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.

DEFENDANTS' JOINT OPPOSITION TO PLAINTIFF'S MOTION TO EXCLUDE DEFENDANTS' EXPERTS

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GLOSSARY

Langseth Dep.	Deposition of David E. Langseth (Sept. 15, 2017)
Langseth June Rep.	Expert Report of David E. Langseth on the Interstate Nature of the Memphis/Sparta Sand Aquifer (June 27, 2017)
Larson Dep.	Deposition of Steven Larson (Sept. 19, 2017)
Larson June Rep.	Expert Report of Steven P. Larson (June 30, 2017)
MLGW	Memphis Light, Gas & Water Division
Op.	Memorandum of Decision on Tennessee's Motion to Dismiss, Memphis and Memphis Light, Gas & Water Division's Motion to Dismiss, and Mississippi's Motion to Exclude, *Mississippi v. Tennessee, et al.*, No. 143, Orig. (U.S. Aug. 12, 2016) (opinion of Special Master) (Dkt. No. 55)
USGS	United States Geological Survey
Waldron Dep.	Deposition of Brian Waldron, Ph.D. (Sept. 27, 2017)
Waldron June Rep.	Expert Report of Brian Waldron, Ph.D. (June 30, 2017)

I. INTRODUCTION

The Special Master should deny Mississippi's motion to exclude the expert testimony of Steven Larson, Brian Waldron, and David Langseth. All three of Defendants' experts offer scientific testimony on the underlying facts the Special Master identified as relevant to determining whether the Aquifer is interstate. The ultimate question for the hearing – whether the Aquifer is interstate – is a mixed question of fact and law, and experts routinely testify to such questions. If Mississippi were correct that this was a pure question of law, an evidentiary hearing would be unnecessary, and Mississippi's claims would fail as a matter of law. *See* Dkt. No. 70 (moving for summary judgment). In any event, an evidentiary hearing is unnecessary because, as explained in Defendants' Motion for Summary Judgment, the facts deemed relevant to the threshold question by the Special Master are not genuinely disputed. *See* Dkt. Nos. 70, 72. But if the Special Master decides that a hearing remains necessary, Defendants' expert testimony analyzing the Aquifer's "interstate" characteristics will contribute to the "adequate record for review" he requested. Op. 36. Such well-supported expert testimony on whether the Aquifer is interstate will assist the Special Master and is properly admissible.

II. ARGUMENT

A. Expert Opinion That Embraces An "Ultimate" Issue Is Admissible If It Is Helpful To The Factfinder

Under the Federal Rules of Evidence, which guide the proceedings in original-jurisdiction cases, *see* Sup. Ct. R. 17.2, Rule 702 governs the admissibility of expert testimony. Expert testimony is admissible if the expert is qualified, the opinion is scientifically valid and reliable, and "the expert's scientific, technical, or other specialized knowledge will help the trier of fact to understand the evidence or to determine a fact in issue." Fed. R. Evid. 702(a). The rule "should be broadly interpreted on the basis of whether the use of expert testimony will assist the trier of fact." *Davis v. Combustion Eng'g, Inc.*, 742 F.2d 916, 919 (6th Cir. 1984).

Expert testimony is "not objectionable just because it embraces an ultimate issue." Fed. R. Evid. 704(a); *see also Beech Aircraft Corp. v. Rainey*, 488 U.S. 153, 169 (1988) ("Rules 702-705 permit experts to testify in the form of an opinion, and without any exclusion of opinions on 'ultimate issues.'"). The touchstone of admissibility on such an issue remains whether the opinion is helpful to the factfinder. When an expert offers a technical or scientific opinion, the opinion may appropriately include an explanation of how the technical analysis leads to a particular conclusion on the ultimate issue in dispute. *See Markman v. Westview Instruments, Inc.*, 517 U.S. 370, 386 (1996) ("expert testimony was properly presented to the jury" on the question whether two "physical objects . . . were identical," even though that was an "ultimate issue" as to patent infringement); *see also United States v. DeClue*, 899 F.2d 1465, 1473 (6th Cir. 1990) (IRS agent could testify on whether a particular tax was due in a tax fraud prosecution, even though that was an "essential element" of the offense). The trier of fact need not agree with the expert's opinion, but an expert is entitled to "draw[] on common sense" to give "his opinion as to the ultimate issue." *United States v. Glover*, 265 F.3d 337, 345 (6th Cir. 2001). The same analysis governs the admission of expert opinions on an "ultimate issue of mixed fact and law." *Markman*, 517 U.S. at 386.[1]

B. Defendants' Experts Will Offer Testimony That Will Assist The Trier Of Fact

Defendants' three experts – two offered by Tennessee and one offered by Memphis and MLGW – will all give scientific testimony critical to understanding the facts of this case. Mississippi does not dispute those experts' qualifications or

[1] Even if the threshold issue were a purely legal question – which it is not – testimony that "arguably amounts to a legal conclusion" may be admitted where it helps the factfinder. *Woods v. Lecureux*, 110 F.3d 1215, 1220 (6th Cir. 1997). In some cases, "testimony offering *nothing more* than a legal conclusion . . . is properly excludable," including opinions using terms that "*have a separate, distinct and specialized meaning in the law different from that present in the vernacular*," but only because such testimony "would not be helpful to the trier of fact." *Id.* (first emphasis added). Where such legal opinions would be useful, courts retain discretion to admit them. That is particularly true when there is no jury and so only limited risk that the testimony might "encroach[] on the province of the trier of fact." *Czarnecki v. United States*, No. C15-0421JLR, 2016 WL 5395549, at *14 n.5 (W.D. Wash. Sept. 27, 2016); *see also Chicago Title Ins. Co. v. IMG Exeter Assoc. Ltd. P'ship*, No. 92-1440, 1993 WL 27392, at *4 (4th Cir. Feb. 8, 1993) (per curiam) (judgment noted at 985 F.2d 553 (table)) (similar).

argue that their opinions should be excluded because they lack reliability[2] or relevance.[3] The vast majority of their testimony will consist of opinions on underlying hydrogeological facts about the Aquifer. That testimony is no less admissible because it also embraces the ultimate issue of "whether the Aquifer is an interstate resource." Op. 36. That testimony, too, will assist the Special Master because the question whether the Aquifer is interstate is a hydrogeological question as much as a legal one; it is not a legal term of art with "a separate, distinct and specialized meaning in the law different from that present in the vernacular." *Woods*, 110 F.3d at 1220 (emphasis omitted).

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[2] Mississippi's passing "prefatory clarification" arguing (at 7-8) that Defendants' experts ignore certain facts about groundwater velocity and residence time is both undeveloped and incorrect. As Defendants have explained, groundwater residence time is not relevant to the question whether the Aquifer, including the groundwater in it, is interstate. *See* Dkt. No. 72, at 6-7. Moreover, Mississippi does not argue that this supposed error supports exclusion of Defendants' experts' testimony.

[3] Mississippi's various suggestions (at 3, 5) that Defendants' experts fail to address the character of the groundwater "at issue" misconstrues the limited issue on which the Special Master ordered an evidentiary hearing. In the Memorandum of Decision, the Special Master identified the "limited issue" as "whether the Aquifer and the water constitutes an interstate resource" and "whether the Aquifer is an interstate resource." Op. 36. The Special Master already has concluded that Mississippi cannot "limit[] its claims to a specific portion of the water" in the Aquifer. Op. 32. In any event, Defendants' experts do address the groundwater in the Aquifer. *See, e.g.*, Ex. 1 (Langseth June Rep. 2) (discussing groundwater flow patterns). Furthermore, Mississippi does not argue that this alleged distinction requires excluding Defendants' experts' testimony.

As disclosed in their expert reports, Defendants' experts all intend to testify about the Aquifer's geological and hydrological characteristics relevant to determining whether it is "interstate." All three (Steven Larson, Brian Waldron, and David Langseth) will offer background information on hydrology and the study of groundwater.[4] All three also will offer the opinion that the Aquifer, including its groundwater, constitutes a single, continuous water resource that extends across eight States, including Mississippi and Tennessee;[5] that pumping from the Aquifer can have cross-border effects;[6] that groundwater in the Aquifer naturally crossed state borders under pre-development conditions (i.e., before pumping began);[7] and that there exist no physical barriers in the Aquifer that impede interstate flow.[8]

Without limiting what testimony any expert may offer, the three experts also emphasized distinct points in their reports. For example, Dr. Langseth has conducted substantial investigations using the MERAS model, the USGS's most

[4] *See* Ex. 2 (Larson June Rep. 6-9); Ex. 3 (Waldron June Rep. 5-8); Ex. 1 (Langseth June Rep. 3-9).

[5] *See* Ex. 2 (Larson June Rep. 2-3); Ex. 3 (Waldron June Rep. 2-3); Ex. 1 (Langseth June Rep. 15-16).

[6] *See* Ex. 2 (Larson June Rep. 10); Ex. 3 (Waldron June Rep. 12); Ex. 1 (Langseth June Rep. 20-22).

[7] *See* Ex. 2 (Larson June Rep. 4); Ex. 3 (Waldron June Rep. 3-4, 13-15); Ex. 1 (Langseth June Rep. 16-19).

[8] *See* Ex. 2 (Larson June Rep. 9-10); Ex. 3 (Waldron June Rep. 10); Ex. 1 (Langseth June Rep. 16).

current computer model of the Mississippi Embayment aquifer system (which includes the Aquifer), and will offer testimony based on those investigations. *See* Ex. 1 (Langseth June Rep. 13-24). Mr. Larson will offer testimony on the hydrological connections between the groundwater in the Aquifer and other water, including groundwater and surface water bodies, and will explain from a hydrogeological perspective why the Aquifer's basic characteristics reveal its interstate character. *See* Ex. 2 (Larson June Rep. 10-21). And Dr. Waldron will explain his own academic work investigating the extent of cross-border flow during pre-development conditions in the Aquifer. *See* Ex. 3 (Waldron June Rep. 13-26).

All of these opinions, and the other hydrological and geological testimony these experts will offer, are the kind of evidence that the Special Master determined would be relevant at this evidentiary hearing. *See* Op. 36. The actual substance of all three experts' opinions is not only "helpful" but critical to resolving the ultimate question whether the water in the Aquifer is subject to the equitable-apportionment doctrine. It therefore should be admitted.

Defendants' experts' additional opinions that the Aquifer is an "interstate" resource should not affect the admissibility of their testimony in any way.[9]

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[9] If the Special Master believes that expert opinions on the "ultimate issue" of whether the Aquifer is interstate should not be admitted, this would only prevent Defendants' experts from testifying about their bottom-line conclusion that the Aquifer is in fact interstate. The vast majority of the proposed testimony – including but not limited to testimony on the geological extent of the Aquifer, the cross-border

Regardless of the semantic distinction between "legal" and "factual" opinions, all three of Defendants' experts amply explain how their underlying scientific analysis leads to their ultimate conclusions on whether the Aquifer is an interstate resource. *See Markman*, 517 U.S. at 386. Those opinions, in their entirety, will assist the Special Master (and ultimately the Court) and should be admitted.

C. Whether A Resource Is Interstate Is A Mixed Question Of Fact And Law About Which Experts Can Properly Testify

Defendants' experts are not offering any *legal* opinions on the question "whether the Aquifer is an interstate resource." Op. 36. In his August 2016 opinion, the Special Master explained that Mississippi's "complaint appears to have failed to plausibly allege that the water at issue is not interstate in nature." Op. 32. That was because "the factual basis for Mississippi's claim that the water at issue is not interstate water" did "not tend to show that the relevant water lacks an interstate character." Op. 28-29. Instead, Mississippi's factual allegations revealed that the

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effects of groundwater pumping, pre-development cross-border flow, and hydrological connections to other interstate waters – is indisputably factual in nature and would remain admissible. *See United States v. Barile*, 286 F.3d 749, 761-62 (4th Cir. 2002) (concluding that expert's testimony on ultimate legal conclusion was within the discretion of the district court to exclude but specifying that on a retrial the district court must permit the expert to testify on underlying questions); *Shahid v. City of Detroit*, 889 F.2d 1543, 1547 (6th Cir. 1989) (noting that "the district court carefully reviewed the deposition and took extra time and effort to resolve the objections and still save as much as possible of the expert's testimony"). Mississippi provides no support for its sweeping request that the Special Master "enter an Order excluding Defendants' experts" in their entirety. Mot. 10.

water at issue was "likely interstate in nature" because the removal of water in one State could directly affect the availability of water in another State. Op. 31. The "geological characteristics" of the water in the Aquifer also could be "relevant to whether it should be considered interstate in nature." *Id.* The Special Master did not treat the term "interstate" as a legal term of art; instead, the opinion suggests a practical, common-sense, "functional" approach to that issue that would benefit from further factual development.

The Special Master does state in one place that "Mississippi's nominal identification of the water at issue as intrastate water – and, conversely, as not having interstate characteristics – is a legal conclusion." Op. 25. Thus, "Mississippi's mere identification of the water at issue as intrastate is 'not entitled to [an] assumption of truth.'" *Id.* (quoting *Ashcroft v. Iqbal*, 556 U.S. 662, 680 (2009)) (alteration in original). But this use of the term "legal conclusion" means only that the "interstate" or "intrastate" character of a resource is not the kind of underlying fact that, if alleged, must be considered true on a motion to dismiss. The point is not that "interstateness" cannot be factually determined; the point is that a bald assertion that a resource is intrastate – and therefore not subject to equitable apportionment – is not a *plausible* allegation that can be *assumed* to be true on the pleadings. *See* Op. 18.

Despite Mississippi's quotations from Defendants' prior briefing,[10] Defendants never have treated the question whether the Aquifer is interstate as a pure legal question. In its Motion for Judgment on the Pleadings, Tennessee pointed out that Mississippi's "attempt to classify [the Aquifer] as 'intrastate' amounts to a mere legal conclusion that the Court should disregard," but that was so because of "Mississippi's *admissions*" and "its own *concrete factual allegations* demonstrating the interstate character of the groundwater at issue." Dkt. No. 30, at 23 (emphases added). Memphis and MLGW made the same point in their motion. *See* Dkt. No. 28, at 18 ("Mississippi's 'intrastate' claim is contradicted by Mississippi's own admissions."). Defendants' argument was that Mississippi could not avoid the *fact* that the water at issue is interstate – as Mississippi's complaint demonstrated – with a conclusory allegation that the water is "intrastate."[11]

Similarly, Defendants objected to Mississippi's proposed statements of fact that the Aquifer was "intrastate" as legal conclusions because Mississippi included proposed *legal consequences* of its factual claim that the water was intrastate. In

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[10] As demonstrated in detail in Defendants' Joint Motion for Summary Judgment, Dkt. No. 70, the question whether the Aquifer is interstate is not subject to reasonable dispute.

[11] This also is consistent with the Special Master's understanding of the parties' respective positons: "Although Mississippi generally claims that the Aquifer is *not* an interstate resource, Tennessee argues that the factual allegations contained in the complaint, Mississippi's briefing, and Mississippi's admissions in prior litigation show that the Aquifer is, in fact, an interstate body of water." Op. 8.

Fact 51, Mississippi stated that the aquifer "is an intrastate natural resource *subject to protection, regulation and preservation only by the State of Mississippi*." Dkt. No. 64, at 28 (emphasis added). And, in Fact 103, Mississippi claimed that the U.S. Constitution required "[r]ecognizing groundwater residing in Mississippi as an intrastate resource" and that it would "promote the protection and conservation of groundwater as a natural resource." *Id.* at 53. Defendants properly objected to the legal conclusions contained within these proposed facts. Those objections do not suggest that the Special Master should exclude expert testimony that offers useful hydrogeological opinions about whether the Aquifer is interstate.

It is clear that Defendants' experts are not opining on the meaning of "interstate" as a legal term of art or on the legal consequences of determining that a resource is interstate; rather, they are attempting to answer the factual questions posed by the Special Master's August 2016 opinion. Defendants' experts explained that their analyses of whether the Aquifer is interstate were based on the hydrogeological definition of interstate and not a legal one. For example, Mr. Larson stated in his report: "*From a hydrogeological perspective*, determining whether the Middle Claiborne aquifer constitutes an interstate resource requires a holistic consideration of all the groundwater within it." Ex. 2 (Larson June Rep. 2) (emphasis added). Similarly, Dr. Langseth based his opinion "on the use of the term 'interstate aquifer' *in scientific literature and the common meaning* of the word ‘interstate.’” Ex. 1 (Langseth June Rep. 15) (emphasis added; footnote omitted); *see also id.* at 15 n.14 (providing an example of the term used in scientific literature and the definition of “interstate” in the *American Heritage College Dictionary*). Even Mississippi’s counsel emphasized that he was asking for Dr. Langseth’s opinions about the interstate character of the Aquifer from a technical, scientific perspective, not a legal one:

> Q. . . . I’m asking you *from your standpoint as a groundwater hydrologist*, the single fact that you have a geological formation that underlies multiple states and contains groundwater is sufficient to make that groundwater an interstate natural resource. Is that correct?
>
> A. Okay. We’re talking about an aquifer. So it both contains water and you can extract water from it. If the delineated extent of that aquifer has a state line crossing through it, that is sufficient to make that an interstate aquifer.

Ex. 4 (Langseth Dep. 116:19-117:7) (emphasis added). Consistent with the question asked of him, Dr. Langseth answered the question as a groundwater hydrologist.

In fact, when asked by Mississippi, all three of Defendants’ experts declined to discuss any legal consequences about entitlement to water that could be drawn from their opinions. As Mr. Larson explained, his “understanding of what the [S]pecial [M]aster was interested in is whether the aquifer, which is the geologic materials as the matrix and the water in it, that together they form the aquifer, and the question is whether that aquifer was an interstate resource.” Ex. 5 (Larson Dep. 98:21-99:2). He specifically explained that he “wasn’t trying to determine entitlement to water of any kind." *Id.* at 100:18-19. Similarly, Dr. Langseth noted that his expert opinion on what constituted an interstate resource was "not intended to be a legal statement. It is a plain-language reading of" the Special Master's opinion. Ex. 4 (Langseth Dep. 34:24-35:2); *see also* Ex. 6 (Waldron Dep. 94:2-13) (Dr. Waldron stating his opinion that the water was "interstate" but not opining on whether that means that such water is "freely available to both parties").

The Special Master should admit those opinions. An expert can testify on factual issues even if legal conclusions flow from that testimony. A question of "mixed fact and law" is thus a proper subject of expert testimony. *Markman*, 517 U.S. at 386. Defendants' experts' view that the Aquifer is an interstate resource is not a naked legal conclusion or a parsing of technical legal terminology, *see Woods*, 110 F.3d at 1220, but a simple application of "common sense" to the facts of this case, *Glover*, 265 F.3d at 345.

By contrast, if Mississippi were correct – and the question whether the Aquifer were an "interstate aquifer" raised a pure question of law – the evidentiary hearing would be unnecessary. In reality, an evidentiary hearing is unnecessary because, as explained in Defendants' Motion for Summary Judgment, there are no genuine disputes of material fact here. *See* Dkt. Nos. 70, 72. Mississippi's claim that it is entitled to a trial rests on legal contentions (such as the equal-footing doctrine and an incorrect view of the equitable-apportionment doctrine) the Special Master already has rejected. *See* Op. 20-24. But if the Special Master determines that a hearing would remain useful, testimony on the core issue in dispute – whether the Aquifer is an interstate resource – will be essential. Having opposed summary judgment by arguing that the Special Master needs live testimony to resolve the threshold question whether the Aquifer is interstate, *see generally* Dkt. No. 71, Mississippi cannot now seek to exclude testimony that addresses the very evidentiary questions identified in the Special Master's decision.

In short, Defendants' experts are able to assist the trier of fact because they have examined the factual questions at issue in the evidentiary hearing and applied their expertise to answer those questions, including the ultimate question whether the Aquifer constitutes an interstate resource. All three experts properly have limited their opinions to hydrogeology, declining to speculate on what legal rights or entitlements may flow from their opinions. The experts have in no way usurped the province of the Special Master, and ultimately the Supreme Court, to determine legal entitlement to the disputed water.

CONCLUSION

The Special Master should deny Mississippi's motion to exclude the expert testimony of Steven Larson, Brian Waldron, and David Langseth.

Respectfully submitted this 20th day of November 2018,

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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 20th day of November 2018.

/s/ *David C. Frederick*

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EXHIBITS IN SUPPORT OF DEFENDANTS' JOINT OPPOSITION TO PLAINTIFF'S MOTION TO EXCLUDE DEFENDANTS' EXPERTS

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TABLE OF EXHIBITS

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1	Excerpts from Expert Report of David E. Langseth on the Interstate Nature of the Memphis/Sparta Sand Aquifer (June 30, 2017)
2	Excerpts from Expert Report of Steven P. Larson (June 30, 2017)
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6	Excerpts from Deposition of Brian Waldron, Ph.D. (Sept. 27, 2017)

Exhibit 1

Excerpts from
Expert Report of David E. Langseth on the
Interstate Nature of the Memphis/Sparta
Sand Aquifer

(June 27, 2017)

Expert Report on the Interstate Nature of the Memphis/Sparta Sand Aquifer

Volume 1 of 2: Report Text

Submitted on behalf of the City of Memphis, Tennessee, and Memphis Light, Gas & Water Division

in the matter of

State of Mississippi
v.
State of Tennessee, City of Memphis, Tennessee, and Memphis Light, Gas & Water Division

Supreme Court of the United States of America, No. 143 Orig.

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1.2 Opinion Summary

My opinion is that the MSSA, the aquifer to which the Special Master referred in his August 12, 2016, Memorandum of Decision (Judge Eugene Siler Jr., Special Master, 2016), is an interstate aquifer. Some of the specific characteristics of the MSSA that support my opinion include:

1. The MSSA lies beneath several states and is a shared resource among all the states that overlie it, including Mississippi and Tennessee.
2. The MSSA is part of a larger, hydrologically interconnected regional aquifer system called the Mississippi Embayment Aquifer System.
3. The Sparta Sand Aquifer and the upper portion of the Memphis Sand Aquifer have long been understood to be equivalent aquifers.
4. In pre-development times (before pumping began), groundwater in the MSSA naturally flowed across multiple state lines, including the Mississippi-Tennessee border.
5. In the Tennessee-Mississippi border region, groundwater travels laterally through the MSSA, vertically between the aquifers lying above or below the MSSA, and vertically between the MSSA and surface water.
6. Pumping from the MSSA in one state can impact the flow direction and potentiometric head in another state.
7. The MSSA has been and is today a dynamic natural system.
8. Water flow patterns in the MSSA were not influenced by state lines under pre-development conditions and are not influenced by state lines under current conditions.
9. Under pre-development conditions, all groundwater that entered the MSSA in Mississippi would eventually leave Mississippi.

These and other concepts are discussed more fully in Section 3 and supported by information in the entirety of the Report.

I reserve the right to amend my Report should additional information not currently known to me become available.

1.3 Qualifications and Compensation

I am qualified to address these issues by virtue of my education, training, and experience. Appendix A contains my professional resume, including a list of testimony given in the past 4 years.

Gradient is compensated at a rate of $355.50/hour for my work on this project.

1.4 Report Structure

This Report contains the following four primary elements:

- Section 1 is a summary of my opinion and other introductory matters.
- Section 2 provides background information concerning applicable scientific principles and the physical setting of the aquifer system in question.
- Section 3 provides detailed support for my opinion.
- The Appendices provide additional supporting information.

This Report is bound in two volumes: Volume 1 (this volume) contains the text of the Report, and Volume 2 contains the referenced Tables and Figures.

1.5 Definitions

Definitions for terms that occur frequently in this Report are set out below:

- **Aquifer:** "A formation, group of formations, or part of a formation that contains sufficient saturated, permeable material to yield significant quantities of water to wells and springs" (USGS, 2016a; see also USGS, 2016b). Other sources, such as widely used textbooks about groundwater, provide similar definitions, sometimes using the word "useable" instead of "significant" when characterizing the amount of water that can be withdrawn from wells or springs. Because a formation must contain and yield water to be considered an aquifer, the term "aquifer" refers simultaneously to the formation and the presence of water within the formation.
- **Confining Layer:** A geological formation that restricts water flow, relative to the ease of water flow in an aquifer (Heath, 1983, p. 6).
- **Evapotranspiration:** The sum of evaporation (water that vaporizes directly into the atmosphere from water surfaces) and transpiration (water vapor released by plants into the atmosphere) (Viessman and Lewis, 2003, p. 2).
- **Geologic Formation (or Unit):** A rock unit with upper and lower boundaries that can be recognized easily in the field and that is large enough to be shown on a map (Leet *et al*., 1978). Stokes and Varnes (1955, p. 57) provide a similar working definition, stating, "For practical purposes, a formation is usually a mappable unit that can be recognized in the field without recourse to detailed paleontological or petrological analysis." In other words, the rocks in one formation can be distinguished from rocks in a different formation using field observations, such as appearance. Note that the word "rock" refers to "any hard, solid matter derived from the earth" (Stokes and Varnes, 1955, p. 124), and thus encompasses the full range of mineral materials that are found in the Earth's solid crust, ranging from massive igneous rocks, such as basalts and granites, to sands, silts, and clays.
- **Hydrogeologic Unit:** Same as "hydrostratigraphic unit." See below.

- **Hydrostratigraphic Unit:** "A formation, part of a formation, or a group of formations in which there are similar hydrologic characteristics that allow for a grouping into aquifers and associated confining layers" (Domenico and Schwarz, 1998, p. 16).
- **Memphis/Sparta Sand Aquifer (MSSA):** The aquifers of the Middle Claiborne, Lower Claiborne, and Upper Wilcox units, represented by layers 5-10 in the US Geological Survey (USGS) Mississippi Embayment Regional Aquifer Study (MERAS) model (see below). The MSSA consists predominantly of the aquifer known as the Sparta Sand Aquifer in Mississippi, southern Arkansas, and Louisiana and the Memphis Sand Aquifer in Tennessee, northern Mississippi, and northeastern Arkansas.
- **Mississippi Embayment:** The northern portion of the Gulf Coast regional syncline (trough) in the Paleozoic rocks that has filled with sediments during subsequent geologic periods, with alternating periods of terrestrial and inundated environments (Hosman and Weiss, 1991, pp. B3-B4; Hosman, 1996, pp. G1, G4). The north-south axis of the Mississippi Embayment is generally coincident with the Mississippi River, the northern extent of the Mississippi Embayment is approximately where the Ohio River joins the Mississippi River, and the southern extent is in southern Mississippi and central Louisiana.
- **Mississippi Embayment Aquifer System:** The regionally extensive and vertically interconnected group of aquifers and confining units present in the Mississippi Embayment (Hart *et al*., 2008, pp. 3, 5).
- **Mississippi Embayment Regional Aquifer Study (MERAS) Model:** A numerical simulation model developed by the USGS for the aquifers in the Mississippi Embayment Aquifer System (Clark and Hart, 2009).
- **Outcrop:** The area where a geologic formation is exposed at or very near the ground surface (Stokes and Varnes, 1955, p. 101).
- **Particle Tracking:** A method of visualizing the pathway traveled by groundwater using discrete, imaginary particles. The particles are initially placed at selected locations in the model and are then repeatedly moved to new locations after a given amount of time, based on the water flow direction and velocity. In this manner the particles move in the same direction and with the same velocity as the water moves. The "track" of the particle then shows the pathway traveled by that parcel of water and, as a result, provides information about the flowpath of the groundwater. Both defining the flow direction/rate and performing the particle tracking itself are most commonly done using electronic computers, due to the computational intensity of these evaluations (Pollock, 2012).
- **Potentiometric Head:** Potentiometric head is the sum of pressure and elevation at a given location in the aquifer and is commonly measured as the height to which water rises in a standpipe open to the aquifer. Equivalent terms include "piezometric head," "hydraulic head," "total head," or "head" (Heath, 1983, p. 10). Potentiometric head is the driving force for groundwater flow, with groundwater flowing from locations of higher head to locations of lower head.
- **Potentiometric Surface:** A representation of the potentiometric head of an aquifer over a region (USGS, 2017a). The surface is often represented in terms of lines of equal potentiometric head, commonly called contour lines.

- **Pre-development:** The time prior to human influence on an aquifer – most commonly, the time before pumping began. For the overall Mississippi Embayment Aquifer System pre-development is generally considered to be before 1870 (Clark and Hart, 2009, p. 1). For the MSSA in the northern Mississippi-western Tennessee area, pre-development is considered to be before 1886.[3]
- **Saturated Zone:** Subsurface zones in which all of the pore space is filled with water (Heath, 1983, p. 4). Near-surface soils in which plants are growing are normally unsaturated, with the pore spaces containing both water and air. Aquifer materials and confining layers between aquifers are normally saturated.
- **Subcrop:** Similar to an outcrop, except that there is a more recent surficial deposit of some substantial thickness overlying the area where the formation would otherwise have been exposed at the ground surface.

[3] The first well known to draw from the MSSA in the northern Mississippi-western Tennessee area was bored in 1886, and by May 1889, there were 52 wells drawing from the MSSA in Memphis, 32 of them belonging to the Artesian Water Company, which was formed after the 1886 discovery of what we now know as the MSSA (Safford, 1890).

2 Scientific Principles and Physical Setting

This section provides an overview of relevant hydrological principles, the physical setting of the MSSA within the Mississippi Embayment Aquifer System, a discussion of the scientific literature addressing the MSSA, and a general review of the computer-based mathematical models created to study the MSSA and the Mississippi Embayment.

2.1 Groundwater Hydrology Overview

Groundwater is broadly defined as water occurring beneath the ground surface. While water is nearly ubiquitous in the ground, especially in generally humid climates, the nature of its occurrence varies widely. Near the Earth's surface, the soil pore spaces are generally not filled with water. This zone is often referred to as the unsaturated zone. Further down, water fills the pore spaces in what is called the saturated zone. The character of the materials in the saturated zone governs whether useful quantities of water can be extracted by pumping. Some materials, such as sand, readily yield water to pumping, while others, such as clay, do not. Subsurface formations that are capable of yielding useful quantities of water to pumping are commonly referred to as aquifers.

Both groundwater and surface water are part of the hydrologic cycle, as shown in Figure 2.1.1. Generally, water percolates down into the ground and then moves through the subsurface to locations where it discharges back to the surface and, through the process of evapotranspiration, returns to the atmosphere until it falls again as precipitation. As Figure 2.1.2 illustrates, aquifers are recharged by precipitation, which initially enters the unsaturated zone and continues to percolate down until it reaches the saturated zone. Some of the water that percolates into the portion of the ground that provides soil moisture in the root zone is subject to evapotranspiration before it reaches the saturated zone. Aquifers can also receive recharge from or provide discharge to surface water bodies, depending on the relationship between the potentiometric head in the groundwater and the water level in the surface water body. Figure 2.1.3 illustrates these relationships.

The flow rate of groundwater through an aquifer or confining unit is described by Darcy's Law, which states that the groundwater flow rate per unit area perpendicular to the flow is proportional to the change in potentiometric head per unit length of the flow path (this change per unit length is commonly called the "gradient"). The proportionality constant in Darcy's Law is a characteristic of the formation through which the water is flowing called the "hydraulic conductivity." Groundwater therefore flows from locations where the potentiometric head is higher to locations where the potentiometric head is lower, at a rate that can be calculated using Darcy's Law.

Aquifers are commonly characterized as being either confined or unconfined. Confined aquifers are those that have an overlying confining layer and the pressure in the aquifer is high enough that the potentiometric head in the aquifer rises above the bottom of that confining layer. An unconfined aquifer either has no upper confining layer or the potentiometric surface is below the bottom of the overlying confining layer. Figure 2.1.2 shows an unconfined aquifer, Figure 2.1.4 shows both confined and unconfined aquifers, and Figure 2.1.5 shows the concept of potentiometric head measurements in both confined and unconfined aquifers.

Pumping wells capture groundwater by lowering the potentiometric head in the well. The primary components of a pumping well (Figure 2.1.6) are:

- The well casing, which provides structural support for the borehole and has a perforated section that allows water to enter the well.
- The pump impellers, which are placed below the water level in the well casing and push groundwater from the aquifer toward the surface.
- The pump riser tube, a pipe inside the well casing, through which the impellers pump water to the surface.

When the pump is not running, the water level in the well is equal to the potentiometric head of the groundwater surrounding the well. When the pump is turned on, water is pumped out of the well through the internal riser tube, which causes the water level in the well between the riser tube and well casing to decline. The lowered water level in the well propagates outward into the aquifer, creating a region of lowered potentiometric head surrounding the pumping well, which is commonly called a cone of depression. The cone of depression causes water to flow toward the well from locations of higher head, in accordance with Darcy's Law, as illustrated in Figures 2.1.6 and 2.1.7.

Potentiometric head measurements from several locations in a given aquifer can be used to create a "potentiometric map" that shows water level elevations across the surface of that aquifer. Once levels have been plotted on the map, contour lines can be drawn connecting locations estimated to have equal potentiometric head. The result is analogous to the contour lines on a topographic map of the land surface.

Potentiometric maps can be used to determine the direction of groundwater flow within an aquifer, which will generally be perpendicular to the contour lines. Figure 2.1.8 illustrates the process of constructing a potentiometric map and using the contour lines to determine flow direction.

2.2 MSSA and Mississippi Embayment Overview

The MSSA is one of several aquifers in the Mississippi Embayment Aquifer System, a large, hydrogeological system underlying parts of several states, including Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. The Mississippi Embayment Aquifer System is, in turn, part of the even larger Coastal Lowlands Aquifer System.

Figure 2.2.1a shows the USGS's most recent map of principal aquifers of the United States.[4] Figure 2.2.1b shows the outline of the Mississippi Embayment Aquifer System superimposed on the principal aquifers map, and Figure 2.2.1c shows the extent of the MSSA within the Mississippi Embayment.

Table 2.2.1 shows the aquifers and confining units in the Mississippi Embayment in a table format.[5] Note that a given aquifer formation is often called by different names in the various states that overlie it. For example, the Middle Claiborne aquifer in Tennessee, northeastern Arkansas, and Missouri is called the Memphis Sands Aquifer. In Mississippi, Louisiana, southern Arkansas, and Kentucky, that same aquifer is called the Sparta Sand Aquifer.

The Mississippi Embayment Aquifer System extends several thousand feet below the ground surface. A useful way of illustrating the depth and subsurface structure of the Mississippi Embayment is with cross-sections. A cross-section shows a view comparable to what is seen when a layer cake is sliced and the cake is viewed from the side. Figure 2.2.2 shows an east-west cross-section through the Mississippi Embayment Aquifer System, highlighting the major hydrogeologic layers, including those that comprise the MSSA. Figure 2.2.2 shows that the layers generally start on the east side of the Embayment at the ground surface (the outcrop areas), descend to reach their lowest elevations generally beneath the Mississippi River, and then ascend as they continue west until reaching western outcrop areas or subcrop areas beneath the alluvial (most shallow) aquifer. The outcrop and subcrop areas for all of the Mississippi Embayment aquifers except the alluvial aquifer are located in a series of bands around the perimeter of the Mississippi Embayment Aquifer System.

Figure 2.2.3 shows a north-south cross-section on a line roughly along the axis (deepest part) of the Mississippi Embayment Aquifer System. Figure 2.2.3 shows that the aquifer layers start at or near the ground surface at the northern end of the Embayment and generally, but not uniformly, decline in a southerly direction, toward the Gulf of Mexico. Figure 2.2.4 is a plan view (overhead) map showing the approximate locations at which the various aquifer layers in the Mississippi Embayment rise to the surface.

The layers in the Mississippi Embayment are hydrogeologic formations that were deposited during the repeated advance and retreat of the ocean over millions of years. The layers are composed of unconsolidated granular materials and are distinguished from each other by the dominant grain sizes. Water flows readily through the layers that are dominantly sands, and those layers constitute aquifers. Water does not flow as easily through the layers dominated by silts and clays, and these layers constitute confining layers between the aquifers. Like aquifers, confining layers are saturated with water and some water does flow through them. However, they generally do not transmit enough water to supply a well.

The arrows on Figure 2.2.2 show the generalized pre-development flow patterns in the Mississippi Embayment aquifers, including the MSSA. Precipitation entered the aquifers in their

[4] Note the Mississippi River Valley alluvial aquifer (shown in blue on Figures 2.2.1a and 2.2.1b) lies above the MSSA and is separated from it by a confining layer.

[5] The model layer numbers in the last column of Table 2.2.1 refer to the USGS MERAS model, discussed briefly in Section 2.4 and further in Appendix C.

outcrop or subcrop areas, flowed laterally within the aquifer formations toward the center of the Embayment, then flowed upwards through the formations, including the confining units, and finally discharged to the surface in the Mississippi River Valley.[6] This pre-development flow pattern is a natural consequence of the stratigraphy (layering) of the aquifers and the topography of the ground surface in the Mississippi Embayment, and is still broadly applicable today.

Renken (1998, p. F18) describes the general flow pattern among the hydrologically connected aquifers and confining units in the Mississippi Embayment as follows:

> Regional movement of water in the aquifer system is from aquifer recharge areas that range from 100 to 400 feet higher than the uniformly low, flat terrain of the Mississippi Alluvial Plain where water discharges. The difference in altitude provides the gravitational energy needed to drive the ground-water flow system.

and

> Before development of the aquifer, water that entered the deeper, regional flow system moved toward the center of the Mississippi Embayment… Water in the confined parts of the system was discharged by upward leakage into shallower aquifers, such as the Mississippi River Valley alluvial aquifer. Ultimately, ground water was discharged to streams and rivers that incised the shallower aquifers.

In summary, the water flowing through the Mississippi Embayment Aquifer system eventually discharges to (1) surface water bodies in the Mississippi River Valley, (2) hydrogeologically connected water bodies outside the Embayment (*e.g.*, the Gulf of Mexico), or (3) pumping.

In southwest Tennessee and northwest Mississippi, the potentiometric surface of the MSSA is above the top of the aquifer (the bottom of the upper confining layer), and hence, the MSSA is classified as a confined aquifer. In the outcrop areas of the MSSA where overlying clay formations do not exist, it is an unconfined aquifer.

South of the Tennessee-Mississippi state line, the MSSA becomes separated into upper and lower aquifers by a clay layer (Clark and Hart, 2009). Figure 2.2.3 illustrates the presence of this confining layer, using the hydrogeologic unit names, rather than the local unit names (see Table 2.2.1 for a cross-reference between the hydrogeologic and local unit names). On Figure 2.2.3, the Lower Claiborne confining unit is shown as starting about 30 miles south of the Tennessee-Mississippi state line and separates the Lower Claiborne-Upper Wilcox aquifer from the Middle Claiborne aquifer. North of the Lower Claiborne confining unit, the Middle Claiborne aquifer is commonly called the Memphis Sand Aquifer. Where the Middle Claiborne aquifer lies above the confining unit, it is called the Sparta Sand Aquifer.

Other interstate aquifers in the Mississippi Embayment lie below and above the MSSA. The Fort Pillow Aquifer, for example, underlies and is separated from the MSSA by a confining layer

[6] The Mississippi River Valley is the region on either side of the Mississippi River, in which the terrain has generally low relief. The edges of the Mississippi River Valley are defined by the occurrence of terrain with greater relief. The Mississippi River Valley is the area that, under natural conditions, would be most often inundated by flood waters.

- Renken (1998, p. F17) stated that "the Memphis Sand is equivalent to the Sparta Sand."
- Arthur and Taylor (1998, p. I11) defined the geologic grouping of the middle Claiborne aquifer as "composed mostly of the Sparta Sand in the southern two-thirds of the study area and the Memphis Sand in the northern one-third (Tennessee, east-central Arkansas, southeastern Missouri, southwestern Kentucky, and northwestern Mississippi)," noting that "the aquifer is the thickest in the vicinity of the juncture of Arkansas, Tennessee and Mississippi" (Arthur and Taylor, 1998, p. I12). The authors further described the historical shared nature of the MSSA: "The first artesian well in the Memphis, Tenn., area was completed in the middle Claiborne aquifer (Memphis Sand) in 1886 (Criner and Parks, 1976). The first known pumpage from the middle Claiborne aquifer in the Pine Bluff, Ark., area was by the Pine Bluff Water and Light Company in 1898 (Klein and others, 1950)" (Arthur and Taylor, 1998, p. I17).
- Brahana and Broshears (2001, p. 4) highlighted studies of pumping "in the Sparta aquifer (equivalent to upper part of Memphis aquifer) in east-central Arkansas" as being relevant to the Memphis area.
- Hart *et al*. (2008, p. 16) showed from an analysis of more than 2,600 geophysical logs that the MSSA "extends to the northeastern edge of the study area in Tennessee and Kentucky and to the southern edge of the study area in Louisiana, Mississippi, and Alabama, occurring almost entirely throughout the study area."
- Schrader (2008) showed the MSSA extending across many state lines and stated that "the sand layers within the Sparta Sand and Memphis Sand that comprise the Sparta aquifer and the Memphis aquifer will be referred to as the Sparta-Memphis aquifer. Water levels in the Sparta aquifer generally correlate with those in the Memphis aquifer; therefore, the water-bearing formations are considered to be one hydrologic unit (Stanton, 1997)." The potentiometric surface map developed in the publication "is based upon water-level data collected in 309 wells in Arkansas, 7 wells in Kentucky, 116 wells in Louisiana, 150 wells in Mississippi, 6 wells in Missouri, and 160 wells in Tennessee in the Sparta-Memphis aquifer" (Schrader, 2008).
- Haugh (2012, pp. 5, 18, 20) referred to the formations collectively as the "Memphis/Sparta aquifer."

I am not aware of any scientific support for the proposition that the MSSA is not a contiguous interstate aquifer or that it is not shared among the several states that overlie it.

2.4 The United States Geological Survey's MERAS Model

Computer-based mathematical models (such as numerical models) are powerful tools for evaluating groundwater flow conditions and quantitatively synthesizing the available information for a hydrogeological system into an integrated conceptual framework. These computer-based models can answer questions about groundwater flow by simulating conditions both before and after pumping began.

Mathematical models of the Mississippi Embayment, and specifically of the MSSA, have been used for decades to investigate technical questions and to better understand these aquifers. The USGS's most recent and most comprehensive mathematical groundwater model of the Mississippi Embayment was developed as part of its Mississippi Embayment Regional Aquifer Study (MERAS) and integrates the geologic, hydrologic, and pumping information for the entire multilayer Mississippi Embayment Aquifer System (this model is hereafter referred to as the USGS MERAS model).

The development of the USGS MERAS model was a multi-year effort that included reviewing thousands of geologic logs, aggregating tens of thousands of pumping records and water level measurements, and estimating groundwater recharge rates from historical precipitation data. A major data collection effort was undertaken in 2007 to develop an accurate potentiometric surface of the MSSA based on observed water levels. That 2007 potentiometric map became one of the primary tools used to verify that the model simulations accurately represent observed groundwater conditions (Clark and Hart, 2009).

Since its initial development, the USGS MERAS model has been used to assess groundwater conditions by multiple states and interstate agencies, including the State of Arkansas (Clark *et al.*, 2013), the Mississippi Department of Environmental Quality (MDEQ, 2014, USGS, 2016c), the Yazoo Mississippi Delta Joint Water Management District (Barlow and Clark, 2011), and the Tennessee Valley Authority (Haugh, 2012, 2016).

One of the helpful tools supported by the USGS MERAS model is particle tracking. Particle tracking allows the model operator to place a simulated water particle in an aquifer or river at a given point and track its movement over a period of time. Particle tracking can be used in conjunction with the USGS MERAS model's ability to simulate groundwater flow under different conditions. Thus, particle tracking can be performed under pre-development conditions to show groundwater flow during that time.

Because the USGS MERAS model represents the most advanced, scientifically rigorous mathematical model of the Mississippi Embayment, and for the reasons set out in greater detail in Appendix C, I determined that the USGS MERAS model was the best mathematical simulation tool to use in the preparation of this Report.

3 Statement of Opinion

My opinion is that the aquifer that is the subject of this case, the MSSA, including the groundwater in it, is an interstate aquifer. The MSSA, known in Tennessee as the Memphis Sand Aquifer and in Mississippi as the Sparta Sand Aquifer, lies beneath several states and is a vital source of water for the states overlying it. Before pumping began, groundwater in the MSSA naturally flowed from Mississippi into Tennessee, from Tennessee into Mississippi, and from both those states into Arkansas. Pumping from the MSSA in one state can impact the flow direction and potentiometric head of the MSSA in other states. The MSSA is hydrologically connected to other interstate aquifers and to interstate streams in the Mississippi Embayment. Factual and scientific support for these and other concepts that support my opinion are discussed in this Section and supported by other information set forth in the entirety of this Report.

3.1 The MSSA is physically located beneath several states, including Mississippi and Tennessee, and is a resource that is shared by and common to the states that overlie it.

Based on the use of the term "interstate aquifer" in scientific literature[13] and the common meaning of the word "interstate,"[14] if some portion of an aquifer is beneath one state and another portion is beneath another state, that aquifer is an interstate aquifer. Said differently, if a state line crosses over some portion of an aquifer, that aquifer is an interstate aquifer. That is the case with the MSSA, and hence, the MSSA is an interstate aquifer.

The MSSA is physically located beneath several states, including Mississippi, Tennessee, Arkansas, Louisiana, Kentucky, and Missouri (see Figure 2.2.1c and Schrader, 2008), and groundwater is laterally continuous throughout the MSSA, including locations where state lines cross over the MSSA. As discussed in Section 2.3, this has been known for over a hundred years.

The MSSA's groundwater is shared by the states overlying the resource. For example, in western Tennessee, the MSSA is the principal source of drinking water (Brahana and Broshears, 2001, p. 2). In northern Mississippi, the MSSA is also the primary source of public drinking water and is increasingly used for agriculture (Newcome, 1976, Plate 1; Wasson, 1986, p. 50; McKee and Hays, 2002, p. 1). In east-central and southern Arkansas and northern Louisiana, the MSSA is used for drinking water, industrial, and agricultural purposes (Burns & McDonnell, Inc., 2007,

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[13] See, for example, "Interstate and International Aquifers," (Bittinger and Jones, 1972). In the first paragraph of the article, the authors note that "State and national boundaries are traversed by natural surface water and groundwater systems. The flow of water in such systems is not at all influenced by these boundaries. The quantity or quality of the water flowing in these systems, however, may be materially influenced by man's activities on one or both sides of the boundary."

[14] *The American Heritage College Dictionary* (1997), Third Edition, defines "interstate" as: "Involving, existing between, or connecting two or more states."

pp. 1-2; Sargent, 2002, p. 100; Joseph, 2000, p. 1; Hays *et al*., 1998, p. 1). All of these water uses are drawing from the same aquifer.

As discussed in Section 2.3, the upper portion of the Memphis Sand Aquifer in Tennessee and Sparta Sand Aquifer in Mississippi are different names for the same aquifer and same hydrogeological formation. There are no lateral barriers aligned with state boundaries that restrict groundwater movement in the MSSA between states. Thus, groundwater pumped from the MSSA in Shelby County, Tennessee, and groundwater pumped from the MSSA in DeSoto County, Mississippi, is coming from a common, underground, interstate water resource.

Further, as discussed in Section 2.2 and Appendix B, the MSSA is part of a larger, hydrologically connected, interstate aquifer system called the Mississippi Embayment. Water has been moving and continues to move into, through, and out of the MSSA and other aquifers of the Mississippi Embayment, crossing the political borders of and supplying water to the states that overlie them.

3.2 In pre-development times (before pumping began), groundwater and surface water originating in Mississippi naturally flowed into and supplied the MSSA beneath Tennessee.

Hydrogeologists have long understood that groundwater in the MSSA naturally flowed across state lines under pre-development conditions (see Section 2.3). The interstate flow of groundwater in the MSSA from Mississippi to Tennessee can be demonstrated by analyzing observed (measured) water levels and by computer-based mathematical models, as discussed below in Sections 3.2.1 and 3.2.2. Additionally, pre-development flow from Mississippi into Tennessee is consistent with the elevation of the bottom of the MSSA in the Tennessee-Mississippi border region, as discussed in Section 3.2.3.

3.2.1 Pre-development flow from Mississippi to Tennessee in the MSSA has been confirmed by analysis of reported data.

There are two published evaluations of the pre-development potentiometric head surface of the MSSA in the Shelby County, Tennessee-DeSoto County, Mississippi, area based on reported data. Both confirm a northerly groundwater flow component in pre-development times that crossed the state line from Mississippi into Tennessee. The earlier evaluation was made by Criner and Parks (1976, Figure 4), who created a potentiometric surface map of the MSSA for the Memphis area that shows groundwater flowing from Mississippi into Tennessee under pre-development conditions (Figure 3.2.1a). More recently, Waldron and Larsen (2015, Figure 4) developed a potentiometric surface map (Figure 3.2.1b) based on new research into historical water level reports that again showed a northward flow of groundwater from Mississippi into Tennessee during pre-development times. The northerly flow component from the Waldron and Larsen (2015) research was stronger than that shown by the Criner and Parks (1976) analysis.

In summary, both Criner and Parks (1976) and Waldron and Larsen (2015), using reported data, confirmed that the natural flow of groundwater in the MSSA – unaffected by pumping – included an interstate component from Mississippi to Tennessee.

3.2.2 Pre-development flow from Mississippi to Tennessee in the MSSA has been confirmed by the USGS MERAS model particle tracking.

Particle tracking based on hydrogeologic simulations from the USGS MERAS model provides enhanced opportunities to analyze groundwater flow as it existed during pre-development times. Particle tracking reveals the presence of more complex interstate flow patterns than could be discerned from the available historic data (see Section 3.2.1). Particle tracking shows that under pre-development conditions, water naturally flowed from Mississippi into the MSSA beneath Tennessee through several different flow pathways, including the following.

3.2.2.1 Precipitation that fell in Mississippi percolated down into the MSSA within Mississippi and then flowed northward in the MSSA across the state line into Tennessee.

Figure 3.2.2 shows water flow pathways within the MSSA under pre-development conditions for water that recharged the MSSA in Mississippi, which I simulated using the USGS MERAS model. These pathways are depicted by particle tracks that originated in MSSA outcrop grid cells[15] in Mississippi north of the Coldwater River. Notable aspects of these flow lines include:

- The particles northeast of the Coldwater River generally traveled northwest into Tennessee. Once in Tennessee, the particles turned to the southwest, crossing from Tennessee into either Arkansas or back into Mississippi, depending on how far east the particles began.
- The particles that re-entered Mississippi (from Tennessee) then crossed into Arkansas for a span of more than 10 miles, before returning again into Mississippi.
- The particles ultimately discharged into the Mississippi River.

This analysis demonstrates that under natural conditions (before pumping), precipitation that recharged to the MSSA outcrop in northern Mississippi did not stay in Mississippi. This is also generally true throughout the MSSA. Precipitation that recharges the MSSA in a given state does not stay in that state, but rather moves through the MSSA to a discharge location, ultimately traveling to the Gulf of Mexico.

[15] As discussed in Appendix C, for purposes of this Report, the outcrop grid cells for the MSSA were identified as those cells in layers 5-10 of the USGS MERAS model where those layers are the uppermost active cells in the USGS MERAS model. See Figure C.3.1.

3.2.2.2 Precipitation that fell in Mississippi entered an interstate river within Mississippi, such as the Wolf River, Hatchie River, or Nonconnah Creek, flowed across the state line in the river, and then percolated down into the MSSA underlying Tennessee.

Figure 3.2.3 shows water flow pathways within the MSSA under pre-development conditions for water that recharged the MSSA from the Wolf River. Again using the USGS MERAS model to simulate pre-development conditions, particles were released in the model cells representing the Wolf River and tracked as they moved through the MSSA under pre-development conditions. The Wolf River begins as a natural spring in the MSSA outcrop area in Benton County, Mississippi. From its source, it flows west until turning north, where it crosses into Tennessee, continuing northwest through Shelby County, Tennessee, and discharging into the Mississippi River (TDEC, 2017). Notable aspects of these flow paths include:

- The Wolf River had and still has a direct hydrological connection to the MSSA in both Mississippi and Tennessee.
- Some of the water crossing from Mississippi into Tennessee in the Wolf River percolated down to recharge the MSSA in Tennessee.
- Water in the Wolf River that percolated down to recharge the MSSA in Mississippi eventually flowed northwest in the MSSA from Mississippi across the state line into the MSSA beneath Tennessee.
- Some of the water that flowed from Mississippi into Tennessee in the MSSA moved upwards after entering Tennessee to re-enter the Wolf River, where it discharged into the Mississippi River from Tennessee.

3.2.2.3 Precipitation that fell in Mississippi percolated down into the deeper Fort Pillow Aquifer within Mississippi, flowed across the state line into Tennessee, and then flowed upward into the MSSA underlying Tennessee. Some of the water entering into the Fort Pillow Aquifer in Mississippi flowed upwards into the MSSA while still in Mississippi and then flowed laterally in the MSSA across the state line into Tennessee.

The particle tracks shown in Figure 3.2.4a are also based on the USGS MERAS model and illustrate water flow pathways under pre-development conditions for water that flowed from Mississippi to Tennessee within the Fort Pillow Aquifer and then, once in Tennessee, flowed upward into the MSSA. In Figure 3.2.4a, the flow pathways are blue while the groundwater is in the Fort Pillow Aquifer and become green once the groundwater moves upward into the MSSA. Note that many of the particles in the Fort Pillow Aquifer originate east of the outermost border of the MSSA, because the outcrop for the Fort Pillow Aquifer lies further east than the outcrop for the MSSA. Once in Tennessee, the flow paths within the MSSA curved in a counterclockwise manner and crossed the state line into Arkansas, where they continued to curve to the south and eventually crossed back into the State of Mississippi or moved vertically upward to recharge the Mississippi River.

Figure 3.2.4b shows water flow pathways under pre-development conditions for water that started in the deeper Fort Pillow Aquifer in Mississippi, flowed up into the MSSA while still beneath Mississippi, and then flowed laterally in the MSSA into Tennessee.

The USGS MERAS model not only confirms the natural interstate flow of groundwater in the MSSA, but also provides expanded insight into the complexity of flow patterns across state lines – especially those in the area of the Tennessee-Mississippi border.

3.2.3 Pre-development flow from Mississippi to Tennessee in the MSSA is consistent with the natural northward slope of the aquifer in the north Mississippi, west Tennessee area.

In the absence of other counteracting forces, groundwater will flow in the downhill direction of the bottom of an aquifer. Two evaluations by the USGS, one based on data evaluation around the mid-1960s (Figure 3.2.5a) and the other based on the recent comprehensive data evaluation performed in support of the MERAS model (Figure 3.2.5b) show that the direction of the slope of the bottom of the MSSA in the vicinity of the Mississippi-Tennessee state line is to the northwest. Thus, the presence of a northerly component to the natural pre-development flow direction, from Mississippi into Tennessee (See Section 3.2.1), is consistent with the slope of the bottom of the MSSA.

3.3 The interstate pre-development flow of groundwater in the MSSA from Mississippi to Tennessee is a component of and consistent with the larger, regional interstate groundwater flow patterns in the northern MSSA.

The USGS MERAS model shows that the pre-development flow patterns from Mississippi to Tennessee described in Section 3.2 are part of a larger, counterclockwise flow pattern in the northern MSSA that naturally (without the influence of pumping) crossed multiple state lines.

Figure 3.3.1a shows the pre-development potentiometric head contours across the full extent of the MSSA simulated by the USGS MERAS model. Figure 3.3.1b shows the same contours as Figure 3.3.1a, but with arrows added to show the generalized flow directions inferred from those contours using the concepts described in Section 2.1. These simulations, based on the USGS MERAS model, demonstrate that the northerly pre-development flow component of groundwater in the area of the Tennessee-Mississippi state line is consistent with and part of a larger flow pattern of the MSSA in the northern Mississippi Embayment region, a natural flow pattern that crossed many state lines, unaffected by state political boundaries.

Figures 3.3.2a and 3.3.2b provide a more detailed view of the flow paths for groundwater in the MSSA in northwest Mississippi, southwest Tennessee, and east-central Arkansas using particle tracking. Specifically, Figures 3.3.2a and 3.3.2b show the flow paths for particles released in the USGS MERAS model grid cells for the MSSA in Mississippi that lie within 4 miles of the Mississippi-Tennessee state line. The particle tracks in these two figures show a northerly pre-development groundwater flow in the MSSA north of the Coldwater River.

The flow patterns shown in Figures 3.3.2a and 3.3.2b are complex, with highly non-linear particle tracks crossing state lines in many places. A dominant feature of the overall flow pattern in the portion of the MSSA around Shelby and DeSoto Counties is the somewhat circular, counterclockwise motion of water that starts in the eastern outcrop of the MSSA in Mississippi, moving initially northward, then curving to the west and eventually turning southward. Figure 3.3.2b shows that east of the approximate mid-point along the DeSoto County-Shelby County border, groundwater in pre-development times naturally traveled northwest from Mississippi into Tennessee, then curved southwest into either Mississippi or Arkansas. West of that same mid-point, groundwater naturally flowed southward from Tennessee into Mississippi. The flow pattern shown by particle tracking is consistent with the structural and hydraulic properties of the MSSA.

Modeling simulations by Arthur and Taylor (1998) found the same generally circular, counterclockwise flow pattern in the MSSA under pre-development conditions in the Tennessee-Mississippi state line area, as shown in Figure 3.3.3.

The regional pre-development flow patterns in the MSSA described above further show that the MSSA is an interstate resource.

3.4 The interstate nature of the MSSA is demonstrated by the fact that pumping from the MSSA in one state can and does affect groundwater in the MSSA in other states.

The fact that pumping from the MSSA in one state can and does impact the groundwater moving through the MSSA in other states demonstrates that the MSSA is a shared interstate resource. Because the MSSA is a resource common to the states that overlie it, it is natural and expected that the impact of pumping from the MSSA from one state would cross into the MSSA beneath another state. In other words, the fact that pumping in one state affects the same resource in another state supports my opinion that the MSSA is an interstate resource.

That the impacts of pumping in the MSSA cross state lines can be demonstrated by evaluating measured/observed data (discussed in Section 3.4.1) and by simulating conditions in the aquifer using mathematical modeling (discussed in Section 3.4.2).

3.4.1 Confirming the Interstate Nature of the MSSA by Evaluating Measured Data

As explained in Section 2.1, pumping groundwater from an aquifer lowers the potentiometric head in the area of the well or well field and creates a cone of depression. The clearest indication of a cone of depression on a potentiometric surface map is where the contour lines are closed and form a concentric series of declining values moving toward the pumping center. Where those closed contours reach or cross a state line, the cone of depression also reaches or crosses the state line.

The most recent potentiometric map of the MSSA published by the USGS appears in Schrader (2008) and is based on water levels in the MSSA that were measured in 2007 (Figure 3.4.1). The Schrader potentiometric map shows the following locations where the impact of pumping from the MSSA in one state has reached or crossed state boundaries into another state:

- The cone of depression centered in Union County, Arkansas, crosses the state line into Louisiana.
- The cone of depression centered in Sharkey and Issaquena Counties, Mississippi, reaches the state line with Louisiana.
- The cone of depression centered in Shelby County, Tennessee, crosses state lines into Mississippi and Arkansas.

Reed (1972, Figure 3) also showed cones of depression crossing state lines in his 1965 analysis of potentiometric head data.

3.4.2 Confirming the Interstate Nature of the MSSA by Mathematical Modeling Simulations

Modeling simulations of the MSSA similarly show pumping impacts that cross state lines and, therefore, further confirm that the states pumping from the MSSA are pumping from a common, interstate resource.

Computer-based mathematical simulation models can show the interstate impacts of pumping in two general ways. First, the model can be used to develop a potentiometric surface map. With the model-generated potentiometric map, the same analysis described in Section 3.4.1 can be performed. Second, the simulation model can be used to develop a drawdown map of an aquifer. Drawdown is the change in the potentiometric surface caused by pumping. A drawdown contour map shows the difference between the potentiometric surfaces with and without pumping. A drawdown contour map provides a more direct indication of the spatial extent of pumping impacts than that provided by a potentiometric surface map. By definition, a location at which pumping causes drawdown is within the cone of depression for that pumping.

Examples of pumping impacts crossing state lines shown by model simulation studies include:

- A potentiometric map created by the USGS MERAS model shows impacts of pumping from the MSSA in 2007 (Clark and Hart, 2009, Figure 17) that are consistent with those indicated by the potentiometric surface map of Schrader (2008), discussed in Section 3.4.1.
- Arthur and Taylor (1998, Plate 8) used a simulation model to develop drawdown maps for the MSSA (which they call the Middle Claiborne aquifer and the Lower Claiborne-Upper Wilcox aquifer) for 1987[16] (Figures 3.4.2a and 3.4.2b), which show several cones of depression (indicated in these figures by drawdown) that cross state lines, including:

[16] The model developed by Arthur and Taylor was part of the USGS Regional Aquifer Simulation Analysis program and was a predecessor to the USGS MERAS model. In this model, the MSSA was simulated in two layers, the Middle Claiborne aquifer and the Lower Claiborne-Upper Wilcox aquifer. See Appendix C for further information.

- The cone of depression caused by pumping in the Monroe, Louisiana, area crosses the state line into Arkansas (Figure 3.4.2a).
- The cone of depression caused by pumping in the Union County, Arkansas, area crosses the state line into Louisiana (Figure 3.4.2a).
- The cone of depression caused by pumping in the Stuttgart, Arkansas, area crosses the state lines into Mississippi and Louisiana (Figure 3.4.2a).
- The cone of depression caused by pumping in the Shelby County, Tennessee, area crosses state lines into Mississippi and Arkansas[17] (Figure 3.4.2a).
- The cone of depression caused by pumping in the Greenville and Indianola, Mississippi, area crosses the state line into Arkansas (Figure 3.4.2b).

Impacts from pumping that cross state lines have also been demonstrated in other confined interstate aquifers in the Mississippi Embayment Aquifer System. For example, Haugh (2012) used the USGS MERAS model to simulate the impacts of pumping from the Fort Pillow Aquifer by a power plant in Southaven, Mississippi. The model showed that the cone of depression caused by the simulated pumping from the Fort Pillow Aquifer extended into both Tennessee and Arkansas (Haugh, 2012, Figure 11) (Figure 3.4.3). Similar results were observed when pumping was simulated for another power plant in Benton County, Mississippi (Haugh, 2012, Figure 13).

Both reported data and mathematical models show the continuity of the MSSA across state lines by demonstrating that pumping from the MSSA in one state can and does impact the MSSA in another state. Wells in the various states overlying the MSSA are pumping from a common water resource, the MSSA. This evaluation further supports my opinion that the MSSA is an interstate aquifer.

3.5 The MSSA has been and is a dynamic natural system. Groundwater flow in the MSSA was not influenced by state lines under pre-development conditions and is not influenced by state lines under current conditions.

The MSSA is a dynamic natural system; it receives water from precipitation, transports water to natural discharge locations, and yields water to wells. While there is a high volume of groundwater beneath the north Mississippi-west Tennessee area at any given time, water is constantly entering, flowing through, and discharging from the system at natural discharge locations or by being pumped out of the ground. The continuing cycle of recharge and discharge for aquifers is well established (Alley *et al*., 1999; Winter *et al*., 1998).

In 1939, Tolman and Stipp (1939, p. 1,700) wrote:

> The significance of the fact that ground water never occurs as a stationary water body should be stressed. Ordinarily, the subsurface reservoir is continuously

[17] Note that some of the drawdown indicated by the cone of depression centered in Shelby County is caused by pumping in Mississippi, particularly in DeSoto County, where the MSSA provides the primary water supply.

> receiving additions by influent seepage from rainfall and surface water bodies and is always discharging water by natural processes. In the subsurface reservoir ground water is percolating toward the discharge area; no static ground-water bodies are known to exist.

This general principle applies to the MSSA and the Mississippi Embayment Aquifer System of which the MSSA is part. The generalized conceptual model of water flow through the MSSA was discussed in Section 2.2. For example, Figure 2.2.2[18] shows an east-west cross-section with water entering the Middle and Lower Claiborne aquifers, the dominant portions of the MSSA, and moving through those aquifers up into the overlying formations. Similarly, Newcome (1976) describes the Sparta Sand Aquifer in Mississippi as receiving recharge from precipitation on its outcrop and subcrop area and discharging water to the alluvium in the Mississippi River Valley.

The MSSA is thus a dynamic natural system and not a static, isolated pool of water. While groundwater generally moves at a slower pace than surface water in a stream or river, groundwater does move, and it has been moving through the MSSA since long before pumping began.

Political borders have no influence or impact on groundwater movement. Groundwater flow patterns are governed by the interaction of physical factors such as rainfall, ground surface features, subsurface geology, and pumping, among other factors.[19] This principle is supported by the particle tracking figures discussed in Section 3.3, which show that the water flow pathways in the MSSA clearly cross state lines but are unaffected by those political boundaries. Further support for this principle is seen in Figures 3.2.1a, 3.2.1b, and 3.3.3.

3.6 Before and after pumping began, all groundwater entering the MSSA in Mississippi eventually leaves Mississippi.

Based on the fundamental principles of water movement through aquifers, groundwater entering and flowing through the MSSA beneath Mississippi will ultimately leave the state by either being pumped out of the ground in Mississippi or by continuing to flow until it leaves Mississippi.

Mississippi's Complaint seems to focus exclusively on MSSA groundwater flow at the Mississippi-Tennessee state line (Mississippi, Attorney General, 2014). However, groundwater in the MSSA also flows from Mississippi to states other than Tennessee. Mississippi's state political borders are simply lines drawn by humans that are projected onto a natural system that existed long before Mississippi and Tennessee became states.

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[18] Figure 2.2.2 was developed originally by Arthur and Taylor (1990) as part of the work under the USGS Gulf Coast Regional Aquifer System Analysis program and adopted by the USGS's Mississippi Embayment Regional Aquifer Study (Hart *et al*., 2008, Figure 4).

[19] The locations of rivers can influence groundwater flow patterns, and in some cases (notably, for example, the Mississippi River), the river location and state line coincide over discrete distances. It is, however, the presence of the river, not the presence of the state line, that influences groundwater flow patterns.

Regardless of MLGW pumping rates, or other pumping in Shelby County, all MSSA groundwater flowing through DeSoto County, Mississippi, that is not pumped by wells in DeSoto County will eventually leave Mississippi. The same can be said for MSSA groundwater flowing anywhere in Mississippi. It will all eventually leave Mississippi, if it is not pumped in Mississippi. However, the groundwater that leaves is continuously replenished, as it is replaced by recharge from precipitation, maintaining a dynamic equilibrium of water in the MSSA. The groundwater in the MSSA beneath Mississippi at any given time is merely passing through as part of the overall hydrologic cycle (see Section 2.1). Pumping by MLGW and other Shelby County users of groundwater affects only the pathways by which some of the MSSA water leaves Mississippi – not the fact that it ultimately leaves Mississippi. This concept further confirms that the MSSA is a shared, interstate resource.

For each and all of the reasons summarized in this Section and detailed throughout my Report, it is my opinion that the MSSA, including the water in it, is an interstate resource that is common to and shared by Mississippi, Tennessee, and the other states that overlie it.

Exhibit 2

Excerpts from
Expert Report of Steven P. Larson

(June 30, 2017)

Expert Report of
Steven P. Larson

No. 143, Original

State of Mississippi v. State of Tennessee; City of Memphis, Tennessee; and Memphis Light, Gas & Water Division

Prepared for:

State of Tennessee

Prepared by:

____

Steven P. Larson

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June 30, 2017

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Section 2
Opinions and Conclusions

4. The following is a list of my expert opinions developed based on a review of relevant scientific documents, reports, and other information and on my education and experience as a hydrologist specializing in groundwater hydrology. In short, I conclude that the groundwater of the Middle Claiborne aquifer is an interstate water resource based on these opinions:

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.

5. The Middle Claiborne aquifer constitutes a single hydrological unit and contains an interconnected body of groundwater that underlies parts of eight states. 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.

6. The geologic strata that constitute the Middle Claiborne aquifer are referred to by different names in different areas. For example, in Mississippi, the term Sparta Sand is used to refer to those geologic strata, while they are referred to as the Memphis Sand aquifer in Tennessee (as well as Missouri and some areas of Arkansas). Reports by the U. S. Geological Survey (USGS) refer to these same geologic strata as the Middle Claiborne Aquifer and provide a table that cross references different names that are used to refer to the same geologic strata (e.g., Hart et al., 2008, Table 1 at 2).[1]

7. From a hydrological perspective, determining whether the Middle Claiborne aquifer constitutes an interstate resource requires a holistic consideration of all the groundwater within it. The groundwater in the Middle Claiborne aquifer cannot be meaningfully separated on a drop-by-drop basis, because that groundwater is not static and is continuously moving from one place to another. Although the physical migration process may occur relatively slowly (e.g., a few hundred feet per year), water that recharges or enters the aquifer cannot remain in one place. Instead, water that feeds into the Middle Claiborne aquifer from different sources of recharge is subject to the force of gravity and begins a journey toward places of discharge from the aquifer (Bell and Nyman, 1968 at 11).

8. The Middle Claiborne aquifer is a continuous hydrogeologic unit that spans a broad regional area and underlies parts of eight states. This hydrogeologic unit is composed largely of extensive deposits of sand with little interbedded clay. These extensive sand deposits allow the unit to contain large amounts of groundwater that can be pumped for water supply. The aquifer

[1] For simplicity, this report refers to this aquifer as the Middle Claiborne aquifer.

has provided a significant source of water to groundwater users in Arkansas, Louisiana, Tennessee and Mississippi. The continuity of this hydrogeologic unit beneath parts of multiple states leads me to conclude that it is an interstate water resource.

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.

9. The Middle Claiborne aquifer is part of a broader, regional aquifer system, which I will refer to as the Mississippi Embayment regional aquifer system, that extends across the boundaries of eight states. An acronym, MERAS (Mississippi Embayment Regional Aquifer Study), has been used to refer to a regional aquifer study of the Mississippi Embayment aquifer system that has been conducted by the USGS (Hart et al., 2008). To simplify subsequent discussions, the MERAS acronym will be used to refer to either the aquifer system or the aquifer study because they are essentially one and the same. The three major aquifers (occupying different vertical positions beneath the ground) in the MERAS are distinct hydrogeologic units, but they are connected to one another hydrologically and cannot be considered or studied in isolation. Throughout the MERAS, there are no physical barriers dividing the groundwater into discrete intrastate portions. Furthermore, the groundwater throughout the MERAS is interconnected with multiple bodies of flowing surface water, and together they form an integrated hydrogeologic system that includes stream flow on the land surface and groundwater flow beneath the land surface. Just as the other aquifers in the MERAS are interstate water resources to which the Middle Claiborne aquifer is connected, the surface streams are, or are connected to, interstate surface waters (including, most importantly, the Mississippi River). The Middle Claiborne aquifer has hydrological connections to waters in this larger hydrologic system, and it cannot be considered in isolation from those other interstate waters.

10. Hydrologists who study the Middle Claiborne aquifer recognize that it cannot be effectively analyzed in isolation from the rest of the MERAS. Numerical models of the MERAS or the Middle Claiborne aquifer reflect this view, as models include parts of multiple states within their geographic scope. Hydrological models of the aquifer system do not take into account political borders, which are not relevant to analysis of groundwater flow in the aquifer. Instead, the recognized boundaries of the Middle Claiborne and other aquifers and confining units of the MERAS are based on hydrological and geological characteristics – for example, the Middle Claiborne is bounded on the east where it outcrops in Tennessee and Mississippi. To construct a numerical model of the Middle Claiborne, a hydrologist must determine the regional extent of the aquifer unit and its hydrological connections to other aquifer units and to surface streams. The fact that the numerical models of the Middle Claiborne are grounded on interstate connections and intended to simulate interstate conditions further supports my view that the groundwater within the Middle Claiborne aquifer is an interstate resource.

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.

11. Mississippi's attempt to identify intrastate groundwater that is "stored" permanently within its territory is hydrologically unfounded. Groundwater that is "stored" within the aquifer system is not static. On the contrary: the groundwater in the Middle Claiborne aquifer, like the surface water to which it is hydrologically connected, moves continuously across state boundaries within the hydrologic system.

12. Under natural conditions, the groundwater in the Middle Claiborne aquifer lying beneath Mississippi's territory would not have stayed there indefinitely. 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 from rainfall infiltration and groundwater flow from overlying or underlying hydrogeologic units. Prior to development of groundwater for water supply within the MERAS, groundwater flowed from Mississippi into other states (including Tennessee, Arkansas, and Louisiana) and ultimately toward places of discharge such as the Mississippi River. To be sure, groundwater flow toward places of discharge has changed over time as groundwater development for water supply has increased and redirected that flow. Those changes, however, have only affected the *direction* and the *rate* of the natural groundwater flow. They have not altered *the fact* that the groundwater within Mississippi's territory would inevitably have moved out of the state even without any pumping.

13. Mississippi's attempt to divide the water in the aquifer into "interstate" and "intrastate" portions conflates the hydrologic concepts of groundwater flow, groundwater recharge, and groundwater storage. These represent different components of the hydrologic water budget and should not be conflated to refer to similar phenomena. Mississippi appears to suggest that a decrease in present water levels (or "hydraulic head") indicates that water has been "taken out" of the aquifer. In fact, water is flowing out of the aquifer continuously even when water levels are static. Mississippi also appears to suggest that an increase in aquifer *discharge* necessarily means that present water levels (head) will be decreased, but that is not the case. Groundwater flow can occur with no change to the amount of groundwater storage, in either the long or the short term, depending on groundwater recharge.

Opinion 4. The United States Geological Survey has repeatedly recognized that the Middle Claiborne aquifer is an interstate resource.

14. For more than 50 years, the USGS has expressed the consistent view that the Middle Claiborne aquifer – and the groundwater within it – form part of a regional water resource that extends into multiple states. The USGS studies recognize the hydrological interconnections between the Middle Claiborne aquifer and the remainder of the regional, interstate MERAS system. In its published analyses, the USGS also has expressly recognized that the MERAS is a "regional" aquifer system that must be studied and managed on an interstate basis. This view,

Section 3
Bases of Opinions and Conclusions

16. The following section provides a discussion of the bases for the opinions and conclusions that were described in Section 2.

Hydrology and Groundwater Flow – Terminology and Principles

17. The scientific field of hydrology relates to the study and evaluation of water in all of its various forms on and beneath the earth's surface. The earth's water circulates continuously in a process referred to as the hydrologic cycle (Freeze and Cherry, 1979 at 3). Water vapor in the earth's atmosphere produces rainfall that provides a source of water to the earth's surface, which in turn flows in streams and rivers and accumulates in lakes and oceans. Some of the water that falls on the earth's surface infiltrates into the subsurface and becomes groundwater, which then flows toward places of discharge into streams, rivers, lakes and oceans. Throughout this process, water evaporates from streams, rivers, lakes, oceans and other sources and replenishes the water vapor in the atmosphere and the cycle continues. This cycle is illustrated in Figure 1 below, a diagram prepared by the USGS.

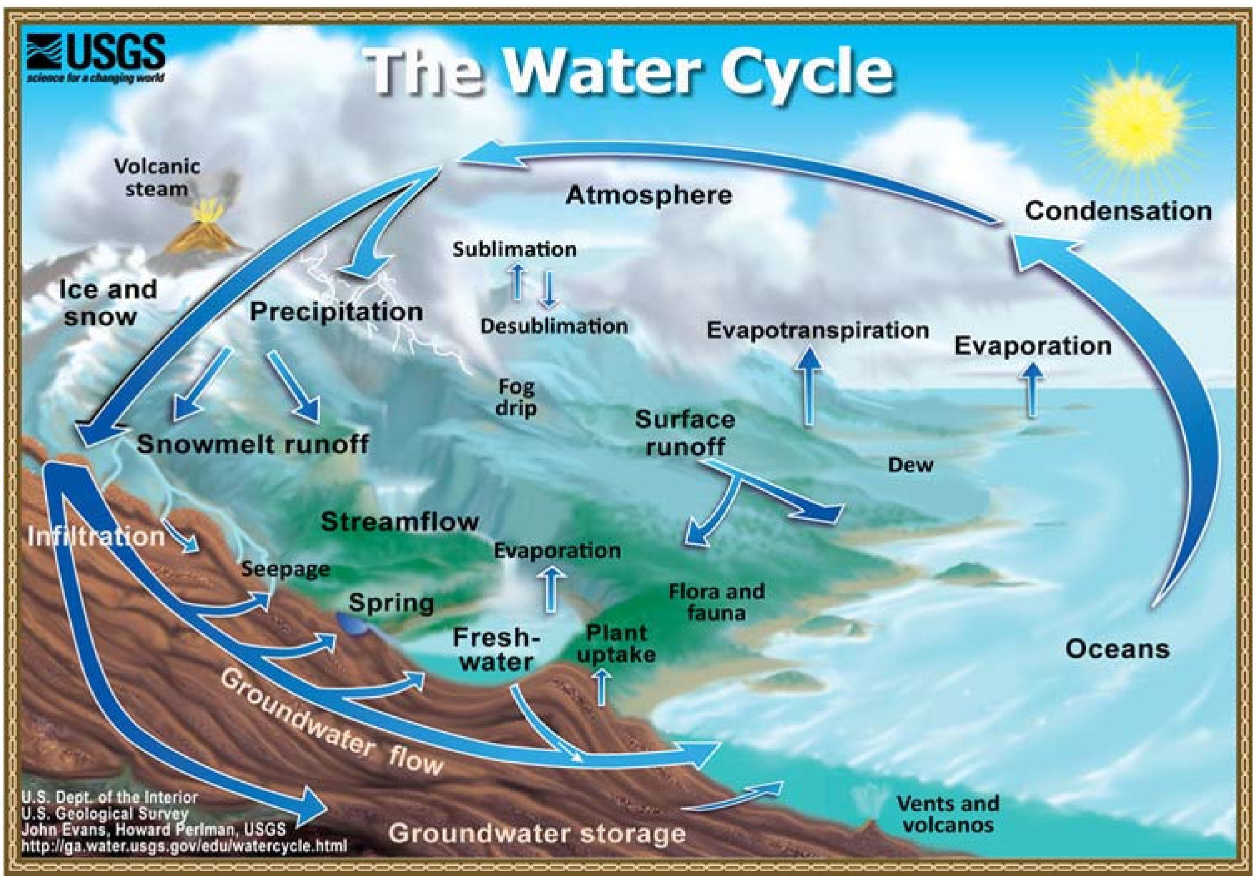

Figure 1: Illustration of the Hydrologic Cycle
(taken from https://water.usgs.gov/edu/watercycle.html)

18. Surface water (water in streams, rivers, lakes, and reservoirs) and groundwater (water held in underground soil or rock) are the principal forms of water resources developed for human use and consumption (Freeze and Cherry, 1979 at 6). The circulation and movement of surface water and groundwater are a fundamental part of the hydrologic cycle. The flow of surface water in streams and rivers is largely controlled by surface topography (that is, it flows downhill under the force of gravity) and generally forms a network of pathways that lead back to the ocean. Similarly, groundwater flow is largely controlled by local and regional topography, although it is much more widely distributed than surface water. Groundwater is an important and integral component of the hydrologic cycle. As noted by Freeze and Cherry (1979 at 8), "*(t)he days when groundwater and surface water could be regarded as two separate resources are past. Resource planning must be carried out with the realization that groundwater and surface water have the same origin*."

19. The basic structures of groundwater systems are generally created by large-scale geologic processes (Freeze and Cherry, 1979 at 145-146). Groundwater systems are often composed of layers of different geologic materials, like a multi-layer cake. Geologic layers or strata can develop over long time periods due to erosion and deposition of sediments in streams, rivers, lakes, and oceans. The sediments in the geologic layers can become consolidated as they become buried by more sediment and can be deformed by tectonic and other geologic forces. The study of the layers in these systems is called stratigraphy, and the study of the geological characteristics of the layers' materials is more particularly lithostratigraphy.

20. Layers can form distinct units comprising similar materials, each with its own geologic and hydrologic properties. Layers that are relatively permeable (that is, allow groundwater to move more easily) are generally referred to as aquifers. Other layers may be much less permeable than the aquifers and function as "confining layers" when they overlie an aquifer. Confining layers inhibit groundwater flow out of and into an aquifer, but are rarely a complete barrier. An aquifer can directly overlie another aquifer, in which case a confining layer would not be present to inhibit flow between the aquifers.

21. An aquifer overlain by a confining layer is called a confined aquifer. Groundwater in a confined aquifer will be under pressure such that when a well is drilled into the confined aquifer, pressure causes the water level in the well to rise above the top of the aquifer. The level to which the water in a confined aquifer would rise at any given point in the aquifer in a tightly cased well is called the potentiometric surface (or "hydraulic head"). "Hydraulics" is the science of fluid mechanics, describing the physical characteristics of a fluid, including its movement under different conditions. The hydraulic head of groundwater describes its mechanical energy, which is primarily a function of gravity and pressure. Hydraulic head is a combination of the elevation head – the height of the position of measurement relative to some arbitrary datum, reflecting the force of gravity – and the pressure head, which reflects external pressure on the water at that position, in this case due to its confinement.

22. A potentiometric surface at a given point can therefore be determined by taking measurements from an appropriate well screened in the confined aquifer, and measurements from multiple wells can be used to estimate the potentiometric surface over a given area of an aquifer.

Water in an aquifer will move from areas of high potentiometric surface to low potentiometric surface. The exact velocity and direction of flow depend on several variables (for example, the hydraulic conductivity, the hydraulic gradient, and porosity of the aquifer material). Heath (2004) provides a good reference for basic principles and terminology related to groundwater hydrology.

23. Because of its physical and chemical properties, groundwater's flow in the aquifer can be described or modeled only in terms of aggregations of water molecules. As groundwater moves, the laws of physics cause individual particles' flow paths to not be straight or predictable, but "tortuous" or winding; particles are subject to mechanical dispersion or mixing (see, for example, Heath, 2004 at 19). Although the majority of molecules will be moving in a particular direction, some molecules will be moving in other directions. The "direction" and "velocity" of groundwater flow is actually the *average* direction and velocity of the actual direction and velocity of individual particles, which do not move uniformly. Thus, the flow of water in an aquifer cannot be separated into certain, discrete paths taken by all of the water in a particular location. When we say that water in a location in an aquifer such as the Middle Claiborne is moving in a particular direction, we mean that that is the average direction of the water movement; individual water molecules are moving in other directions.

24. Because groundwater is continually flowing throughout an aquifer, it is continually both recharging and discharging. Recharge generally comes indirectly from precipitation; it may directly seep into the aquifer, or it may become part of streams or other surface water that, in turn, seep into the aquifer. Aquifers may also recharge one another through vertical seepage upward or downward. A confined aquifer that has an unconfined portion (an "outcrop") may receive much of its recharge there. Aquifers discharge into streams or other surface water, into other aquifers, and into wells where developed. (Some streams may both contribute water to and receive water from an aquifer, either in different places or during different seasons.) If total recharge and discharge are equal and remain constant, the amount of water in an aquifer will remain constant (even though the particular water in the aquifer is continually moving). If they are not, the total amount will change until recharge and discharge reach a new equilibrium.

25. The principle mechanism for utilizing groundwater resources is through wells. Pumping of groundwater from wells will change groundwater levels (or the potentiometric surface) and groundwater flow pathways. These changes are natural results of pumping, as groundwater flow will be redirected from its prior trajectory toward the locations of wells, where the groundwater can be removed and used for a variety of purposes such as irrigation water supply or municipal water supply.

26. When pumping from a well begins, groundwater levels near the well decline and groundwater flow is directed toward the well (Freeze and Cherry, 1979 at 315). As pumping continues, the area of declining groundwater levels expands in an increasing, approximately circular area around the well, and the rate of decline in groundwater levels typically decreases as the area experiencing declining levels increases. At some point, the groundwater levels can become relatively stable even though the pumping has continued, and the rate of decline will approach zero. Simply put, the pumping eventually creates a new stable pattern of groundwater flow where flow that previously discharged at other locations now discharges at the well. The

lowered or "depressed" water levels around a well, which are lowered less as distance from the well increases, form a pattern that is sometimes referred to as a "cone of depression" centered on the well.

27. Geologic layers can extend over broad areas and across political boundaries. The layers may be relatively flat-lying or may be sloping because of large-scale geologic processes. As a practical matter, the layers are basically static in that they do not move from one place to another. As noted, however, groundwater that occurs within the geologic layers is not static. Just like water on the ground surface, groundwater in the pore spaces and other openings within the geologic layers moves under the force of gravity from one place to another. If geologic layers extend across political boundaries, the groundwater in those geologic layers often moves from one jurisdiction to another.

28. The delineation and characterization of an aquifer are determined by drilling wells or boreholes into the earth and observing the types of materials that are extracted during the drilling. This information is often supplemented by geophysical studies that record the response to various stimuli such as electric current or sonic waves. Testing of wells can be conducted to evaluate the hydraulic characteristics of an aquifer such as transmissivity, hydraulic conductivity, and storage capacity.

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.

29. The areal extent of the MERAS is shown on Figure 2 (adapted from Plate 1 of Arthur and Taylor, 1998). The Memphis Sand aquifer underneath Memphis and Shelby County, Tennessee, is a part of the MERAS and consists of what are referred to more broadly as the "Middle Claiborne" and "Lower Claiborne" layers, which are excellent sources of water because they consist primarily of highly transmissive sand. In Mississippi, the "Sparta Sand" consists of the same two layers in the north, while south of a "transition line" in Mississippi (see Figure 4), there is a confining layer between the Middle and Lower Claiborne, as shown in Figure 3 (Clark and Hart, 2009, Table 1 at 8). The Middle Claiborne, referred to both as the Memphis Sand and the Sparta Sand, is a single aquifer that extends across the Tennessee-Mississippi border. In fact, the Middle Claiborne extends underneath eight states, as shown in Figure 4.

30. The aquifer is composed of various layers of sand, silt, clay, and lignite (Arthur and Taylor, 1998 at I11). The more permeable sand layers provide most of the water to wells that are screened in the aquifer. The total thickness of sands within the Middle Claiborne aquifer ranges from about 100 to more than 700 feet (Arthur and Taylor, 1998 at I12).

31. As discussed above, an aquifer is a single layer and a single geological and hydrological unit. The Middle Claiborne aquifer is not divided into distinct parts by any barrier, either at the Mississippi-Tennessee border or elsewhere. There is no physical impediment that precludes

groundwater in the Middle Claiborne from migrating across the various state boundaries (whether Mississippi-Tennessee, Mississippi-Arkansas, Arkansas-Tennessee, or others).

32. All the groundwater in an aquifer like the Middle Claiborne is hydraulically and hydrologically connected. That means that discharge from one part of the aquifer (for example, from wells) affects water elsewhere in the aquifer; similarly, recharge to one part of the aquifer affects water elsewhere in the aquifer. As a confined aquifer (in the relevant region, i.e., other than at the outcrop region), the Middle Claiborne aquifer is under pressure. Within the aquifer, water will tend to move from areas of higher hydraulic head (the combination of pressure and elevation) toward areas of lower hydraulic head. Anything that affects pressure or hydraulic head in one part of the aquifer will necessarily have an effect on the water (and pressure or hydraulic head) around the area and, albeit on a decreasing scale, on the groundwater in other parts of the aquifer. Thus, pumping from the aquifer in one place will have such an effect, as would pumping from connected aquifers such as the shallow or alluvial aquifer. In this sense, all the water in the aquifer forms a single body.

33. Groundwater is not precisely analogous to surface water, and the groundwater in an aquifer is not precisely analogous to a surface water body like a lake. However, based on the above characteristics, it is fair to describe the groundwater in the Middle Claiborne as a continuous body of water that extends underneath eight states, and therefore an "interstate water resource."

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.

34. As noted, the Middle Claiborne aquifer is part of a regional aquifer system that can be referred to as the Mississippi Embayment regional aquifer system (MERAS). The MERAS is a well-documented hydrogeological system defined by hydrologic extent rather than political borders and extends over an area of about 160,000 square miles, underlying parts of eight states (see Figure 2). In particular, Figure 2 shows the outcrops of the various geologic layers of the MERAS. The Claiborne group, which includes the Middle Claiborne aquifer, is shown outcropping through middle Mississippi and western Tennessee, among other places.

35. The aquifer system is composed of six aquifers and five confining layers. The illustration in Figure 3 below (Figure 8 from Clark and Hart, 2009, at 13) depicts the various aquifer and confining layers that comprise the MERAS. In order from the surface down, the major aquifers and confining layers (with their geologic names) are:

a. The alluvial or "shallow" aquifer, which is generally unconfined;
b. The Vicksburg-Jackson confining unit;
c. The Upper Claiborne aquifer, a minor aquifer sometimes referred to as the Cockfield formation;
d. The Middle Claiborne confining unit, sometimes referred to as the Cook Mountain formation;
e. The Middle Claiborne aquifer, sometimes referred to as the Sparta Sand or Memphis Sand;

f. In some parts of the MERAS, including central Mississippi, a Lower Claiborne confining unit, which includes parts sometimes referred to as the Zilpha Clay, Winona Sand (an aquifer), and Tallahatta formations;

g. Where there is a Lower Claiborne confining unit, the Lower Claiborne aquifer, sometimes referred to as the Meridian Sand;

h. The Middle Wilcox, which in the area of Memphis is a confining unit referred to as the Flour Island formation;

i. The Lower Wilcox aquifer, which in the area of Memphis is referred to as the Fort Pillow Sand.[2]

36. Beneath the Wilcox formations lies the Midway confining group, which may be considered to include, under the Fort Pillow Sand, the Old Breastworks formation. Under the Midway confining group lies the Cretaceous aquifer system, which is not considered to be part of the MERAS (see generally Hart et al., 2008; Clark and Hart, 2009). The Midway confining group is considered to have very low transmissivity, effectively separating the MERAS from aquifers below it.

37. Some of the MERAS layers change "facies" (geological appearance or character) across the areal extent of the MERAS. However, the Middle Claiborne is fairly consistent across the MERAS. In the area of Memphis, there is no Lower Claiborne confining unit; as discussed, it appears somewhat south of the Mississippi-Tennessee border (see Arthur and Taylor, 1998, Plate 2), and so "Memphis Sand" may refer to the Middle and Lower Claiborne aquifers, which are not divided by a confining layer.

38. Note that the cross-sectional diagram shown on Figure 3 is exaggerated vertically by 200 times. The purpose of vertical exaggeration is to allow better visualization of the vertical characteristics of the subsurface strata. On Figure 3, the horizontal span of the diagram extends over a distance of about 240 miles while the vertical span extends over a distance of only about one-half mile. Without vertical exaggeration, the diagram would be unreadable on a typical page size. The slopes of the layers shown on the diagram are therefore also highly exaggerated. The actual slopes of the various layers shown on the diagram are only about 30 feet per mile or less, or a slope of less than one percent.

[2] In other states, local naming conventions may apply other names to these recognized hydrogeologic units.

39. The names given to specific aquifers and confining layers of the MERAS can vary depending on location. As discussed above, the Middle Claiborne aquifer is also referred to as the Memphis Sand aquifer in Tennessee, while in Mississippi, the Middle Claiborne is also referred to as the Sparta Sand aquifer.[3] Consequently, references to the Memphis Sand aquifer and the Sparta Sand aquifer refer to parts of one continuous aquifer (the Middle Claiborne). There is no hydrologic or geologic distinction between the Sparta Sand aquifer in northern Mississippi near the Mississippi-Tennessee border and the upper portion of the Middle Claiborne aquifer in Tennessee.

40. The primary aquifers in the MERAS are the Mississippi River Valley alluvial aquifer and the Middle Claiborne aquifer (Clark and Hart, 2009 at 2). The Middle Claiborne aquifer is generally the most transmissive and productive aquifer in the MERAS, and is therefore the most extensively developed aquifer within the MERAS (Arthur and Taylor, 1998 at I11). A map depicting the thickness of the Middle Claiborne aquifer within the MERAS is shown on Figure 4 below (Figure 13 from Hart et al., 2008 at 20). As the map shows, the Middle Claiborne extends from Missouri, Illinois, and Kentucky in the north to Alabama and Louisiana in the southeast and southwest, respectively. In comparison, the Lower Wilcox has much less areal extent than the Middle Claiborne within the entire MERAS, but like the Middle Claiborne is a multistate aquifer. The Mississippi River Valley alluvial aquifer is also a multistate aquifer, providing substantial water (especially for agriculture) in Arkansas, Mississippi, and Tennessee. The various aquifers in the MERAS are most sensibly considered together, because they are hydrogeologically connected. Pumping in one aquifer may have effects, to different degrees, in other aquifers (see Clark et al., 2011 at 32).

41. The aquifers in the MERAS are also connected with many surface waters in the region, and particularly to streams and rivers, as shown in Figure 5, below. In places where stream elevations are above the levels of underlying groundwater, seepage losses from the streams are a component of recharge to the groundwater. In places where stream elevations are below the levels in underlying groundwater, the streams can act as a location for groundwater to discharge into the streams. Most centrally, the Mississippi River lies close to the axis of the dip of the Mississippi Embayment. Under predevelopment conditions, therefore, regional topography led groundwater in various aquifers to flow, broadly speaking, toward the axis and to discharge upward, through the various aquifers and confining layers, into the Mississippi River (Clark et al., 2011, Figure 6 at 11). In other words, a significant percentage of the groundwater in the MERAS, including some of the water in the Middle Claiborne aquifer in Mississippi and Tennessee, flowed into the Mississippi River.

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[3] As noted, in parts of Mississippi, there are additional confining layers that divide the Middle Claiborne from the Lower Claiborne, which transition out toward the Mississippi-Tennessee border and the Lower Claiborne is no longer divided from the Middle Claiborne. Thus, in northern Mississippi, the Sparta Sand aquifer may refer to both the Middle and Lower Claiborne formations (where they are not divided by a confining unit) and both may be referred to as the Memphis Sand aquifer in Tennessee. This naming convention issue does not affect the continuity of the hydrogeologic units between Tennessee and Mississippi.

42. The various smaller streams and rivers in the region – see Figure 5, below – are also connected to the aquifer system. At different points, the streams may leak into the aquifers (generally, through the alluvial aquifer) or the aquifers may discharge into streams. Streams may seep directly into the Middle Claiborne aquifer in the outcrop area, or seep into the alluvial aquifer and then into the Middle Claiborne aquifer (whether slowly through the confining layer or more quickly where there are gaps in the confining layer). Changes in the streams therefore have effects on the aquifers, and changes in the aquifers (including due to pumping) also have effects on the streams (Clark et al., 2011, Figure 8 at 17, and Figure 11 at 20). The larger streams and rivers in the region that are connected to the aquifer include many tributaries to the Mississippi River. In the direct vicinity of the Shelby County-DeSoto County area, those include the Nonconnah River, the Loosahatchie River, and the Wolf River. The Wolf River, in addition to being a tributary of the Mississippi River, is itself a multistate river, flowing from Mississippi into Tennessee, and then through Memphis itself and into the Mississippi River. Recharge to the aquifers, which occurs through streams and outcrops as well as other paths, occurs throughout the MERAS and is not limited to any single state.

43. The above connections, both to other interstate aquifers and to interstate surface waters including the Mississippi River, mean that the Middle Claiborne aquifer cannot be disentangled from those aquifers and streams. Any substantial use or development of the water in the Middle Claiborne aquifer will have an effect on other interstate water resources. This leads me to conclude that the water in the Middle Claiborne aquifer would have to be considered an interstate resource independent of the fact that the aquifer is itself an interstate body.

44. As the above discussion would suggest, a hydrologist cannot create a numerical model of the groundwater in the Middle Claiborne aquifer without reference to the MERAS as a whole. Groundwater models provide a quantitative framework for evaluating the interaction among the various components of an aquifer system, including interaction with surface water. The process of creating a groundwater model involves defining the nature and extent of aquifer units and associated confining layers, estimating their physical properties such as transmissivity, and defining and quantifying associated hydrologic features such as streams, rivers, and lakes. This information is assembled in a quantitative numerical framework for computing rates and directions of groundwater flow and interaction with other hydrologic features. Groundwater models are then calibrated by comparing calculated values such as groundwater levels to corresponding measurements. The calibration process seeks to ensure that the groundwater model reasonably represents the actual groundwater system.

45. The leading numerical model of the MERAS as a whole is the USGS MERAS model. The current MERAS model has been largely developed by Clark and Hart (2009) based on the USGS's MODFLOW computer code, which is a widely-used computer code that can serve as the structure for groundwater flow models of particular regions. The model domain covers an area of about 78,000 square miles that includes parts of eight states and includes about 6,900 miles of surface streams. The model domain is divided into a grid network of cells that each represent an area of one square mile. The vertical dimension of the grid network includes 13 model layers to represent the various aquifers and confining units of the MERAS. To calibrate the model, an historical simulation beginning in 1870 and extending for 137 years to 2007 was developed. The

simulation included estimated historical pumping from the various aquifers, and results of that simulation were compared to historical measurements of groundwater levels and stream flows to calibrate the model parameters.

46. Clark and Hart (2009) used the 2005 version of the USGS's MODFLOW code to create an updated numerical model of the MERAS. The layer designations on Figure 3 refer to the subdivisions that were established to simulate the various aquifers and confining units; some of the aquifers and confining layers were divided into more than one layer for purposes of the model, resulting in 13 model layers. The differentiation of layers, including dividing single formations into multiple layers for purposes of the model, is necessary to model the complex effects that different aquifers have on one another. The hydrologic effects of the Mississippi River and its tributary streams are included through their geographic locations and interconnection to the model layers. Hydrogeologic characteristics of the aquifers, confining units, and streams such as transmissivity (a combination of hydraulic conductivity and thickness), storage coefficients, and seepage rates were estimated and refined through model calibration. The ultimate result is a mathematical model that is a tool for evaluating groundwater flow and effects of groundwater development within the large regional domain covered by the model.

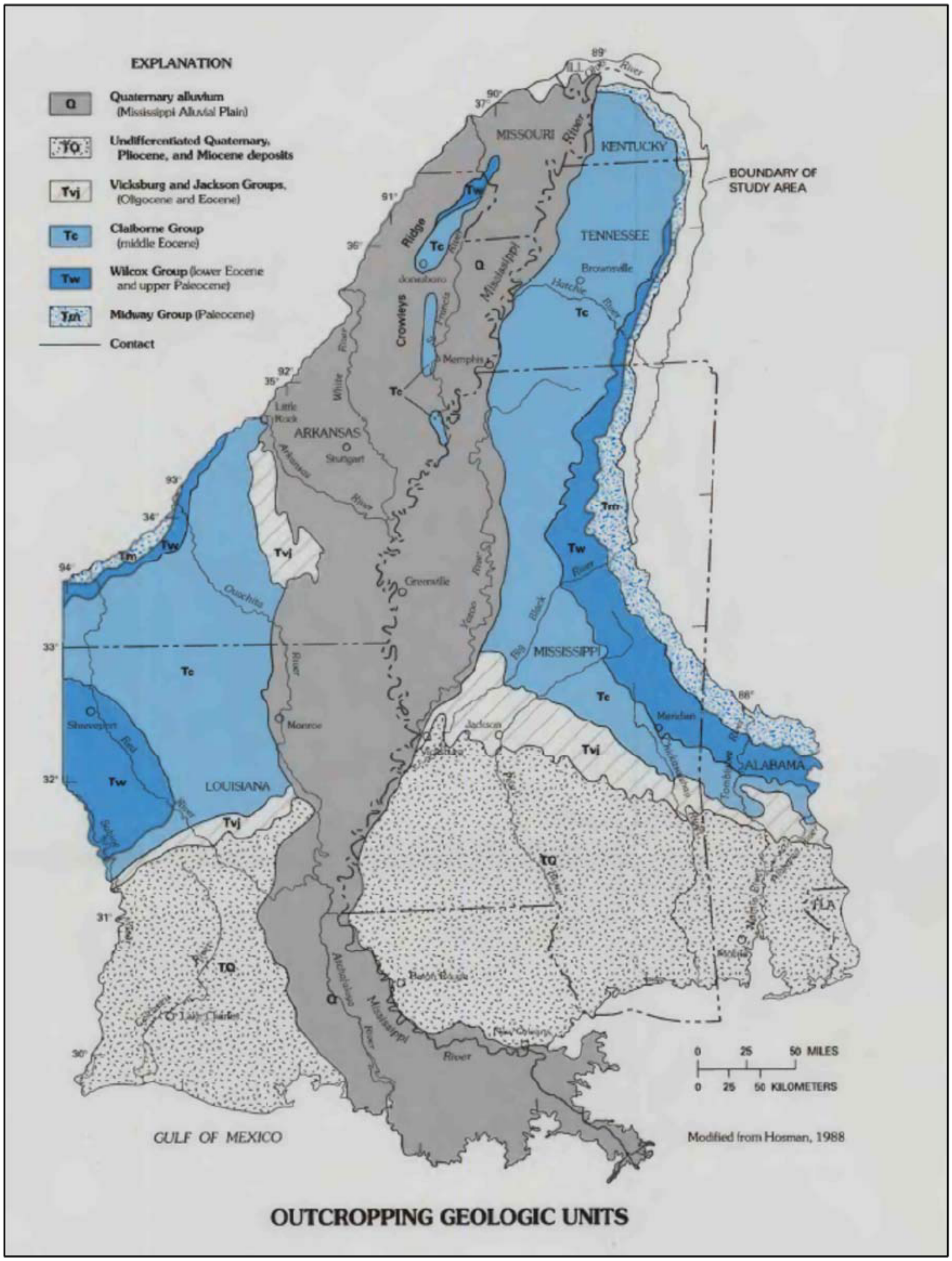


Figure 2: Mississippi Embayment Regional Aquifer System
(Adapted from Arthur and Taylor, 1998, Plate 1)

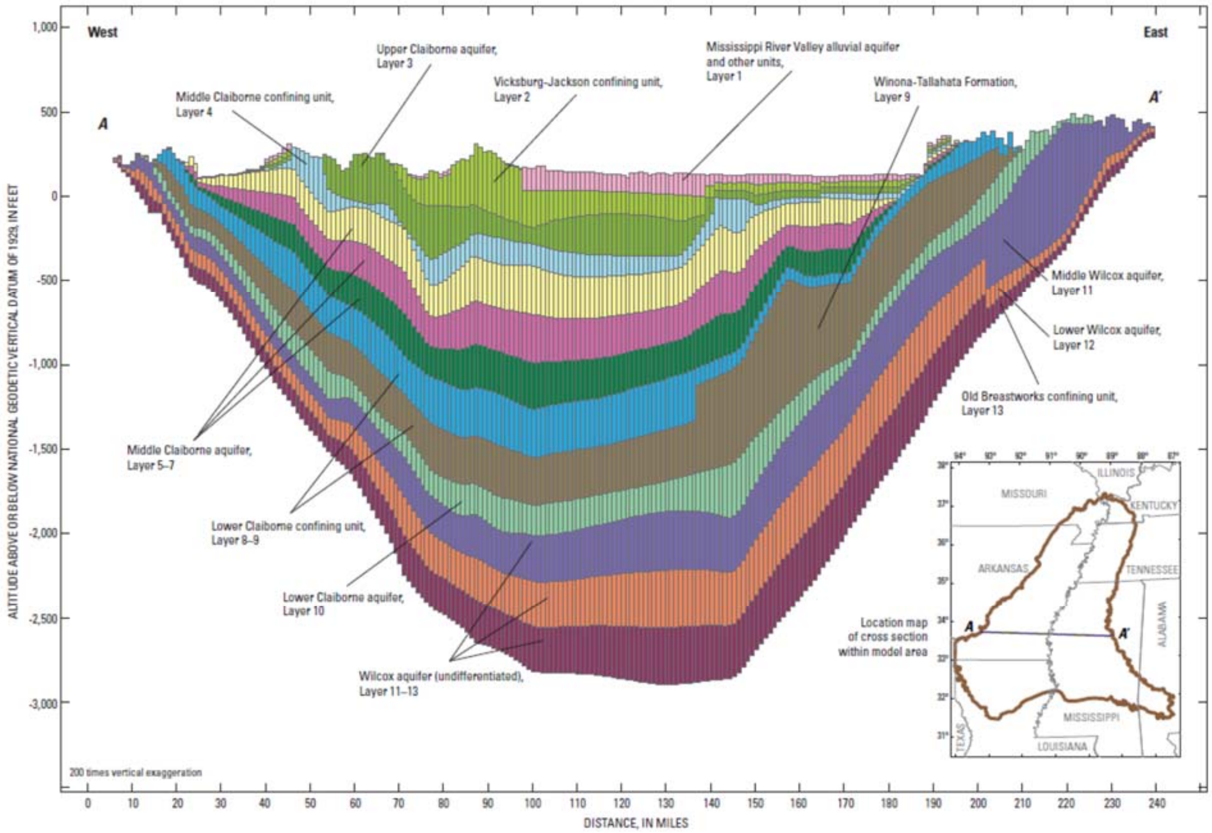


Figure 8. Cross section of model grid from west to east through row 258. Cross-section location is shown on inset map.

Figure 3: Example cross-sectional profile of the MERAS
(Clark and Hart, 2009, Figure 8 at 13)

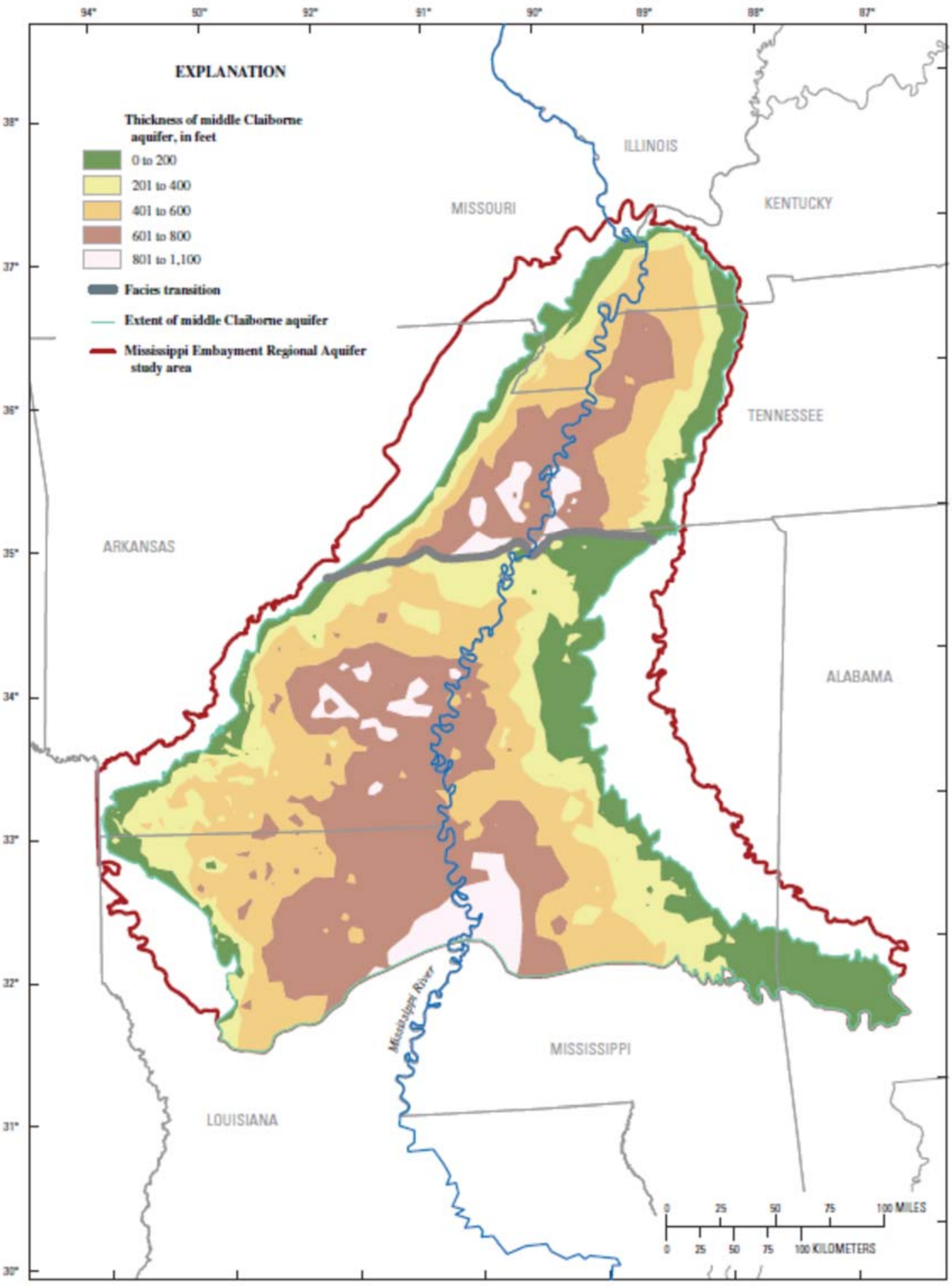
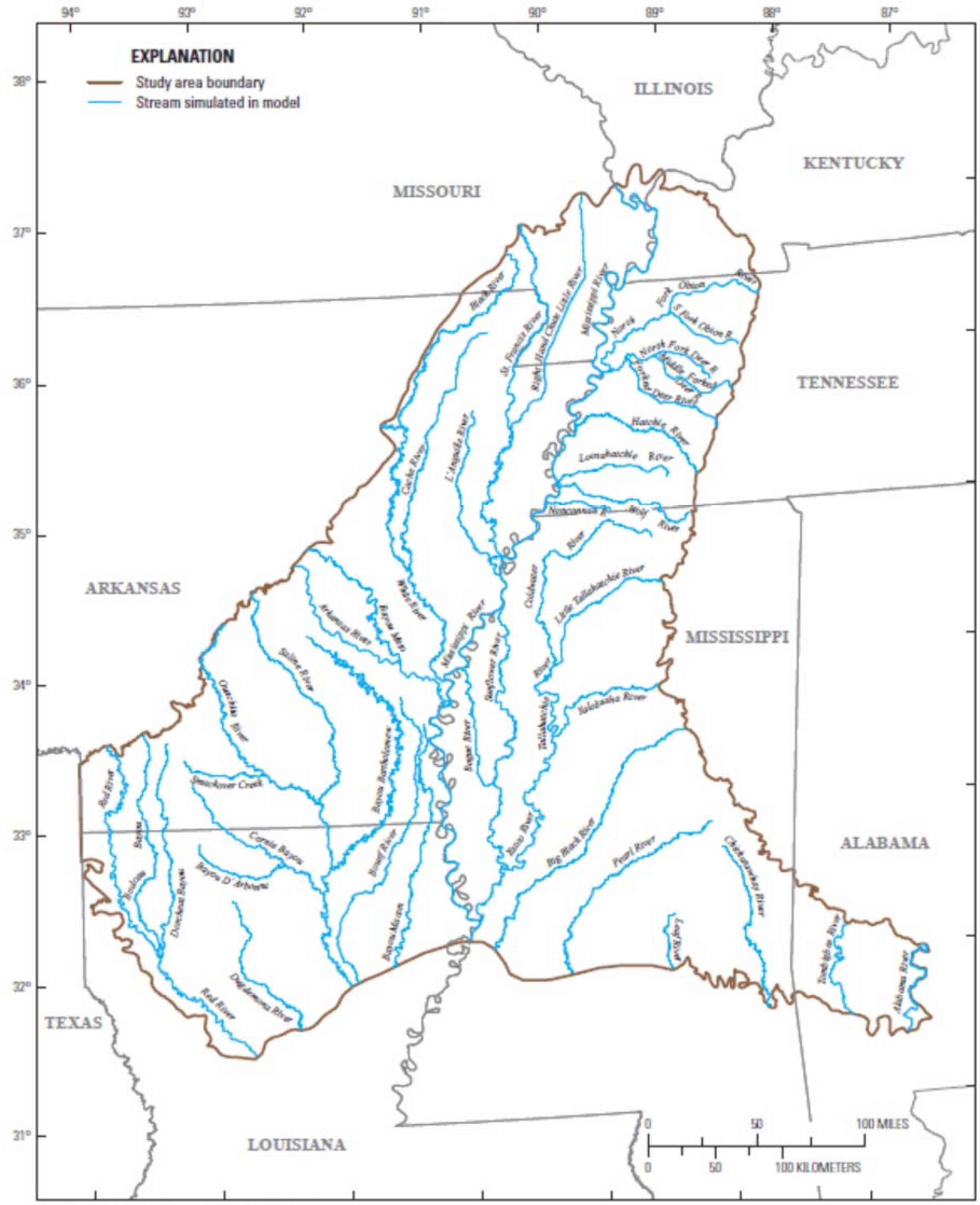


Figure 13. Thickness of middle Claiborne aquifer.

Figure 4: Thickness of Middle Claiborne Aquifer
(from Hart et al., 2008, Figure 13 at 20)



Base from U.S. Geological Survey digital data, 1:100,000

Figure 2. Streams simulated in the study area.

Figure 5: Stream Network Interconnected with the MERAS
(from Clark et al., 2011, Figure 2 at 6)

47. Figure 5 depicts various streams and rivers that were included in the groundwater model of the MERAS developed by the USGS (Clark and Hart, 2011). The streams and rivers were included as part of the groundwater model because of their interconnection with the groundwater system and their potential influence on groundwater recharge and groundwater discharge. As discussed above, prior to significant groundwater development, the Mississippi River and other tributary streams were the primary locations for groundwater discharge within the MERAS (Clark et al., 2011 at 15). In the area around Memphis, streams were added to the model based on their "known interactions" with the Memphis aquifer (Clark and Hart, 2009 at 18). The streams are also important to model how the aquifer system is recharged by surface runoff.

48. Streams provide a hydrologic mechanism to both recharge the MERAS groundwater and to allow groundwater to discharge. For example, upper reaches of the Wolf River (which crosses the Mississippi-Tennessee border) provide recharge via seepage from the stream. In lower reaches, this flow reverses and groundwater discharges into the stream.

49. The MERAS groundwater model was calibrated using a combination of manual and automated parameter adjustments (Clark and Hart, 2009 at 37). The objective of the calibration process is to adjust various model parameters within reasonable ranges so that the model would be able to simulate groundwater levels and stream flow interactions that are consistent with corresponding measurements and observations. Clark and Hart (2009) provide various statistical and qualitative evaluations of the MERAS model calibration that characterize the level of confidence and uncertainty in model results.

50. The result of the calibration of the MERAS model is a simulation of groundwater levels, changes in groundwater levels, stream flows, and changes in stream flows over the period from 1870 to 2007. These results demonstrate the impacts of significant groundwater resource development in parts of Arkansas, Louisiana, Mississippi, and Tennessee. These results also demonstrate that in some areas, such as Shelby County, Tennessee, groundwater levels have stabilized in recent decades after declining for several prior decades.

51. The USGS MERAS model, like other numerical models, seeks to accurately simulate conditions in the Middle Claiborne by covering a multistate area, analyzing the connections among the aquifers and between the aquifer system and interstate surface waters. This further supports my view that the groundwater within the Middle Claiborne aquifer is an interstate resource, and should be considered an interstate water resource both on its own terms and because of its integral hydrological connections with other interstate bodies of water.

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.

52. I understand that Mississippi asserts that it has an interest in certain groundwater that was "stored" permanently underneath it, or that would have remained underneath Mississippi under natural conditions. There is no such groundwater: the water in the Middle Claiborne aquifer

beneath Mississippi was moving under natural conditions, and it would have moved out of the state as it was replenished by a continuing recharge of new groundwater. None of the groundwater would have remained permanently "stored" beneath Mississippi under natural, predevelopment conditions. The fact that groundwater in the Middle Claiborne aquifer is not static has been well known for a long time. Criner and Armstrong, in their 1958 report on the groundwater supply of the Memphis area, stated, "Ground water moves from the areas of recharge toward areas of natural or artificial discharge" (Criner and Armstrong, 1958 at 9). In 1968, Bell and Nyman noted, specifically with regard to the Middle Claiborne aquifer that they refer to as the "500-foot" sand, "Water in the '500-foot' sand, as in any other aquifer, moves from areas of recharge to points of discharge" (Bell and Nyman, 1968 at 11). It remains true today that no water will be permanently stored beneath Mississippi. Any assertion that water is or would be stored permanently beneath Mississippi is hydrologically unfounded.

53. I base this conclusion primarily on the most recent MERAS numerical model developed by Clark and Hart (2009) of the USGS. The MERAS numerical model was run over a historical period of 137 years, divided into 69 discrete time periods. The first of these periods was a "steady state" period representing the conditions of the MERAS before any significant pumping began, in this case dated to 1870. The first major commercial well screened in the Middle Claiborne aquifer was drilled in 1886 (Criner and Armstrong, 1958 at 16), so the 1870-time period is intended to reflect the condition of the Middle Claiborne (along with the other aquifers) prior to that well and other major groundwater development.

54. The MERAS model bases its initial, predevelopment conditions on Reed (1972). Reed (1972) shows a potentiometric map of predevelopment conditions (see Reed 1972, Figure 2) with potentiometric contours of equal head. Based on this contour map, and the fact that groundwater flow gradients are generally perpendicular to potentiometric contours, groundwater in the Middle Claiborne aquifer was flowing from Mississippi into Tennessee, Arkansas, and Louisiana. There is no identifiable location in this model where water is not flowing in a path that directs it out of the state.

55. Other models of predevelopment conditions, including that relied on by Mississippi in its Motion for Leave To File a Bill of Complaint in this case (Brahana and Broshears 2001, also a USGS report), show the groundwater under Mississippi moving out of the state. Brahana and Broshears (2001) show some groundwater movement into Tennessee and significant groundwater movement into Arkansas. The contour map does not extend far enough south to show the groundwater moving into Louisiana.

56. Based on the conditions reflected in the MERAS numerical model and others, there is no reason to believe that groundwater under Mississippi is static now or was static under predevelopment conditions. The basic geological characteristics of the MERAS, which is essentially a giant trough, lead to this continual groundwater flow. Because the MERAS is a trough or dip, groundwater in the MERAS (including in the Middle Claiborne) will tend to flow down toward the axis of the MERAS, which is the lowest point, under the force of gravity. The axis of the MERAS, however, is generally understood to be roughly parallel to the Mississippi River (Clark et al., 2011 at 8) falling, in this region, in Crittenden County, Arkansas to the west of the

river (Brahana and Broshears, 2001, at 6). Thus, under predevelopment conditions, the groundwater would broadly tend to flow toward the axis (located close to the river in Arkansas) and tend to discharge into the Mississippi River.

57. There is no geological or hydrological property of the Middle Claiborne under Mississippi that would prevent this flow out of the state, whether to Tennessee, Arkansas, Louisiana, or the Mississippi River. Mississippi appears to suggest that there is, or was, groundwater "stored" within the state. The fact that groundwater is "stored" does not mean that it is not moving; "storage" may be shorthand for describing the capacity of an aquifer for containing water, but it should not be taken to imply that the water is not flowing.

58. Like a reservoir, the Middle Claiborne aquifer under Mississippi contains a large volume of water at any given time. Also like many reservoirs, however, water is continually flowing out and continually flowing in. If the amount of water in the reservoir does not change, that reflects the fact that inflows and outflows are equal, not that the particular water in the reservoir remains the same. Similarly, if the amount of groundwater in the aquifer remains the same, that reflects the fact that discharge and recharge are the same, not that the groundwater is actually the same water.

59. Any suggestion or implication that the same groundwater remains indefinitely in the Middle Claiborne aquifer, just like any suggestion that it remains static, is incorrect. No model of either past or present conditions supports such an assertion; all models show that the groundwater underneath Mississippi in the Middle Claiborne flowed, and flows, into other states or into interstate surface waters like the Mississippi River.

Opinion 4. The United States Geological Survey has repeatedly recognized that the Middle Claiborne aquifer is an interstate resource.

60. The above conclusions rely heavily on the work of the USGS. The USGS is a federal agency, created in 1879, and is part of the Department of the Interior. It is a scientific agency that monitors and evaluates the nation's water resources.

61. The USGS has long recognized that the Middle Claiborne aquifer is an interstate water resource that needs to be studied and managed as such. An assessment of the groundwater resources associated with the MERAS is part of an ongoing nationwide program of water resource evaluation conducted by the USGS (Grubb, 1998; Arthur and Taylor, 1998). The Regional Aquifer-System Analysis (RASA) is a program started in 1978 to study and evaluate various regional aquifer systems throughout the United States (USGS, 1986). As the Foreword to one RASA paper puts it: "The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are **identified by the hydrologic extent of each system and accordingly transcend the political subdivisions** to which investigations have often arbitrarily been limited in the past" (Hosman 1996, Foreword by then-USGS Director Gordon P. Eaton) (emphasis supplied). The RASA program resulted in the Clark and Hart (2009) MERAS model,

Exhibit 3

Excerpts from
Expert Report of Brian Waldron, Ph.D.

(June 30, 2017)

Expert Report of Brian Waldron, Ph.D.

Prepared on Behalf of the State of Tennessee

In the Matter of *Mississippi v. Tennessee et al.*, No. 143, Original (U.S.)

June 30, 2017

Signed: ______________________

Brian Waldron, Ph.D.

SECTION 2. Summary of opinions

5. The central question that I have been asked to give my opinion about is whether the groundwater in the Middle Claiborne aquifer is an "interstate resource."

6. The Middle Claiborne aquifer is part of a larger set of aquifers within the regional geologic framework, the Mississippi embayment, which underlies portions of the states of Louisiana, Mississippi, Tennessee, Arkansas, Alabama, Kentucky, Illinois, and Missouri. Naming conventions of the aquifers change as they cross state boundaries and as the formations split, merge, or otherwise change over distance. Waldron et al. (2011) detailed these naming convention changes and correlated geologic formations across state boundaries. In Shelby County, Tennessee, the Middle Claiborne is locally named the Memphis Sand. In DeSoto County, Mississippi, the Middle Claiborne is locally named the Sparta Sand. The Middle Claiborne aquifer will be the geologic name applied in this report to represent the Memphis aquifer and the Sparta aquifer.

7. I understand that Mississippi asserts that a certain portion of the groundwater within the Middle Claiborne aquifer under Mississippi constitutes an "intrastate" resource because it allegedly would remain confined within the state boundaries under natural conditions, because it allegedly crosses into Tennessee only because of pumping, and because it would not otherwise flow across the Mississippi-Tennessee boundary. These assertions are not supported by the scientific consensus about the nature of the aquifer generally or by any valid analysis of groundwater flow in the aquifer.

8. The water in the aquifer is an interstate resource. I base this conclusion on two opinions, as described below.

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.

9. There is a scientific consensus that the "Memphis aquifer" and the "Sparta aquifer" are parts of one aquifer, a single hydrological unit referred to as the Middle Claiborne aquifer. The Middle Claiborne aquifer extends, continuously and without meaningful change that would prevent groundwater flow from one part to another, under Mississippi, Tennessee, and Arkansas, as well as other states. There are no physical or hydrological barriers that separate the portions of the aquifer within Mississippi from other parts of the same aquifer at the Tennessee-Mississippi-Arkansas state lines, and groundwater naturally can and does move freely across political boundaries within the aquifer.

10. The term "confined" as used in Mississippi's assertions differs in meaning from the same term used in basic hydrology when characterizing an aquifer as confined or unconfined. A confined aquifer is vertically bounded above and below by a less permeable layer such as clay that pressurizes the groundwater. As a result, when a well is emplaced into a confined aquifer, the static water level in the well rises above the basal elevation of the upper impermeable (or confining) layer. An unconfined aquifer is not under pressure, and the static water level in a well rises to the elevation of the water table.

11. 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 and does not face any hydraulic (e.g., groundwater divide) or structural impediment at the state line.

12. The groundwater under Mississippi in the Middle Claiborne aquifer is not, and was not under predevelopment conditions, "confined" to Mississippi in any meaningful hydrological sense. The concept that groundwater is or would be confined within one part of a multistate aquifer is contrary to fact that the Middle Claiborne in the area of the Tennessee-Mississippi-Arkansas state borders is a singular, hydraulically connected aquifer.

13. This consensus view of the aquifer is further demonstrated by different attempts to numerically model groundwater flow in the aquifer, and in the larger aquifer system within the Mississippi embayment. Although there are sometimes important differences between models, all models treat as fundamental the fact that the Middle Claiborne aquifer is a single hydrological unit.

Opinion 2: Under predevelopment conditions, there was substantial flow of groundwater within the Middle Claiborne aquifer from Mississippi into Tennessee.

14. With respect to predevelopment conditions, Mississippi's assertion that no groundwater (or minimal groundwater) flowed from Mississippi into Tennessee is incorrect. A number of researchers have investigated groundwater flow in the Middle Claiborne aquifer prior to 1886, when the first commercial well was drilled into the aquifer. All studies agree that there was at least some interstate flow of groundwater from Mississippi into Tennessee, Arkansas, and Louisiana under predevelopment conditions. Thus, it is not true either that all water within the aquifer would generally remain in Mississippi in the absence of pumping or that water would specifically not travel from Mississippi into Tennessee in the absence of pumping.

15. Different studies have used different assumptions and have used different "control points" (actual measurements taken from wells) in their studies of the Middle Claiborne generally and of predevelopment conditions specifically. The studies generated different potentiometric surfaces and different gradients of groundwater flow. With respect to predevelopment conditions, I (along with my co-author, Dan Larsen) published a paper in 2015 using data closer in time to predevelopment conditions than any other study (and using more control points than other studies), making it more likely to accurately approximate predevelopment conditions. Our study indicated that more groundwater migrated in the Middle Claiborne aquifer from Mississippi to Tennessee under predevelopment conditions than others had concluded previously.

16. The model of predevelopment conditions that Mississippi used as the basis for its assertions in its Bill of Complaint does not provide substantial support for its assertion that the aquifer constitutes an intrastate water resource. Even taken at face value, Mississippi's own figures show groundwater flowing from Mississippi into Tennessee (as well as other interstate groundwater flow). Moreover, the data used to create the contour map are limited and do not provide a reliable basis for drawing conclusions about flow near the Mississippi-Tennessee border. The data also postdate the predevelopment era by many decades, rendering any conclusions about that era unreliable. When

analysis is performed based on more suitable data, the conclusion is clear: the groundwater within the Middle Claiborne had a significant gradient from Mississippi into Tennessee in the area around Memphis under natural conditions. That flow emphasizes the interstate nature of the groundwater in the aquifer.

SECTION 3. Background on the Middle Claiborne aquifer

17. The Middle Claiborne aquifer is both confined and unconfined. Approaching eastern Shelby County, Tennessee, and into Fayette County, Tennessee, and part of Hardeman County, Tennessee, the overlying Upper Claiborne confining clay is absent. This eliminates any pressurization of the aquifer in that area. It also allows for recharge via both precipitation and leakage from surface waters, as water moves under gravity to fill the void space between the sand grains. As illustrated in Figure 1, this zone of unconfinement extends northward into Tennessee and southward into Mississippi. Underneath much of Shelby County, however, the Upper Claiborne is more continuous and confines the Middle Claiborne. Because the Upper Claiborne consists primarily of clay, it has a much lower hydraulic conductivity than the Middle Claiborne (i.e., water moves much less easily through the unit). Because groundwater cannot move easily up from the Middle Claiborne through the Upper Claiborne, the groundwater becomes pressurized (both through compression of the water and the "overburden pressure" imposed by the weight of the overly sediments). Like the zone of unconfinement, this area of vertical confinement, as shown in Figure 1, extends northward into Tennessee and southward into Mississippi.

18. It is difficult to obtain information about underground water resources, because their presence and physical/chemical characteristics can be derived only from exploratory measures such as drilling, sampling, and geophysical mapping. When drilling to an underground unit, drillers were and still are cognizant of the sequencing of geologic material that they encounter as they drill. Drillers note changes in material, recording the geologic units penetrated and their approximate depth below ground surface. Compiling drilling records from different locations can allow scientists to determine the vertical and horizontal extent of geologic layers such as aquifers and their confining units by matching geologic unit facies[1] across drilling records.

19. Similarly, water levels from different wells emplaced within the same geologic unit provide a means of studying groundwater gradients. Groundwater will flow from a higher water-level elevation (or head) to a lower elevation. In confined aquifers, the head is not the physical elevation of the groundwater throughout the aquifer (which is limited by the overlying confining layer), but the potentiometric head, which is the elevation to which the water would rise in a tightly cased well emplaced in the aquifer. With water levels from many wells, water levels can be interpolated and extrapolated to map water levels based on the data, and consequently to determine groundwater flow direction.[2] Interpolation is by definition constrained to within a "convex hull" defined by connecting the outermost measurements (like connect-the-dots). Interpolated values are better constrained as they fall within the outermost measurements, though some interpolation algorithms allow for interpolated values to fall above or below measured values. Extrapolation, in contrast, extends beyond the convex hull and becomes less constrained as the distance from the convex hull increases.

[1] Facies refers to the character of a geologic material.

[2] Interpolation and extrapolation refer to the estimation of unknown values from neighboring known values.

20. Characterization of geologic formations comes from sampling and testing the sediments and waters. Two important measures of an aquifer are its storage and hydraulic conductivity. Storage defines how water is stored and released from the aquifer matrix. A measure of how much water is released from storage through withdrawal is storativity: the volume of water released from storage, per unit of decline in the water level, per unit area of aquifer.[3] The storativity for the Middle Claiborne aquifer varies. Hydraulic conductivity is the ease at which a fluid moves through porous media – in this context, the ease at which water moves through the Middle Claiborne sands or the Upper Claiborne clay. Aquifer tests can measure storativity and hydraulic conductivity, with different degrees of reliability or accuracy depending on the quality of the test. An investigation through the Environmental Protection Agency (EPA) (Waldron et al., 2011) included an assessment by the United States Geological Survey (USGS) of historically recorded aquifer tests in the Mid-South region that included Shelby County, Tennessee, and DeSoto County, Mississippi. Based on that review: (1) only 17 of the 122 historic aquifer tests met the study's quality assessment criteria; (2) 11 of the 17 tests were for the Middle Claiborne; and (3) all of the quality tests resided in Shelby County as shown in the studies. (See Figure 2, Waldron et al.'s *Figure 60*, p. 88.) In areas where no well tests meet quality standards, data used in groundwater studies are more uncertain and more likely to be inaccurate.

21. Simulating transient groundwater flow within a heterogeneous, anisotropic[4] aquifer under multiple stresses (e.g., pumping, recharge, groundwater-surface water exchange) requires the use of numerical models as the complexity of groundwater flow exceeds the idealized flow modeled through analytical means.[5] The most commonly used numerical model for simulating saturated groundwater conditions in porous media is the USGS MODFLOW finite-difference model. Other numerical models exist, like FEMWATER, a finite-element model, but are less common than MODFLOW. MODFLOW has been used by past researchers to simulate transient groundwater conditions in the Middle Claiborne aquifer and other aquifers in the Mississippi embayment over differing time periods with many modelers starting their simulation at predevelopment (c. 1886). To model groundwater using MODFLOW, aquifer properties such as areal and vertical extent, hydraulic conductivity, storage, starting heads (or water levels), and boundary conditions must be specified by the modeler. Aquifers' areal and vertical extents are derived from the interpolation of drilling records. Hydraulic conductivity and storage are derived from aquifer tests. Starting heads are estimated from the interpolation of heads measured at the initial time (or stress) period. Lastly, boundary conditions are set in accordance with geologic and hydraulic constraints. Accurate inputs and proper assignment of boundary conditions reduce model bias and non-uniqueness. After

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[3] In a confined aquifer, a withdrawal of water releases water from storage and results in aquifer decompression. In contrast, in unconfined aquifers, the water is not under pressure and water is emptied from the void space between the sand grains. For unconfined aquifers, this storage is termed specific yield and is often equated to the porosity (i.e., percentage of void space) of the aquifer. (By way of example, a porosity value used for the Middle Claiborne is 0.3.)

[4] Meaning that intrinsic permeability is not similar in space and direction.

[5] An "analytical" model would use equations to produce an exact model, but it can be used only with highly simplified or idealized assumptions.

specifying initial conditions, the modeler can use locations of known aquifer heads in different time periods to calibrate the numerical model, making adjustments to model inputs (within a reasonable range based on observations) in an effort to minimize simulated-to-observed head differences. After calibrating the model, the modeler may perform sensitivity analyses, varying parameters to determine the level of influence that model parameter variability has on model results.

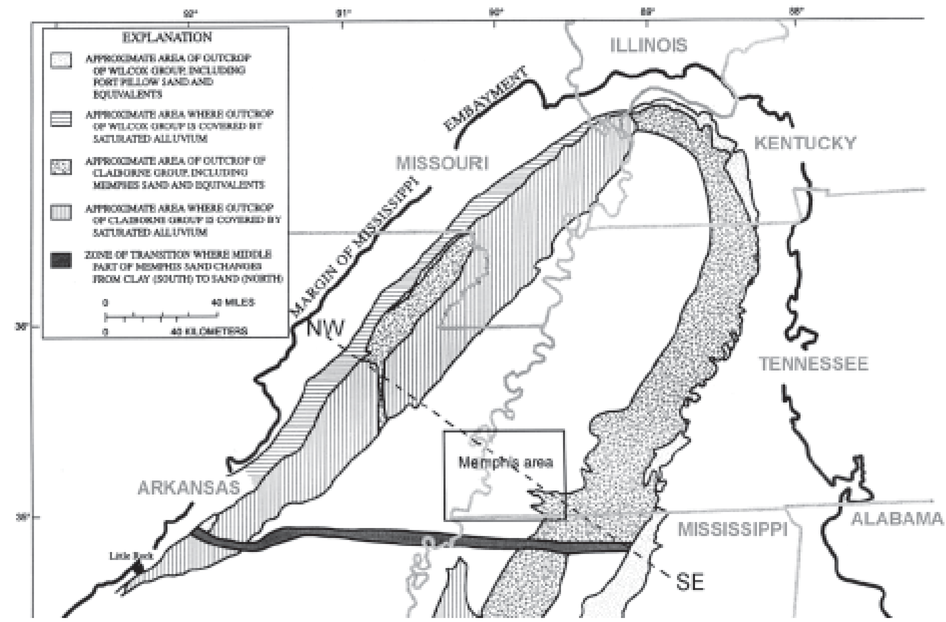

Figure 1. Waldron et al. (2011), *Figure 2*, p. 16. Map showing the approximate location of the outcrop of the Middle Claiborne in Tennessee and Mississippi (from Brahana and Broshears, 2001).

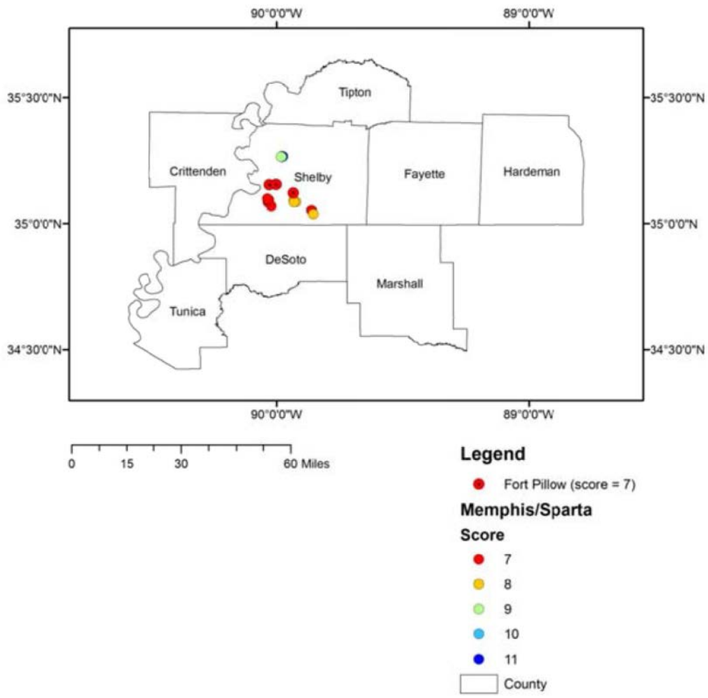

Figure 60. USGS aquifer parameter records with a score of 7 or greater.

Figure 2. Waldron et al. (2011), *Figure 60*, p. 88. Map showing relatively reliable USGS aquifer testing locations based on a review of USGS aquifer parameter data.

- The Middle Claiborne aquifer (variously called the Sparta Sand, Memphis Sand, and other names);
- In parts of Arkansas, a Lower Claiborne confining unit and aquifer (Cane River and Carrizo Sand, respectively);
- In parts of Mississippi, a confining unit and aquifer (Zilpha Shale and Winona Sand) followed by another confining unit and aquifer (Tallahatta Formation and Meridian Sand), all within the Lower Claiborne;
- The Wilcox group, which contains the Flour Island confining unit and the Fort Pillow Sand.

In Tennessee, where there are no confining units in the Lower Claiborne, the Memphis Sand aquifer may extend to include Middle Claiborne and Lower Claiborne formations, both consisting primarily of transmissive sand. Waldron et al. (2011)'s *Table 4* [6] (p. 30) provides a more complete description of the different geologic formations of the Mississippi embayment in the Mid-South region.

24. The Middle Claiborne aquifer is a highly transmissive geological unit consisting mostly of sand, with some clay and minor lignite. The Middle Claiborne aquifer is the source of most of the groundwater currently pumped by the Memphis Light, Gas & Water Division for drinking water purposes, with very limited groundwater withdrawn from the Wilcox aquifer.

25. Scientific literature has long recognized that the Middle Claiborne extends continuously from Shelby County, Tennessee, to DeSoto County, Mississippi, as well as elsewhere. There is no geological or hydrological barrier or impediment between those parts of the Middle Claiborne aquifer that underlie Mississippi and those that underlie Tennessee. Water can flow equally freely throughout the aquifer regardless of political boundaries.

26. One of the earliest papers on the subject, Stephenson et al. (1928), describes the groundwater resources of Mississippi in a USGS publication, including a section on DeSoto County. In their description, Stephenson et al. assert: "As the western part of De Soto County is due south of Memphis, directly on the strike of the formations, similar abundant supplies of water could undoubtedly be developed at comparable depths from the southward extension of the same water-bearing beds." (pp. 152-155) Hence, Stephenson et al. conclude that the prolific water-bearing unit (which they suspect is "probably in the Grenada formation") is the same in Tennessee as in Mississippi.[7]

27. Another early USGS study, Hosman et al. (1968), discusses and provides an illustration of the subsurface geological connection of the Middle Claiborne aquifer beneath Shelby County,

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[6] Figure and table numbers as given in sources are italicized to distinguish them from the figures in this report.

[7] The "Grenada" formation is an older name for the geologic unit underlying the Tallahatta formation in Mississippi. Stephenson et al. (1928) place the Grenada formation as the uppermost formation of the Wilcox group, but today the formation underlying the Tallahatta is understood to be the Meridian Sand or Lower Claiborne aquifer, in the Claiborne Group. (See Waldron et al., 2011, *Table 4*, p. 30.)

aquifers are separated by the Lower Claiborne confining unit. However, the Lower Claiborne confining unit laterally pinches out near the Tennessee-Mississippi stateline (and in adjacent Arkansas), such that the Lower and Middle Claiborne aquifers merge to form the Memphis aquifer in western Tennessee and adjacent Arkansas (Hart et al., 2008; Hosman and Weiss, 1991; Parks and Carmichael, 1990a." (p. 26, last paragraph) (emphasis supplied).

30. In sum, the literature demonstrates conclusively that the Memphis aquifer and the Sparta aquifer are parts of a single hydrological unit better termed the Middle Claiborne. There is no barrier between Tennessee and Mississippi that would prevent water in the Middle Claiborne aquifer from traveling as easily from one side of the state border to the other as it does elsewhere in the aquifer. Thus, regardless of the actual direction of groundwater flow at any given time, water has never been "confined" to the political boundaries of Mississippi (or any other state).

31. Water is only "confined" or bounded within the aquifer as a whole by the aquifer's confining layers (generally made of clay, which is much less transmissive and therefore keeps the aquifer under pressure) and by the geographic or areal extent of the aquifer as a whole. Thus, the aquifer, and the water within it, is laterally "confined" only by the areal extent of the system – for example, where the Memphis Sand outcrops in Fayette County, Tennessee, and Marshall County, Mississippi (see Figure 1).

32. Because the aquifer is a single hydrological unit, changes in conditions in one part of the aquifer, such as changes in recharge or discharge (including pumping), will affect other parts of the aquifer without regard to political borders. The groundwater in different parts of the aquifer cannot be considered separately where there is no hydrogeological barrier separating those parts. In short, there is no basis for Mississippi's assertion that any groundwater is "confined" to Mississippi's portion of the Middle Claiborne aquifer.

SECTION 5. Under predevelopment conditions, there was substantial flow of groundwater within the Middle Claiborne aquifer from Mississippi into Tennessee.

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33. I understand that Mississippi asserts that the groundwater under Mississippi within the Middle Claiborne aquifer would, under predevelopment conditions, remain within the state boundaries. In other words, Mississippi asserts that, but for the municipal water-supply pumping in Memphis, that water would not otherwise naturally leave or cross the Mississippi boundary. However, all studies of the predevelopment flow of groundwater in the Middle Claiborne aquifer, including those resulting in the development of numerical models, show groundwater flow from Mississippi into Tennessee. The study that is likely most accurate shows very substantial groundwater flow from Mississippi into Tennessee. In addition to Mississippi-to-Tennessee flow, all studies also show flow out of Mississippi into Arkansas.

34. The basic equations of groundwater flow allow for modeling of flow in idealized systems, and an "analytical" model based on those equations can provide an exact solution under certain simplified assumptions. However, the complexities and uncertainties of the real world mean that such a model cannot provide an accurate depiction of real aquifer systems.

35. A numerical model uses a computer program to simulate changes to water levels, and water flow, in different parts of an aquifer system iteratively over a given period of time. Although a numerical model provides an approximation rather than an exact solution, it can be used to model systems with much more complex assumptions or conditions, including multiple interrelated aquifers, heterogeneous geology, and realistic boundary conditions. Numerical models require accurate experimental data in order to be created and calibrated to produce an accurate approximation of the system.

36. There have been numerical groundwater models that have simulated groundwater flow from the date generally used as the cutoff for "predevelopment" (1886) to near the date of the publication of each respective groundwater model. Many of these groundwater model reports provide illustrations of predevelopment groundwater conditions.

37. Arthur and Taylor (1998) developed a numerical groundwater model of the Mississippi embayment that simulated groundwater conditions from 1886 to 1987 with predictions made to 2000. The authors provide illustrations of predevelopment conditions for the Upper, Middle, and Lower Claiborne aquifers (Arthur and Taylor, 1998, *Plate 5*). As shown below (Figure 4), an excerpt of predevelopment conditions in the Middle Claiborne aquifer indicates (as shown by red arrows) that groundwater flowed from Mississippi into Tennessee towards the eastern extent of the aquifer and flowed from Mississippi into Arkansas and Louisiana. In south Arkansas, groundwater flowed back from Arkansas into Mississippi. Similar exchanges of groundwater during predevelopment conditions occurred in the Lower Claiborne-Upper Wilcox aquifer, Middle Wilcox aquifer, and Lower Wilcox aquifer (Arthur and Taylor, 1998, *Plate 5*).

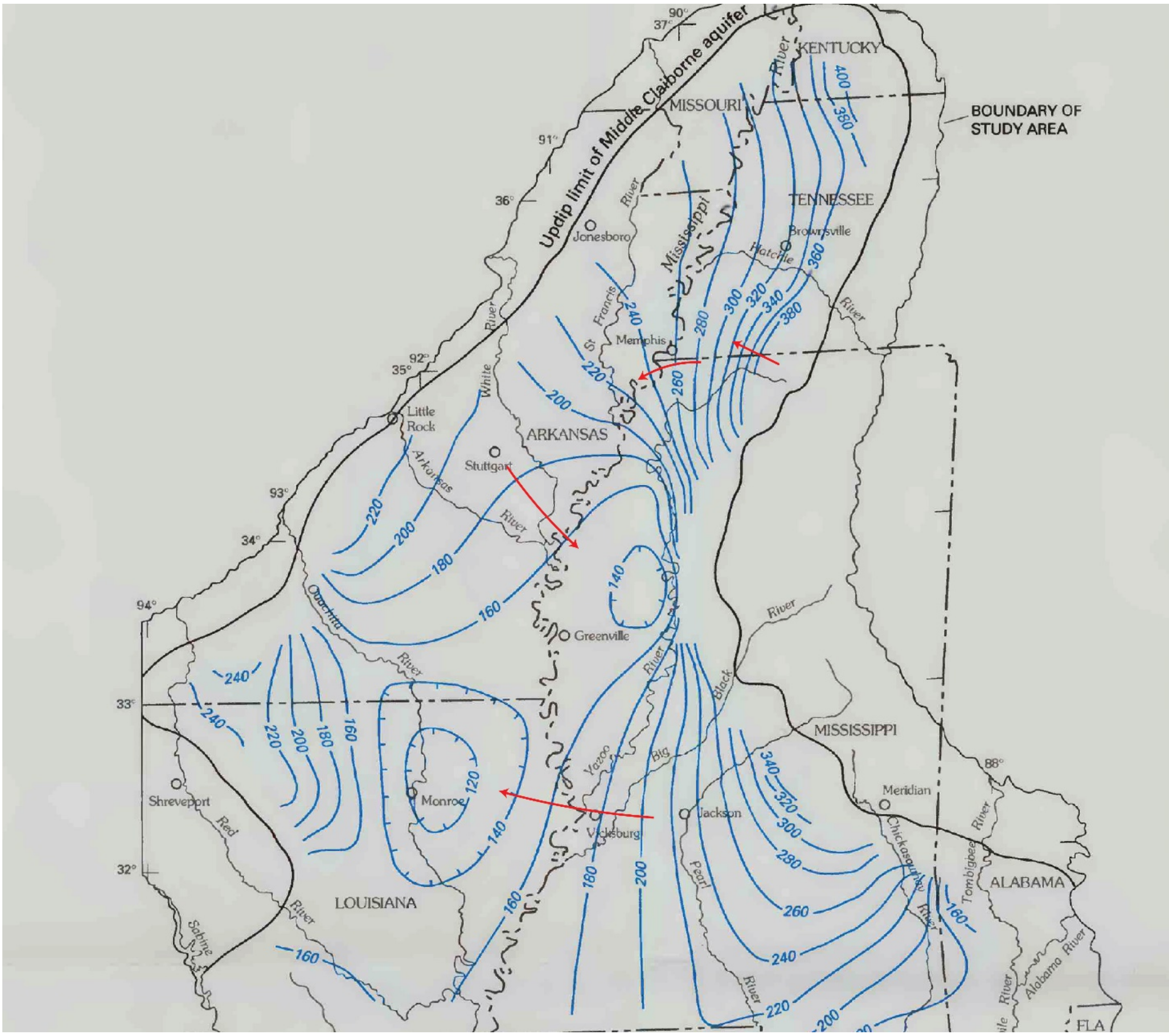


Figure 4. Illustration of predevelopment groundwater conditions in the Middle Claiborne aquifer (Arthur and Taylor, 1998). Red arrows are drawn atop the original report figure to illustrate groundwater flow direction as taken perpendicular to head contours.

38. Brahana and Broshears (2001) developed a numerical groundwater model that included the Memphis and Fort Pillow aquifers in the Memphis Area. The model boundary extended into Mississippi, Arkansas, Missouri, Kentucky, and Illinois. Their model simulation started in 1886 at the end of predevelopment conditions. This model derived its predevelopment conditions from prior USGS investigations such as Arthur and Taylor (1990), Hosman et al. (1968), and Reed (1972). However, specific to the Memphis area, the authors used the suggested predevelopment conditions derived by Criner and Parks (1976), shown in their report as *Figure 4* (p. 15), which is reproduced by Brahana and Broshears (2001) in their report as *Figure 16* (p. 30) (see Figure 5, below). As a point of comparison, the predevelopment conditions as suggested by Criner and Parks (1976) (their *Figure 4*, p. 15) is shown as Figure 6. Mississippi suggests that this figure from Brahana and Broshears (2001) shows that groundwater in the Middle Claiborne aquifer flowed east to west, perpendicular to the Tennessee-Mississippi state line; therefore, groundwater under predevelopment conditions never

moved across the border. (Brief in Support of Motion To File a Bill of Complaint, Appendix A, 70a and 77a.) However, there are significant points about this figure that cast doubt on whether it supports Mississippi's suggestion that there was no cross-border groundwater flow, including across the Tennessee-Mississippi border.

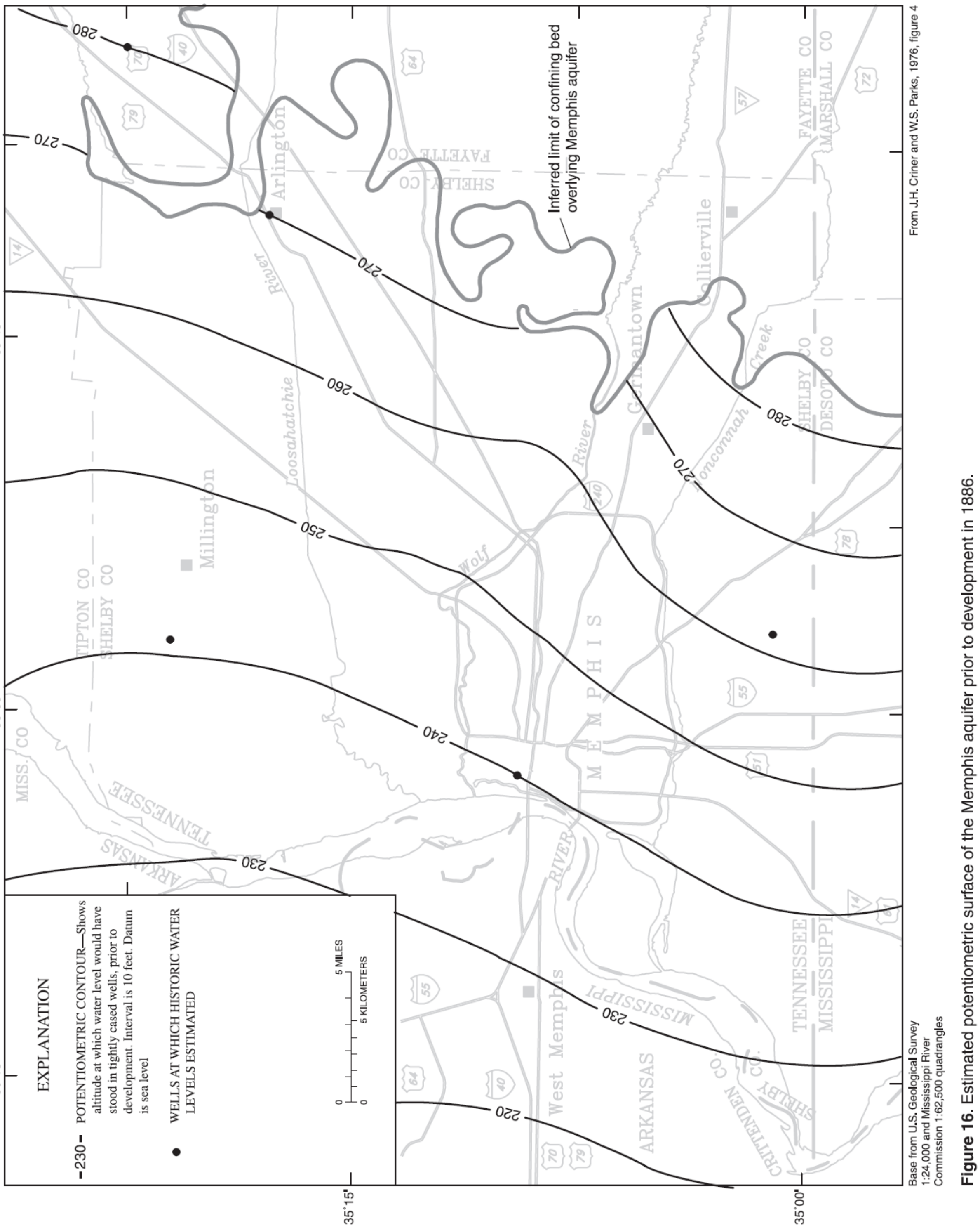


Figure 5. Reproduction of the Criner and Parks (1976) predevelopment condition of the Middle Claiborne aquifer.

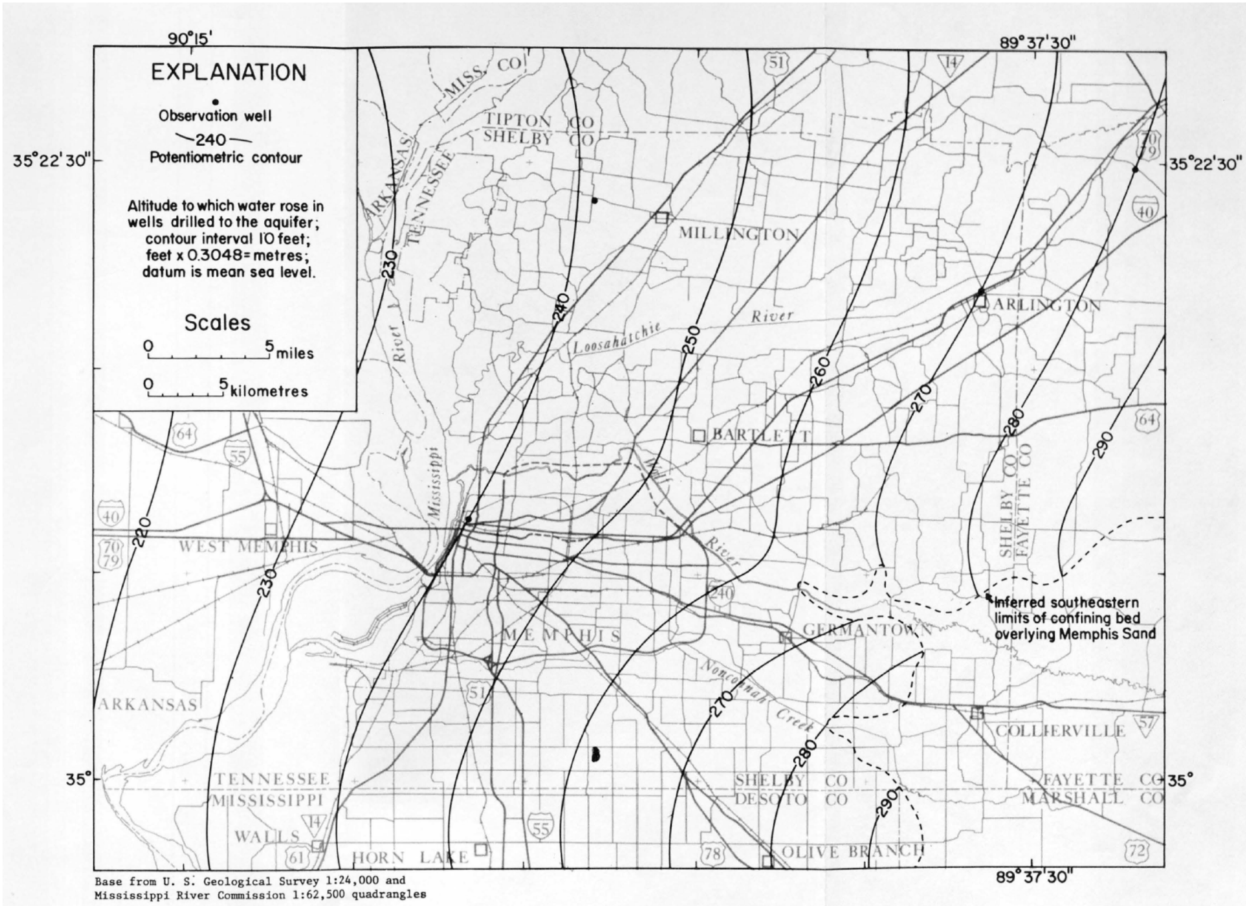


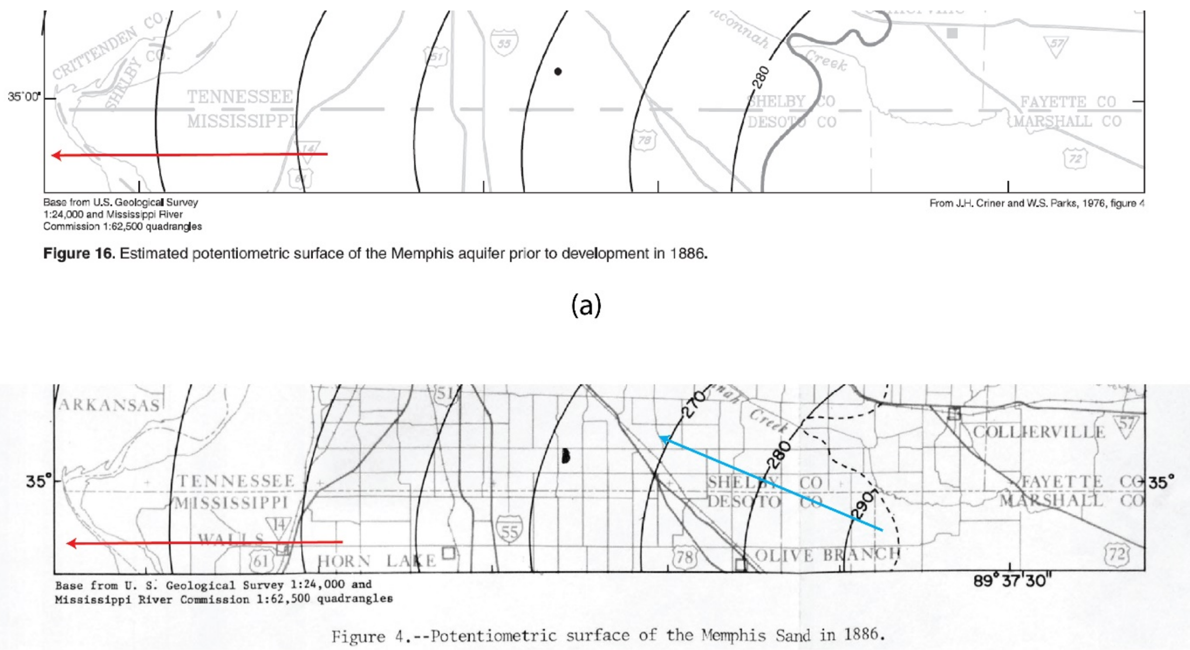
Figure 6. Reproduction of the Criner and Parks (1976) predevelopment condition of the Middle Claiborne aquifer.

39. There are three important points about this contour map: (1) based on Figures 5 and 6, groundwater direction indicates that groundwater in the Middle Claiborne aquifer leaves Mississippi and enters into Arkansas; (2) Criner and Parks (1976) show the groundwater gradient moving from Mississippi into Tennessee in the eastern part of Shelby County; and (3) the southern-most groundwater level control point shown in Figures 5 and 6 does not exist.[12] The first two points

[12] Further, note that the figure used by Mississippi (Figure 8, below) does not actually match the figures from either Brahana and Broshears (2001) or Criner and Parks (1976), although Mississippi asserts that it derives its figure from Brahana and Broshears (2001), which in turn derived it from Criner and Parks (1976). Mississippi's figure shows an extension of the predevelopment groundwater level contours further south into Mississippi than what is depicted in the Brahana and Broshears figure (see Figure 5). It may be that Mississippi acquired these additional contours from Brahana and that they were results of his model. Mississippi may have also run the model to extract predevelopment heads, but there is no explanation that such a model was used. Either way, however, there is a question as to what control points were used to create the contour map. The issue of control points as it pertains to a comparison between Figures 5 and 6 is discussed in paragraphs 41-44.

demonstrate that, even under this model, there is significant interstate groundwater flow out of Mississippi. The third point casts significant doubt on the accuracy of the model, particularly near the Mississippi-Tennessee border.

40. Regarding the first two points, Mississippi claims that the Middle Claiborne aquifer is an intrastate groundwater system such that groundwater remained in the predevelopment period (prior and up to 1886) within the boundaries of Mississippi. Yet the groundwater direction shows a clear movement of groundwater from within Mississippi into Arkansas (see Figure 7). Mississippi also has not denied that some small portion of groundwater moves into Tennessee. In its Appendix Figure 70a, Mississippi highlights a section of groundwater flow moving from Mississippi into Tennessee, labeling it as an *Area of Limited Natural Flow from Mississippi to Tennessee* (see Figure 8). Though not quantified by Criner and Parks (1976), groundwater clearly leaves Mississippi and enters Tennessee (Figure 7).



(b)

Figure 7. Comparison of the depiction of predevelopment groundwater conditions along the Shelby County–DeSoto County border by (a) Brahana and Broshears (2001) and (b) Criner and Parks (1976). Red arrows indicate the groundwater gradient suggesting groundwater movement from Mississippi into Arkansas. Blue arrow indicates the groundwater gradient suggesting water movement from Mississippi into Tennessee.

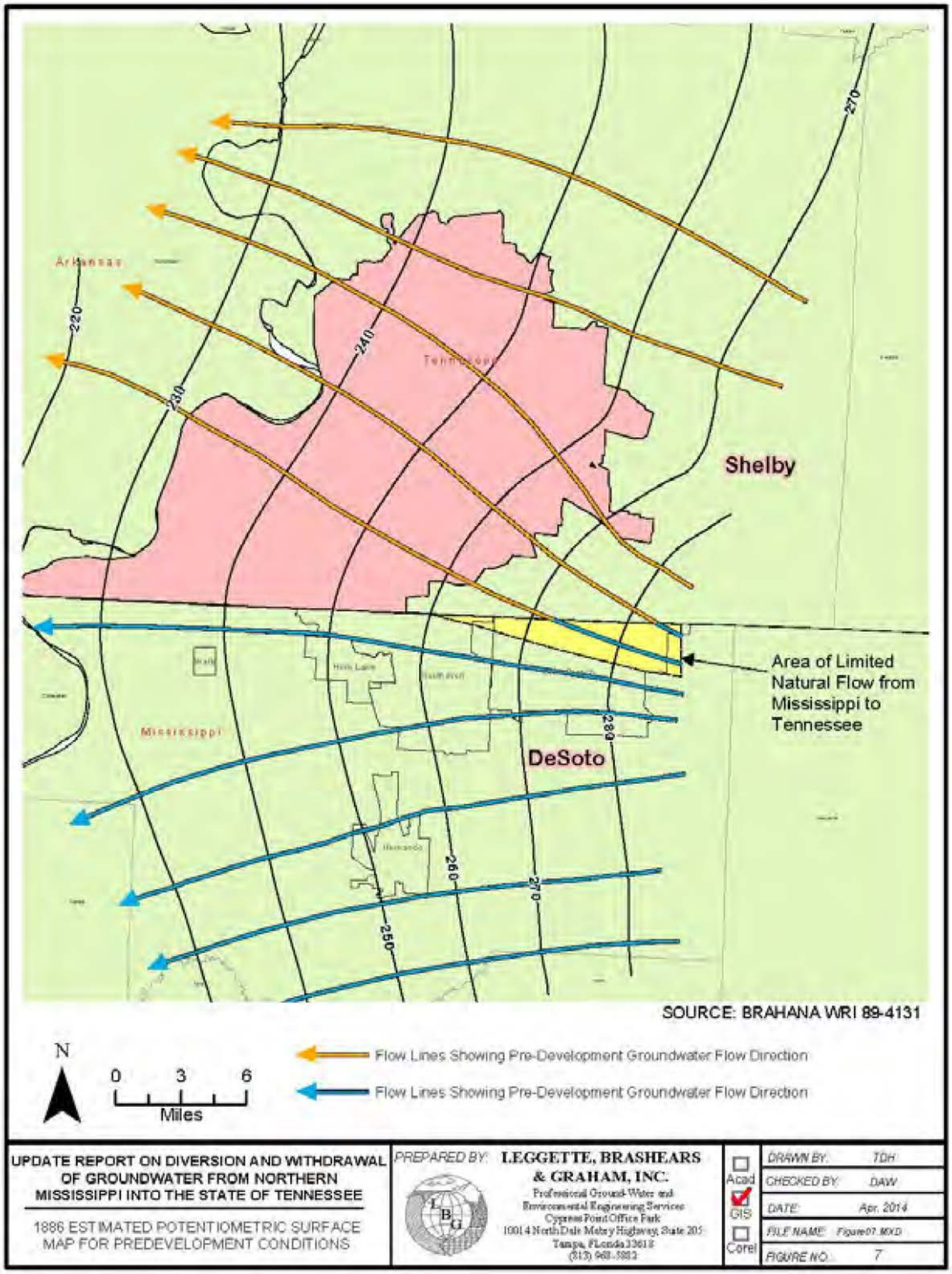


Figure 8. Reproduction of State of Mississippi's Appendix A, 70a figure (Appendix *Figure 7*) depicting predevelopment groundwater conditions including flow direction.

41. As to the third point, it appears that the southernmost groundwater level control point (i.e., one of the wells used to define the contours) shown in Figures 5 and 6 does not exist. This fact raises speculation on how the predevelopment groundwater contours in Brahana and Broshears (2001), particularly the contours along the Tennessee-Mississippi state line, were determined. Criner and Parks (1976) state: "The control wells shown in figure 4 were selected for their locations away from pumping centers and for their long records which were used to estimate the probable original potentiometric surface." (p. 14) (see Figure 6). Figure 9 shows the map of all wells used as control points by Criner and Parks in the development of their maps. Describing that figure (their *Figure 1*, p. 3), they state: "The present boundaries and the locations of observation wells used for diagrams and maps presented in this report are shown in figure 1." (p. 2) That map does not show any control well at the location that Brahana and Broshears (2001) later describe as one of the control points for the contours in Criner and Parks (1976). As shown in Figure 9, the southernmost "control point" on Brahana and Broshears' reproduction *in fact appears to be a smudge* on Criner and Parks' potentiometric map.

42. One may quickly suggest that the southern control point exists and that Criner and Parks merely misplaced one of their control points ("point 28") on their predevelopment potentiometric map (see Figures 6, 7.b, 9, and 10). But review of Criner and Parks shows that their "point 28" (or Sh:K-28, p. 43): (1) had a single water level reading of 211 feet; (2) was not used in preparing their *Figure 4*; and (3) if placed on the predevelopment map, would fall between groundwater contours 250 and 260 feet. The control point near the state boundary identified by Brahana and Broshears does not exist.

43. The next-closest control point to the Mississippi-Tennessee state line is in downtown Memphis, approximately 11 miles from the state line (Sh:O-124 in 1927, p. 11). Criner and Parks are unsure of the groundwater level used for the downtown Memphis control point, stating: "Although the original altitude of the potentiometric surface is uncertain, it is estimated to have been about 240 ft (73 m) above sea level at the site of the first well on Court Avenue and Gayoso Bayou (Bohlen-Huse Ice Company)." (p. 14) Of the three remaining control points used by Criner and Parks to draw predevelopment groundwater conditions, the closest to the Mississippi-Tennessee state line is in Arlington, Tennessee, approximately 21 miles north of Mississippi and along the Shelby-Fayette county line (Sh:W-3). The date of the groundwater level reading used at Arlington was 1958, about 72 years after the predevelopment era's end in 1886. The other two well control water level dates are as follows: Sh:U-2 (1949) west of Millington, Tennessee, and Fa:R-2 (1949) in northwest Fayette County, near Galloway, Tennessee.

44. In sum, the closest control point to the Mississippi-Tennessee border does not exist, and the second-closest is described by the authors as uncertain at best. Because of these two issues, the predevelopment groundwater contours drawn by Criner and Parks are questionable, particularly along the Tennessee-Mississippi state line, which is relatively far from any control points.

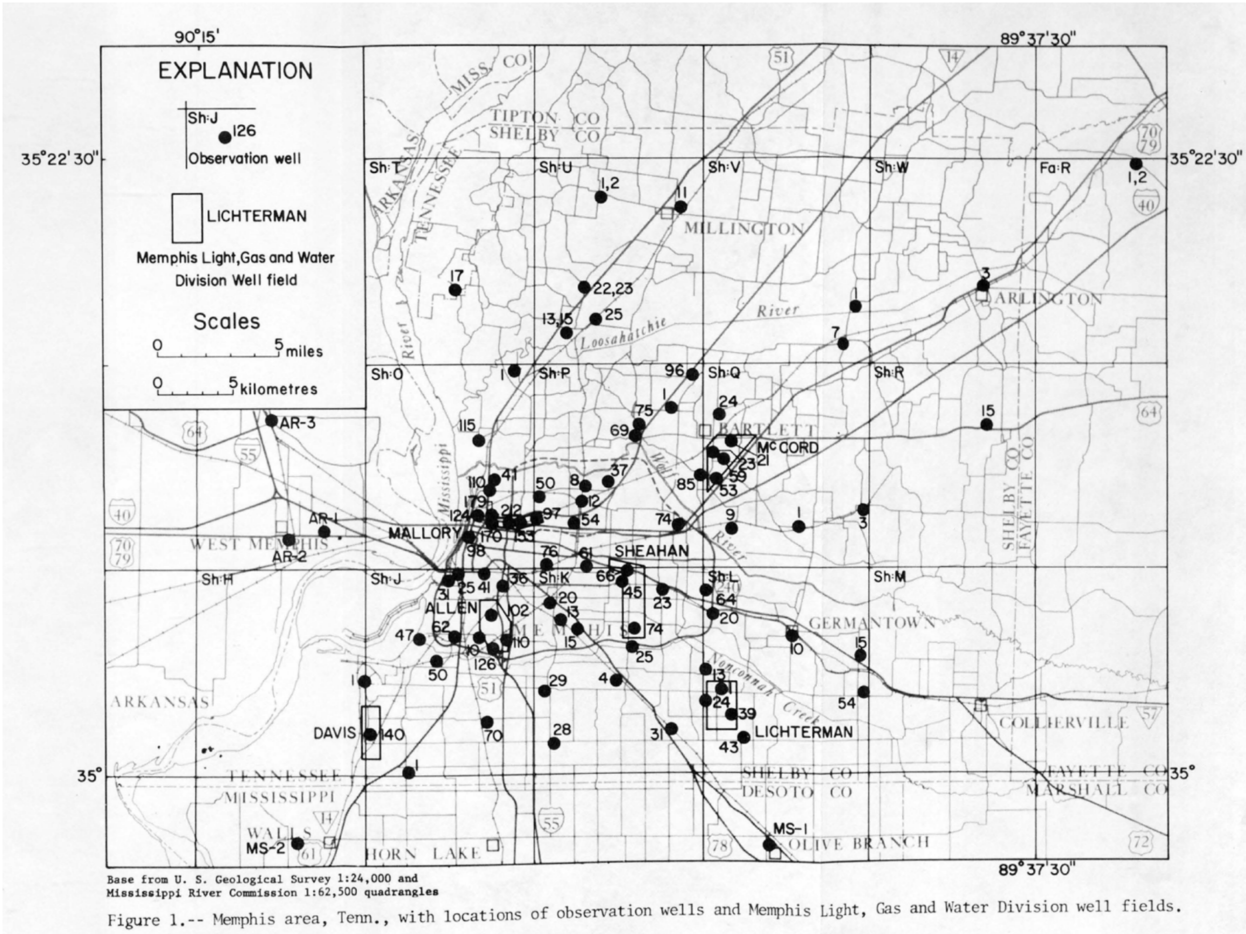
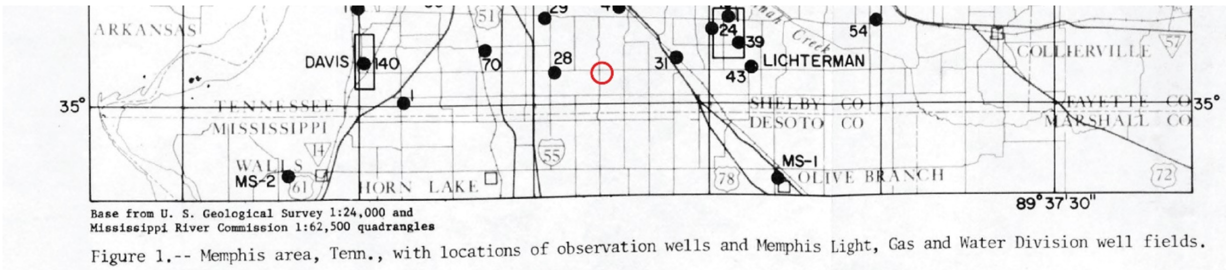
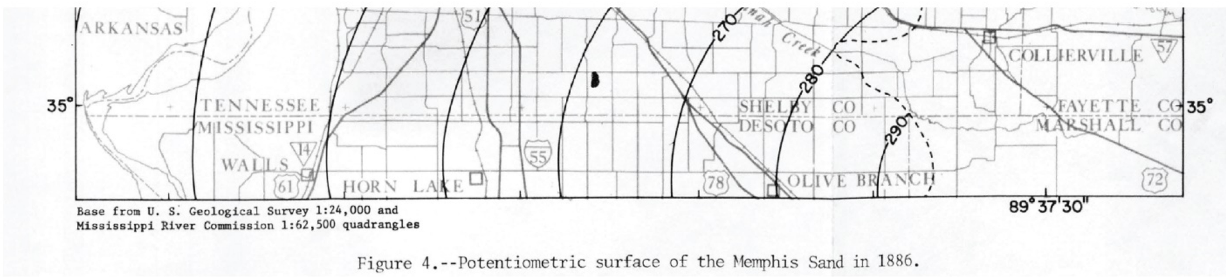


Figure 9. Distribution of groundwater levels used by Criner and Parks (1976) in the development of their potentiometric surfaces.



(a)



(b)

Figure 10. Close-up map of control point #28 (Sh:K-28), comparing its location on Criner and Parks (1976) *Figure 1* (see Figure 9) to their predevelopment map (*Figure 4*) (see Figure 6). Red circle indicates where Brahana and Broshears (2001) placed an erroneous control point (see Figures 5 and 7.a).

45. Clark and Hart (2009) developed a groundwater model of the Mississippi embayment simulating groundwater conditions within the primary freshwater aquifer systems. This Mississippi Embayment Regional Aquifer Study ("MERAS") model begins under "predevelopment" conditions (for purposes of this model, conditions prior to January 1870), and the simulations terminate in April 2007. Clark and Hart's model derives its predevelopment conditions for the Middle Claiborne aquifer from Reed (1972). Reed (1972) depicts groundwater flowing primarily east to west along the Tennessee-Mississippi state line, yet clearly indicates movement from Mississippi into Tennessee in the outcrop region of the Middle Claiborne aquifer (see Figure 11, excerpt from Reed (1972), *Plate 1*, at the 400-ft contour). Figure 11 also shows groundwater moving from Mississippi into Arkansas at the tri-state boundary of Tennessee, Mississippi, and Arkansas. Reed (1972) also depicts groundwater moving from Mississippi into Arkansas and Louisiana in the southern region of the Sparta aquifer as they illustrated in their *Plate 1*.

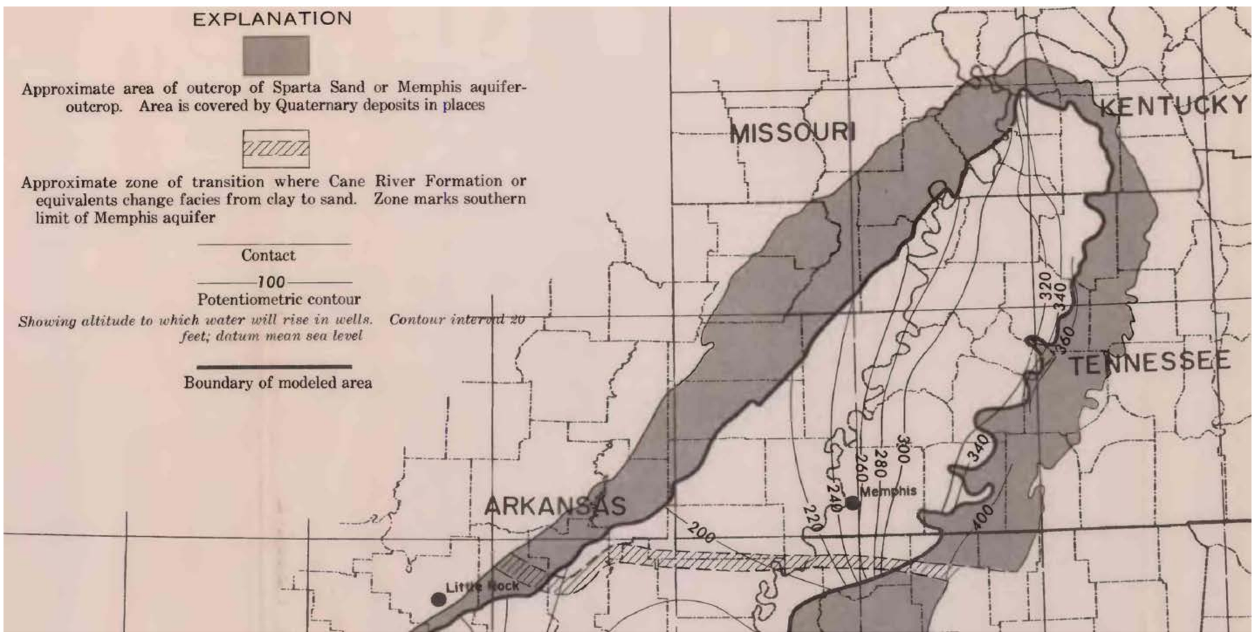


Figure 11. Excerpt of Reed (1972) *Plate 1* showing predevelopment conditions along the Tennessee-Mississippi state line.

46. Clark and Hart (2009) create their model by applying the USGS's MODFLOW model (as noted above, a general, standard computer program for modeling groundwater) to the Mississippi embayment, simulating groundwater levels from 1870 to 2007. Although Clark and Hart (2009) state that they start from a steady state period in 1870, reflecting the lack of development of the aquifer system up to that point, they do not present an illustration of predevelopment conditions in their publication. I therefore obtained their numerical MODFLOW groundwater model from Brian Clark (USGS) and ran the Clark and Hart (2009) model in order to obtain their starting head (i.e., potentiometric surface) conditions based on the calibrated model. The resulting groundwater predevelopment condition is shown in Figure 12. The groundwater heads shown are for layer 5 of their model, which depicts the upper section of the Middle Claiborne aquifer. The surface was interpolated using Delaunay triangulation, also called a triangular irregular network (TIN). This method attempts to draw equilateral triangles between the control points using circumcircles drawn

through the midpoint distances between the points. Interpolated values within the plane that passes through the three points defining that plane are constrained to be within the range of the values of the three defining points. The solution is quick, linear in nature, and unique.

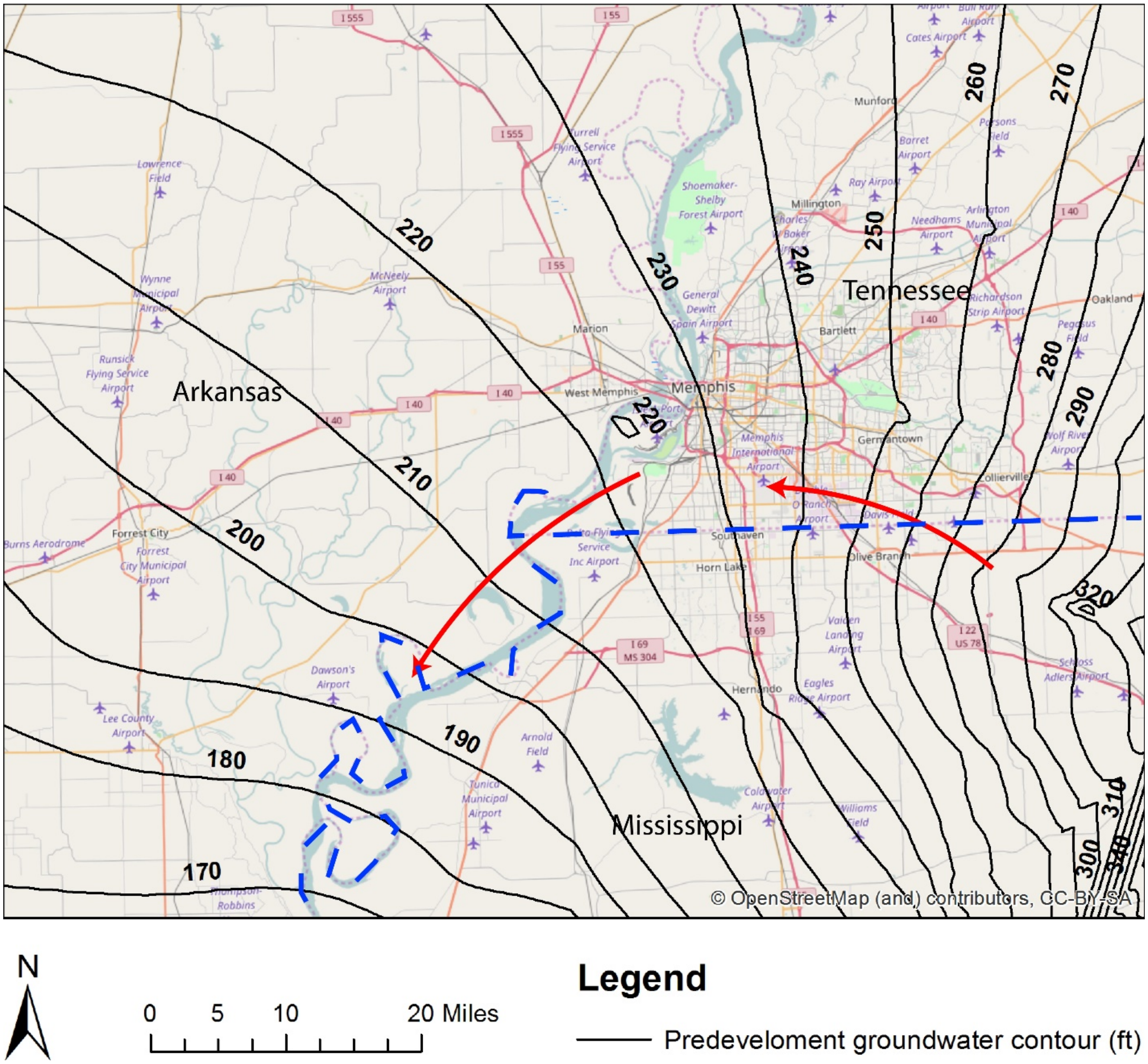


Figure 12. Resulting groundwater predevelopment conditions derived from output from MERAS model (Clark and Hart, 2009). Red arrows have been overlaid to numerically indicate groundwater flow direction and blue hatched line approximates state line boundaries.

47. As shown in Figure 12, the predevelopment conditions (1870) from the Clark and Hart (2009) MERAS numerical groundwater model indicate that groundwater in the Middle Claiborne aquifer was flowing from Mississippi into Tennessee and from Tennessee and Mississippi into Arkansas.

48. Waldron and Larsen (2015) developed a predevelopment surface (1886) of the Middle Claiborne aquifer using 27 groundwater levels from 1886-1906 focused on the Mississippi-Arkansas-Tennessee tri-state region (Figure 13). Compared to past investigations, our data were closest to the

period of predevelopment. The latest measurements we used were from wells that were recorded in one 1903 and two 1906 publications – thus, all wells dated to within 20 years of the first development of the Middle Claiborne aquifer. In comparison, for example, the control wells used by Criner and Parks (1976) and therefore by Brahana and Broshears (2001) date to at least 40 and as many as 70 years after the first development in 1886.

49. Waldron and Larsen (2015) also used substantially more data points than prior analyses of predevelopment conditions. The final analysis used 27 control wells, distributed across multiple counties in Tennessee, Mississippi, and Arkansas. In contrast, Criner and Parks (1976) used four control wells, three in Shelby County and one in Fayette County, and none close to the Mississippi-Tennessee border. Both of these aspects of Waldron and Larsen (2015) – using controls closer in time to the relevant period, and using more controls distributed more broadly over the relevant geographic area – make it likely that this analysis better approximates the predevelopment groundwater conditions of the Middle Claiborne aquifer in the Mid-South region.

50. The resulting predevelopment conditions (1886) are shown in Figure 13. The potentiometric surface shows that, under natural conditions, water did move from Mississippi into Tennessee. Along the Mississippi-Tennessee border, the gradient (which moves perpendicularly to the lines of equal head shown on the map) is mostly north-moving in the area of Marshall County and Fayette County, and gradually turns in a northwest direction in western Shelby County and DeSoto County. This gradient is more northerly, showing more groundwater flowing from Mississippi into Tennessee, than prior analyses.

51. Additionally, using the groundwater gradients derived for 1886 and those developed by Schrader (2008), Waldron and Larsen (2015) estimated that the quantity of groundwater exchanged between Shelby County and DeSoto County was approximately 221,000 m^3/d (cubic meters per day) in 2008 and 186,000 m^3/d in 1886. (pp. 18-19)

52. The investigations by Arthur and Taylor (1990), Reed (1972), Criner and Parks (1976), Brahana and Broshears (2001), Clark and Hart (2009), and Waldron and Larsen (2015) consistently substantiate the fact that, during the predevelopment period (pre-1886), groundwater in the Middle Claiborne aquifer and its equivalents moved from beneath Mississippi across state lines into adjoining states (Tennessee, Arkansas, Louisiana) and as such was not confined within the state boundaries of Mississippi. As discussed above, different studies show different groundwater flow paths transporting water across the Mississippi-Tennessee line to different degrees. Waldron and Larsen (2015) show the most substantial natural movement of groundwater from Mississippi into Tennessee, and quantify that transfer. For the reasons discussed above, the analysis in that paper is most likely to accurately approximate predevelopment conditions in the aquifer. Based on all of these studies, and most especially Waldron and Larsen (2015), there was substantial groundwater flow in the Middle Claiborne aquifer under predevelopment conditions from Mississippi to Tennessee. These studies also emphasize that the Middle Claiborne cannot be considered to "confine" groundwater within Mississippi vis-à-vis Tennessee or other states, and must be considered an interstate aquifer.

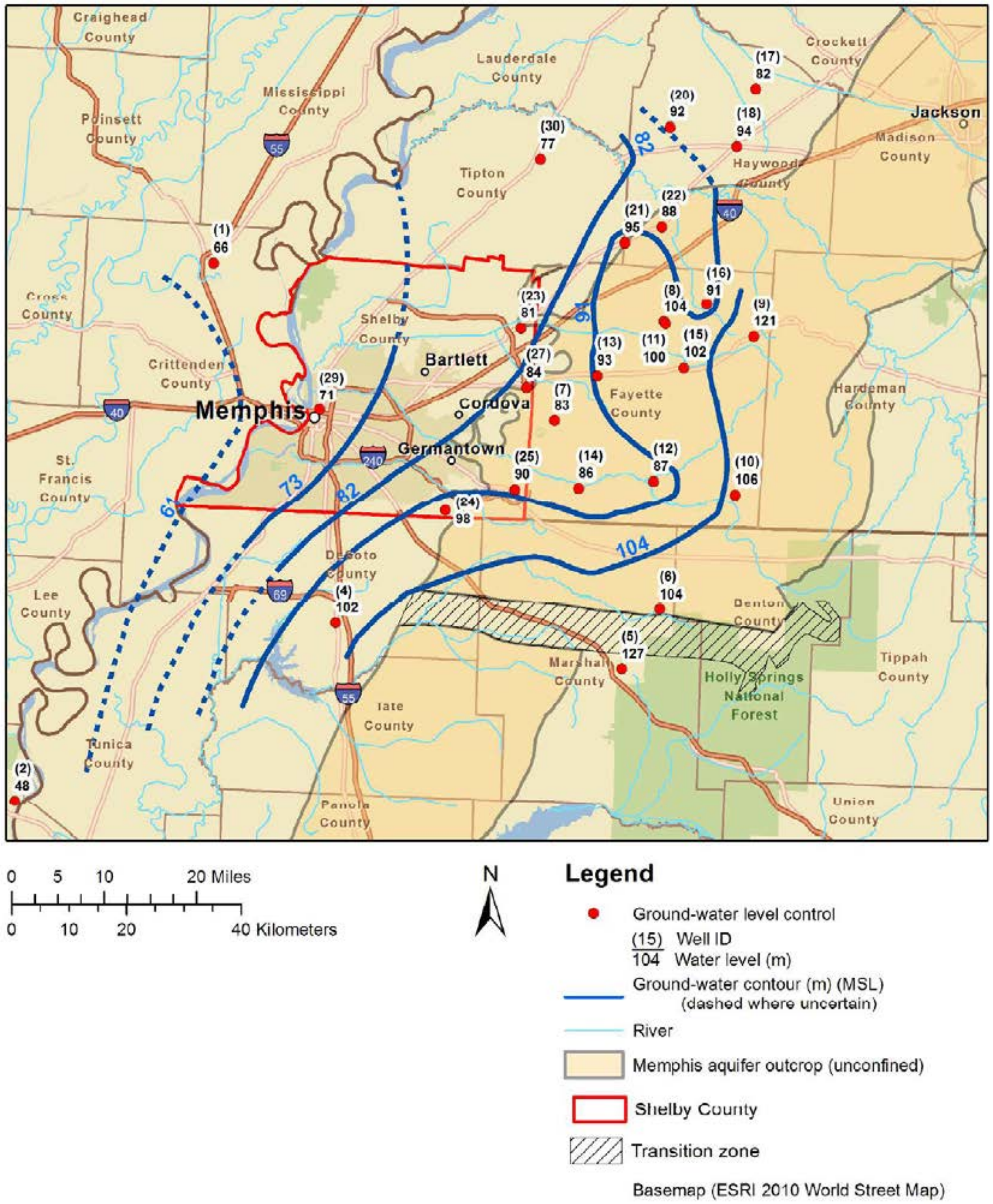


Figure 13. Predevelopment groundwater conditions for the Middle Claiborne aquifer (Waldron and Larsen, 2015).

Exhibit 4

Excerpts from
Deposition of David E. Langseth

(September 15, 2017)

In the Matter Of:

STATE OF MISSISSIPPI vs

STATE OF TENNESSEE

DAVID LANGSETH

September 15, 2017

IN THE SUPREME COURT OF THE UNITED STATES

STATE OF MISSISSIPPI,
Plaintiff,
Vs. Action 143
STATE OF TENNESSEE,
CITY OF MEMPHIS and
MEMPHIS LIGHT, GAS &
WATER DIVISION,
Defendants.

DEPOSITION
OF
DAVID E. LANGSETH
September 15th, 2017

ALPHA REPORTING CORPORATION
236 Adams Avenue
Memphis, TN 38103
901-523-8974
www.alphareporting.com

The deposition of DAVID E. LANGSETH is taken on this, the 15th day of September, 2017, on behalf of the Plaintiff, pursuant to notice and consent of counsel, beginning At approximately 8:31 a.m., in the offices of Baker, Donelson, Bearman, Caldwell & Berkowitz, 165 Madison Avenue, Memphis, Tennessee

This deposition is taken pursuant to the terms and provisions of the Federal Rules of Civil Procedure.

All forms and formalities are waived. Objections are reserved, except as to form of the question, to be disposed of at or before the hearing.

The signature of the witness is not waived.

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Special Master Siler prepared and asked me to address that issue.

Q. Okay. I just want to be clear. I'm not trying to be to difficult here. But it says that you are "to opine on whether" and then it says "the aquifer known in Tennessee as Memphis Sand Aquifer and known in Mississippi as the Sparta Sand Aquifer and the groundwater in it constitutes an interstate aquifer." Is that your -- did you come up with that sentence in that definition of what you were going to offer an opinion on?

A. I would say that this sentence is my characterization of what I understood to be the issue that Special Master Siler described in his memorandum of I think August, 2016, or somewhere. I don't know if I have the date exactly right.

Q. You didn't need any legal assistance to come up with this particular statement of opinion, that's something you developed based on your study of his order?

A. I would say that's a fair characterization. This is not intended to be a

legal statement. It is a plain-language reading of his order.

Q. But I'm asking -- you were told to read his order, you determine what the issue is, and then you write the sentence, and you didn't have any assistance from counsel in doing that?

MR. DAVID BEARMAN: I object to the form of the question.

A. I don't recall that in writing this particular sentence I had what I would call assistance of counsel to MLG&W or the City of Memphis, which is who the firm Baker-Donelson is counsel for, as it indicates here.

Certainly in the process of drafting this report they provided comments on things that I wrote, but this is my -- this sentence here reflects my understanding of the question that Special Master Siler described as being the subject that he wanted to have addressed in I guess ultimately a hearing that is described in that memorandum.

Q. What definition do you have -- did you use for "interstate aquifer"?

A. I state that in my report, and we can

lines and that it is essentially a shared water resource for any state that can drill down and draw water from that resource, which includes certainly both Mississippi and Tennessee and Arkansas and Louisiana and possibly some other states, but certainly those four are the predominant states that can easily draw water from the Sparta and Memphis Sand Aquifer.

Q. So they all have the right to -- they have a claim to that water because the geological formation and water in it underlies all states?

MR. DAVID BEARMAN: Object to the form. It calls for a legal conclusion.

MR. ELLINGBURG: He has already given one. He says it is an interstate aquifer.

MR. DAVID BEARMAN: He hasn't given a legal conclusion.

Q. (BY MR. ELLINGBURG) I'm asking you from your standpoint as a groundwater hydrologist, the single fact that you have a geological formation that underlies multiple states and contains groundwater is sufficient to make that groundwater an interstate natural resource. Is that correct?

A. Okay. We're talking about an aquifer. So it both contains water and you can extract water from it. If the delineated extent of that aquifer has a state line crossing through it, that is sufficient to make that an interstate aquifer.

Q. In and of itself?

A. That is the -- if you go back to the definition, that is the way I described it.

Q. That's your definition?

A. That is the definition I described in my report.

Q. Have you ever -- you said in your report at places that the USGS has defined the water in Mississippi and Tennessee as interstate water. Is that correct?

A. Can you point me to where I said that?

Q. I think in your rebuttal report you said the USGS has identified it as interstate -- as an interstate aquifer, right?

A. I'd like to be sure I'm looking at the exact language you are talking about before I answer that question.

Exhibit 5

Excerpts from
Deposition of Steven P. Larson

(September 19, 2017)

In the Matter Of:

STATE OF MISSISSIPPI vs

STATE OF TENNESSEE

OF TENNESSEE,

STEVEN LARSON

September 19, 2017

BEFORE THE SUPREME COURT
OF THE UNITED STATES

STATE OF MISSISSIPPI,
Plaintiff,
Vs. NO.
STATE OF TENNESSEE,
CITY OF MEMPHIS and
MEMPHIS LIGHT, GAS &
WATER DIVISION,
Defendants.

DEPOSITION
OF
STEVEN J. LARSON
September 19th, 2017

ALPHA REPORTING CORPORATION
236 Adams Avenue
Memphis, TN 38103
901-523-8974
www.alphareporting.com

The deposition of STEVEN J. LARSON is taken on this, the 19th day of September, 2017, on behalf of the Plaintiff, pursuant to notice and consent of counsel, beginning at approximately 8:31 a.m., in the offices of Baker, Donelson, Bearman, Caldwell & Berkowitz, 165 Madison Avenue, Memphis, Tennessee

This deposition is taken pursuant to the terms and provisions of the Federal Rules of Civil Procedure.

All forms and formalities are waived. Objections are reserved, except as to form of the question, to be disposed of at or before the hearing.

The signature of the witness is not waived.

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from the geology in which that aquifer system exists?

A. Well, I'm not sure I understand the question. My understanding was whether the aquifer is an interstate resource, which would include the geologic materials that comprise the aquifer and the water in it.

Q. The sand, the clay, all those things, and the water in it, they are all indistinguishable from your standpoint?

MR. BRANSON: Object to form.

A. They are all part and parcel of the aquifer system?

Q. (BY MR. ELLINGBURG) In All of your work over the years you really have never paid attention separately to the water contained in the system, you've really just looked at what is this geology and, you know, that has water in it, right? That's your approach, isn't it?

MR. BRANSON: Object to form.

A. Well, my understanding of what the special master was interested in is whether the aquifer, which is the geologic materials as the matrix and the water in it, that together they

form the aquifer, and the question is whether that aquifer was an interstate resource.

Q. (BY MR. ELLINGBURG) You stated you believed it was, right?

A. I did.

Q. And so from your standpoint all of the water within the Middle Claiborne and the Mississippi Embayment from Kentucky to Louisiana and intervening states, all of that water is interstate water available for whichever state can develop it. Is that correct?

MR. BRANSON: Object to form.

A. My conclusion was that the aquifer itself was an interstate water resource that spans several states.

Q. (BY MR. ELLINGBURG) That all of the water in it, no matter where it is located within the geography of those states, is available to any single state that has the ability to produce it within their state. Is that correct?

MR. BRANSON: Object to form.

Q. (BY MR. ELLINGBURG) Is that part of your opinion or not?

Exhibit 6

Excerpts from
Deposition of Brian Waldron, Ph.D.

(September 27, 2017)

In the Matter Of:

State of Mississippi Vs.

City of Memphis and MLG&W

BRIAN WALDRON

September 27, 2017

BEFORE THE SUPREME COURT
OF THE UNITED STATES

STATE OF MISSISSIPPI,

Plaintiff,

Vs. Case No.

STATE OF TENNESSEE,
CITY OF MEMPHIS and
MEMPHIS LIGHT, GAS &
WATER DIVISION,

Defendants.

THE DEPOSITION OF BRIAN WALDRON, Ph.D.

September 27, 2017

*****THE DEPOSITION CONTAINS SOME ITEMS COVERED UNDER THE CONFIDENTIAL PROVISIONS OF THE CASE MANAGEMENT ORDER*****

ALPHA REPORTING CORPORATION
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The deposition of BRIAN WALDRON, Ph.D., taken on this, the 27th day of September, 2017, on behalf of the Plaintiff, pursuant to notice and consent of counsel, beginning at approximately 8:55 a.m. in the law offices of Baker, Donelson, Bearman, Caldwell & Berkowitz, 165 Madison Avenue, 20th Floor, Memphis, Tennessee.

This deposition is taken in accordance with the terms and provisions of the Federal Rules of Civil Procedure.

All forms and formalities are waived. Objections are [reserved/not reserved], except as to form of the question, to be disposed of at or before the hearing.

The signature of the witness is not waived.

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Reported by:

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