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.

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SECTION 1. Qualifications and Background

1. I am currently an Associate Professor in the Department of Civil Engineering at the University of Memphis. My research focuses on groundwater, including numerical modeling of groundwater flow. I am also the Director of the Center for Applied Earth Science and Engineering Research at the University of Memphis, an interdisciplinary research center that combines the resources of two previous University of Memphis research centers, the Center for Partnerships in GIS and the Ground Water Institute. I previously served as interim director of the Ground Water Institute and director of the Center for Partnerships in GIS.

2. I obtained my B.A. and M.A. in Civil Engineering from the University of Memphis (formerly known as Memphis State University) and my Ph.D. in Civil Engineering from Colorado State University. I have published articles in a variety of peer-reviewed journals, including specifically about groundwater modeling and the Middle Claiborne aquifer. My full CV is attached as Appendix A to this report, and it includes all of my publications from the last ten years. I have not testified as an expert in any proceeding in the past four years.

3. I prepared this report at the request of the State of Tennessee for use in the original Supreme Court proceeding, *Mississippi v. Tennessee et al.*, No. 143, Original (U.S.). Specifically, I have been asked to opine on the question that I understand is at issue at this stage of the proceedings, which is whether the Middle Claiborne aquifer is an interstate water resource. My opinions are based on my training as an engineer specializing in the study of groundwater and on the sources and data identified in this report. I reserve the right to revise or amend this report as necessary based on new information that may become available.

4. I am not being compensated for my expert services in this proceeding other than my ordinary compensation for my full-time positions at the University of Memphis. My compensation does not depend in any way on my opinions or on the outcome of this proceeding. The Office of the Tennessee Attorney General has an agreement to compensate the University of Memphis for my time at the rate of $275 per hour, in addition to paying the University for reasonable expenses I incur that are related to serving as an expert.

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

[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.

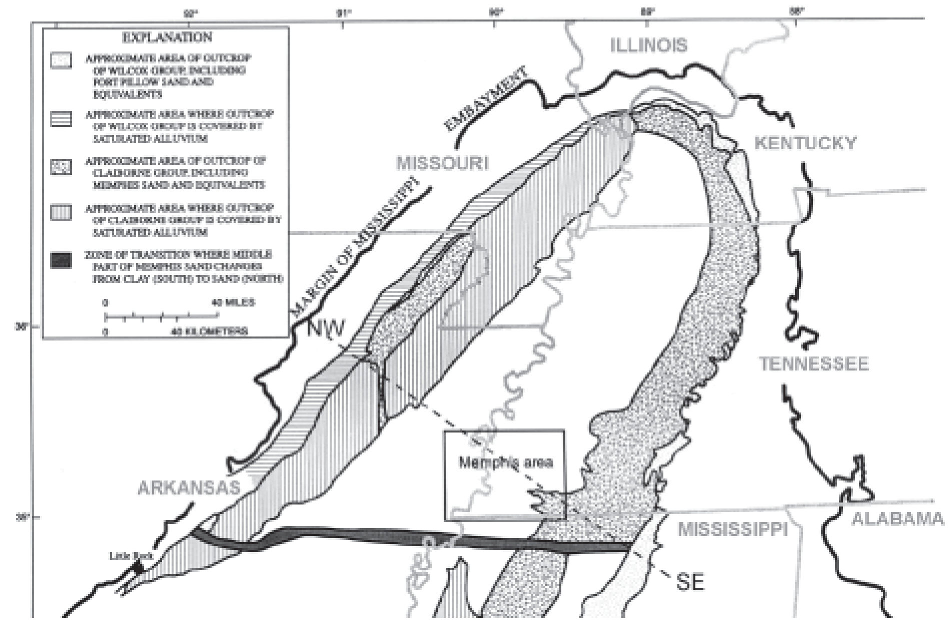

Figure 1. Waldron et al. (2011), *Figure 2*, p. 16. Map showing the approximate location of the outcrop of the Middle Claiborne in Tennessee and Mississippi (from Brahana and Broshears, 2001).

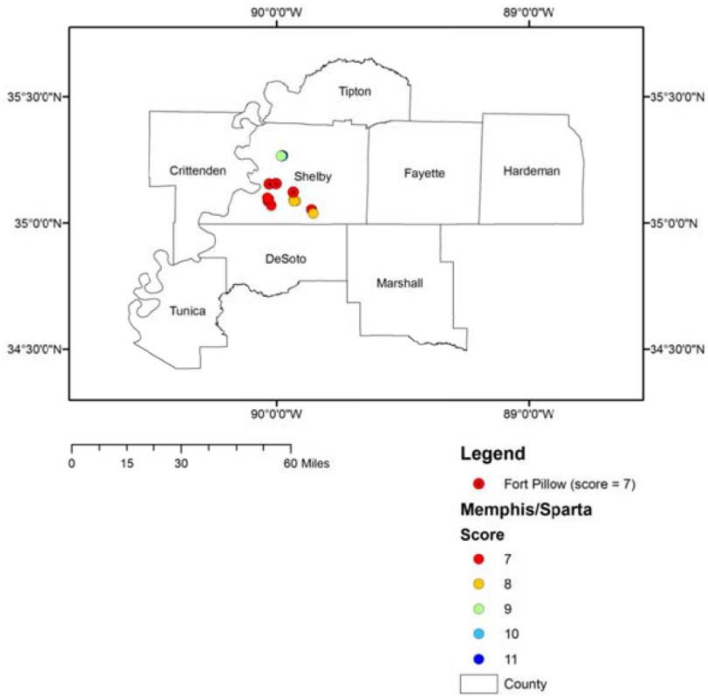

Figure 60. USGS aquifer parameter records with a score of 7 or greater.

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.

SECTION 4. 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.

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22. The Middle Claiborne aquifer is part of a larger aquifer system encompassed within the Mississippi embayment. The Mississippi embayment is a broad basin extending south from the southern tip of Illinois to Alabama, Mississippi, and Louisiana. (Figure 3) It contains layers of different geological units or formations, deposited over millions of years. The Mississippi embayment contains numerous aquifers; the most important are the Mississippi River alluvial aquifer, which is a semi-confined aquifer; and the Claiborne and Wilcox aquifers, including their confining units.

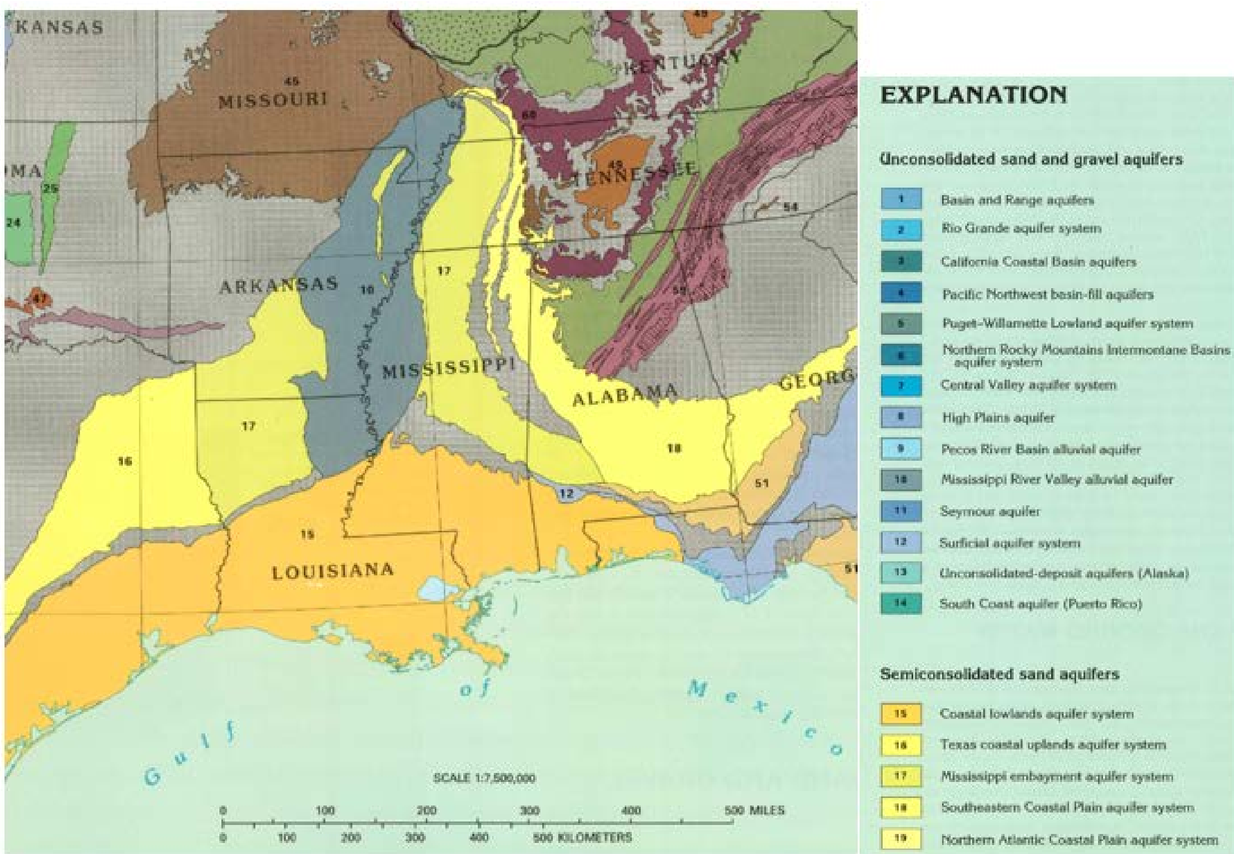

Figure 3. Proposed lithostratigraphic correlation for the northern and central Mississippi Embayment (modified from Hosman and Weiss, 1991)

23. From the surface down, major hydrogeological units of the Mississippi embayment in this area include:

- The alluvial aquifer;
- The Jackson formation;
- The Upper Claiborne confining units (Cook Mountain and Cockfield formations);

- 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.)

Tennessee, to its equivalent beneath northern DeSoto County, Mississippi. The authors note that the Sparta Sand "is correlative with the upper part of the Memphis aquifer." (p. D18) Their study, based on well logs, illustrates the continuity of the Memphis aquifer and the Sparta Sand aquifer – hence, the Middle Claiborne aquifer. Specifically, Hosman et al.'s *Plate 1* shows the geographic locations of different series of wells used to produce cross-sections of the area's geology, including cross-section F-F', which extends from Kentucky down through Shelby County and DeSoto County, and beyond. As shown on Hosman et al.'s *Plate 2*, the Memphis Sand equivalent in Tennessee continues into DeSoto County, Mississippi, before separating into the Sparta Sand, Cane River formation, and Carrizo Sand further to the south and west into Lee County, Arkansas.[8]

28. Another USGS paper, Hosman (1996), describes the subsurface stratigraphy in the region of eastern Arkansas, northern Mississippi, and southwest Tennessee. In particular, this paper describes how the Carrizo Sand – that is, the basal or lowest Claiborne unit in Arkansas – becomes the equivalent basal section of the Middle Claiborne aquifer in northern Mississippi as the Cane River formation transitions to sand facies near the 35th parallel (i.e., the clay layer separating the formations becomes sand, which does not hydrologically separate the layers, and the layers together comprise the Memphis Sand – p. G19, see Carrizo Sand and Cane River subsections). Hosman explains that the Sparta Sand "extends as far northward as the underlying Cane River Formation" but north of that limit "is a part of a larger unit, the Memphis Sand." (p. 20)[9]

29. Funded and published by the EPA, Waldron et al. (2011) details the subsurface stratigraphy[10] of the tri-state region of northern Mississippi, eastern Arkansas, and western Tennessee (p. 15, first paragraph). This analysis clarifies lithostratigraphic nomenclature from an extensive literature review and develops stratigraphic correlation among the aquifers, using geophysical logs to construct cross-sections across different portions of the tri-state region.[11] As illustrated in the paper's *Figure 6* (p. 31), cross-section D-D' goes through Crittenden County (Arkansas), Shelby County (Tennessee), and DeSoto County (Mississippi). The correlation of hydrogeologic units as shown in cross-section D-D' (*Plate 5*, p. 140) indicates the equivalency of the Memphis Sand in Arkansas and Tennessee with that in northern Mississippi, down to the transition region in Mississippi where the aquifer is subdivided into multiple aquifers by clay intervals (in the Tallahatta and Zilpha formations, p. 33, second paragraph). Cross-section C-C' demonstrates the same equivalency, although it runs from Shelby County through Fayette County (Tennessee) and Marshall County (Mississippi). Based on the comprehensive literature review and the cross-sections, a lithostratigraphic correlation of the region is proposed in *Table 4* (p. 30). Further, Waldron et al. (2011) state: "*The Claiborne interval includes three regional aquifers. In northern Mississippi and adjacent Arkansas, the Lower and Middle Claiborne*

[8] These subdivisions of the Claiborne are divided by clay formations that do not exist in the northern part of DeSoto County or in Shelby County.

[9] The Carrizo and Cane River are local names in Arkansas for the Lower Claiborne aquifer and Lower Claiborne confining layer, respectively. (See Table 1.)

[10] Stratigraphy refers to the classification of layers, in this case different rock layers.

[11] The geophysical logs utilize gamma and conductivity sensors in a borehole, allowing determination of the geologic facies (e.g., sand, clay, and silt) in the subsurface at different depths.

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*).

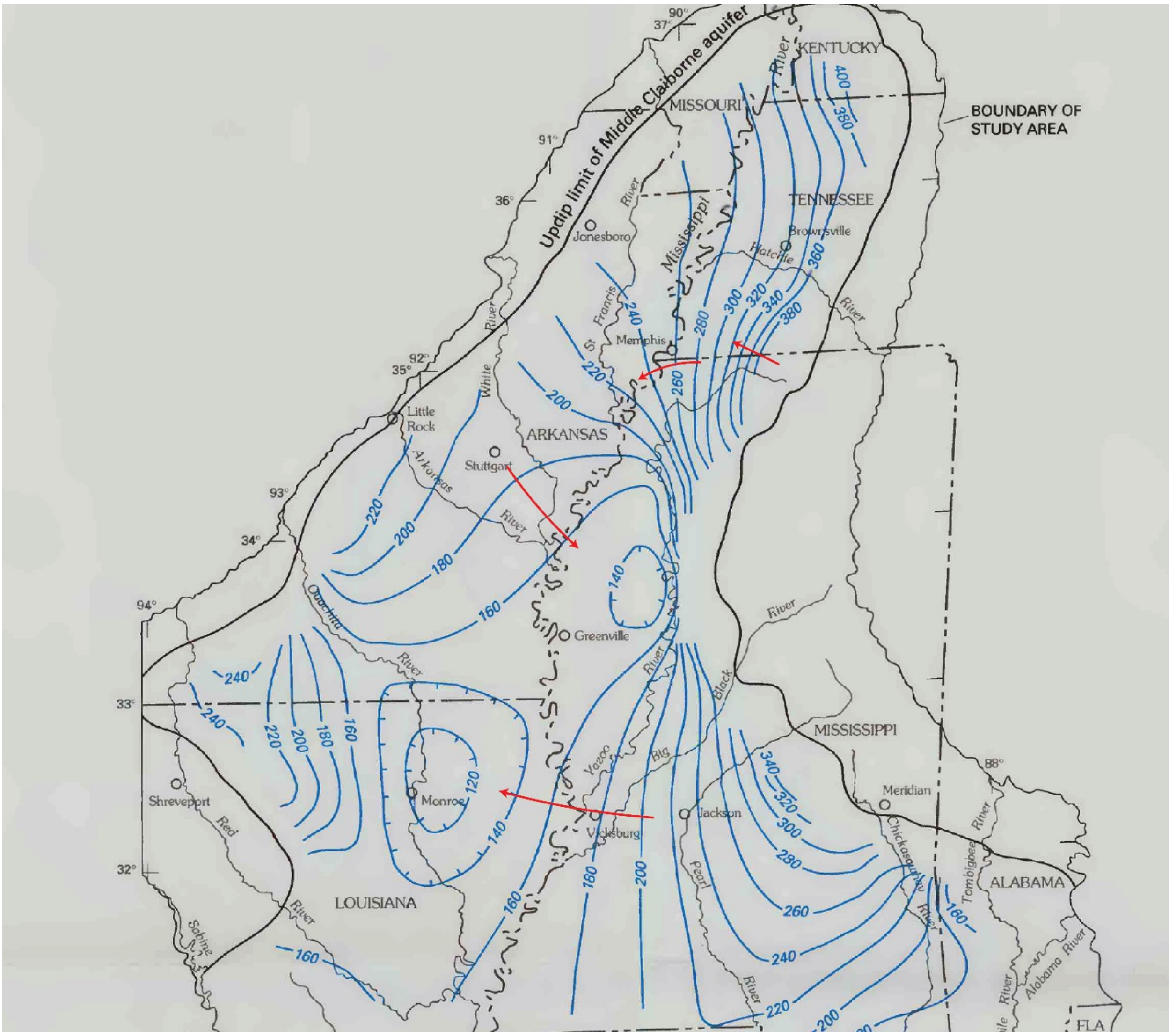


Figure 4. Illustration of predevelopment groundwater conditions in the Middle Claiborne aquifer (Arthur and Taylor, 1998). Red arrows are drawn atop the original report figure to illustrate groundwater flow direction as taken perpendicular to head contours.

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.

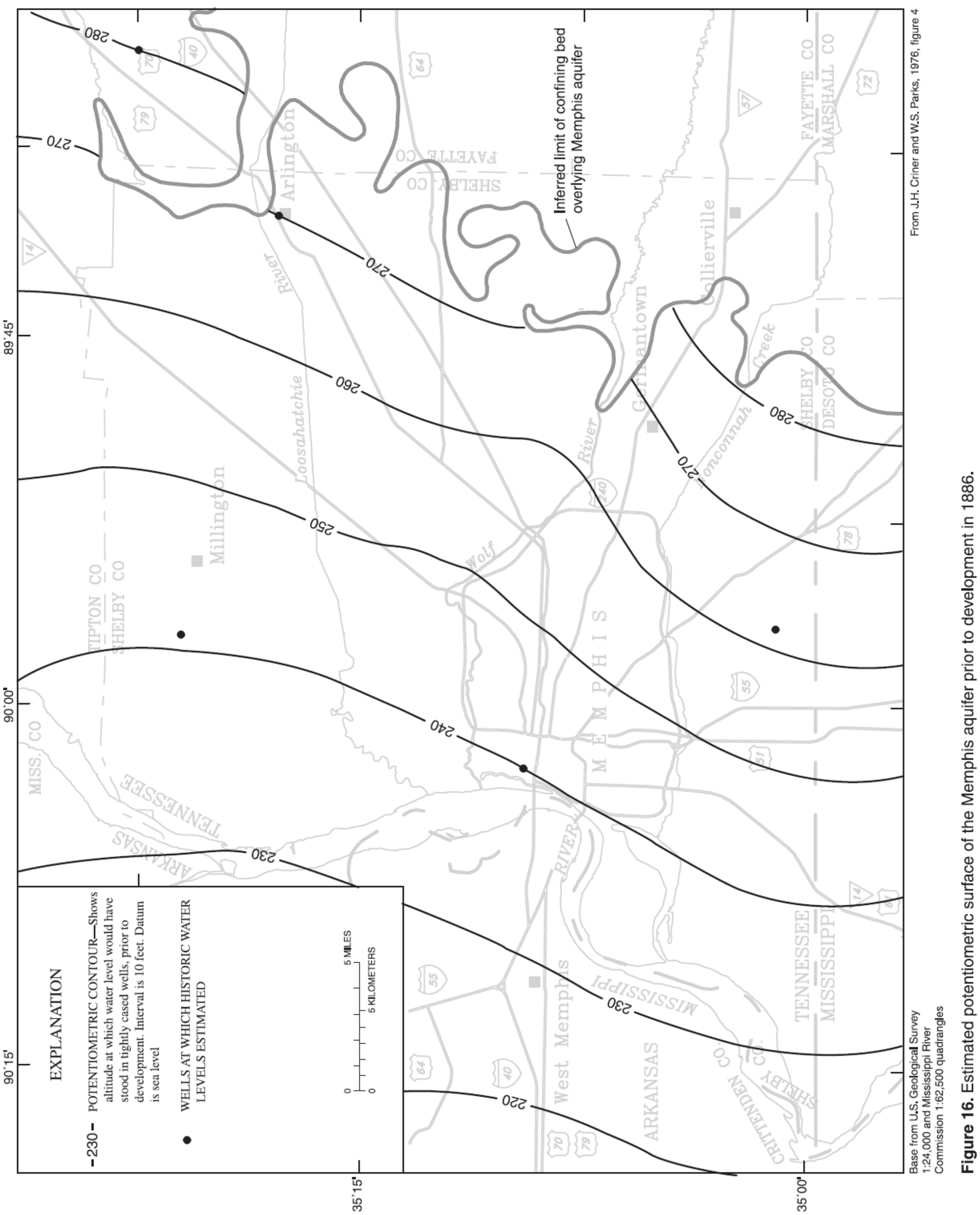


Figure 5. Reproduction of the Criner and Parks (1976) predevelopment condition of the Middle Claiborne aquifer.

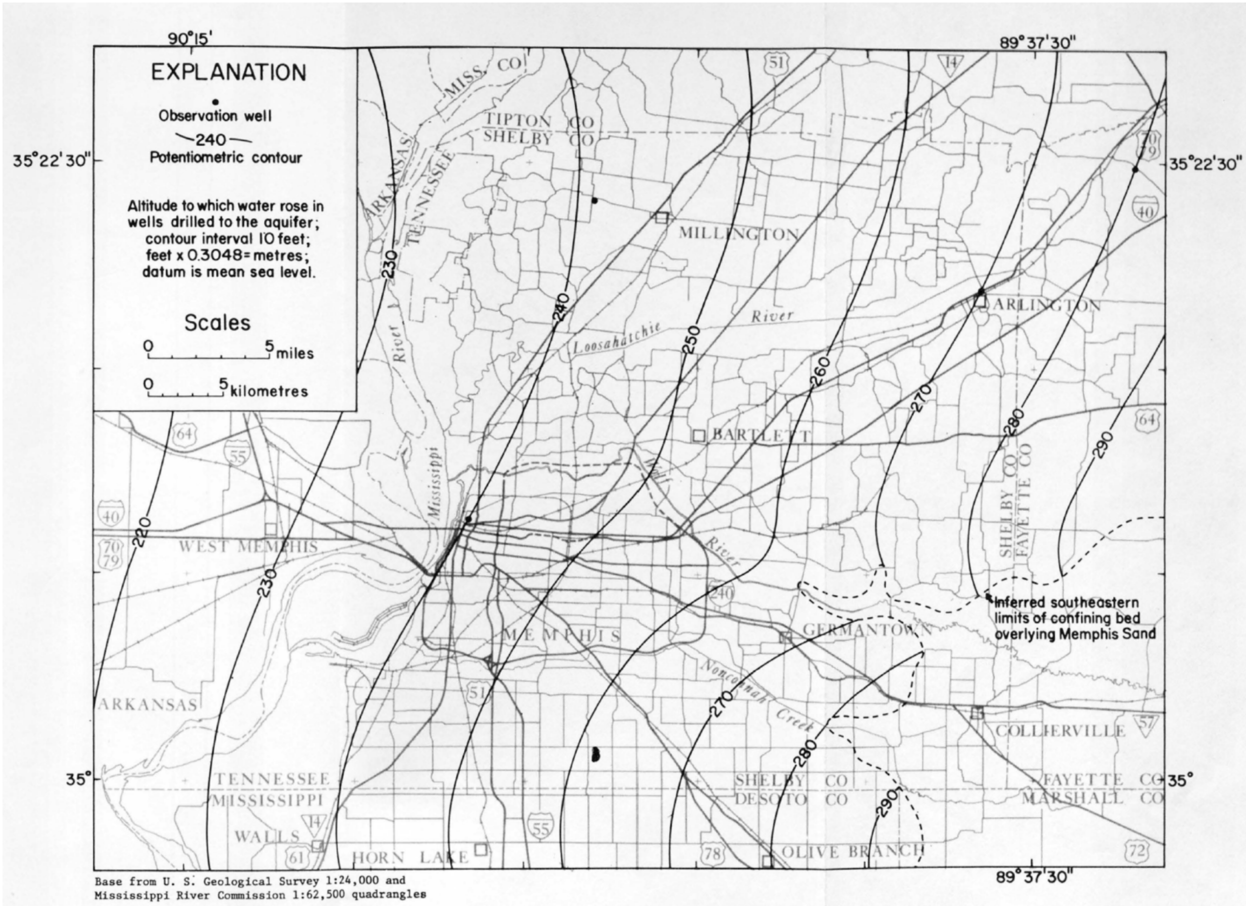


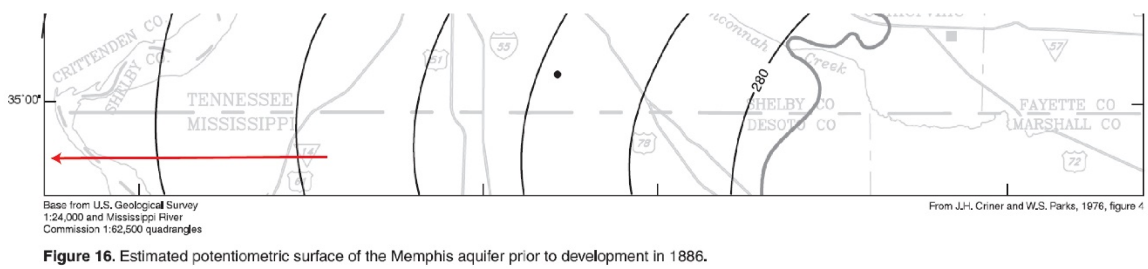
Figure 6. Reproduction of the Criner and Parks (1976) predevelopment condition of the Middle Claiborne aquifer.

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

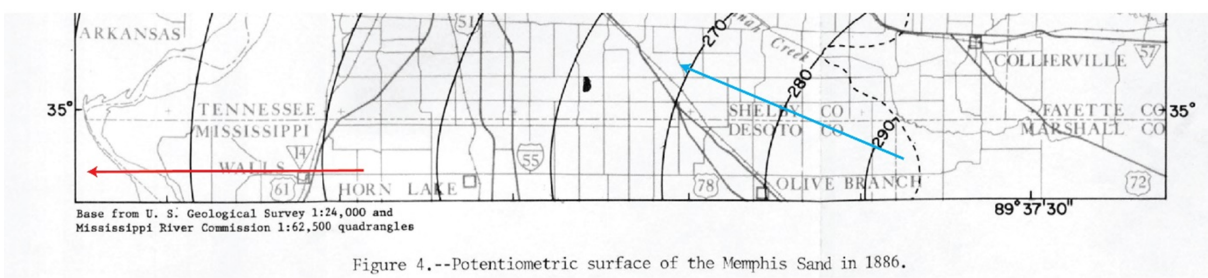
[12] Further, note that the figure used by Mississippi (Figure 8, below) does not actually match the figures from either Brahana and Broshears (2001) or Criner and Parks (1976), although Mississippi asserts that it derives its figure from Brahana and Broshears (2001), which in turn derived it from Criner 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).



(a)



(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.

70a

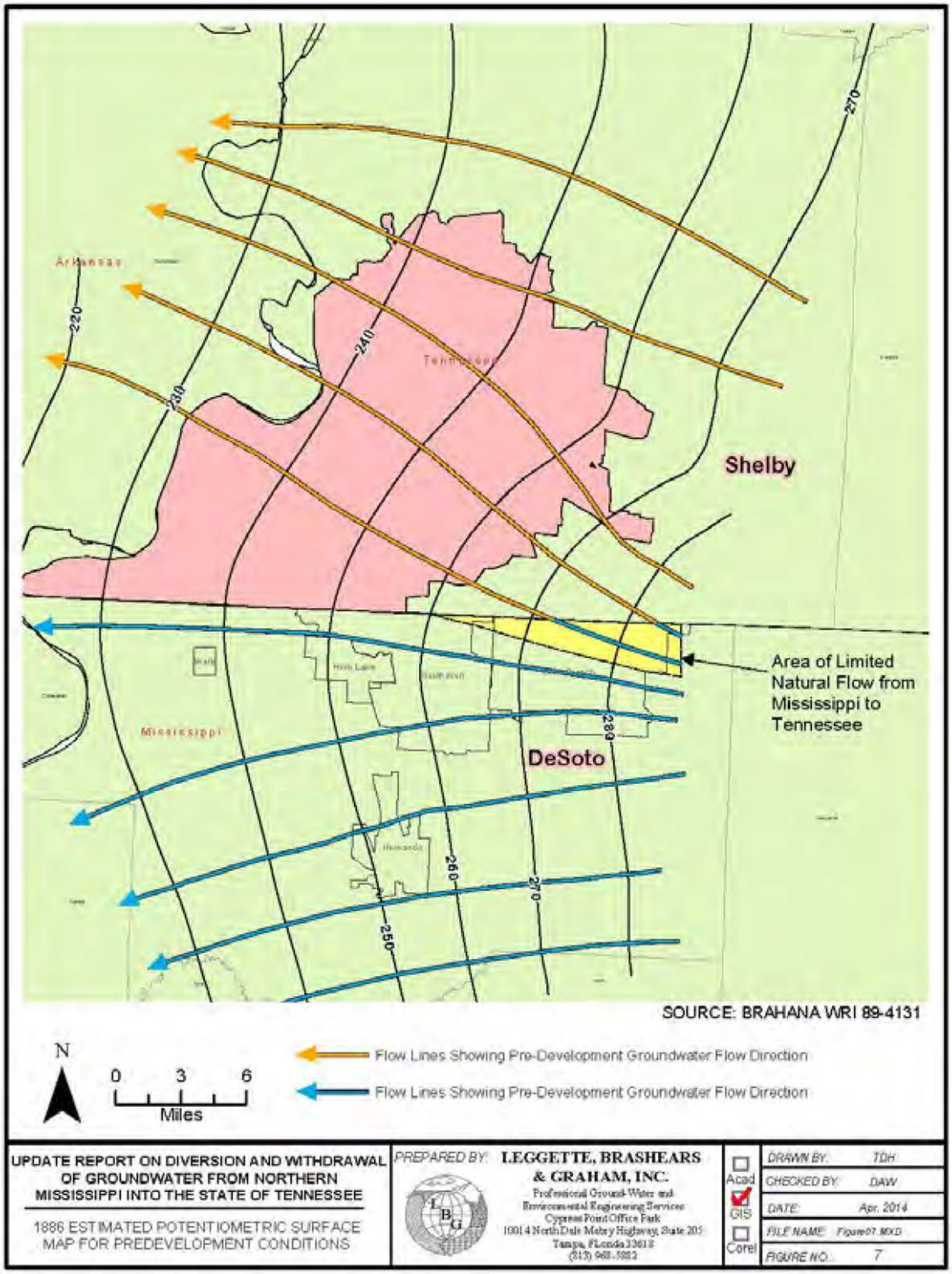


Figure 8. Reproduction of State of Mississippi's Appendix A, 70a figure (Appendix *Figure 7*) depicting predevelopment groundwater conditions including flow direction.

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.

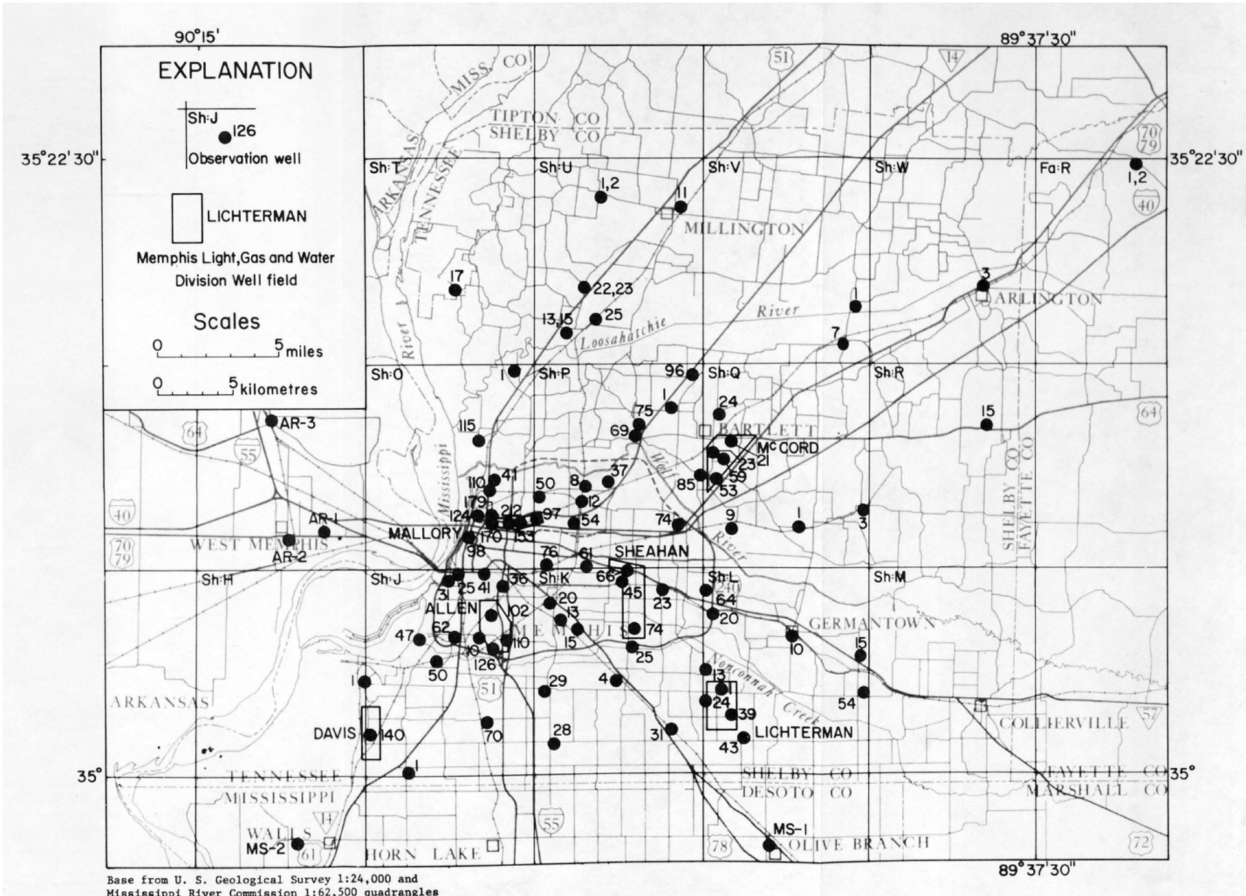
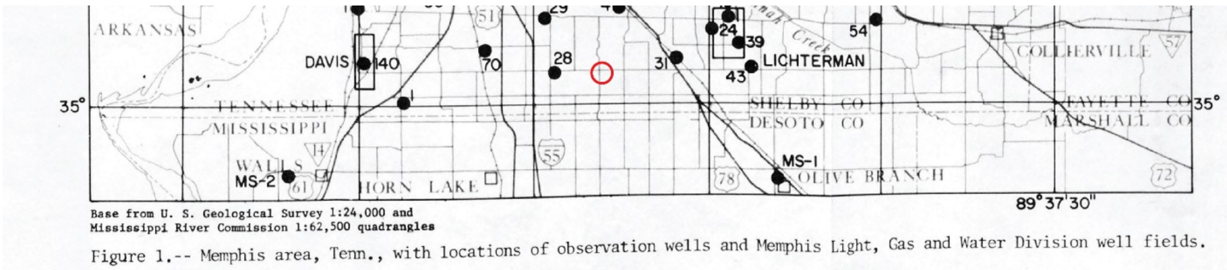
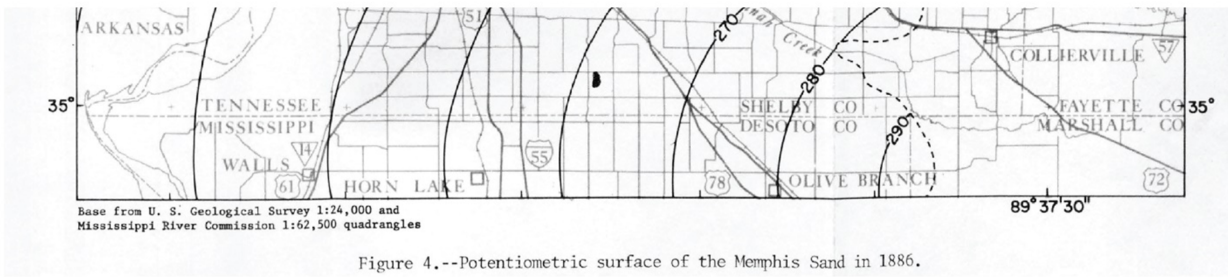


Figure 1.-- Memphis area, Tenn., with locations of observation wells and Memphis Light, Gas and Water Division well fields.

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*.

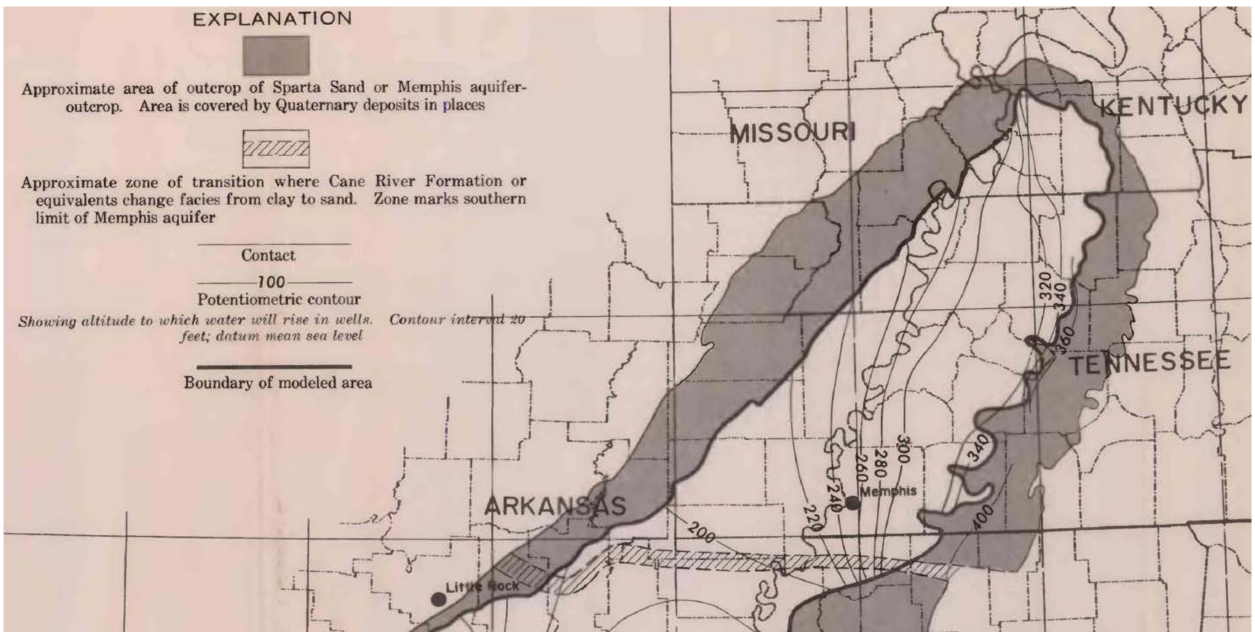


Figure 11. Excerpt of Reed (1972) *Plate 1* showing predevelopment conditions along the Tennessee-Mississippi state line.

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.

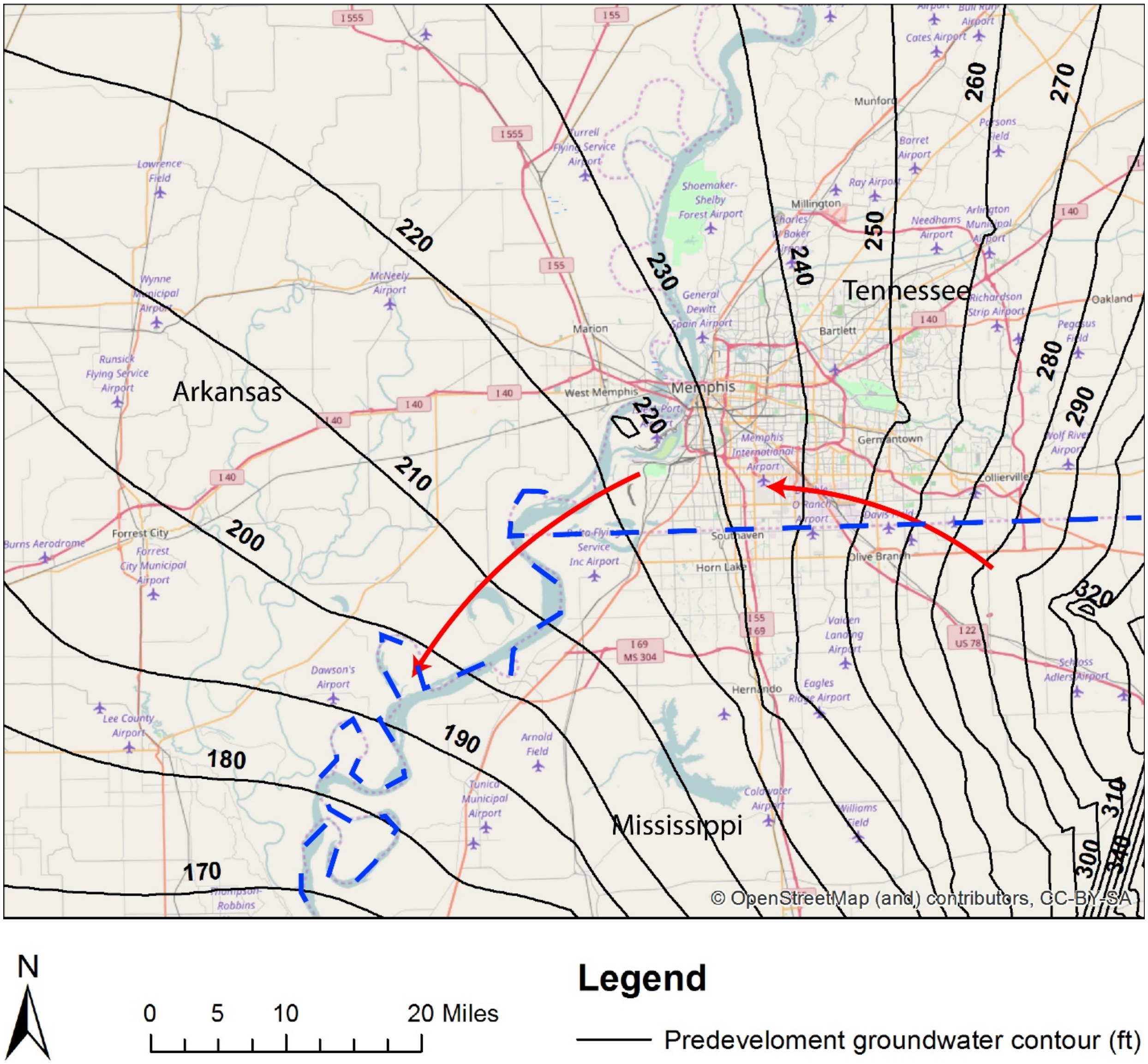


Figure 12. Resulting groundwater predevelopment conditions derived from output from MERAS model (Clark and Hart, 2009). Red arrows have been overlaid to numerically indicate groundwater flow direction and blue hatched line approximates state line boundaries.

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.

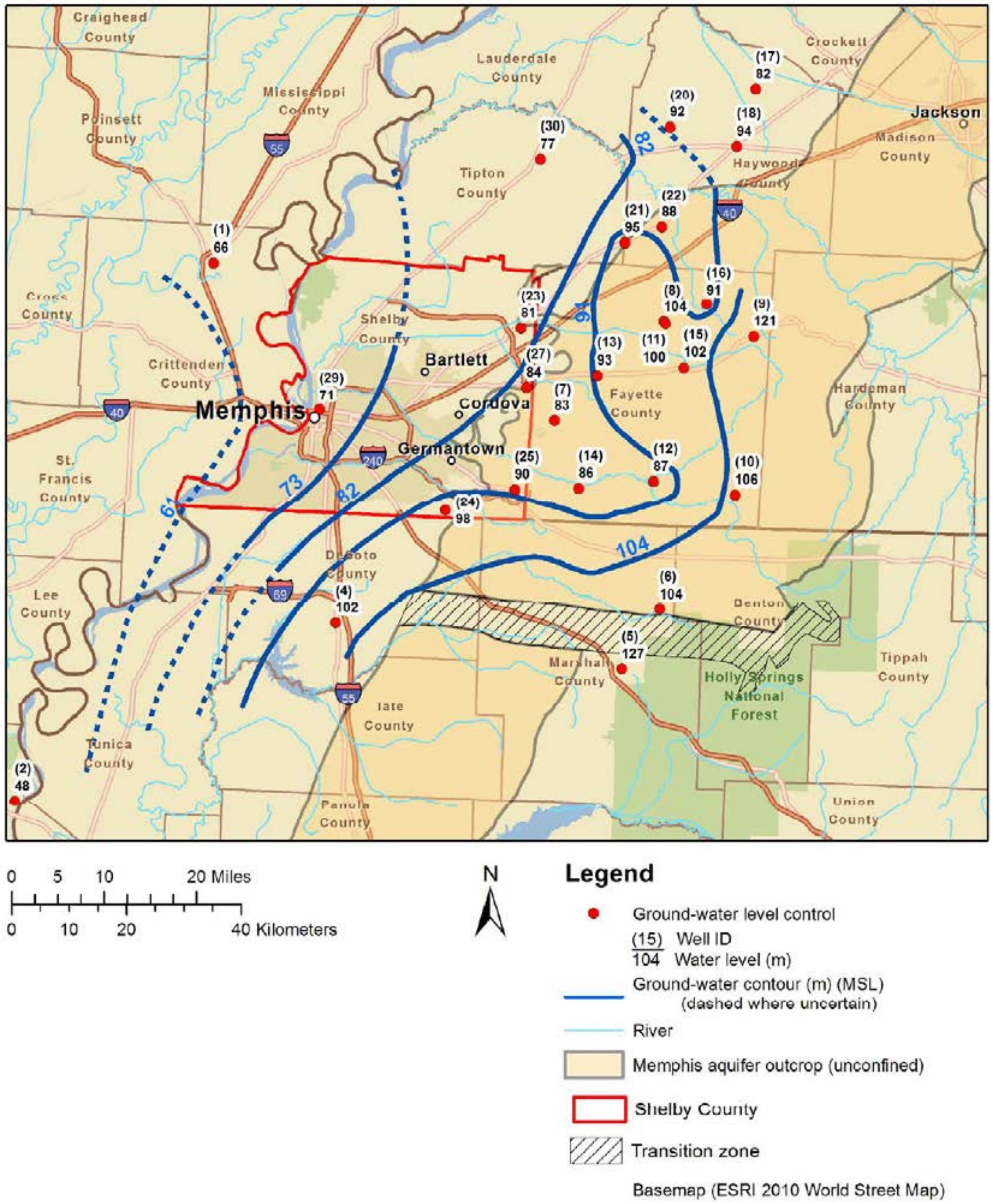


Figure 13. Predevelopment groundwater conditions for the Middle Claiborne aquifer (Waldron and Larsen, 2015).

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Appendix A

Brian Waldron

Associate Professor, Department of Civil Engineering
Herff College of Engineering
University of Memphis

CURRENT ACADEMIC POSITIONS

Associate Professor, Civil Engineering, University of Memphis
Director, Center Applied Earth Science and Engineering Research, University of Memphis

EDUCATION

Aug. 1995 to Aug. 1999	Colorado State University **Doctor of Philosophy, Civil Engineering**	Fort Collins, Colorado
Jan. 1992 to Aug. 1994	University of Memphis **Master of Science, Civil Engineering**	Memphis, Tennessee
Aug. 1989 to Dec. 1991	Memphis State University **Bachelor of Science, Civil Engineering**	Memphis, Tennessee

YEARS OF SERVICE

August 2010 to present	Associate Professor	Memphis, Tennessee University of Memphis
August 2006 to 2010	Assistant Professor	Memphis, Tennessee University of Memphis
Sept. 1999 to August 2006	Research Assistant Professor	Memphis, Tennessee University of Memphis

OTHER EXPERIENCE

Teaching: CIVL 3101 Computational Methods; CIVL 3181 Hydraulics and Hydrology, CIVL 4180-6180 Advanced Hydraulics and Hydrology, CIVL 3180, MECH 3331 Civil Engineering Hydraulics (Fluid Mechanics); CIVL 4111 Engineering Economics; CIVL 4195 Professional Practice; CIVL 7001-8001 Engineering Analysis; CIVL 7170-8170 Ground Water Contaminant Fate and Transport; CIVL 7195-8195 Groundwater Hydraulics; CIVL 7197-8197, GEOL 7197 Ground Water Quality Control, CIVL 7177-8177 Quantitative Hydrogeology; CIVL 7900 Ground Water Modeling; CIVL 7909-8909 Advanced Applications in GIS; CIVL 7001 Engineering Analysis; CIVL 7191 Computer Methods in Hydrology; GEOG 4515-6515,PLAN 6515 Geographic Information Systems

STATE REGISTERED AS PROFESSIONAL ENGINEER

Tennessee

PUBLICATIONS

Refereed Journal Publications:

Javadnejad, F., **Waldron, B.** and Hill, A., 2017. LITE Flood: Simple GIS-Based Mapping Approach for Real-Time Redelineation of Multifrequency Floods, Natural Hazards Review, 13 p., 10.1061/(ASCE)NH.1527-6996.0000238.

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Waldron, B. Designing of a Centralized Database for Simplifying Ground Water Model Development, TN American Water Resources Association Conference Proceedings, 2001.
Larsen, D., Gentry, R., Waldron, B., *et al.* Variations in Water Quality and Tritium in the Sheahan and Morton Well Fields, Memphis, Tennessee, USA, TN American Water Resources Association Conference Proceedings, 2001.

GRANTS AND CONTRACTS

MLGW GSR full mapping – (2016) $412,000 (PI)
Town of Collierville – (2016) $9,000 (PI)
City of Germantown – (2016) $16,100 (PI)
City of Bartlett – (2016) $16,100 (PI)
MLGW – (2016) $250,000 (PI)
City of Millington – (2016) $5,000 (PI)
Shelby County (DHS-UASI) – (2016) GIS develop of the Memphis/Shelby County UASI GIS system. $58,000 (PI)
UTK-USDA – (2016) $77,309 (co-PI)
City of Memphis Mayor's Office: City Assessment – (2016) $30,000 (PI)
ETI storm water – (2016) $25,161 (PI)
UTK-USDA – (2015) $77,309 (co-PI)
Non-disclosed – (2015) $26,542 (PI)
Non-disclosed – (2015) $15,971 (PI)
Shelby County (DHS-UASI) – (2015) GIS develop of the Memphis/Shelby County UASI GIS system. $61,000 (PI)
Shelby County Public Works – (2015) $50,000 (PI)
EDGE – (2015) $50,000 (PI)
Town of Collierville – (2015) $15,910 (PI)
Town of Collierville – (2015) $9,000 (PI)
City of Germantown – (2015) $16,100 (PI)
City of Bartlett – (2015) $16,100 (PI)
City of Millington – (2015) $5,000 (PI)
MLGW – (2015) $250,000 (PI)
Ecuador groundwater inventory – (2015) $109,000 (PI)
City of Memphis Mayor's Office: City Assessment – (2015) $30,000 (PI)
Pickering storm water – (2015) $21,400 (PI)
Non-disclosed – (2014) $148,500 (PI)
Non-disclosed – (2014) $135,000 (PI)
Alta – (2014) $21,035 (PI)
Livability: Community Foundation – (2014) $147,000 (PI)
Hyde Family Foundation – (2014) $41,925 (PI)
TN WRRC – (2014) $18,000 (co-PI)
Shelby County Health Department – (2014) Ground water age-dating $10,000 (co-PI)
City of Germantown – (2014) $16,100 (PI)
City of Bartlett – (2014) $16,100 (PI)
City of Millington – (2014) $5,000 (PI)
MLGW – (2014) $250,000 (PI)
City of Memphis Mayor's Office: City Assessment – (2014) $10,000 (PI)
Town of Collierville – (2014) $9,000 (PI)
Buchart Horn - City of Memphis Stormwater Control – (2014) $137,055 (PI)
Pickering – (2014) $22,500 (PI)
Shelby County (DHS-UASI) – (2014) GIS develop of the Memphis/Shelby County UASI GIS system. $61,000 (PI)
MPO sidewalks – (2014) $67,500 (PI)
MLGW GSR full mapping – (2014) $412,000 (PI)
MLGW MAOP – (2014) 29,200 (PI)
MLGW GSR scanning statistics – (2013) $6,175 (PI)

Shelby County Health Department – (2013) Ground water age-dating $10,000 (co-PI)
Geo-Jobe GIS data capture, software and support – (2013) $30,340 (PI)
Non-disclosed – (2013) $250,000 (PI)
TN Water Resources Research Center ground water recharge – (2013) $18,800 (PI)
GDR-911 – (2013) $417,720 (PI)
State of Tennessee Urban Tree Canopy Study – (2013) $90,080 (PI)
Memphis Metropolitan Planning Organization Phase 2 – (2013) $95,000 (PI)
Non-disclosed – (2013) $250,000 (PI)
Non-disclosed – (2013) $56,600 (PI)
Shelby County visual stream assessment – (2013) $376,000 (PI)
MLGW groundwater support – (2013) $250,000 (PI)
Shelby County (DHS-UASI) – (2013) GIS develop of the Memphis/Shelby County UASI GIS system. $132,100 (PI)
City of Bartlett groundwater support – (2013) $16,100 (PI)
City of Germantown groundwater support – (2013) $16,100 (PI)
City of Millington groundwater support – (2013) $5,100 (PI)
Town of Collierville groundwater support – (2013) $9,000 (PI)
Shelby County Greenprint – (2013) $150,759 (PI)
International Paper Water on Wheels (WOW) Mobile – (2013) $70,000 (PI)
Mayor's Initiative for Excellence in Government – (2012) $120,000 (PI)
Memphis Metropolitan Planning Organization Phase 1 – (2012) $95,000 (PI)
Shelby County (DHS-UASI) – (2012) GIS develop of the Memphis/Shelby County UASI GIS system. $750,000 (PI)
City of Bartlett groundwater support – (2012) $16,100 (PI)
City of Germantown groundwater support – (2012) $16,100 (PI)
City of Millington groundwater support – (2012) $5,100 (PI)
Town of Collierville groundwater support – (2012) $9,000 (PI)
Town of Collierville – (2012) Storm water pilot $4,300 (PI)
City of Memphis – (2012) Color study for MS River $290,900 (PI)
MLGW – (2012) Gas Business Districts $14,800 (PI)
MLGW – (2012) Right-of-Way $9,000 (PI)
MLGW – (2012) GSR and gas service lines $14,900 (PI)
Shelby County Health Department – (2012) Ground water age-dating $10,000 (co-PI)
International Paper – (2012) Water on Wheels (WOW) Mobile (gift) $70,000 (PI)
Non-disclosed – (2012) $250,000 (PI)
Non-disclosed – (2011) $250,000 (PI)
Urban Land Institute – (2011) $5,000 (PI)
Shelby County (DHS-UASI) – (2011) GIS develop of the Memphis/Shelby County UASI GIS system. $850,000 (PI)
City of Bartlett – (2011) $16,100 (PI)
City of Germantown – (2011) $16,100 (PI)
City of Millington – (2011) $5,100 (PI)
Town of Collierville – (2011) $9,000 (PI)
Shelby County Health Department – (2011) Ground water age-dating $10,000 (co-PI)
NSF – (2010) Collaborative research: Toward an understanding of the long-term deformation in the Mississippi Embayment - Phase II. $316,456 (co-PI)
Non-disclosed – (2010) $250,000 (PI)
Non-disclosed – (2009) $69,390 (PI)
Non-disclosed – (2009) $896,000 (PI)
City of Memphis – (2009) Sanitary Sewer Area 6 $50,000 (PI)
Memphis Police Department – (2009) GIS $140,000 (PI)
Non-disclosed – (2009) $250,000 (PI)
Non-disclosed – (2009) $115,000 (PI)
Non-disclosed – (2008) $83,000 (PI)
NSF – (2007) Collaborative research: Toward an understanding of the long-term deformation in the Mississippi Embayment. $60,534 (co-PI)
USGS-NEHRP – (2007) Toward an understanding of the long-term deformation in the Mississippi Embayment: Collaborative research with University of Memphis and University of Texas. $43,720 (co-PI)
Non-disclosed – (2008) ADA and GIS data migration $178,789 (PI)
City of Memphis – (2007) GIS data migration. $40,000 (PI)
City of Memphis – (2007) GIS data migration. $49,900 (PI)
City of Memphis – (2007) Paving survey, $33,909 (PI)
MLGW – (2007) Congressional earmark match: Mississippi Embayment Regional Aquifer Study. $250,000 (PI)
EPA – (2007) Congressional earmark: Mississippi Embayment Regional Ground Water Study. $480,300 (PI)

TDEC – (2006) GIS services. $49,034 (PI)
Shelby County – (2005) Identifying Conduits for Potential Contamination to Enter the Memphis Aquifer. $125,000 (PI)
TDEC – (2005) GIS Support of Division of Water Supply. $12,478 (PI)
TDEC – (2005) GIS Support to Division of Water Pollution Control. $3,393 (PI)
TDEC – (2005) GIS Support to Division of Natural Heritage. $5,233 (PI)
TN WRRC – (2004) An Investigation of Surface-Ground Water Connections at Nonconnah Creek: A Source of Recharge to the Memphis Aquifer in Shelby County, Tennessee. $81,046 (co-PI)
TDEC – (2004) Identifying Conduits for Potential Contamination to Enter the Memphis Aquifer. $125,000 (PI)
Cargill – (2004) Gift. $10,000
Coors – (2004) Gift. $5,000
City of Memphis – (2004) Update City of Memphis paving database. $51,600 (PM)
TDEC – (2004) Educational video on source water protection. $70,000 (PI)
TDEC – (2004) Development of TDEC GIS network and GIS training. $35,420 (PI)
TDEC – (2003) Produce West Tennessee Ground Water Video (educational). $50,000 (PI)
TDEC – (2002) Development of TDEC GIS/GIS network and GIS training. $92,827 (PI)
TDEC – (2000) Source Water Assessment – Risk Ranking of ground-water and surface water systems in Tennessee. $300,000 (PI)
USGS – Database management and subsurface stratigraphic surface interpolation for the Shelby County Hazard Mapping project. $11,438 (PI)
The University of Memphis FRG – Use of Naturally Occurring Chloride as an Inexpensive and Accurate Measure of Water Infiltration Below the Root Zone in West Tennessee. $4,000 (PI)
USGS – Unsolicited Proposal for the Continuation of the Creation, Expansion, Maintenance, and Application of a Subsurface Database for Shelby County, Tennessee – A Cooperative Agreement Between the Center for Earthquake Research and Information and the Ground Water Institute at The University of Memphis. $43,016 (PM)

ORGANIZATIONS

Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) (member since 2003, Board of Directors 2012 – 2015)
Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) (member since 2003, treasurer 2008 – 2010)
State of Tennessee: Water Resources Technical Advisory Committee (2007 – 2012)
TN American Water Resources Association – President 2006, Conference Chair 2005 and 2006
Wolf River Conservancy – Board Member (2004 – 2008)
Children's Health Data Consortium – Advisory Council (2002)
National Ground Water Association (member)

AWARDS

Ensafe Professor (2012)
Askew Hargraves Harcourt & Associates, Inc - Junior Faculty Fellow (2009)
Memphis' Top 40 Under 40 (2009)

ROLES

Vice Provost for Research – Research Capacity Analysis team 2014
Information Technology – Teaching and Learning Advisory Committee (UoM) 2013-2014
Provost – New Technology Evaluation Team (UoM) 2014
University of Memphis – Standing Committee on Traffic and Parking 2011-2013
Vice Provost for Research – Faculty Advisory for Research Committee 2012-2013
Herff College of Engineering – Strategic Planning Committee 2014-present