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.

PLAINTIFF'S RESPONSE TO DEFENDANTS' JOINT MOTION TO EXCLUDE THE TESTIMONY OF DR. RICHARD SPRUILL

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

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

Counsel for the State of Mississippi

I. INTRODUCTION

Defendants have moved to exclude *all* testimony and opinions of Mississippi's expert Dr. Richard Spruill. *See* Dkt. No. 70. As discussed further below, Defendants' Motion is nothing more than disingenuous characterizations and arguments of counsel. Dr. Spruill's expert opinions are appropriately qualified and clearly set forth in each of his detailed expert reports—both of which are supported by discussion of geological and hydrogeological scientific facts directly related to the groundwater at issue in this case. Review of these reports reveals that Defendants' assertions are no more than misleading distractions. There is simply no basis for exclusion of Dr. Spruill's testimony. The Court should deny Defendants' Motion.

II. BACKGROUND

This Court has ordered that "an evidentiary hearing should be held on the limited issue of whether *the water that is at issue in this case* is interstate in nature." Dkt. No. 56, 8/12/16 Case Management Order at 1 (emphasis added). "Evidence that would likely be relevant to this determination includes the nature and extent of hydrological and geological connections between the groundwater in Memphis and that in Mississippi, the extent of historical flows in the Aquifer between Mississippi in Tennessee, and similar considerations." Dkt. No. 69, 8/12/19 Memorandum of Decision at 36.

Accordingly, the stated purpose of the upcoming evidentiary hearing is to take evidence of the historical, geological, and hydrological facts needed to support the Special Master's Recommendation on the ultimate legal issue defined for this stage of the proceeding: Whether the water at issue is interstate in nature under the United States Constitution. *Id.*

III. ARGUMENT

Dr. Spruill is an expert in the science and application of the disciplines of geology, hydrogeology, and well field design and operation for the protection and sustainable production of groundwater resources—not Constitutional law. His work and opinions in this dispute are focused on the groundwater at issue, not generalized theories and definitions intended for broad application to all groundwater systems in legal disputes. As such, Dr. Spruill's testimony meets this and the other requirements of Rule 702.[1]

A. Dr. Spruill's Expert Opinions Are Reliable and Directly Relevant to the Intrastate Nature of the Groundwater at Issue

1. Dr. Spruill is a Qualified Expert in the Areas Identified by the Special Master and Was Retained to Offer Such Opinions

Dr. Spruill is a practicing geologist and hydrogeologist with over thirty years of experience teaching at both the undergraduate and graduate levels. *See* Ex. 1,

[1] As the Court has previously recognized, the Federal Rules of Evidence are not binding in original actions of first impression where the criteria determining the rights of the respective states are being developed. *See* Sup. Ct. R. 17.2.

June 30, 2017 Spruill Report ("Spruill Report") at 1-2; *id.* at App. B (Curriculum Vitae). As the President and Principal Hydrogeologist of Groundwater Management Associates, Inc., he also has extensive experience in the practical application of these scientific disciplines—*i.e.*, the study of groundwater resources and the planning/oversight of well field design and operation to assure protection and long-term sustainability of high-quality groundwater resources. *Id.*

Despite Defendants' attempts to obfuscate, the Spruill Report clearly sets out the scope of his engagement for this case:

> [T]o 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 hosts the Sparta-Memphis Sand aquifer system in northwest Mississippi and southwest Tennessee.

Id. at 1.

2. Dr. Spruill's Opinions are Relevant and Supported by Recognized Scientific Literature

As with Mississippi's other expert (David Wiley), Dr. Spruill is not going to offer an opinion on whether the Aquifer or the groundwater in it is an interstate resource—*because that is a legal question and thus not the proper subject of expert testimony*. *See* Dkt. No. 76 (Mississippi's Motion to Exclude Defendants' Experts). Rather, the Spruill Report provides a summary of his general opinions as follows:

- 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.

Id. at 2-3. Notably, Dr. Spruill based these opinions on his: (1) 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; and (4) specific resources and materials referred to and identified with this report. *Id.* at 2.

Contrary to Defendants' selective representations, the next thirty-one (31) pages of the Spruill Report discuss the underlying scientific facts and principles of geology and groundwater hydrology that support these opinions, including: "Principles of Groundwater Hydrology;" "Geology and Hydrogeology of the Mississippi Embayment;" and "Groundwater Flow Patterns in Unconfined Versus Confined Aquifers." *Id.* at 4-38. During this entire discussion, the word "interstate" only appears <u>once</u> within the discussion of the natural flow of the groundwater at issue and the changes caused by Defendants' pumping:

> 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.

Id. at 24. Notably, this scientific fact is not limited solely to Dr. Spruill's observation or testimony. For example, in 2001 the United States Geological Survey ("USGS") published a peer-reviewed report describing a three-dimensional model showing the cone of depression created by Defendants' pumping that was drawing groundwater out of Mississippi into Tennessee. *See* Ex. 2, USGS Water-Resources Investigations Report 89-4131 at 16; *see also* Ex. 3, 11/5/07 Brahana Dep. Tr. at 117:23-118:7, 119:7-120:8, 206:14-23. This peer-reviewed report is just one of the 74 geological and hydrogeological publications contained in the partial list of scientific resources Dr. Spruill included in support of his opinions. *See* Ex. 1, Spruill Report at 39-44.

Dr. Spruill's opinions are therefore relevant and supported by recognized scientific literature.

3. Dr. Spruill's Opinions Directly Address the Nature of the Groundwater at Issue

Defendants' argument that Dr. Spruill merely offers a general "theory of what makes an aquifer 'interstate'" is without merit. As grounds, Defendants point to a single page of the Spruill Report where he offers "two *hypothetical cases* to *illustrate* how groundwater within a confined aquifer *may or may not be a shared resource*." *Id*. at 32 (emphasis added). Defendants never mention this was merely a hypothetical illustration. In contrast, all of Dr. Spruill's expert opinions (as detailed in his expert reports and deposition testimony) are specifically directed to the groundwater at issue within the context of the relevant geology and hydrogeology. These opinions—not Defendants' theory—will be offered at the evidentiary hearing and subject to cross-examination.

Similarly, Defendants' attack on Dr. Spruill's opinions contained in his July 31, 2017 Rebuttal Report ("Spruill Rebuttal") are disingenuous at best. The Spruill Rebuttal is fifty-one (51) pages long—yet Defendants ignore all but a handful of pages to support their argument that "the core of Dr. Spruill's proffered affirmative testimony is his most recent definition of "intrastate aquifer.'" *See* Dkt. No. 79 at 4-5. Defendants' Motion makes this false assertion no less than eleven (11) times—

but it cannot be used to justify denigration of Dr. Spruill's expertise or Defendants' argument.

The entire basis for this false assertion is found on page 5 of Defendants' Motion, in what purports to be a quotation of Dr. Spruill's Rebuttal Report:

> According to Dr. Spruill's most recent theory, ***an aquifer is an intrastate resource*** if, "under natural conditions" (1) "the majority of groundwater in an aquifer enters the groundwater system by recharge within a specific state"; (2) "that water flows <u>*VERY*</u> slowly through the aquifer within that same state"; and (3) "such that the water remains in the state for a <u>*VERY*</u> long periods of time before ultimately being discharged from the groundwater system." Ex. 2 (Spruill July Rep. 37).

Dkt. No. 79 at 5 (emphasis added). But this is not what Dr. Spruill says on page 37—or any other page of his Rebuttal Report. His actual language reads as follows:

> <u>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*</u>. 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.

Ex. 4, Spruill Rebuttal at 37 (emphasis added). This most certainly is not a definition of an "intrastate or interstate aquifer." Nor is it easy to conceive Defendants' mischaracterizations of Dr. Spruill's report as a mistake—because this is the very distinction that has existed between Mississippi and Defendants from the outset of this original action. It is even more difficult to see Defendants' statements as an unintentional error given: (1) the stated purpose of the Spruill Rebuttal—an evaluation and critique of Defendants' reports from Dr. Waldron and Mr. Larson;[2] (2) Dr. Spruill's express affirmation of his opinions by repeating them in their entirety;[3] and (3) Dr. Spruill's consistent use of the word "groundwater" (not Defendants' conflation of groundwater and the earth in which it resides into the word "aquifer").

B. Dr. Spruill's Rebuttal Report Offers Detailed Criticisms of Plaintiff's Experts—Which Should be Considered with All other Expert Testimony in this Original Action

Nothing in the closing sections of Defendants' Motion supports the relief requested. A few observations should provide a basis for denial.

First, Dr. Spruill's actual opinions from his Rebuttal Report should be stated:

> Overall, it is my opinion that [Defendants' Expert 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

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[2] *See* Ex. 4, Spruill Rebuttal at 6 ("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.").

[3] *See* Ex. 4, Spruill Rebuttal at 2-3.

> 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.
>
> [Defendants' 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.

Ex. 4, Spruill Rebuttal at 4.

Second, Defendants cite no legal authority for the proposition that one party's expert cannot critique the opponents' expert (and be subjected to cross-examination on such critique). Nor can they, as such reports are expressly permitted by both the Federal Rules and prior orders of this Court. *See* Fed. R. Civ. P. 26(a)(2)(D)(ii) (permitting expert report "intended solely to contradict or rebut evidence on the same subject matter identified by another party Under Rule 26(a)(2)(B) or (C) . . . ."); *Peals v. Terre Haute Police Dep't*, 535 F.3d 621, 630 (7th Cir. 2008) ("The proper function of rebuttal evidence is to contradict, impeach or defuse the impact of the evidence offered by an adverse party."); *see also* Dkt. No. 143, 10/26/16 Case Mgmt. Plan at 6 (authorizing the filing of rebuttal expert reports).

Third, Dr. Spruill criticized Tennessee's expert Dr. Brian Waldron in part because Dr. Waldron's opinions favored his own (Dr. Waldron's) work (published *after* the commencement of this litigation) over official USGS publications—while his employer's largest single source of funding came from MLGW and the City of Memphis. *See* Ex. 5, 9/27/17 Waldron Dep. Tr. at 47:9-48:7.

Fourth, Dr. Spruill's opinions are not "litigation driven" as Defendants allege. Simply put, this is nothing like the "quintessential expert for hire" cases cited by Defendants. *See Johnson v. Manitowoc Boom Trucks, Inc.*, 484 F.3d 426 (6th Cir. 2007) (excluding alternative design expert who "conducted no empirical research" and had "spent the last twenty plus years of his life testifying as an expert in a wide variety of design defect cases[]");[4] *Clear v. Burlington N. R. Co.*, 29 F.3d 499 (9th Cir. 1994) (excluding causation experts who "formed their opinions before reading

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[4] In fact, language in *Johnson* actually supports denial of Defendants' Motion: If (as here) "a proposed expert's testimony flows naturally from his own current or prior research (or field work), then it may be appropriate for a trial judge to apply the *Daubert* factors in somewhat more lenient fashion." 484 F.3d at 435.

the relevant literature, even though they admitted that they were not sufficiently familiar with the field to diagnose the causes of plaintiffs' injuries without first reviewing that literature[]"). The concerns outlined in these cases are not present here.

Finally, Dr. Spruill's critique of Defendants' experts is thoroughly documented and includes detailed references to numerous USGS publications. *See generally*, Ex. 4, Spruill Rebuttal. Ironically, Defendants criticize Dr. Spruill for failing to question the quality of the USGS with the same level of scrutiny. Defendants' arguments to the contrary are without merit.

The Court should deny Defendants' Motion, hear the Parties' evidence (including Dr. Spruill's expert testimony) and give it the appropriate weight. *See Montana v. Wyoming*, No. 137, Dec. 29, 2014 Special Master Report at 31-33 (denying motion to exclude expert testimony in favor of "address[ing] the issues at the conclusion of the trial");[5] *Nebraska v. Colorado*, No. 126, Nov. 15, 2013 Special Master Report at 13 ("[T]he parties were allowed to submit objections to any pre-filed testimony or expert reports. Because there was no jury, I discouraged the filing of so-called *Daubert* motions. Simply put, it made the most sense to hear the expert testimony and to determine whether or not it was relevant and persuasive, thereby

[5] Available at: https://www.supremecourt.gov/SpecMastRpt/137Orig_122914.pdf.

mooting any need to make the more refined determination of whether it was so inadequate as to be inadmissible.");[6] *see also New Jersey v. New York*, No. 120, Mar. 31, 1997 Special Master Report at 30 (stating that the Supreme Court's rules require "a generous view of the admission of evidence and factual development" and "favor[] a principle of inclusion over exclusion in creating a record" (citing *United States v. Texas*, 339 U.S. 707, 175 (1950)).[7]

IV. CONCLUSION

Defendants' Motion contains little but arguments of counsel fashioned from distortions and material omissions of Dr. Spruill's expert opinions. Cursory review of his expert reports demonstrates that he is qualified and will present important and helpful testimony needed to determine the nature of the water at issue under the United States Constitution. The Court should deny Defendants' Motion.

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[6] Available at: https://www.supremecourt.gov/SpecMastRpt/Org%20126%20Jan%2013%20Special%20Master%20Report.pdf.

[7] Available at: https://www.supremecourt.gov/SpecMastRpt/Orig120_033197.pdf.

Dated: November 20, 2018

Respectfully submitted,

THE STATE OF MISSISSIPPI

/s/ C. Michael Ellingburg

C. Michael Ellingburg

DANIEL COKER HORTON & BELL, P.A.

C. MICHAEL ELLINGBURG
4400 Old Canton Road, Suite 400
P.O. Box 1084
Jackson, MS 39214
(601) 914-5230
mellingburg@danielcoker.com

LARRY D. MOFFETT
265 North Lamar Blvd., Suite R
P.O. Box 1396
Oxford, MS 27544
(662) 232-8979
lmoffett@danielcoker.com

MISSISSIPPI ATTORNEY GENERAL'S OFFICE

JIM HOOD, *Attorney General*
DONALD L. KILGORE
GEORGE W. NEVILLE
Walter Sillers State Office Building
550 High Street, Suite 1200
Jackson, MS 39201
(601) 359-3680
dkilg@ago.state.ms.us
ngevi@ago.state.ms.us

BARRETT LAW GROUP, P.A.

JOHN W. (DON) BARRETT
DAVID M. MCMULLAN, JR.
404 Court Square North
P.O. Box 927
Lexington, MS 39095
(662) 834-2488
dbarrett@barrettlawgroup.com
dmcmullan@barrettlawgroup.com

NEAL & HARWELL, PLC

CHARLES F. BARRETT
WILLIAM J. HARBISON II
1201 Demonbreun Street, Suite 1000
Nashville, TN 37203
(615) 244-1713
cbarrett@nealharwell.com
jharbison@nealharwell.com

GEORGE B. READY ATTORNEYS

GEORGE B. READY
P.O. Box 127
Hernando, MS 38632
(662) 429-7088
gbready@georgebreadyattorney.com

CERTIFICATE OF SERVICE

Pursuant to Paragraph 3 of the Special Master's Case Management Plan (Dkt. No. 57), I hereby certify that all parties on the Special Master's approved service list (Dkt. No. 26) have been served by electronic mail, this the 20th day of November, 2018.

/s/ C. Michael Ellingburg
C. Michael Ellingburg

Counsel for Plaintiff

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

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.

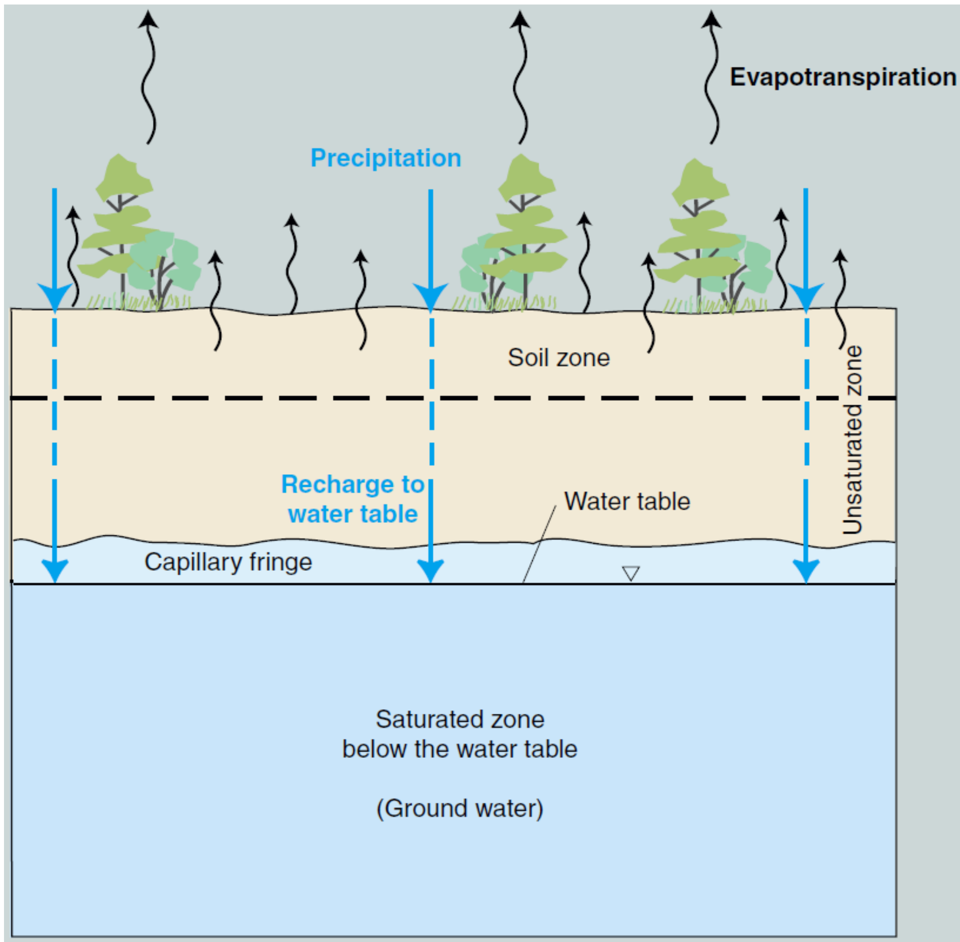
TRANSMISSIVITY: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness.

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)

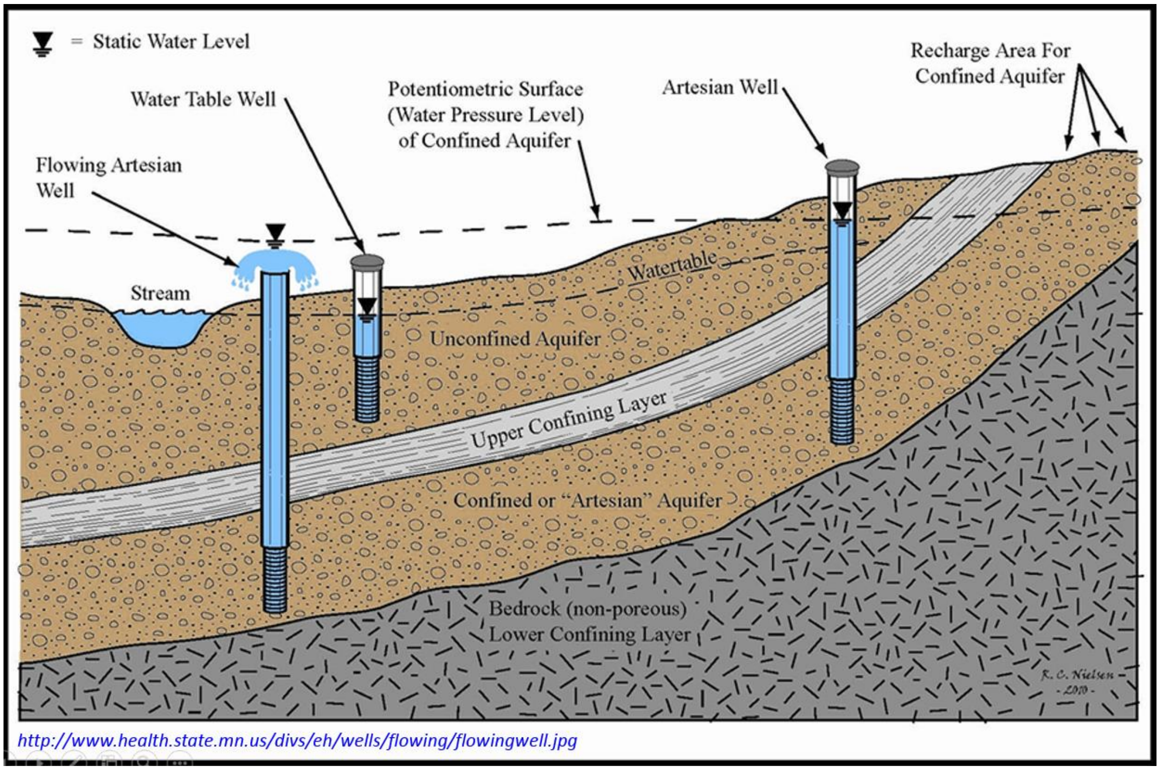


Aquifers consist of groundwater hosted by unconsolidated sedimentary deposits (e.g., sand) or consolidated rocks. To be considered an aquifer, there must be adequate interconnection of the primary and/or secondary porosity such that the geologic materials can hold, transmit, and release groundwater in 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 <u>increases</u> 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.

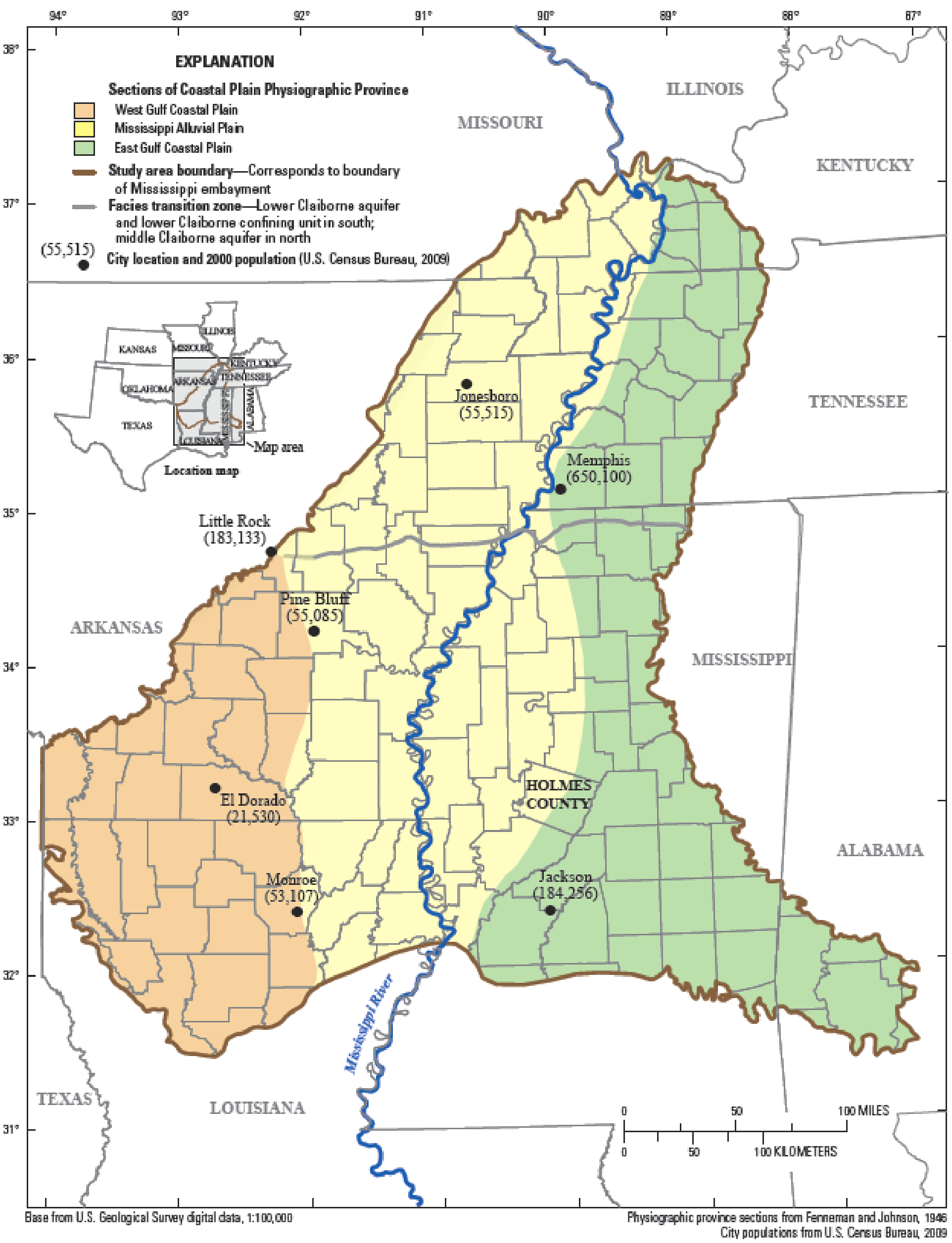
V. Geology and Hydrogeology of the Mississippi Embayment

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

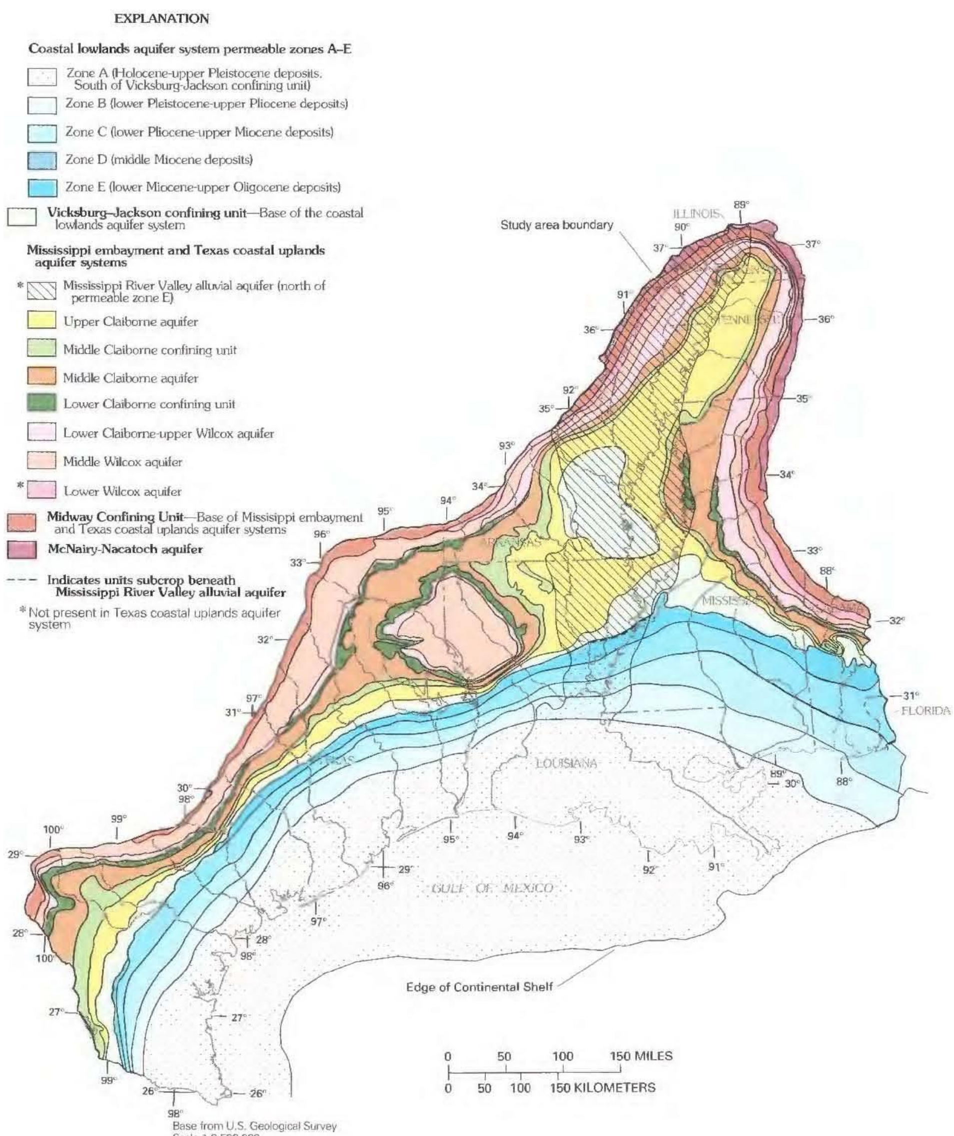
(Haugh, 2016, Table 1)

<table>
<tr><th>System</th><th>Series</th><th>Group</th><th>West Tennessee</th><th>Northern Mississippi</th><th>Regional hydrogeologic unit</th></tr>
<tr><td>Quaternary</td><td>Holocene and Pleistocene</td><td></td><td>Alluvium</td><td>Alluvium</td><td rowspan="2">Shallow aquifer</td></tr>
<tr><td>Quaternary</td><td>Pleistocene</td><td></td><td>Fluvial Deposits (terrace deposits)</td><td>Fluvial Deposits (terrace deposits)</td></tr>
<tr><td rowspan="11">Tertiary</td><td rowspan="6">Eocene</td><td rowspan="5">Claiborne</td><td>Cockfield Fm</td><td>Cockfield Fm</td><td>Upper Claiborne aquifer</td></tr>
<tr><td>Cook Mountain Fm</td><td>Cook Mountain Fm</td><td>Middle Claiborne confining unit</td></tr>
<tr><td rowspan="3">Memphis Sand (Memphis aquifer)</td><td>Sparta Sand (Sparta aquifer)</td><td>Middle Claiborne aquifer</td></tr>
<tr><td>Zilpha Clay</td><td>Lower Claiborne confining unit</td></tr>
<tr><td>Lower sands in the Claiborne Group</td><td rowspan="2">Lower Claiborne-Upper Wilcox aquifer</td></tr>
<tr><td rowspan="4">Wilcox</td><td>Flour Island Fm</td><td rowspan="2">Upper sands in the Wilcox Group</td></tr>
<tr><td rowspan="5">Paleocene</td><td rowspan="2">Fort Pillow Sand (Fort Pillow aquifer)</td><td rowspan="2">Middle Wilcox aquifer</td></tr>
<tr><td rowspan="2">Lower sands in the Wilcox Group</td></tr>
<tr><td>Old Breastworks Fm</td><td>Lower Wilcox aquifer</td></tr>
<tr><td rowspan="2">Midway</td><td>Porters Creek Clay</td><td>Porters Creek Clay</td><td rowspan="2">Midway confining unit</td></tr>
<tr><td>Clayton Fm</td><td>Clayton Fm</td></tr>
</table>

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.

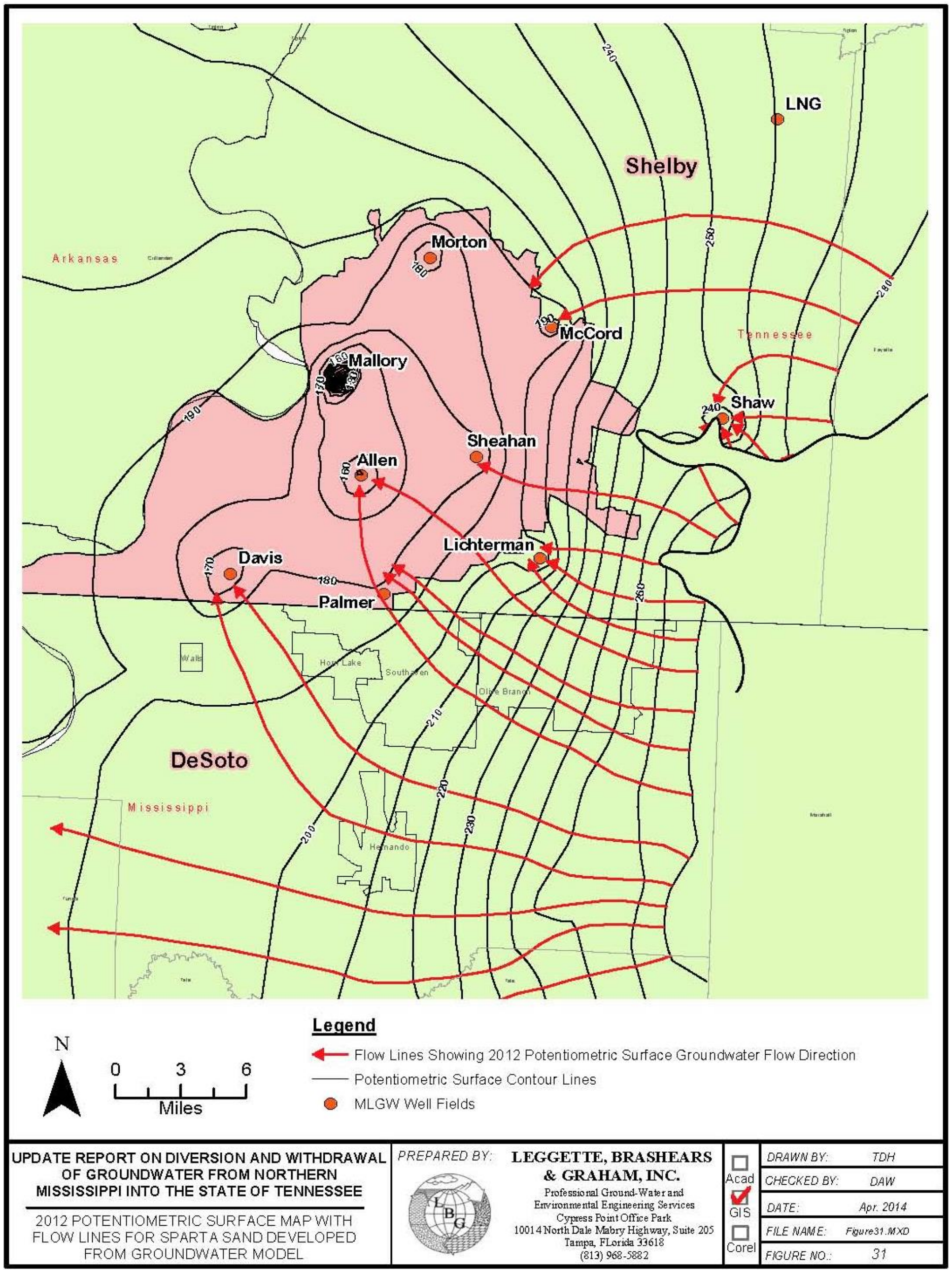
The Mississippi River Alluvial Aquifer (aka, Surficial Aquifer) lies atop these mostly-buried Eocene-age aquifers, and the Surficial Aquifer is exposed at the surface within the Mississippi River floodplain. This aquifer is generally unconfined, and consists of sands, silts, and clays deposited by the 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)

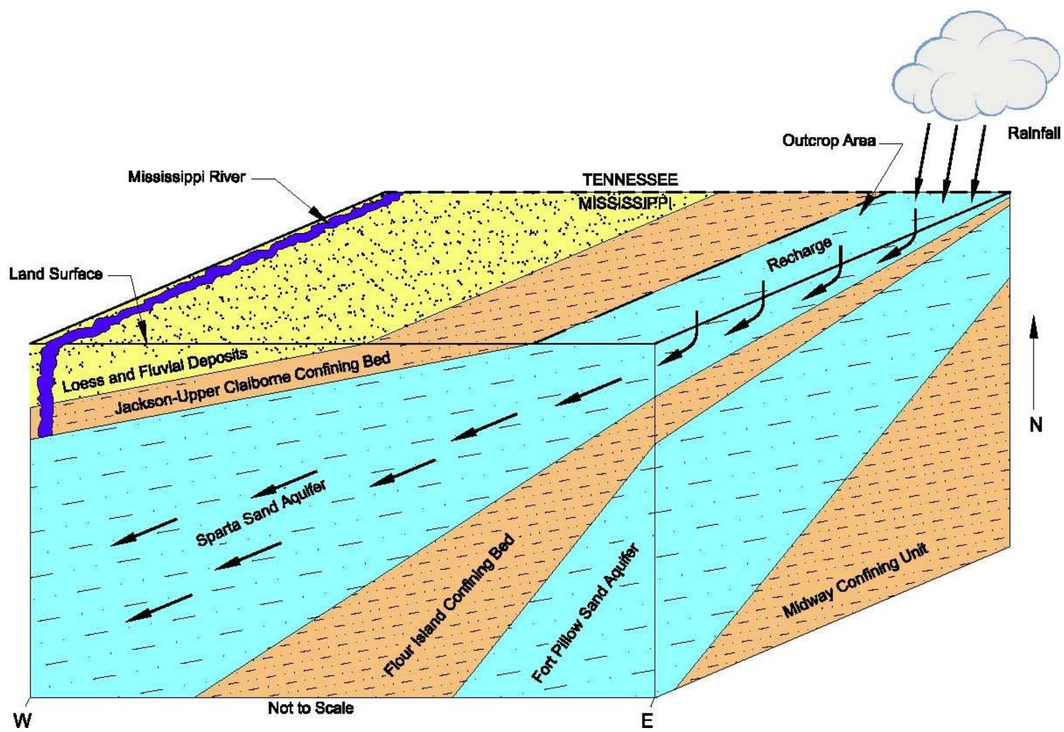
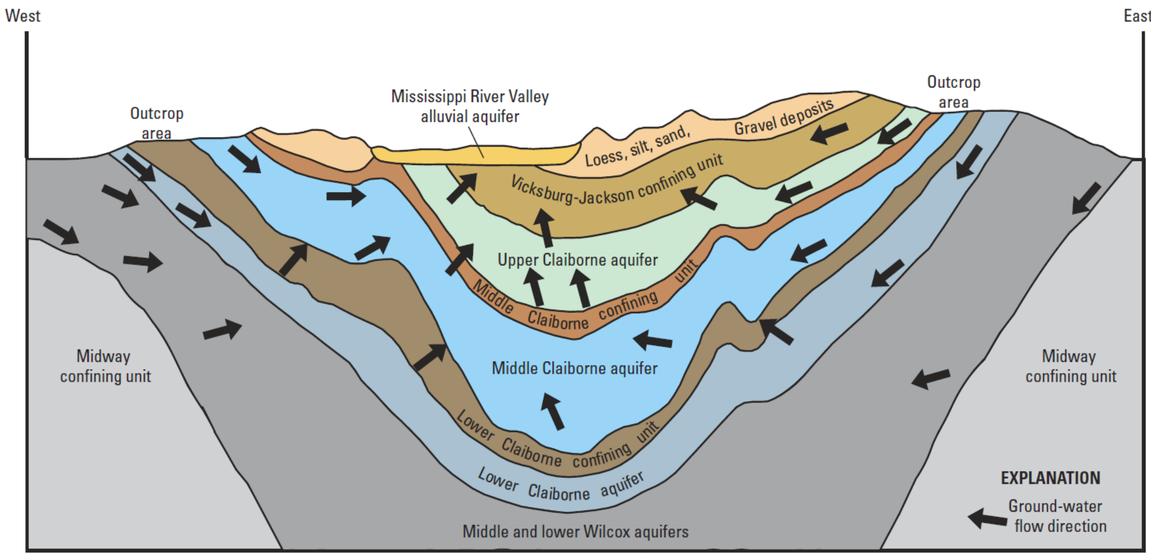


Figure 8 is a schematic east-west cross section (side view) through the Mississippi Embayment that includes arrows depicting the general pattern of groundwater flow before development began in the late 1800s. Some regional flow paths for water movement were as long as 200 miles from the recharge area 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)

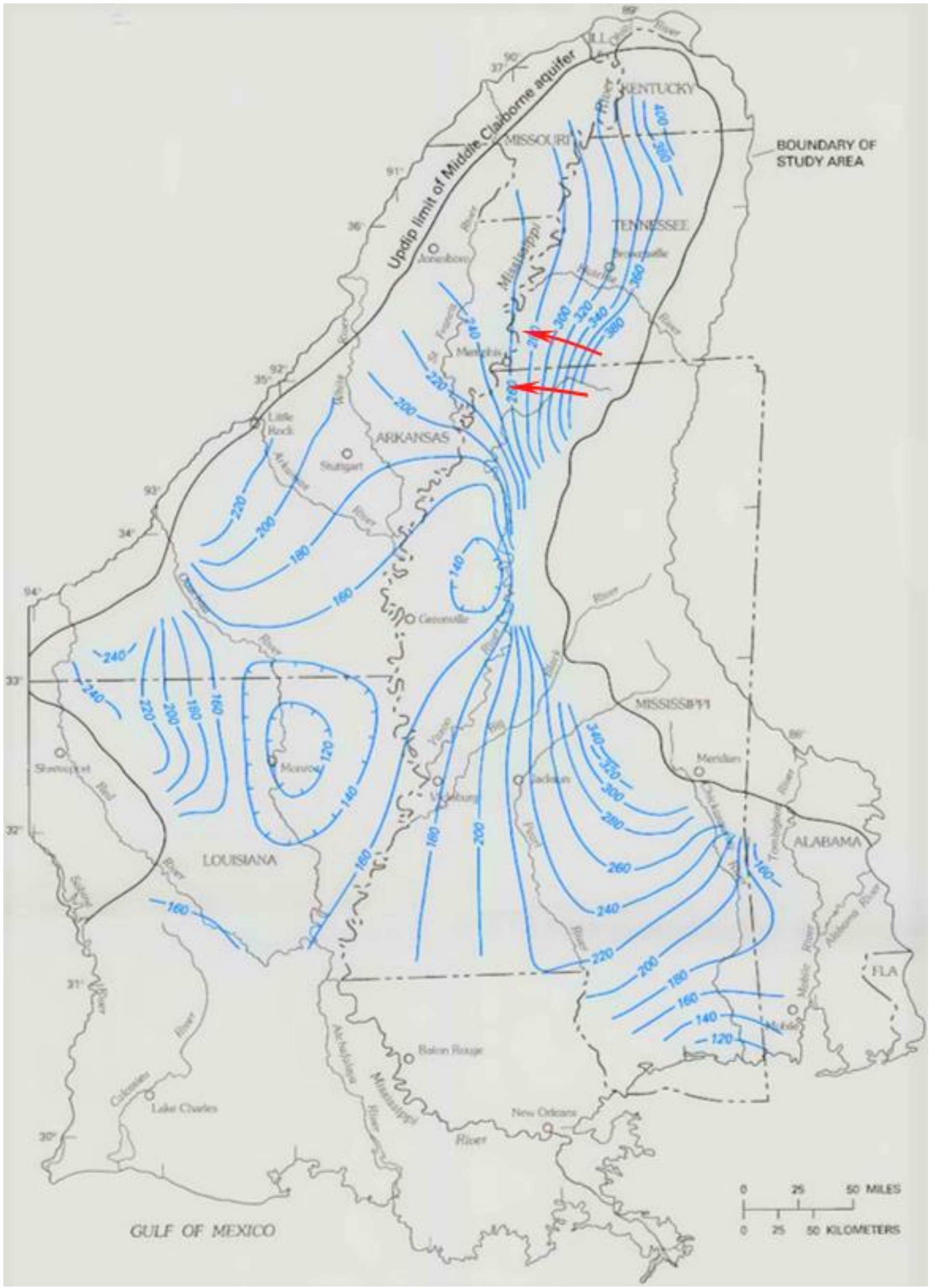
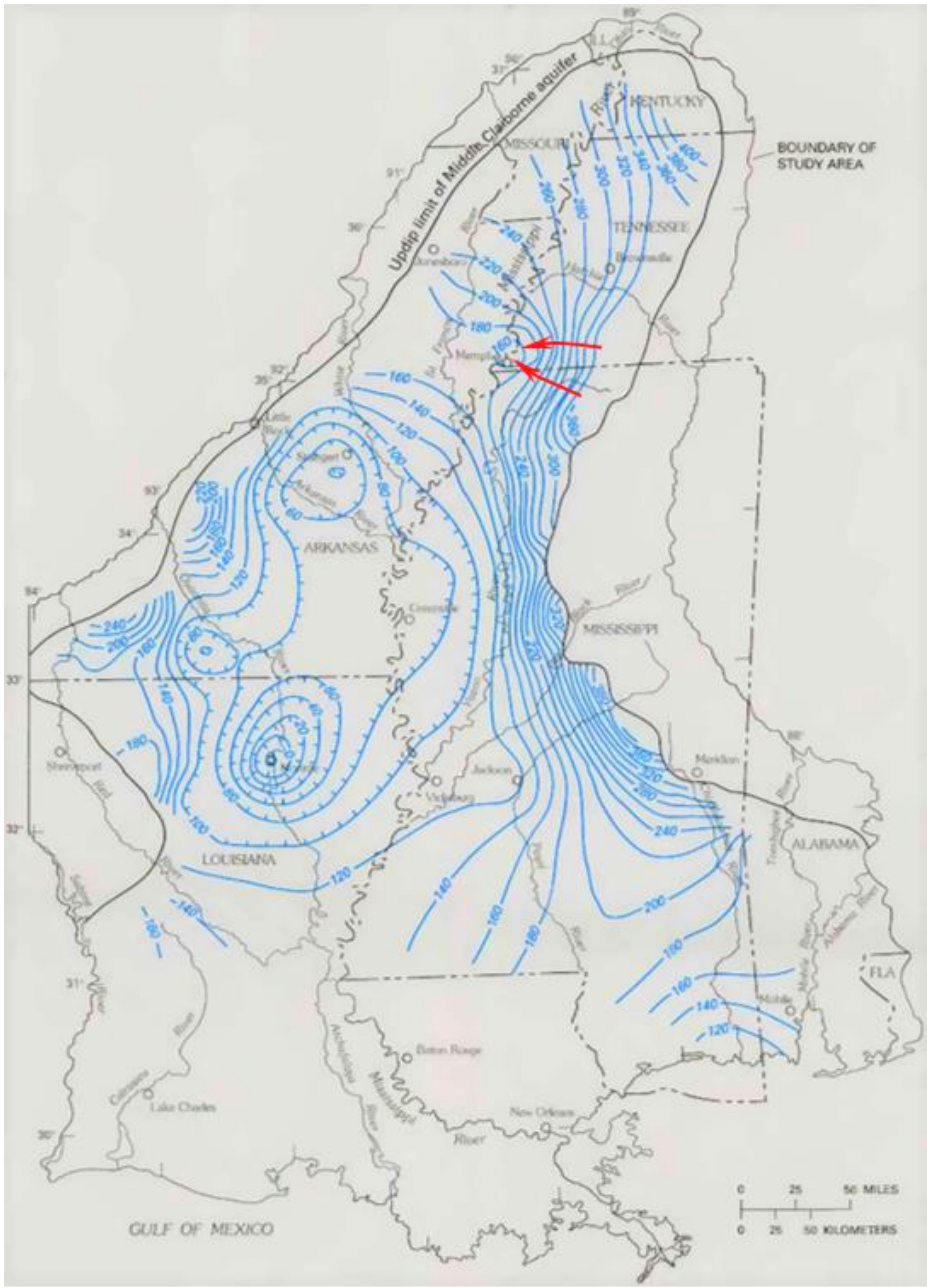


Figure 10: Post-Development Groundwater Equipotential Map and Flow Patterns in the Middle Claiborne Aquifer (modified from Plate 7 of Arthur and Taylor, 1998)



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.

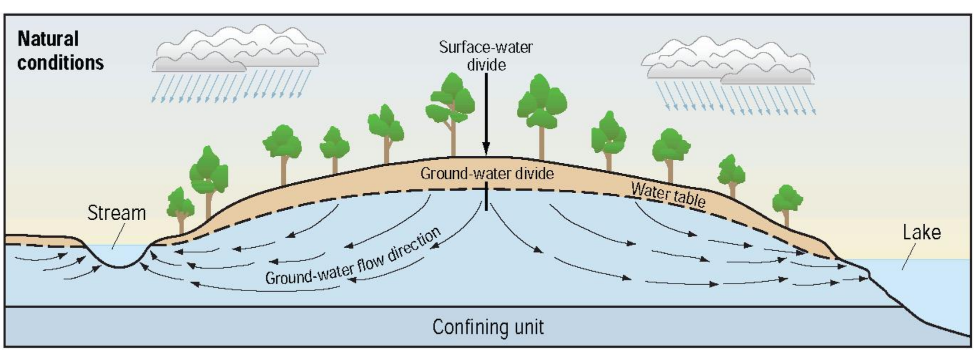
Transmissivity is used to describe the flow of groundwater through aquifers, and it is defined as the hydraulic conductivity multiplied by the thickness of the aquifer. Transmissivity is a property that is commonly determined to understand and quantify how much water moves through, and thus can be recovered 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

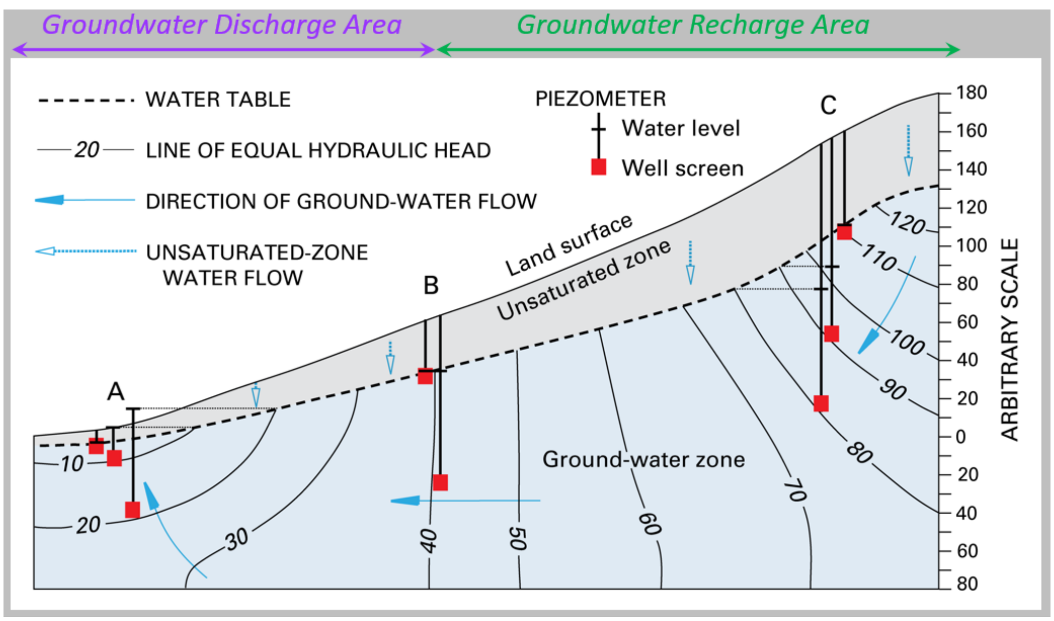
Groundwater flow patterns in unconfined portions of the groundwater system are extremely complex. To illustrate these patterns, Figure 11 is a generalized groundwater illustration that depicts flow in the shallow groundwater system from a groundwater divide in an elevated area to the location of a stream 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

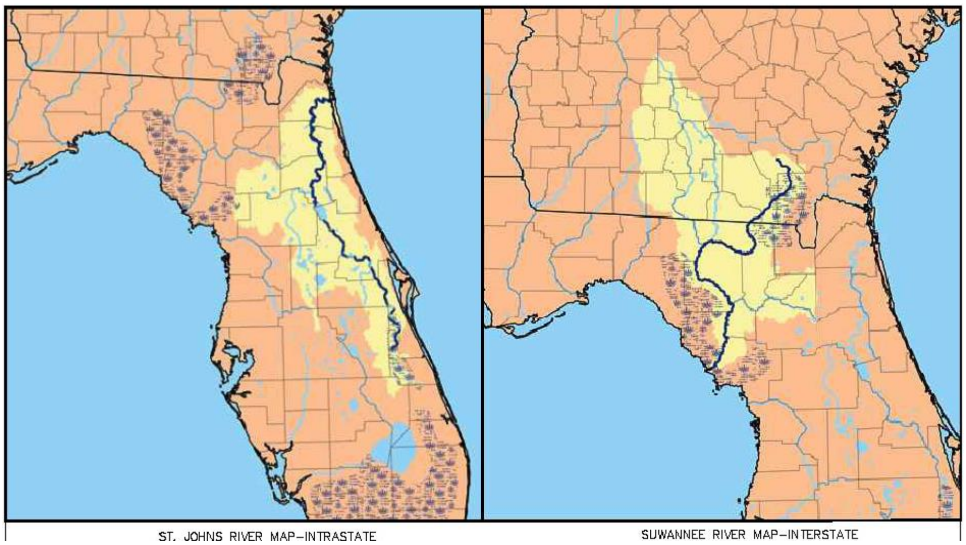
The shape of the cone of depression associated with a pumping well in a confined aquifer has two important aspects. First, the depth of the cone adjacent to the well is controlled by the hydraulic properties of the aquifer, the pumping rate, and the pumping period. The theoretical lateral limit of the 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.

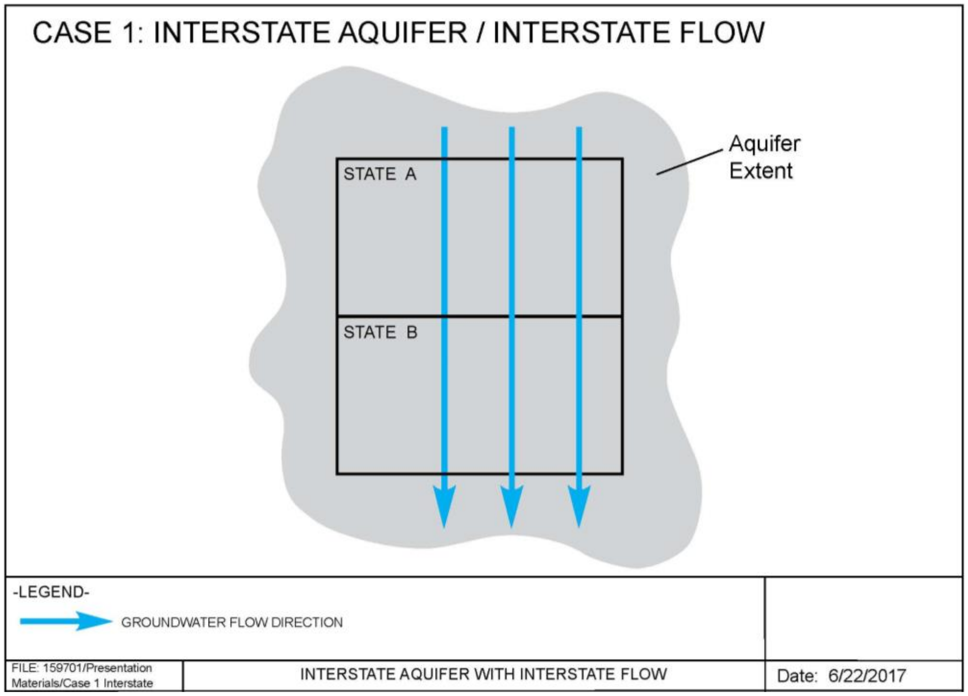
Fresh water is one of our most important natural resources, and its availability has become a major concern in many parts of the United States and elsewhere. Claims to surface water have historically been recognized based on the location and flow path of the water under natural conditions. Figure 13 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)

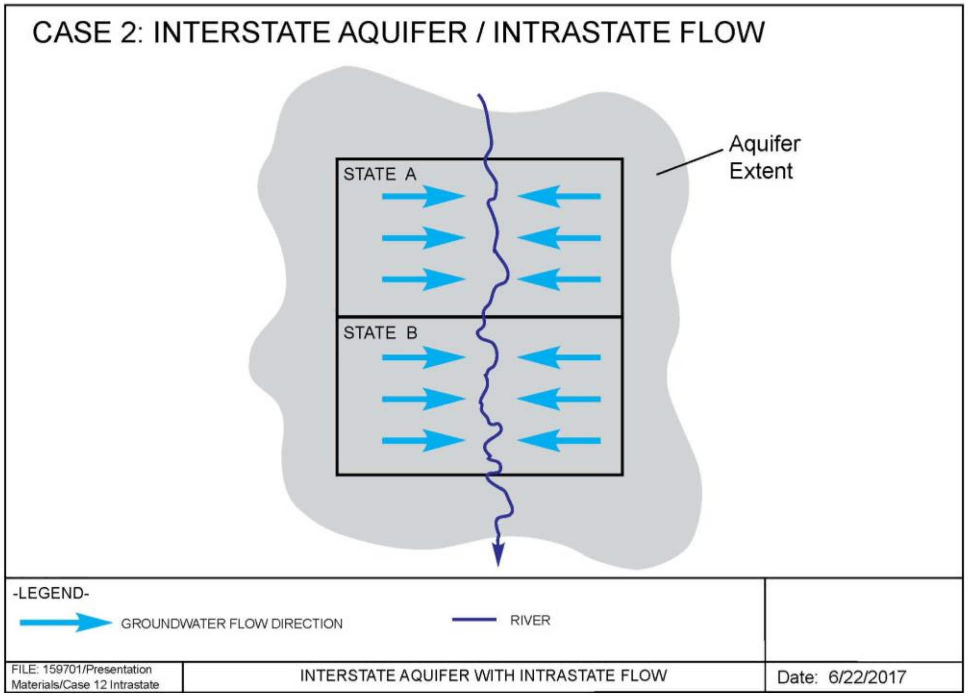


The natural territorial accumulation and flow of surface water along the lowest path created by geological processes is visible to the entire world. While it is not as visible, thus making it inherently more complicated, the natural territorial accumulation and flow of groundwater within a confined aquifer 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 prior 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)

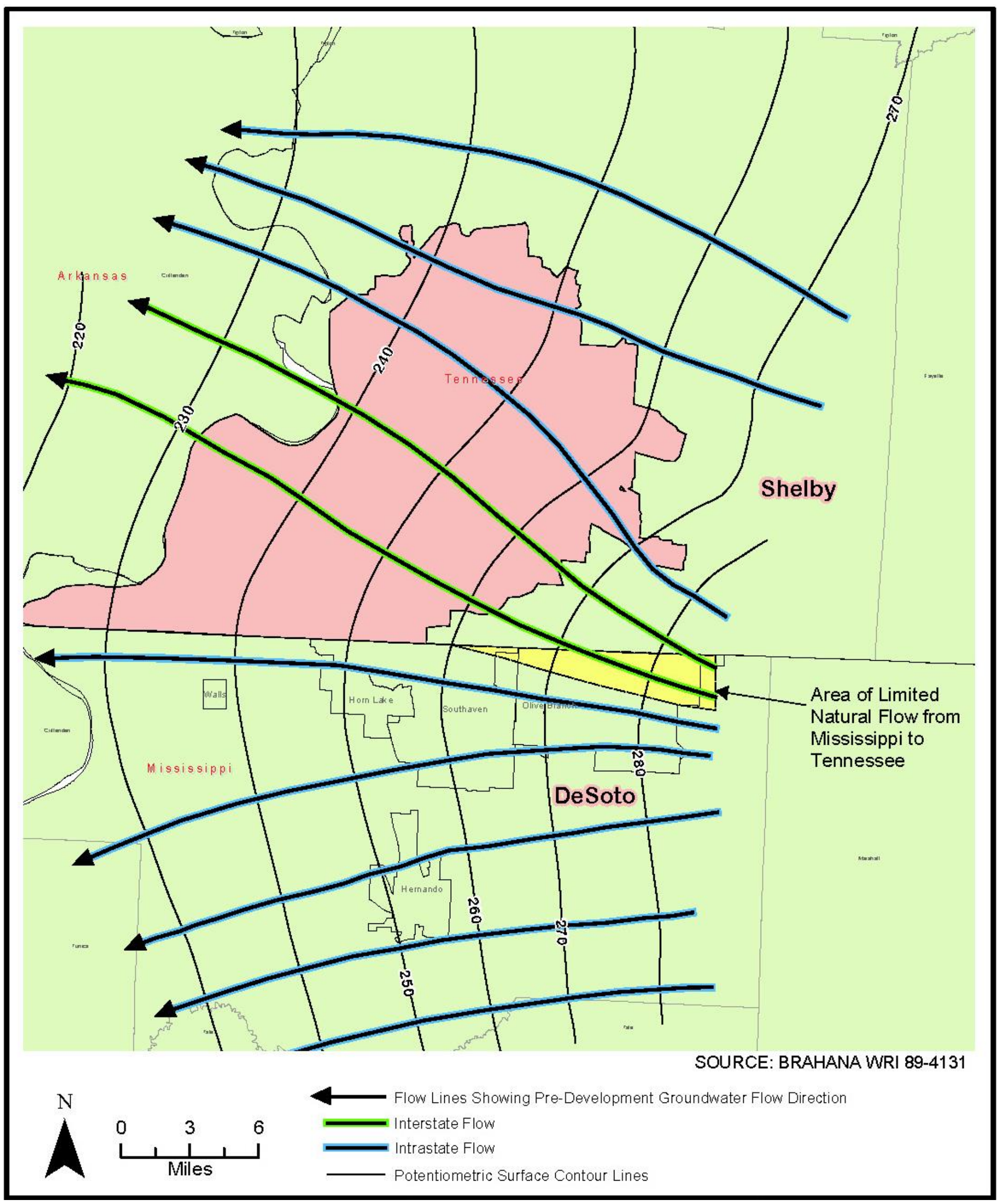
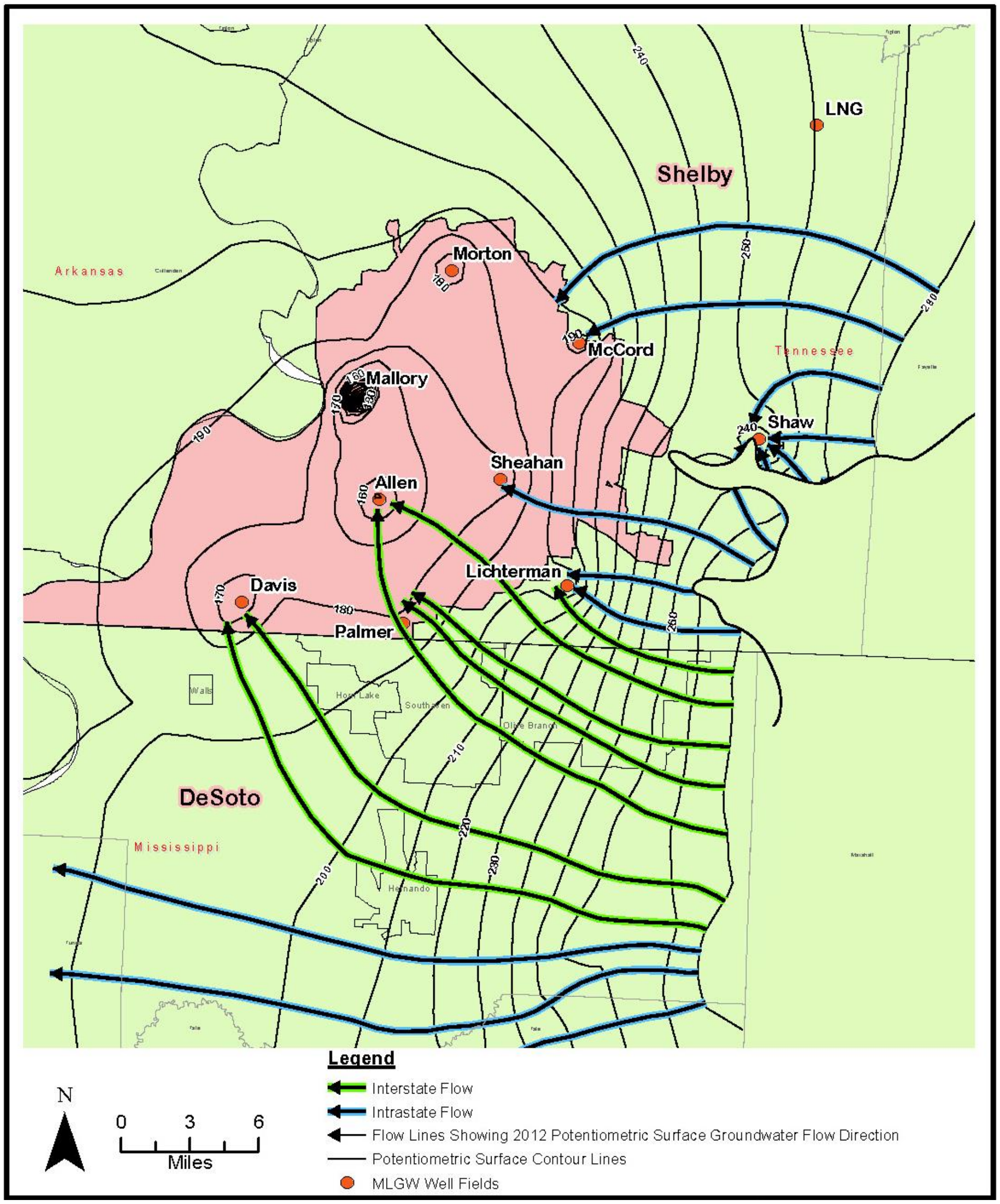


Figure 18: Legette, Brashears, and Graham, Inc. (2014) Post-Development Equipotential Map for the Sparta-Memphis Sand Aquifer (modified to highlight groundwater-flow paths)



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.

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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

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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.

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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.

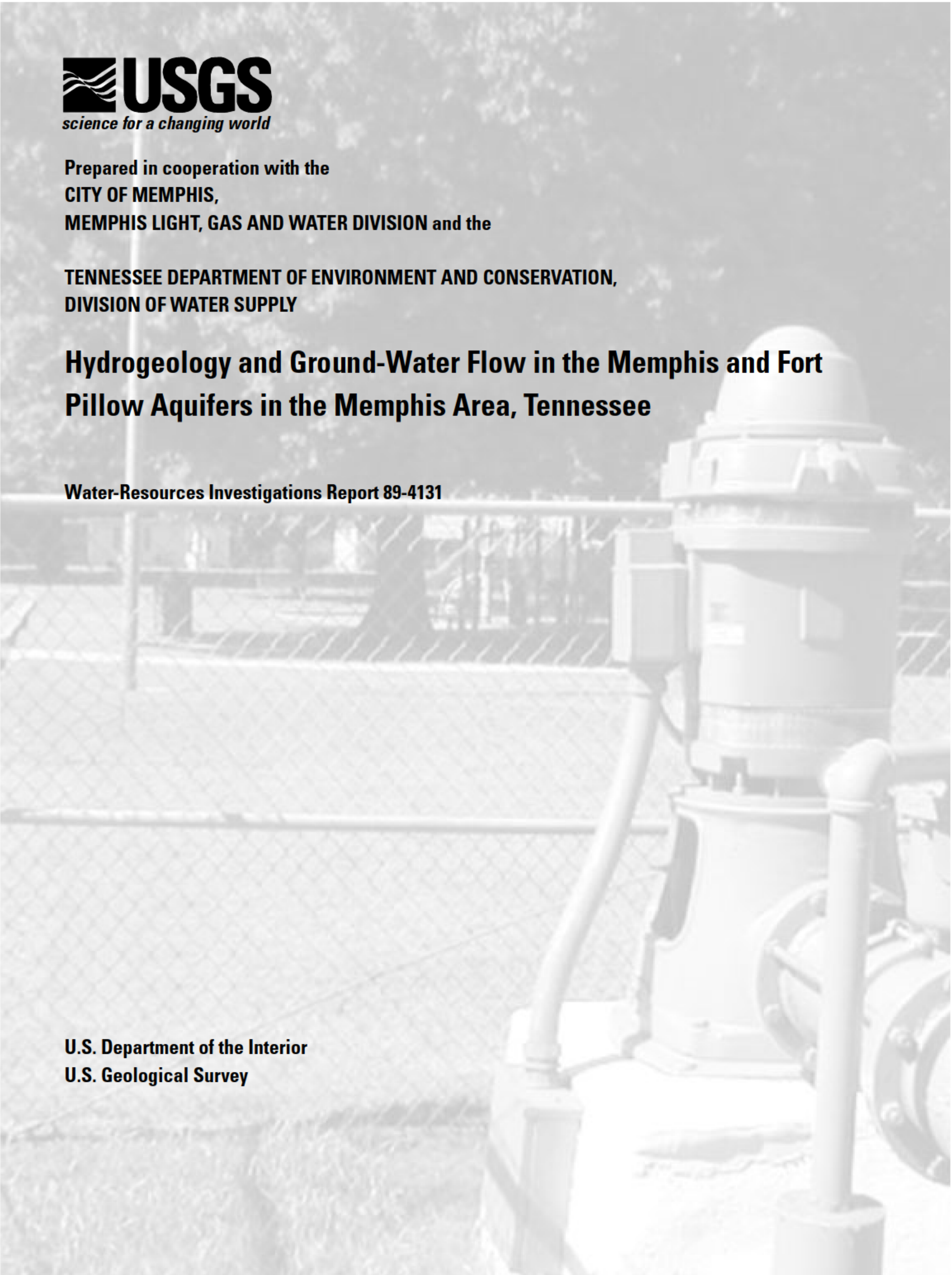
2003 Expert witness deposition in Joel & Janice Drum v. Schronce and Superior Petroleum and Fuel Company, Inc., Superior Court of Catawba County, North Carolina, File No. 01 CVS 3998. Retained by James F. Hopf.

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.



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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.

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By J.V. Brahana and R.E. Broshears

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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

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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).

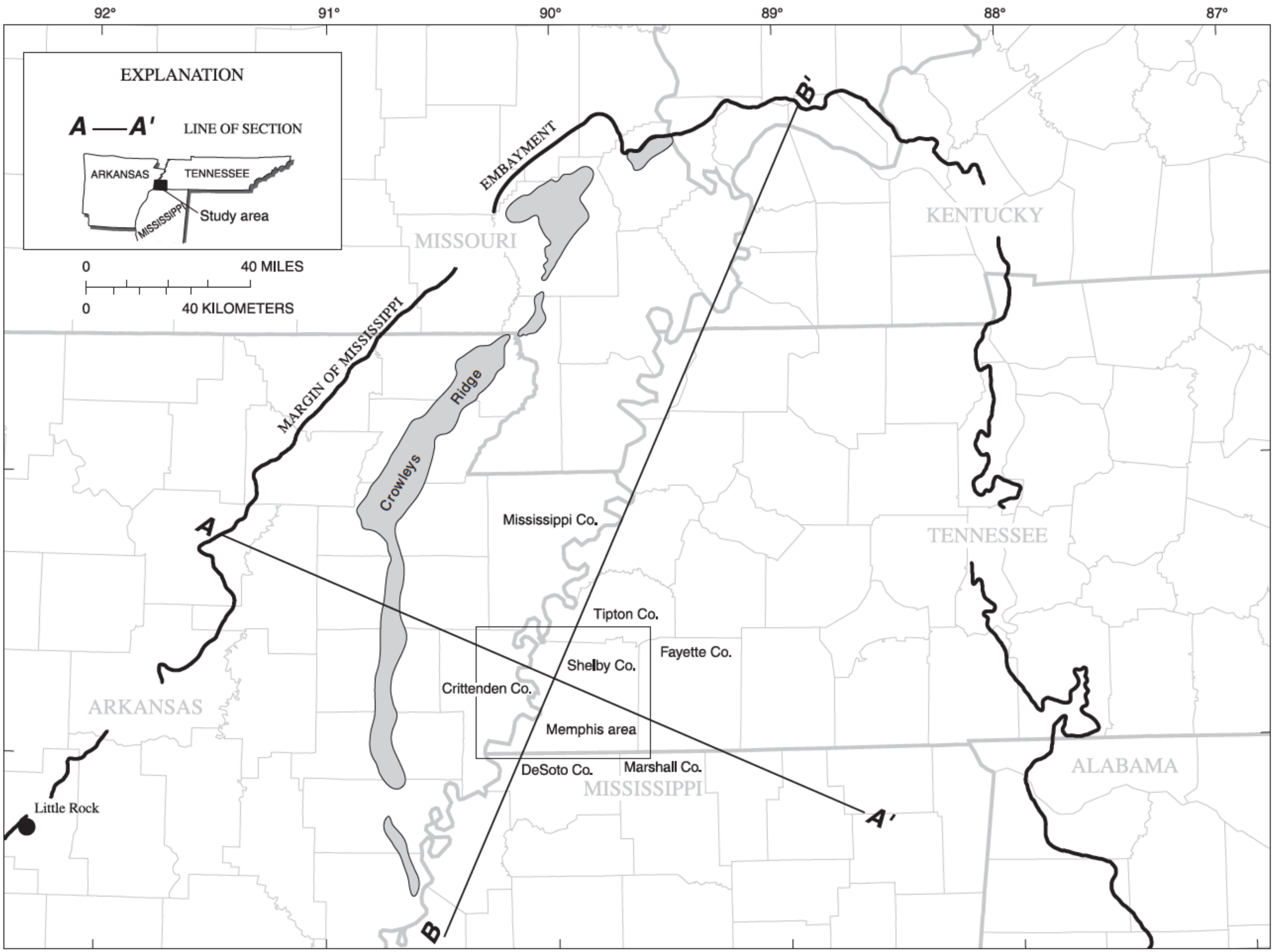


Figure 1. Location of the Memphis area and hydrogeologic sections along lines A-A′ and B-B′ in the Mississippi embayment.

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).

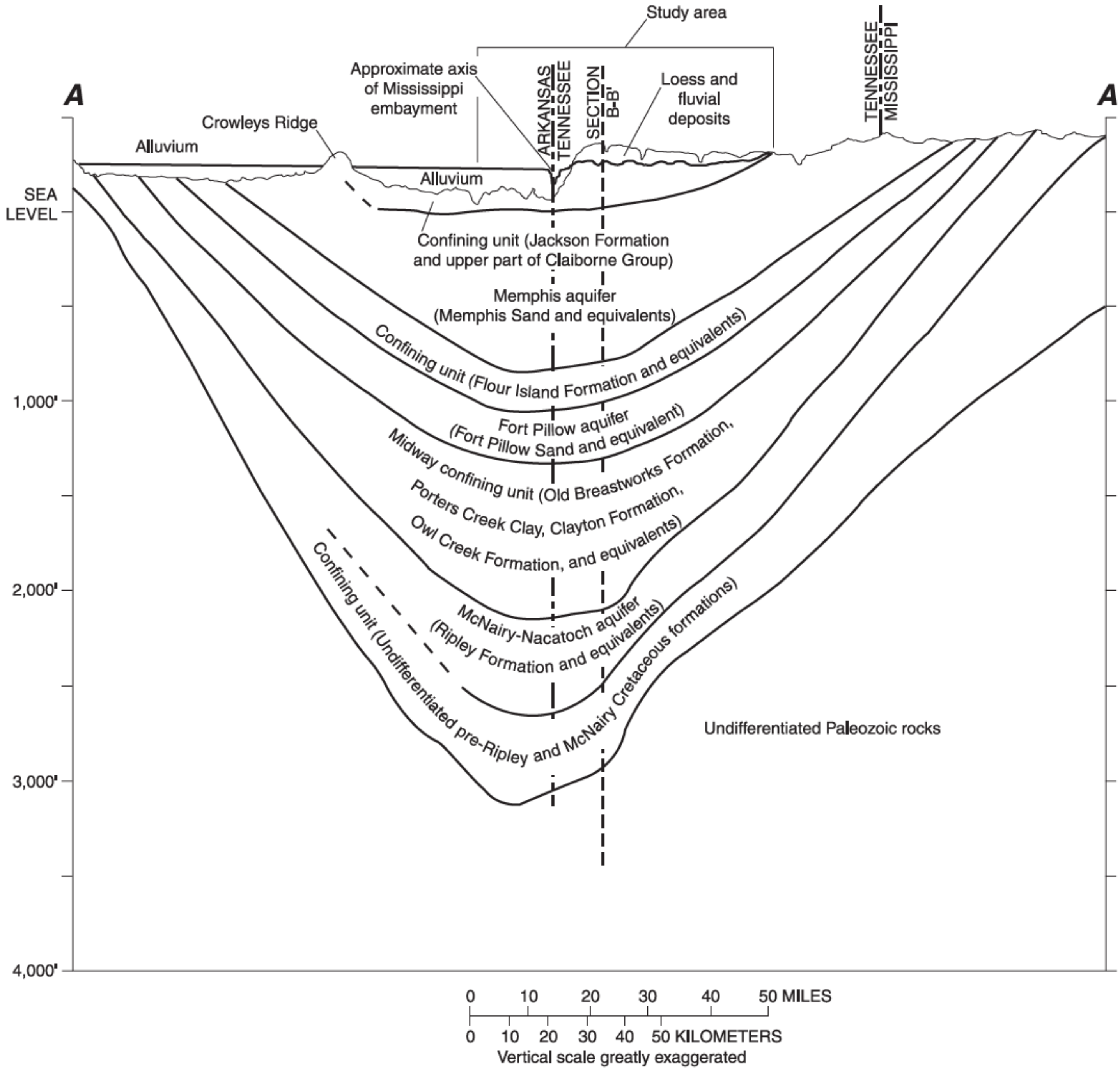


Figure 2. Hydrogeologic section showing principal aquifers and confining units, west to east, through the Mississippi embayment along line A-A'.

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

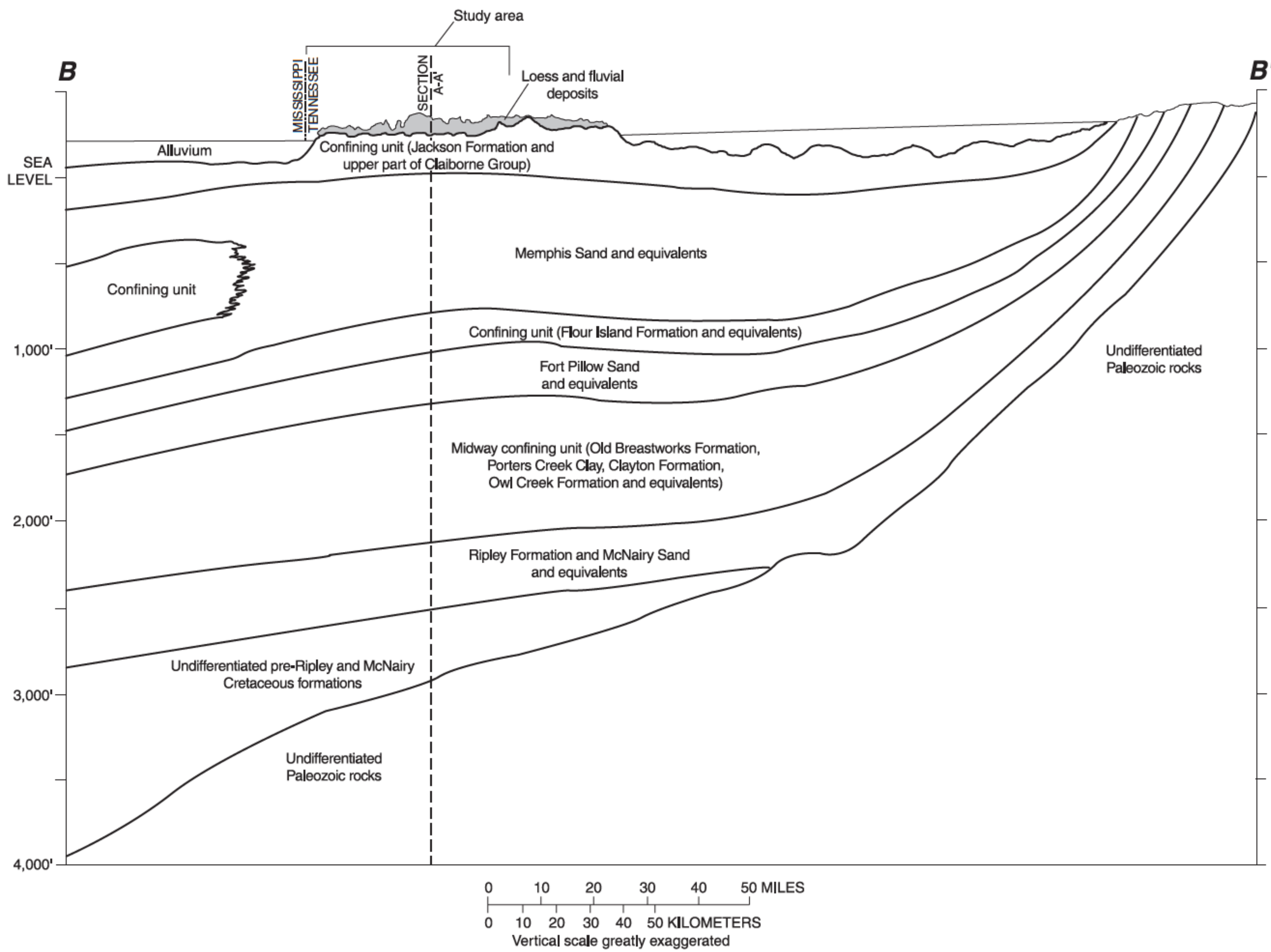


Figure 3. Hydrogeologic section showing principal aquifers and confining units, south to north, through the Mississippi embayment along line B-B′.

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.
	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 Cockfleld 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.

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

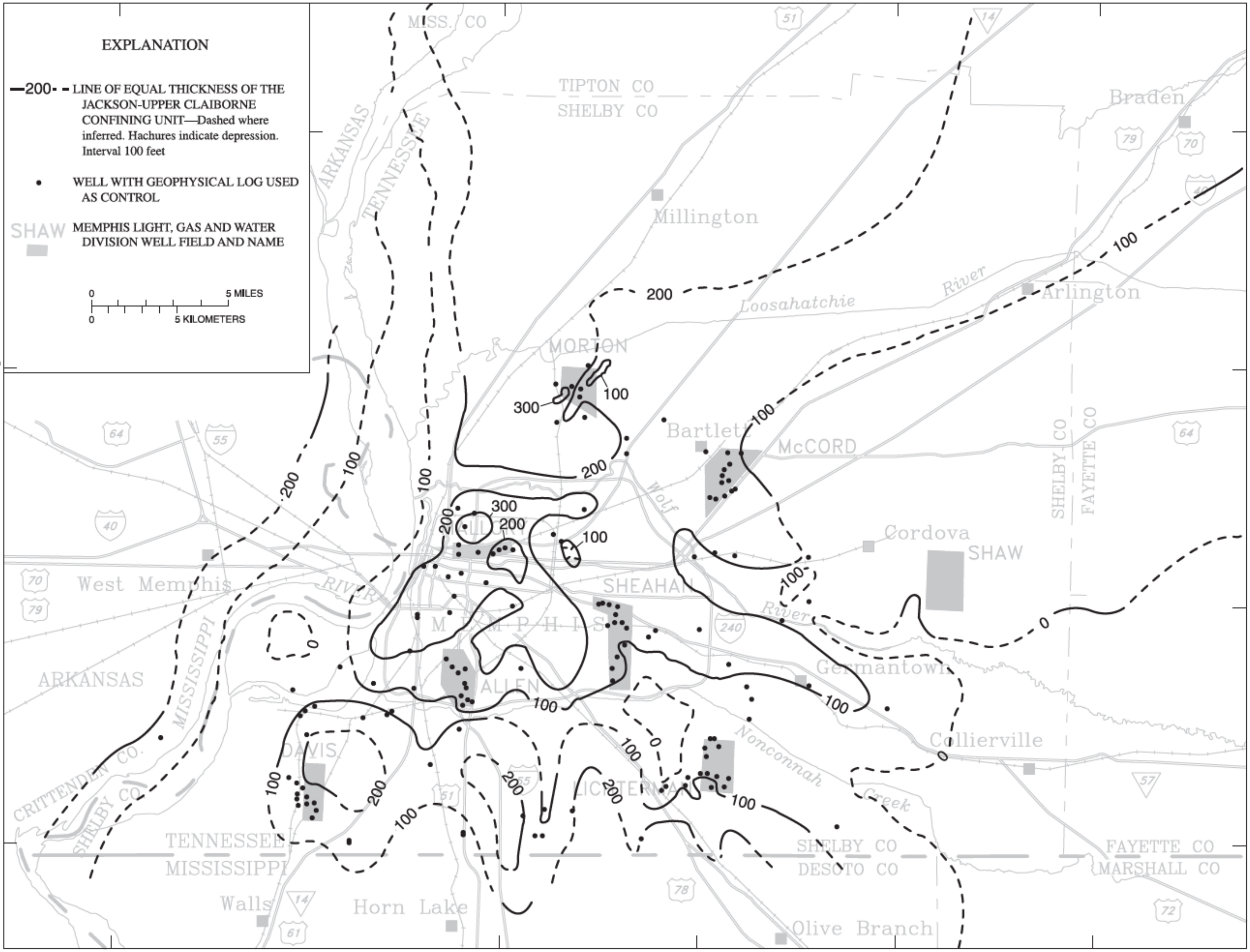
Hydrogeologic unit	Generalized present-day flow directions	Depth commonly encountered (feet)	Thickness (feet)	Water-bearing character	Hydraulic properties of unit		
					T (ft^2/d)	S (unitless)	K′ (ft/d)
Alluvium	Toward major streams—downstream.	Surface	0-175	Unconfined aquifer Mississippi River alluvium 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.

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.



Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

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

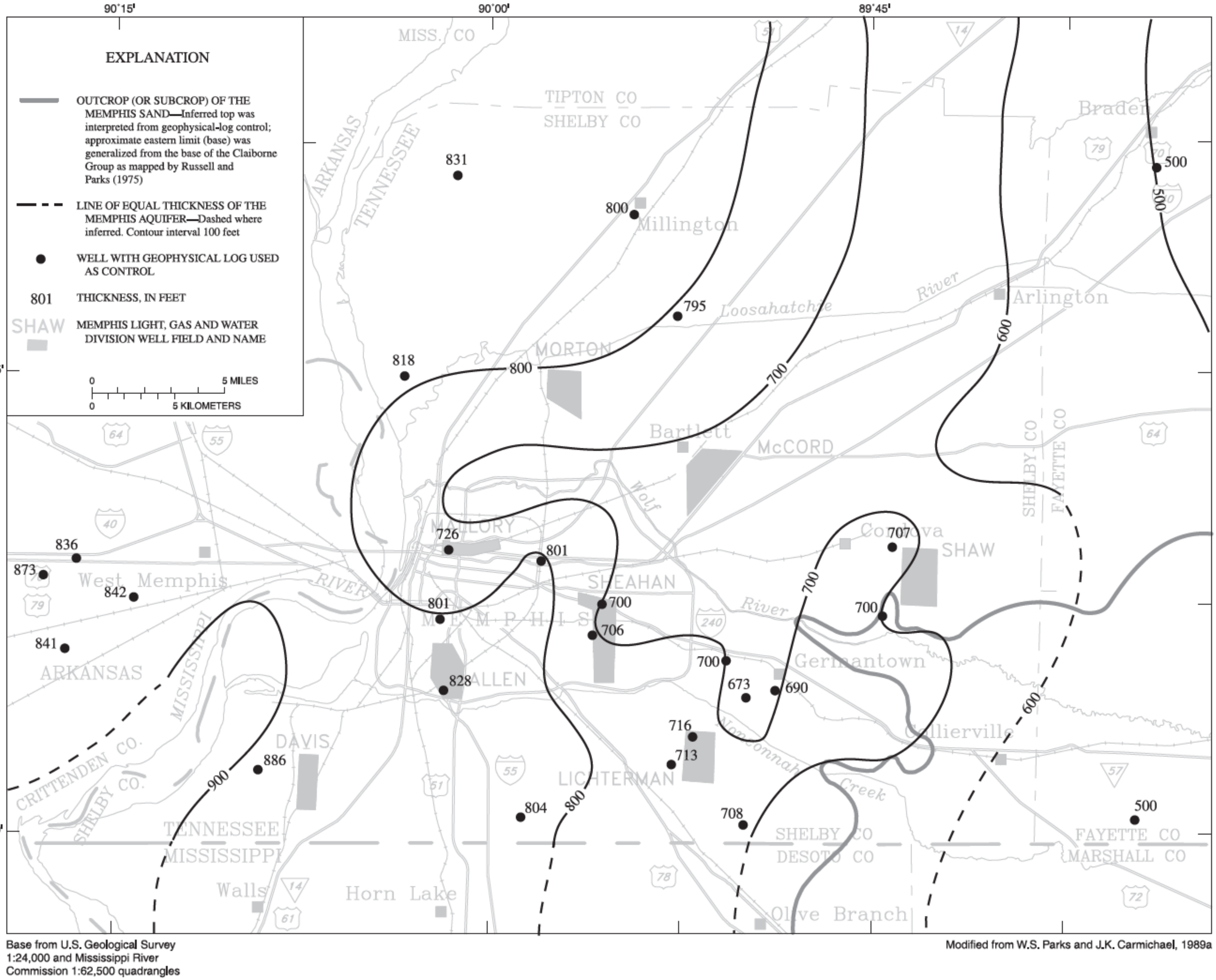


Figure 6. Generalized thickness of the Memphis aquifer in the Memphis area.

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

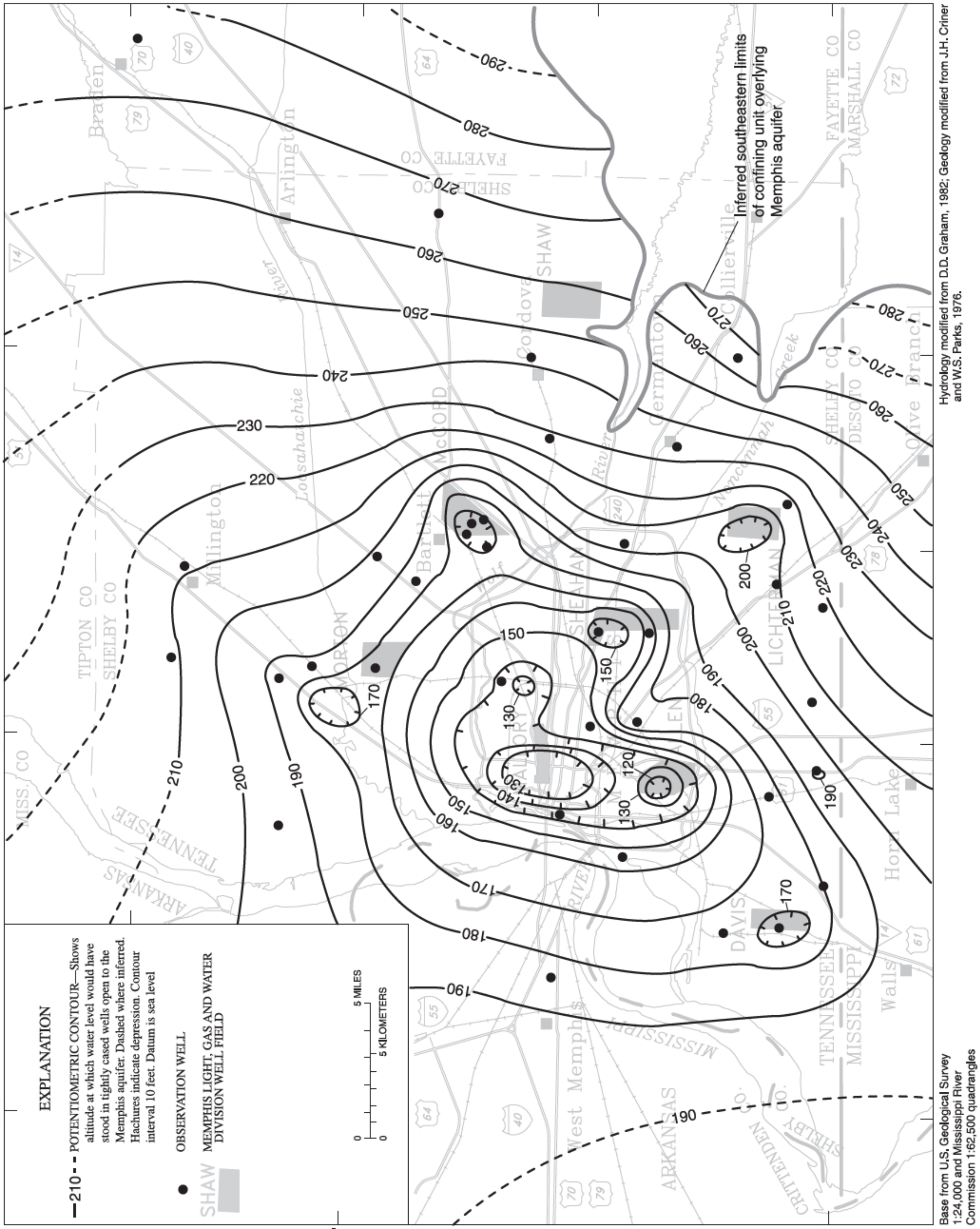


Figure 7. Altitude of the potentiometric surface of the Memphis aquifer in the Memphis area, 1980.

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

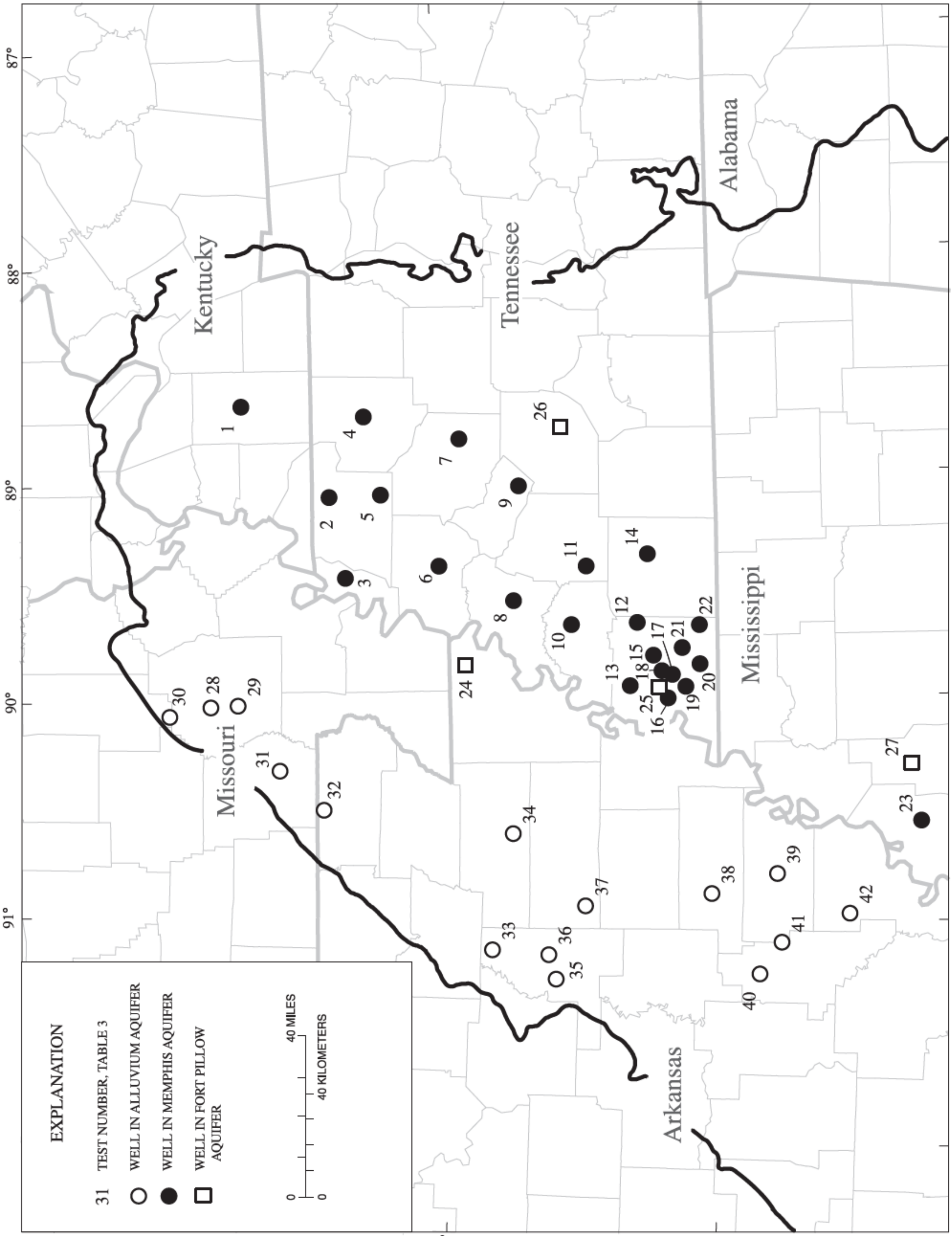
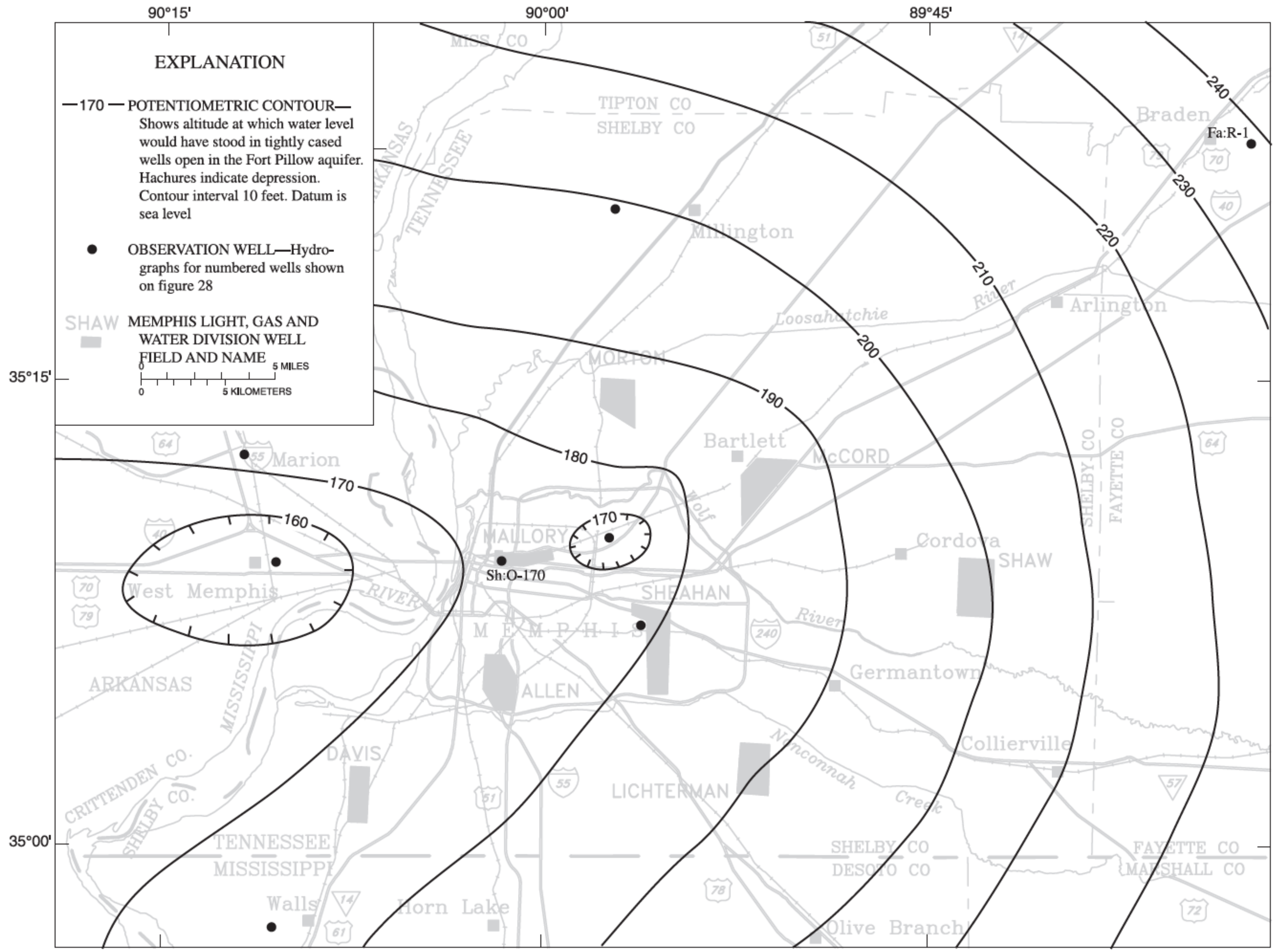
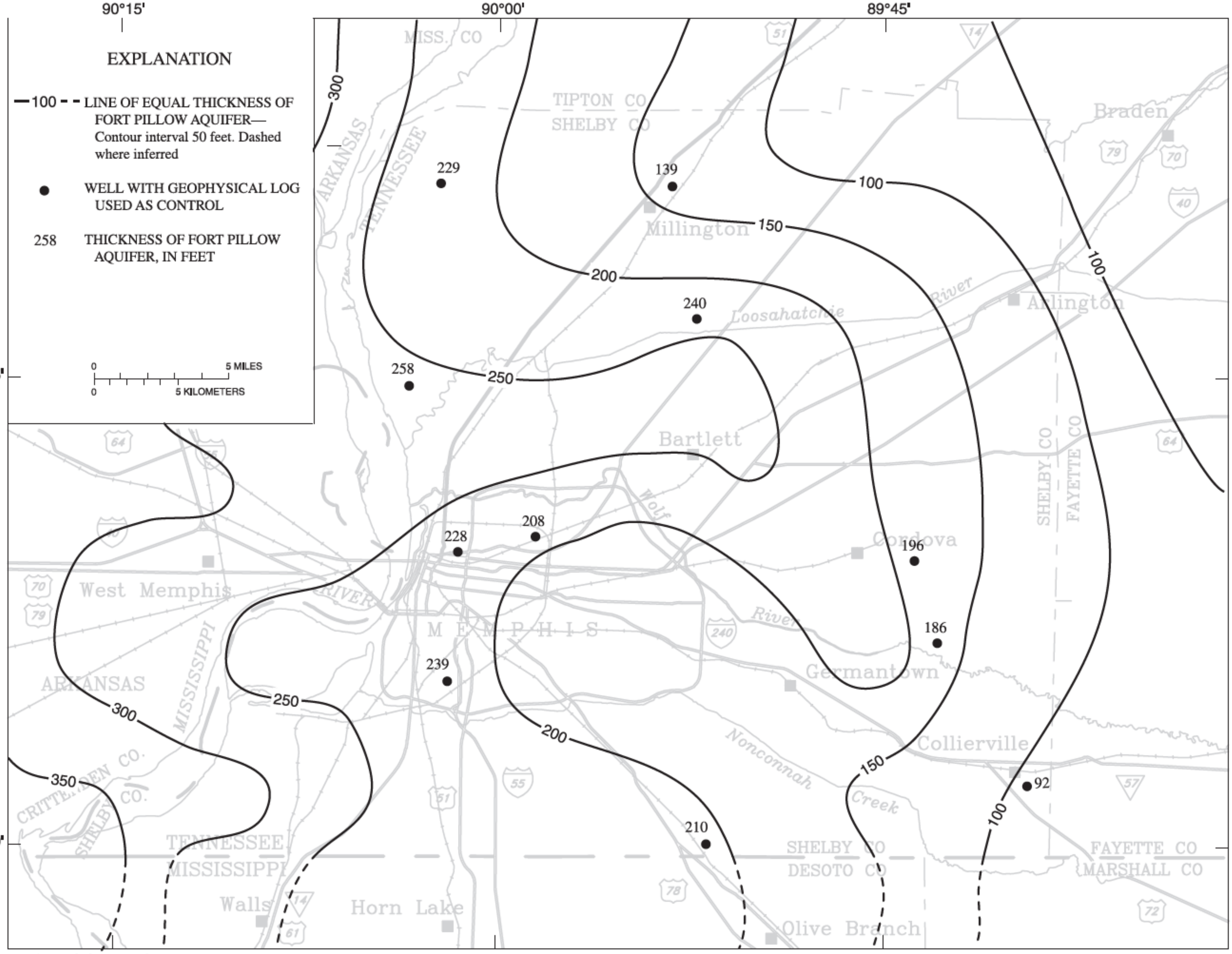


Figure 8. Location of selected aquifer tests.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

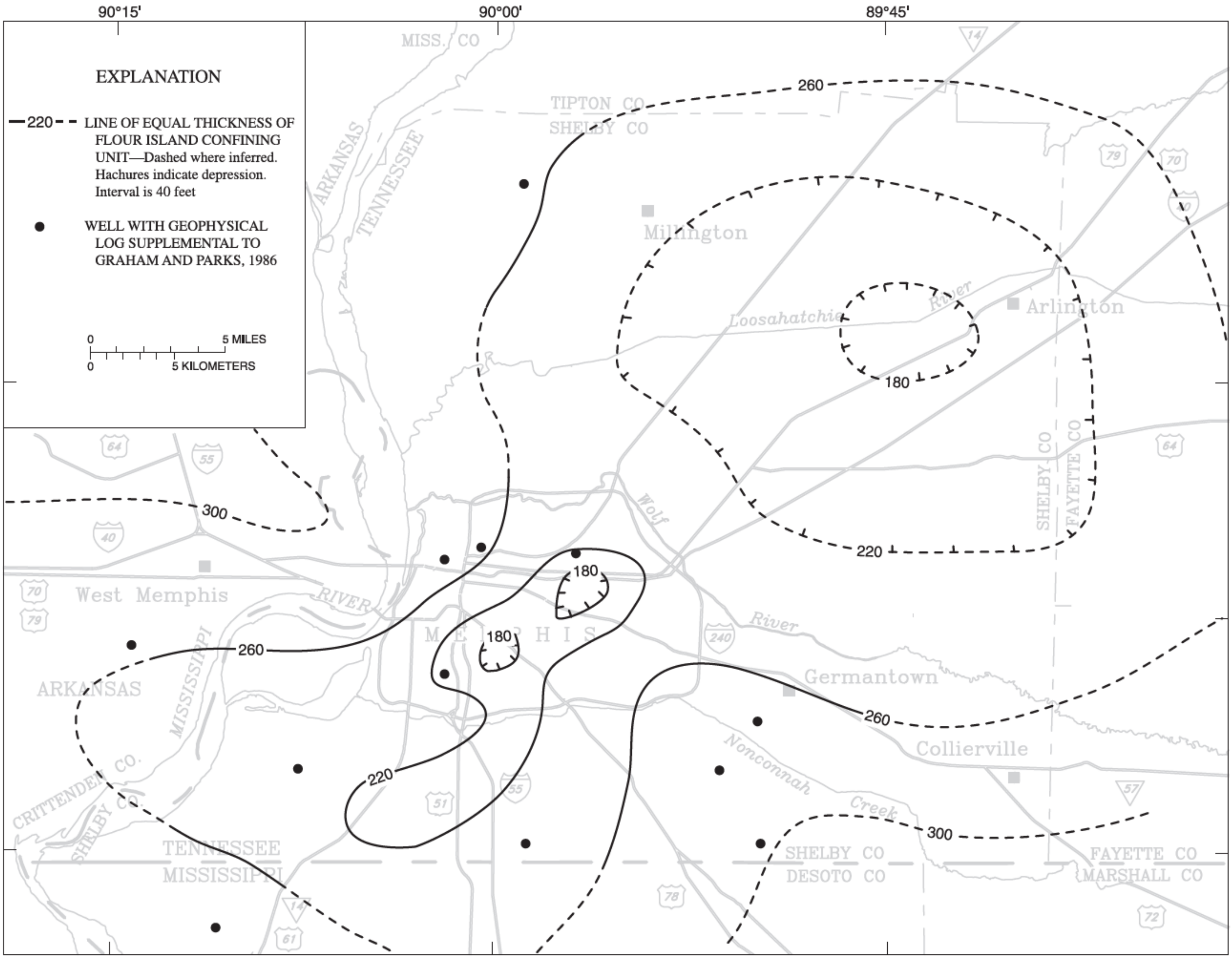
Figure 9. Altitude of the potentiometric surface of the Fort Pillow aquifer in the Memphis area, 1980.



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

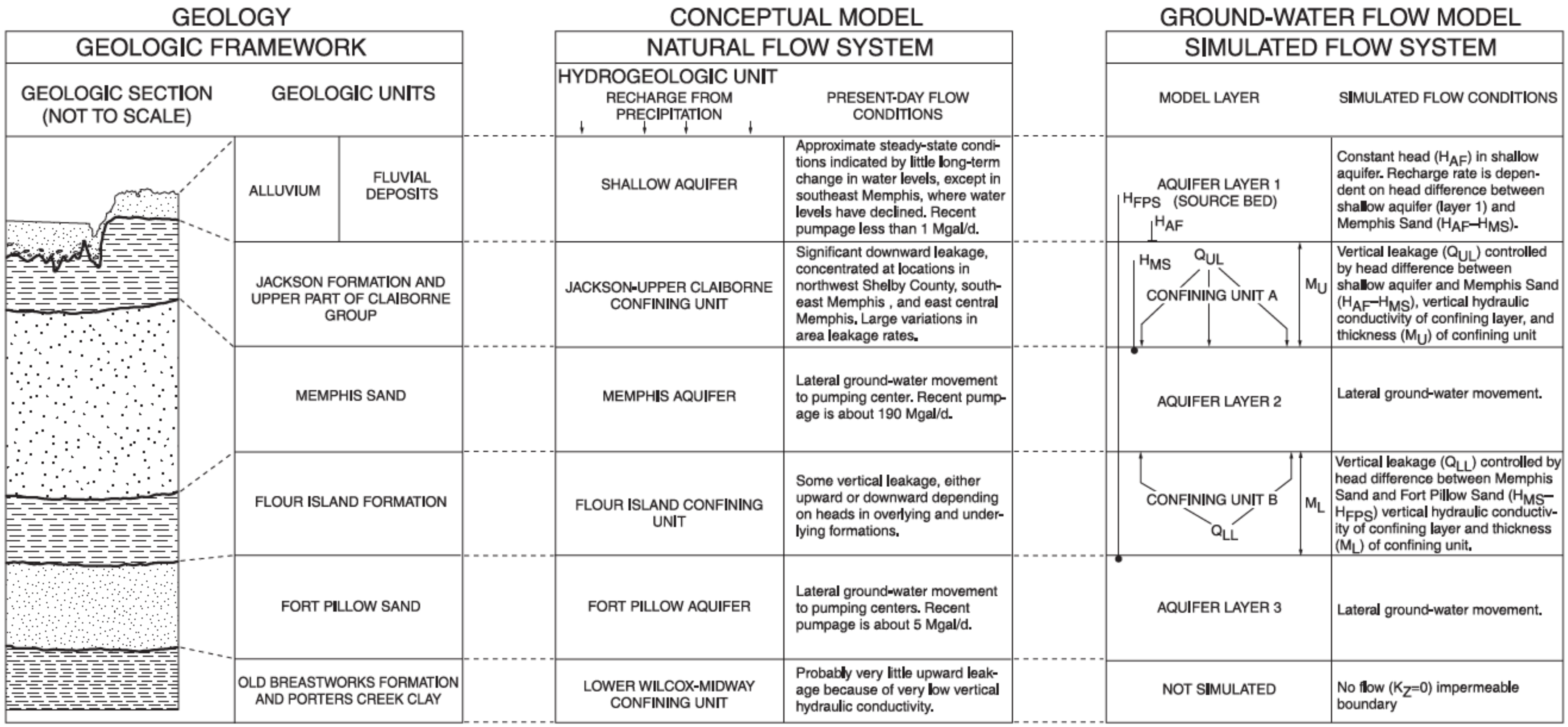
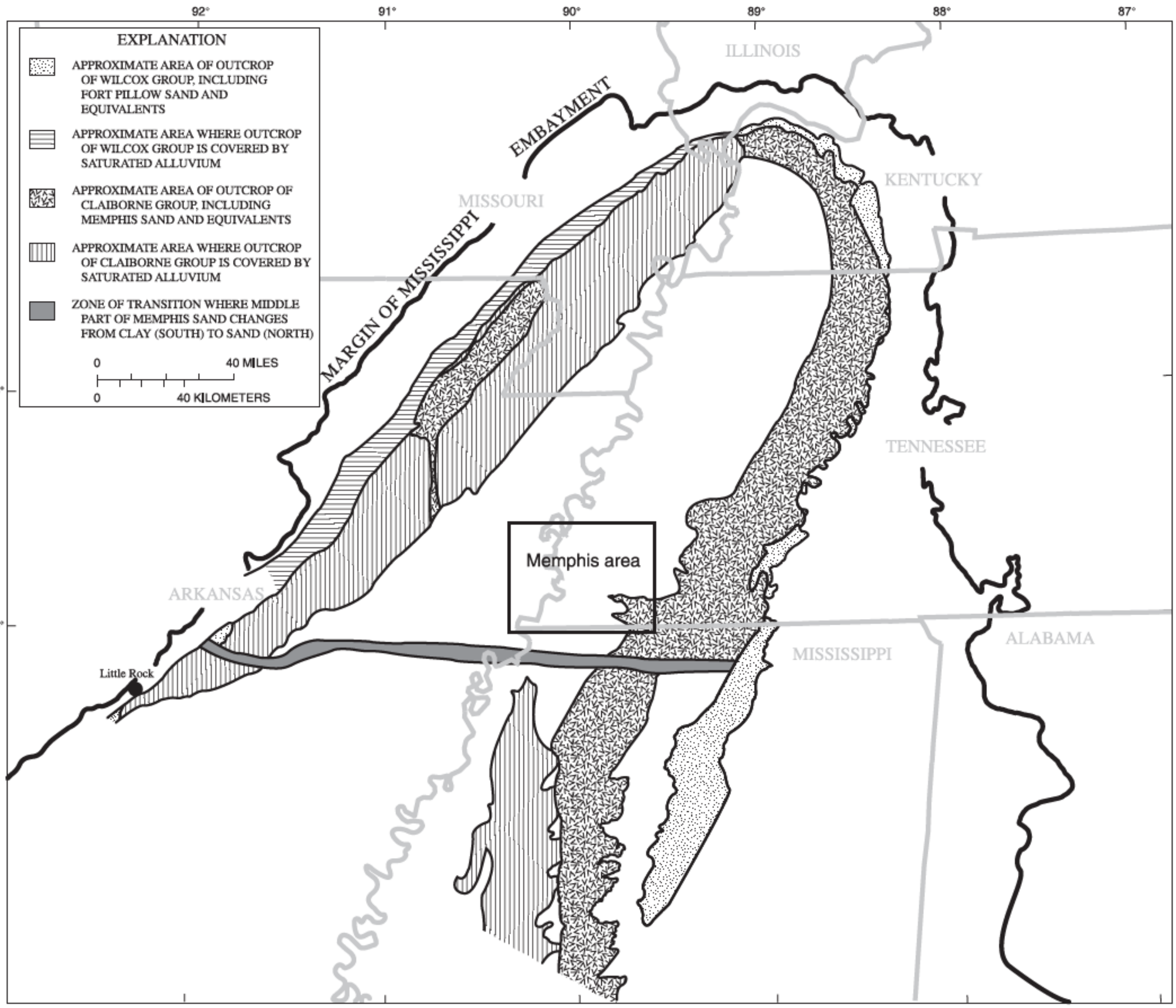


Figure 12. Relation between units of the geologic framework, the natural flow system of the conceptual model, and the simulated flow system of the ground-water flow model.



Geology modified from R.L. Hosman, A.T. Long, and T.W. Lambert and others, 1968, Plate 7; and J.H. Criner and W.S. Parks, 1976, figure 4.

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.

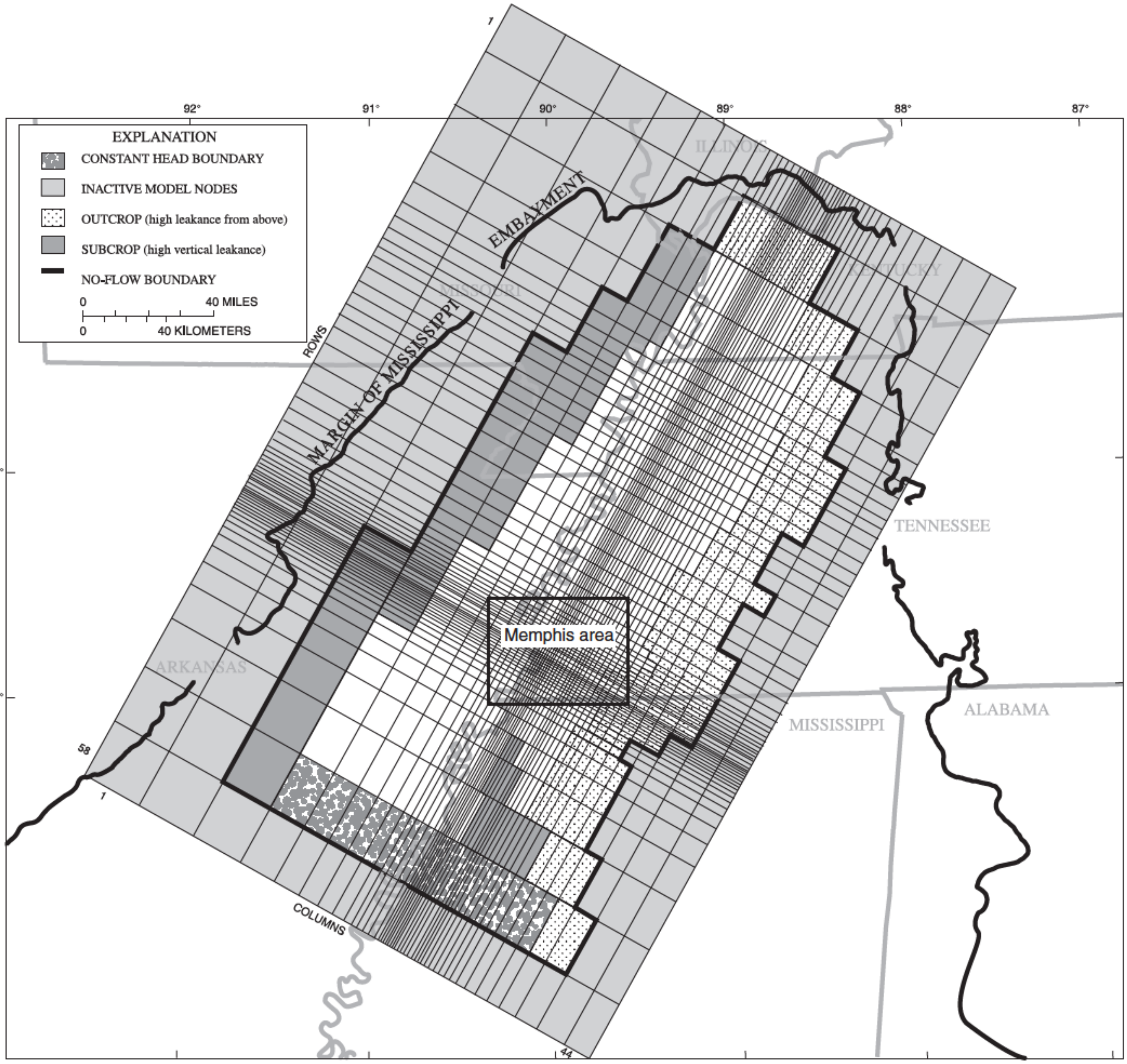
The second and third layers represent the Memphis and Fort Pillow aquifers, respectively. The areal extent of the formations that make up the Memphis and Fort Pillow aquifers are shown in figure 13.

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

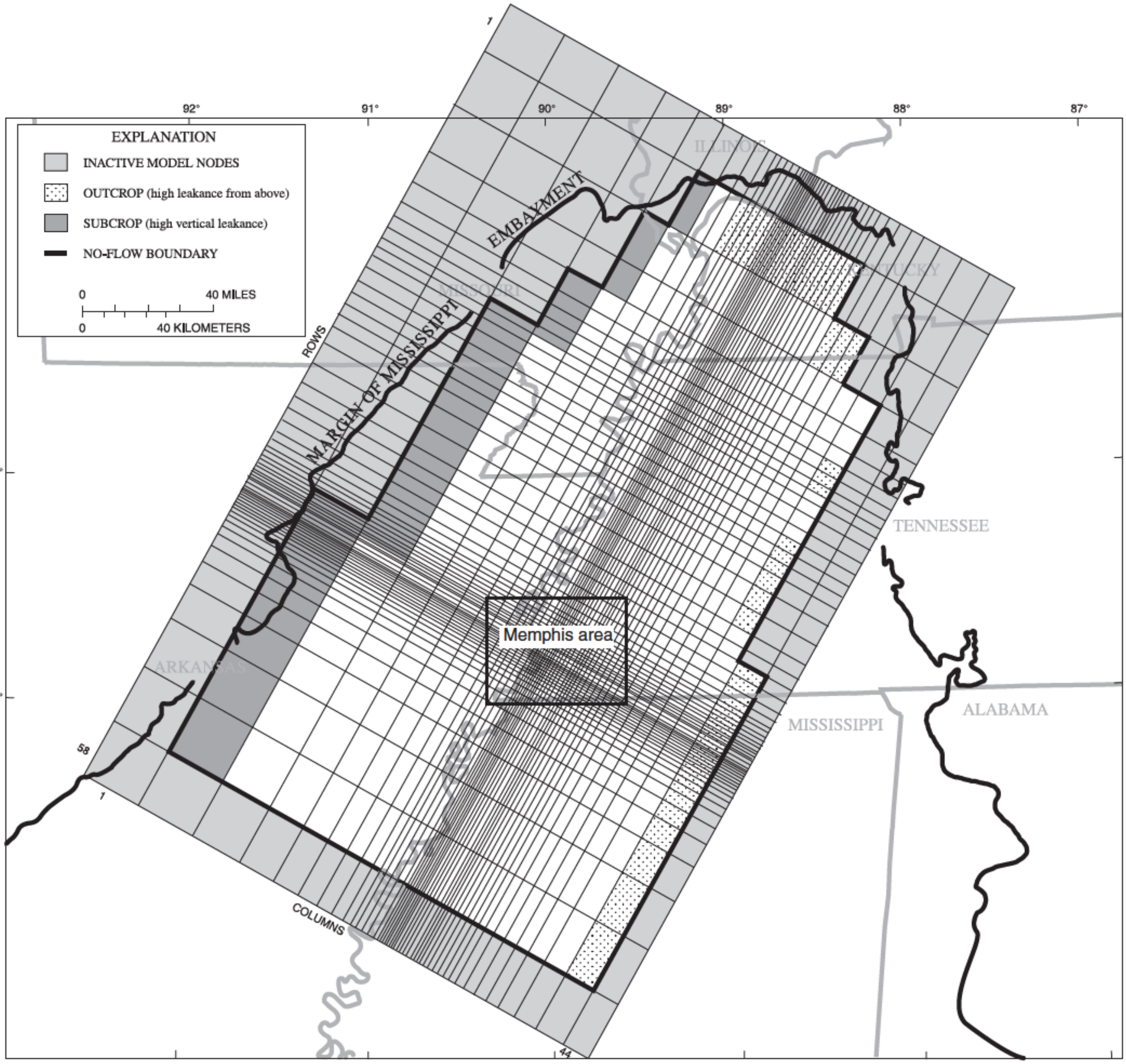
The area simulated by the digital model (fig. 14) is much larger than the Memphis study area. Evaluation of the larger area allows simulation of regional flow in the aquifer using realistic representations of the natural boundaries of the Memphis and Fort Pillow aquifers on the western, northern, and 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^{o} 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.

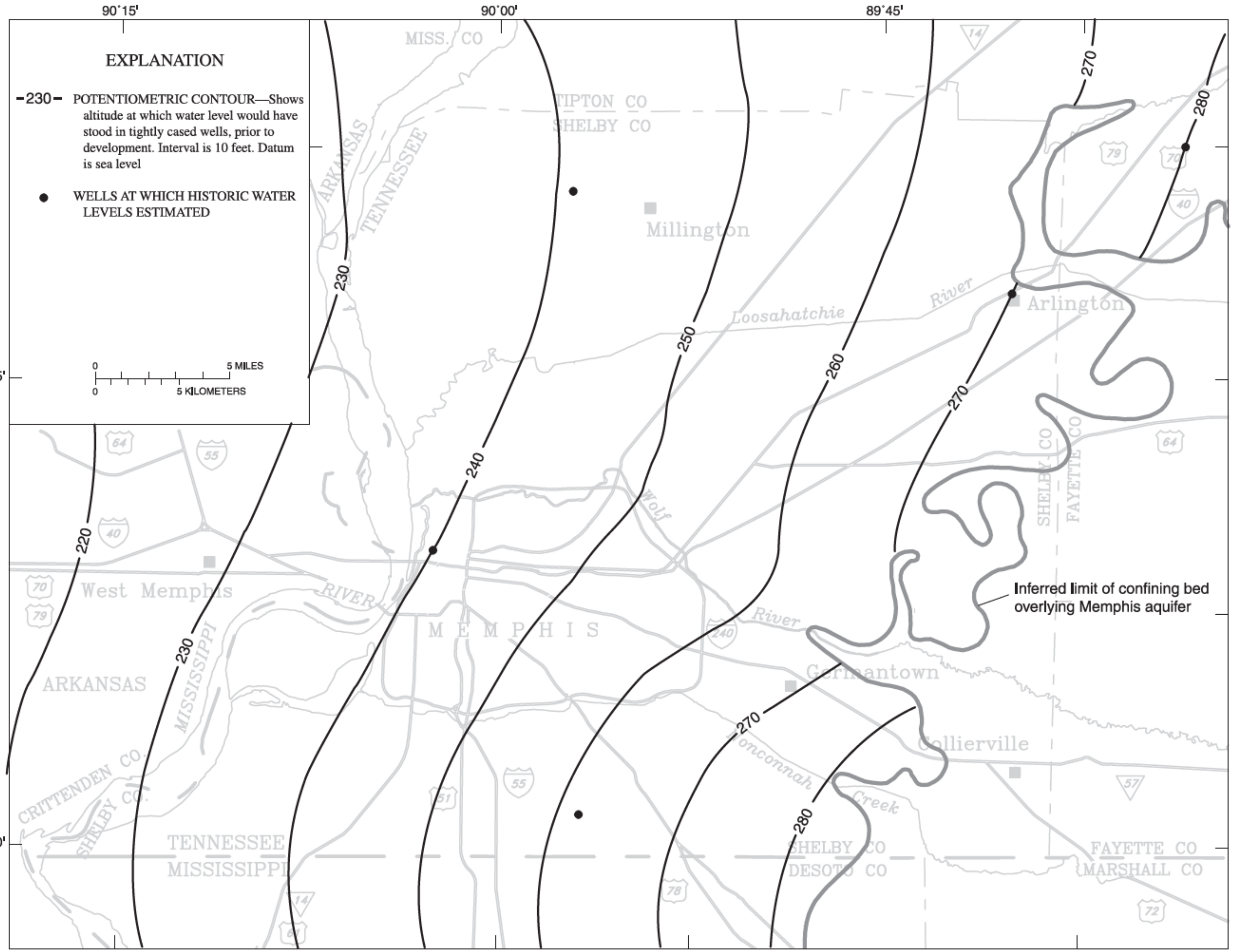
Boundary Conditions

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).

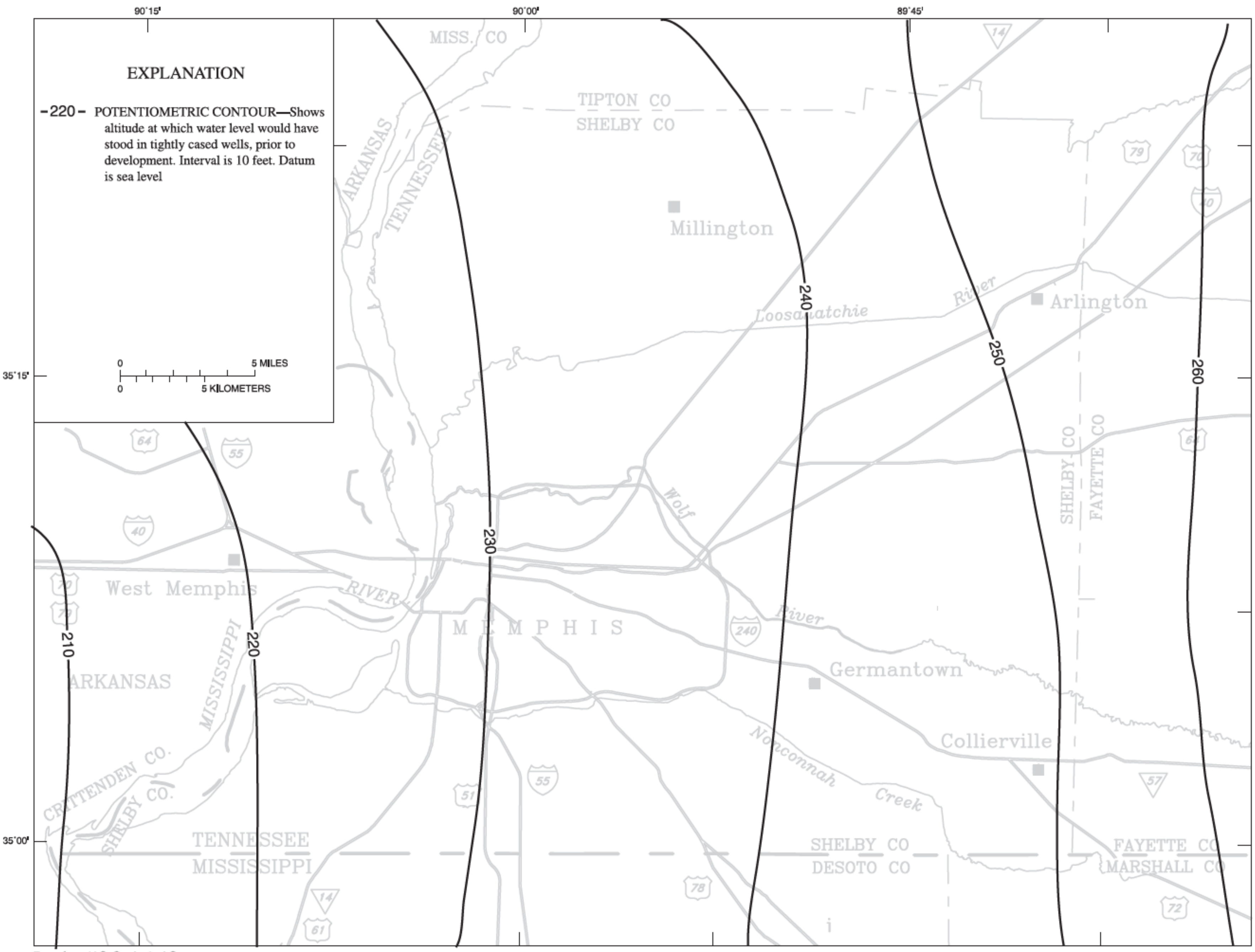
The Midway confining unit underlying the Fort Pillow aquifer is assumed to be impermeable, and its upper surface is specified as a "no-flow" boundary. This assumption is supported by lithologic, chemical, and hydrologic data (Brahana and Mesko, 1988, figs. 8, 10, and 11, and table 2).



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

From J.H. Criner and W.S. Parks, 1976, figure 4

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

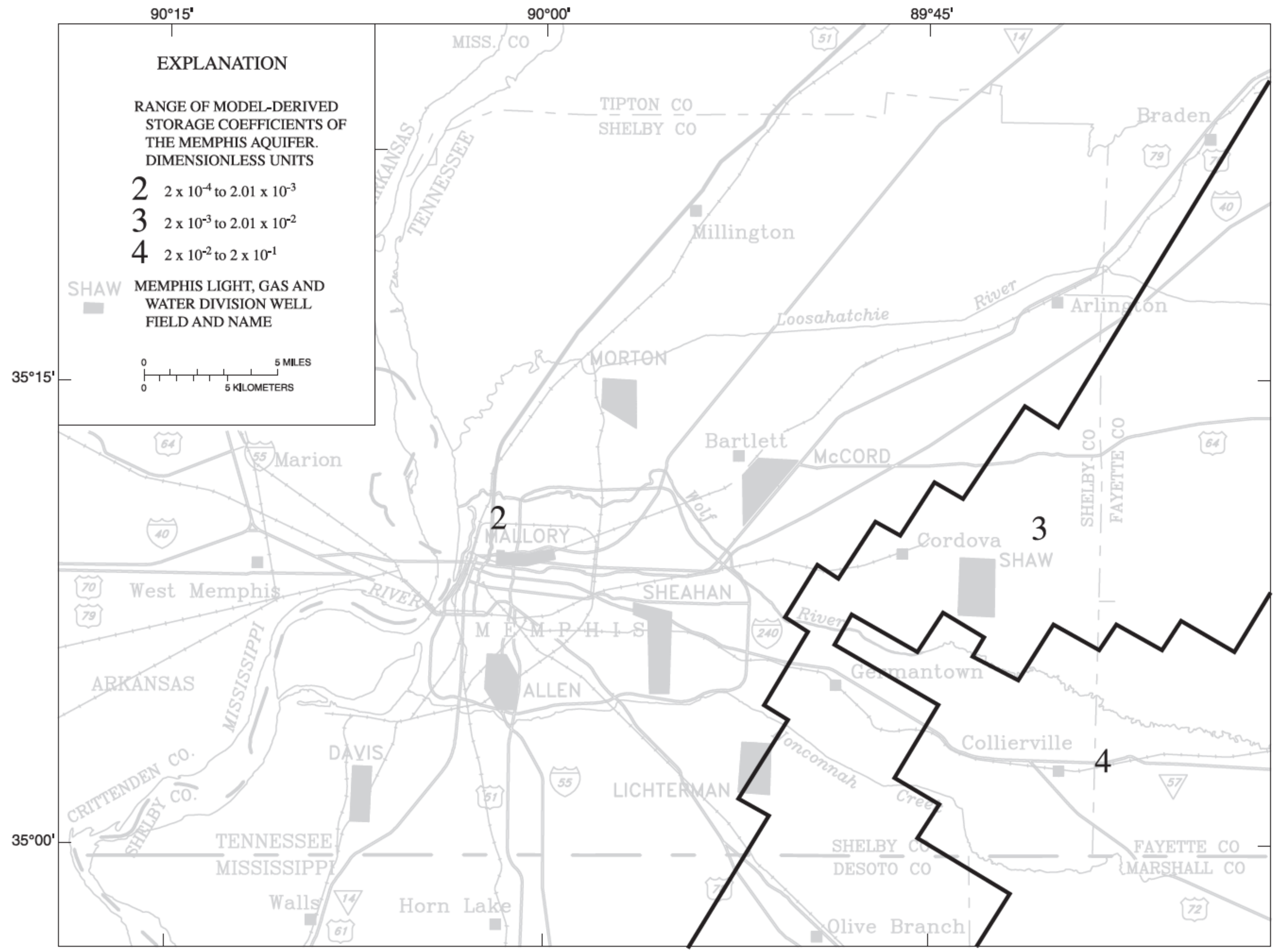
Pumping from the Memphis aquifer began in 1886, and pumping from the Fort Pillow aquifer began in 1924. Withdrawals from these two major aquifers have occurred at varying rates and with a changing areal distribution. Because of variation with time, pumping data were introduced in the model in nine discrete 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.

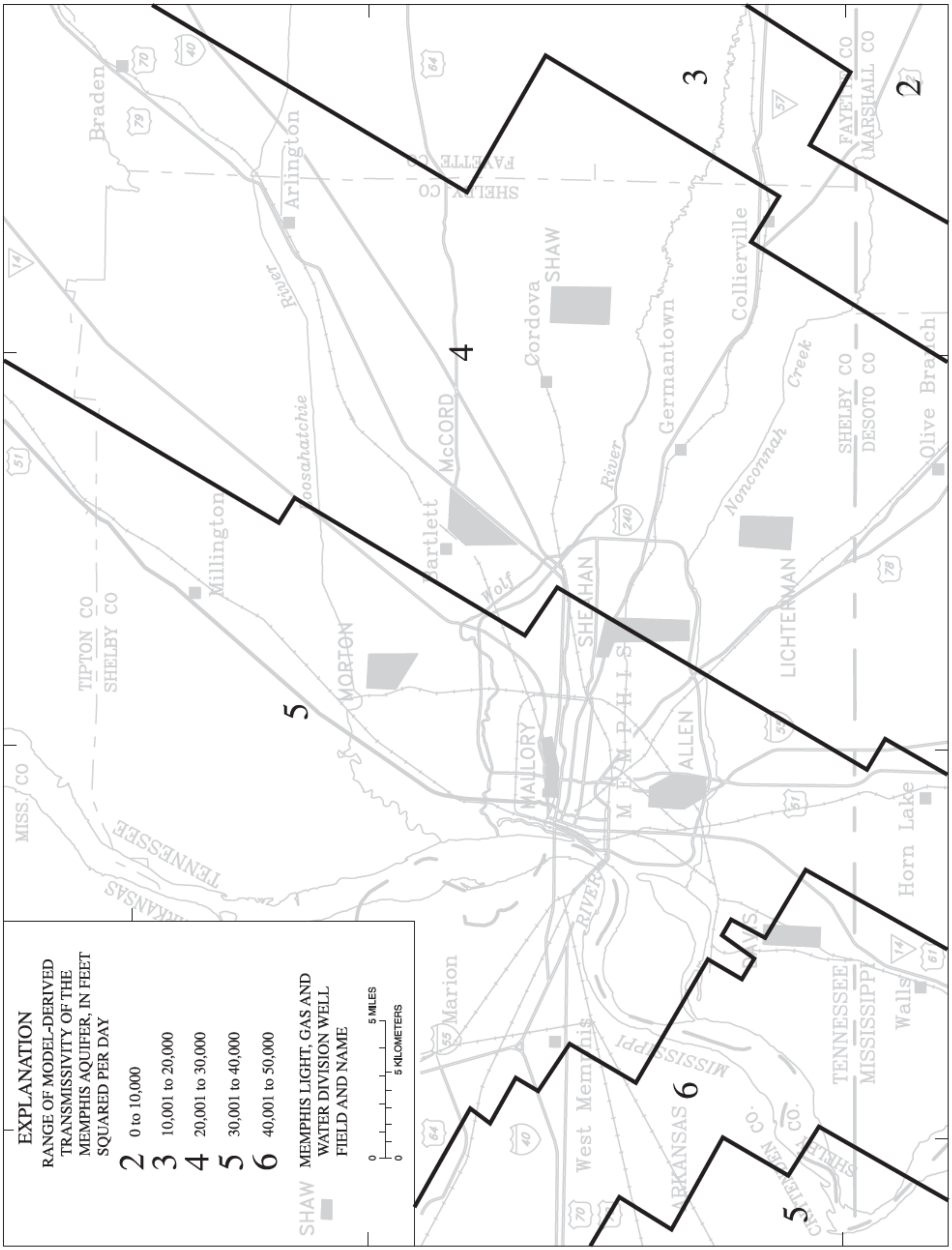
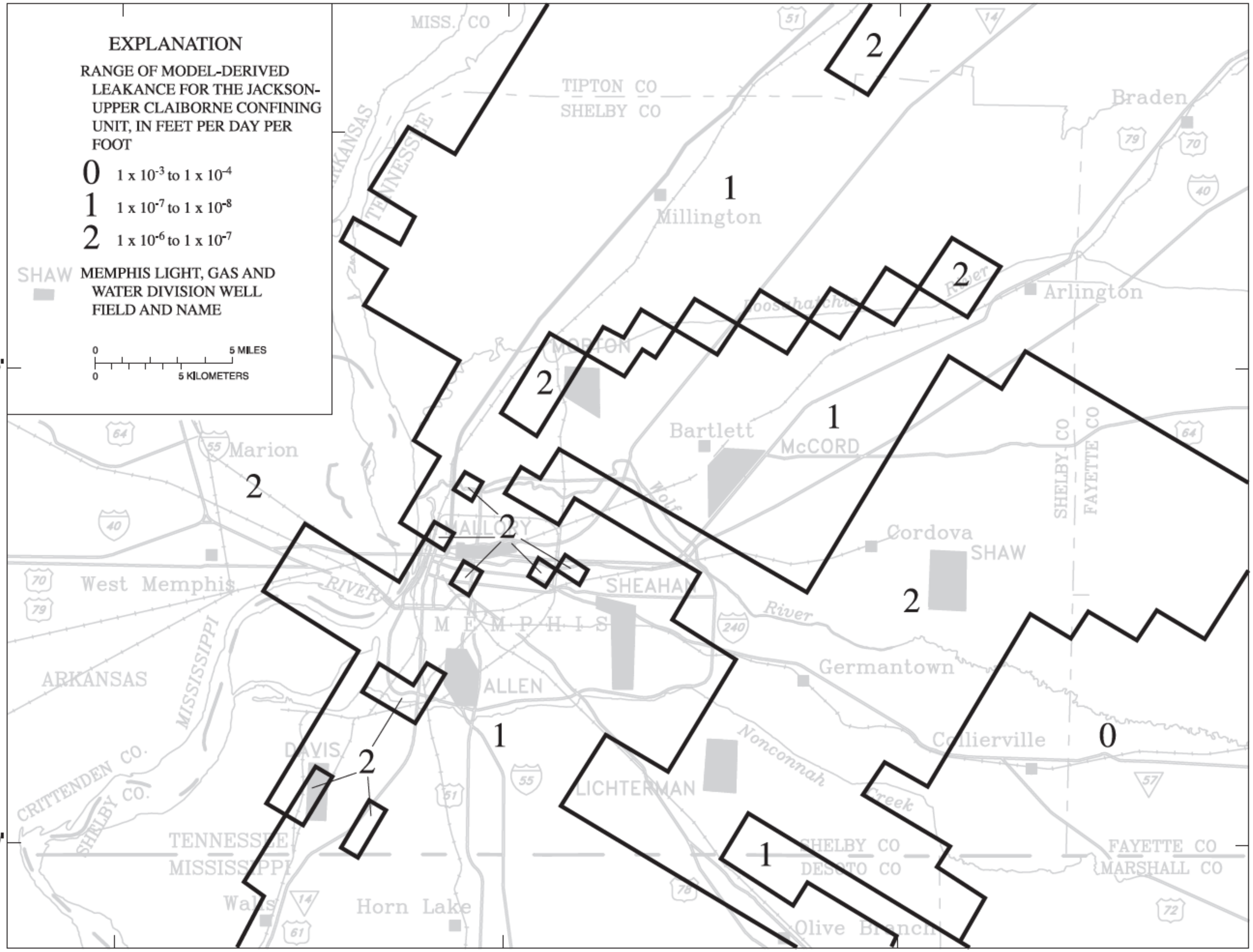
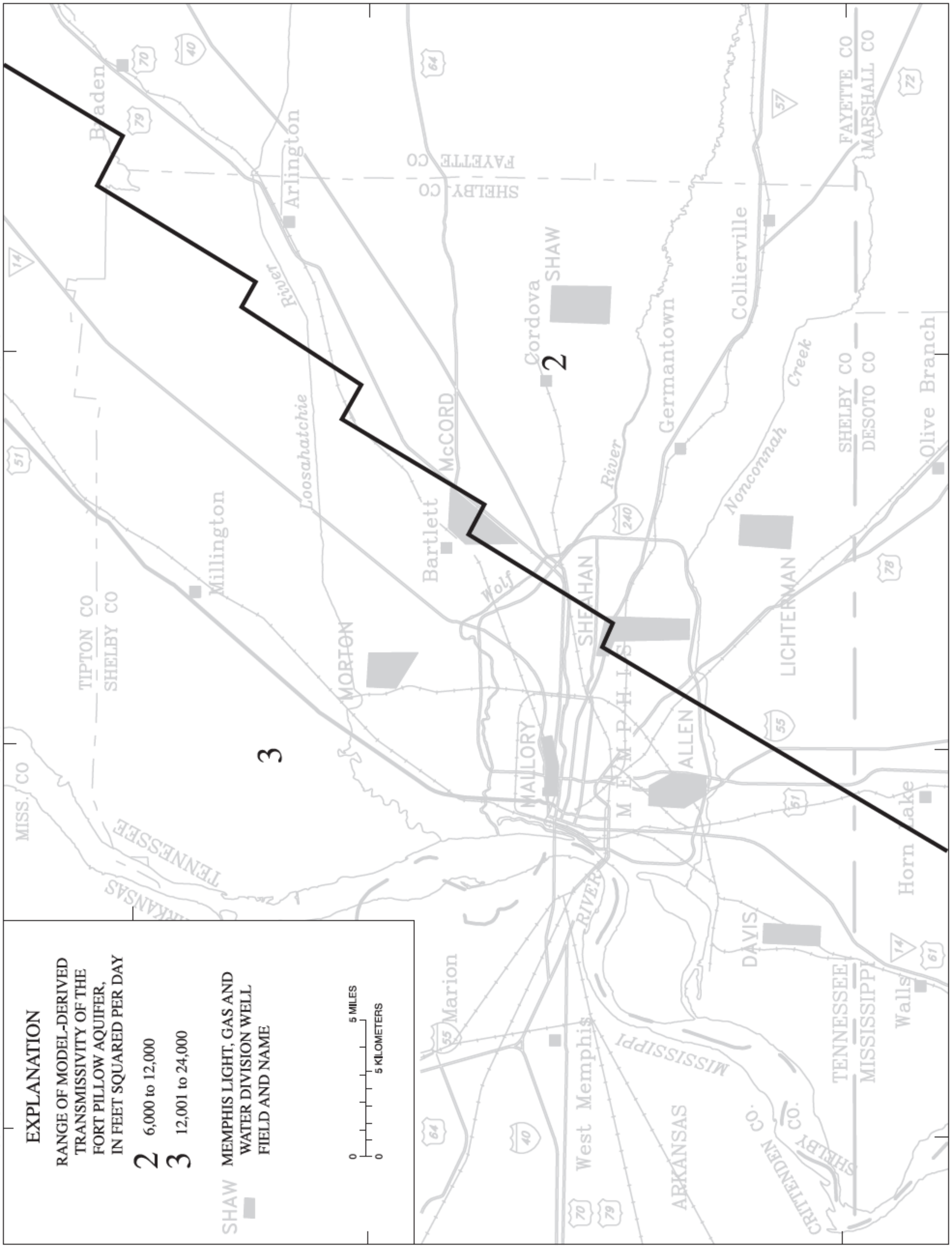


Figure 19. Model-derived transmissivity of the Memphis aquifer.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 20. Model-derived leakance of the Jackson-upper Claiborne confining unit.



Base from U.S. Geological Survey
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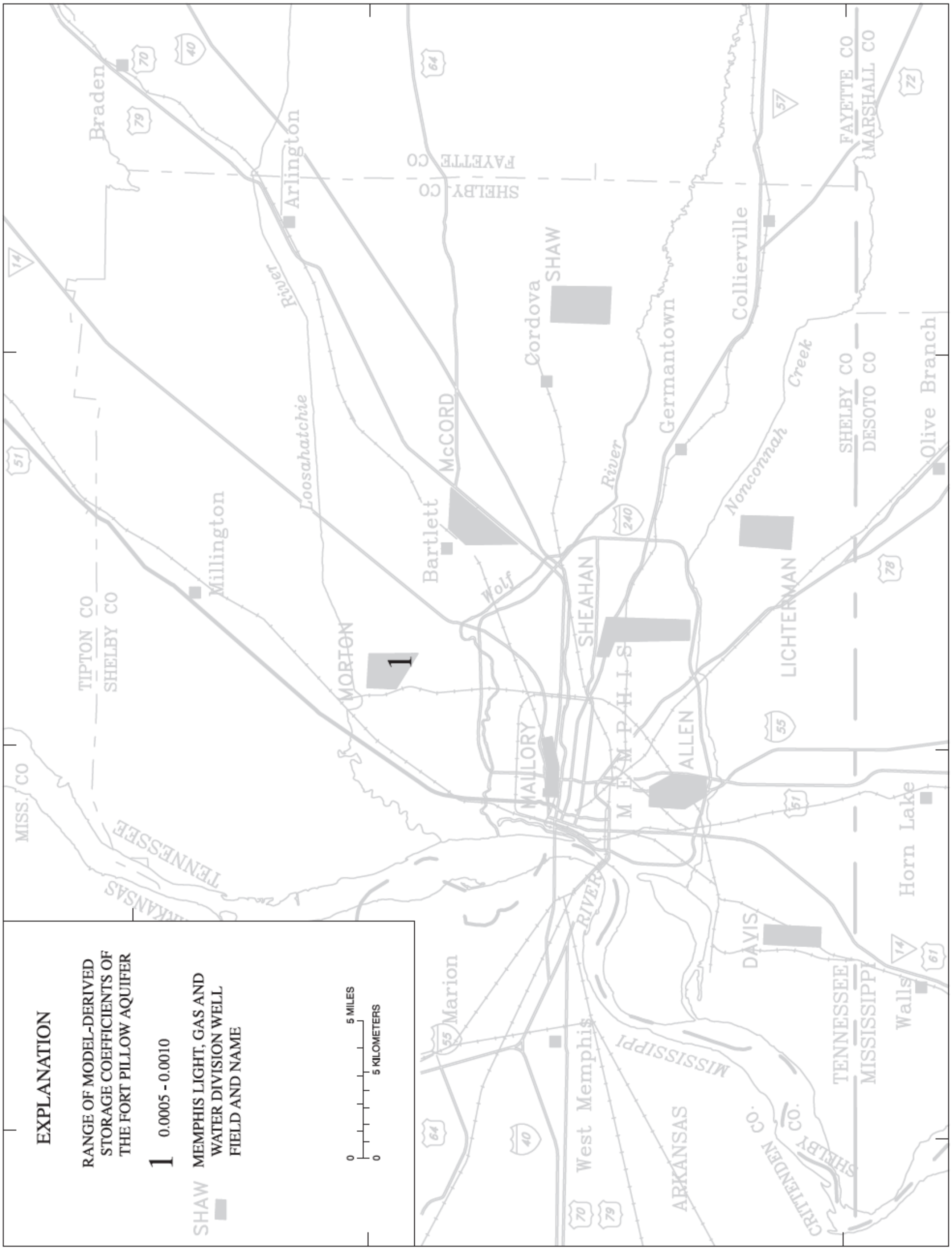
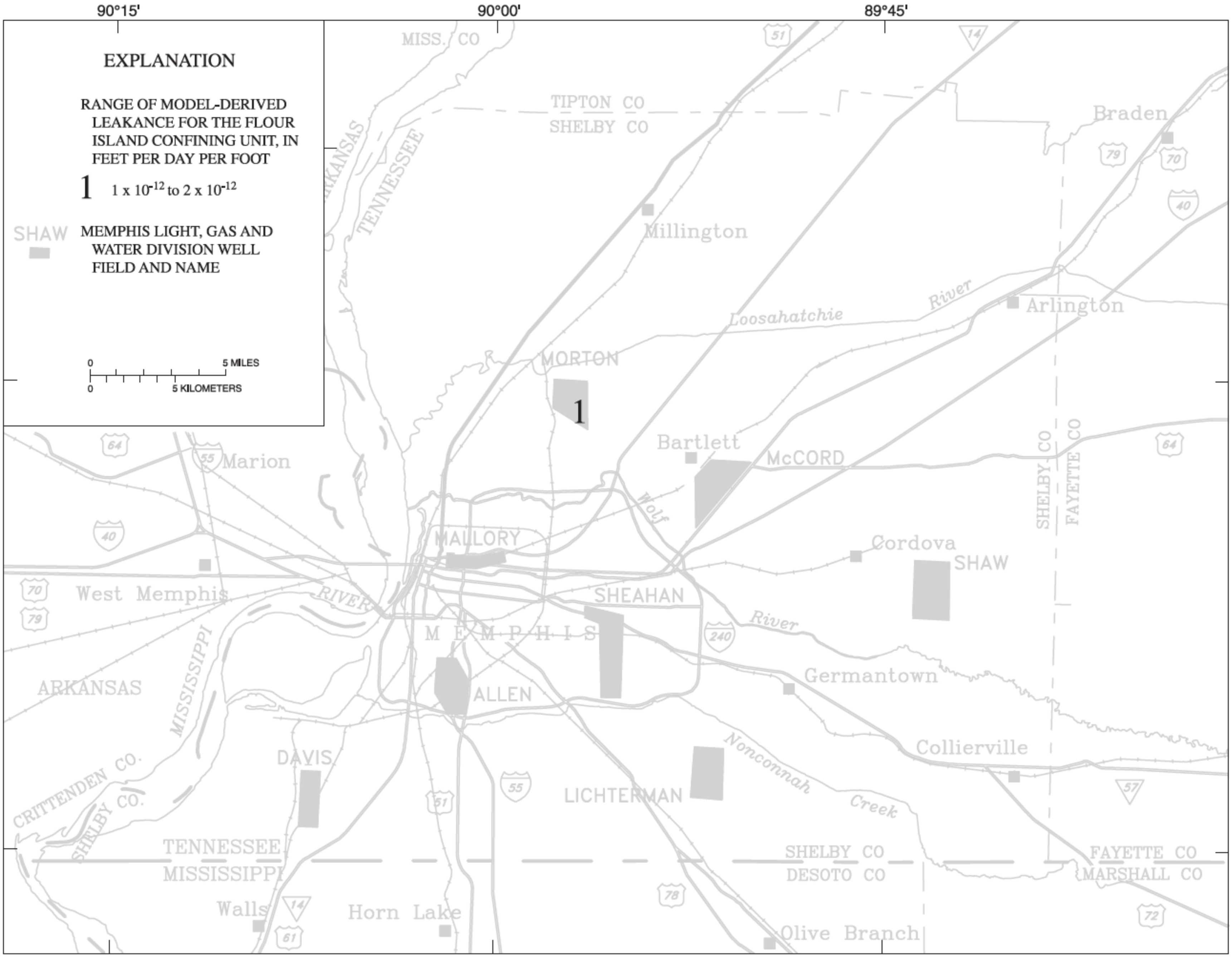
Figure 21. Model-derived transmissivity of the Fort Pillow aquifer.



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
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Figure 23. Model-derived leakance of the Flour Island confining unit.

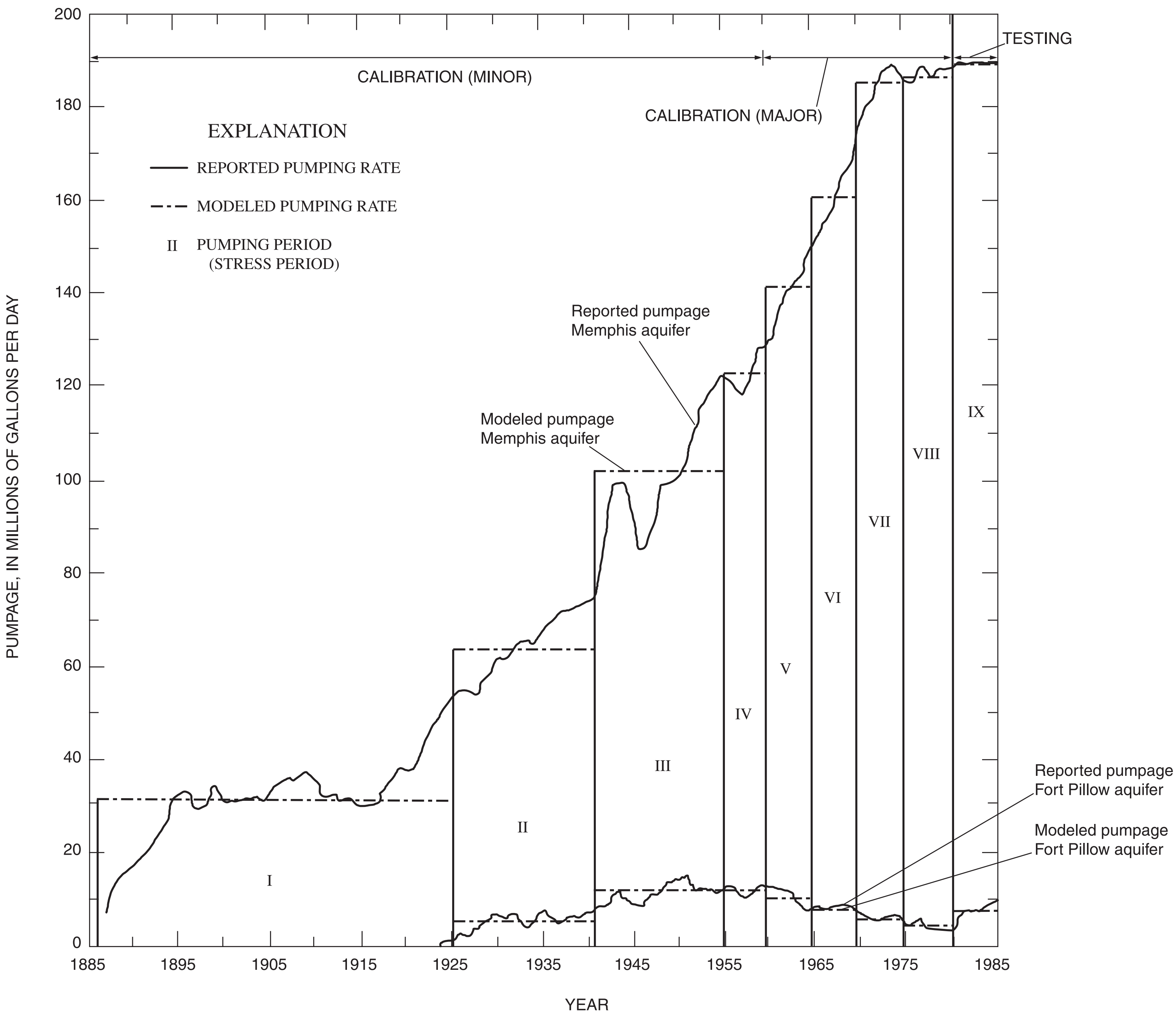


Figure 24. Actual and modeled pumpage from the Memphis aquifer and Fort Pillow aquifer in the Memphis area, 1886-1985.

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.

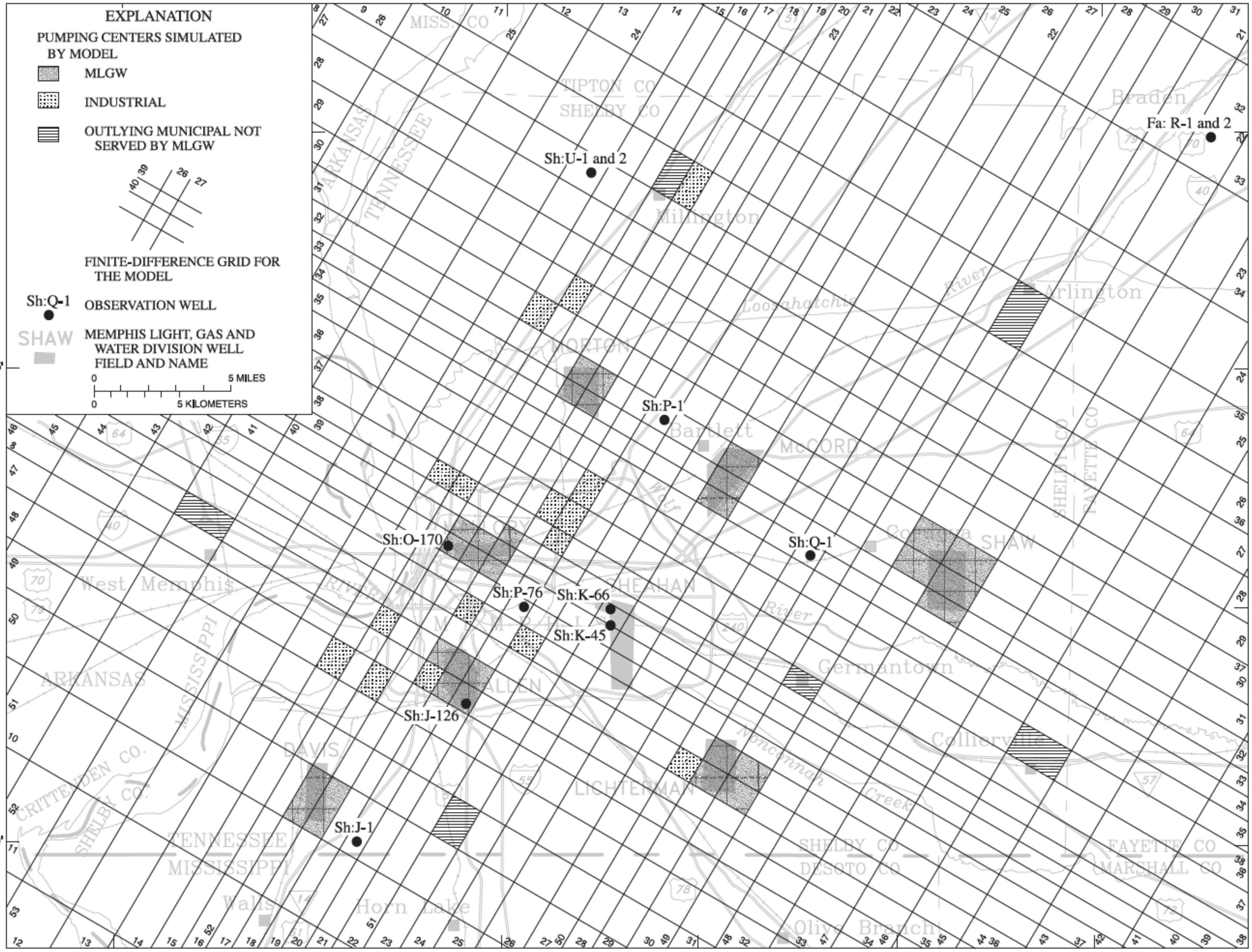
For example, the prepumping (1886) potentiometric surface of the Memphis aquifer is based on four data points (Criner and Parks, 1976), all of which were extrapolated (fig. 16). Data points for the Fort Pillow aquifer in the Memphis area likewise are lacking for this period. Because of this data, no 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.

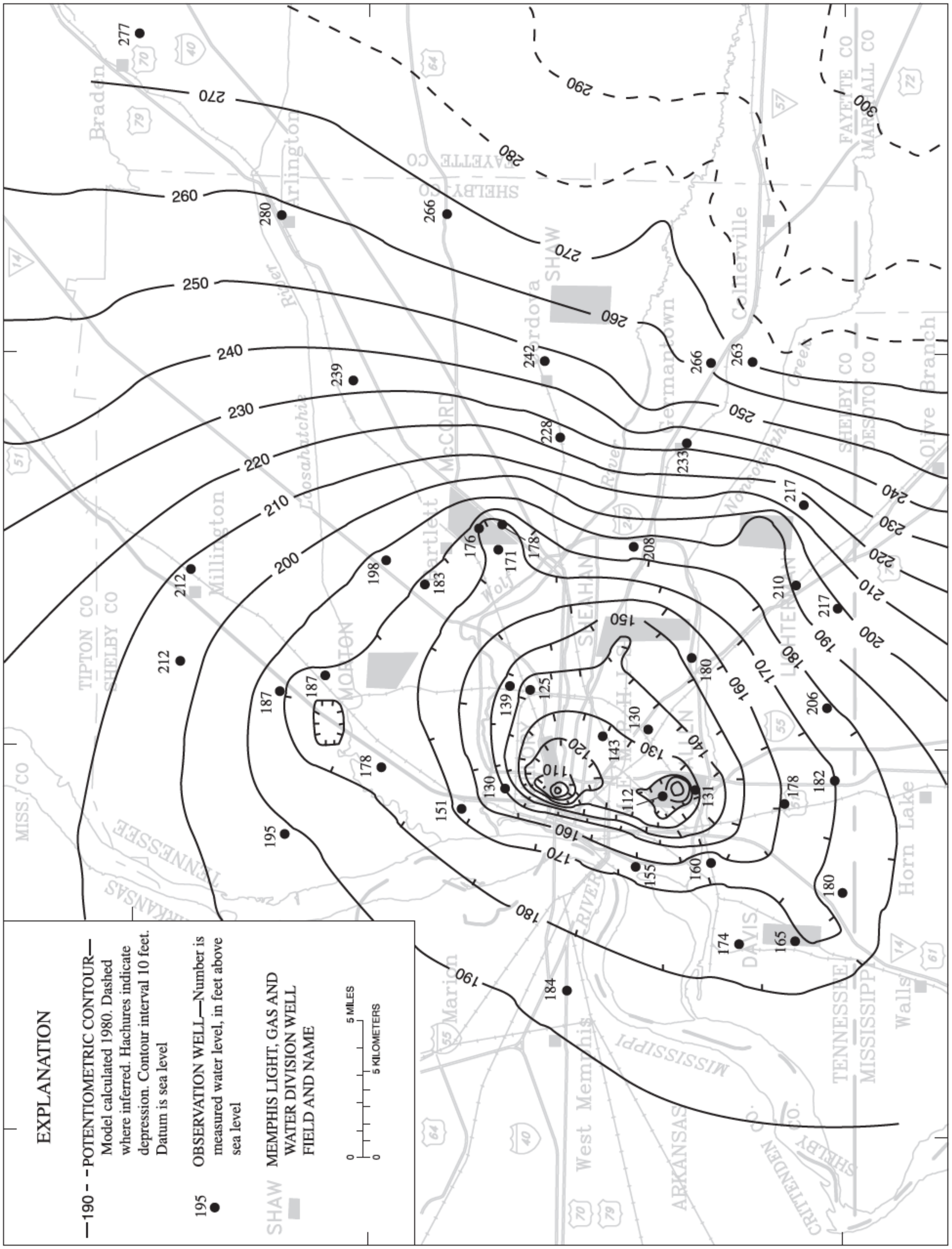
Although the overall simulation of heads in the Memphis aquifer is considered to be good, heads matched poorly in one subarea lying near Nonconnah Creek and the Tennessee-Mississippi border in south Memphis (figs. 26 and 7). Many alternative representations of transmissivity, leakage, and recharge were 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.

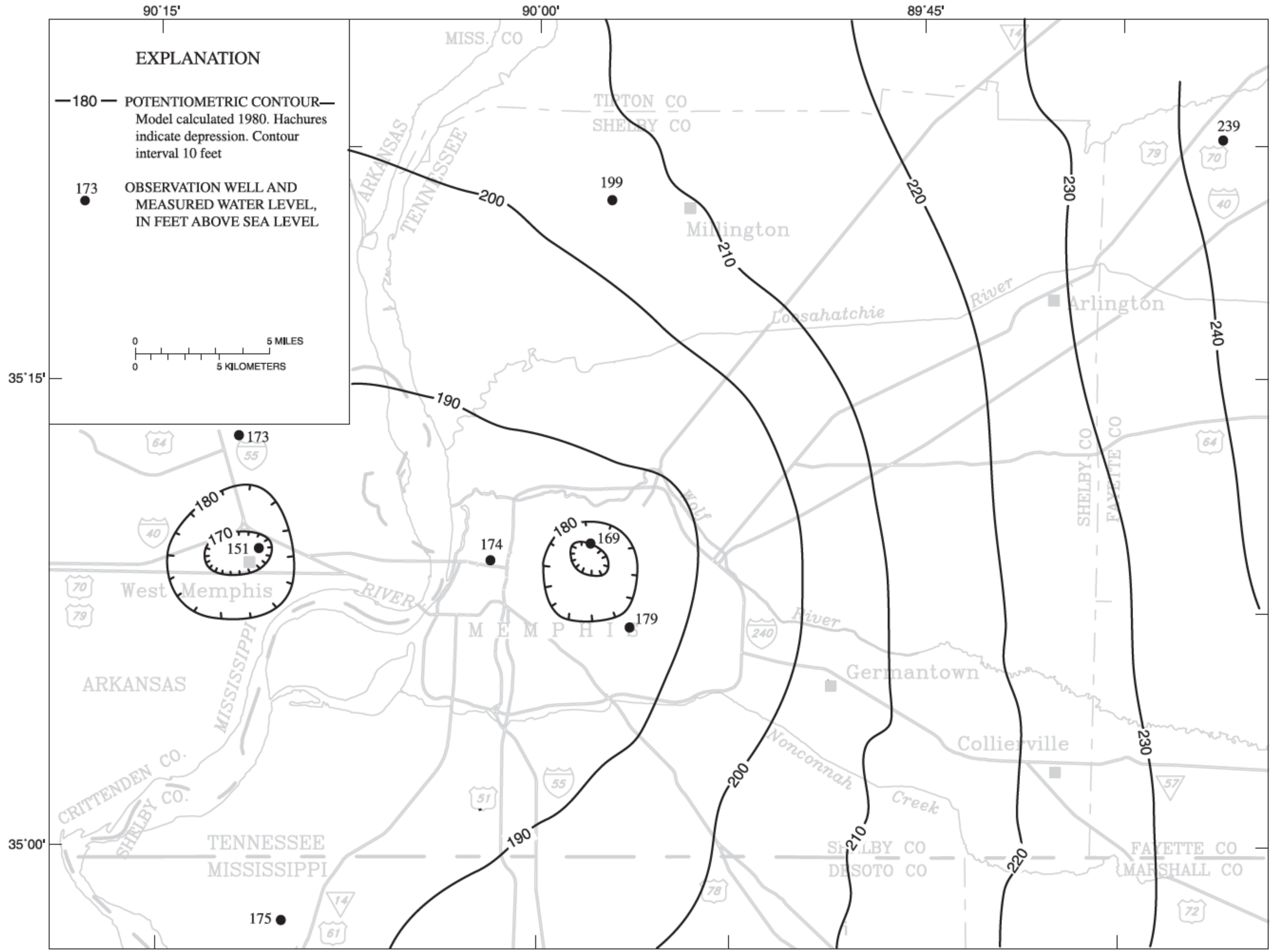
Model Testing

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.



Base from U.S. Geological Survey
1:24,000 and Mississippi River
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Figure 27. Comparison of observed water levels and model-computed potentiometric surface of the Fort Pillow aquifer, Memphis area, 1980.

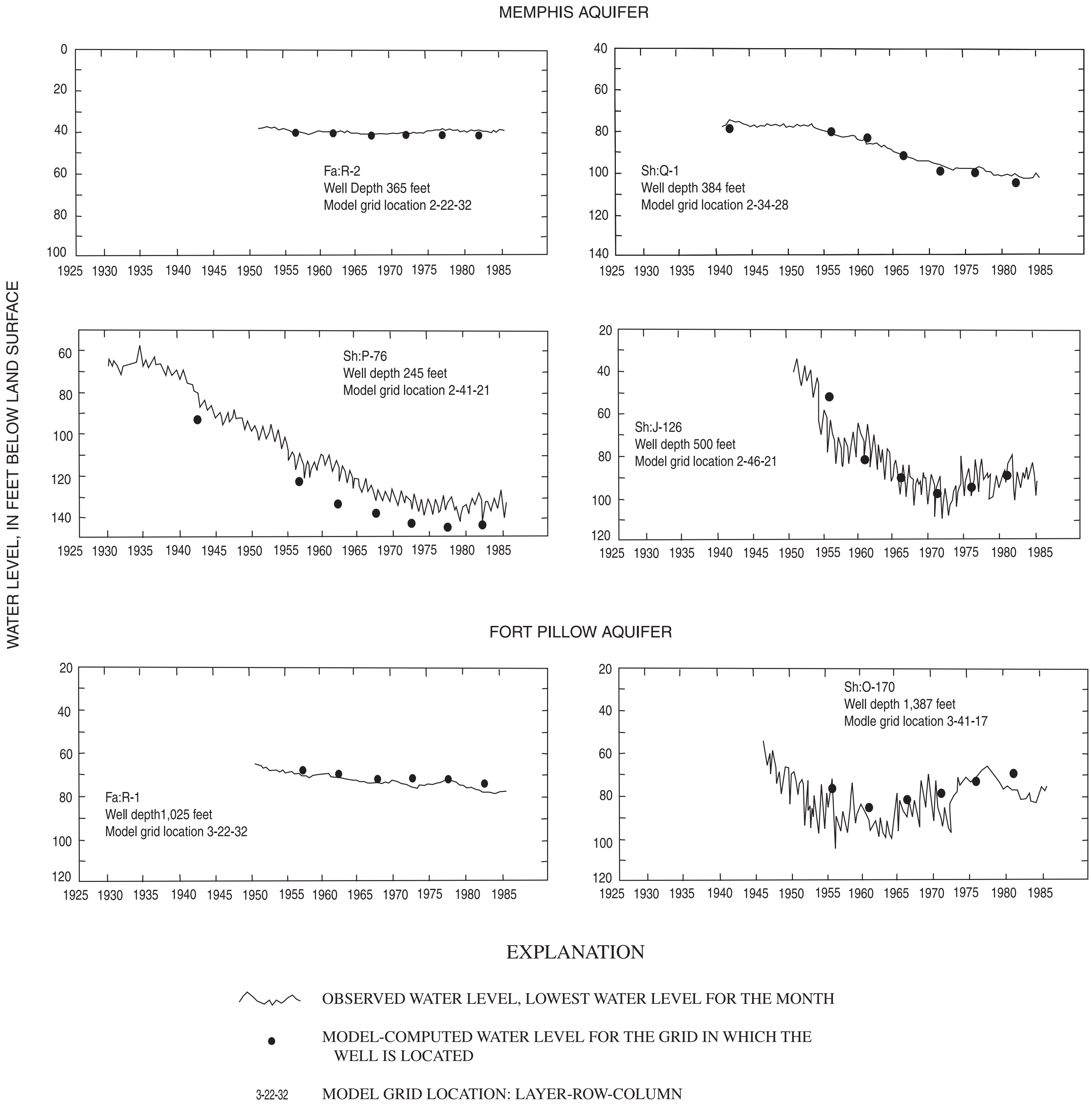


Figure 28. Selected hydrographs of observed and model-computed water levels for wells in the Memphis and Fort Pillow aquifers in the Memphis area.

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

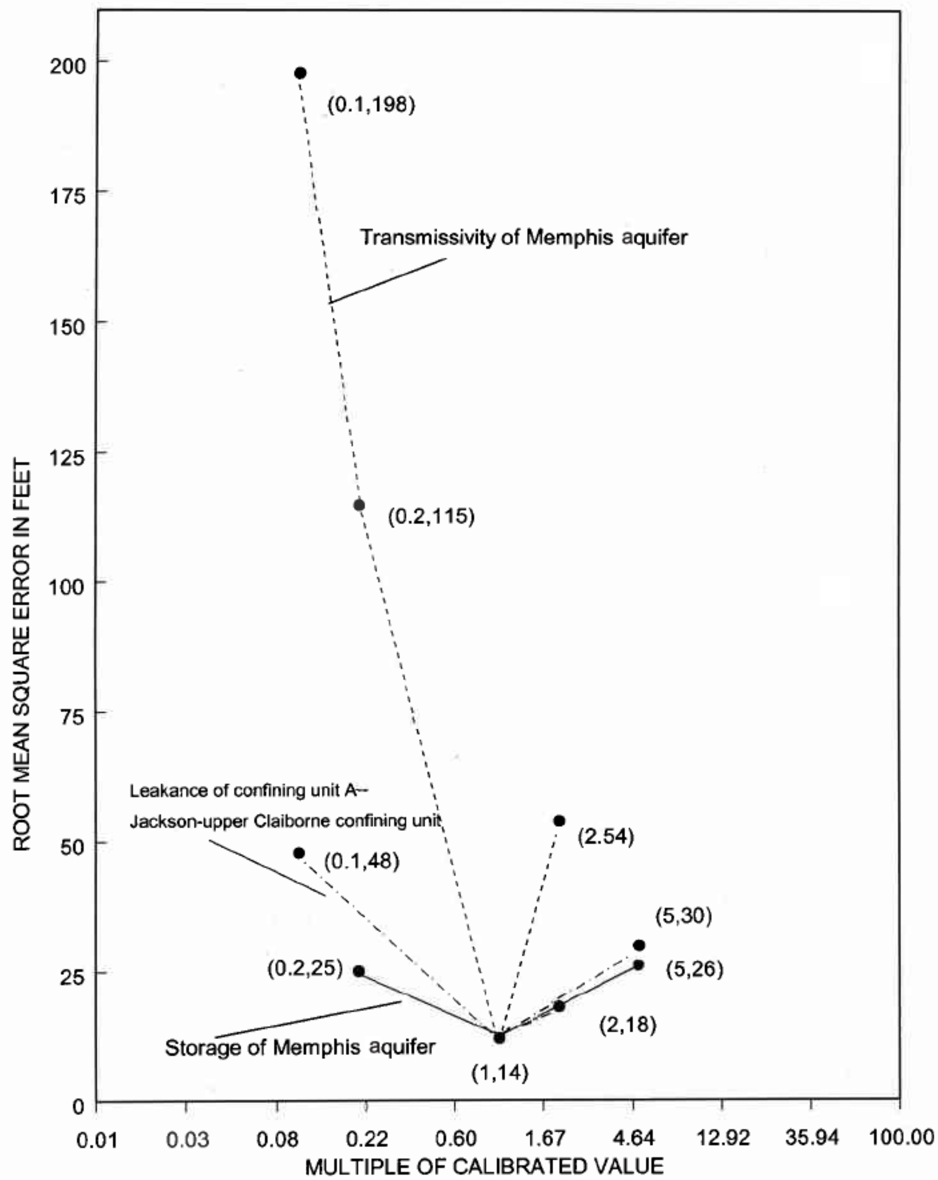


Figure 29. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Memphis aquifer.

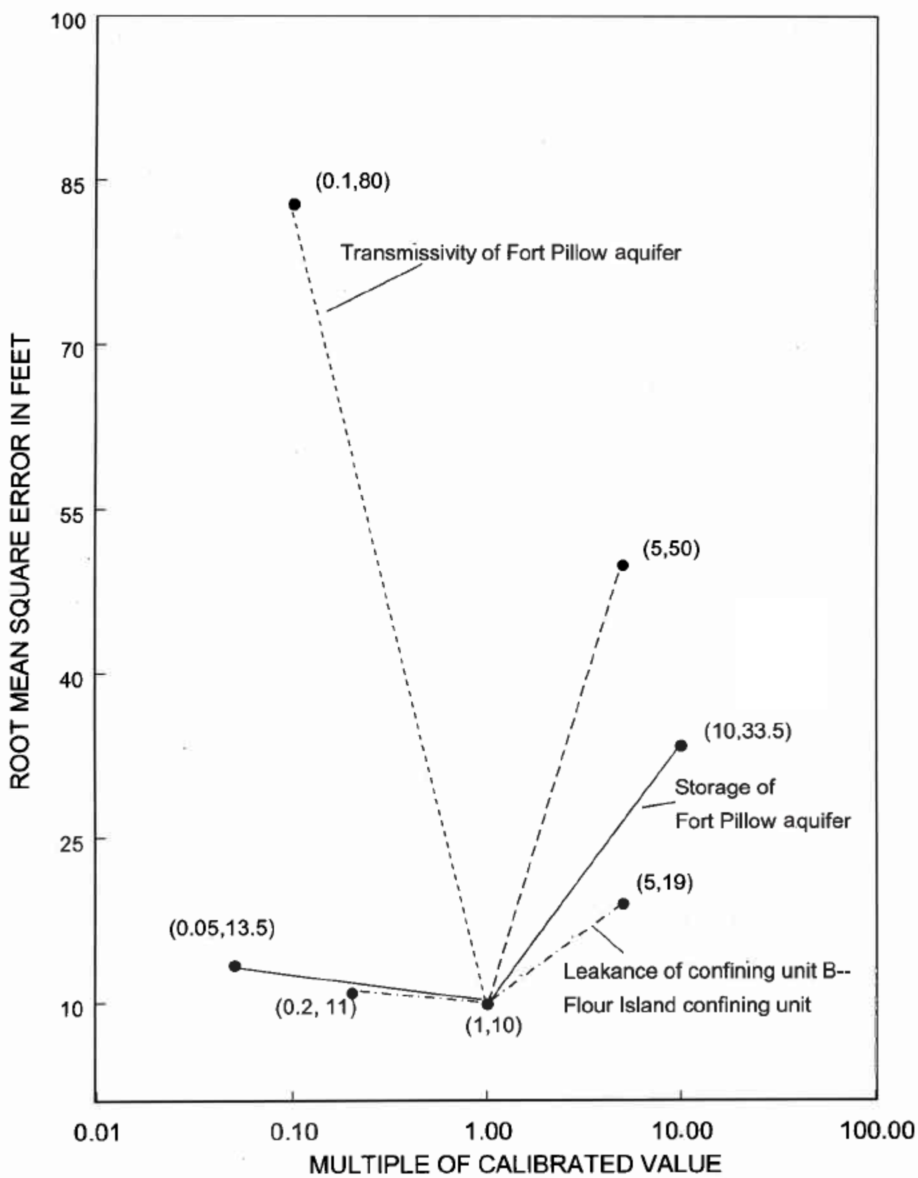


Figure 30. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Fort Pillow aquifer.

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).

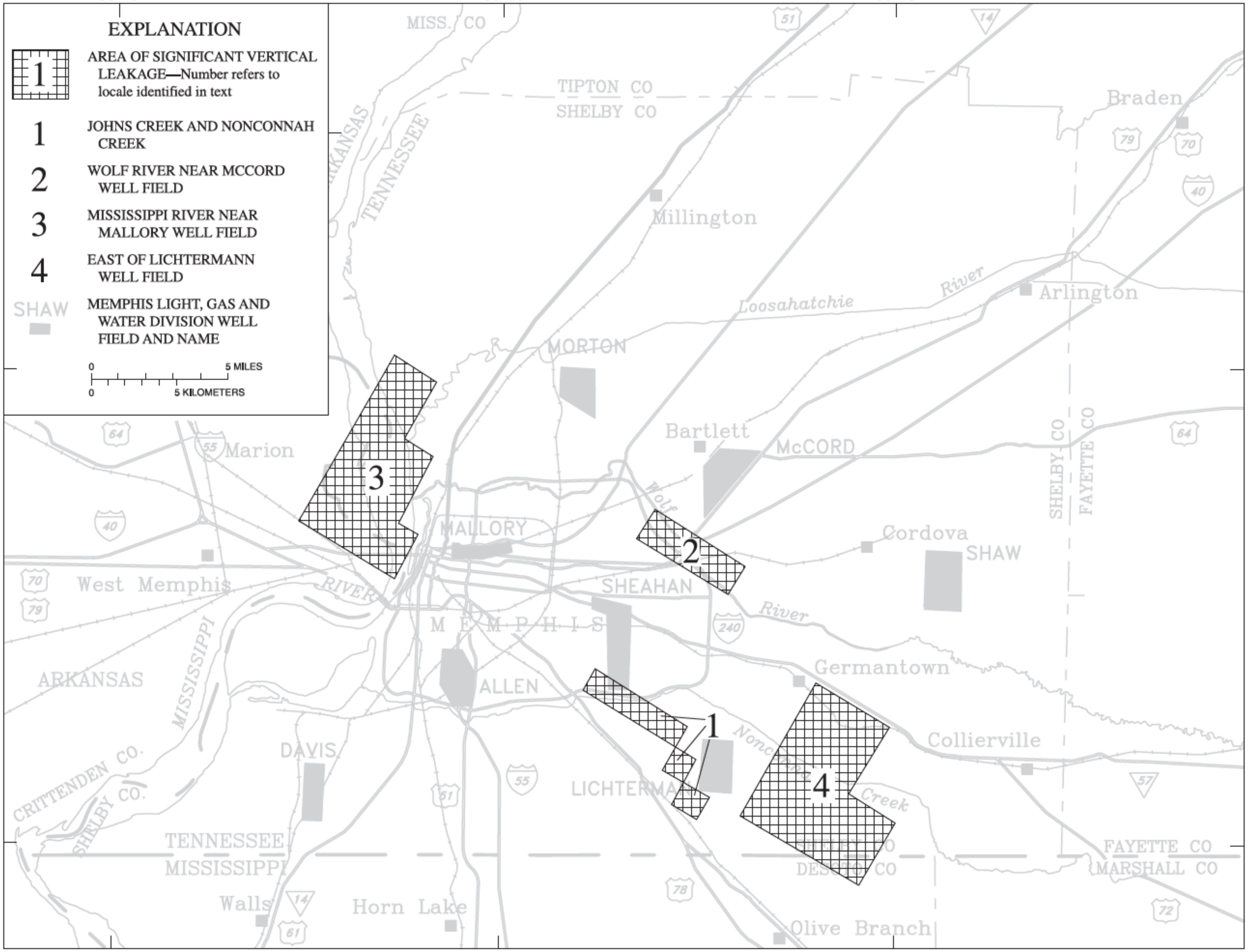
Model Limitations

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 cublc 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.

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.

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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, 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 <u>intrastate</u> natural resource under natural conditions, especially when one considers the component of time that Mr. Larson and Dr. Waldron elect to disregard.

<u>V. Scope of Addendum #1</u>

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.

<u>VI. Summary of My Evaluation of the 2015 Report by Waldron and Larsen</u>

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)

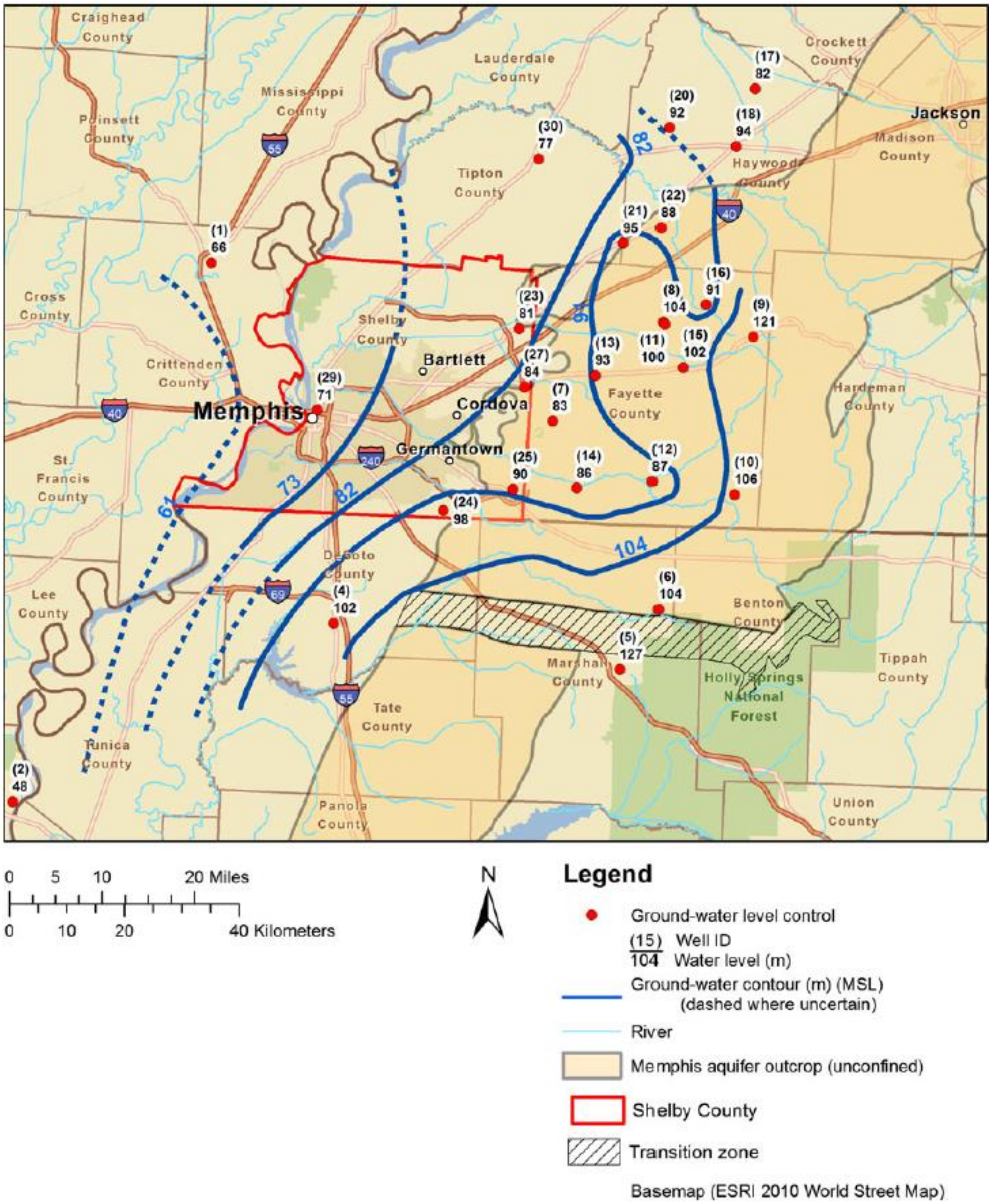


Figure 2: Criner and Parks (1976) Graph of Groundwater Withdrawals from the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) between 1886 and 1975.

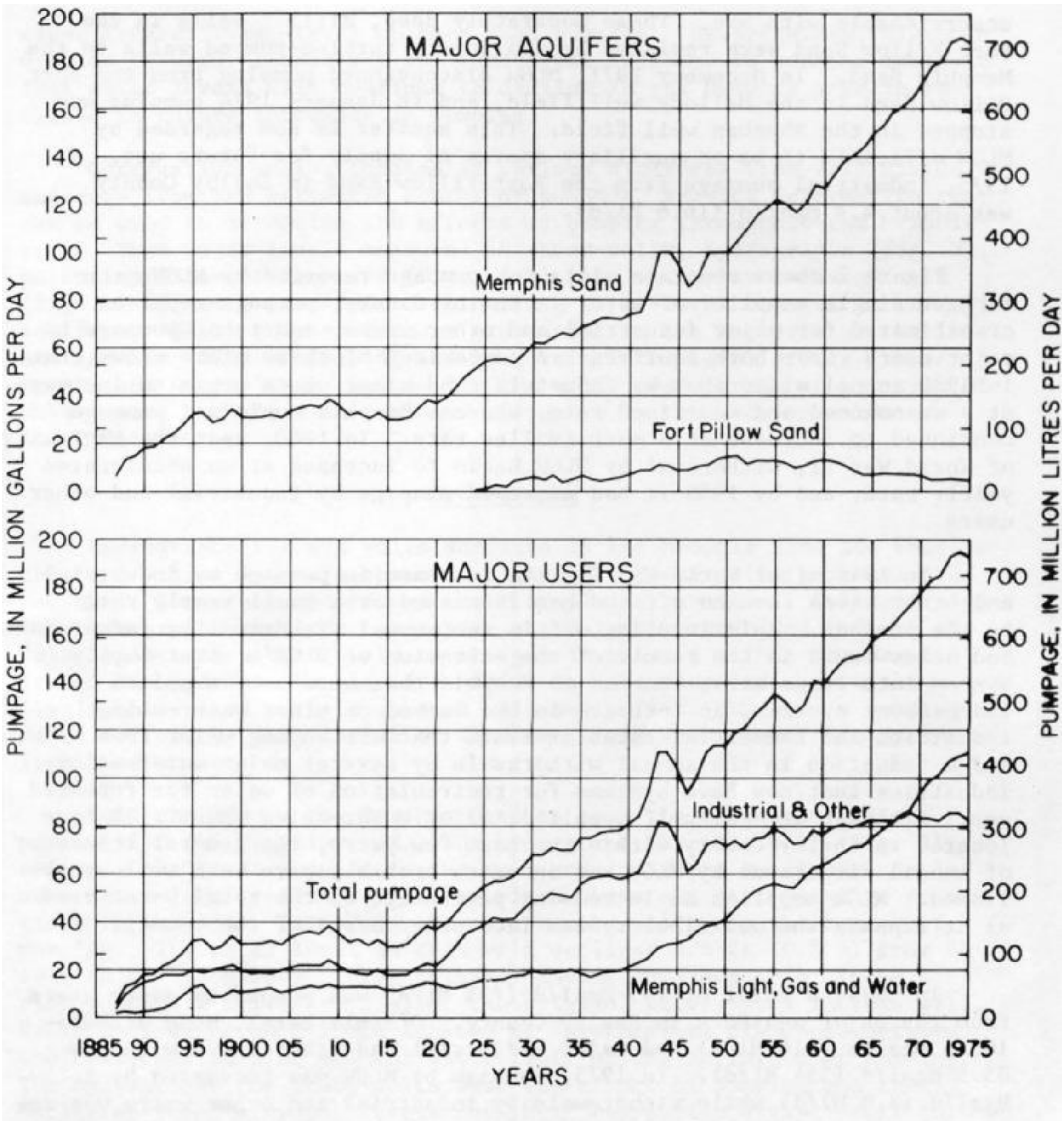


Figure 2.--Pumping rates from major aquifers by major users in Shelby County, Tennessee, 1887-1975.

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, **nearly flat**, 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 **not** include pumpage from a few thousand suburban and rural wells **nor** any wells in the Arkansas and Mississippi parts of the Memphis area*" but that 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*" (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 <u>hydraulically-confined</u> 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.

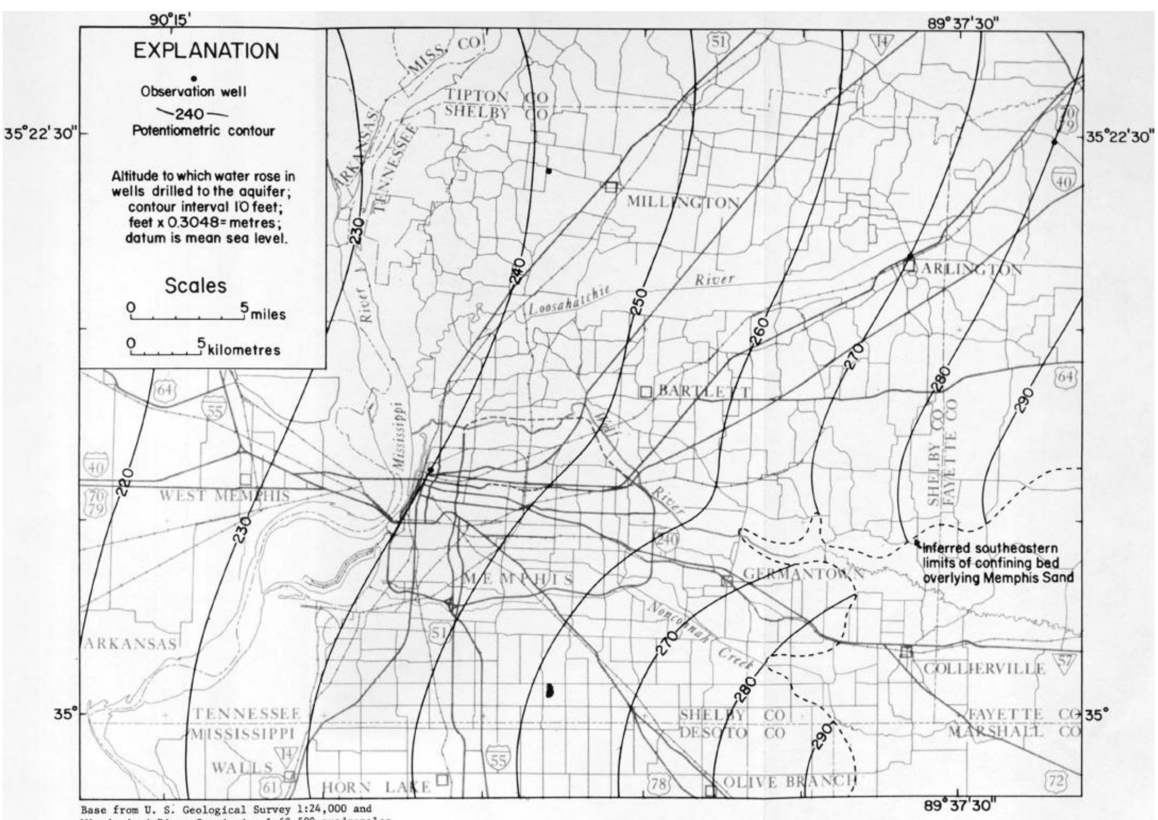


Figure 4: Reed (1972) Equipotential Map for Confined Portions of the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) in 1886. (Note: the image was converted to black-and-white and the contrast was enhanced to facilitate readability.)

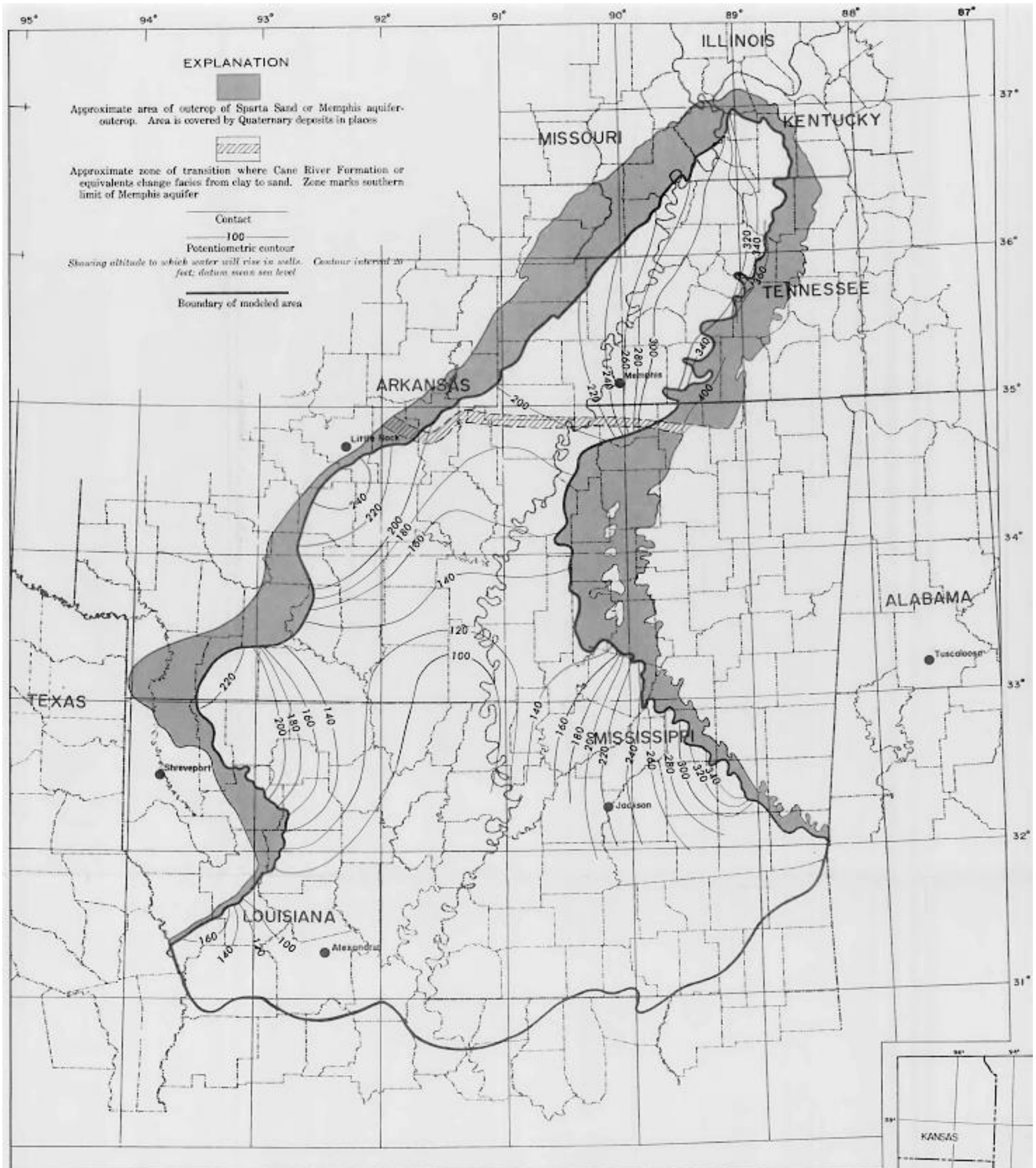
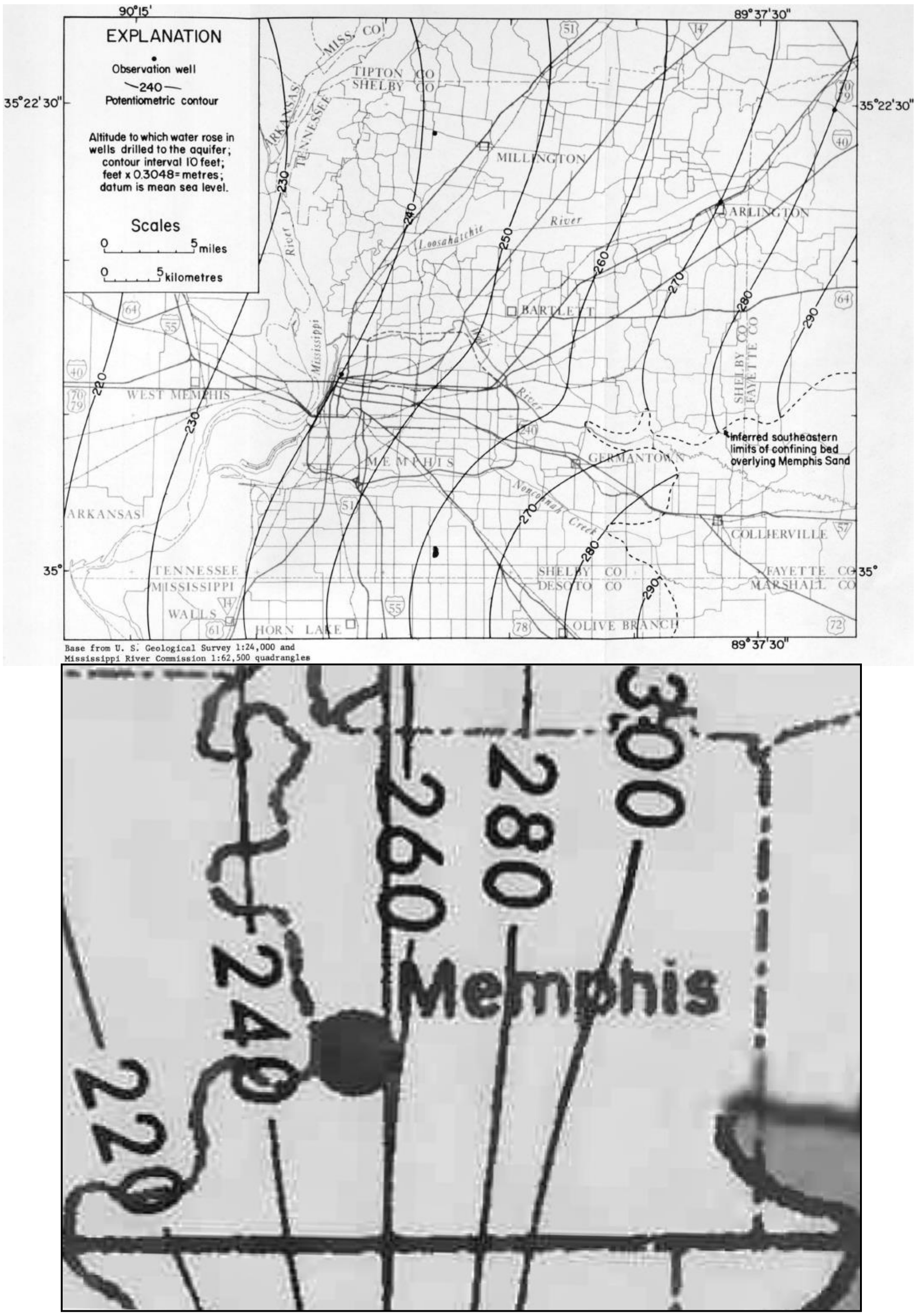


FIGURE 2.—Potentiometric surface of the Sparta Sand and Memphis aquifer in 1886.

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 only 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 cannot 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.

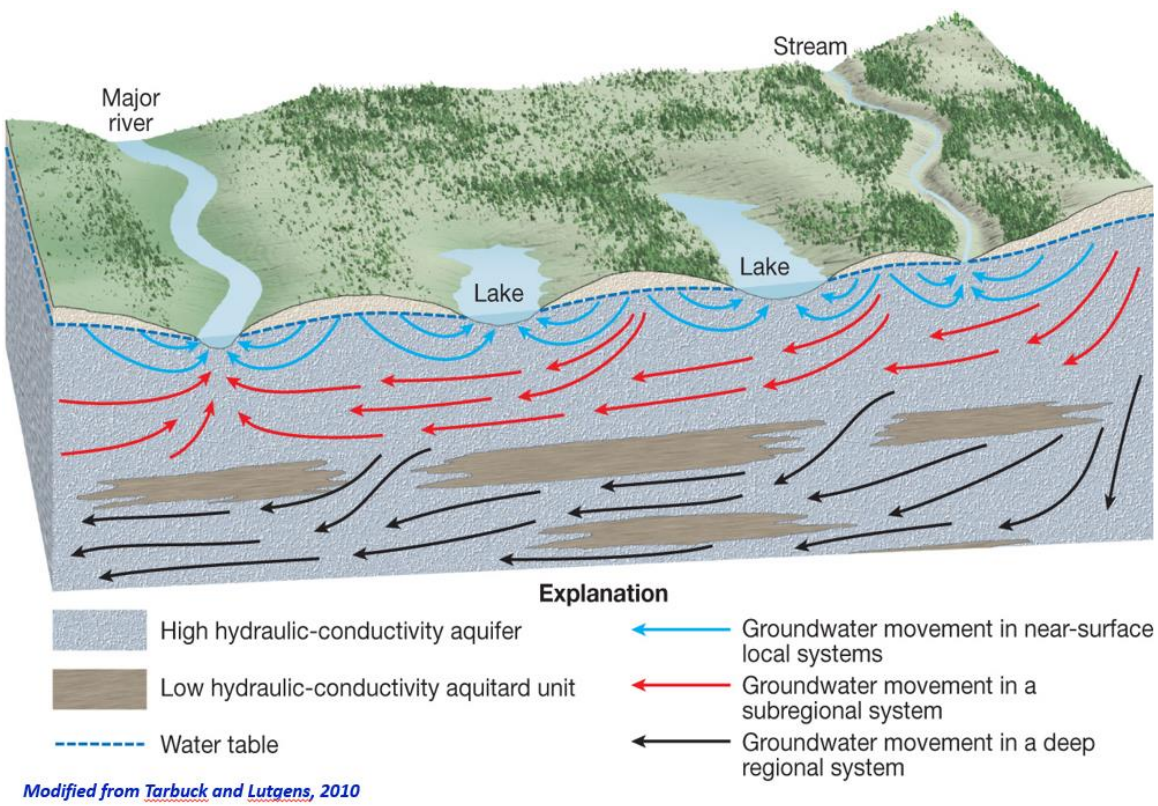
1. Many "wells" cited W&L 2015 *are <u>not</u> actually wells.* Instead, those "wells" are generic observations or claims about zones that were being targeted in particular areas for the potential drilling of water-supply wells in the late 1800s or very early 1900s. In the following discussion, I will 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 <u>not</u> have been considered for pre-pumping equipotential contouring. Historic data for Well #12 does <u>not</u> 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, <u>not</u> 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 <u>no</u> 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 <u>most</u> of the water levels presented in Figure 4 of W&L 2015 are <u>not</u> scientifically supportable. At many locations, Waldron and Larsen's map suggests pre-development equipotential surface elevations that are actually <u>lower</u> 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) <u>higher</u> 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) <u>higher</u> 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 <u>not</u> 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 if the groundwater is flowing under the pre-development 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.

<u>VIII. Summary of My Evaluation of the Expert Report by Brian Waldron</u>

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). <u>Groundwater</u> is the issue at the heart of this legal matter, but the emphasis by Waldron is on the Middle Clairborne <u>aquifer</u>, 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 <u>hydrologic</u> 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 <u>not</u> 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 <u>0.3 miles</u>! 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 <u>all</u> 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 <u>nothing</u> 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 <u>time</u>, 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 pre-development 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.

IX. Concluding Opinions

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 not exist to provide management directives or options for use of the groundwater resources by individual states. I find no consistent evidence in any USGS reports or statements that the agency has defined any 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 no 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 interstate groundwater resource, 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 ***NOT*** 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 .

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

think I called or we updated those by calling, by taking the individual sources, because we needed to apportion those within the individual grid per se within the blocks of the model.
Again, that's a component I don't remember exactly, because it doesn't come from -- most of the metropolitan area I could get from one or two sources.
Q. I'm going to hand you a document that I've marked as Exhibit 9 and ask you to, please, sir, identify that for the record.
(The above-mentioned document was marked Exhibit 9.)
A. This is a report on the water quality of the aquifers and the well fields from Memphis. It is USGS Water Supply Paper 86-4052.
Q. (BY MR. CAMERON) Did you prepare this document?
A. I did.
Q. For what purpose?
A. To describe the water quality from the area and the flow modeling, the 3-D flow

modeling, it took a long time this terms of approval. I don't think it was approved until 1989. This was an intermediate step to provide products to MLG&W.
Q. What do you mean "provide products to MLG&W"?
A. Well, they paid for a 3-D flow model. The review process took a long time to finish.
Q. The review process within --
A. Within the USGS.
Q. Yes, sir. So this 1987 report was a step along the way, I guess?
A. It was an intermediate step. When I talked, I used terminology before that I didn't clearly identify. This was some information that had come as a result of data collection that was -- it is valuable. It is ancillary to understanding groundwater flow systems, but it does not involve any modeling components.
This was able to -- we were able to complete this. Bill Parks played a big role in this, as did the other co-author. Mike

Gatos didn't play as much. Bill Parks did a lot of work on this was well.
Q. This one was prepared in cooperation with the City of Memphis, Memphis Light, Gas & Water Division?
A. It was, yes.
Q. Had there been a report prior to this time that was specifically -- well, I guess other than Exhibit 8, which is the model runs that you did for Mr. Pickel, was there any other report that had been prepared specifically by you in cooperation with the City of Memphis prior to 1987 when you prepared Exhibit 9?
A. I don't remember any other.
Q. Look over on page Bates-numbered JVB01048.
A. Okay.
Q. You see that the study area designated "the Memphis study area" also included not only Shelby County but parts of Fayette and Tipton Counties, Tennessee, DeSoto and Marshall Counties, Mississippi, and Crittendon and Mississippi Counties in

Arkansas. Do you see that?
A. Yes.
Q. Why was that?
MR. LEO BEARMAN: What did you say, why is that?
MR. CAMERON: Yeah, did the study area include those --
MR. LEO BEARMAN: I'm sorry. I just didn't hear you.
A. They are proximate to the Memphis metropolitan area, their proximity. Initially the decision was made -- Bill Parks had published some previous reports, and to be consistent within those, the USGS district chief at that time chose to maintain that same area of study.
Q. (BY MR. CAMERON) All right. I'm going to hand you some other documents. We'll begin with a document which I'll mark as Exhibit Number 10.
(The above-mentioned document was marked Exhibit 10.)
Q. (BY MR. CAMERON) I'll ask you to identify that document for the record,

please, Dr. Brahana.
A. This is a USGS Water Resources Investigation Report 89-41-31. The title is "Hydrogeology and Groundwater Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee," by myself and Bob Broshears.
Q. Who is Bob Broshears?
A. Bob Broshears is recent retiree of the USGS. He was the water-quality specialist in the central region for ten years almost, I think, and also was a hydrologist, an excellent hydrologist and superb writer.
Q. This report is dated 2001, correct?
A. Yes, it is.
Q. It was prepared in cooperation with the City of Memphis and the Memphis Light, Gas & Water Division, right?
A. Yes, it was.
Q. How long did you work on this report?
A. My difficulty in answering is it was published long after it was approved. It was approved in 1989, and I think I probably

worked less than a month at the stage from 1989 until this to get it published.
Q. So this is the --
A. That is a summary of the 3-D, that's correct.
Q. That --
A. This is the narrative report --
Q. -- describes the 3-D model.
A. The narrative report of that three-dimensional flow model, that's correct.
Q. This is the same three-dimensional flow model from which you did some model runs for Charlie Pickel back in 1984?
A. That's correct.
Q. So you actually completed the three-dimensional model that is the subject of this 2001 report sometime prior to July of 1984?
A. I had a version created at that time, yes. The final one -- the USGS requirements, as I mentioned before, it was approved -- the 89-41, it was approved in 1989. And it wasn't published until --
Q. When you say "approved," you mean by

the USGS?
A. By the USGS. It goes through a rigorous peer review. That is correct.
Q. And it has to be approved by the director?
A. Yes.
Q. Before it is released?
A. That is correct.
Q. We will return to Exhibit 10, so I'd ask you to keep that one handy.
A. Okay.
Q. I'm going to hand you a document I've marked as Exhibit 11. I'll ask you to please identify that document for the record, Dr. Brahana. Do you recognize this document?
A. I do.
(The above-mentioned document was marked Exhibit 11.)
Q. (BY MR. CAMERON) And what is that?
A. It shows the water-level surface of the Fort Pillow Sand in the fall of 1980, and it is water-level surfaces, Fort Pillow Sand.
Q. In fact, I want to trade with you.
A. Okay.

Q. I want to withdraw that document because I handed you the wrong darn document. I'm going to hand you another document which I'm going to mark as Exhibit 11.
MR. CAMERON: David Bearman, this is a document that I would like to have copied because it is the original and I don't have an extra copy. I apologize for that. I actually made a copy of the wrong document.
THE WITNESS: Okay.
Q. (BY MR. CAMERON) Would you please look at that document and identify it for the record, sir.
(The above-mentioned document replaced what was previously marked Exhibit 11.)
A. This is the altitude of the water-level surface of the Memphis Sand in the fall of 1980.
Q. (BY MR. CAMERON) Did you prepare that document?
A. I did.
MR. DAVID BEARMAN: Alan, what's

Q. Out of Mississippi into the Memphis area?
A. It is flowing, yes, from Mississippi into the Memphis area. And this from Tipton County is flowing due south into the Memphis area. And from Arkansas we have a -- so the direction of flow, when we say it is 360 degrees, it is into that central portion of the cone.
Q. So Figure 26 reflects the cone of depression we've discussed?
A. This is the model of the cone of depression, that is correct.
Q. And it demonstrates, does it not, based on the flow lines you've just drawn, that water, groundwater, in fact was flowing from Mississippi into the Memphis well fields?
A. There is water that has fallen on Mississippi that is moving into the Memphis metropolitan area.
Q. Is that result of pumpage?
A. Yes.
Q. If you had an opportunity to

recalibrate, to revisit the model that is described in Exhibit 10 to your deposition today, what would you do? Are there any changes you would make or modifications you would consider?
A. The recalibration would be the addition of new data. Are there new wells in that area? Are there new water levels to which to calibrate? Are there pumping tests that have been run?
Could it be done with this model? I had think it is reasonably accurate, but it is not the final picture by any stretch of the imagination. I would add those additional pieces of data, because the data tied the model to the real world.
Q. For example, the Charles Pickel Treatment Plant either has or will come on line at some point?
A. You just gave me a new piece of information. Is that true?
Q. They are going to name, as I understand from talking to Mr. Pickel, a treatment plant after him, which is great.

A. He is a gentleman. He is a fine individual.
Q. And the pumpage from that new plant would be something that you would add to refine the model at some future point?
A. Yes.
Q. Would this model that is right here described in Exhibit 10 to your deposition still operate as a good predictive tool for water management?
A. I feel it would. I feel that there is definitely room for improvement, but new things that have been found since that time. Hell, this was done in 19 -- in the mid-1980's.
Q. When you say "improvement," you are talking about refinement?
A. Refinement by adding. There would be subtle changes.
Q. With new data?
A. With new data.
Q. All right. Earlier you testified that in your opinion MLG&W was a good steward of the Memphis Sand Aquifer. Do you recall

that?
A. I do.
Q. My notes indicate that you testified that MLG&W had a positive vision and was good steward. Do you recall saying those things?
A. I do.
Q. What are the bases of those opinions, Dr. Brahana?
A. Primarily in terms of looking to the future, of not only -- anything that we found, from a technical standpoint, if it looked like there was young water getting in that was leaking into the system, they didn't try to hide any of that. Though tried to address the problems.
They tried -- in terms of predictive capability in looking toward the future, they didn't want to do anything that was doing have any long-term deleterious impacts. Specifically those were water quality as much as anything else, but they were consistent about that in terms of handling things.
Some organizations or groups with whom I've worked, they have PR, they have

In the Matter Of:

STATE OF MISSISSIPPI vs

CITY OF MEMPHIS

BRIAN WALDRON

September 27, 2017

Q. Okay. And then did you come back to work here directly after that?
A. Yes, sir.
Q. Were you teaching at that time or were you --
A. I taught some. It was called a research assistant professor.
Q. What classes do you teach now?
A. Now, I teach fluid mechanics and professional practice and some graduate level classes like contaminant fate and transport and groundwater modeling.
Q. How many classes are you currently teaching just in terms of number of classes, two, three, five?
A. One a semester.
Q. One a semester?
A. Yes, sir.
Q. Okay. And the rest of the time is at the Institute?
A. Yes, sir. Or doing service.
Q. Or?
A. Doing service.
Q. Doing service. Okay. What kind of service?

A. Service is considered participating in departmental committees, University committees.
Q. With the University of Memphis?
A. Yes, sir.
Q. Okay. And you don't do any consulting work outside of that area or any other work we haven't discussed?
A. No, sir.
Q. Okay. At the present time what percentage of the total amount of funding for the Institute of Applied Earth Sciences comes from MLGW?
A. Probably about 40 percent.
Q. What percentage comes from utilities collectively?
A. So are you wanting me to take the added utilities and lump them into --
Q. One group.
A. One group. Probably like 45, 46 percent.
Q. Okay. Any funding from the State of Tennessee?
A. The West Tennessee River Basin Authority is a State of Tennessee agency.
Q. And what percentage of the funding comes from there, do you know?
A. No. In context everything else, I can't do it in my head but it's -- I don't remember.

Q. What are the sources of funding -- how much of the funding comes from the City of Memphis?
A. I think we have a $200,000 grant with them, contract with them.
Q. And I don't know what your total budget is but --
A. It varies so much that's why it's difficult to come up with a percent because it's -- grants come and go so fast.
Q. Well, this year approximate, I mean, would it be -- $200,000 would be -- what is the average annual or the range?
A. Normally we do it off of expenditures is the easiest way that the University calculates it, and it's between -- probably around 1.2 to 1.5 --
Q. Million?
A. -- million.
Q. So the City of Memphis is something in excess of 10 percent?
A. If that's what it calculates out to be.
Q. Okay. So what are the --
A. We have a new contract with them for -- we do handicap ramps and we do GIS storm water re-integration. So I think storm water -- I'm sorry, we do so much. Storm water re-integration is probably about -- I think it's 170 and ADA ramps is like 30 or 40.

Q. Okay. So around $200,000.
A. No. In addition to the zoning which is 200,000.
Q. Oh, the zoning is 200,000. Okay.
A. So whatever that calculates out to be.
Q. So generally where does the balance come from? Are there any other -- are there any other consistent sources of funding other than the City of Memphis and the utilities?
A. We get kind of funding year to year from the Mayor's innovation group. They call it Innovate Memphis.
Q. Okay.
A. We also get kind of year-to-year funding from the Community Foundation. We get funding from Shelby County Office of Preparedness. That's another grant we have. That's Homeland Security.
Q. Okay. Thank you. Have you or the Institute performed any groundwater consulting services of any kind outside of the state of