EXPERT REPORT
Addendum #1

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

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July 31, 2017

Richard K Spruill

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I. Introduction

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

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

II. Qualifications

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

Richard K Spruill

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

III. Summary of General Opinions Provided in My Expert Report

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

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

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

IV. Summary of General Opinions Provided in Addendum #1

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

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

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

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

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

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

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

in the subsurface. In my opinion, there is no doubt that the groundwater within the Middle Claiborne (aka, SMS) aquifer beneath Mississippi is an intrastate natural resource under natural conditions, especially when one considers the component of time that Mr. Larson and Dr. Waldron elect to disregard.

V. Scope of Addendum #1

On June 30, 2017, the City of Memphis, MLGW, and the State of Tennessee submitted three expert reports as part of the defense of the litigation initiated by the State of Mississippi that is being addressed herein. Specifically, expert reports were submitted by Dr. David Langseth, Mr. Steven Larson, and Dr. Brian Waldron. I was tasked with evaluating, critiquing, and responding to the two latter reports. The Langseth report is being addressed by another expert for the State of Mississippi. Section VI of my Addendum #1 report evaluates and summarizes the 2015 publication by Dr. Waldron and Dr. Daniel Larsen that is integral to arguments made by these parties. The Waldron and Larsen report states that "*The pre-development map constructed from* [our] *research will have direct bearing on what injury, if any, can be substantiated*" (Waldron and Larson, 2015, page 5). Appendix B-1 provides my detailed analysis of the historic data used by Waldron and Larsen (2015) to produce what they consider to be the most correct and reliable equipotential map available that shows the pre-development distribution of hydraulic head in the Sparta-Memphis Sand aquifer and the natural pattern of groundwater flow. Sections VII and VIII of my Addendum #1 address the expert reports submitted by Mr. Larson and Dr. Waldron, respectively.

VI. Summary of My Evaluation of the 2015 Report by Waldron and Larsen

The Waldron and Larsen (2015) report was evaluated in connection with preparation of my expert report and this addendum. I summarize herein some basic aspects of the work described in that publication that render their interpretations and conclusions unreliable for determining the natural characteristics of the groundwater in Mississippi, which has been, and continues to be, pumped out of Mississippi and into Tennessee to a measurable degree.

VI.1 Introduction

The purpose of Waldron and Larsen's 2015 study (W&L 2015) was clearly to contradict the accuracy of the USGS' pre-development groundwater flow patterns in the boundary region between Mississippi and Tennessee, with special emphasis on flow patterns in the Sparta-Memphis Sand in the vicinity of the City of Memphis and Shelby County, Tennessee. Figure 4 of W&L 2015 is the final summary of their investigation and the pertinent figure discussed here, so it is reproduced below as Figure 1 for discussion in this addendum to my report. Appendix B-1 of my addendum provides a detailed evaluation of the data sources reportedly used by W&L 2015. In this section, I summarize my opinions regarding the data relied on within W&L 2015, the methods and assumptions used in their study, and the errors embedded in their analysis of, and conclusions regarding, pre-development groundwater flow in the SMS aquifer in northwestern Mississippi and southwestern Tennessee.

W&L 2015 states that significant extraction of groundwater from the Sparta-Memphis Sand (aka, Middle Claiborne aquifer) began in 1886 with the first commercial production well installed in the City of Memphis, and that withdrawals from the aquifer "*in Shelby County, Tennessee, has continued to increase exponentially since 1886*" (Waldron and Larsen, 2015, page 3). W&L 2015 reports that "current" withdrawals are 712,000 cubic meters per day (m^3/day), which is approximately 188,089,000 gallons per day (gpd). However, it appears that the "exponential" withdrawal volume in Shelby County, Tennessee, was reached long before the present; "*a maximum of 190 Mgal/d* (190 million gpd; mgd) w*as reached in 1974*" (Criner and Parks, 1976, page 1). In fact, I contend that the graph by Criner and Parks (1976) provided below as Figure 2 shows that there was a linear increase during the first 10 years of withdrawals from the SMS, no obvious increase for the following quarter century (steady at ~33 mgd), and a linear increase in withdrawals between approximately 1920 and 1975.

Figure 1: Waldron and Larsen (2015) Pre-Development Equipotential Map for the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer)

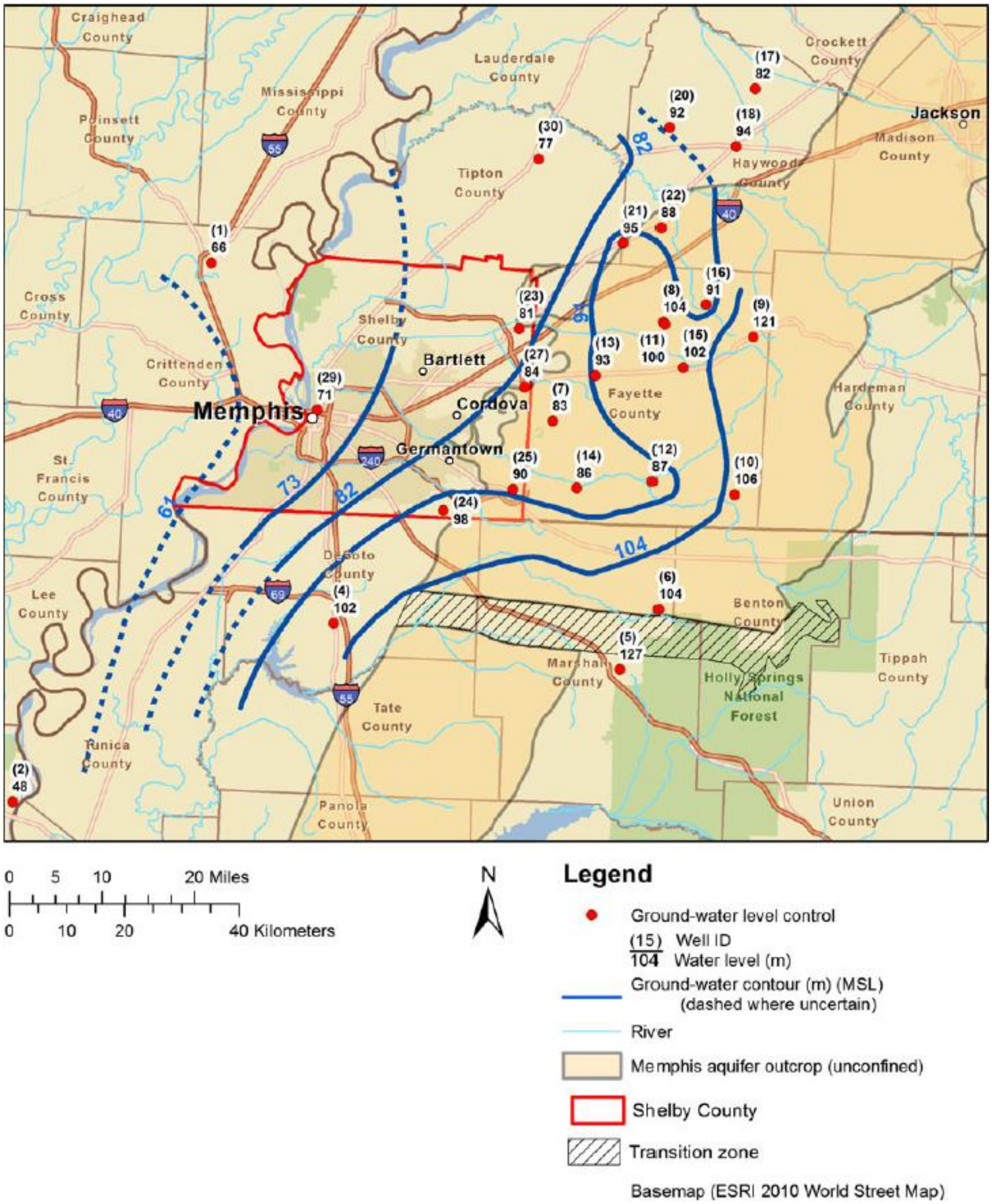


Figure 2: Criner and Parks (1976) Graph of Groundwater Withdrawals from the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) between 1886 and 1975.

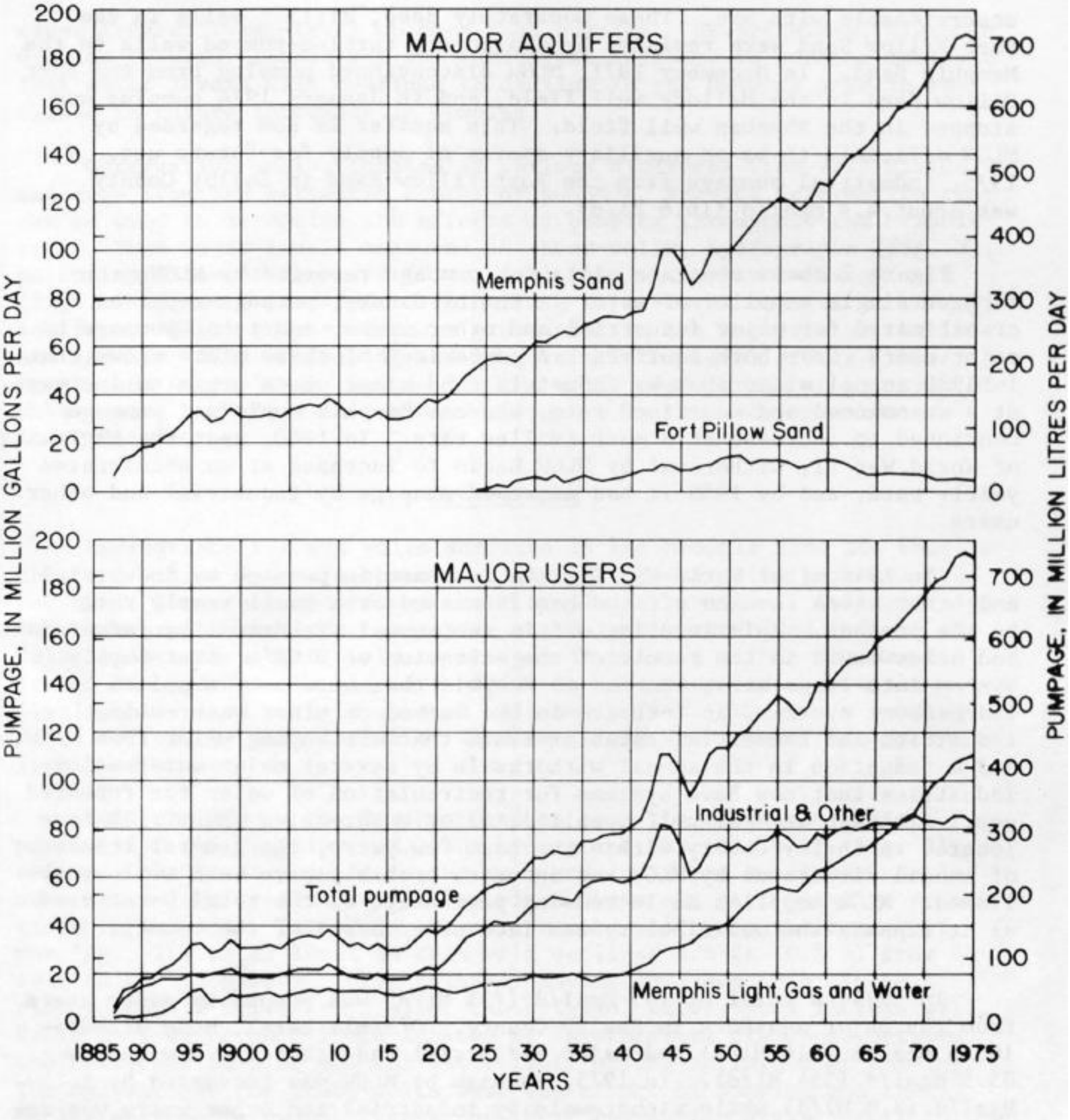


Figure 2.--Pumping rates from major aquifers by major users in Shelby County, Tennessee, 1887-1975.

W&L 2015 is focused on (1) critiquing a pre-development equipotential map for the SMS produced by Criner and Parks (1976), and (2) evaluating a data set that they consider to be more pertinent and robust than that employed by Criner and Parks. W&L 2015 does not mention a study by the USGS (Reed, 1972) which pre-dates, and shows good agreement with, the report by Criner and Parks (1976). Waldron and Larsen's apparent goal was to produce their own pre-development equipotential map (Figure 1) that could be used to contradict the USGS study that showed "*zero or no flow according to Criner and Parks (1976)*" for the trans-border migration of SMS groundwater from Mississippi to Tennessee. Waldron and Larsen used their new and purportedly superior equipotential map to determine that "*the estimated average quantity of flow from Mississippi into Shelby County around the time of pre-development was approximately 220,000 m^3/day*" (~58,118,000 gpd) (W&L, 2015, page 151).

VI.2 Comments on the Report by Criner and Parks (1976)

Before discussing the flaws and errors in the data used and conclusions reached in W&L 2015, some background on the Criner and Parks (1976) report is useful to provide context for W&L 2015.

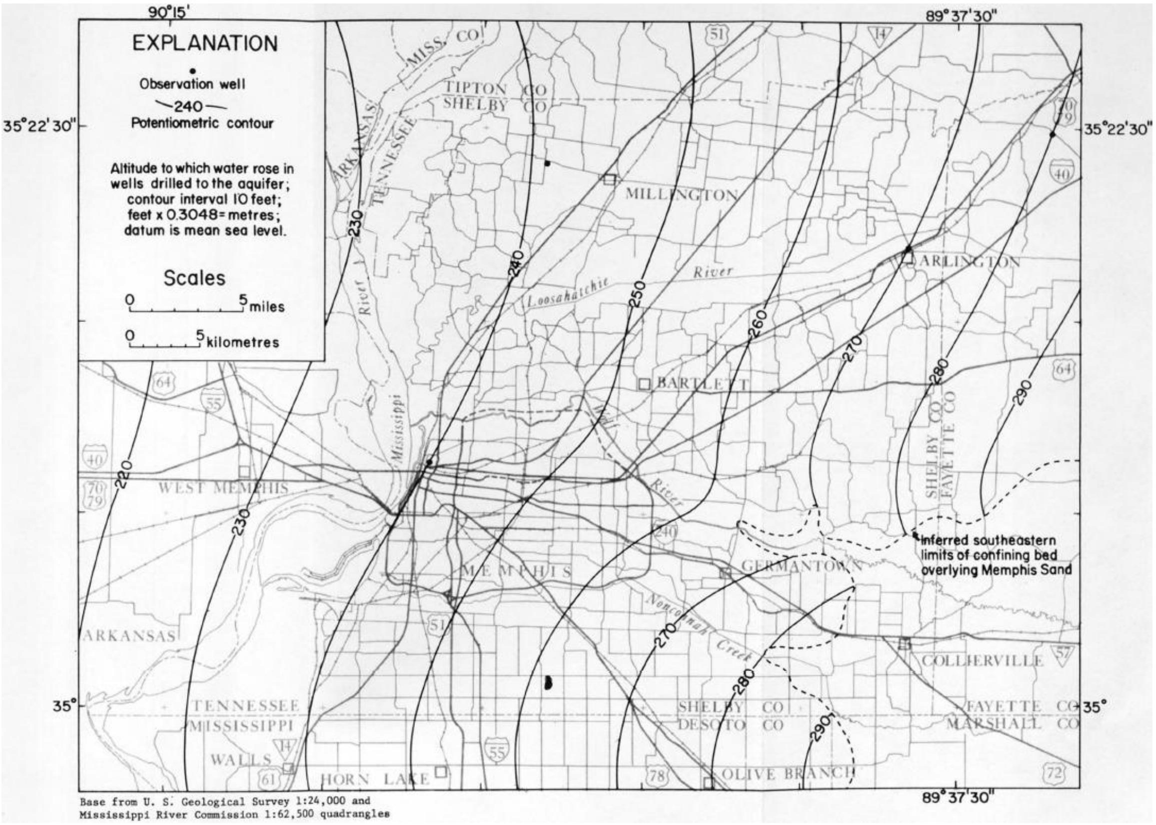
- Criner and Parks (C&P) were USGS employees who acknowledge that their report was "*Prepared in cooperation with the City of Memphis* (and) *Memphis Light, Gas and Water Division*" (C&P, 1976, page I). However, this was an independent USGS investigation and report funded by the United States government.
- Criner and Parks do not estimate the volume of SMS groundwater flowing from Mississippi into Tennessee prior to or after extensive pumping in Tennessee. The report does, however, make it unambiguously clear that "*one of the effects of escalating pumping* (in the Memphis area) *has been the development of a broad cone of depression in the originally, **nearly flat**, potentiometric surface*" of the SMS (C&P, 1976, page 14, emphasis added).
- The C&P report states that the evaluation of water-use patterns in the vicinity of Memphis and Shelby County, Tennessee, "*did **not** include pumpage from a few thousand suburban and rural wells **nor** any wells in the Arkansas and Mississippi parts of the Memphis area*" but that the "*annual pumpage from these wells probably does **not** amount to more than an additional 2 or 3 percent of the total pumpage values given in this report*" (C&P, 1976, page 35, emphasis added).

- C&P relied upon historic water-level data "*for six wells screened in the Memphis Sand*" that "*were selected for their long-term record and their areal distribution…within the Memphis area*" (C&P, 1976, page 11). Significantly, C&P only relied upon data from "*observation wells, located at various distances from well fields and away from the estimated center of pumping*" (C&P, 1976, page 11).
- Measurements from those six well-documented observation wells were "*projected backward in time to illustrate the probable original* (pre-1886) *water level with respect to the land surface*" (C&P, 1976, page 11) to illustrate the most likely configuration of the pre-development equipotential surface for <u>hydraulically-confined</u> portions of the SMS aquifer (Figure 3). It is significant that Criner and Parks only employed data from confined portions of the SMS aquifer system. Problems introduced by mixing water-level data for confined and unconfined portions of an aquifer were discussed in my expert report, and the topic is revisited below in the context of the Waldron and Larsen (2015) study and their pre-development map.
- While the Criner and Parks study was not perfect, it employed data from reliable sources, and their pre-development equipotential map (Figure 3) provides a reasonably-sound basis for illustrating, testing, and refining changes to the SMS' equipotential surface that have resulted from intense and localized groundwater withdrawals in southwestern Tennessee.
- Criner and Parks were fully aware that their methods could not yield the data necessary to produce the most detailed and accurate pre-development equipotential map, but their resulting map (Figure 3) provides a reasonable basis for illustrating subsequent changes to the SMS' equipotential surface as a result of intense and localized groundwater withdrawals in southwestern Tennessee.
- The pre-development equipotential map (Figure 3) produced by C&P (1976) correlates reasonably well with equipotential maps produced for the SMS within other studies (e.g., Reed, 1972). Likewise, USGS and other computer simulations of the pre-development equipotential surface for the SMS yields patterns that generally agree with the interpretation by C&P (e.g., LBG, 2014). In fact, the map produced as Figure 4 of W&L 2015 being discussed herein is the only significant interpretation of the pre-development equipotential surface within the SMS in

Tennessee and northwest Mississippi that differs considerably from the work of all other researchers.

- W&L 2015 does not mention the earlier USGS study (Reed, 1972) that produced a pre-development (1886) equipotential map for the SMS (Figure 4) that appears remarkably similar in the vicinity of southwestern Tennessee to the interpretation produced by Criner and Parks (1976). A comparison of the map by C&P (1972) with the pertinent portion of the map by Reed (1972) is provided below (Figure 5).
- Significantly, the recent expert report by Mr. Steven Larson (page 20, paragraph 54) identifies the Reed (1972) pre-development equipotential surface as the basis for the regional computer modeling of the SMS conducted by the USGS (e.g., Clark and Hart, 2009). (See Section VII below)

Figure 3: Criner and Parks (1976) Equipotential Map for Confined Portions of the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) in 1886.



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

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

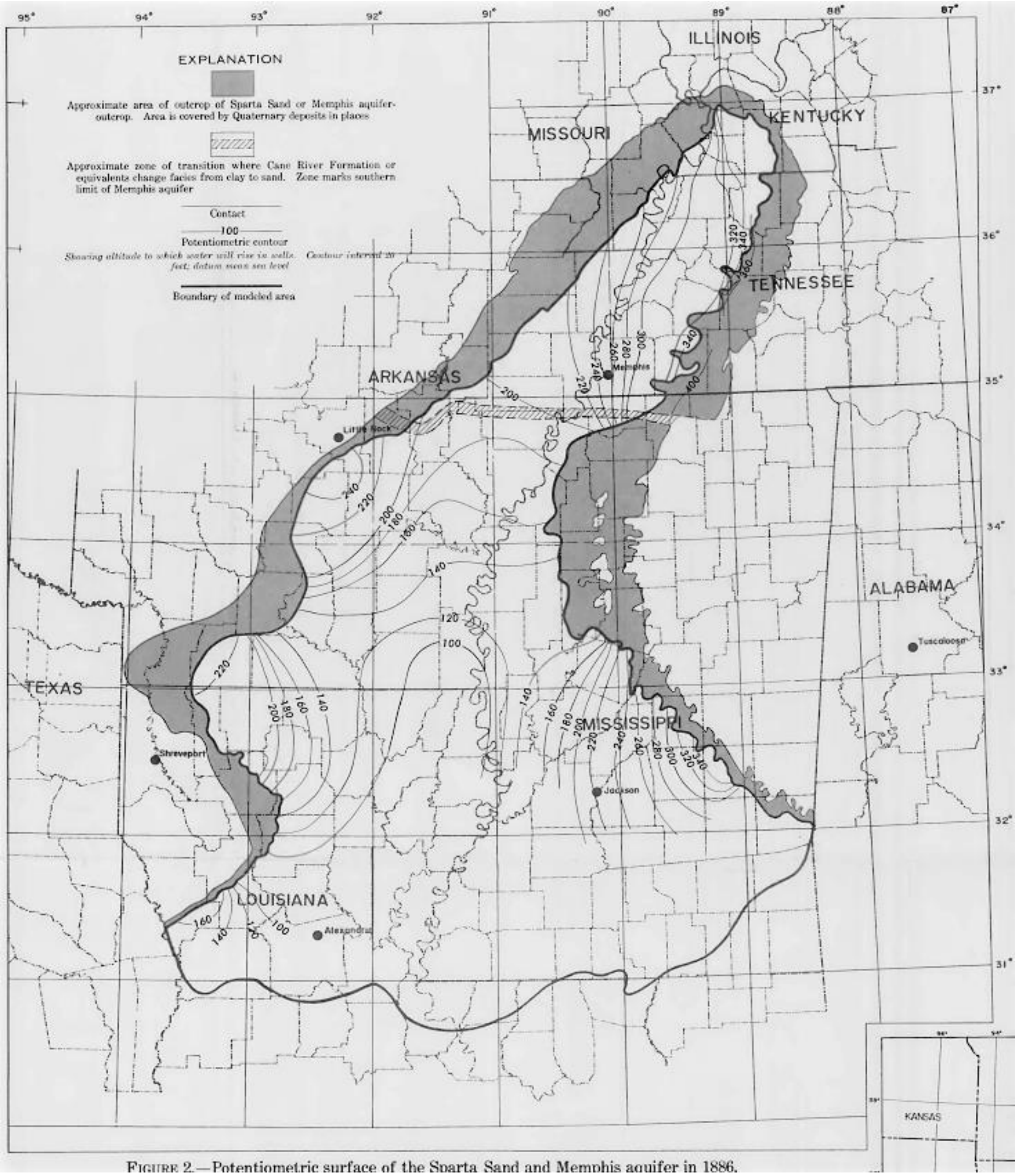
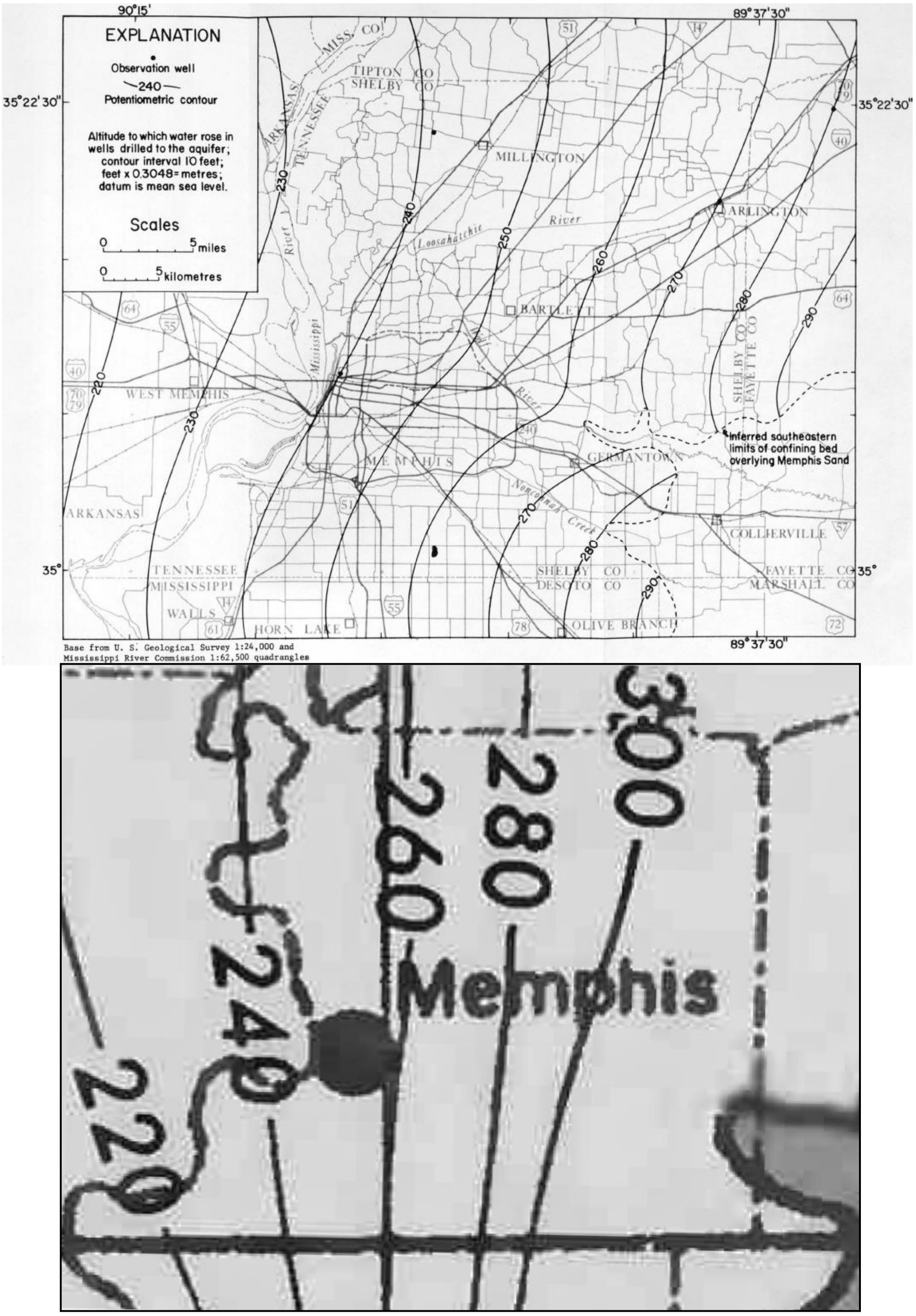


FIGURE 2.—Potentiometric surface of the Sparta Sand and Memphis aquifer in 1886.

Figure 5: Comparison of Equipotential Maps for Confined Portions of the Middle Claiborne Aquifer (aka, SMS or Memphis Aquifer) in 1886 Produced by Criner and Parks (1976) and Reed (1972), Top and Bottom, Respectively.

(Note: The image for Reed (1972) was converted to black-and-white, contrast was enhanced, and the image was cropped, rotated slightly, and scaled to better match the area shown in the map by Criner and Parks (1972).)



VI.3 Summary of Flaws in Data and Methods Used in the Waldron and Larsen (2015) Study

Hydrogeologists have long recognized that accurate and meaningful results and interpretations of the distribution of hydraulic head and patterns of groundwater flow within an aquifer can only occur if significant controls are maintained during collection of water-level data from properly designed new and/or vetted existing monitoring wells. It is particularly critical to ensure that such controls are applied when evaluating an unconfined aquifer because that system is characterized by downward-directed flow patterns in local recharge areas, and upward-directed flow patterns in local discharge areas. These flow patterns cannot be quantified or evaluated properly in unconfined aquifers by using data from wells that have long sections of screens and/or have unknown construction details. Examination of the data sources cited by W&L 2015, and the locations assigned for many of their "well" data points used to create their Figure 4, reveals that they elected to combine indiscriminately data from confined and unconfined portions of the Sparta-Memphis Sand aquifer. Waldron and Larson's decision to combine these disparate data, in addition to the fundamentally flawed nature of the data itself, render the interpretation of the SMS' pre-development equipotential surface in W&L 2015 meaningless, and also explains why their interpretation is considerably different from that of USGS researchers (e.g., Reed, 1972; Criner and Parks, 1976).

The following additional observations and opinions reinforce my conclusions and opinions that Waldron and Larsen's (2015) alternative interpretation of the pre-development equipotential surface for the SMS is fundamentally flawed.

- The abstract of W&L 2015 states that *"The basis of the* (MS v. TN) *lawsuit was potentiometric maps of groundwater levels for the Memphis aquifer that showed under suggested pre-development conditions no flow occurring across the Mississippi-Tennessee state line, but subsequent historic potentiometric maps show a cone of depression under the City of Memphis with a clear northwesterly gradient from Mississippi into Tennessee."* This statement contains two notable mischaracterizations. First, Mississippi acknowledges that there was some limited, natural, cross-border exchange of groundwater prior to development, but that does not materially change its position about the location of this Mississippi groundwater resource. Second, Mississippi's claim is <u>not</u> based solely on pre- and post-development potentiometric maps, but also on the results of a calibrated groundwater-flow model produced by Leggette, Brashears & Graham, Inc. (LBG) early in this dispute, and that model has been refined and updated to include all currently available data appropriate for use. LBG's modeling confirms the natural pre-development flow pattern, and clearly demonstrates the formation of a vast cone of depression extending from MLGW's well fields to deep within Mississippi which has changed the natural east to west flow in Mississippi to south to north in response to MLGW's pumping. Not only has the intense pumping in Shelby County, Tennessee, changed the natural direction of movement in the Mississippi groundwater, but this high-volume pumping has significantly accelerated the velocities of groundwater flow from Mississippi toward MLGW's pumping centers. This process and its impact were well established by the mid-1970s; the report by Criner and Parks (1976) identified a dramatic five- to seven-fold steepening of the pre-development SMS hydraulic gradient between 1886 and 1970 (to 10 feet per mile) between Olive Branch, Mississippi, and MLGW's Allen well field (C&P, 1976, page 11).

- In addition to their use of ambiguous, uncertain, or clearly defective historic data from wells of unknown construction to develop a map based on those completely unreliable data, W&L 2015 employed numerous errant assumptions in manipulating the elevation references that introduced additional uncertainty and error into their already-flawed analysis. I discuss these issues below.
- In summary, Waldron and Larsen (2015) produced "*FIGURE 4. Pre-development Potentiometric Surface for the Memphis Aquifer from This Study.*" by relying upon data that are inherently unreliable and should <u>not</u> have been used to draw <u>any</u> conclusions, let alone to produce their Figure 4, making it scientifically unreliable.

A complete evaluation of the specific data employed by Waldron and Larsen (2015) is provided in Appendix B-1 of this expert report. I summarize below some very serious issues that demonstrate the lack of value in the historical data used by W&L to prepare their flawed Figure 4.

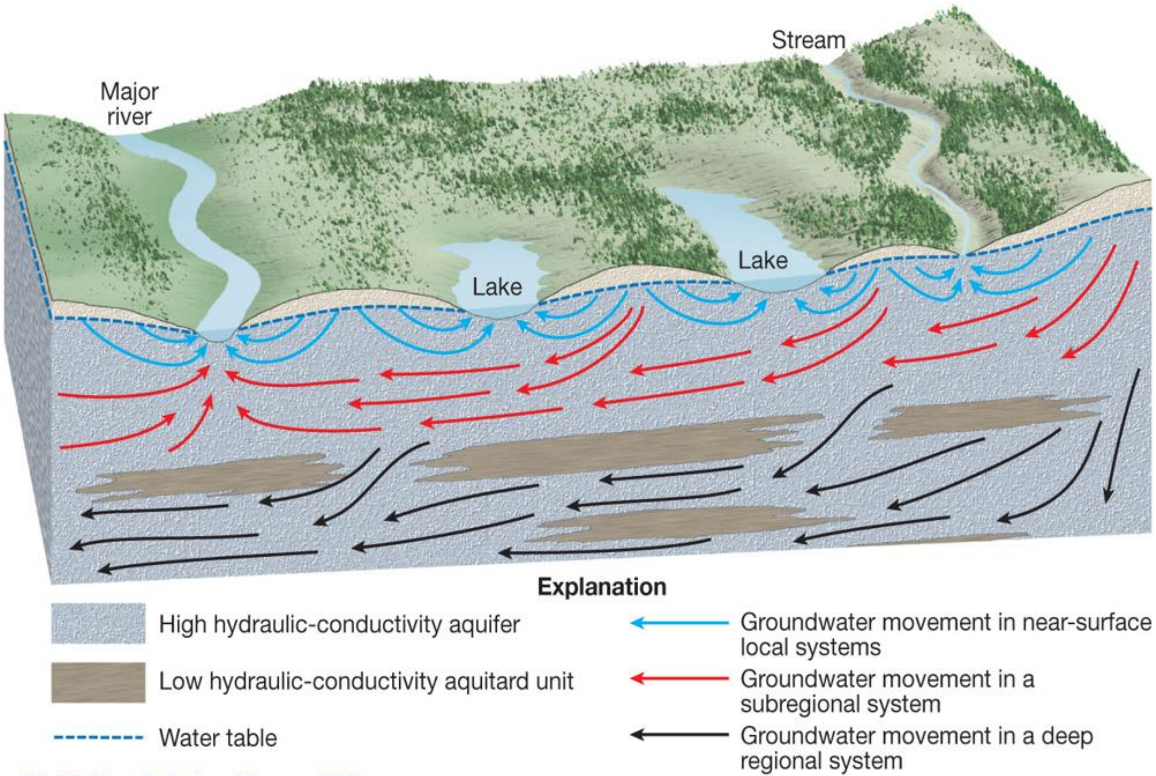
1. Many "wells" cited W&L 2015 *are <u>not</u> actually wells.* Instead, those "wells" are generic observations or claims about zones that were being targeted in particular areas for the potential drilling of water-supply wells in the late 1800s or very early 1900s. In the following discussion, I will refer to all W&L 2015 data points as "wells" to simplify the discussion, but the fact remains that a significant percentage of the data cited in W&L 2015 is invalid for this reason alone.
2. Exact locations for most wells used by W&L were simply not known, so they estimated the locations based on various lines of information, narrative , and/or assumption. W&L 2015 assumed land surface elevations based upon criteria of their choosing, and those values often do not match the elevations reported in the three source documents that date from 1903 and 1906 (see Appendix B-1).
3. Methods of measurement of water levels are not documented in any of the three original source reports. This fact alone introduces an unacceptable level of uncertainty for the stated or assigned values for depth to groundwater.
4. All of these historic measurements represent a period of time that post-dates the start of municipal/commercial pumping in the vicinity of Memphis in 1886, typically by at least a decade.
5. Historic water-level values in the three data-source reports used in W&L 2015 are listed as whole numbers in feet, which, at best, provide accuracy to the nearest foot (~0.305 meters). W&L rounded all land elevations used for calculating water level elevations to the nearest meter, which further degrades the accuracy of contoured head values presented on their Figure 4.
6. Historical records of groundwater measurements do not specify the pumping conditions of the wells. It is not known if the reported water levels were measured during active pumping or under non-pumping (static) conditions.
7. Reference points for water-level measurements are not given. Many of the historical publications list the depth to water below the "mouth" of the well, and the height of the mouth of the well (above or below land surface) is not listed.
8. The total head difference presented in Figure 4 of W&L 2015 is 79 meters (259 feet). W&L 2015 reported the estimated vertical errors for land surface elevations of up to 5.5 meters (18 feet; approximately a 7% error). The estimated vertical error for elevation reference does <u>not</u> take into account the inherent error in

rounding values to the nearest meter for each water level value used for contouring head in Figure 4.

9. Head values used to produce Figure 4 of W&L 2015 do not consider the effects of well construction on the reliability of the water level data. If a well installed into a confined aquifer does not have a properly grouted casing seal, there will be vertical hydraulic interconnection with the unconfined surficial aquifer via the ungrouted borehole. Until relatively recently, it was common practice to 'seal' water-supply well casings using very little grout that typically extended just a short distance below the land surface. Historic records used in W&L 2015 to obtain water level data do <u>not</u> provide <u>any</u> information about well construction and grouting.
10. Figure 4 of W&L 2015 does <u>not</u> discriminate between head values representing confined and unconfined portions of the aquifer system, and fully 60 percent of the data set used by W&L represent wells that are placed within <u>unconfined</u> portions of the SMS aquifer. In contrast, maps produced by Criner and Parks (1976) and Reed (1972) only consider groundwater-flow conditions in the <u>confined</u> portions of the aquifer. The distinction between confined and unconfined portions of the aquifer system correlates with the differences in regional versus local groundwater flow systems, respectively, as illustrated generically below in Figure 6.
11. W&L's dataset lists Well #3 (Forest City, Arkansas), but the well was excluded from their map even though it is located closer to Memphis than many other wells used to construct their Figure 4. Well #3 had an estimated elevation of 28 meters, the lowest head value reported in W&L 2015. Had this data point been used in contouring, the orientation of groundwater flow via equipotential lines in the confined portion of the aquifer system would have been more westerly, rather than northwesterly. Two other wells (#1 and #2) in eastern Arkansas were used to construct Figure 4, and W&L 2015 offers no justification for ignoring Well #3.
12. W&L 2015 commonly uses the land surface elevation as the head elevation for wells reported to be free-flowing (artesian). That assignment of head elevation is not accurate because those values are too low for those locations. By definition, a free-flowing (artesian) well has a hydraulic head that is at some elevation *above*

the local land surface. To determine the correct head for free-flowing wells, the well must be equipped with a pressure gauge, or the well casing must be extended above the land surface to a height that prevents free flow of water from the top of the pipe. Only then can the amount of hydraulic pressure above the land surface at those locations be determined accurately. The historic records relied upon by W&L 2015 never include this information, so it not scientifically-reliable data to use to produce their Figure 4.

Figure 6: Local versus Regional Groundwater Flow Systems in Unconfined and Confined Aquifers, Respectively.



Modified from Tarbuck and Lutgens, 2010

13. Figure 4 of W&L 2015 contains numerous errors in contouring the pre-pumping equipotential surface, including: (1) an inconsistent contour interval that varies from 9 to 13 meters, (2) assigning Well #16 (Taylor's Chapel, Tennessee) a head value of 91 meters, but the data point is contoured incorrectly on the inside (i.e., lower elevation) of the 91-meter contour line, (3) Well #17 (Bell Eagle, Tennessee) is located in a contoured area that should give the well a head

elevation greater than 91 meters, but the value assigned to Well #17 is only 82 meters, and (4) Well #6 (Hudsonville, Mississippi) has an estimated head elevation of 104 meters, yet the well is shown almost 6 miles (~9,500 meters) up-gradient from the 104 meter contour line in an area where W&L's contouring indicates that the elevation should be more than 106 meters. Collectively, these issues demonstrate that W&L's Figure 4 does not conform to standard contouring rules and thus presents a fundamentally flawed interpretation of the pre-pumping equipotential surface in the aquifer system.

14. An area of low head elevation is illustrated in Figure 4 in southern Tennessee near the Mississippi border. The head representation of this area is dominated by values assigned to Wells #12 (Moscow, Tennessee) and #14 (Rossville, Tennessee). These are fundamentally flawed data points that should not have been considered for pre-pumping equipotential contouring. Historic data for Well #12 does not reflect a specific well at a known location, and there is no specific reference of water level for Well #12, only the meaningless statement that "*water is found in abundance at depths of 60 to 80 feet".* In the context of the discussion by Glenn (1906), these depths identify drilling target depths at which known water-producing strata occur, not the depth of the water level in any well. Similarly, the data from Well #14 at Rossville, Tennessee, does not include a reported water level in a well. Like Well #12, it only reflects a general statement of the drilling depth to a sand layer from which water can reportedly be obtained. Simply put, there are no reported water level values for Wells #12 and #14 that can be used to construct Figure 4. When the fictitious head values assigned to these wells are removed from Figure 4 of W&L 2015, there is no longer any indication of a steep pre-development hydraulic gradient directed northward.

15. It is clear that most of the water levels presented in Figure 4 of W&L 2015 are not scientifically supportable. At many locations, Waldron and Larsen's map suggests pre-development equipotential surface elevations that are actually lower than more recent post-development observations. This is especially noticeable in areas of eastern and central Fayette County, Tennessee. A comparison of head elevations shown in Figure 4 of W&L 2015 with post-development equipotential measurements shown in Schrader (2008) indicates that Moscow, Tennessee, has

a post-development head of approximately 107 meters, which is 20 meters (more than 65 feet) higher than the estimated pre-development head. The estimated head at Moscow, Tennessee, presented on Figure 4 of W&L 2015 is significantly in error because this location is within the well-known pumping cone of depression centered on Shelby County, Tennessee. Likewise, there is a post-development head of approximately 96 meters at Rossville, Tennessee, which is 10 meters (more than 32 feet) higher than the estimated pre-development equipotential values shown in Figure 4 of W&L 2015. These are two clear examples of egregious errors in the interpretations of W&L 2015.

The following are my concluding opinions regarding Waldron and Larsen's approach to investigating and illustrating the pre-development groundwater flow patterns in their study area:

- The study lacks the rigorous data control that is essential to producing any meaningful hydrological interpretations or conclusions.
- Minimal data control requirements include precisely known locations and elevations of the measuring point at the tops of well casings. The specific screened interval(s) of the wells must be known, not assumed. Well construction records should also be available and considered, in addition to other information such as driller's logs. Measured depth to water in the well must be reported. It must be known that the well has not been pumped recently (i.e., the water level is static) and that there are no nearby wells pumping from the same aquifer. The data used by Waldron and Larsen in their 2015 study *do not meet any of these requirements*, making their Figure 4, and any conclusions or inferences drawn from it, completely unreliable.
- As described and illustrated in my report, monitoring wells with short screen intervals placed at accurately known depths must be used for evaluations of groundwater flow in unconfined aquifer systems. Data in the Waldron and Larson 2015 report indicate that this was not done.
- Interpretations of flow patterns based on incomplete or inaccurate well and head data fail to account for local flow patterns in the unconfined portions of the

groundwater system, wherein groundwater generally moves from recharge to discharge areas along circuitous flow paths, as illustrated above in Figure 6.

- Groundwater flow patterns in unconfined portions of the groundwater system are complex, and reflect relatively small, local groundwater 'basins.' Data for the unconfined aquifer system should never be used to define groundwater flow patterns in the confined portions of the aquifer system which reflect regional flow patterns.
- Considering the unreliability of the data employed, and the fundamental errors identified in their study, I assert that (1) Waldron and Larson did *not* provide a scientifically-reliable basis to support the pre-development distribution of hydraulic head and associated flow patterns for the SMS aquifer that are described and illustrated as Figure 4 in their 2015 report, and (2) there is no meaningful application of their work or their interpretations in Figure 4 to the border region between northwestern Mississippi and southwestern Tennessee.
- Interpretations by other researchers regarding the pre-development equipotential surface of the Middle Claiborne aquifer are properly focused on the confined portions of the groundwater system, and thus provide the best evidence and basis for accurate groundwater modeling and evaluation.
- It is my opinion that, with limited variations near the common border between Mississippi and Tennessee, the natural groundwater flow in the confined portions of the Middle Claiborne aquifer and other regional aquifers in both Mississippi and Tennessee is from eastern recharge areas toward western discharge areas. As demonstrated by computer simulations (e.g., LBG, 2014), there is a small area near the border between Mississippi and Tennessee where limited cross-border flow may occur under natural conditions. However, almost all groundwater in these regionally-important aquifers in Mississippi originates from recharge occurring inside the state. This groundwater naturally travels within the confined portions of the aquifer system in Mississippi and, absent intense pumping in Tennessee, the same water ultimately discharges to the Mississippi River many thousands of years later by moving upward through younger strata.

VI.3 Failure by Waldron and Larsen (2015) to Consider the Time Component

Time, specifically geologic time, is a key aspect of groundwater flow and aquifer hydraulics that must be considered in evaluating confined groundwater as a natural resource. It is easy for a layman to examine a groundwater equipotential map or computer simulation and assume incorrectly that the groundwater is migrating at a significant rate. As described in my expert report, time and flow velocity are what clearly separate concepts of surface water flow at the land surface from groundwater flow in geological materials.

The velocity of groundwater flow in a particular location can be described by the relationship between the hydraulic gradient (dh/dl), the aquifer's porosity (n), and the permeability (hydraulic conductivity, or k) of the aquifer. The velocity of the horizontal component of groundwater flow (V_h) can be calculated as $V_h = (k/n)*(dh/dl)$. I have assumed, for purposes of this illustration, that the SMS has the following parameters: an average k of 51.8 feet/day (mean of the range per Waldron and Larsen, 2015), 30 percent porosity (per page 6 of Dr. Waldron's expert report), and an average pre-development hydraulic gradient of 0.00033 feet/foot (per Criner and Parks, 1976). These values yield a calculated V_h of 0.057 feet/day (20.8 feet/year), which translates to only 2,725 feet (~0.5 miles) of natural groundwater migration between 1886 and 2017 (131 years) *if* there had been no steepening of the hydraulic gradient by massive pumping in Shelby County, Tennessee.

In my report, I noted that a relatively slow example of stream flow will transport water more than 16 miles in a day, which is more than 30 times as far in a single day as what the SMS groundwater would have migrated in 131 years if not for the intense pumping in Shelby County, Tennessee. Put another way, my hypothetical stream will transport a specific quantity or mass (packet) of surface water farther in a single day than an equivalent packet of groundwater in the SMS would travel in 4,061 years <u>if</u> the groundwater is flowing under the <u>pre-development</u> hydraulic gradient. The roughly five-fold steepening of the hydraulic gradient attributed to copious withdrawals in Shelby County, Tennessee, by Criner and Parks (1976) accelerated flow velocity to a calculated SMS groundwater flow rate towards Tennessee of approximately 120 feet per year.

The border between Mississippi and Tennessee along the east-west length of Shelby County is approximately 37.6 miles in length. Assuming the pre-development hydraulic gradient of Criner and Parks (1976) and flow parallel to that state boundary at approximately 20.8 feet per year, my back-of-the-envelope calculations indicate that a generic packet of SMS groundwater would require more than 9,500 years for SMS groundwater to traverse this 37.6-mile east to west trip within Mississippi. The United States is only 241 years old, or roughly 1/40th of the 9,500-year age of that illustrative groundwater packet migrating parallel to the state boundary located between Shelby County, Tennessee, and DeSoto County, Mississippi. For all practical intents, the natural groundwater in the SMS in Mississippi would _not_ have left the state to any appreciable degree if massive quantities of groundwater had not been pumped out of the SMS in Shelby County, Tennessee. Nevertheless, even though groundwater may be flowing slowly, the area and thickness of the SMS are large, and the volumes of water moving each day across the Mississippi-Tennessee border under the influence of pumping in Shelby County, Tennessee, are immense. This subject is addressed in Section VIII.

VII. Summary of My Evaluation of the Expert Report by Steven Larson

I have evaluated the expert report submitted by Mr. Steven P. Larson in support of the defendants. Mr. Larson cites four (4) core opinions in support of his conclusion that "*the groundwater of the Middle Claiborne aquifer is an interstate water resource*" (Page 2, paragraph 4). His four opinions are essentially variations on an initial position that conflates a broad regional view of the Middle Claiborne aquifer (aka, the SMS) with the more nuanced issues that exist at the border area between northwestern Mississippi and southwestern Tennessee. I address Larson's four opinions individually below in the order that he presents them.

Larson, page 2: "*Opinion 1. The Middle Claiborne aquifer and the groundwater within it constitute an interstate resource because they form a single hydrological unit that extends beneath eight states: Louisiana, Mississippi, Tennessee, Arkansas, Alabama, Kentucky, Illinois, and Missouri.*"

Larson disregards the differences between a geologic formation and an aquifer. The Eocene-age geologic materials comprising the Claiborne Group include multiple formations of varying lithology, specifically including the deposits known as the Sparta Sand and Memphis Sand in Mississippi and Tennessee, respectively. Those geologic deposits are not an aquifer except where saturated by groundwater and where other criteria are met, such as the ability to produce sufficient quantities of water for use by people. The solid materials and/or the water moving slowly through that regional aquifer system most certainly does not represent a single, homogeneous entity.

The Sparta-Memphis Sand and related time-contemporaneous geologic deposits do exist beneath multiple states within the structural sedimentary basin known as the Mississippi Embayment. Larson's claim is incorrect that "*As in all aquifers, the groundwater in the Middle Claiborne aquifer is hydraulically and hydrologically connected. There is no physical impediment that precludes groundwater from migrating across State boundaries under natural conditions within the Middle Claiborne aquifer.*" (page 2, paragraph 5). In fact, most named aquifers are highly complex mixtures of rock, sediment, and water. The rate and direction of groundwater migration and 'connection' in those aquifers under natural conditions varies tremendously, both vertically and horizontally, as a function of the geology and setting of a specific location. This inherent heterogeneity is most certainly true of the SMS on the scale of the Mississippi Embayment that Larson is focusing on in his expert report. For example, in the vicinity of the Mississippi-Tennessee border area, the SMS contains a 'transition' zone (a sedimentary facies change) in northern Mississippi (e.g., Hosman and others, 1968; Reed, 1972) at roughly 34.8 degrees north latitude where the relatively low-permeability Cane River Formation to the south becomes more sandy and permeable, thus 'thickening' the Sparta Sand as it merges with the Memphis Sand north of the 'transition' zone (see Figure 4) to 'become' what is termed here the Sparta-Memphis Sand. Likewise, it is well known that "…*there are many normal faults with vertical displacements ranging from about 50 to 150 feet*" that crosscut and displace the SMS in and near Shelby County, Tennessee (Kingsbury and Parks, 1993, page 1). Differences in sedimentary lithology and/or vertical and lateral continuity of the SMS can and do influence greatly the rate and pattern of groundwater flow within the Middle Claiborne aquifer system, especially at the scale of the Mississippi-Tennessee border region under discussion here.

Another key aspect of inherent aquifer heterogeneity involves geologic time. Virtually all aquifers consist of materials with relatively high and low permeability. If groundwater migration in more permeable portions of the aquifer occurs at, for example, a rate of 20 feet per year, then flow in low-permeability portions of that same aquifer may occur at a rate several orders of magnitude slower (e.g., 0.02 feet per year). Hydrogeologists have long recognized that hydraulic head patterns change significantly at boundaries between materials with different permeability, and therefore flow patterns will also change. One simply cannot claim that because similar solid geologic materials hosting groundwater exist across multiple states, the entrained groundwater necessarily behaves the same in all places and at all times; that is simply not true. The pervasive hydraulic 'connection' that Mr. Larson claims is only present as a pressure distribution within confined portions of an aquifer, not as any wholesale exchange of groundwater due to the important but too often overlooked component of <u>time</u> that I discussed in the previous section. My professional experience has shown that there can be substantial differences in aquifer geology and hydraulic characteristics within a single well field, to say nothing of an area the size of Shelby County, Tennessee, or the larger Mississippi-Tennessee border region under discussion herein.

Larson, page 3: "*Opinion 2. The Middle Claiborne aquifer and the groundwater within it constitute an interstate water resource because they are hydrologically connected to other bodies of interstate groundwater and surface water.*" Larson claims that the Mississippi Embayment Regional Aquifer System Study (MERAS) produced by the USGS, a computer modeling framework or tool, can "…*be used to refer to either the aquifer system or the aquifer study because they are essentially one and the same*." (page 3, paragraph 9). Here, he improperly conflates a very large and extremely complex natural system with a computer simulation that attempts to mimic some aspects of the natural system by employing a necessarily large number of simplifying assumptions; these two things are most certainly <u>*not*</u> "one and the same" in <u>any</u> sense. Larson attempts to merge these two distinct things by invoking the scientific reputation of the USGS to support an opinion that is not an expert geological or hydrological opinion. Larson actually acknowledges that he is conflating a physical system with a computer simulation to meet his objective by stating that "*The fact that the numerical models of the Middle Claiborne are grounded on interstate connections and intend to simulate interstate conditions further supports my view that the groundwater within the Middle Claiborne aquifer is an interstate resource*." (page 3, paragraph 10).

While one USGS publication describes their computer framework as a "*…tool that is useful for interstate sustainability issues while focusing on a particular State…*" (Clark et al., 2013, page 2), my search of the pertinent MERAS literature has revealed that this is the <u>only</u> instance where the USGS has used the words 'interstate' or 'intrastate' in <u>any</u> context. Likewise, Larson's claim that "*…a hydrologist cannot create a numerical model of the groundwater in the Middle Claiborne aquifer without reference to the MERAS as a whole*." (page 13, paragraph 44) is astonishing and conflicts with the facts. Computer simulations have long been created, tested, and used by many entities other than the USGS, sometimes in order to capture and evaluate details or scenarios that cannot be simulated accurately by the MERAS code because of the inherent limitations and simplifying assumptions of the USGS' tool. Furthermore, depending on Mr. Larson's use of his broad definition of the term 'MERAS', it is not necessary for a computer simulation to consider all confining beds and permeable zones above and/or below an aquifer of interest to evaluate specific issues of interest.

Larson, page 4: "*Opinion 3. The groundwater within the Middle Claiborne aquifer under Mississippi is an interstate water resource because, under any reasonable assumptions, none of the groundwater beneath Mississippi, under current or historical conditions, would remain permanently within Mississippi's territory.*" Larson states that "*Groundwater that is "stored" within the aquifer system is not static*." (page 4, paragraph 11) From a technical standpoint, groundwater in the SMS in Mississippi is not 'static', nor is it flowing dynamically like surface water. Larson simply ignores the key components of natural groundwater flow direction and time of travel. My illustrative calculations in the expert report and in this addendum report represent the scientific reality that groundwater within Mississippi in the SMS aquifer originated and resided within Mississippi's state territory for thousands of years under natural conditions on a slow-motion journey that has lasted many times longer than the United States has been in existence. Larson's only acknowledgement of the time component of groundwater flow is misleading at best: "*Because groundwater moves continuously (albeit slowly) under natural conditions, it eventually would have left Mississippi's territory – with or without any pumping – and would have been replaced by new groundwater recharge…*" (page 4, paragraph 12). The fact that this groundwater would *eventually* naturally leave Mississippi many thousands of years after it initially entered the subsurface by recharge has no practical application to the issue of whether the groundwater is a natural resource within the territory of the state of Mississippi.

Larson's justifying paragraph 13 contains several fundamental misstatements about hydrogeology that appear designed to confuse or misrepresent the concept of an aquifer's groundwater budget. I surmise that Larson is attempting to justify his unsupported notion that massive groundwater pumping in Tennessee has not had, and will not have, any meaningful impact on Mississippi's natural groundwater resources. From a hydrologic standpoint, the reduction of pressure in a confined aquifer system induced by pumping will not only change the pattern and velocity of flow, it reduces the volume of recoverable groundwater and well yield, thus limiting the quantity that can be withdrawn by a well and increasing the total cost of recovery.

Larson, page 4: "*Opinion 4. The United States Geological Survey has repeatedly recognized that the Middle Claiborne aquifer is an interstate resource.*" This is not an expert opinion of a geologist or hydrologist. Nor have I located a single written instance where the USGS has referred to the Middle Claiborne aquifer as an "interstate resource". As stated above, the USGS did use the word 'interstate' on one occasion, describing their computer framework as a "…*tool that is useful for interstate sustainability issues while focusing on a particular State*…" (Clark et al., 2013, page 2). This single statement by the USGS is not a comment about, or opinion on, any aspect of any state's claim to, or management of, the naturally present groundwater within its borders.

The mission of the USGS is to serve the national interest by supplying scientific information that others may then use to make informed decisions. The USGS does not have the mandate or authority to manage groundwater or dictate patterns of groundwater use within the borders of the separate states. The USGS has developed a computer simulation that it makes available to others (e.g., individual states) to better understand and visualize how groundwater within a large regional system of aquifers behaves, and that tool facilitates simulation of past, present, and future events on a groundwater system or component of interest. How the USGS *views* aquifer systems is important to how they choose to study those features, and potentially to make recommendations that may assist the state's use and regulation of its groundwater resources. However, the USGS does not address the rights of the respective states regarding the groundwater within their borders, and it specifically does not address the origin and location of the specific groundwater in Mississippi that is in dispute.

To summarize, Mr. Larson's position that the groundwater in the entire Middle Claiborne aquifer is an interstate resource is predicated on: (1) conflation of a massive geologic feature (Claiborne Group sedimentary deposits) with a hydrogeologic feature (water-producing portions of an aquifer system); (2) a simplistic view that, because the geology of an aquifer system may exist across state lines, the groundwater within that system must be considered an interstate resource, and specifically without regard to the natural hydrologic conditions under which the groundwater was recharged, exists, and ultimately discharges within separate states; and, (3) what he contends to be authoritative declarations of the USGS that he adopts as support for his opinion. As such, his opinions do not address the factual and scientific issues relating to the specific groundwater underlying Mississippi and Tennessee which are critical to understanding the natural occurrence, availability, sustainability, protection, and conservation involved in this dispute. These are the issues that are unique to each specific occurrence of groundwater natural resources that must be evaluated in each dispute of this type.

VIII. Summary of My Evaluation of the Expert Report by Brian Waldron

I have evaluated the expert report submitted by Dr. Brian Waldron in support of the defendants. Waldron focuses throughout his report on the question of "*whether the groundwater in the middle Claiborne aquifer is an 'interstate resource'*" (page 2, paragraph 5). Groundwater is the issue at the heart of this legal matter, but the emphasis by Waldron is on the Middle Clairborne aquifer, which he defines as "*part of a larger set of aquifers within the regional geologic framework, the Mississippi Embayment…*" (page 2, paragraph 6). He cites two (2) core opinions in support of his conclusion that "*the water in the aquifer is an interstate water resource*" (Page 2, paragraph 8).

Waldron, page 2: "*Opinion 1: The Middle Claiborne aquifer extends continuously underneath Tennessee and Mississippi, and groundwater in the aquifer is not and has never been "confined" to the borders of Mississippi or any other state.*" In his justifications for Opinion 1, Waldron introduces a convoluted definition of the term "confined" by stating that "*Mississippi's use of the term 'confined' implies that groundwater within a singular aquifer such as the Middle Claiborne does not flow laterally across state lines even though the geologic formation is continuous…*" (page 3, paragraph 11). I do not know the origin or intent of the verbiage that Waldron is supposedly referencing, but it is my opinion that the term "confined" is a hydrologic term with a specific meaning, and groundwater flows in both confined and unconfined aquifers in response to changes in hydraulic head.

I generally agree with the hydrologic use of the term "confined" as Waldron employs it (page 3, paragraph 10), although I disagree with Waldron that the presence of a less permeable layer (e.g., clay) above an aquifer necessarily makes the aquifer confined. For example, an aquifer with a clay layer above the aquifer that has a static water level below the top of the aquifer is not confined in a hydrologic sense because it exhibits a large value for storativity. Confined aquifers have small values of storativity relative to unconfined aquifers, and the degree of confinement of an aquifer is based on the actual value of storativity of that aquifer.

A single important scientific fact absent in Waldron's analysis and description of groundwater flow in the Middle Claiborne aquifer is the concept of groundwater velocity, or the amount of distance that groundwater travels per unit of *time*. My opinion is that groundwater in the Middle Claiborne aquifer naturally flows very slowly. Using the aquifer characteristics that I describe above in Section VI, and assuming Criner and Parks' (1976) pre-development hydraulic gradient in the SMS, groundwater in northwestern Mississippi would only be expected to move approximately 1,456 feet in an average human's lifetime (70 years times 20.8 feet per year), a distance of less than 0.3 miles! Even under Criner and Parks' (1976) pumping-steepened hydraulic gradient, the groundwater in the SMS would be moving from Mississippi and toward Memphis and Shelby County, Tennessee, at a rate of approximately 120 feet per year, or a distance of less than 1.6 miles in a lifetime. Considering such slow velocities, I can understand how the non-scientific community could perceive that groundwater is "confined" to a general location such as a state or county. Relative to a human life span, or even the age of the United States, groundwater seems to be immobile, and it certainly is *not* flowing at a rate anywhere close to that of stream or river water. Of course, MLGW's pumping continued after 1976, thus further steepening hydraulic gradients towards its well fields.

Regarding Waldron's use of the term "confined" for aquifer systems, it is my opinion that groundwater naturally flows very slowly in all portions of the Middle Claiborne aquifer. The fact that researchers such as the USGS have produced groundwater flow models that "…*treat as fundamental the fact that the Middle Claiborne aquifer is a single hydrological unit*" (page 3, paragraph 13) has nothing to do with the degree of hydraulic confinement of the aquifer. Waldron's entire discussion of whether or not groundwater is 'confined' to within Mississippi's borders is based on a failure to understand and/or acknowledge the component of natural flow time, and specifically the inherently slow nature of groundwater flow.

Waldron, page 3: "*Opinion 2: Under predevelopment conditions, there was substantial flow of groundwater within the Middle Claiborne aquifer from Mississippi into Tennessee.*" Many of Waldron's claims in support of his second opinion are based on his own publication (Waldron and Larsen, 2015) regarding the pre-development distribution of hydraulic head in the border region between northwestern Mississippi and southwestern Tennessee. He provides a detailed discussion of his perceptions of the many problems with water-level data used in other studies, primarily those performed by the USGS (e.g., Criner and Parks, 1976). As I describe above in Section III, it is ironic that Waldron and Larsen's 2015 analysis of pre-development hydraulic conditions in the Middle Claiborne aquifer relies upon data which fail to meet the rigorous criteria necessary for such studies (also see Appendix B-1 of my addendum report). I reiterate my opinion that the Waldron and Larsen (2015) interpretation of the SMS' pre-development equipotential surface is fundamentally and fatally flawed, and thus provides no reliable information about interstate flow prior to intense pumping in Shelby County, Tennessee.

I acknowledged in my expert report, and I reaffirm here, that there probably was a relatively small component of groundwater flow directed from Mississippi to Tennessee during pre-development time, as demonstrated by several studies other than Waldron and Larsen (2015). But, Waldron's extensive discussion of groundwater-flow patterns in a narrow strip of land adjacent to the state border (e.g., his Figure 10 on page 22) is, in my opinion, little more than a distraction. The more important issues concern the regional-scale flow patterns, velocity, and residence time of groundwater in the Middle Claiborne aquifer, especially in the context of post-development pumping by Tennessee. Extensive pumping of the SMS aquifer in southwestern Tennessee has altered significantly the natural groundwater-flow patterns, dramatically increased the hydraulic gradient toward MLGW's well fields, and markedly increased the rate and volume of groundwater flowing from Mississippi into Tennessee. Confined portions of the SMS aquifer are impacted significantly by those groundwater withdrawals and reductions in hydraulic pressure. Although groundwater flows very slowly in confined portions of the aquifer, the water is indeed moving. Groundwater in the aquifer within the State of Mississippi on the whole flows from recharge areas located in Mississippi, through the confined aquifer within Mississippi at very slow rates, and most of the water ultimately discharges to overlying aquifers and/or to streams and the Mississippi River within the State of Mississippi.

Waldron appears to be claiming in his expert report that groundwater is automatically an "interstate" resource if any component of groundwater flow in a regionally-extensive aquifer is directed from one State to another State under natural conditions over an extremely long period of time. I disagree completely with such an expansive definition. Waldron cites the fatally-flawed, pre-development equipotential map and study byEven if W&L 2015 (see Section VI) to claim (page 25, paragraph 51) that the volume of pre-pumping flow of groundwater from Mississippi to Tennessee in 1886 was approximately 49,136,000 gpd (~186,000 cubic meters per day, or m^3/day). Waldron concludes that by 2008, pumping had only increased the cross-border flow from Missississippi to Tennessee by about 9,250,000 gpd (~35,000 m^3/day), which equates to less than five (5) percent of the total daily withdrawals in Shelby County, Tennessee. If one assumes that Waldron's number are correct, then he is implicitly acknowledging that pumping in Shelby County, Tennessee, is causing about 3.38 Billion gallons of groundwater to leave Mississippi and enter Tennessee each year due to MLGW's pumping.

Assuming a north-south aquifer width of 300 miles, an aquifer thickness of 500 feet, and a hydraulic gradient of 0.001 feet per foot, I calculate that the total flow in the Middle Claiborne aquifer in Mississippi is approximately 591,740,000 gallons per day (~2,240,000 m^3/day). Even if one accepts Waldron's estimated volume of groundwater that left Mississippi and entered Tennessee under natural, pre-development conditions, that volume is roughly eight (8) percent of the total flow occurring solely within the State of Mississippi. The volume of water flowing from one state to another along a narrow section of a shared border should not be used to evaluate the nature of groundwater flow on a more regional scale, and it should not serve at the basis for defining the intrastate versus interstate nature of the groundwater resource.

IX. Concluding Opinions

From a hydrological perspective, the ultimate decision to classify groundwater in the Claiborne aquifer as an intrastate versus an interstate resource should be based on overall flow patterns within the aquifer, and not on flow patterns in the border region between states, as implied by Dr. Waldron's report. Alternatively, Mr. Larson's view that groundwater flow in a stratigraphically-equivalent aquifer located elsewhere in a very large sedimentary basin (e.g., northeastern Texas), and as modeled with a computer program replete with inherent assumptions and simplifications, has no potential bearing on this issue. It is well known that groundwater-flow patterns in an aquifer located within a state can be dramatically altered by groundwater withdrawals occurring nearby within adjacent states. An example of the impact of groundwater withdrawals on flow patterns in an adjacent state is the case of Hilton Head Island, South Carolina, a focus area for my own research for more than a decade. Prior to any development on Hilton Head Island, groundwater in the preferred aquifer was from south to north across the island. Extensive pumping by the City of Savannah, Georgia, located south of Hilton Head Island, resulted in a reversal of the natural groundwater-flow direction and caused saltwater to migrate into the aquifer beneath the island. Development in Georgia has rendered much of the preferred aquifer beneath Hilton Head Island unusable without costly treatment. This is but one example of predevelopment groundwater flow being dramatically changed by withdrawals initiated in an adjacent state.

It is clear that some aquifers extend over very large areas, including multiple states. However, the geographic distribution of those aquifers does not define the groundwater resources as interstate. Imagine a layer of coal that underlies the border region between two states; is the coal layer an interstate or intrastate resource? Would one state have the right to directionally bore and mine the coal from beneath the adjacent state? My opinion is that the answer to that question is <u>no</u>. Likewise, groundwater in the case of the Middle Claiborne aquifer in Mississippi is an intrastate resource that would not leave the state to any appreciable extent in the absence of intense pumping in adjacent Tennessee.

There is no dispute that withdrawing more than 180 Million gallons per day in southwestern Tennessee has changed the natural flow patterns in the Middle Claiborne aquifer in the trans-border region. Unless these withdrawals are reduced dramatically, the groundwater-flow patterns will <u>not</u> be returned to their natural, pre-development condition. The development potential of the natural groundwater resource (e.g., available drawdown) in northwestern Mississippi has been adversely impacted by the large-scale and long-term withdrawals in southwestern Tennessee. I fully described this impact on total available drawdown and the concept of a well's specific capacity in my expert report.

Mr. Larson and Dr. Waldron have evaluated and relied upon the work of the USGS very differently within their respective expert reports. On the one hand, Larson seems to believe that the USGS' computer modeling framework and tool can, and should, be used as a basis for classifying all SMS groundwater as a shared interstate natural resource. Conversely, Waldron provides a detailed critique of the work of the USGS, criticizing the quality of their underlying database and their analyses and interpretations of the pre-development groundwater conditions. In fact, the USGS is not an aquifer management or regulatory organization, it is a federal, taxpayer-funded scientific organization with the following water-related mission statement: "*Information about water is fundamental to the national and local economic well-being, protection of life and property, and effective management of the Nation's water resources. The USGS works with partners to monitor, assess, and conduct targeted research on the wide range of water resources and conditions, including streamflow, groundwater, water quality, and water use and availability*". (https://www.usgs.gov/science/mission-areas) The USGS' Water Resources Mission (https://water.usgs.gov/mission.html) is "*To provide reliable, impartial, timely information that is needed to understand the Nation's water resources. WRD actively promotes the use of this information by decision makers to –*

- *Minimize the loss of life and property as a result of water-related natural hazards, such as floods, droughts, and land movement. Effectively manage ground-water and surface-water resources for domestic, agricultural, commercial, industrial, recreational, and ecological uses.*
- *Protect and enhance water resources for human health, aquatic health, and environmental quality.*
- *Contribute to wise physical and economic development of the Nation's resources for the benefit of present and future generations.*

It is my opinion that the USGS does not exist to provide management directives or options for use of the groundwater resources by individual states. I find no consistent evidence in any USGS reports or statements that the agency has defined any specific groundwater resources as "interstate" with respect to state use or management options.

Several important concepts should be considered regarding classification of the groundwater resources of the Middle Claiborne aquifer as intrastate versus interstate. Because no criteria have been developed and vetted for classification of groundwater resources as either intrastate or interstate, my opinion is that management of the groundwater resources of individual states should be left to the individual states. In this particular case involving this particular aquifer system, I see no hydrological basis for either state claiming a right to take any groundwater that occurs naturally in the other state without the neighboring state's permission. Different natural geological and hydrological conditions might demonstrate the presence of groundwater resource that is naturally shared by more than one state that simply cannot be developed by both states without producing an unreasonable impact on the other, but case under litigation here is not such a situation.

What are the specific criteria to be used to establish the definition of intrastate versus interstate groundwater resources? I have not found any statements by Dr. Waldron or Mr. Larson in their reports to clearly define the meaning of the term interstate groundwater resource, or identify valid general or specific criteria that can be used to define an interstate groundwater resource. In the remainder of this section, I offer my opinions on this subject, as an experienced practicing hydrogeologist specializing in the evaluation, development, and management of groundwater resources in aquifer systems analogous to those of the Mississippi Embayment.

First, it is my opinion that the claims by Waldron and/or Larson are *NOT* criteria that can be used to define the nature or classification of intrastate versus interstate groundwater resources. It is my opinion that:

- An aquifer system is *not* an interstate resource because the aquifer's geologic framework (i.e., solid parts of the system such as grains of sand, sedimentary rock, etc.) extends over large areas.
- An aquifer system is *not* an interstate resource because hydrogeologists and hydrologists study aquifer systems over large areas.
- An aquifer system is *not* an interstate resource because some well-meaning scientists have produced groundwater computer models that extend over multi-state regions.
- An aquifer system is *not* an interstate resource because a small percentage of groundwater flowing in the aquifer crosses the boundary from one state to another state.
- An aquifer system in *not* an interstate resource because a scientist says it is an interstate resource based on an interpretation of what the USGS may or may not have said.

It is my opinion that the definition of an intrastate groundwater resource must be based on the fate of water in the groundwater system under natural conditions. If the majority of groundwater in an aquifer enters the groundwater system by recharge within a specific state, and that water flows *VERY* slowly through the aquifer within that same state, such that the water remains in the state for *VERY* long periods of time before ultimately being discharged from the groundwater system, then that groundwater is an intrastate resource.

Aquifers are *not* rivers of water flowing underground. The residence time for groundwater in the hydraulically-confined portions of the Middle Claiborne aquifer within Mississippi is measured in thousands of years, not days. Groundwater in this important and valuable aquifer is a life-sustaining resource for the residents of Mississippi, and it is an intrastate resource as based on my definition.

It is also my opinion that decisions regarding the classification of groundwater resources as intrastate versus interstate should not be conducted without a detailed consideration of the advantages and disadvantages of such a classification on the ability of a state to protect and manage the resource for the full benefit of its citizens. My professional experience has provided many examples of groundwater resource management issues that involve the problematic withdrawal of water from regionally-extensive confined aquifer systems by water purveyors located in border regions between states. In my experience, it is *not* the withdrawal of groundwater from these aquifers by production well fields located significant distances from state borders that is problematic. The conflicts occur in border regions between states when water purveyors unilaterally develop large-scale groundwater systems near state borders and create regional-scale cones of depression. My recommendation is to encourage states to use their state-specific regulatory framework to *not* allow the development of large-scale pumping centers located in trans-border regions if scientific studies indicate that such development will have a clear detrimental impact on the groundwater resources of the neighboring state.

Appendix A-1: List of References

This list supplements Appendix A of the expert report, and it includes references cited in Addendum #1. Additional documents and data may be reviewed or considered.

Arthur, J.D. and Taylor, R.E., 1998, Ground-Water Flow Analysis of the Mississippian Embayment Aquifer System, South-Central United States, U.S. Geological Survey Professional Paper 1416-I, 148 p.

Clark, B.R., and Freiwald, D.A., 2011, A new tool to assess groundwater resources in the Mississippi embayment: U.S. Geological Survey Fact Sheet 2011–3115, 4 p.

Clark, B.R., and Hart, R.M., 2009, The Mississippi embayment regional aquifer study (MERAS): Documentation of a groundwater-flow model constructed to assess water availability in the Mississippi embayment: U.S. Geological Survey Scientific Investigations Report 2009–5172, 61 p.

Clark, B.R., Westerman, D.A., and Fugitt, D.T., 2013, Enhancements to the Mississippi Embayment Regional Aquifer Study (MERAS) Groundwater-Flow Model and Simulations of Sustainable Water-Level Scenarios, U.S. Geological Survey Scientific Investigations Report 2013-5161, 29 p.

Criner, J.H., and Parks, W.S., 1976, Historic water-level changes and pumpage from the principal aquifers of the Memphis area, Tennessee: 1886–1975: U.S. Geological Survey Water-Resources Investigations Report 76–67, 45 p.

Kingsbury, J.A., and Parks, W.S., 1993, Hydrogeology of the principal aquifers and relation of faults to interaquifer leakage in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93–4075, 18 p.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416–B, 19 p.

Larson, S.P., 2017, Expert report of Steven P. Larson, 46 p.

Leggette, Brashears & Graham, Inc., 2014, Update report on diversion and withdrawal of groundwater from northern Mississippi into the state of Tennessee, 24 p.

Reed, J.E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geological Survey Hydrologic Atlas, HA 434, 5 maps.

Schrader, T.P., 2008, Potentiometric surface in the Sparta-Memphis aquifer of the Mississippi Embayment, spring 2007: U.S. Geological Survey Scientific Investigations Map 3014, 1 sheet.

Waldron, B., 2017, Expert report of Brian Waldron, Ph.D., 37 p.

Waldron, B., and Larson, D., 2015, Pre-development groundwater conditions surrounding Memphis, Tennessee: Controversy and unexpected outcomes, Journal of the American Water Resources Association, v. 51, p. 133-153.

Appendix B-1: Evaluation of the Well Data Used by Waldron and Larsen (2015) to Produce Figure 4 of Their Report

Data Sources Cited by Waldron and Larsen (2015)

Crider, A.F., and Johnson, L.C., 1906, Summary of the underground-water resources of Mississippi: U.S. Geological Survey Water-Supply and Irrigation Paper No. 159, 86 p.
Fuller, M.L., 1903, Contributions to the hydrology of eastern United States: U.S. Geological Survey Water-Supply and Irrigation Paper No. 102, 522 p.
Glenn, L.C., 1906, Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geological Survey Water-Supply and Irrigation Paper No. 164, 173 p.

Well #1 at Turrell, Arkansas (Fuller, 1903). Exact location of the well is not known. Location of the Baker Lumber Company property was apparently selected from a search of the name Baker within the Tyranza Township. Then, the land surface elevation was estimated for this property location. Local elevations at Turrell range from approximately 202 feet (61.5 M) at Big Creek to approximately 225 feet (68.6 M) in the center of Turrell. Well construction details are not reported (i.e., screen interval of the well and whether or not the casing was grouted). Method of water depth measurement is not reported. Height of the top of well casing is also not reported.

Well #2 at Helena, Arkansas (Fuller, 1903). Means of water level measurement not specified. Accuracy of reading reported is unknown. Well construction details (screened interval and status of grouting of the well casing) are unknown. Status of well pumping relative to water-level measurement is unknown (i.e., was the reported water level the original static level or had the well been in operation for some period of time before the water level was reported). Water level is referenced below the "mouth" of the well, but the height of the well "*mouth*" relative to land surface is not referenced. Because the elevation of the original "*mouth*" of the well is unreported, and because Waldron and Larsen rounded the reported water level to the nearest meter, it is incorrect to list the estimated vertical error as 0.0 M within Table 1. Rounding the water level from 30 feet to 9 meters already introduces a minimum error of 0.146 meters.

Well #3 at Forest City, Arkansas (Fuller, 1903). Well construction details (screen placement, grout interval, and height of "*mouth*" of the well) are unknown. Rounding of water level from 160 feet to 49 meters incorporates an error of 0.22 meters. Rounding of the land surface elevation to the nearest whole meter also incorporates an error. Likewise, the unknown height of the "*mouth*" of the well adds uncertainty as to the elevation reference for the reported water level. Therefore, it is incorrect to represent the estimated vertical error as 0.0 meters. Status of well pumping relative to water-level measurement is unknown (i.e., was the reported water level the original static level or had the well been in operation for some period of time before the water level was reported).

Well #4 at Hernando, Mississippi (Crider and Johnson, 1906). The data source describes, in general terms, some information about depth, stratigraphy, yield, and water level for "*a well in Hernando*." Ownership of the well and the well's specific location are not provided. Methods of measurement of water level are not presented. Waldron and Larsen summarize information about the well in Table 1. The reported well depth (165 feet on Table 1) does not match the documentation in Crider and Johnson (1906) where the total drilling depth can be calculated to be 220 feet. Well construction details (depth, screened interval, and depth of any grout seal) are not presented in Crider and Johnson. Waldron and Larsen locate the well at the "*City center*" and they estimate the land surface elevation to be 109 meters AMSL. A review of the USGS topographic quadrangle map of Hernando indicates that land surface elevation within Hernando ranges from about 350 feet (106.7 meters) to over 400 feet (~122 meters), a range of more than 15 meters. However, Waldron and Larsen suggest that their estimated vertical error is only 4.2 meters. Furthermore, the method of measurement of the estimated water level, the date of measurement, and whether the water level is an original static level versus the reported level in 1906 after some years of pumping at the reported 150 gallons per minute is unknown.

Well #5 at Holly Springs, Mississippi (Fuller, 1903). Reportedly, there are two adjacent wells on the same site. It is not known how the water-level was measured and whether or not one or both of the wells on site may have been pumping. Height of the mouth of the well is unreported. Waldron and Larsen report that method of location is "*Located in the town center.*" Exact location of well (and associated land elevation) is unknown. Local land elevation at Holly Springs varies from 530 feet (161.5 m) to 620 feet (189 m) AMSL. Waldron and Larsen indicate a vertical error of only 2.5 meters, but clearly the elevation error is likely much greater than that.

Well #6 at Hudsonville, Mississippi (Fuller, 1903). The data source does not identify specific well location at Hudsonville. Waldron and Larsen researched property records from 1900 census to identify property that they assumed to represent the well site, they then assumed a location (and associated elevation) on that property. The local topography near Hudsonville includes significant elevation variances, ranging from about 460 feet (140 m) to about 520 feet (158.5 m). Therefore, the potential elevation error for the well location could be as much as 18.5 meters. The height of the mouth of the well above land surface is unknown. The method of water-level measurement and the accuracy of measurement is unknown. The depth of the well is reported to be 168 feet, and the well was indicated to have only 15 feet of water depth. Details of well construction are unknown, including type and depth of well opening, construction method, and grout seal (if any). The reported water depth of 153 feet is much deeper than would be expected for an unconfined section of the aquifer, especially considering that the nearby perennial stream (Coldwater River) at Hudsonville has a local elevation of 460 feet (140 m). The calculated water elevation (104 m) presented in the Waldron report would be 36 meters lower than the Coldwater River elevation. This would not be expected if the Memphis Aquifer were unconfined at Hudsonville. Based upon documentation of Well #6 at Hudsonville, it is not appropriate to rely upon this well for mapping the pre-development potentiometric surface mapping for the aquifer.

Well #7 at Canadaville, Tennessee (Glenn, 1906). However, the discussion of groundwater conditions at Canadaville is not about any specific individual well example. Glenn discusses generalities about depths of wells and estimated depths to groundwater levels. Waldron and Larsen incorrectly list a specific well at Canadaville with a depth of 150 feet. No such well is mentioned in Glenn for this location. Likewise, the mention of depth to the water level being 125 feet is not specific to a particular well. Rather, the report states "*Some small bored wells, ranging from 90 to 140 feet in depth, yield an abundant supply of good soft water, but in the deeper wells it rises only within 125 feet of the surface.*" It is important to note that topography in the area near Canadaville varies from a high of about 477 feet (145 M) MSL to a low of about 375 feet (114 M). Because no specific well location is referenced in Glenn for the reported 125 feet depth to groundwater, the selection of an estimated land surface elevation in the Waldron report is arbitrary and unreliable. The elevation error for this estimated location could be as much as 31 meters, depending upon the specific location selected as representative of the well site used for Well #7. The water-level contouring presented in Waldron and Larsen's Figure 4 or their report is strongly influenced by the estimated water level value shown for Well #7. This is unfortunate, because the cited reference for this water-level does not reflect any specific well location in the area.

Well #8 at Claxton, Tennessee (Glenn, 1906). The discussion of conditions at Claxton does <u>not</u> reference any specific well, and instead Glenn describes wells typical in the area and states that wells "*may go 75 to 100 feet deep, and the water rises within about 40 feet of the surface.*" The location selected for the well is based upon an interview with an elderly lady who supposedly worked for the Claxton family. No specific details of well locations are available for this station. Clearly this discussion of generalities and approximations should not be relied upon for contouring of an equipotential map.

Well #9 at Ina, Tennessee (Fuller, 1903). The exact location of the well is not known. The location of the well was assumed by Waldron and Larsen based upon property records and research of the OMNI Gazetteer. Well location and elevation cannot be verified, and the height of the well opening is not known. The reported well depth and water depth cannot be verified, and the method of water-level measurement (and accuracy of measurement) is also not known. Using topographic maps, the land elevation near Ina ranges from 480 feet (146 m) to 520 feet (158 m).

Well #10 at LaGrange, Tennessee (Glenn, 1906). The exact locations of wells referenced in the source publication are not known. General statements are made about wells being drilled to 175 and 213 feet depth. No specific measurement of water depth is referenced for these wells in LaGrange. Waldron and Larsen assume incorrectly that well depth equates to non-pumping water level depth by selecting a water depth of 194 feet (59 m). Because one well referenced by Glenn was stated to be 175 feet depth, it is certainly not clear that the depth to water was less than 175 feet pre-development. There is no reasonable way that one could conclude that the pre-development water level could be as deep as 194 feet at LaGrange. It is obvious that there is no reliable means of determining a pre-development water level for the Town of Lagrange to use for preparing an equipotential contour map. Furthermore, the Glenn (1906) publication states explicitly that the Town of LaGrange is "*532 feet above the sea.*" But, the Waldron report selects a land surface elevation of 165 meters (541 feet) for calculating a water elevation. Because the specific locations of wells are not known, the adjustments of land elevation for this datum are based upon assumptions that simply cannot be tested. The estimated water level for LaGrange are totally unreliable and further render the pre-pumping equipotential map of Figure 4 to be incorrect.

Well #11 at Moorman, Tennessee (Glenn, 1906).. As with many other wells used by Waldron and Larsen to produce their pre-development equipotential map, the exact location of the well(s) is not identified. Glenn reports that, "*One 103 feet deep struck water of good quality at 53 feet.*" This statement does not say that the static water level was 53 feet deep, it just implies that water was "*struck*", which could mean that water-bearing strata were encountered at 53-feet depth during drilling. The non-pumping water level is not known for this well. Nonetheless, Waldron and Larsen chose to use the 53 feet depth as a non-pumping water level for a well with an unknown location and unknown construction. Furthermore, the location listed in Table 1 of Waldron and Larsen is "*Intersection of Hwy 222 and Winfrey*" which corresponds closely to the location of Well #8 at Claxton.

Well #12 at Moscow, Tennessee (Glenn, 1906). Again, the reference provided by Glenn only relates to the target depth of drilling at which water-producing materials are reportedly encountered. No specific wells are referenced as to location and specific construction details. Glenn makes no explicit statement referring to the depth to which water is measured in a well, let alone under non-pumping conditions, so this location should not be used for contouring the pre-development equipotential surface of the aquifer. Instead, Waldron and Larsen chose to arbitrarily select the location of the "*well*" at the town center, which is not supported by any specific historical records. Glenn also reports generally that "*…water is found in abundance at depths of 60 to 80 feet*". Waldron and Larsen assumed a specific value of 69 feet as the water level for their mapping purposes, which is 9 feet below the reported minimum depth of 60 feet referenced by Glenn. There is no justification for Waldron and Larsen's arbitrary assignment of this water level depth. Finally, Table 1 incorrectly lists the estimated water elevation as 27 meters; the estimated value shown on Figure 4 for this station is 87 meters.

Well #13 at Oakland, Tennessee (Fuller, 1903). Specific location of the well is not known from information presented by Fuller. Waldron and Larsen arbitrarily select a location in the center of a block defined by four roads, even though the "s*upplemental information*" in their Table 1 states that there is "*no location information*". Based upon a USGS topographic map, the land elevation at Oakland ranges from 350 to 400 feet elevation. Waldron and Larsen use an assumed land elevation at the assumed well location of 116 meters (380.5 feet), but the actual well elevation could be as low as 107 meters to as high as 122 meters, depending on where the actual well was originally located. Although the depth to the water level in the well is reported as 75 feet below the "mouth" of the well, the method of water-level measurement is not stated, and the degree of accuracy of this water level is simply not known. Also, the height of the "mouth" of the well above land surface is not known. Finally, the original source (Glenn, 1906) states that "*At Oakland, elevation 388 feet, the wells are from 60 to 125 feet in depth.*" This information suggests that water level depths shallower than 75 feet may have occurred at Oakland prior to extensive pumping of the aquifer at Memphis.

Well #14 at Rossville, Tennessee (Glenn, 1906). No specific location of a well is given for the Town of Rossville. Waldron and Larsen arbitrarily selected a well location at the intersection of Main Street and the railroad. Glenn actually states that "*At Rossville, elevation 311 feet, water is obtained from white sand beneath a layer of pipe* *clay at 28 to 35 feet*". No well depth is reported, and no specific water level measurement is reported for a well tapping the "white sand". Waldron and Larsen assumed a depth to water of 32 feet (10 M) for the pre-development water level at Rossville, but this assumption is not supported by any actual data for a well at Rossville.

Well #15 at Somerville, Tennessee (Glenn, 1906).. Glenn presents some generalities about multiple wells drilled from depths of 100 to 150 feet at Somerville. No specific well location is described, however, Glenn does reference a land elevation of 356 feet (108.5m). Inexplicably, Waldron and Larsen decided to adjust the assumed land surface elevation at Somerville upward by 8 meters (or 26 feet) based upon their arbitrary selection of the well location. This is a large adjustment and injects a significant potential error to the Well #15 data. Furthermore, Waldron and Larsen use a water depth of 50 feet (15 m) for this location, despite Glenn's specific statement that "*The water rises in some of these* (wells) *within 50 feet of the surface*". Because Glenn's term "*within*" means inside of or less than, assigning 50 feet as the water depth for Well #15 will produce a water elevation that is too low. [Fuller (1903) mentions a specific well owned by C.W. Robertson, but the location of that well is still not known.]

Well #16 at Taylor's Chapel, Tennessee (Fuller, 1903). The exact location of well is not identified. Waldron and Larsen assumed a land surface elevation of 109 meters (357.5 feet). Local topography of the Taylor's Chapel area ranges from approximately 340 feet to 370 feet in the vicinity of Taylor's Chapel church and the Taylor's Chapel cemetery. Water depth is reported at 60 feet below the "mouth" of the well, but the actual elevation of the "mouth" is not known. Means and accuracy of the water depth measurement is not reported. Glenn (1906) provides additional information about water depth at Taylor's Chapel, stating that "*At Taylors Chapel water is obtained from some good strong springs and wells that range from 25 to 125 feet in depth. In many places at depths of 30 to 40 feet a stratum of black mud is struck, averaging about 40 feet thick and furnishing foul-smelling water. It is underlain by a thin ironstone layer and when this is pierced good water, that rises 30 or 40 feet, is found in abundance.*" Based on Glenn's description, a well drilled to 70 or 80 feet depth would have a non-pumping water level of 30 to 50 feet depth. This suggests that the 60 feet water depth assigned by Waldron and Larsen to the Taylor's Chapel area may be too deep by 10 to 30 feet.

Well #17 at Belle Eagle, Tennessee (Fuller, 1903). Fuller does not indicate the land surface elevation of Belle Eagle or the exact location of the well used by Waldron and Larsen. The well location is only referenced relative to a property owner (R.H. Taylor). The USGS topographic map of the Belle Eagle area indicates that local land elevation ranges between approximately 320 and 370 feet AMSL. The method of water depth measurement and height of the well casing are not reported. Well construction details are not provide, nor is information about the lithology of sediments encountered or tapped by the well. The well depth is 70 feet, which makes it uncertain if this well actually penetrates the Memphis Sand.

Well #18 at Brownsville, Tennessee (Glenn, 1906). Glenn states that the land surface elevation at Brownsville is 344 feet (105 meters) AMSL. Waldron and Larsen adjusted the assigned land elevation upward to 108 meters AMSL. Glenn reports multiple wells at Brownsville, and the water level depth (14 meters) reported for Well #18 is apparently an average from a number of wells in Brownsville. Averaging the depth to water is inappropriate where the land surface elevation has variability. The topographic variation at Brownsville is substantial (ranging locally from less than 337 feet to more than 390 feet AMSL). The method of water depth measurement is not reported, nor is the height of the top of well casing. Glenn describes large withdrawals (150,000 to 500,000 gallons per day) from individual municipal wells at Brownsville. The original (pre-development) static water level at Brownsville is not reported. Considering the large withdrawals reported from multiple wells at Brownsville, one must conclude that the water levels reported by Glenn have been lowered as a result of local groundwater withdrawals. Therefore, these water-levels cannot be equated with pre-development groundwater levels, but Waldron and Larsen elected to do so anyway.

Well #19 at Forked Deer, Tennessee (Fuller, 1903). No data on the land surface or exact well location is provided by Fuller for the well at Forked Deer. Waldron and Larsen estimated the land surface to be 106 meters AMSL based upon the well owner named H.A. Rainey. The method of water depth measurement is not reported, nor is the height of the top of well casing. Waldron and Larsen describe the well as being free flowing, but Fuller lists the depth to water at -0 feet. If the well was a free-flowing artesian well, then the static water level would actually be at some (unknown) height above the top of the well casing.

Well #20 at Ged, Tennessee (Glenn, 1906). The elevation was determined for Ged by triangulation "from current road intersections to historic location". The "Hinkle well" was located "half a mile" in no specific direction from the town of Ged on "high ground". So, it seems the elevations assigned to the town and to the Hinkle well are essentially guesses that render any water level elevation data suspect or useless. The Hinkle well is listed as having a water level that rises to "within" 60 feet of the surface. Waldron and Larsen assign 60 feet (18m) as the depth to water at this unknown location on "high ground". The reality is that Waldron and Larsen have no reliable knowledge of the well location or depth to water at Ged.

Well #21 at Keeling, Tennessee (Glenn, 1906). Very minimal well information is listed by Glenn, essentially that there are a number of wells in the area and one of them is 96 feet deep with a water-level within 46 feet of the land surface. The exact location of that, or any, well is not known. The land surface elevation was estimated based upon a general location of the town, and the land surface elevation in the immediate vicinity of Keeling can vary by more than 40 feet. Well construction details are not reported, nor is the method of measuring the depth to water. Lithology penetrated by the well is not reported, and it is not known if the well reported by Glenn actually taps the Memphis Sand.

Well #22 at Stanton Depot, Tennessee (Glenn, 1906). Glenn says that the <u>town</u> elevation is 290 feet AMSL, but there is no mention of land surface elevation for any specific well in or near the town. Glenn states that water rose to within 40 feet of the land surface when an "indurated layer had been penetrated", but there is no mention of a specific well or location. Waldron and Larsen decided that the land surface elevation at the "well" was 13 meters (41 feet) <u>higher</u> than the elevation reported by Glenn.

There is no justification for making this large adjustment in land surface elevation. If the depth to water was 40 feet and the land surface was 290 feet, as stated by Glenn, then the water-level elevation would be 250 feet (76 meters) AMSL. The method of water depth measurement, the height of the top of well casing, and the construction of the well are not reported by Glenn.

Well #23 at Arlington, Tennessee (Fuller, 1903). The depth of the well listed in Waldron and Larsen's Table 1 (228 feet) does not match the original data provided by Fuller (221 feet). Waldron and Larsen incorrectly report the water-level elevation that they assigned to Well #25 in Table 1 as 25 meters, although they correctly list the water level elevation (81 meters) on Figure 4. The exact location of the well is not known. The land surface elevation was estimated based upon a general location of the town. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #24 at Bleak, Tennessee (Glenn, 1906). Only minimal well information is listed by Glenn, although he reports that there is a well 176 feet deep with a water level within 47 feet of the land surface. The exact location of the well is not known, and Bleak is no longer an established town. The land surface elevation was estimated based upon a general location of the town from a 1916 U.S. Soils Map. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #25 at Collierville, Tennessee (Glenn, 1906). Glenn states that there are two wells, six feet apart, at depths of 239 and 248 feet with water levels between 95 and 100 feet below land surface. Waldron and Larsen assigned 95 feet as the depth to water, but that depth could just as easily have been 100 feet based on Glenn's report. Once again, the water-level elevation is incorrectly listed in Waldron and Larsen's Table 1 as 27 meters, although the correct water level value (90 meters) is listed on Figure 4. The method of water depth measurement is not reported. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #26 at Cordova, Tennessee (Fuller, 1903). The location of the well is not known, and the land surface elevation was estimated based upon a general location of the historic community. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #27 at Eads, Tennessee (Fuller, 1903). Minimal well details are reported by Fuller. The exact location of the well is not known, and the land surface elevation was estimated based upon a general location of the well owner from the 1910 Census. The local relief of the land surface elevation in Eads varies by as much as 50 feet, so a significant potential error is introduced by not knowing the location and assigning an elevation for the well head. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known. Fuller reported that the well was 100 feet deep, so it may be too shallow to be open to the confined aquifer.

Well #28 at Massey, Tennessee (Fuller, 1903). Fuller provides minimal well information. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known.

Well #29 at Memphis, Tennessee (Glenn, 1906). Minimal details are provided in the original data source. Well construction details, height of the top of well casing, and the method of measuring the depth to water are not known. Glenn states that the well is "artesian", and Waldron and Larsen uses the land surface elevation to assign the water elevation, which by the very definition of a free-flowing well tapping a confined aquifer is too low. The height of the water elevation above the "mouth of the well" is not known.

Well #30 at Covington, Tennessee (Glenn, 1906). The discussion of conditions at Covington does not reference any specific well, and instead describes typical wells in the area by stating that the wells "*may go 75 to 100 feet deep, and the water rises within about 40 feet of the surface.*" Clearly, such a discussion of generalities and approximations should not be relied upon for contouring an equipotential map. This same situation describes other "wells" used by Waldron and Larsen (e.g., Well #8).

Well #31 at Ina, Tennessee (Fuller, 1903). The exact location of the well is not known, and the location and elevation were assumed based upon property records and research into the OMNI Gazetteer. Well construction, height of the well opening and method of measuring the depth to water are not known. USGS topographic maps indicate that the land elevation near Ina ranges from 480 feet (146 m) to 520 feet (158 m), so any assumed elevation based upon property records without specific details of a well location can result in an error in elevations assigned to the land surface and water level of up to 40 feet .