Sur-Rebuttal Expert Report of Brian Waldron, Ph.D.

Prepared on Behalf of the State of Tennessee

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

August 30, 2017

Signed: B

Brian Waldron, Ph.D.

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SECTION 1. Qualifications and Background

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

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

3. I prepared this report at the request of the State of Tennessee for use in the original Supreme Court proceeding, *Mississippi v. Tennessee et al.*, No. 143, Original (U.S.). Specifically, I have been asked to respond to the rebuttal expert report of Richard K. Spruill submitted by the State of Mississippi on July 31, 2017 – in particular, Spruill's discussion of the 2015 article I co-published with Dan Larsen. My opinions are based on my training as an engineer specializing in the study of groundwater and on the sources and data identified in this report. I reserve the right to revise or amend this report as necessary based on new information that may become available.

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

SECTION 2. Opinions

5. Spruill's criticisms of Waldron and Larsen (2015) ("W&L") in his rebuttal report fall into three general categories. First, he criticizes the reliability of the data underlying W&L's analysis and compares it unfavorably with the data underlying other attempts to estimate the predevelopment potentiometric surface of the Middle Claiborne. Second, he criticizes W&L's analysis of those data, including the contouring technique used. Third, he suggests (at 23) that W&L failed to "consider the time component."

6. I respond below in some detail to the critiques that fall into the first and second categories. In most cases, Spruill's characterizations of W&L are simply erroneous and fall apart upon closer inspection. Spruill also notes some of the limitations of using data that are more than a century old, but fails to show that there are better data for this purpose or that the data are too unreliable to use. He also fails to account for the fact that W&L performed an error analysis that specifically showed that uncertainty relating to old data did not have a significant effect on the resulting predevelopment surface set forth in the paper.

7. As for Spruill's suggestion that W&L failed to "consider the time component," he apparently means that W&L did not discuss the velocity of groundwater flow, at least in detail. However, there is no reason to have done so. Although Spruill opines (at 23) that a "layman" might "assume incorrectly that the groundwater is migrating" faster than it is, laymen were not the article's intended audience. In any event, the distinction is irrelevant to the question raised by the Special Master. Indeed, the precise speed of the groundwater flow does not determine whether the Middle Claiborne is an interstate resource. As explained in my prior reports and in more detail below, the Middle Claiborne is plainly an interstate resource, even though the groundwater within it is migrating at a slower rate of speed than surface waters.

Spruill's Criticism of the Data's Reliability Is Misplaced

8. To begin with, Spruill states (at 17) that many of the wells cited by W&L "*are not actually wells*" (emphasis by Spruill), but 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 fact, however, the points used by W&L are wells identified in three early U.S. Geological Survey (USGS) publications – Fuller (1903), Crider and Johnson (1906), and Glenn (1906) – which also describe their uses as water for steam locomotives, mercantile stores, post offices, stage coach stops, lumber mills, and private usage.

Spatial Accuracy

9. Spruill suggests (at 17) that "[e]xact locations" of the wells are unknown. However, W&L used a number of methods to determine the location of each well as precisely as possible, and in each case the location was determined with enough precision for the article's purposes. In the USGS publications (Fuller, 1903; Crider and Johnson, 1906; Glenn, 1906), well locations were identified by town; however, additional information allowed for improved mapping of well locations such as: (1) well ownership; (2) water usage; (3) witness accounts; and (4) building blueprints.

a. Well ownership: Ownership provided a means for better locating a well's actual location. Well ownership was cross-referenced with 1900 and 1910 census records, which served two purposes: (1) the well owner's name may have an associated street address that would place the well along the correct road and (2) the well owner's job may be listed in the census, further substantiating use of the groundwater at a mercantile or lumber mill. Any address information was correlated with historic town maps available at the county seat library, from parcel maps usually existing within Plat Book 1 (the first record of parcel ownership in the county) available at the county courthouse or planning office, or approximated using existing road networks.

b. Water usage: When addresses where not available, the purpose of each well was used to improve the accuracy of its location. For example, railroads used groundwater for steam locomotives. Historic town maps were used to identify railyard locations that often were near the town center. Sometimes rail company maps were used to verify the existence of rail in the town. As rail lines extend through a town, well placement was placed near the town center at the intersection of main roads (identified by name such as Main or because the road existed as a county road as it entered and left the town).

c. Witness accounts: In some cases, personal investigation allowed W&L to more accurately locate historical wells. For the well in Ged, Tennessee, the well was used at a home that also served as a store. During a visit to the Haywood courthouse, an older resident whose mother was friends with the owner of the relevant well, Mrs. E.A. Davie, who was able to provide the approximate location of Ged (as the town is no longer there) and the store. In another instance, I visited the Kirby family, after whom Kirby Road in Memphis, Tennessee, is named. I visited them at their home, and they personally walked me into the field where the old well used to exist.

d. Building blueprints: When attempting to locate the well in Forest City, AR, I was visiting the current water utility facility. Hanging on their wall was a framed blueprint of the original water facility, which showed the room where the well existed. The original building still existed, though in disrepair. Using the blueprint, I found the room. I then surveyed to the well location using a benchmark on the local post office steps. Similarly, though not an actual blueprint, Sanborn maps detail structures and their wall construction for fire resistance purposes. The R.C. Graves ice house well, which reportedly was the first well to tap the Middle Claiborne in Shelby County, was thought to have existed near present day St. Jude Children's Research Hospital. However, upon a detailed investigation, the R.C. Graves ice house was located further south using an 1890 Sanborn map that depicted the ice house. A historic road network was used to locate the well site, as the road network has since been altered and road names had changed.

10. Recognizing that each method of identifying well location has some uncertainty, we estimated spatial error for each well; in essence, creating a radial "buffer" of possible locations around the well site. The more information used to locate the well, the smaller diameter a buffer was applied, because of the greater confidence in its location. Conversely, larger diameter buffers were applied where well locations were more uncertain, such as when the well was placed at the town center. In these latter cases, we used historic road maps obtained in each county courthouse or library to investigate the extent of the town's road network, and the radial buffer diameter was set to the furthest extent of the town's road network. W&L discusses this and lists examples on page 16 under the section entitled "Finding Historic Well Locations." Though not mentioned by Spruill, I accounted for the spatial error derived from the error buffers when developing the contours; however, even at the maximum measured spatial error of 450 m (Waldron and Larsen (2015) p. 16), the scale of the water level map (covering eight counties) vastly dwarfed any spatial error in contour placement. Thus, the well locations were sufficiently precise for the purpose of creating the water level map.

Vertical Accuracy

11. Spruill suggests (at 17-18) that the well elevations W&L used are speculative and unsubstantiated. Spruill also mentions that the published elevations in the USGS reports differ from elevations used by W&L. W&L recorded the published ground surface elevations in *Table 1* of the article (pp. 7-15) as well as the elevations used in their calculations, and a detailed discussion of how ground surface elevations were derived is provided on page 16. Four methods were employed to derive ground surface elevations, each with varying degrees of accuracy but sufficiently reliable for the article's purposes.

a. The most accurate elevations were from field surveys. We performed field surveys for the wells in Forest City and Helena, AR, where the actual well location was known.

b. The second most accurate elevation was taken from a U.S. Army Corps of Engineers land survey map of downtown Memphis in 1932. This was used to obtain the elevation of the R.C. Graves well.

c. The third accurate method was using LiDAR data of Shelby County, which has a 1-meter spatial resolution. Many of the well sites in Shelby County are rural, so the ground surface is not likely to have changed much between when the historical water levels were measured and now; or the well sites were in town centers that still exist (e.g., Collierville, Tennessee).

d. The least accurate method was using the USGS National Elevation Dataset (NED), which has a 30-meter resolution.

12. Again, though not mentioned by Spruill, W&L recognized the uncertainty inherent in the well elevations and performed an analysis of the possible impact of vertical error on the article's results. Vertical errors were set to a maximum based on either measurement or inherent data error (e.g., the USGS NED, which have a large error, would be chosen if it was greater than the local mean vertical error around a location plus a standard deviation). W&L adjusted chosen ground

surface elevations to both ends of the vertical error range to measure whether contour placement or flow direction changed, i.e., whether vertical error might affect the water level map. Accounting for the vertical error at each well, the range of flow quantities moving from Mississippi into Tennessee expands, but the contour placement and flow direction do not change significantly. In particular, flow direction does not materially change to a direct east-west direction.

Combining Confined and Unconfined Water Levels

13. Spruill expresses the view that using groundwater levels or drawing contours from both the confined and unconfined portions of the Middle Claiborne invalidates the representation of actual conditions and flow. He states (at 22) that mixing water level contours between confined and unconfined is improper: "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." (emphasis by Spruill) Spruill further states that Reed (1972) and Criner and Parks (1976) do not include water levels in the unconfined section of the Middle Claiborne, and he relies extensively on these two publications for his arguments. In fact, however, it is standard practice to measure levels and draw contours from both confined and unconfined portions of the aquifer, as demonstrated by USGS hydrologists, including the very authors on which Spruill relies.

14. To see clearly that USGS hydrologists analyze both the confined and unconfined areas together, it is important to determine where those regions are. Parks (1990) identifies thickness of the Upper Claiborne confining clay for the Shelby County area (Figure 1), and shows the limit of the Upper Claiborne pinching out before reaching Fayette County, Tennessee, to the east. Therefore, west of the dotted line the Middle Claiborne is considered confined and to the east unconfined.

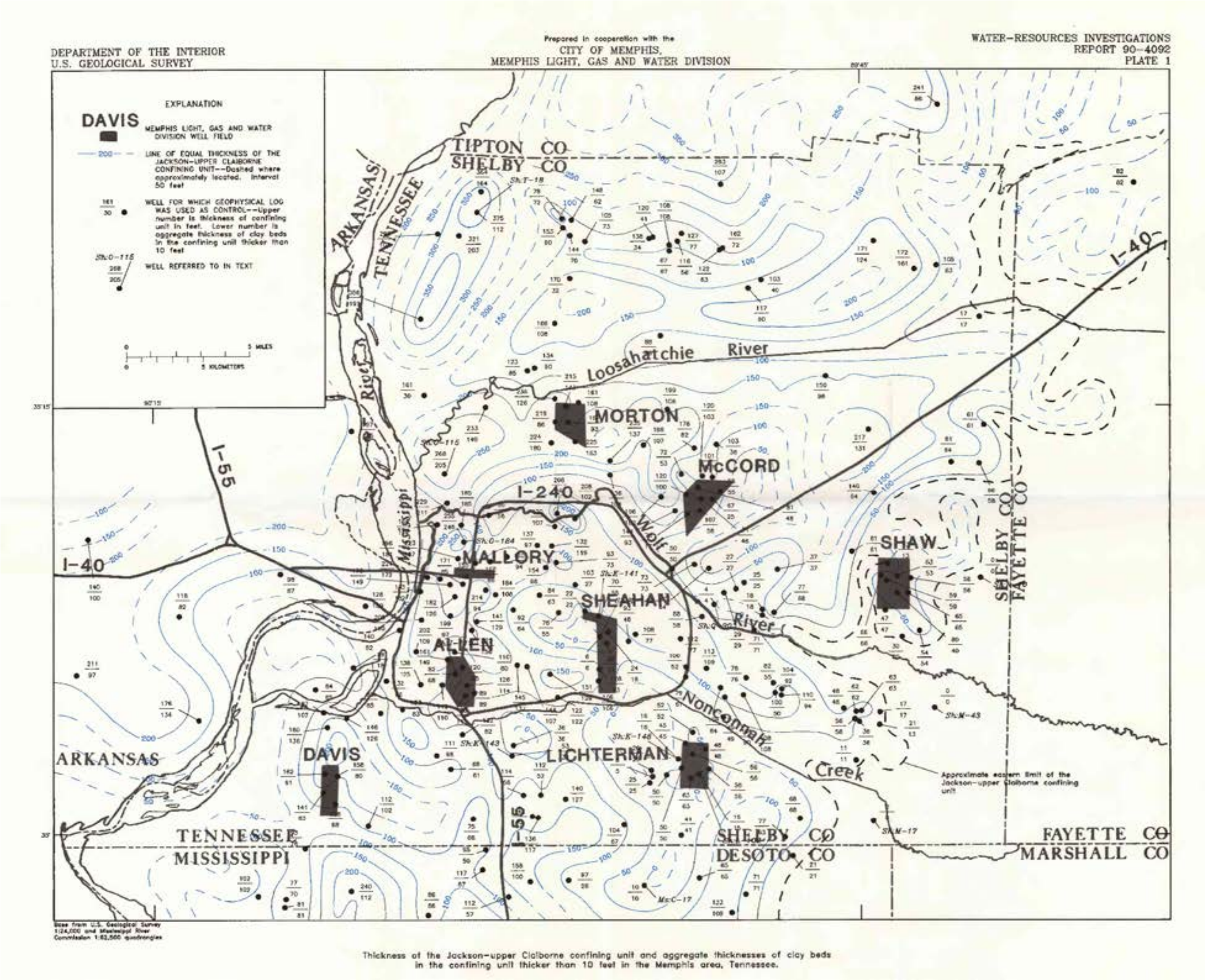

Figure 1. Thickness of Upper Claiborne confining clay with outcrop region of Middle Claiborne shown occurring along eastern Shelby County and into Fayette, Desoto, and Marshall Counties.

15. Lloyd and Lyke (1995) similarly provide in their USGS publication an illustration of the outcrop of section of the Middle Claiborne, and thus show the unconfined region (Figure 2) (Lloyd and Lyke, Figure 126, p. K27). They depict the unconfined region of the Middle Claiborne in West Tennessee passing through Fayette, Haywood, Crockett, Gibson, and Weakley counties, then continuing into Graves, Carlisle, and a small portion of Hickman counties in Kentucky.

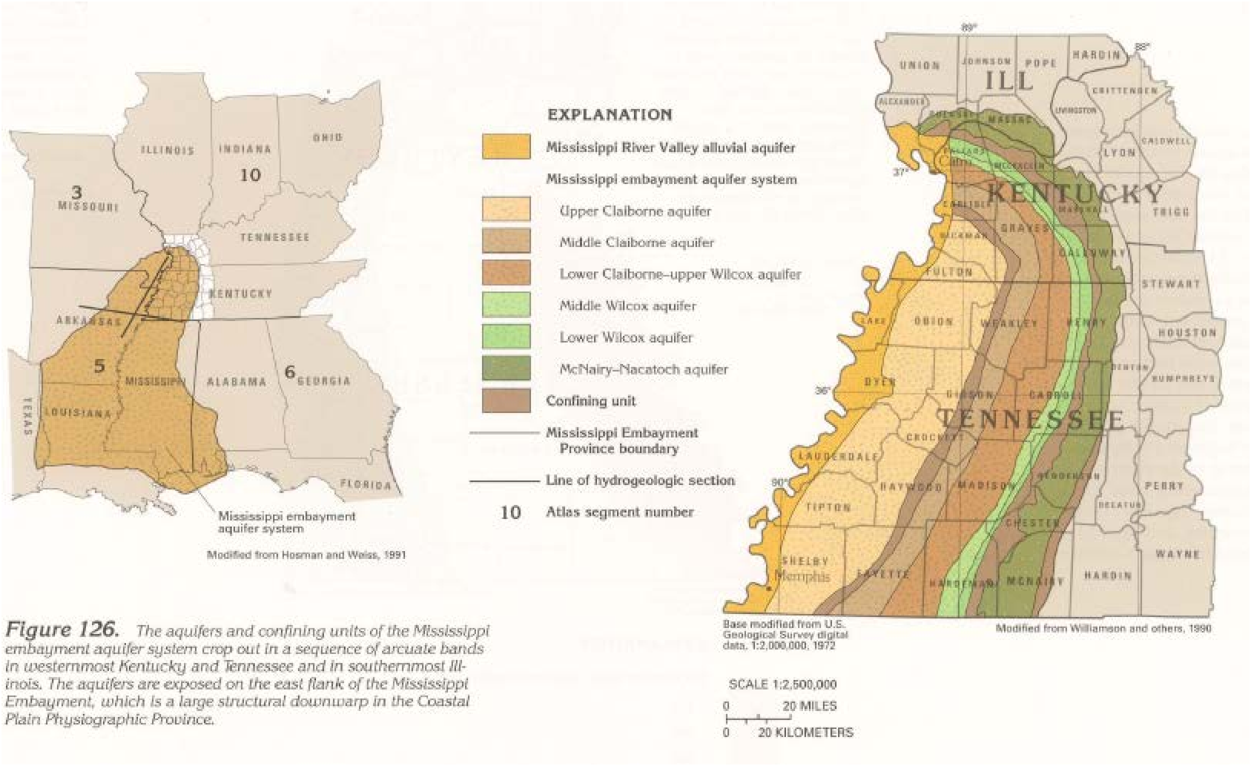

Figure 2. Depiction of extent and outcrop of Middle Claiborne in West Tennessee.

16. Spruill states (at 18) that "maps produced by Criner and Parks (1976) and Reed (1972) only consider groundwater-flow conditions in the confined portions of the aquifer" (emphasis by Spruill). Spruill also states: "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" (p. 11) and "[d]ata 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" (p. 22) (emphasis by Spruill). Based on that view, Spruill states, "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)." (p. 15) Spruill relies heavily on Reed (1972) and Criner and Parks (1976) for his arguments.

17. Contrary to Spruill's assessment and argument regarding mapping confined and unconfined water levels together, Reed (1972) does in fact map water levels for the Middle Claiborne in the confined and unconfined sections (Figure 3). As shown in the red box, Reed (1972) maps water levels for the Middle Claiborne in Fayette County, Tennessee – shown by Parks (1990) and Lloyd and Lyke (1995) to be unconfined – while also mapping water levels in the confined portion of the Middle Claiborne in Shelby County. Reed (1972) further maps water levels in the Middle Claiborne

throughout West Tennessee and into southwest Kentucky in the same counties listed above minus Graves County, Kentucky (Figure 3, green box). As can be seen, Reed depicts (with the grayed area) the approximate area of the outcrop of the Middle Claiborne and maps a 400 ft water level in this area (Figure 3, blue box).

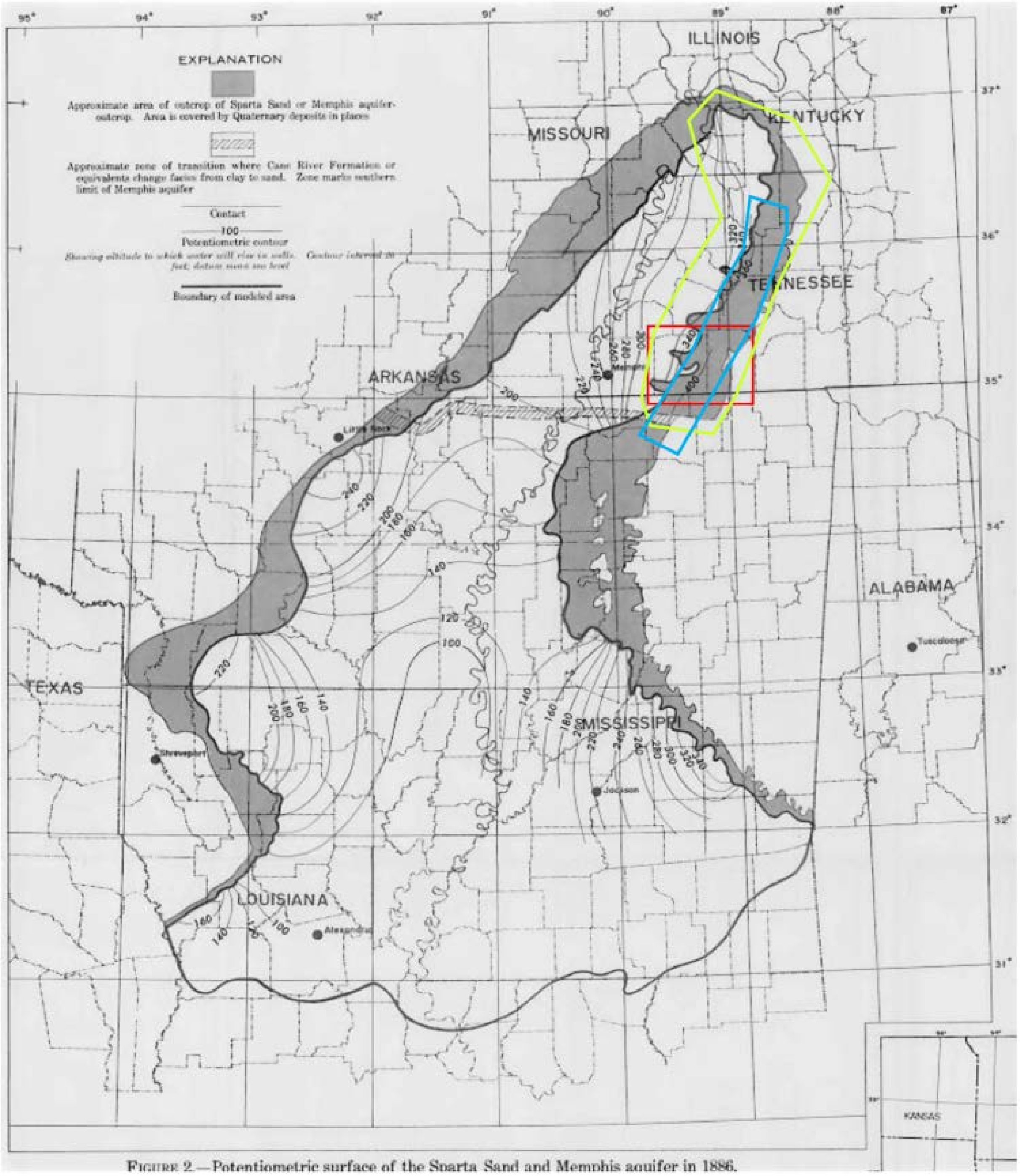

FIGURE 2.—Potentiometric surface of the Sparta Sand and Memphis aquifer in 1886.

Figure 3. Predevelopment potentiometric surface contours of the Middle Claiborne suggested by Reed (1972), including outcrop (unconfined) region of the Middle Claiborne in West Tennessee.

18. Similarly, Criner and Parks (1976) can be seen mapping water levels in both the confined and unconfined regions. Criner and Parks use a well in Fayette County, Tennessee, with the USGS label Fa:R-002. According to Parks (1990),* this well is in the *unconfined* section of the Middle Claiborne residing within a remnant Upper Claiborne clay lens. This well is used in subsequent water level maps of the Middle Claiborne. Further, according to Parks (1990)'s new rendition of the outcrop section of the Middle Claiborne, the eastern water level contours of Criner and Parks (1976) reside in the unconfined section of the Middle Claiborne.

19. Additionally, Parks and Carmichael (1990) mapped the thickness of the Middle Claiborne throughout West Tennessee and depicted on their *Figure 2* (Figure 4) the outcrop (i.e., unconfined section) of the Middle Claiborne residing between two thick black lines. Parks and Carmichael (1990) produce in their subsequent *Figure 3* (Figure 5) the "potentiometric surface" of the Middle Claiborne in 1983. Clearly, water levels are mapped in the confined and unconfined sections of the Memphis aquifer.

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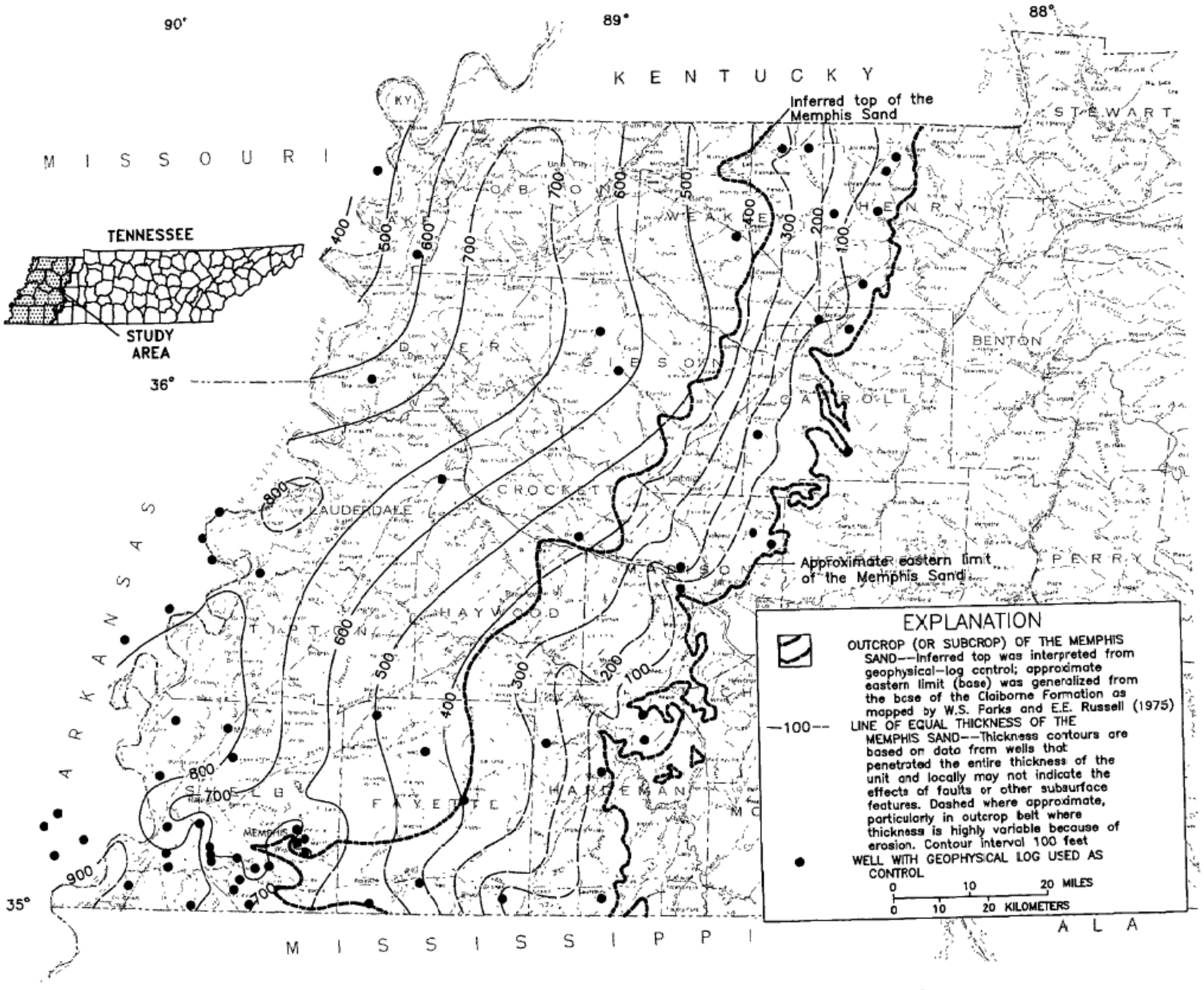
*Each reference to "Parks" among these papers refers to the same W.S. Parks.



EXPLANATION

OUTCROP (OR SUBCROP) OF THE MEMPHIS SAND--Inferred top was interpreted from geophysical-log control; approximate eastern limit (base) was generalized from the base of the Claiborne Formation as mapped by W.S. Parks and E.E. Russell (1975)

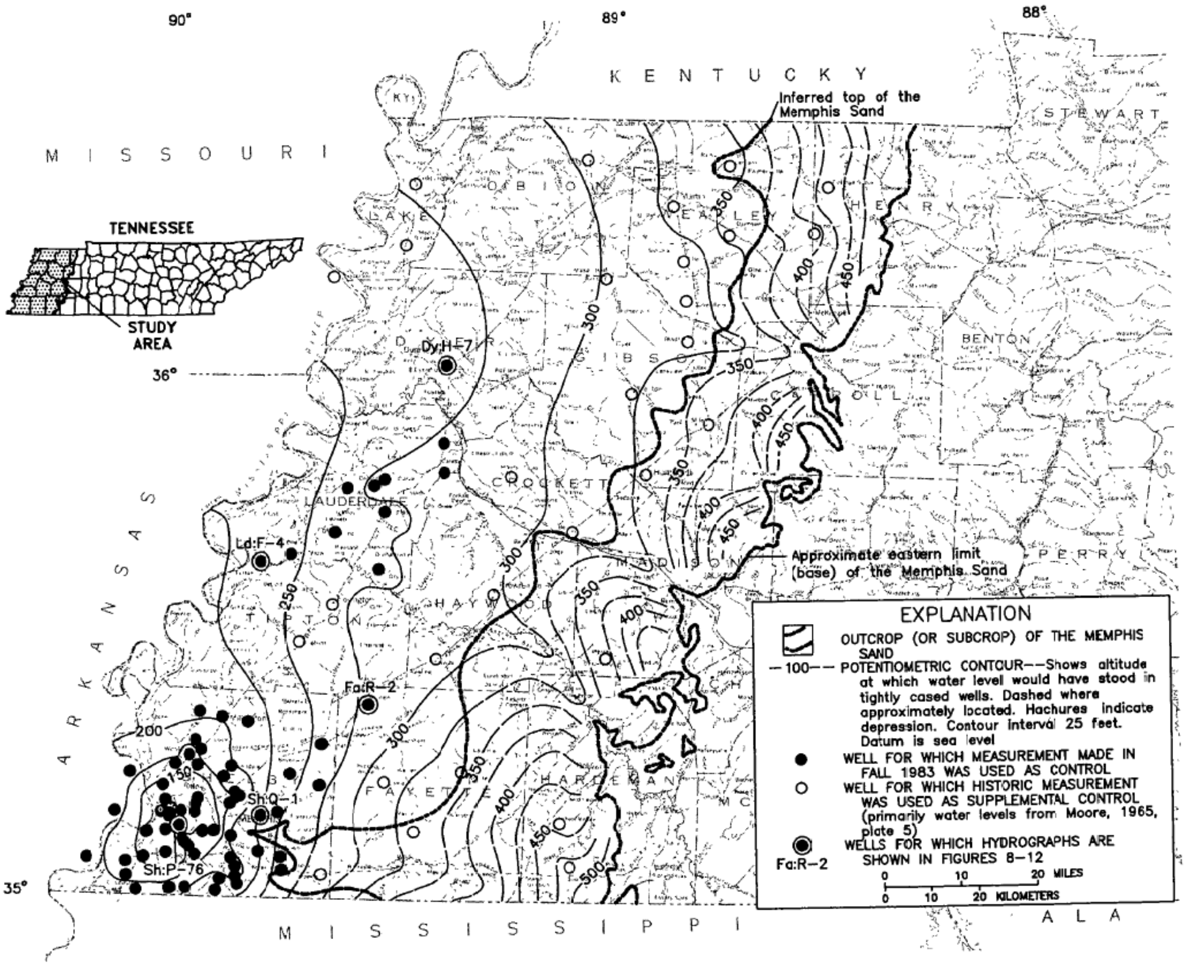
—100-- LINE OF EQUAL THICKNESS OF THE MEMPHIS SAND--Thickness contours are based on data from wells that penetrated the entire thickness of the unit and locally may not indicate the effects of faults or other subsurface features. Dashed where approximate, particularly in outcrop belt where thickness is highly variable because of erosion. Contour interval 100 feet

● WELL WITH GEOPHYSICAL LOG USED AS CONTROL

Base from U.S. Geological Survey, State base map, 1:500,000, 1973

Figure 2.--Generalized thickness of the Memphis Sand.

Figure 4. Extent of the Middle Claiborne in West Tennessee, including depiction of the outcrop (unconfined) region of the Middle Claiborne.



Base from U.S. Geological Survey, State base map, 1:500,000, 1973

Figure 3.—Generalized potentiometric surface in the Memphis aquifer, fall 1983.

Figure 5. Potentiometric surface of the Middle Claiborne in West Tennessee depicted in the confined and unconfined regions of the Middle Claiborne.

20. Spruill (at 20-22) cites Schrader (2008) in his argument over changes in water levels between 1886 levels as analyzed by W&L and 2007 levels as analyzed by Schrader (2008). Spruill's own argument involves a well in the unconfined portion of the Memphis aquifer (according to Parks, 1990) using a study by Schrader (2008) that, like others, maps water levels in both the confined and unconfined sections of the Middle Claiborne (Figure 6, see grayed areas) in Tennessee and Mississippi. (W&L also use Schrader (2008) in their analysis of comparing groundwater quantities passing from Mississippi into Tennessee.)

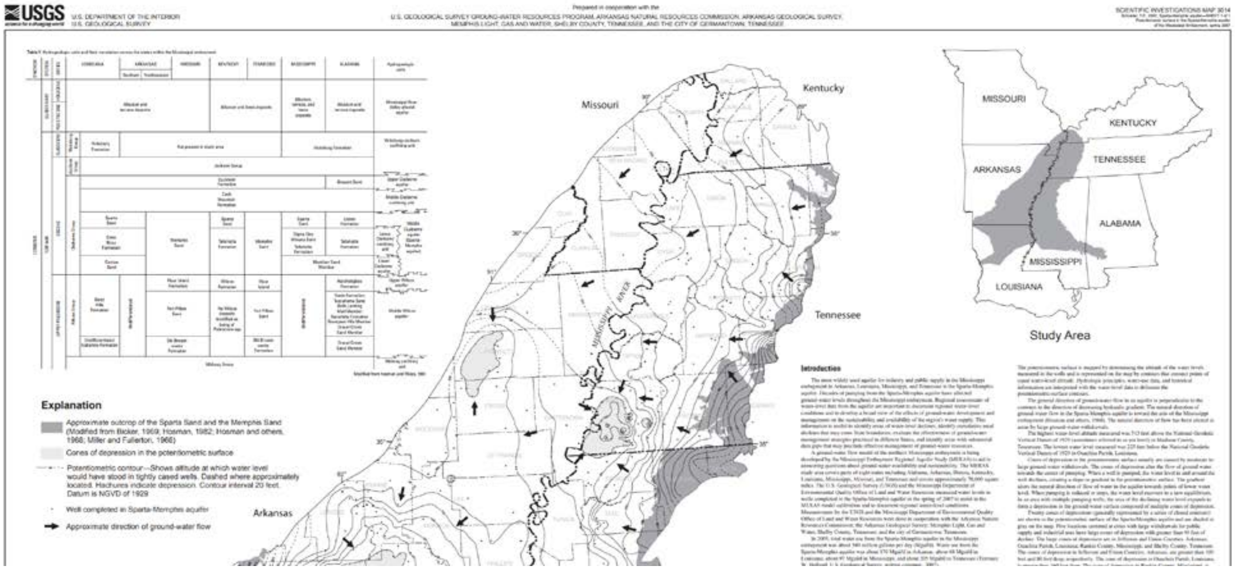


Figure 6. Potentiometric contours of the Middle Claiborne in 2007 mapped within the confined and unconfined regions (lower half of original figure has been cut off).

21. Mapping water levels in the Middle Claiborne confined and unconfined regions is a common practice followed by many of the very USGS authors Spruill cites. W&L followed this ordinary practice in mapping both confined and unconfined regions together.

22. The same practice is followed for other aquifers, as well. For example, Lloyd and Lyke (1995) map water levels in the Lower Wilcox aquifer confined and unconfined portions in West Tennessee in their *Figure 137* (Figure 7), again illustrating the commonality of mapping confined and unconfined water levels together.

Wells Used by Waldron and Larsen Were Recorded in USGS Publications

23. Spruill remarks on the lack of well construction data, arguing that it reduces the reliability of the water level data used by W&L. Although construction techniques were not as well-documented as they would be today, the USGS reported the water levels nonetheless. If the water levels were questionable because of unusual construction in particular wells, it seems unlikely that USGS authors (Fuller, 1903; Crider and Johnson, 1906; Glenn, 1906) would have recorded water levels for scientific purposes, as the USGS is a scientific research and data collection body. Spruill goes on to say (at 18): "Historic records used in W&L 2015 to obtain water level data do not provide any information about well construction and grouting." (emphases by Spruill). [In fact, an early publication by Brown (1947) as part of a Mississippi State Geological Survey lists numerous wells in each county in Mississippi that includes water levels but not a single mention of well construction information (Figure 12).]

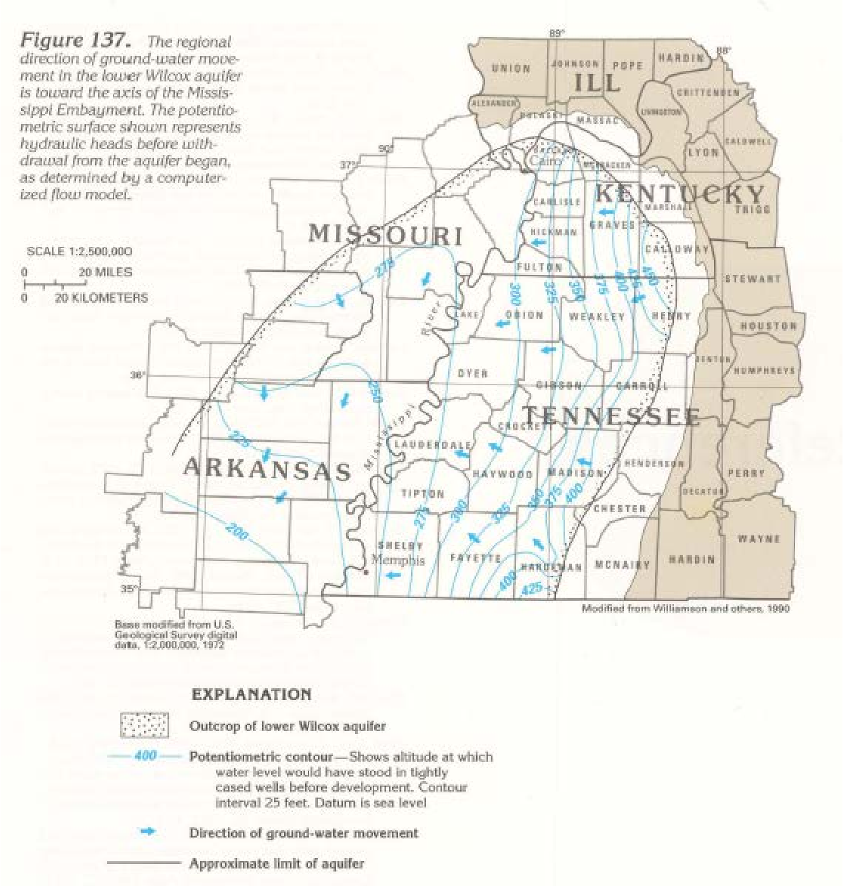


Figure 7. Following the extent and outcrop regions of the Middle Claiborne shown in Figure 2, Lloyd and Lyke (1995) map potentiometric contours within the confined and unconfined regions.

Spruill Overstates the Relative Reliability of Alternative Data

24. Spruill suggests that the data used by Criner and Parks (1976) to construct their predevelopment potentiometric surface are superior to the data used by W&L. However, a number of Spruill's arguments on this point are irrelevant, overstated, or incorrect.

25. Spruill states (at 10) that Criner and Parks (1976) did not include pumpage from a few thousand suburban and rural wells in the vicinity of Memphis and Shelby County, Tennessee; he seems to be suggesting that using these wells would not be relevant because they accounted for a small percentage of overall pumpage volume. However, volume is not the point; the question is what water levels were at the time of predevelopment. At any rate, for this purpose, measurements from these few thousand suburban and rural wells would post-date predevelopment conditions by many years and be less relevant than those measurements used by W&L.

26. Spruill also suggests (at 11) that Criner and Parks (1976)'s data were superior because "[s]ignificantly, 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)." However, W&L did not focus on obtaining data away from the center of pumping or well fields, because at the

(near-predevelopment) time of the historical data used by W&L there were neither major well fields nor major pumping centers causing potential distortions of water levels.

27. Spruill states (at 11) that Criner and Parks (1976) used water level measurements of six wells that 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)." However, this statement is incorrect. Criner and Parks (1976) clearly state that only a single well – USGS well Sh:O-124 – was projected back in time. Criner and Parks assumed that it would follow a linear trend over a 41-year span, as shown in Figure 8 (*Figure 3, upper graph*) and Figure 9.

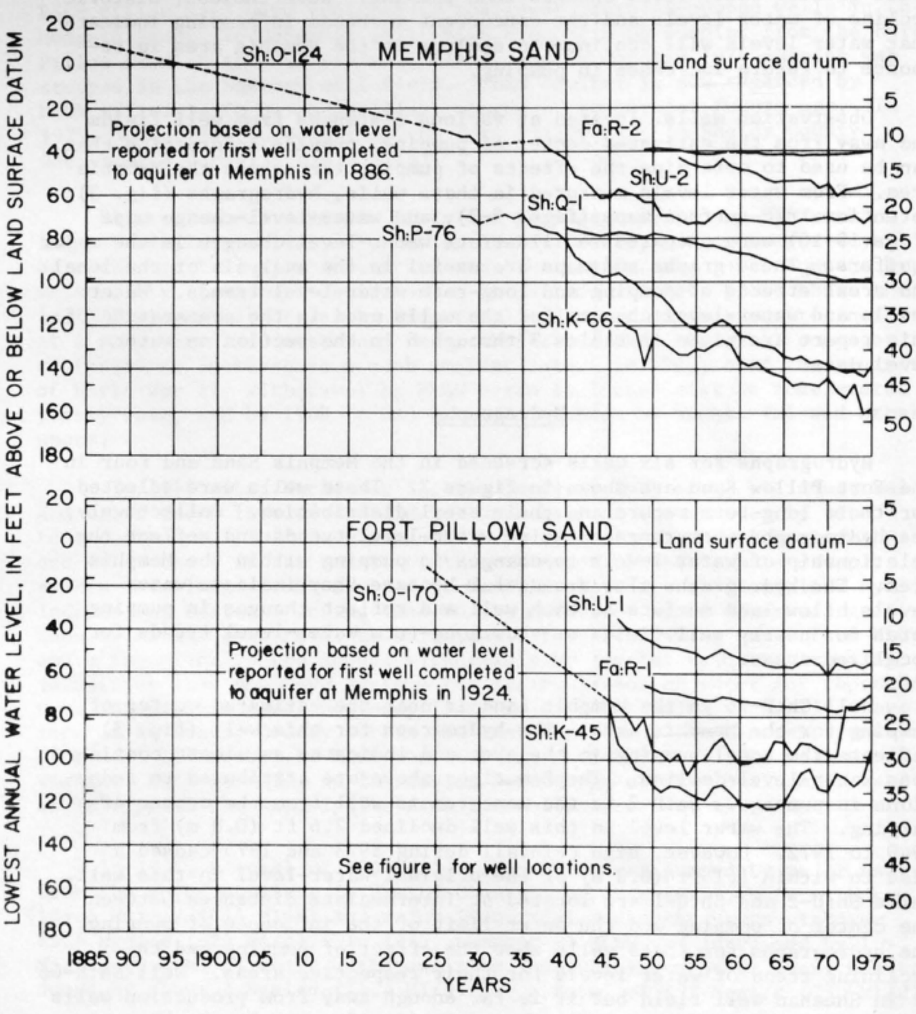
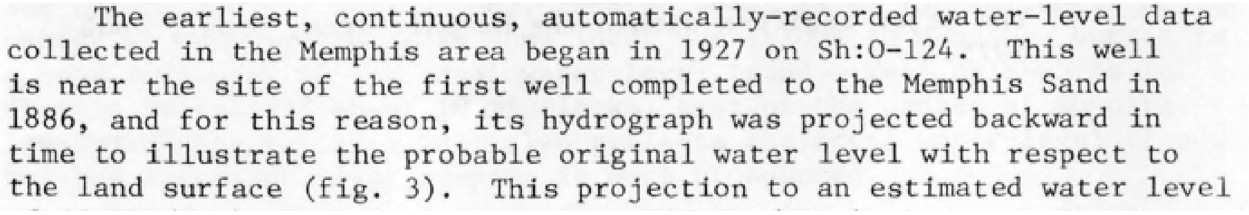


Figure 3. -- Water-level changes in observation wells screened in the major aquifers within the Memphis area, Tenn., 1886-1975.

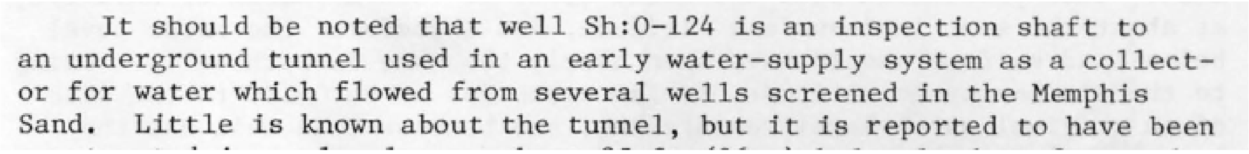
Figure 8. Wells whose hydrographs and water levels were used by Criner and Parks (1976) from predevelopment conditions, and illustration of linear back-projection of Sh:O-124 (tunnel) water level to arrive at estimated predevelopment water level of R.C. G.



The earliest, continuous, automatically-recorded water-level data collected in the Memphis area began in 1927 on Sh:O-124. This well is near the site of the first well completed to the Memphis Sand in 1886, and for this reason, its hydrograph was projected backward in time to illustrate the probable original water level with respect to the land surface (fig. 3). This projection to an estimated water level

Figure 9. Excerpt from Criner and Parks (1976) regarding back-projection of only Sh:O-124.

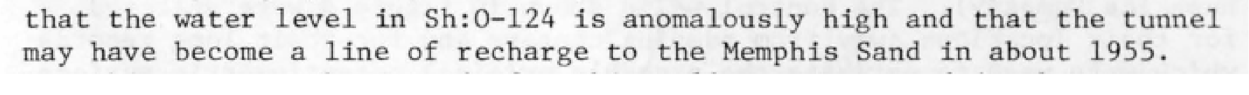
28. As noted, Spruill suggests (at 17) that "[m]any 'wells' cited W&L 2015 *are not actually wells*" (emphasis by Spruill). Though this statement is incorrect (as discussed), Spruill argues (at 17) that water level data derived from what he thinks are not wells in W&L renders our analysis invalid. Yet, in fact, the single well Criner and Parks (1976) project backwards in time to define actual predevelopment water level conditions for the region (i.e., Sh:O-124) is not a well, but a water collection shaft (see Figure 10).



It should be noted that well Sh:O-124 is an inspection shaft to an underground tunnel used in an early water-supply system as a collector for water which flowed from several wells screened in the Memphis Sand. Little is known about the tunnel, but it is reported to have been

Figure 10. Excerpt from Criner and Parks (1976, p. 13) on Sh:O-124, the single and only well used to project probable predevelopment conditions.

29. Spruill also questions the reliability of the data used by W&L by stating (at 16): "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." Again, however, Criner and Parks (1976), on which Spruill heavily relies, expressly state that Sh:O-124 is of questionable reliability, noting that: (1) Sh:O-124 is not a well but a tunnel (Figure 10); (2) "[l]ittle is known about the tunnel" (Figure 10); and (3) water levels in the tunnel were "anomalously high" and influenced by recharge (Figure 11).



The hydrograph (fig. 3) and potentiometric-surface maps indicate that the water level in Sh:O-124 is anomalously high and that the tunnel may have become a line of recharge to the Memphis Sand in about 1955.

Figure 11. Excerpt from Criner and Parks (1976, p. 13) on Sh:O-124 and observed anomalously high water levels.

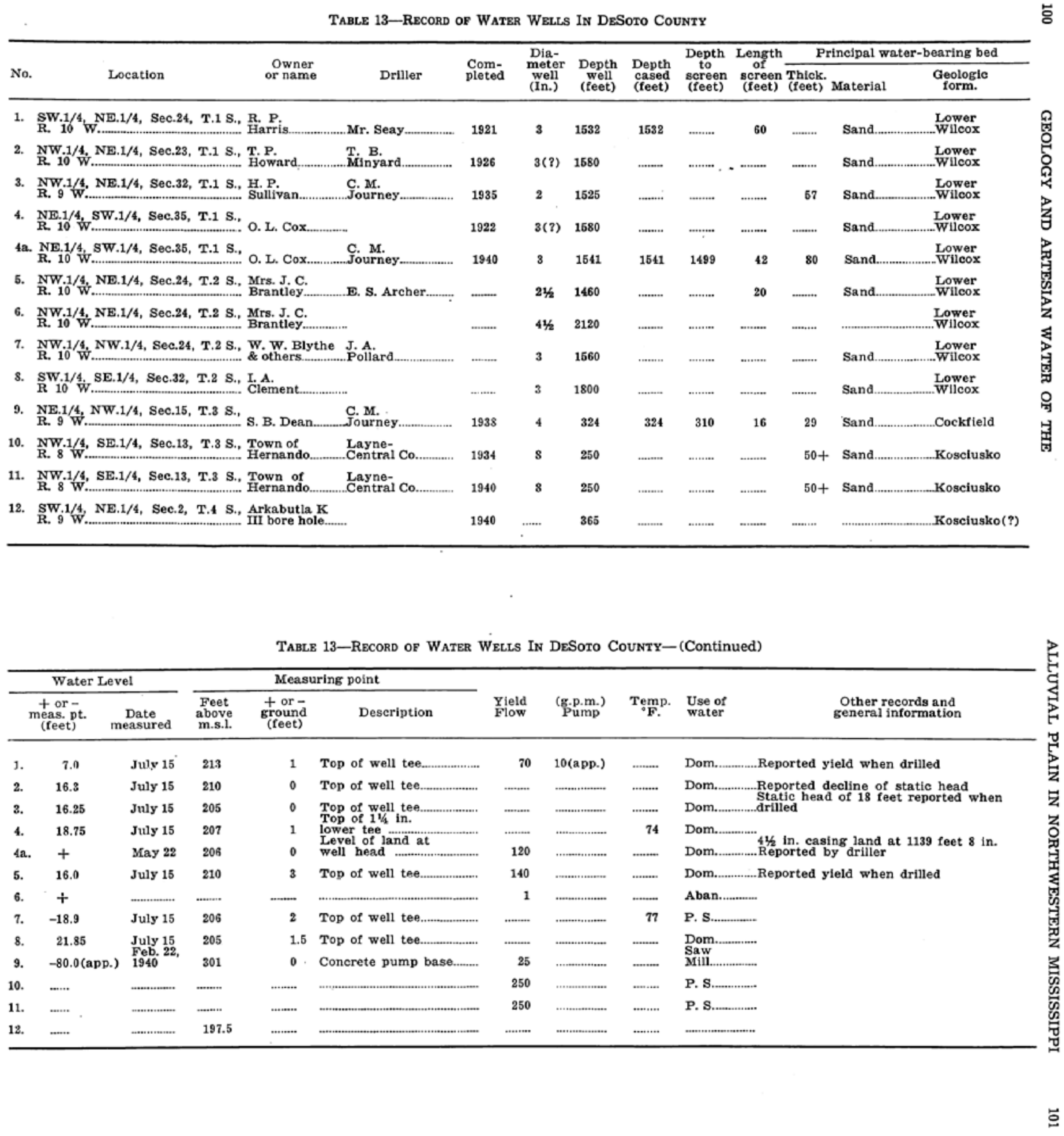


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TABLE 13—RECORD OF WATER WELLS IN DESOTO COUNTY

GEOLOGY AND ARTESIAN WATER OF THE

No.	Location	Owner or name	Driller	Completed	Diameter well (In.)	Depth well (feet)	Depth cased (feet)	Depth to screen (feet)	Length of screen (feet)	Principal water-bearing bed		
										Thick. (feet)	Material	Geologic form.
1.	SW.1/4, NE.1/4, Sec.24, T.1 S., R. 10 W.	R. P. Harris	Mr. Seay	1921	3	1532	1532		60		Sand	Lower Wilcox
2.	NW.1/4, NE.1/4, Sec.23, T.1 S., R. 10 W.	T. P. Howard	T. B. Minyard	1926	3(?)	1580					Sand	Lower Wilcox
3.	NW.1/4, NE.1/4, Sec.32, T.1 S., R. 9 W.	H. P. Sullivan	C. M. Journey	1935	2	1525				57	Sand	Lower Wilcox
4.	NE.1/4, SW.1/4, Sec.35, T.1 S., R. 10 W.	O. L. Cox		1922	3(?)	1580					Sand	Lower Wilcox
4a.	NE.1/4, SW.1/4, Sec.35, T.1 S., R. 10 W.	O. L. Cox	C. M. Journey	1940	3	1541	1541	1499	42	80	Sand	Lower Wilcox
5.	NW.1/4, NE.1/4, Sec.24, T.2 S., R. 10 W.	Mrs. J. C. Brantley	E. S. Archer		2½	1460			20		Sand	Lower Wilcox
6.	NW.1/4, NE.1/4, Sec.24, T.2 S., R. 10 W.	Mrs. J. C. Brantley			4½	2120						Lower Wilcox
7.	NW.1/4, NW.1/4, Sec.24, T.2 S., R. 10 W.	W. W. Blythe & others	J. A. Pollard		3	1560					Sand	Lower Wilcox
8.	SW.1/4, SE.1/4, Sec.32, T.2 S., R 10 W.	I. A. Clement			3	1800					Sand	Lower Wilcox
9.	NE.1/4, NW.1/4, Sec.15, T.3 S., R. 9 W.	S. B. Dean	C. M. Journey	1938	4	324	324	310	16	29	Sand	Cockfield
10.	NW.1/4, SE.1/4, Sec.13, T.3 S., R. 8 W.	Town of Hernando	Layne-Central Co.	1934	8	250				50+	Sand	Kosciusko
11.	NW.1/4, SE.1/4, Sec.13, T.3 S., R. 8 W.	Town of Hernando	Layne-Central Co.	1940	8	250				50+	Sand	Kosciusko
12.	SW.1/4, NE.1/4, Sec.2, T.4 S., R. 9 W.	Arkabutla K III bore hole		1940		365						Kosciusko(?)

TABLE 13—RECORD OF WATER WELLS IN DESOTO COUNTY—(Continued)

ALLUVIAL PLAIN IN NORTHWESTERN MISSISSIPPI

	Water Level		Measuring point							
	+ or – meas. pt. (feet)	Date measured	Feet above m.s.l.	+ or – ground (feet)	Description	Yield Flow	(g.p.m.) Pump	Temp. °F.	Use of water	Other records and general information
1.	7.0	July 15	213	1	Top of well tee	70	10(app.)		Dom.	Reported yield when drilled
2.	16.3	July 15	210	0	Top of well tee				Dom.	Reported decline of static head
3.	16.25	July 15	205	0	Top of well tee				Dom.	Static head of 18 feet reported when drilled
4.	18.75	July 15	207	1	Top of 1¼ in. lower tee			74	Dom.	
4a.	+	May 22	206	0	Level of land at well head	120			Dom.	4½ in. casing land at 1139 feet 8 in. Reported by driller
5.	16.0	July 15	210	3	Top of well tee	140			Dom.	Reported yield when drilled
6.	+					1			Aban.	
7.	–18.9	July 15	206	2	Top of well tee			77	P. S.	
8.	21.85	July 15	205	1.5	Top of well tee				Dom.	
9.	–80.0(app.)	Feb. 22, 1940	301	0	Concrete pump base	25			Saw Mill	
10.						250			P. S.	
11.						250			P. S.	
12.			197.5							

101

Figure 12. Table 13 for groundwater wells in DeSoto County, Mississippi (Brown, 1947).

30. Spruill states (at 18) that W&L mentioned Well #3 (Forrest City, Arkansas), but did not use it in their analysis; he further suggests that, if W&L had done so, it would reorient the Middle Claiborne predevelopment gradient to be more east-to-west. In fact, however, W&L did incorporate this well into their analysis. The well is on the extreme outskirts of the data area, and there are not enough other data near that well to draw a 2D contour for a single point (following the logic that two points define a line). Figure 13 shows the Forrest City well, which is present in the analysis though not shown on W&L's *Figure 4*.

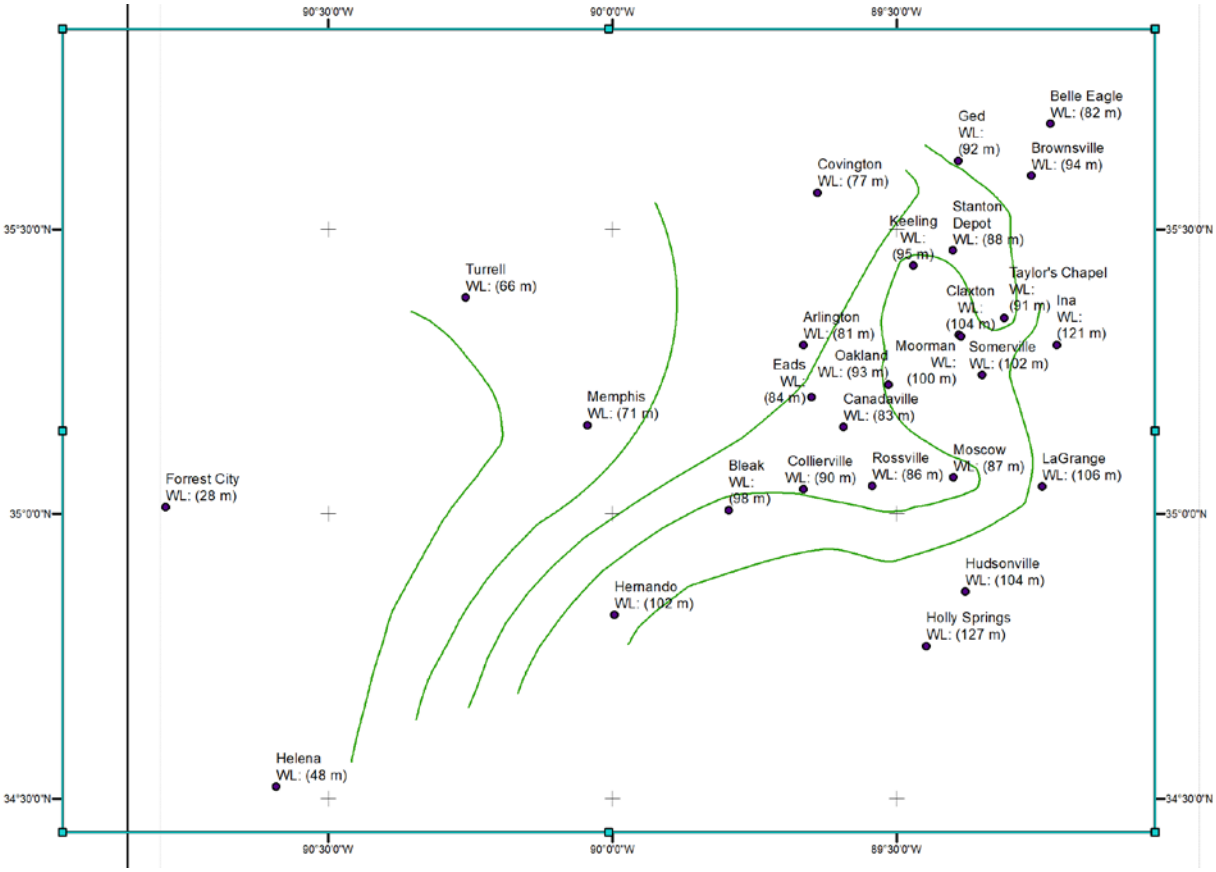
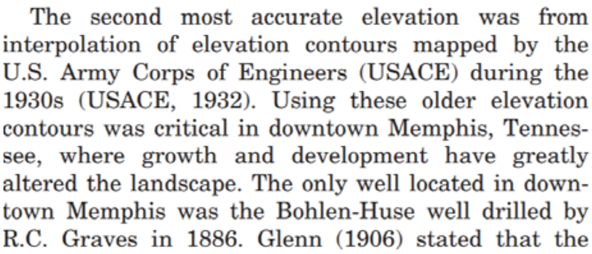
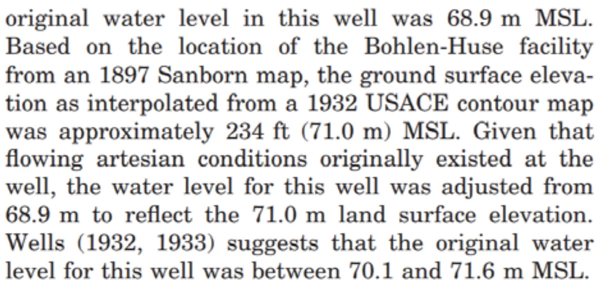


Figure 13. Expansion of W&L wells used for determining predevelopment conditions showing Forrest City, Arkansas, well.

31. Spruill comments on W&L's use of land surface elevations for artesian well conditions, arguing that the resulting water levels are inaccurate. In the case of the historically significant R.C. Graves well in downtown Memphis, W&L extensively reviewed other sources to arrive at the best possible water level elevation for this artesian well (Figure 14). Interestingly, Criner and Parks (1976) use a linear interpolation from a water level reading taken in a tunnel (not a well) in 1927 back over a 41-year span to arrive at their predevelopment water level, yet Spruill does not question the validity of their value.



The second most accurate elevation was from interpolation of elevation contours mapped by the U.S. Army Corps of Engineers (USACE) during the 1930s (USACE, 1932). Using these older elevation contours was critical in downtown Memphis, Tennessee, where growth and development have greatly altered the landscape. The only well located in downtown Memphis was the Bohlen-Huse well drilled by R.C. Graves in 1886. Glenn (1906) stated that the



original water level in this well was 68.9 m MSL. Based on the location of the Bohlen-Huse facility from an 1897 Sanborn map, the ground surface elevation as interpolated from a 1932 USACE contour map was approximately 234 ft (71.0 m) MSL. Given that flowing artesian conditions originally existed at the well, the water level for this well was adjusted from 68.9 m to reflect the 71.0 m land surface elevation. Wells (1932, 1933) suggests that the original water level for this well was between 70.1 and 71.6 m MSL.

Figure 14. Excerpt from Waldron and Larsen (2015) on determination of the artesian water level for the famous R.C. Graves well in downtown Memphis using multiple sources.

Spruill's Critiques of W&L's Contours Are Unfounded and Insubstantial

32. Regarding Spruill's criticisms (at 19-20) of W&L's drawing of contours, he raises four points.

   a. Point 1 – *The contour interval varies from 9 to 13 meters*: This point is irrelevant because a varying contour interval is an appropriate method to use in this instance. The water levels were spread over a large area, and, instead of interpolating contours at an equal interval (which inherently has its own subjectivity), contours were drawn to match measured values.

   b. Point 2 – *Well #16 has a water level elevation of 91 m, but is drawn on the opposite side of the line*: The placement is correct. The original measurements were made in English units (i.e., feet). Many journal publications require units to be in metric units because their audience is international. Figure 15 shows the water levels in feet before conversion. Well #16 (green box) has a water elevation of 298 ft and is correctly placed on the inside of the 300-foot contour. In SI units (metric system), well #16's water elevation is 90.83 m and the 300 ft contour would be 91.44 m. Rounding to the nearest meter, well #16 would be 91 m and the contour 91 m. Due to conversion and rounding, in SI the point would look erroneous, but, in the original English system, the placement is correct.

   c. Point 3 – *Well #17 is in a contoured area of 91 m, but the water level for this well is 82 m*: Well #17 (Figure 15 purple/pink box) has a water elevation of 270 ft (82 m), which near wells #20 and #18 would be near a 91-m contour. Well #17's water level is correct as well as its placement. We speculate that the water level in #17 is low because it is near the South Fork Deer River and thus groundwater is moving not southward at this location, but northward toward the river valley where the groundwater would discharge to the river. As there are not more wells in this river valley near well #17, we could not draw a contour with confidence.

   d. Point 4 – *Well #6 has a water level of 104 m, but is more than 6 miles out of place*: Similar to Point 2, Well #6 (Figure 15 orange box) has a water elevation of 342 ft (104.24 m) and is correctly drawn on the upgradient side of a 340-ft contour (103.63 m); when the SI units are rounded both elevations show as 104 m. The measurements and position are correct in their original English units.

33. Spruill suggests (at 20) that these four points, which he labels errors, show that the predevelopment map by W&L "presents a fundamentally flawed interpretation of the pre-pumping equipotential surface in the aquifer system." As shown, however, the four points are not errors, and the map is in fact drawn correctly.

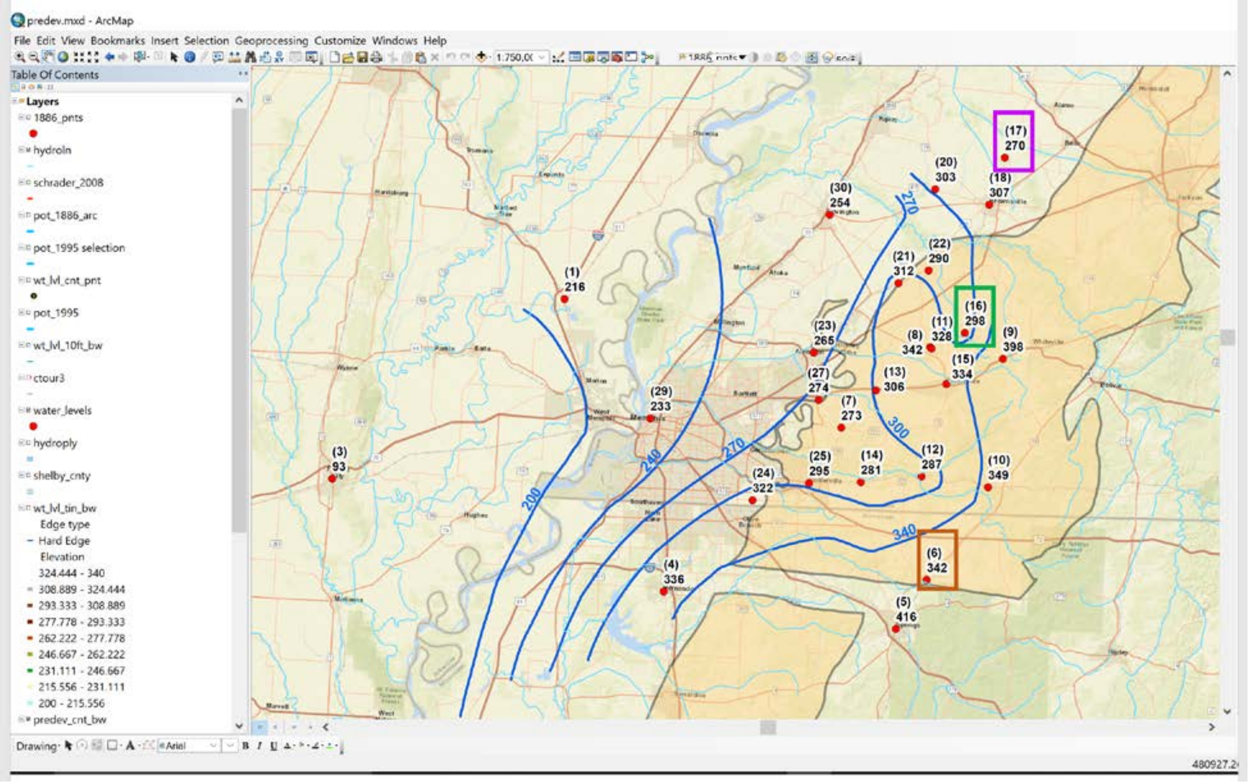
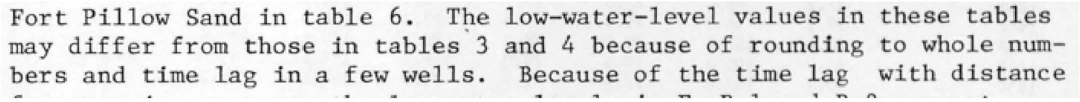


Figure 15. Depiction of wells drawing unfounded scrutiny from Spruill.

Spruill's Allegations of Various Additional Uncertainties Are Unfounded

34. Spruill states (at 17-18) that the land surface elevation error (5.5 m) "does not take into account the inherent error in rounding values to the nearest meter for each water level value used for contouring head" (emphasis by Spruill), yet error between two independent variables (land surface and rounding) in this case is not cumulative. Instead, for independent variables the largest error encapsulates any smaller error (similar to saying it is within the margin of error). Rounding in SI units would have a maximum error of <0.5 m. W&L assumed the largest vertical error in their analysis in order to assess the maximum potential impact of that error on their results.

35. Spruill raises concern that W&L round their water levels to whole numbers. It is unclear why this would be considered an error; and, in fact, Criner and Parks (1976) do the same (Figure 16).



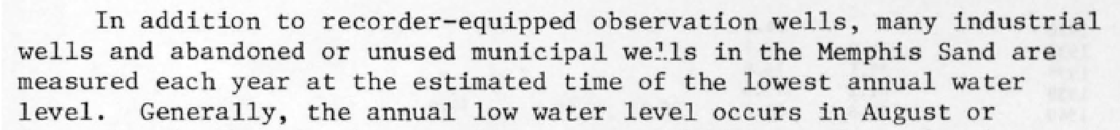
Fort Pillow Sand in table 6. The low-water-level values in these tables may differ from those in tables 3 and 4 because of rounding to whole numbers and time lag in a few wells. Because of the time lag with distance

Figure 16. Criner and Parks (1976) excerpt. (p. 39); the authors mention that they rounded water levels to whole numbers, similar to W&L.

36. Spruill argues (at 17) that reference points for water level measurements are not provided in the early USGS publications used by W&L. I assume Spruill is saying that this introduces error into the vertical measurement of the calculated water levels. We were aware that reference points (or measuring points) were not provided. Yet based on our knowledge of measuring point heights of typical wells, most especially those in the Mid-South region, the height falls well within the largest vertical error for each well and thus follows the same logic as the discussion in paragraph 34, above.

37. Spruill states (at 17), "All of these historic measurements [used by W&L] 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." Of course they do, as the only well used in any *pre*development report is the R.C. Graves well in downtown Memphis. But W&L's water levels are the closest water level measurements to the predevelopment era used by anyone who has likewise developed a predevelopment groundwater level map of the Middle Claiborne. W&L's water level measurements range between the dates 1886-1906, compared with Criner and Parks (1976) whose water levels measured between the dates 1927-1960.

38. Spruill states (at 21) that observation wells for taking water levels should have short screens, and that, without screen information on the wells used by W&L, the measures are questionable. It is recognized that observation wells should have short screen lengths. However, the USGS has been developing water level maps of the Middle Claiborne for many years and has used both observation wells and production wells in mapping. MLGW and other municipal production wells have screen lengths of 80-100 ft. Industry wells do not have short screens. Nevertheless, Criner and Parks (1976), a publication relied on heavily by Spruill, developed potentiometric maps of the Middle Claiborne for 1960, 1970, and 1975 as part of their publication. In developing their maps, they used observation wells (i.e., with short screens that Spruill suggests are required to be valid) and municipal and industrial wells (i.e., with long screens, suggested to be invalid by Spruill) (Figure 17).



In addition to recorder-equipped observation wells, many industrial wells and abandoned or unused municipal wells in the Memphis Sand are measured each year at the estimated time of the lowest annual water level. Generally, the annual low water level occurs in August or

Figure 17. Criner and Parks (1976) (p. 39), stating that in additional to using observation well water levels, levels from municipal and industrial wells were also used, which typically have long screens.

39. Spruill argues that W&L's wells are invalid because: (1) their screen length is unknown, as just described, and (2) there are no well construction records. Other studies also lack well construction records, however.

40. Reed (1972) does not show any well locations used to derive his predevelopment groundwater level map of the Middle Claiborne, so no determination can be made about the wells' quality or validity. Reviewing the three references listed by Reed (1972) does not reveal any well locations.

41. Criner and Parks (1976) use water levels from six wells (though, as noted, Sh:O-124 is a tunnel) to show water level changes in the Middle Claiborne between 1886 and 1975. (See Figure 8, upper graph.) These wells are labeled Sh:O-1274, Sh:U-002, Sh:Q-001, Sh:P-076, Sh:K-066, and Fa:R-002.

42. The University of Memphis' Center for Applied Earth Science and Engineering Research has well information as follows:

a. Sh:K-066: screen length of 61 ft (Figure 18) and no construction record

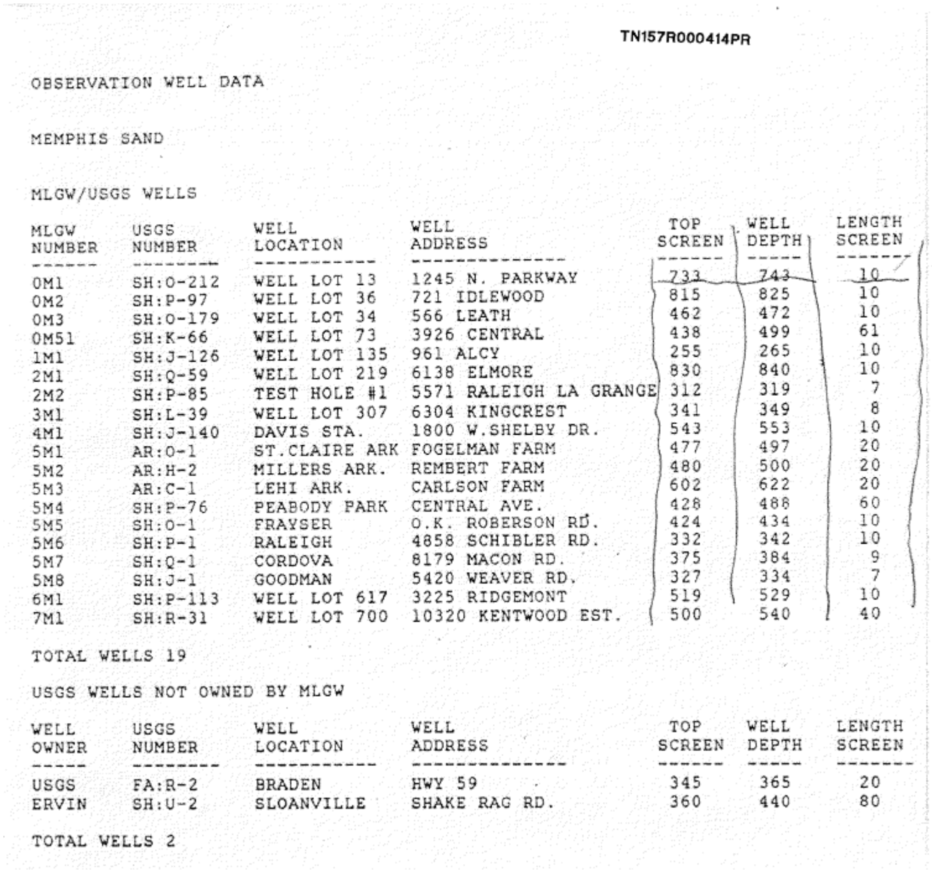
b. Sh:Q-001: screen length of 9 ft (Figure 18) and no construction record (Figure 19)

c. Sh:P-076: screen length of 60 ft (Figure 18) and no construction record (Figure 20)

d. Sh:U-002: screen length of 80 ft (Figure 18) and no construction record (Figure 21)

e. Sh:O-124: no screen (not a well; see Figure 10) and no construction record

f. Fa:R-002: screen length of 20 ft (Figure 18) and no construction record



TN157R000414PR

OBSERVATION WELL DATA

MEMPHIS SAND

MLGW/USGS WELLS

MLGW NUMBER	USGS NUMBER	WELL LOCATION	WELL ADDRESS	TOP SCREEN	WELL DEPTH	LENGTH SCREEN
0M1	SH:O-212	WELL LOT 13	1245 N. PARKWAY	~~733~~	~~743~~	~~10~~
0M2	SH:P-97	WELL LOT 36	721 IDLEWOOD	815	825	10
0M3	SH:O-179	WELL LOT 34	566 LEATH	462	472	10
0M51	SH:K-66	WELL LOT 73	3926 CENTRAL	438	499	61
1M1	SH:J-126	WELL LOT 135	961 ALCY	255	265	10
2M1	SH:Q-59	WELL LOT 219	6138 ELMORE	830	840	10
2M2	SH:P-85	TEST HOLE #1	5571 RALEIGH LA GRANGE	312	319	7
3M1	SH:L-39	WELL LOT 307	6304 KINGCREST	341	349	8
4M1	SH:J-140	DAVIS STA.	1800 W.SHELBY DR.	543	553	10
5M1	AR:O-1	ST.CLAIRE ARK	FOGELMAN FARM	477	497	20
5M2	AR:H-2	MILLERS ARK.	REMBERT FARM	480	500	20
5M3	AR:C-1	LEHI ARK.	CARLSON FARM	602	622	20
5M4	SH:P-76	PEABODY PARK	CENTRAL AVE.	428	488	60
5M5	SH:O-1	FRAYSER	O.K. ROBERSON RD.	424	434	10
5M6	SH:P-1	RALEIGH	4858 SCHIBLER RD.	332	342	10
5M7	SH:Q-1	CORDOVA	8179 MACON RD.	375	384	9
5M8	SH:J-1	GOODMAN	5420 WEAVER RD.	327	334	7
6M1	SH:P-113	WELL LOT 617	3225 RIDGEMONT	519	529	10
7M1	SH:R-31	WELL LOT 700	10320 KENTWOOD EST.	500	540	40

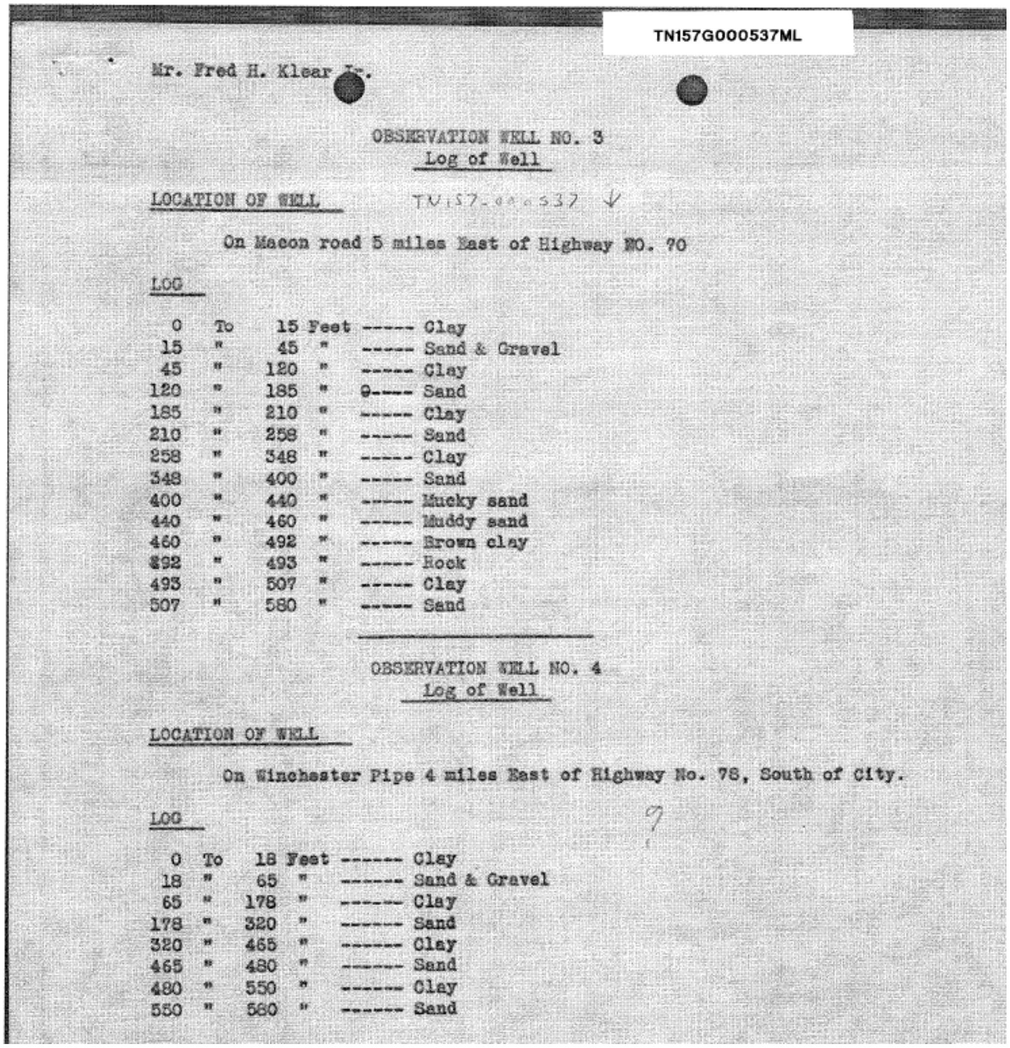
TOTAL WELLS 19

USGS WELLS NOT OWNED BY MLGW

WELL OWNER	USGS NUMBER	WELL LOCATION	WELL ADDRESS	TOP SCREEN	WELL DEPTH	LENGTH SCREEN
USGS	FA:R-2	BRADEN	HWY 59	345	365	20
ERVIN	SH:U-2	SLOANVILLE	SHAKE RAG RD.	360	440	80

TOTAL WELLS 2

Figure 18. Screen lengths of wells, including those used by Criner and Parks (1976).



TN157G000537ML

Mr. Fred H. Klear Jr.

OBSERVATION WELL NO. 3

Log of Well

LOCATION OF WELL TN157-000537 ✓

On Macon road 5 miles East of Highway NO. 70

LOG

0	To	15	Feet	----- Clay
15	"	45	"	----- Sand & Gravel
45	"	120	"	----- Clay
120	"	185	"	9---- Sand
185	"	210	"	----- Clay
210	"	258	"	----- Sand
258	"	348	"	----- Clay
348	"	400	"	----- Sand
400	"	440	"	----- Mucky sand
440	"	460	"	----- Muddy sand
460	"	492	"	----- Brown clay
492	"	493	"	----- Rock
493	"	507	"	----- Clay
507	"	580	"	----- Sand

OBSERVATION WELL NO. 4

Log of Well

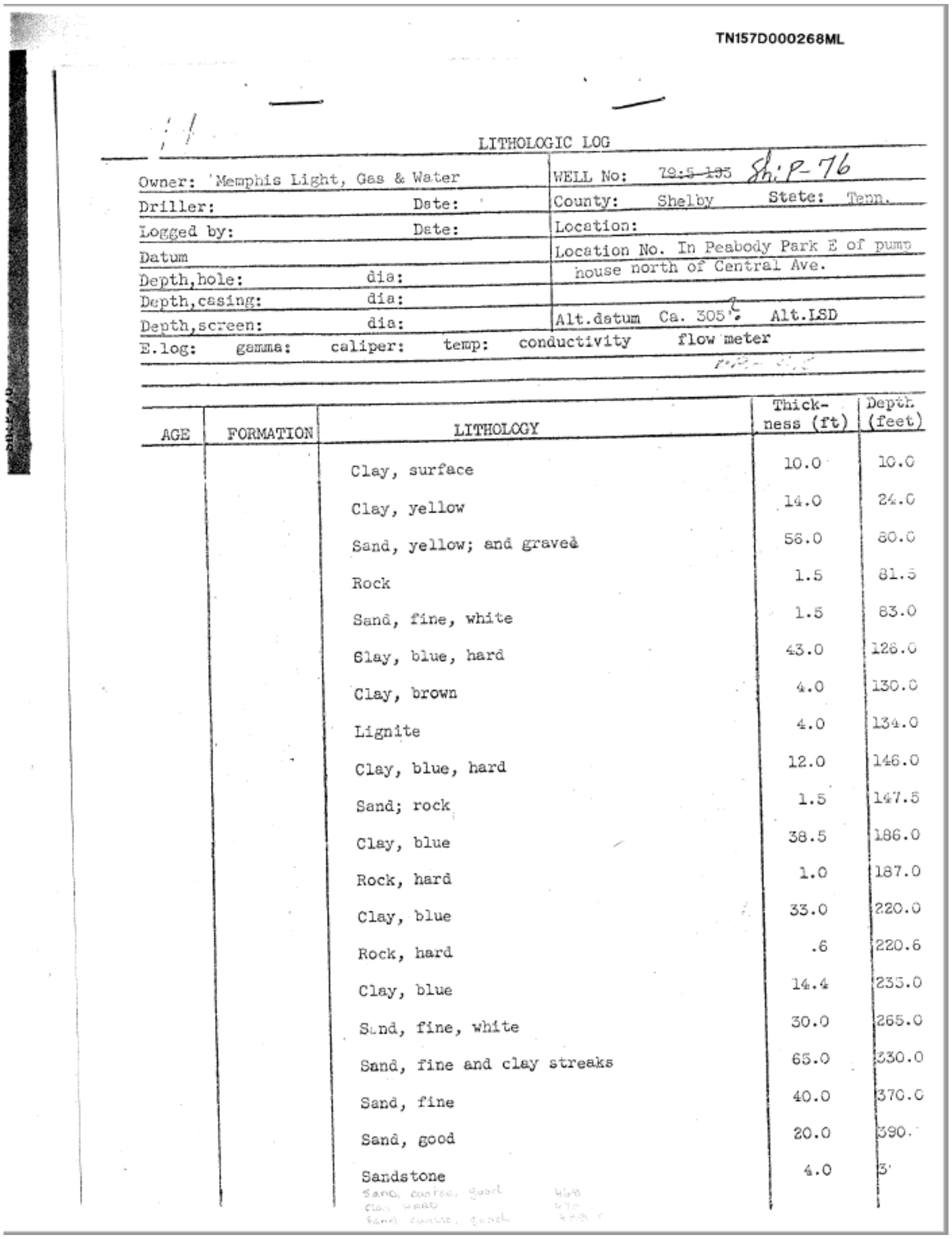
LOCATION OF WELL

On Winchester Pipe 4 miles East of Highway No. 78, South of City.

LOG ?

0	To	18	Feet	------ Clay
18	"	65	"	------ Sand & Gravel
65	"	178	"	------ Clay
178	"	320	"	------ Sand
320	"	465	"	------ Clay
465	"	480	"	------ Sand
480	"	550	"	------ Clay
550	"	580	"	------ Sand

Figure 19. Only available information for Sh:Q-001, which is a driller's log (above) and a geophysical log, available at CAESER or USGS.



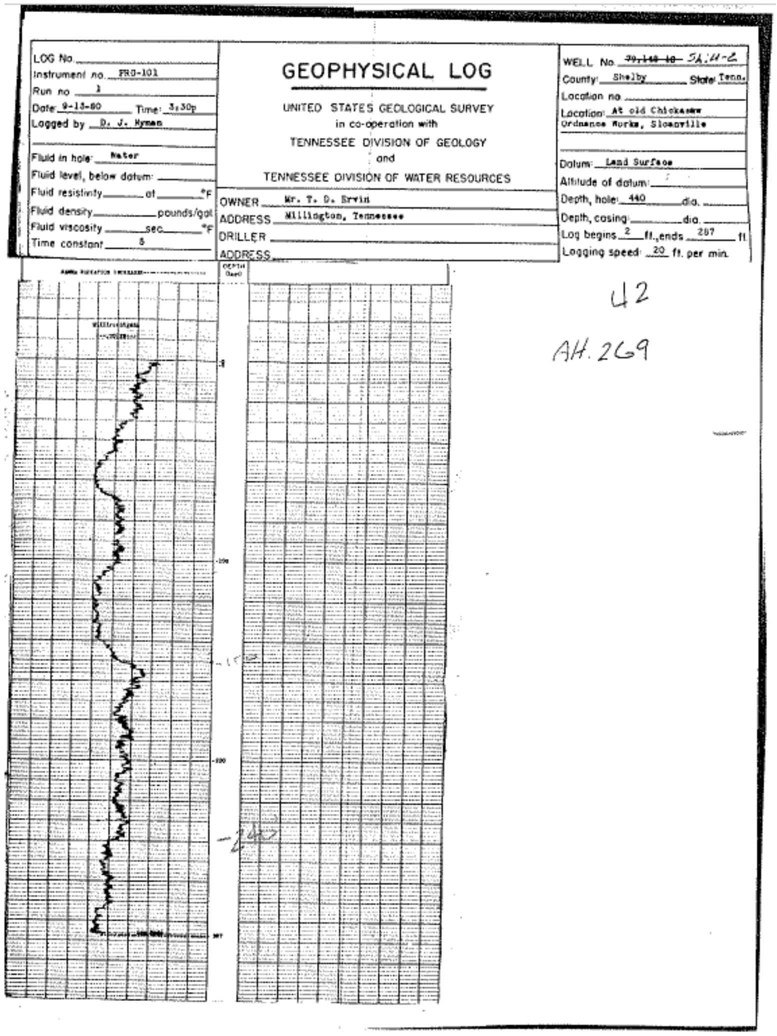
TN157D000268ML

LITHOLOGIC LOG

Owner: Memphis Light, Gas & Water
WELL No: ~~79:5-135~~ Sh:P-76
Driller: Date:
County: Shelby State: Tenn.
Logged by: Date:
Location:
Datum
Location No. In Peabody Park E of pump house north of Central Ave.
Depth, hole: dia:
Depth, casing: dia:
Depth, screen: dia:
Alt. datum Ca. 305'? Alt. LSD
E.log: gamma: caliper: temp: conductivity flow meter

AGE	FORMATION	LITHOLOGY	Thick-ness (ft)	Depth (feet)
		Clay, surface	10.0	10.0
		Clay, yellow	14.0	24.0
		Sand, yellow; and gravel	56.0	80.0
		Rock	1.5	81.5
		Sand, fine, white	1.5	83.0
		Clay, blue, hard	43.0	126.0
		Clay, brown	4.0	130.0
		Lignite	4.0	134.0
		Clay, blue, hard	12.0	146.0
		Sand; rock	1.5	147.5
		Clay, blue	38.5	186.0
		Rock, hard	1.0	187.0
		Clay, blue	33.0	220.0
		Rock, hard	.6	220.6
		Clay, blue	14.4	235.0
		Sand, fine, white	30.0	265.0
		Sand, fine and clay streaks	65.0	330.0
		Sand, fine	40.0	370.0
		Sand, good	20.0	390.
		Sandstone	4.0	3'
		Sand, coarse, good		468
		Clay, hard		470
		Sand, coarse, good		478

Figure 20. Only available information for Sh:P-076, which is a driller's log (above) and a geophysical log, available at CAESER or USGS.



LOG No. ____
Instrument no. FRO-101
Run no 1
Date 9-13-80 Time: 3:30p
Logged by D. J. Hyman

Fluid in hole: Water
Fluid level, below datum: ____
Fluid resistivity ____ at ____ °F
Fluid density ____ pounds/gal
Fluid viscosity ____ sec ____ °F
Time constant 5

GEOPHYSICAL LOG

UNITED STATES GEOLOGICAL SURVEY
in co-operation with
TENNESSEE DIVISION OF GEOLOGY
and
TENNESSEE DIVISION OF WATER RESOURCES

OWNER Mr. T. D. Ervin
ADDRESS Millington, Tennessee
DRILLER ____
ADDRESS ____

WELL No. ~~79,148-18~~ Sh:U-2
County: Shelby State: Tenn.
Location no. ____
Location: At old Chickasaw Ordnance Works, Sloanville

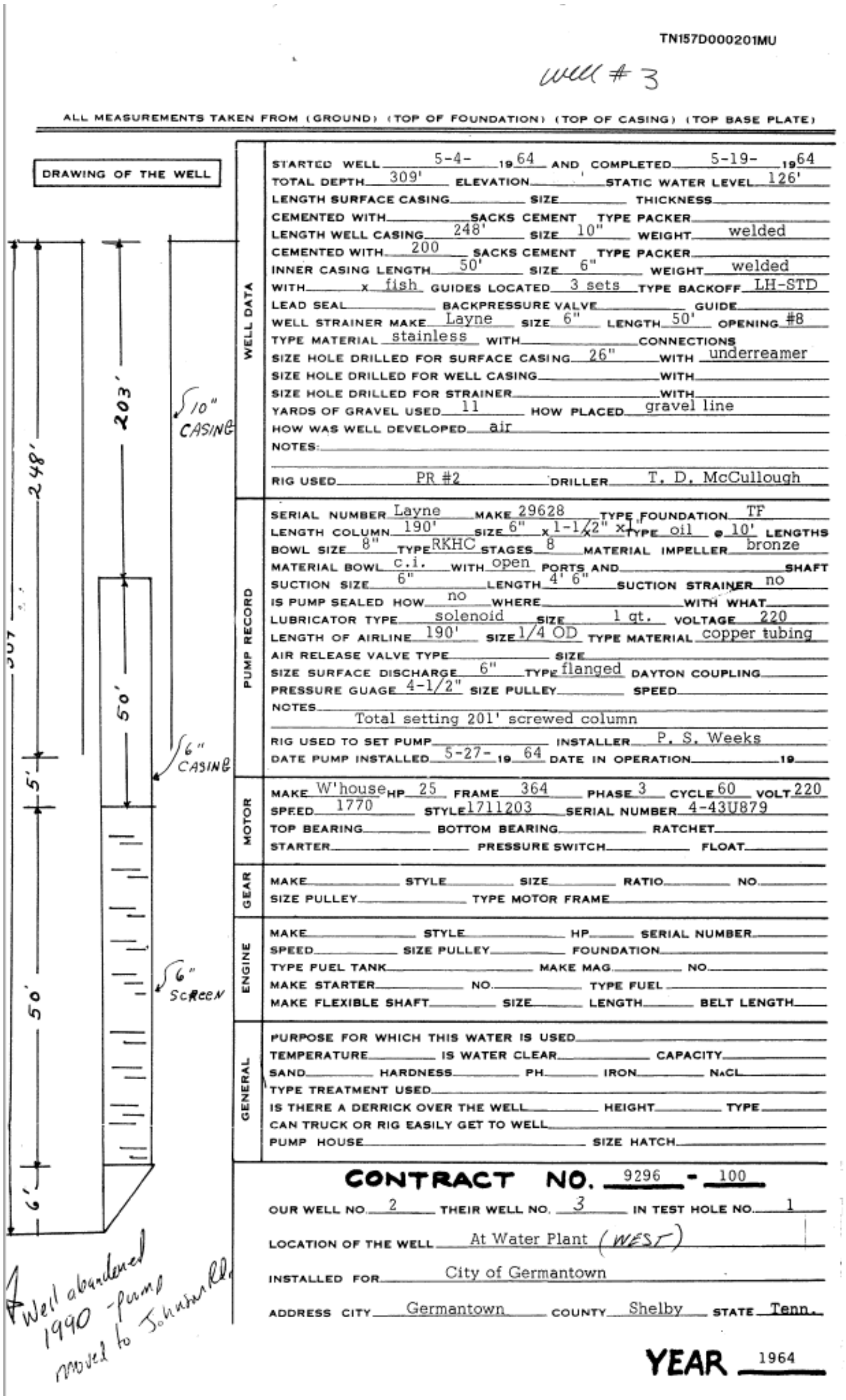
Datum: Land Surface
Altitude of datum: ____
Depth, hole: 440 dia. ____
Depth, casing: ____ dia. ____
Log begins 2 ft., ends 287 ft.
Logging speed: 20 ft. per min.

42

AH. 269

Figure 21. Only available information for Sh:U-002 (geophysical log).

43. An example of a construction log is shown in Figure 22 for Sh:L-010, used by Criner and Parks (1976) in developing their potentiometric surfaces of the Middle Claiborne for the years 1960, 1970, and 1975 (not predevelopment). Note that the 6-inch screen (Layne with #8 opening) has a length of 50 ft, a length Spruill expresses he believes to be invalid for developing water level maps.



TN157D000201MU

well # 3

ALL MEASUREMENTS TAKEN FROM (GROUND) (TOP OF FOUNDATION) (TOP OF CASING) (TOP BASE PLATE)

DRAWING OF THE WELL

WELL DATA

STARTED WELL 5-4- 19 64 AND COMPLETED 5-19- 19 64
TOTAL DEPTH 309' ELEVATION ____ STATIC WATER LEVEL 126'
LENGTH SURFACE CASING ____ SIZE ____ THICKNESS ____
CEMENTED WITH ____ SACKS CEMENT TYPE PACKER ____
LENGTH WELL CASING 248' SIZE 10" WEIGHT welded
CEMENTED WITH 200 SACKS CEMENT TYPE PACKER ____
INNER CASING LENGTH 50' SIZE 6" WEIGHT welded
WITH ____ x fish GUIDES LOCATED 3 sets TYPE BACKOFF LH-STD
LEAD SEAL ____ BACKPRESSURE VALVE ____ GUIDE ____
WELL STRAINER MAKE Layne SIZE 6" LENGTH 50' OPENING #8
TYPE MATERIAL stainless WITH ____ CONNECTIONS
SIZE HOLE DRILLED FOR SURFACE CASING 26" WITH underreamer
SIZE HOLE DRILLED FOR WELL CASING ____ WITH ____
SIZE HOLE DRILLED FOR STRAINER ____ WITH ____
YARDS OF GRAVEL USED 11 HOW PLACED gravel line
HOW WAS WELL DEVELOPED air
NOTES: ____
RIG USED PR #2 DRILLER T. D. McCullough

PUMP RECORD

SERIAL NUMBER Layne MAKE 29628 TYPE FOUNDATION TF
LENGTH COLUMN 190' SIZE 6" x 1-1/2" x 1" TYPE oil @ 10' LENGTHS
BOWL SIZE 8" TYPE RKHC STAGES 8 MATERIAL IMPELLER bronze
MATERIAL BOWL c.i. WITH open PORTS AND ____ SHAFT
SUCTION SIZE 6" LENGTH 4' 6" SUCTION STRAINER no
IS PUMP SEALED HOW no WHERE ____ WITH WHAT ____
LUBRICATOR TYPE solenoid SIZE 1 qt. VOLTAGE 220
LENGTH OF AIRLINE 190' SIZE 1/4 OD TYPE MATERIAL copper tubing
AIR RELEASE VALVE TYPE ____ SIZE ____
SIZE SURFACE DISCHARGE 6" TYPE flanged DAYTON COUPLING ____
PRESSURE GUAGE 4-1/2" SIZE PULLEY ____ SPEED ____
NOTES Total setting 201' screwed column
RIG USED TO SET PUMP ____ INSTALLER P. S. Weeks
DATE PUMP INSTALLED 5-27- 19 64 DATE IN OPERATION ____ 19 ____

MOTOR

MAKE W'house HP 25 FRAME 364 PHASE 3 CYCLE 60 VOLT 220
SPEED 1770 STYLE 1711203 SERIAL NUMBER 4-43U879
TOP BEARING ____ BOTTOM BEARING ____ RATCHET ____
STARTER ____ PRESSURE SWITCH ____ FLOAT ____

GEAR

MAKE ____ STYLE ____ SIZE ____ RATIO ____ NO. ____
SIZE PULLEY ____ TYPE MOTOR FRAME ____

ENGINE

MAKE ____ STYLE ____ HP ____ SERIAL NUMBER ____
SPEED ____ SIZE PULLEY ____ FOUNDATION ____
TYPE FUEL TANK ____ MAKE MAG ____ NO. ____
MAKE STARTER ____ NO. ____ TYPE FUEL ____
MAKE FLEXIBLE SHAFT ____ SIZE ____ LENGTH ____ BELT LENGTH ____

GENERAL

PURPOSE FOR WHICH THIS WATER IS USED ____
TEMPERATURE ____ IS WATER CLEAR ____ CAPACITY ____
SAND ____ HARDNESS ____ PH ____ IRON ____ NACL ____
TYPE TREATMENT USED ____
IS THERE A DERRICK OVER THE WELL ____ HEIGHT ____ TYPE ____
CAN TRUCK OR RIG EASILY GET TO WELL ____
PUMP HOUSE ____ SIZE HATCH ____

CONTRACT NO. 9296 - 100

OUR WELL NO. 2 THEIR WELL NO. 3 IN TEST HOLE NO. 1
LOCATION OF THE WELL At Water Plant (WEST)
INSTALLED FOR City of Germantown
ADDRESS CITY Germantown COUNTY Shelby STATE Tenn.

YEAR 1964

Well abandoned 1990 - pump moved to Johnson Rd.

Figure 22. Construction log for Sh:L-010.

Validating Wells' Placement in the Middle Claiborne

44. Spruill argues that well depths derived from the USGS publications used by W&L are insufficient to actually show that each well tapped into the Middle Claiborne and not some other aquifer. However, W&L carefully checked their well depths against the available data to ensure that each well was in fact in the Middle Claiborne.

45. With the exception of Well #14 in Rossville, Tennessee, every single well mapped by W&L had a known well depth, and that well depth was checked against known well/geotechnical/exploratory boring logs housed at the University of Memphis' Center for Applied Earth Science and Engineering Research. These log records may consist in part or whole of geophysical logs, driller's logs, geologist logs, construction logs, and reports. In the geographical extent of the wells used by W&L in construction of predevelopment conditions, there are 11,551 possible control logs that could be used (Figure 23). Those closest to the predevelopment data points were investigated to ascertain that the wells were in fact screened in the Middle Claiborne. In the case of Well #14, a geologic description of the drilling was provided by Glen (1906) as passing below a clay layer and being screened in a white sand (a description common to the Middle Claiborne).

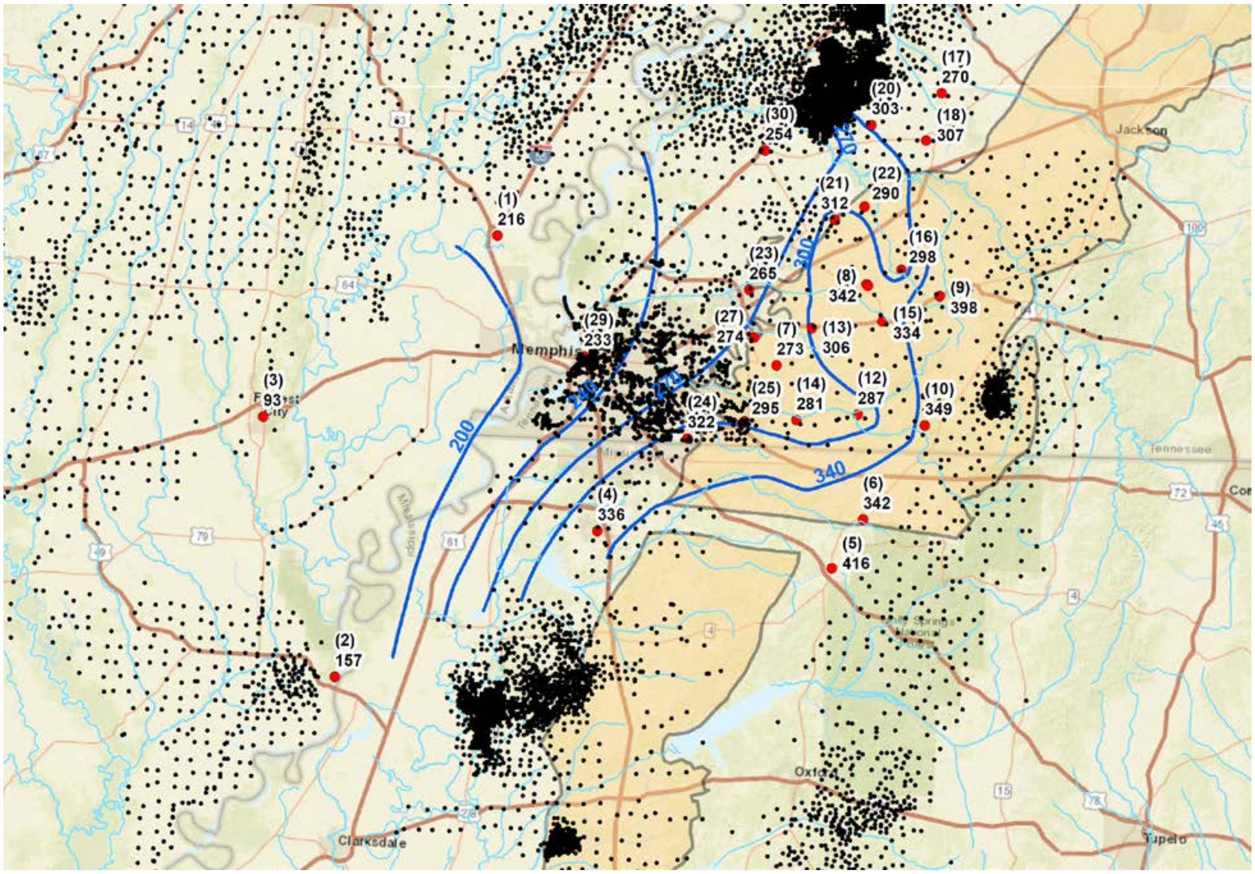


Figure 23. Location of 11,551 well records at the Center for Applied Earth Science and Engineering Research at the University of Memphis in the vicinity of the W&L study area.

Materials Considered

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