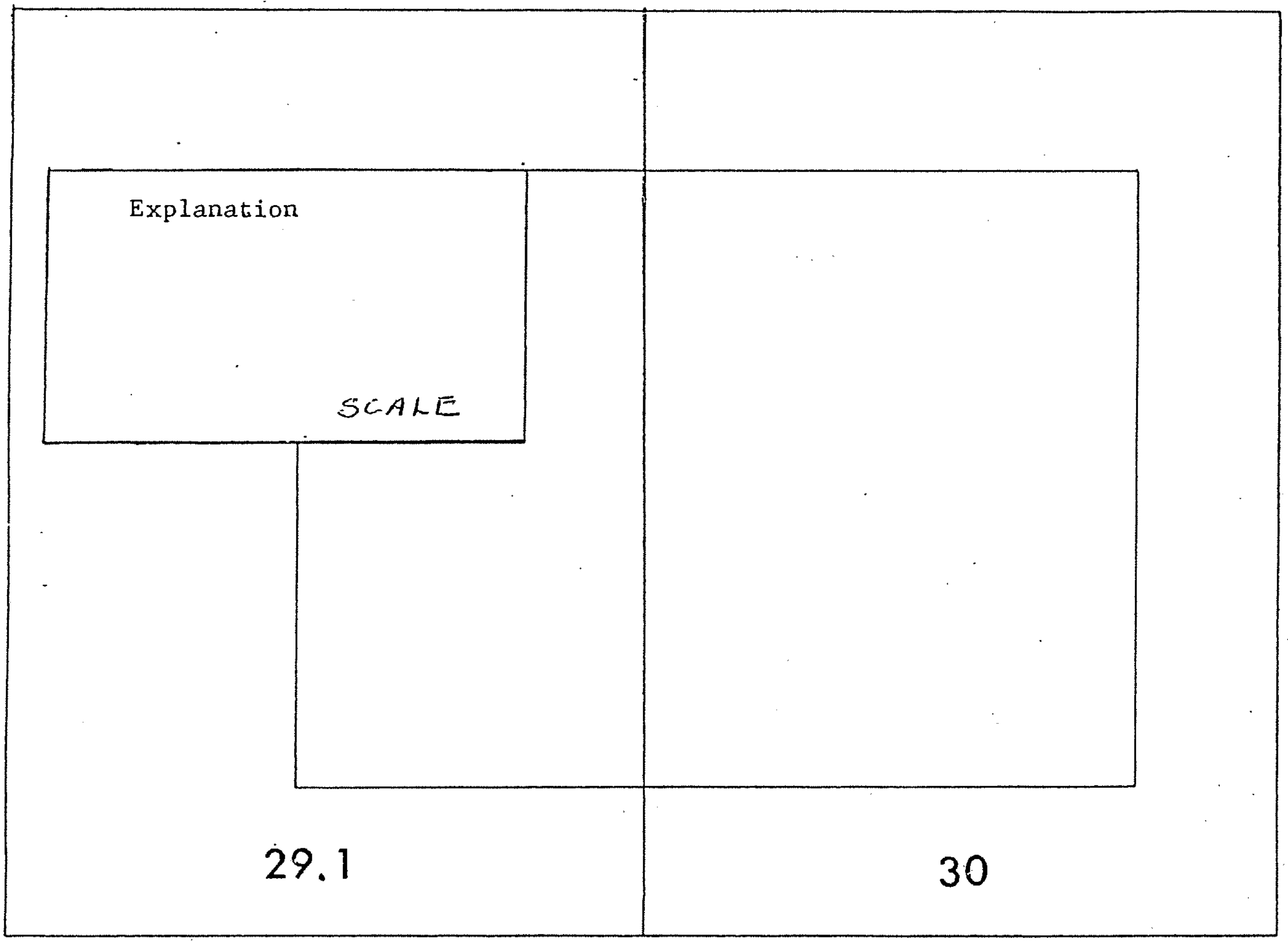
Figure 9.--Water-level changes in the Memphis Sand from August 1960 to September 1970.



Base from U. S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

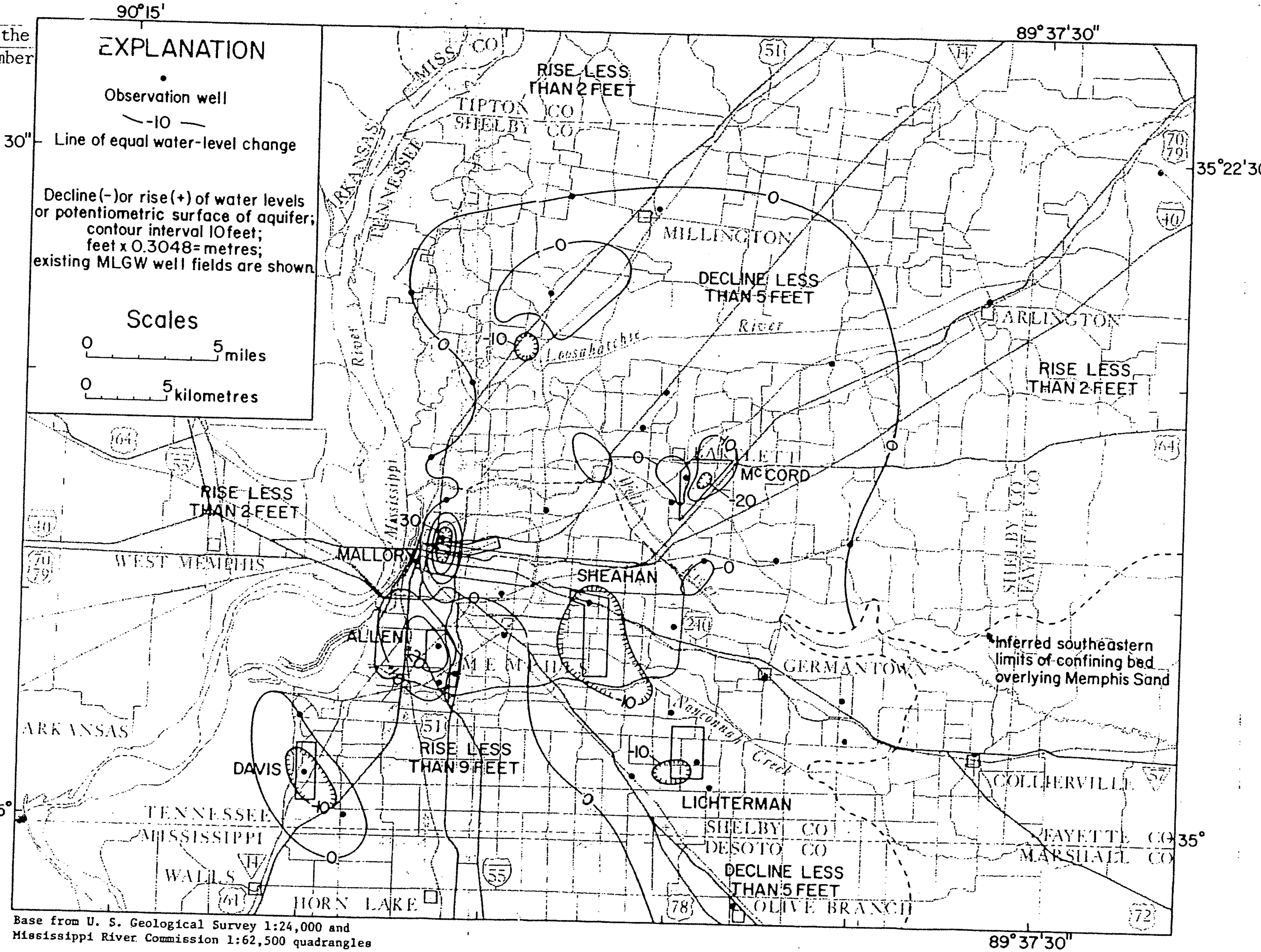
27.1

FIGURE 10



Index map showing page numbers of each component of figure 10.

Figure 10.--Water-level changes in the Memphis Sand from September 1970 to August 1975.



Local water-level fluctuations are caused primarily by variations in the pumping rates. In the McCord well field, pumping increased from 1960 to 1970 and, as a result, the hydraulic gradient continued to steepen, as evidenced by a decline of water levels in that part of the area. Water levels fluctuated only slightly from 1970 to 1974 as the result of a nearly constant pumping rate; however, in 1975, pumpage in that field was increased by about 25 percent over the amount for 1974. Consequently, most of the water-level decline from 1970 to 1975 actually occurred during 1975. This indicates that water-level changes in response to pumping changes are immediate or within the year.

Water-level fluctuations have been greatest in the Allen well field. From 1960 to 1970 pumpage was almost doubled and caused a sharp decline of the potentiometric surface in this area. From 1970 to 1975 pumpage was reduced by about 35 percent and resulted in a corresponding rise in water levels.

In areas where pumping is constant, water levels remain stable. In the Mallory well field, pumping was nearly constant from 1960 to 1970. Water levels in this vicinity underwent less change during the 1960's than at any other municipal well field, indicating near equilibrium between pumping rate and the rate of water movement into the vicinity. Then, from 1970 to 1975 when pumpage was increased by about 75 percent, the water level in the field declined more rapidly, as indicated by a 38-ft (11.6-m) drop in well Sh:O-179.

Similarly, water levels in the Fort Pillow Sand declined from 1924 to 1954 as withdrawals increased. Water levels stabilized when pumping was held nearly constant and recently have recovered a large amount following the cessation of pumping from the two largest well fields in the area. The water levels and pumping from this aquifer are expected to remain nearly stable in the immediate future.

The pumpage and water-level data indicate that a constant pumping rate in the area, in time, would result in a stable water level. Thus, the regional and local water levels may be altered by changing the pumping rates or by varying the areal distribution of pumping. This characteristic of the aquifer system is of utmost importance to planners and water managers for developing the aquifers to their full potential and avoiding development that would be detrimental to the resource.

SELECTED REFERENCES

Bell, E. A., 1966, Water resources of the Memphis area, Tennessee: Progress in fiscal year 1966: U.S. Geol. Survey open-file report, 4 p.

Bell, E. A., and Nyman, D. J., 1968, Flow pattern and related chemical quality of ground water in the "500-foot" sand in the Memphis area, Tennessee: U.S. Geol. Survey Water-Supply Paper 1853, 27 p.

Black & Veatch Consulting Engineers, 1949, Report on water supply--Memphis Light, Gas and Water Division--City of Memphis, Tennessee: March 3, 1949, Kansas City, Mo., 130 p.

Boswell, E. H., Cushing, E. M., and Hosman, R. L., 1968, Quaternary aquifers in the Mississippi embayment: U.S. Geol. Survey Prof. Paper 448-E, 15 p.

Chester & Fleming Consulting Engineers, 1920, Report on water supply in Memphis, Tennessee: Memphis, Tenn., 173 p.

Criner, J. H., and Armstrong, C. A., 1958, Ground-water supply of the Memphis area: U.S. Geol. Survey Circ. 408, 20 p.

Criner, J. H., Sun, P-C. P., and Nyman, D. J., 1964, Hydrology of aquifer systems in the Memphis area, Tennessee: U.S. Geol. Survey Water-Supply Paper 1779-O, 54 p.

Cushing, E. M., Boswell, E. H., Speer, P. R., and Hosman, R. L., 1970, Availability of water in the Mississippi embayment: U.S. Geol. Survey Prof. Paper 448-A, 13 p.

Fuller & McClintock Consulting Engineers, 1922, Report on water supply of Memphis, Tennessee: March 1, 1922, Memphis, Tenn., 88 p.

Glenn, L. C., 1906, Underground water of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geol. Survey Water-Supply Paper 164, 173 p.

Hosman, R. L., Long, A. T., and Lambert, T. W., 1968, Tertiary aquifers in the Mississippi embayment: U.S. Geol. Survey Prof. Paper 448-D, 29 p.

Kazmann, R. G., 1944, The water supply of the Memphis area: U.S. Geol. Survey open-file report, 66 p.

Lundie, John, 1898, Report on the waterworks system of Memphis, Tennessee: Memphis, Tenn., 46 p.

Moore, G. K., 1965, Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geol. Survey Water-Supply Paper 1809-F, 44 p.

Nyman, D. J., 1965, Predicted hydrologic effects of pumping from the Lichterman well field in the Memphis area, Tennessee: U.S. Geol. Survey Water-Supply Paper 1819-B, 26 p.

Parks, W. S., and Lounsbury, R. W., 1975, Environmental geology of Memphis in Field trips in West Tennessee: Tennessee Div. Geol. Rept. Inv. 36, p. 35-63.

Reed, J. E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geol. Survey HA-434, 1 pl.

Safford, J. M., 1890, The water supply of Memphis, Tennessee Board of Health Bull., v. 5.

Schneider, Robert, and Cushing, E. M., 1948, Geology and water-bearing properties of the "1,400-foot" sand in the Memphis area: U.S. Geol. Survey Circ. 33, 13 p.

Wells, F. G., 1931, A preliminary report on the artesian water supply of Memphis, Tennessee: U.S. Geol. Survey Water-Supply Paper 638-A, 34 p.

___________, 1933, Ground-water resources of western Tennessee: U.S. Geol. Survey Water-Supply Paper 656, 319 p.

PUMPAGE DATA

Records concerning ground-water pumpage for public supply at Memphis have been kept by early private water companies and municipal systems and by MLGW since the discovery of the artesian system in 1886. Since 1940, the Geological Survey has collected pumpage data from all large water-using industries and commercial establishments and municipal water companies in Shelby County. The data for some of the industries have been furnished to the Survey under an agreement that individual company statistics would remain confidential. Many of the reports have been made monthly and have showed daily totals; other reports have been made by telephone and have indicated monthly or yearly estimates. This information has been supplemented by water-use surveys of the nonreporting industries and commercial establishments in 1955 and 1974. The results of these surveys showed that in 1955 about 67 percent of the pumpage by industrial and other users was reported to the Geological Survey, and in 1974 the reported pumpage was about 83 percent of the total. These percentages have been used to adjust pumpage totals for the intervening years. Pumpage reported to the Geological Survey for 1975 was raised to about 85 percent of the total to reflect an increase resulting from the inclusion of an additional major water-using industry.

The water-use surveys did not include pumpage from a few thousand suburban and rural wells nor any wells in the Arkansas and Mississippi parts of the Memphis area. These wells pump from the Memphis Sand, Fort Pillow Sand, fluvial deposits, and alluvium. The annual pumpage from these wells probably does not amount to more than an additional 2 or 3 percent of the total pumpage values given in this report. The pumping rates from the major aquifers by major users in Shelby County from 1886 to 1975 are given in table 2.

Preceding page blank

Table 2.--Pumping rates from the Memphis and Fort Pillow Sands by major water users in Shelby County, Tennessee, 1886-1975

(in million gallons per day)

Year	Memphis Sand			Fort Pillow Sand			Remarks
	MLGW 1/	Industrial and other	Total	MLGW 1/	Industrial and other	Total	
1886	0.1	?	?				First well completed to Memphis Sand.
1887	2	4	6				
1888	2.9	10	13				Two water companies completed 16 wells.
1889	2.1	13	15				Forty-two public supply wells completed.
1890	3.0	15	18				Auction Avenue station began operation.
1891	2.9	16	19				
1892	4.0	18	22				
1893	6.5	18	24				
1894	10.1	18	28				
1895	12.7	20	32				
1896	14.0	19	33				
1897	9.0	20	29				
1898	9.4	21	30				
1899	11.7	22	34				
1900	10.8	20	31				
1901	11.6	19	31				
1902	12.0	19	31				
1903	12.7	19	32				Memphis Artesian Water Department organized.
1904	11.3	20	31				
1905	11.8	21	33				
1906	12.9	22	35				South Memphis station began operation.
1907	13.8	22	36				
1908	13.1	22	35				Central Avenue station began operation.
1909	14.0	24	38				
1910	13.5	22	36				Segregated wells began operation.
1911	13.0	19	32				
1912	13.6	19	33				
1913	13.0	18	31				
1914	13.3	20	33				
1915	11.8	18	30				

Table 2.--Pumping rates from the Memphis and Fort Pillow Sands by major water users in Shelby County, Tennessee, 1886-1975--Continued

(in million gallons per day)

Year	Memphis Sand			Fort Pillow Sand			Remarks
	MLGW 1/	Industrial and other	Total	MLGW 1/	Industrial and other	Total	
1916	11.9	18	30				
1917	12.7	18	31				
1918	13.7	21	35				
1919	15.0	23	38				
1920	14.9	22	37				
1921	13.2	25	38				Chester and Fleming engineering study listed 58 self-supplied industries.
1922	12.7	30	43				
1923	13.4	35	48				Fuller and McClintock engineering study began.
1924	14.2	37	51	0.1	-	0.1	First well drilled to Fort Pillow Sand and Parkway (Mallory) station began operation.
1925	14.5	39	54	0.9	-	0.9	
1926	12.9	42	55	2.5	-	2.5	
1927	13.8	41	55	2.2	-	2.2	
1928	13.1	41	54	4.5	-	4.5	
1929	12.2	45	57	5.7	-	5.7	
1930	13.4	49	62	6.2	-	6.2	
1931	13.3	49	62	5.4	-	5.4	
1932	12.4	52	64	6.5	-	6.5	
1933	15.3	51	66	3.8	-	3.8	
1934	15.1	50	65	4.9	-	4.9	Sheahan station began operation.
1935	12.5	56	68	6.3	-	6.3	
1936	12.3	58	70	5.4	-	5.4	
1937	13.9	59	72	4.5	-	4.5	
1938	13.6	59	72	5.6	-	5.6	
1939	13.8	58	72	6.0	-	6.0	
1940	15.1	59	74	6.5	0.1	6.6	MLGW organized.
1941	15.6	59	75	7.5	1.2	8.7	Water-use data collection begun by USGS.
1942	17.5	68	85	7.4	1.2	8.6	
1943	20.0	80	100	9.4	1.7	11.1	
1944	21.8	79	100	9.1	1.7	10.8	
1945	24.4	71	95	6.6	2.1	8.7	

Table 2.--Pumping rates from the Memphis and Fort Pillow Sands by major water users in Shelby County, Tennessee, 1886-1975--Continued

(in million gallons per day)

Year	Memphis Sand			Fort Pillow Sand			Remarks
	MLGW 1/	Industrial and other	Total	MLGW 1/	Industrial and other	Total	
1946	24.7	60	85	8.1	0.6	8.7	
1947	26.6	63	90	9.5	0.7	10.2	
1948	29.7	70	100	8.6	2.0	10.6	
1949	31.0	69	100	8.5	4.9	13.4	
1950	33.5	66	100	8.3	5.3	13.6	
1951	37.2	68	105	8.6	5.7	14.3	
1952	41.5	68	110	8.2	2.9	11.1	Allen station began operation.
1953	44.8	71	116	8.1	3.7	11.8	
1954	47.4	72	119	7.8	3.8	11.6	
1955	48.3	74	122	7.7	4.8	12.5	Survey of 135 self-supplied water users.
1956	48.1	72	120	7.0	5.0	12.0	
1957	47.6	69	117	6.7	3.6	10.3	
1958	50.4	70	120	7.5	3.3	10.8	McCord station began operation.
1959	54.9	73	128	7.6	5.1	12.7	
1960	55.5	72	127	8.1	4.7	12.8	
1961	58.1	75	133	7.9	4.5	12.4	
1962	62.0	76	138	6.9	4.4	11.3	
1963	66.1	75	141	5.4	4.2	9.6	
1964	68.3	76	144	3.6	4.2	7.8	
1965	71.8	78	150	3.2	4.5	7.7	Lichterman station began operation.
1966	76.3	77	153	2.4	5.3	7.7	
1967	78.6	77	156	2.6	5.1	7.7	
1968	81.8	79	161	3.4	4.3	7.7	
1969	84.0	81	165	2.4	5.3	7.7	
1970	90.8	80	171	3.0	3.5	6.5	
1971	97.8	80	178	1.6	3.5	5.1	Davis station began operation.
1972	101.0	79	180	0.8	4.3	5.1	
1973	107.2	81	188	1.1	4.6	5.7	
1974	109.5	80	190	0	5.6	5.6	Water-use survey of 99 self-supplied users.
1975	110.5	78	188	0	4.4	4.4	MLGW discontinued use of Fort Pillow Sand.

1/ Pumpage by Memphis Light, Gas and Water Division and its predecessors

WATER-LEVEL DATA

The first systematic collection of water-level records in the Memphis area began in 1927 with the installation of an automatic recorder on Sh:O-124. The following year another recorder was installed on Sh:P-76. These and other early observation wells were screened in the Memphis Sand. It was not until 1945 that observation wells in the Fort Pillow Sand were available for water-level measurements. The lowest annual water levels in selected observation wells in the Memphis and Fort Pillow Sands were computed from recorder charts and are presented in tables 3 and 4, respectively.

In addition to recorder-equipped observation wells, many industrial wells and abandoned or unused municipal wells in the Memphis Sand are measured each year at the estimated time of the lowest annual water level. Generally, the annual low water level occurs in August or September in Memphis when pumping rates are highest. Water-level measurements in these miscellaneous wells and equivalent values determined from recorder charts for August or September each year were converted to sea level reference for the preparation of the potentiometric-surface maps. Values for the Memphis Sand are given in table 5 and those for the Fort Pillow Sand in table 6. The low-water-level values in these tables may differ from those in tables 3 and 4 because of rounding to whole numbers and time lag in a few wells. Because of the time lag with distance from pumping centers, the low water levels in Fa:R-1 and R-2 may not occur until the following December or January.

Table 3.--Lowest annual water levels recorded from selected observation

Year \ Well number LSD	Sh:O-124 229.7 ft	Sh:P-76 286.7 ft	Sh:O-1 228.7 ft	Sh:P-1 299.8 ft	Sh:Q-1 330.4 ft	Sh:O-179 256.7 ft	Sh:K-66 302.7 ft	Fa:R-2 317.2 ft
1927	31.7							
1928	32.9	69.4						
1929	32.4	69.5						
1930	37.0	73.4						
1931								
1932								
1933		68.6						
1934		70.5						
1935		68.7						
1936		74.1						
1937	34.9	74.7						
1938	39.1	76.6						
1939	41.2	77.6						
1940	43.8	81.4	18.1	68.2	74.6			
1941	51.6	88.2	24.3	74.0	76.1			
1942	52.8	90.9	25.4	75.7	76.9			
1943	56.9	95.3	27.5	78.2	77.9			
1944	61.5	97.6	29.9	79.3	78.4	106.3		
1945	60.5	96.4	28.7	78.5	78.0	110.1		
1946	57.2	96.0	23.5	73.7	77.3	103.8	117.1	
1947	59.2	98.9	25.9	75.8	77.7	113.4	120.5	
1948	60.6	101.4	28.7	78.2	78.5	115.8	122.6	
1949	63.2	105.6	29.4	79.0	118.6	138.4	39.0	39.0
1950	63.7	105.2	27.9	77.7	77.9	116.6	125.2	38.3
1951	69.4	106.5	28.9	78.6	78.2	127.5	127.1	38.4
1952	69.7	110.8	33.3	81.0	79.2	129.2	130.6	39.0
1953	71.3	116.2	39.0	85.0	80.5	129.7	133.7	39.7
1954	73.4	120.0	41.4	86.5	81.8	131.9	133.8	40.5
1955	72.4	122.1	42.8	88.3	82.5	129.6	130.6	40.9
1956	72.6	123.1	43.4	89.6	83.4	130.9	132.0	41.3
1957	69.8	119.7	42.4	88.8	83.4	118.4	129.1	41.4
1958	67.2	117.6	39.8	92.0	84.6	115.9	127.0	40.6
1959	71.9	120.4	44.8	96.0	86.2	138.5	128.6	
1960	71.9	124.4	45.0	95.3	86.8	136.0	136.3	40.8
1961	71.9	124.6	47.0	97.8	87.5	131.5	138.3	40.8
1962	72.2	128.8	48.4	100.0	88.6	132.0	137.1	40.9
1963	72.4	129.9	51.2	103.0	90.3	141.2	141.0	41.7
1964	73.2	130.5	53.2	105.0	92.1	142.4	142.5	41.9
1965	73.3	134.2	53.6	105.8	93.0	142.9	143.9	41.8
1966	73.3	135.6	52.1	105.6	94.2	145.8	147.5	41.9
1967	71.7	134.3	51.1	105.9	95.0	136.8	146.7	42.1
1968	71.8	137.0	52.1	108.4	95.8	139.4	147.0	42.0
1969	71.1	136.3	53.8	109.4	96.7	137.4	147.7	42.0
1970	70.5	138.2	54.6	110.3	97.5	131.5	144.2	41.9
1971	71.3	140.3	54.9	111.6	98.4	154.3	150.3	41.7
1972	71.0	141.8	56.2	113.6	99.4	168.4	153.1	41.6
1973	69.9	141.2	55.0	114.1	99.0	164.8	147.5	40.8
1974	72.9	143.6	56.0	113.5	98.9	161.3	160.3	40.3
1975	70.0	139.4	54.4	112.1	99.1	169.6	158.3	40.1

wells in the Memphis Sand in the Memphis area, Tennessee 1972-1975

Sh:J-126 234.5 ft	Sh:Q-24 282.4 ft	Sh:U-2 268.8 ft	Sh:P-85 293.1 ft	Sh:J-1 240.5 ft	Sh:L-10 369 ft	Sh:L-39 340.7 ft	Sh:L-15 278.5 ft	Sh:W-3 278.5 ft	Sh:O-41 240 ft
41.2									
48.3									
46.5									
54.0									
72.0	41.3	43.3	69.3						
79.1	61.8	45.6	72.4						
85.3		46.8	71.7						
86.7		47.6	73.5						
86.1		47.4	73.0						
83.7	61.0	43.8	91.4					18.4	
82.4	63.3	46.9	94.1	40.8	115.5	100.2	73.6	18.6	
82.7	62.1	48.4	93.3	40.6	116.1	100.7	73.8	19.2	104.2
87.9	64.2	49.1	91.3	41.0	117.5	100.8	74.0	19.2	112.3
93.7	67.0	50.1		42.7	118.4		74.1	19.2	113.0
94.5	69.9	52.8		45.2	118.4		74.9		116.3
99.6	71.8	54.2		46.1	120.8		76.2		117.2
101.0	72.4	54.0		46.4	122.1	114.6	77.0		118.4
105.1	72.8	53.8		47.4	122.2	118.9	78.0		122.4
100.0	73.5	53.7			124.4	123.3	78.8		117.8
104.2	73.9	53.1		49.4		126.0	79.4	19.1	118.2
109.7	72.6	55.6		49.4	127.7	127.5	81.0	19.4	119.4
111.6	71.4	55.2	109.51	51.0	129.1	130.0		19.3	124.0
110.7	70.0	55.8		55.5	129.8	131.5	81.4	19.2	120.4
106.1	71.4	56.7		58.0	129.4	134.0	81.5	19.3	118.7
101.2	70.7	55.4	115.3	54.7		135.9	81.5	18.6	118.6
100.6		57.0	116.4	55.3	136.9	137.1	81.8	18.4	119.1
99.2		55.3	114.2	56.5	138.6	137.9	82.9	18.6	113.7

Table 4.--Lowest annual water levels in feet below land surface datum (LSD) recorded from selected observation wells in the Fort Pillow Sand in the Memphis area, Tenn., 1945-1975.

Year — Well number / LSD	Sh:K-45 284.2 ft	Sh:0-170 255.4 ft	Sh:U-1 264.2 ft	Fa:R-1 317.5 ft
1945	75.3	73.2		
1946	92.4	74.9	34.5	
1947	96.5	79.3	38.9	
1948	104.0	86.2	40.6	
1949	105.4	80.5	43.4	65.9
1950	111.8	95.0	45.5	66.6
1951	114.6	96.8	47.8	68.5
1952	112.0	100.6	48.0	69.3
1953	112.3	97.1	48.2	69.6
1954	114.6	107.9	49.4	70.3
1955	116.7	100.2	50.4	71.1
1956	118.0	99.8	52.6	72.3
1957	112.4	93.2	50.8	72.2
1958	111.6	89.7	48.3	70.8
1959	115.4	96.2	50.7	71.3
1960	119.8	101.9	52.5	72.3
1961	121.7	101.6	53.5	72.8
1962	119.4	99.7	53.5	73.3
1963	122.2	98.2	56.0	74.1
1964	122.1	90.9	56.8	75.0
1965	119.6	91.8	56.6	75.2
1966	113.0	97.0	56.7	75.3
1967	105.8	92.1	54.1	74.5
1968	103.7	92.4	53.8	74.1
1969	112.9	95.0	57.2	75.0
1970	114.1	97.2	60.4	76.3
1971	106.0	97.7	60.2	77.0
1972	108.0	75.7	57.8	76.0
1973	111.8	75.1	57.4	75.6
1974	108.3	72.4	56.1	75.4
1975	96.0	69.7	54.9	74.3

Table 5.--Water levels used in the preparation of potentiometric-surface maps (figs. 5-7) for the Memphis Sand

(datum is mean sea level)

Well Number	Altitude of land surface (feet)	Altitude of water level (feet)			Water-level change (feet)	
		Aug 1960	Sept 1970	Aug 1975	1960-1970	1970-1975
Fa:R-2	317	276	275	277	-1	+2
Sh:H-1	312	188	180	180	-8	0
Sh:J-1	240	200	190	184	-10	-6
Sh:J-10	260	139				
Sh:J-25	280	159				
Sh:J-31	292	158				
Sh:J-36	300	144				
Sh:J-41	278	146				
Sh:J-47	235	173				
Sh:J-50	241		157			
Sh:J-62	224	163				
Sh:J-70	298			181		
Sh:J-102	256	130	99	124	-31	+25
Sh:J-110	253	145	123	129	-22	+ 6
Sh:J-126	234	151	122	135	-29	+13
Sh:J-140	293		188	171		-17
Sh:K-4	292	211	192		-19	
Sh:K-13	292	171				
Sh:K-15	292	184				
Sh:K-20	295	170	153	155	-17	+ 2
Sh:K-23	315	190	186		- 4	
Sh:K-25	252	201				
Sh:K-28	330	211				
Sh:K-29	271	199				
Sh:K-31	317		220	215		- 5
Sh:K-66	303	166	159	145	- 7	-14
Sh:K-74	257	178				
Sh:L-1	332	241				
Sh:L-10	369	253	243	239	-10	- 4
Sh:L-13	295		208	200		- 8
Sh:L-15	341	266	260	258	- 6	- 2
Sh:L-20	330	230				
Sh:L-24	344	238				
Sh:L-39	346	245	216	208	-29	- 8
Sh:L-43	365	249	230	222	-19	- 8
Sh:L-54	350		264	263		- 1
Sh:L-64	305	225	212	211	-13	- 1

Table 5.--Water levels used in the preparation of potentiometric-surface maps (figs. 5-7) for the Memphis Sand--Continued

(datum is mean sea level)

Well No.	Altitude of land surface (feet)	Altitude of water level (feet)			Water-level change (feet)	
		Aug 1960	Sept 1970	Aug 1975	1960-1970	1970-1975
Sh:0-1	229	184	174	174	-10	0
Sh:0-41	240	133	126	126	- 7	0
Sh:0-98	255		140	142		+ 2
Sh:0-110	238	131				
Sh:0-115	272	161	157	157	- 4	0
Sh:0-153	250	130				
Sh:0-179	257	124	127	88	+3	-39
Sh:0-212	251			105		
Sh:P-1	300	205	190	188	-15	- 2
Sh:P-8	244	144	144	141	0	- 3
Sh:P-12	262	143				
Sh:P-37	249	162		157		
Sh:P-50	240	145				
Sh:P-54	260	154				
Sh:P-61	280	168	157		-11	
Sh:P-69	310		170			
Sh:P-74	254	202	190		-12	
Sh:P-75	325	193				
Sh:P-76	287	163	149	148	-14	- 1
Sh:P-85	293	200	183	182	-17	- 1
Sh:P-96	320		201	198		- 3
Sh:P-97	250			131		
Sh:Q-1	330	243	233	231	-10	- 2
Sh:Q-3	332	257	249	249	- 8	0
Sh:Q-9	275		210	210		0
Sh:Q-21	295	217				
Sh:Q-23	283	209	184	188	-25	+ 4
Sh:Q-24	282	220	211		- 9	
Sh:Q-53	282			181		
Sh:Q-59	307			168		
Sh:R-15	347			271		
Sh:T-17	336		192	192		0
Sh:U-2	269	221	214	214	- 7	0
Sh:U-11	267	223	213	212	-10	- 1
Sh:U-13	241			157		
Sh:U-15	237		168			
Sh:U-22	300	199				

Table 5.--Water levels used in the preparation of potentiometric--surface maps (figs. 5-7) for the Memphis Sand--Continued

(datum is mean sea level)

Well No.	Altitude of land surface (feet)	Altitude of water level (feet)			Water-level change (feet)	
		Aug 1960	Sept 1970	Aug 1975	1960-1970	1970-1975
Sh:U-23	300		186	187		+ 1
Sh:U-25	248	187		183		
Sh:V-1	250	246				
Sh:V-7	278	246	242	240	- 4	- 2
Sh:W-3	279	258	258	260	0	+ 2
AR-1	215	186	183		- 6	
MS-1	388	263	256	254	- 7	- 2

Table 6.--Water levels used in the preparation of the 1970 potentiometric-surface map (fig. 8) for the Fort Pillow Sand. Datum is mean sea level

Well No.	Altitude of land surface (feet)	Altitude of water level in 1970 (feet)	Remarks
Fa:R-1	318	242	August measurement
Sh:K-45	284	170	do
Sh:O-170	255	159	do
Sh:U-1	264	205	do
AR-2 1/	210	161	July measurement
AR-3 2/	222	181	April measurement
MS-2 3/	205	183	do

1/ Arkansas number, 6N9E - 18 bbb1.

2/ Arkansas number, 7N8E - 24 bdb1.

3/ Mississippi number, A103.

EXHIBIT 20

David Feldman and Julia O. Elmendorf
Final Report: Water Supply Challenges Facing Tennessee:
Case Study Analyses and the Need for Long-Term Planning
(Excerpts)

FINAL REPORT

WATER SUPPLY CHALLENGES FACING TENNESSEE: CASE STUDY ANALYSES AND THE NEED FOR LONG-TERM PLANNING

by

David Lewis Feldman, Ph.D.
Principal Investigator and Senior Research Scientist,
Energy, Environment and Resources Center,
The University of Tennessee-Knoxville

Julia O. Elmendorf, J.D.
College of Law and Energy, Environment and Resources Center,
The University of Tennessee-Knoxville

Prepared for the Environmental Policy Office,
Tennessee Department of Environment and Conservation,
Nashville, Tennessee

Produced by the Energy, Environment and Resources Center
The University of Tennessee-Knoxville
311 Conference Center Building
Knoxville, TN 37996-4134
Phone (865) 974-4251

June, 2000

law. Although the headwaters of several Tennessee tributaries rise in Georgia, Georgia isn't a riparian to the Tennessee River. Courts are unlikely to apportion water to a state that isn't a riparian.

- **Although there are no cases deciding interbasin transfers in Tennessee, diverting large amounts of water without return flow is probably impermissible under Tennessee law if any downstream riparian complains.** The lower riparian may not even have to show damages to stop the diversion (e.g., large interbasin transfers). Generally, existing conditions are one factor which the courts consider when deciding the merits of such diversions.

- **While Georgia now receives some Tennessee River water, the amounts are small and the flow is returned to the river, generating no riparian conflicts.** Since 1997, Tennessee American Water Company has supplied water to Ft. Oglethorpe and Catoosa County, Georgia: communities experiencing high population growth. However, the volumes discussed for an Atlanta diversion must be greater than 30 Mgal/d to be "economically feasible."

- **The U.S. Supreme Court has never considered the allocation of interstate waters to a state that has no riparian right to the water.** Thus, if the issue went to the court because of an equitable apportionment suit, the diversion would probably be prevented. Legal scholars think it is unlikely that the Court would act in a manner that would create a property right where no such right now exists.

(B) Competition between water users in West Tennessee and Northern Mississippi over the Memphis Sand Aquifer

Background. Memphis is one of the largest cities in the world to rely on groundwater wells for its water supply. The city's water is provided by a publicly-owned municipal utility, Memphis Light, Gas, and Water (MLGW). MLGW's wells tap into the Memphis Sand Aquifer, a reservoir underlying nearly 7400 mi^2 of W. Tennessee and parts of N. Mississippi, SW Kentucky, and E. Arkansas. While MLGW is the largest aquifer user, DeSoto County, Mississippi, an area experiencing rapid population growth, views the aquifer as a potential source of future supply. 20-40 Mgal/d of Memphis' nearly 145 Mgal/d withdrawn from the aquifer come from beneath DeSoto County. Thus, demands have arisen to pursue a more integrated, regional approach to aquifer management.

- **Two major problems could give rise to legal conflict between Mississippi and Tennessee regarding the MSA - Mississippi's concern with declining water levels in the aquifer, and the MSA's susceptibility to contamination.** Aquifer recharge occurs along a broad belt encompassing parts of three states and this area needs protection from development to preserve the aquifer. A major cone of depression *has* developed in the Memphis area but it has not been determined if any "overdrafting" has occurred; i.e., that water levels could not return to normal if pumping ceased.

- **There is concern that pumping from the MSA - by parties in Mississippi *or* Tennessee - may impair the rights of users in the other state. Thus, under common law, MLGW could be held liable if it is shown that it is pumping in quantities that impair the rights of other land owners who overlie the aquifer in Tennessee or**

West Tennessee. Its source is precipitation falling above the outcrop, combined with downward infiltration from overlying fluvial deposits and alluvium. Water moves westward down the dip of the aquifer and toward the major streams draining the area. In recent years, scientists have learned that the recharge area begins just inside southeast Shelby County - where high levels of development are occurring.[24] Thus, balancing local growth against the need to protect the recharge area remains a major challenge which has sparked local efforts (e.g., Collierville, Germantown) to require 'open space' and to place limits on development so as to permit natural 'ponding' of standing water and aquifer recharge.

As a result of long-term pumping (begun in 1886), a cone of depression has developed in the Memphis area. However, it is unclear what long-term effects this may have. Data from observation wells shows that the water level in Shelby county declined nearly 77 ft. between 1928-1985, an average rate of decline of 1.3 ft/yr. Water levels also are declining in areas away from a "cone" at the center of the aquifer in Memphis., and smaller cones are found around major well field in the city of Memphis. In DeSoto County, Mississippi, for example, declines of one foot or more a year have been reported due to the effects of local pumping, as well as pumping in Memphis.[25] It has not been determined if any "overdrafting" has occurred; i.e., that water levels could not return to normal if pumping ceased. Nor has it been proven that there has been a significant decline in water levels in Mississippi or a measurable effect on well yields in northern Mississippi.

The Memphis Sand Aquifer is susceptible to contamination. Trace constituents of arsenic, barium, cadmium, chromium, copper, lead, mercury, strontium, and zinc - in very small concentrations - have been found in the aquifer. While well below EPA's maximum allowable concentrations for drinking water supplies, their discovery is a cause for concern because the aquifer system constitutes the principal potable water supply source for Memphis and outlying areas. Moreover, it had previously been thought that the aquifer was overlain by a thick, impermeable clay layer protecting it from contamination. Officials now realize the potential for contamination in the vicinity of waste disposal sites, and contaminants are known to be present in water-table aquifers in the Memphis area at several abandoned dump sites.[26]

Mississippi is concerned with declining water levels in the aquifer. Currently, that state derives 80% (2.6 out of a total of 3.3 BGD) of its daily potable water supply from underground sources. Calls for a comprehensive study of groundwater use, groundwater movement between the two states, and the causes of groundwater level declines have been growing, particularly among Mississippi officials. Uncertainty still surrounds the movement of groundwater beneath the two states. It is possible that parties in *either* Tennessee or Mississippi could be impairing the rights of users in the other state if they pump in high quantities. Local experts concur that any multi-jurisdictional approach to managing groundwater will require consensus among many stakeholders. At least one study has attempted to gauge stakeholder attitudes regarding these issues and has concluded that stakeholders in each state perceive a potential threat to its groundwater from users in the other state. In addition, a collaborative study involving several institutions has begun, with involvement by USGS and the Groundwater Institute of the University of Memphis.[27] Mississippi's Department of Environmental Quality is also expected to become a study participant.

The Memphis Sand Aquifer currently faces three interrelated challenges. First, an increase in the current rate of water withdrawal in and around Memphis could have various "recharge" effects. It might serve to continue to lower the water table. On the other hand, it might actually accelerate

(9) For details, see Kathy Gilbert (1999). "City Drops Water War," *Chattanooga Times and Free Press,* October 26:

(10) Source: www.tawc.com, J. Frances Alexander, Director of Communications, (423)755-7606

(11) See the TVA Act (1933).

(12) This is not to suggest that Tennessee still subscribes to the "natural flow" theory of water law. Expanding definitions of "reasonable use" and increasing reliance on municipal water systems have made t

(13) Tenn. Code Ann. § 69-8-105.

(14) *Id.*

(15) Tenn. Code Ann. § 69-3-108(b)

(16) See *Public Water Policy in Tennessee*, State of Tennessee Water Policy Commission, Public Administration Service, Chicago, Illinois, 1956.

(17) *See* Note 10 *supra.*

(18) Grant, Douglas L., *Equitable Apportionment Suits Between States,* in Beck, *Waters and Water Rights* § 45.01-577.

(19) *Lucas v. South Carolina Coastal Council*, 112 S.Ct. 2886 (1992), held that land-use regulation that denies an ov thereby deprives them of economically viable use of their riparian land.

(20) Nicki Robertshaw, 1999. "Memphis' Fine Groundwater a Growing Factor in Construction," *Memphis Business Jo*

(21) Tom Charlier, 1999. "Memphis Taps into DeSoto County Well Levels," *The Commercial Appeal - Memphis, T*

(22) See: W. Parks and J.K. Carmichael (1990) *Geology and Ground-Water Resources of the Memphis Sand in Wes the Memphis Aquifer in Western Tennessee.* Water-Resources Investigations Report 88-4180. Memphis, Tennessee: U.S. Geological Survey. Also, see: J.V. Brahana, et. al. (1987) *Quality of Water from Freshwater Aquifers and Principal Well Fields in the Memphis Area, Tennessee.* Prepared in Cooperation with the City of Memphis, Memphis Light, Gas and Water Division. Water-Resources Inve known as the "500-foot" sand because the aquifer is, in general, about 500 ft. below the surface in the Memphis area. The thickness of the aquifer is from 500-890 ft. in the Memphis area. The aquifer is recharged to the east of Shelby County (see: Ground Water Institute (1995) *A Ground Water Flow Analysis of the Memphis Sand Aquifer in the Memphis, Tennessee Area.* Technical Brief #7, Memphis, Tennessee: University of Memphis, February).

(23) See, "Tennessee Water Use-Data Tabling," 1998. (no author). USGS Website (http:// www.usgs. gov/edu-cgi- Prepared in Cooperation with the City of Memphis, Memphis Light, Gas and Water Division. Water-Resources Investigations Report 93- 4075. Memphis, Tennessee: U.S. Geological Survey. Kingsbury and Parks, 1993).

(24) Parks and Carmichael, 1990; also, Robertshaw, 1999.

(25) Charlier, 1999: A9; Ground Water Institute, 1995; Parks and Carmichael, 1990, *Altitude of Potentiomet* Report 89-4048. Memphis, Tennessee: U.S. Geological Survey.

(26) Parks and Carmichael, 1990a; Brahana, Parks, & Gaydos, 1987; Robertshaw, 1999.

(27) For a summary of this stakeholder interview study, see John Wingard (2000), *The Community Dynamics of Source Water Protection: the Structure and Dynamics of the Human Dimensions of Source Wat the Minds. Source Water Protection Workshops, Coordinated by the Ground Water Institute of the University of Memphis (*Memphis, TN: University of Memphis); also, Charlier, 1999).

(28) Brahana, Parks, and Gaydos, 1987.

(29) <www.mlgw.com.>

(30) Tarlock, A. Dan, *Law of Water Rights and Resources,* § 4.06(3)

(31) See *Nashville, Chattanooga & St. Louis v. Rickert,* 19 Tenn. App. 446, 89 S.W.2d 889 (1935), *cert denied* (193

(32) Tarlock, *supra* note 11.