No. 143, Original

IN THE
Supreme Court of the United States

STATE OF MISSISSIPPI,
Plaintiff,
v.

STATE OF TENNESSEE, CITY OF MEMPHIS, TENNESSEE,
AND MEMPHIS LIGHT, GAS & WATER DIVISION,
Defendants.

On Bill of Complaint
Before the Special Master, Hon. Eugene E. Siler, Jr.

EXHIBITS IN SUPPORT OF MOTION OF DEFENDANTS STATE OF TENNESSEE, CITY OF MEMPHIS, AND MEMPHIS LIGHT, GAS & WATER DIVISION FOR SUMMARY JUDGMENT

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June 1, 2018

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3	Excerpts from Expert Report of Steven P. Larson (June 30, 2017)
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10	J.E. Reed, Analog Simulation of Water-Level Declines in the Sparta Sand, Mississippi Embayment (1972)
11	Excerpts from J. Kerry Arthur and Richard E. Taylor, Ground-Water Flow Analysis of the Mississippi Embayment Aquifer System, South-Central United States: Regional Aquifer System Analysis – Gulf Coastal Plain (1998)
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18	Excerpts from The State of Mississippi’s Responses to City Of Memphis, Tennessee, and Memphis Light, Gas & Water Division’s First Set of Request for Admissions (Jan. 20, 2017)

Exhibit 1

Potentiometric Surface in the Sparta-
Memphis Aquifer of the Mississippi
Embayment, Spring 2007
By T.P. Schrader

(2008)

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
U.S. GEOLOGICAL SURVEY GROUND-WATER RESOURCES PROGRAM, ARKANSAS NATURAL RESOURCES COMMISSION, ARKANSAS GEOLOGICAL SURVEY, MEMPHIS LIGHT, GAS AND WATER, SHELBY COUNTY, TENNESSEE, AND THE CITY OF GERMANTOWN, TENNESSEE

SCIENTIFIC INVESTIGATIONS MAP 3014
Schrader, T.P., 2007, Sparta-Memphis aquifer—SHEET 1 of 1
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Table 1. Hydrogeologic units and their correlation across the states within the Mississippi embayment.

ERATHEM	SYSTEM	SERIES	GROUP	LOUISIANA	ARKANSAS Southern	ARKANSAS Northeastern	MISSOURI	KENTUCKY	TENNESSEE	MISSISSIPPI	ALABAMA	Hydrogeologic units
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	TERTIARY	OLIGOCENE	Vicksburg Group	Vicksburg Formation	Not present in study area					Vicksburg Formation		Vicksburg-Jackson confining unit
		EOCENE	Jackson Group	Jackson Group								
			Claiborne Group	Cockfield Formation							Gosport Sand	Upper Claiborne aquifer
				Cook Mountain Formation								Middle Claiborne confining unit
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				Cane River Formation				Tallahatta Formation		Zilpha Clay Winona Sand Tallahatta Formation	Tallahatta Formation	Lower Claiborne confining unit
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Modified from Hosman and Weiss, 1991

Explanation

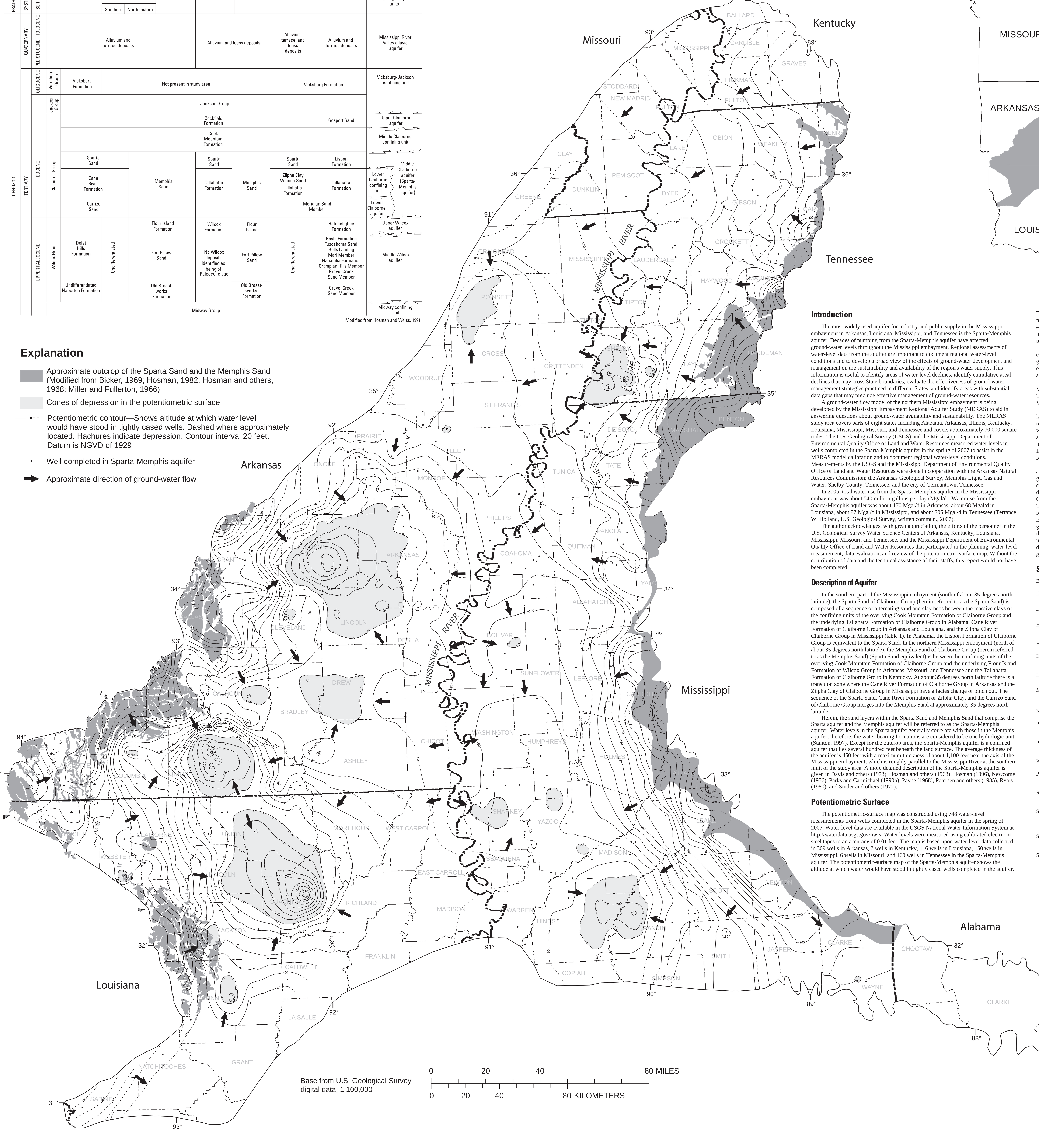
Approximate outcrop of the Sparta Sand and the Memphis Sand (Modified from Bicker, 1969; Hosman, 1982; Hosman and others, 1968; Miller and Fullerton, 1966)

Cones of depression in the potentiometric surface

Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Hachures indicate depression. Contour interval 20 feet. Datum is NGVD of 1929

Well completed in Sparta-Memphis aquifer

Approximate direction of ground-water flow



Study Area

Introduction

The most widely used aquifer for industry and public supply in the Mississippi embayment in Arkansas, Louisiana, Mississippi, and Tennessee is the Sparta-Memphis aquifer. Decades of pumping from the Sparta-Memphis aquifer have affected ground-water levels throughout the Mississippi embayment. Regional assessments of water-level data from the aquifer are important to document regional water-level conditions and to develop a broad view of the effects of ground-water development and management on the sustainability and availability of the region's water supply. This information is useful to identify areas of water-level declines, identify cumulative areal declines that may cross State boundaries, evaluate the effectiveness of ground-water management strategies practiced in different States, and identify areas with substantial data gaps that may preclude effective management of ground-water resources.

A ground-water flow model of the northern Mississippi embayment is being developed by the Mississippi Embayment Regional Aquifer Study (MERAS) to aid in answering questions about ground-water availability and sustainability. The MERAS study area covers parts of eight states including Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee and covers approximately 70,000 square miles. The U.S. Geological Survey (USGS) and the Mississippi Department of Environmental Quality Office of Land and Water Resources measured water levels in wells completed in the Sparta-Memphis aquifer in the spring of 2007 to assist in the MERAS model calibration and to document regional water-level conditions. Measurements by the USGS and the Mississippi Department of Environmental Quality Office of Land and Water Resources were done in cooperation with the Arkansas Natural Resources Commission; the Arkansas Geological Survey; Memphis Light, Gas and Water; Shelby County, Tennessee; and the city of Germantown, Tennessee.

In 2005, total water use from the Sparta-Memphis aquifer in the Mississippi embayment was about 540 million gallons per day (Mgal/d). Water use from the Sparta-Memphis aquifer was about 170 Mgal/d in Arkansas, about 68 Mgal/d in Louisiana, about 97 Mgal/d in Mississippi, and about 205 Mgal/d in Tennessee (Terrance W. Holland, U.S. Geological Survey, written commun., 2007).

The author acknowledges, with great appreciation, the efforts of the personnel in the U.S. Geological Survey Water Science Centers of Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee, and the Mississippi Department of Environmental Quality Office of Land and Water Resources that participated in the planning, water-level measurement, data evaluation, and review of the potentiometric-surface map. Without the contribution of data and the technical assistance of their staffs, this report would not have been completed.

Description of Aquifer

In the southern part of the Mississippi embayment (south of about 35 degrees north latitude), the Sparta Sand of Claiborne Group (herein referred to as the Sparta Sand) is composed of a sequence of alternating sand and clay beds between the massive clays of the confining units of the overlying Cook Mountain Formation of Claiborne Group and the underlying Tallahatta Formation of Claiborne Group in Alabama, Cane River Formation of Claiborne Group in Arkansas and Louisiana, and the Zilpha Clay of Claiborne Group in Mississippi (table 1). In Alabama, the Lisbon Formation of Claiborne Group is equivalent to the Sparta Sand. In the northern Mississippi embayment (north of about 35 degrees north latitude), the Memphis Sand of Claiborne Group (herein referred to as the Memphis Sand) (Sparta Sand equivalent) is between the confining units of the overlying Cook Mountain Formation of Claiborne Group and the underlying Flour Island Formation of Wilcox Group in Arkansas, Missouri, and Tennessee and the Tallahatta Formation of Claiborne Group in Kentucky. At about 35 degrees north latitude there is a transition zone where the Cane River Formation of Claiborne Group in Arkansas and the Zilpha Clay of Claiborne Group in Mississippi have a facies change or pinch out. The sequence of the Sparta Sand, Cane River Formation or Zilpha Clay, and the Carrizo Sand of Claiborne Group merges into the Memphis Sand at approximately 35 degrees north latitude.

Herein, the sand layers within the Sparta Sand and Memphis Sand that comprise the Sparta aquifer and the Memphis aquifer will be referred to as the Sparta-Memphis aquifer. Water levels in the Sparta aquifer generally correlate with those in the Memphis aquifer; therefore, the water-bearing formations are considered to be one hydrologic unit (Stanton, 1997). Except for the outcrop area, the Sparta-Memphis aquifer is a confined aquifer that lies several hundred feet beneath the land surface. The average thickness of the aquifer is 450 feet with a maximum thickness of about 1,100 feet near the axis of the Mississippi embayment, which is roughly parallel to the Mississippi River at the southern limit of the study area. A more detailed description of the Sparta-Memphis aquifer is given in Davis and others (1973), Hosman and others (1968), Hosman (1996), Newcome (1976), Parks and Carmichael (1990b), Payne (1968), Petersen and others (1985), Ryals (1980), and Snider and others (1972).

Potentiometric Surface

The potentiometric-surface map was constructed using 748 water-level measurements from wells completed in the Sparta-Memphis aquifer in the spring of 2007. Water-level data are available in the USGS National Water Information System at http://waterdata.usgs.gov/nwis. Water levels were measured using calibrated electric or steel tapes to an accuracy of 0.01 feet. The map is based upon water-level data collected in 309 wells in Arkansas, 7 wells in Kentucky, 116 wells in Louisiana, 150 wells in Mississippi, 6 wells in Missouri, and 160 wells in Tennessee in the Sparta-Memphis aquifer. The potentiometric-surface map of the Sparta-Memphis aquifer shows the altitude at which water would have stood in tightly cased wells completed in the aquifer. The potentiometric surface is mapped by determining the altitude of the water levels measured in the wells and is represented on the map by contours that connect points of equal water-level altitude. Hydrologic principles, water-use data, and historical information are interpreted with the water-level data to delineate the potentiometric-surface contours.

The general direction of ground-water flow in an aquifer is perpendicular to the contours in the direction of decreasing hydraulic gradient. The natural direction of ground-water flow in the Sparta-Memphis aquifer is toward the axis of the Mississippi embayment (Hosman and others, 1968). The natural direction of flow has been altered in areas by large ground-water withdrawals.

The highest water-level altitude measured was 513 feet above the National Geodetic Vertical Datum of 1929 (sometimes referred to as sea level) in Madison County, Tennessee. The lowest water level measured was 225 feet below the National Geodetic Vertical Datum of 1929 in Ouachita Parish, Louisiana.

Cones of depression in the potentiometric surface usually are caused by moderate to large ground-water withdrawals. The cones of depression alter the flow of ground water towards the center of pumping. When a well is pumped, the water level in and around the well declines, creating a slope or gradient in the potentiometric surface. The gradient alters the natural direction of flow of water in the aquifer towards points of lower water level. When pumping is reduced or stops, the water level recovers to a new equilibrium. In an area with multiple pumping wells, the area of the declining water level expands to form a depression in the ground-water surface composed of multiple cones of depression.

Twenty cones of depressions (generally represented by a series of closed contours) are shown in the potentiometric surface of the Sparta-Memphis aquifer and are shaded in gray on the map. Five locations centered at cities with large withdrawals for public supply and industrial uses have large cones of depression with greater than 40 feet of decline. The large cones of depression are in Jefferson and Union Counties, Arkansas; Ouachita Parish, Louisiana; Rankin County, Mississippi; and Shelby County, Tennessee. The cones of depression in Jefferson and Union Counties, Arkansas, are greater than 100 feet and 80 feet deep, respectively. The cone of depression in Ouachita Parish, Louisiana, is greater than 160 feet deep. The cone of depression in Rankin County, Mississippi, is greater than 40 feet deep. The cone of depression in Shelby County, Tennessee, is greater than 60 feet deep. The remaining 15 depressions are mostly centered near small or intermediate cities where withdrawals have formed a cone of depression less than 40 feet deep. The large withdrawals that caused the cones of depression also alter the natural ground-water flow direction towards the cones of depression.

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POTENTIOMETRIC SURFACE IN THE SPARTA-MEMPHIS AQUIFER OF THE MISSISSIPPI EMBAYMENT, SPRING 2007

By
T.P. Schrader
2008

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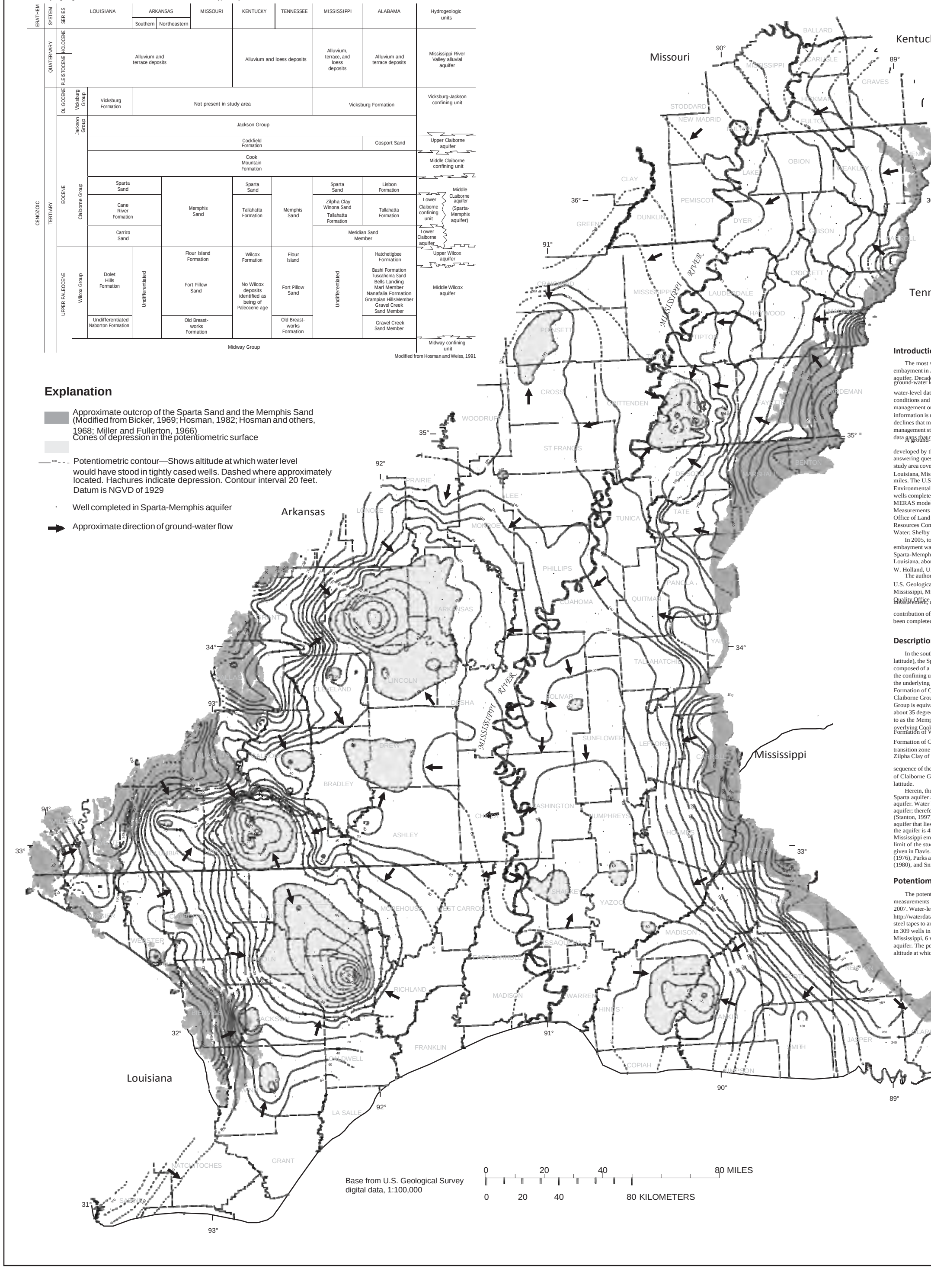

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Twenty cones of depressions (generally represented by a series of closed contours) are shown in the potentiometric surface of the Sparta-Memphis aquifer and are shaded in gray on the map. Five locations centered at cities with large withdrawals for public supply and industrial uses have large cones of depression with greater than 40 feet of decline. The large cones of depression are in Jefferson and Union Counties, Arkansas; Ouachita Parish, Louisiana; Rankin County, Mississippi; and Shelby County, Tennessee. The cones of depression in Jefferson and Union Counties, Arkansas, are greater than 100 feet and 80 feet deep, respectively. The cone of depression in Ouachita Parish, Louisiana, is greater than 160 feet deep. The cone of depression in Rankin County, Mississippi, is greater than 40 feet deep. The cone of depression in Shelby County, Tennessee, is greater than 60 feet deep. The remaining 15 depressions are mostly centered near small or intermediate cities where withdrawals have formed a cone of depression less than 40 feet deep. The large withdrawals that caused the cones of depression also alter the natural ground-water flow direction towards the cones of depression.

Selected References

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POTENTIOMETRIC SURFACE IN THE SPARTA-MEMPHIS AQUIFER OF THE MISSISSIPPI EMBAYMENT, SPRING 2007
By
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2008

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Exhibit 2

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

(June 30, 2017)

Expert Report of Brian Waldron, Ph.D.

Prepared on Behalf of the State of Tennessee

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

June 30, 2017

Signed: B

Brian Waldron, Ph.D.

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

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

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

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

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

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

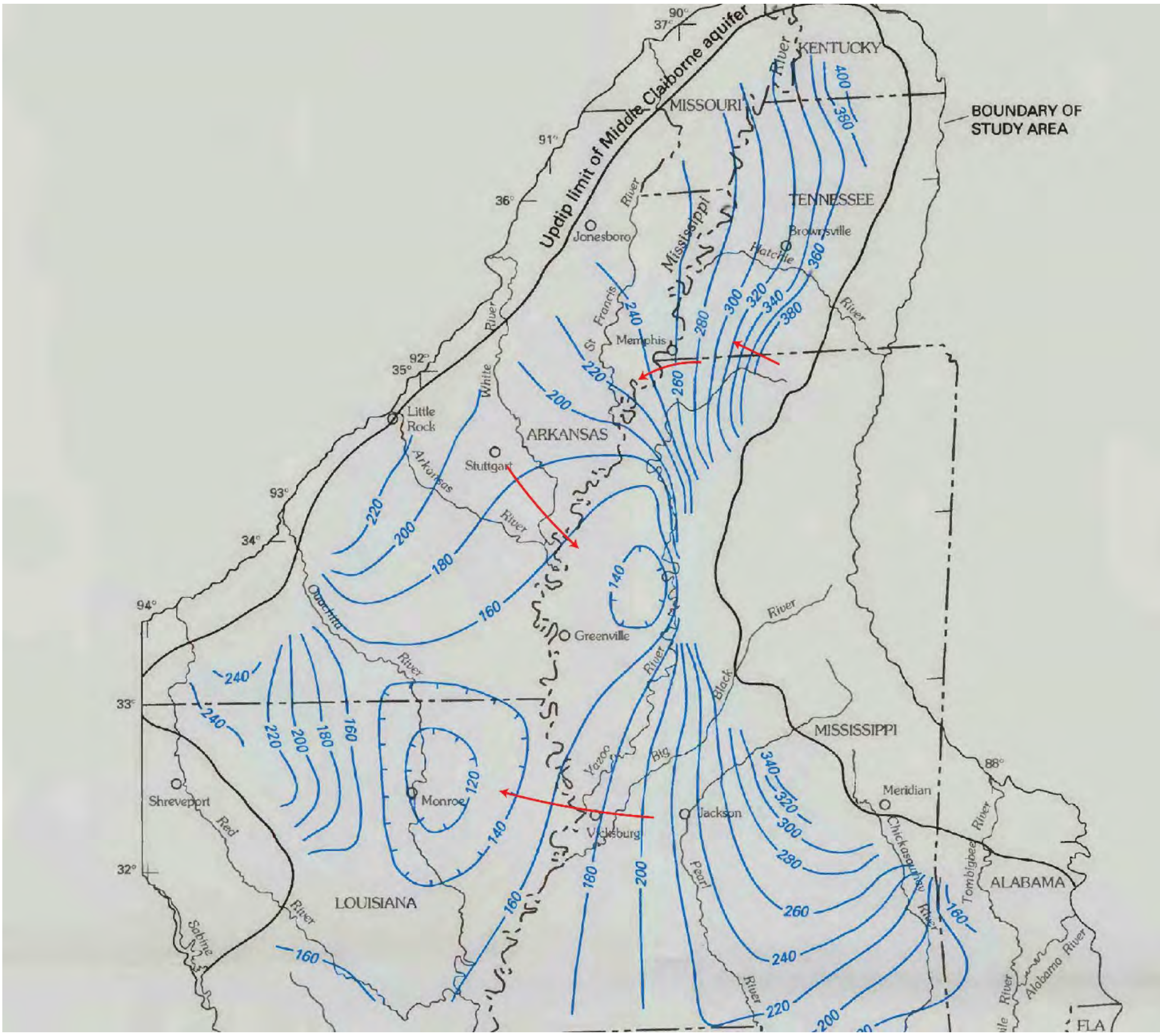


Figure 4. Illustration of predevelopment groundwater conditions in the Middle Claiborne aquifer (Arthur and Taylor, 1998). Red arrows are drawn atop the original report figure to illustrate groundwater flow direction as taken perpendicular to head contours.

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

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

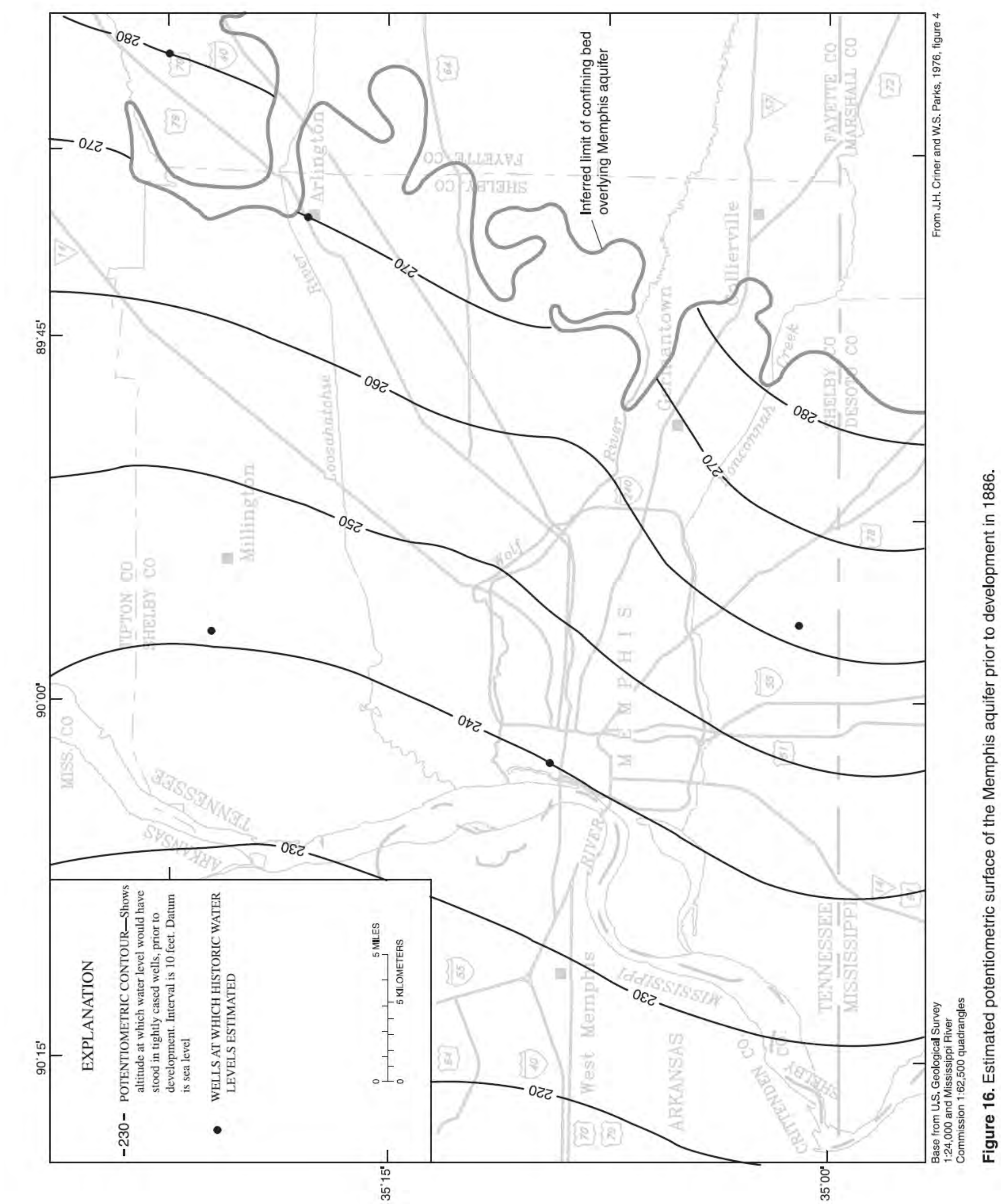


Figure 5. Reproduction of the Criner and Parks (1976) predevelopment condition of the Middle Claiborne aquifer.

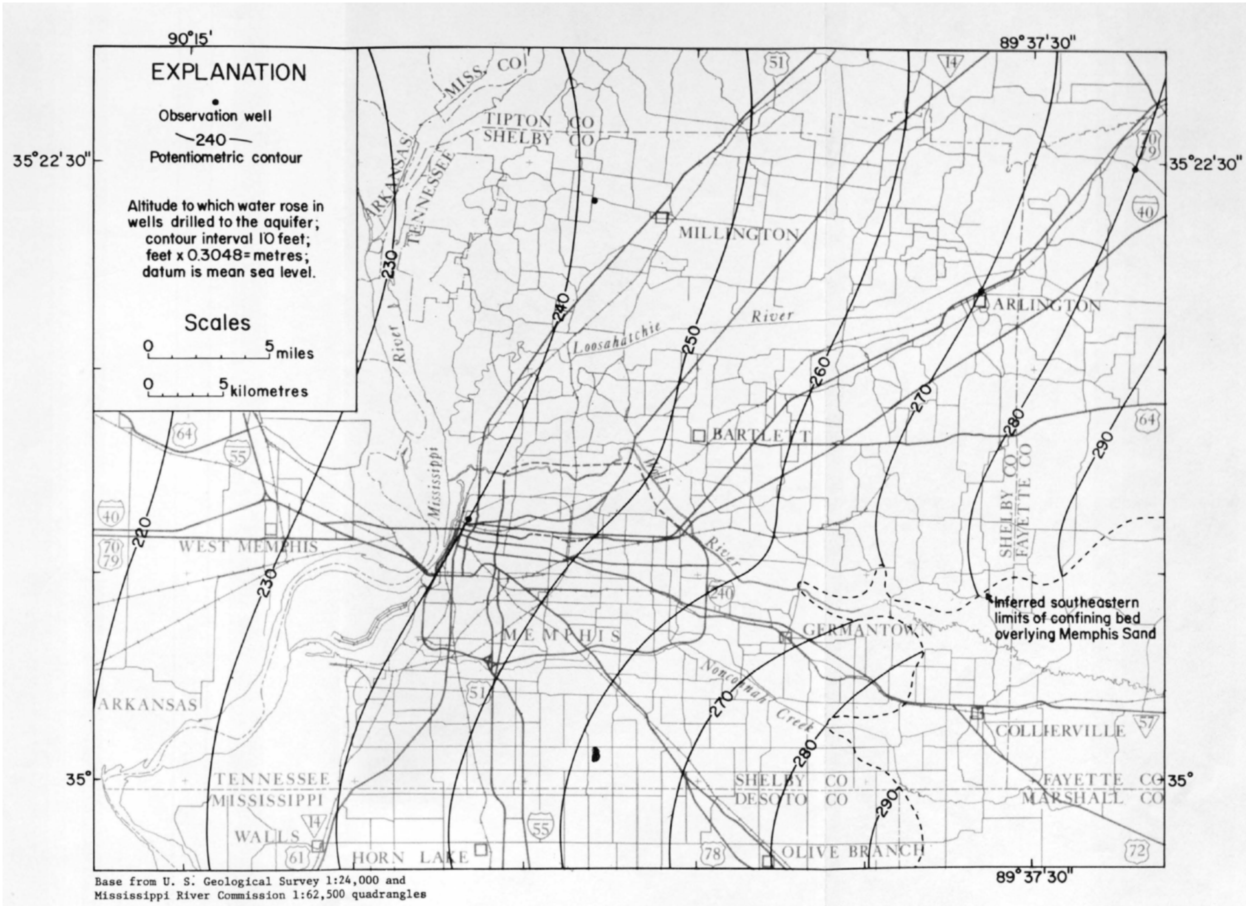


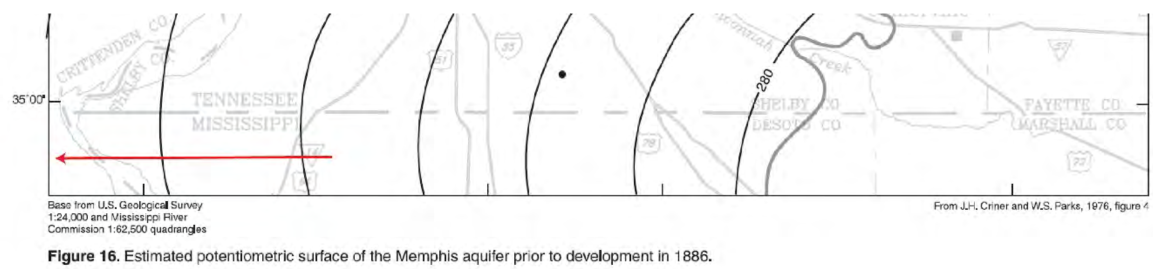
Figure 6. Reproduction of the Criner and Parks (1976) predevelopment condition of the Middle Claiborne aquifer.

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

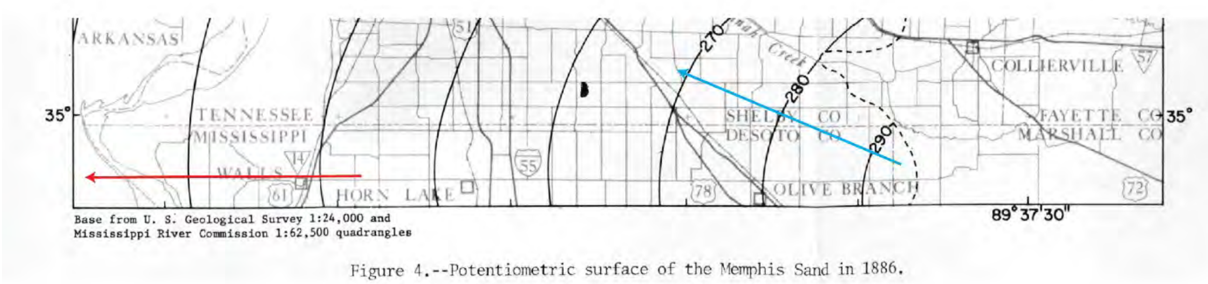
[12] Further, note that the figure used by Mississippi (Figure 8, below) does not actually match the figures from either Brahana and Broshears (2001) or Criner and Parks (1976), although Mississippi asserts that it derives its figure from Brahana and Broshears (2001), which in turn derived it from Criner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

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

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



(a)



(b)

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

70a

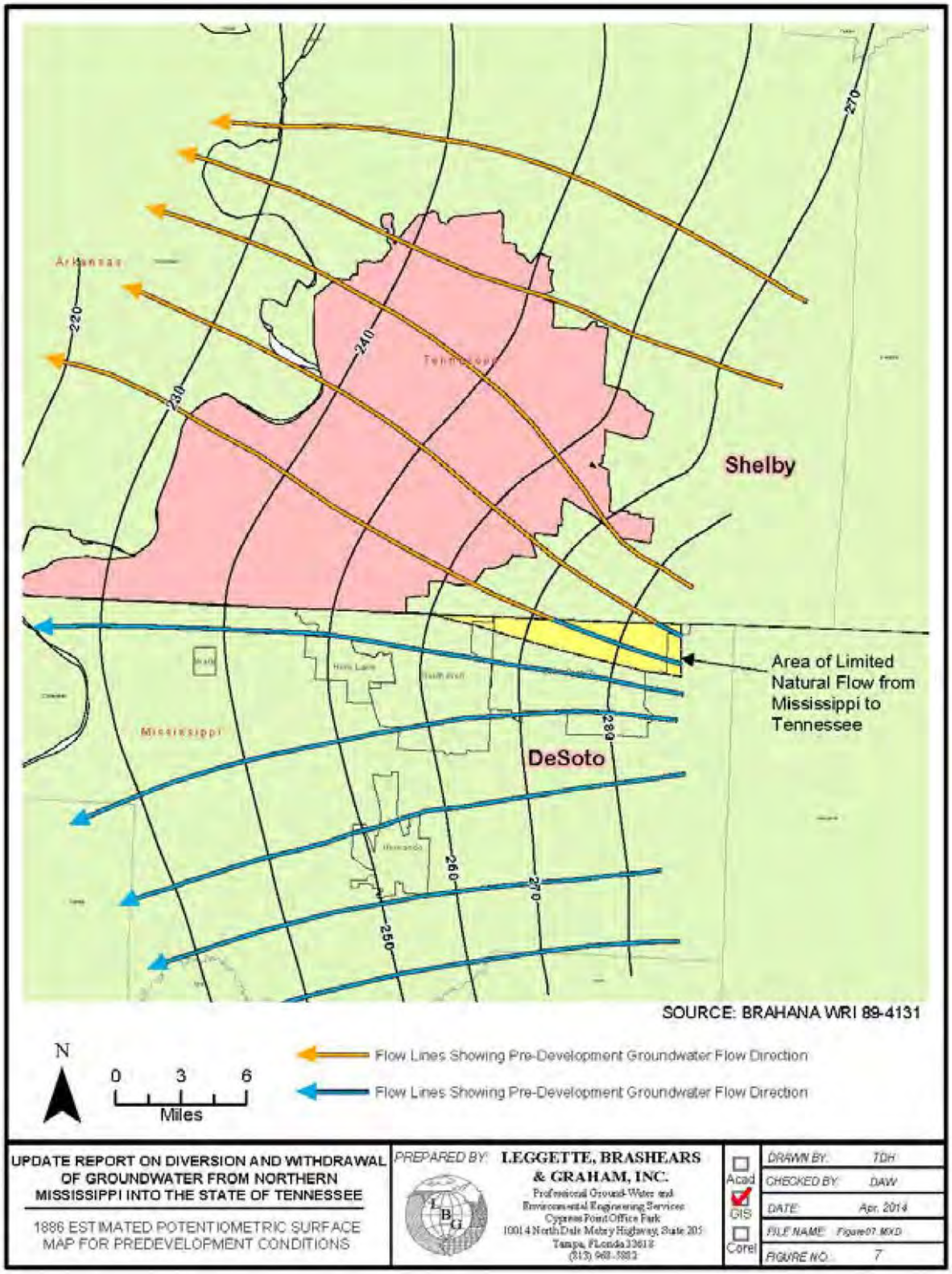


Figure 8. Reproduction of State of Mississippi's Appendix A, 70a figure (Appendix *Figure 7*) depicting predevelopment groundwater conditions including flow direction.

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

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

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

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

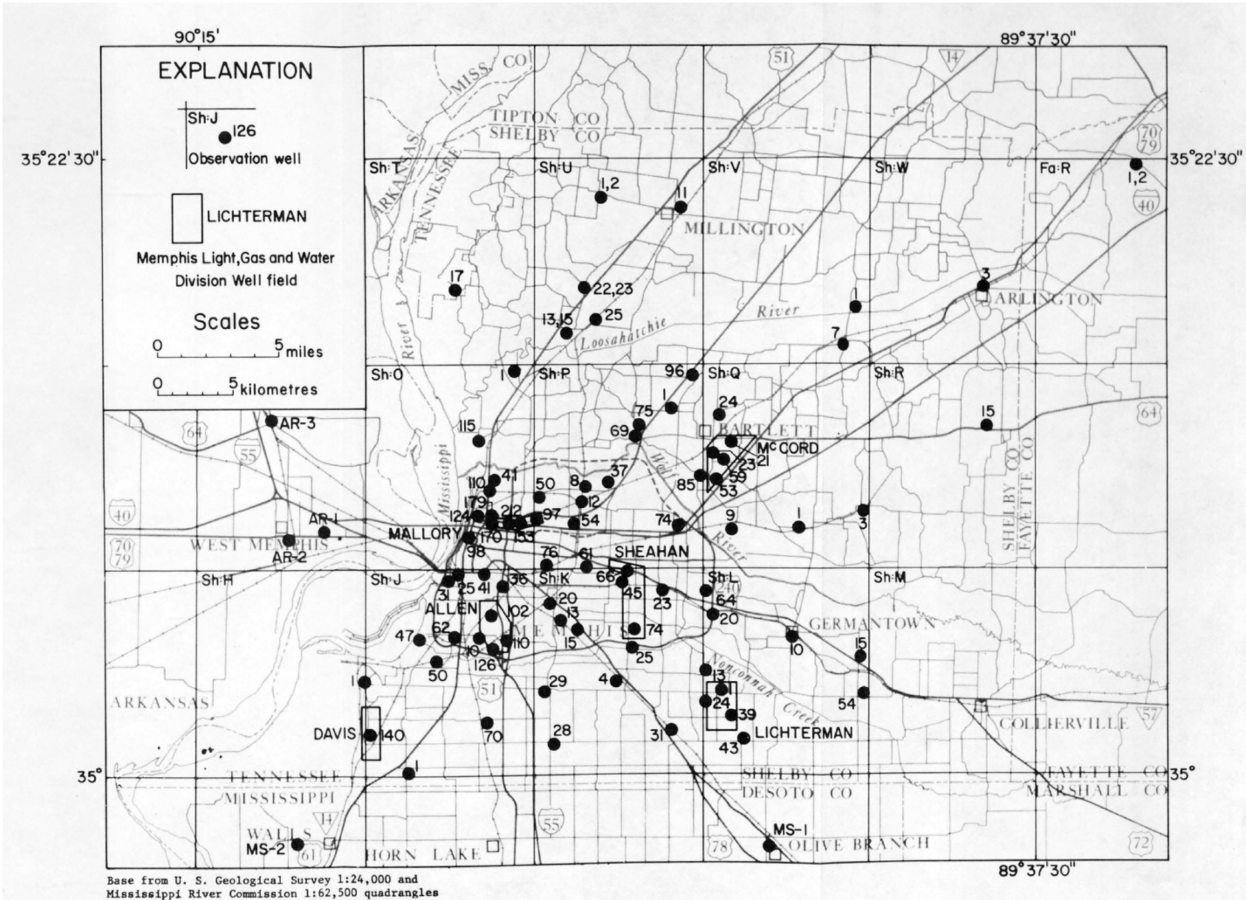
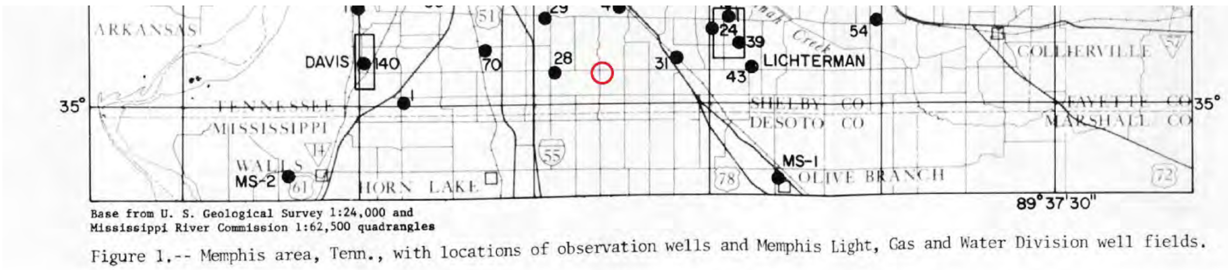
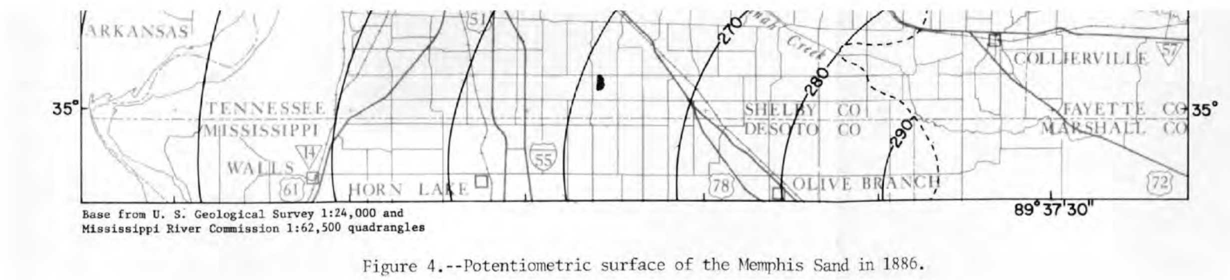


Figure 1.-- Memphis area, Tenn., with locations of observation wells and Memphis Light, Gas and Water Division well fields.

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



(a)



(b)

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

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

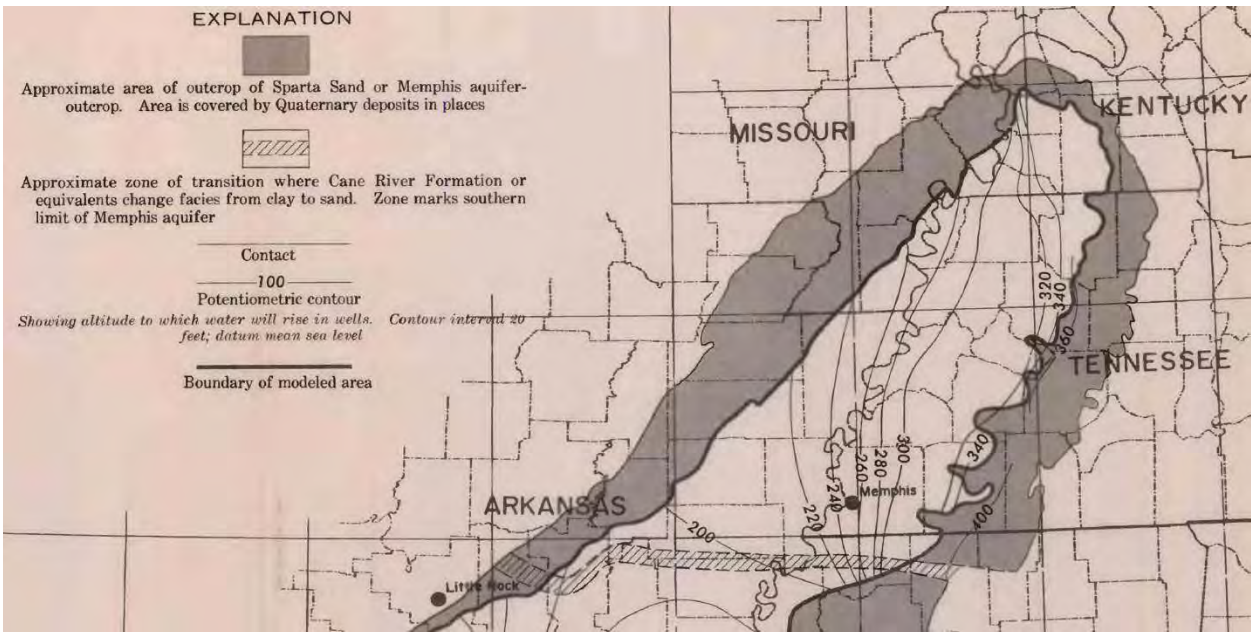


Figure 11. Excerpt of Reed (1972) *Plate 1* showing predevelopment conditions along the Tennessee-Mississippi state line.

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

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

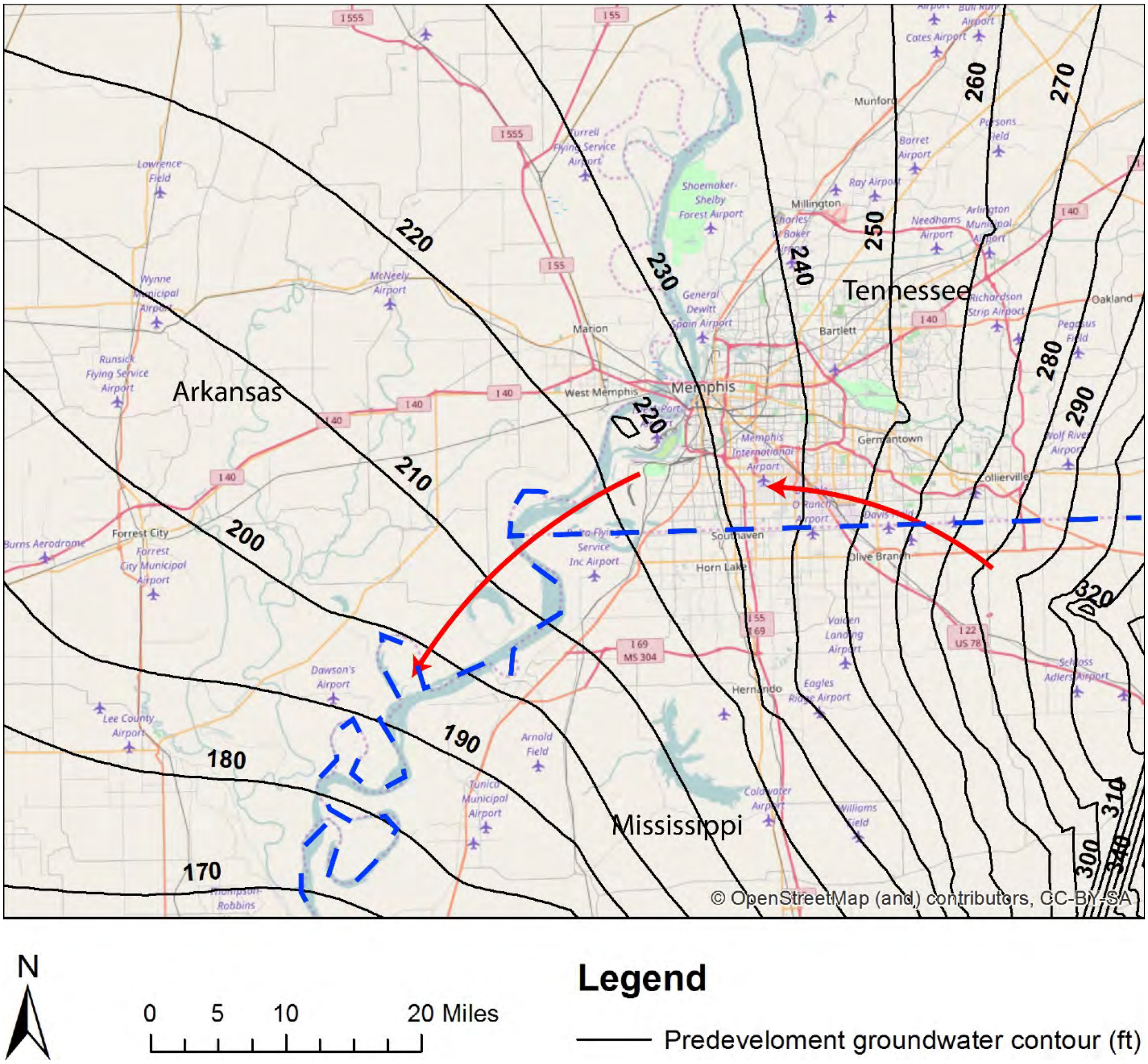


Figure 12. Resulting groundwater predevelopment conditions derived from output from MERAS model (Clark and Hart, 2009). Red arrows have been overlaid to numerically indicate groundwater flow direction and blue hatched line approximates state line boundaries.

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

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

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

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

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

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

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

Exhibit 3

Excerpts from
Expert Report of Steven P. Larson
(June 30, 2017)

Expert Report of Steven P. Larson

No. 143, Original

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

S.S. PAPADOPULOS & ASSOCIATES, INC.
Environmental & Water-Resource Consultants

June 30, 2017

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

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

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

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

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

Opinion 3. The groundwater within the Middle Claiborne aquifer under Mississippi is an interstate water resource because, under any reasonable assumptions, none of the groundwater beneath Mississippi, under current or historical conditions, would remain permanently within Mississippi's territory.

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

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

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

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

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

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

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

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

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

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

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

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

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

and "(t)he goal of the MERAS model was to develop a model capable of suitable accuracy at regional scales" (Clark and Hart, 2009 at 56). Also, "(a)lthough the MERAS model may not represent each local-scale detail, it is relevant for a better understanding of the regional flow system" (Clark and Hart, 2009 at 56).

62. As another USGS publication, looking at the potentiometric surface of the Middle Claiborne aquifer, stated: "Regional assessments of water-level data from the aquifer are important to document regional water-level conditions and to develop a broad view of the effects of ground-water development and management on the sustainability and availability of the region's water supply" (Schrader, 2008). The study continued: "This information is useful to identify areas of water-level declines, **identify cumulative areal declines that may cross State boundaries**, **evaluate the effectiveness of ground-water management strategies practiced in different States**, and identify areas with substantial data gaps that may preclude effective management of ground-water resources" (Schrader, 2008) (emphasis supplied). In other words, the USGS views the water in the Middle Claiborne aquifer as a regional or interstate resource that requires interstate study and, ultimately, interstate management.

63. Other USGS studies and papers have also recognized that the Middle Claiborne aquifer is a single interstate resource. For example, between 1990 and 1992, the USGS undertook a study of leakage in the Middle Claiborne and Fort Pillow aquifers in the Memphis area, which included parts of Mississippi and Arkansas (Kingsbury and Parks, 1993).

64. Indeed, the USGS has recognized the interstate nature of the Middle Claiborne, and the importance of treating it as an interstate resource, for the better part of a century. In one USGS water supply paper, Bell and Nyman (1968) recognized that the Middle Claiborne was a continuous water source under Mississippi, Tennessee, and Arkansas (Bell and Nyman, 1968 at 4). In another USGS paper, Cushing et al. (1964) recognized that many prior studies had been "restricted to local areas," and "they do not treat the subject of water resources on a regional basis," particularly with respect to the "vast aquifers" that "cross State boundaries and are of regional importance" (Cushing et al., 1964 at B1). The paper continued: "Proper development, use, and conservation of the water resources can be achieved only through an understanding of the regional geologic environment and its influence on the response of the hydrologic system to climate and to water-supply development" (Cushing et al., 1964 at B1). Still earlier USGS papers also treated the Middle Claiborne on a multistate basis, considering even just the "Memphis area," for purposes of the aquifer, to contain parts of Arkansas and Mississippi (Criner and Armstrong, 1958 at 1). Even earlier, some of the investigations recognized that the aquifers of western Tennessee and northern Mississippi were parts of the same aquifer (Stephenson, 1928; Wells et al., 1933).

65. In sum, the USGS has long recognized that the Middle Claiborne aquifer is an interstate resource, and for at least half a century has been explicitly focused on ensuring that the Middle Claiborne aquifer is studied and managed on a regional, multistate basis. Based on the expertise of the USGS and its status as the leading federal agency in the evaluation of water resources, this current and historical recognition lends further support to my conclusion that the aquifer is an interstate water resource.

Exhibit 4

Excerpts from
Expert Report of David E. Langseth on the
Interstate Nature of the Memphis/Sparta
Sand Aquifer
(June 27, 2017)

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

Volume 1 of 2: Report Text

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

in the matter of

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Exhibit 5

Excerpts from
Update Report on Diversion and Withdrawal of Groundwater from Northern Mississippi into the State of Tennessee (expert report of David Wiley)
(June 30, 2017)

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

Prepared For:

Jim Hood, Attorney General of the State of Mississippi

June 30, 2017

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BACKGROUND

The primary source of fresh water supply for most of northwest Mississippi and the Memphis, Tennessee areas is the deep confined Sparta Sand formation, referred to as the Memphis Sand in Tennessee within the Claiborne Geological Group. The confined Sparta Sand formation beneath northwest Mississippi and southwest Tennessee is a discrete geological formation which has existed for thousands of years. Since its formation, a significant but not unlimited quantity of high quality groundwater was collected and was stored under hydrostatic pressure from rainwater falling on outcrops within each state's current borders. Because it allows the transmission and storage of groundwater in usable quantities and is overlaid by a confining layer, the Sparta Sand is classified as a confined aquifer. But the fact that the geological formation underlies both states does not mean that any meaningful quantity of the groundwater stored and flowing over time within either state has ever been naturally shared between the states.

Substantially all of the groundwater naturally flowing, collected and stored within the Sparta Sand in each state originated, and was stored inside that state's borders over thousands of years. As a confined aquifer, the natural groundwater flow and storage in each state has resided in the current borders of that state because it naturally seeped from the outcrops in the state and moved exceedingly slowly in a predominantly east to west/southwest direction in Mississippi and an east to west/northwest direction in Tennessee.

The water supply in Shelby County, Tennessee, is primarily provided by groundwater, and most of the groundwater pumped in the county is pumped by MLGW, a public utility owned by the City of Memphis. Since its creation in 1939, MLGW has relied exclusively on groundwater from what was originally called the "500-foot Sand" or Memphis Sand. In the mid-1960's Tennessee learned that the upper part of the "500-Foot Sand" was correlated with the Sparta Sand (Moore, 1965). Based on available records since 1965, MLGW has consistently, annually increased its groundwater pumping for governmental use and sale in Shelby County and surrounding areas over the next several decades. Between 1965 and 2000, MLGW developed one of the largest artesian water pumping operations in the world, with over 170 commercial water wells located in 10 well fields. Three of these well fields are within 2 to 3 miles of the aquifer (groundwater system). If pumping exceeds the rate of recharge, the depth to which a pump is lowered will have to be increased, and the area drained by the cone of depression will continue to grow. The upper part of **Figure 2** with only a few wells pumping shows that the cones of depression for each well do not overlap by exceeding the pre-pumping potentiometric surface causing a regional cone of depression. The lower part of **Figure 2** shows a greater number of wells closer together and their respective cones of depression. In this figure the cones of depression for these wells overlap and stay below the pre-pumping potentiometric surface causing a regional cone of depression. Historically recorded observations show that potentiometric surface (water levels) for the Sparta Sand have declined (dropped) by as much as 100 feet under Memphis since 1886 as a result of MLGW pumping, forming a large cone of depression extending into substantially all of DeSoto County, Mississippi. As a result, recorded water levels in the Sparta Sand under north DeSoto County, Mississippi have been estimated from a USGS model (Arthur and Taylor, 1990) to have declined by up to 90 feet. In a deposition on March 27, 2007 of Charles H. Pickel, a retired MLGW water manager, he confirmed that the cone of depression created by MLGW pumpage extended into northern Mississippi. This current large cone of depression only exists because of the continuous, cumulative increases in groundwater pumping in Shelby County, Tennessee, primarily in MLGW's 170+ commercial wells. Essentially, the ten significant MLGW well field cones of depression overlap forming one, large oval-shaped cone of depression centered in Memphis from which MLGW draws groundwater. **Figure 1** illustrates the area of the larger and somewhat oval-shaped cone of depression that occurs from the cumulative MLGW well field pumping. The Davis, Palmer and Lichterman well fields, which are located near the Mississippi state line, more readily withdraw groundwater out of the Sparta Sand in Mississippi.

Figure 3 is a three-dimensional illustration showing the approximate total area from which the MLGW cone of depression withdraws groundwater. The Arthur and Taylor model shows that Mississippi groundwater has been pulled out of storage and from its natural west/southwest direction of seep and drawn north into Tennessee by the MLGW cone of depression. These conditions were recognized by David Feldman from the University of Tennessee, prompting the publishing of a report titled "Water Supply

HYDROGEOLOGY OF SPARTA SAND

There are a number of aquifers and confining units in the northwestern Mississippi and southwestern Tennessee area. The major aquifers are the Sparta/Memphis Sand and the Fort Pillow Sand. The Sparta Sand is a distinct geological formation and primary source of groundwater in northwest Mississippi and Shelby County, Tennessee. **Figure 4** is a generalized hydrogeologic cross section showing the Sparta Sand and lower Fort Pillow confined aquifers.

The Sparta Sand is a thick, variable sand and sandstone formation made up of fine to very coarse sand with lenses of clay and silt (Graham and Parks, 1986). In north Mississippi, the Sparta Sand occurs at a depth of 0 to 600 feet, and varies in thickness between 200 to 900 feet. The formation is thinnest at outcrops at or near the surface in the eastern Shelby County and northwestern Fayette County, Tennessee, and in north Mississippi beginning in east Marshall County. The outcrops continue in a north and south strike along the edge of the Mississippi Embayment in both states. An outcrop is defined as the location where a laterally extensive dipping subsurface rock formation is exposed at or near land surface. **Figure 5** shows the outcrop area of the Sparta Sand. The formation descends from the outcrops. Getting progressively thicker, and is thickest near the Mississippi River in Shelby County, Tennessee, and in DeSoto County, Mississippi. Within north Mississippi and along the common border with Tennessee, the Sparta Sand formation has a dominant, gentle dip from eastern outcrops to the west/southwest across north Mississippi and Tennessee to the Mississippi River.

The Sparta Sand is confined above by the Jackson Formation and the upper part of the Claiborne Group which consist primarily of clay, silt and fine sand. This serves as a confining bed retarding vertical groundwater flow between the unconfined Surficial aquifer above and the Sparta Sand. Except in areas where the upper confining bed is breached, it protects the high quality of the stored water from surface pollution. The thickness of this confining bed is variable in the Tennessee and northwestern Mississippi areas, ranging from 0 to 360 feet (Graham and Parks, 1986). The Flour Island Formation is a confining bed consisting primarily of silty clay and sandy silt that underlies the Sparta Sand and separates it from the deeper Fort Pillow Sand. The Fort Pillow Sand is comprised of fine to medium-grained sand in the subsurface throughout the Memphis area and is the second most used aquifer by MLGW. The Sparta Sand formation has allowed the transmission and accumulation of high quality water stored under hydrostatic pressure over a long period time within each states border.

The Sparta Sand is one of the principal and most productive aquifers in Shelby County, Tennessee, and northwestern Mississippi. It is reported that the aquifer provides about 95 percent of the water used for all municipal and industrial water supplies in the Memphis area. Aquifer is defined as: A subsurface geologic formation capable of storing and transmitting usable amounts of water. This sandstone formation is saturated and stores groundwater collected over thousands of years, and very slowly transmits usable amounts of water within the formation, classifying it as an aquifer. The primary source of any new groundwater for collection and storage in the Sparta Sand is the recharge that occurs from rainfall. This groundwater recharge generally occurs east of Shelby County, Tennessee, east of Memphis, and in east Marshall County, Mississippi at the outcrop areas as shown on **Figure 5**. Within this outcrop belt, recharge occurs by infiltration of rainfall directly into the Sparta formation or by downward seepage of water from the overlying Surficial aquifer. **Figure 6** is a 3-dimensional diagram showing a cross-section of the hydrogeologic formations in the Memphis and northwestern Mississippi area. This diagram shows that the formations are dipping generally from east to west and the Sparta outcrop occurs in the eastern portion of the area. As rain falls on the outcrop area of the Sparta it slowly percolates downward and then under gravity and the weight of the water accumulated above it in the formation slowly provides recharge as it seeps through the tiny pore spaces of the sandstone down gradient following the dip of the formation in a slightly west to southwesterly direction under natural conditions. The groundwater recharge is exceedingly slow under natural conditions seeping through the sandstone at a rate of about 1 inch per day. At this rate, groundwater naturally collected resides in the Sparta Sand for thousands of years as it gradually moves down gradient towards the Mississippi River. **Figure 7** is an idealized hydrogeologic section from east to west across the Mississippi Embayment that shows the general relationship between the aquifers, confining units, topography and general flow patterns (Arthur & Taylor, 1998). Water levels in the aquifer outcrop areas on the eastern side of the embayment are higher than on the western side of the embayment due to higher land surface altitudes. The Middle Claiborne aquifer, where the Sparta Sand occurs underlies the Mississippi Alluvial Plain near the Mississippi River, where the water level is lower than the outcrop areas as shown on **Figures 7 and 8** (Arthur& Taylor, USGS,1990). As a result of these water-level differences in the potentiometric surface, water naturally moves from the outcrop areas on the eastern side of the embayment westward through the aquifer, then eventually upward through the confining units into the Mississippi River Alluvial aquifer. The eastern boundary of Mississippi Alluvial Plain aquifer in western Mississippi which overlies the Middle Claiborne aquifer runs north-south in northwest Mississippi as shown on **Figure 8** (Arthur& Taylor, USGS, 1990) and receives discharge from the Middle Claiborne aquifer. This causes potentiometric surface levels to equilibrate in a north-south direction through northwest Mississippi forcing groundwater to flow east to west from the recharge area on the east side of Mississippi Embayment in northwestern Mississippi under pre-development conditions. As a result, structural geology in northwest Mississippi influences the shape of potentiometric surface contours and direction of groundwater flow, which is westward.

Figure 9 shows the pre-development potentiometric surface under natural conditions generated from groundwater modeling and shows this generally east to west/southwest groundwater directional movement perpendicular to the contours in northwest Mississippi consistent with information presented by Arthur & Taylor of the USGS. As shown on **Figure 9** in blue, all but a very small portion of groundwater flow in northern Mississippi stays in Mississippi under pre-development conditions until its natural discharge at the Mississippi River Alluvial aquifer system near the river. Only a very small area in northeastern DeSoto County has groundwater flow entering Tennessee under pre-development conditions as shown in green in **Figure 9**.

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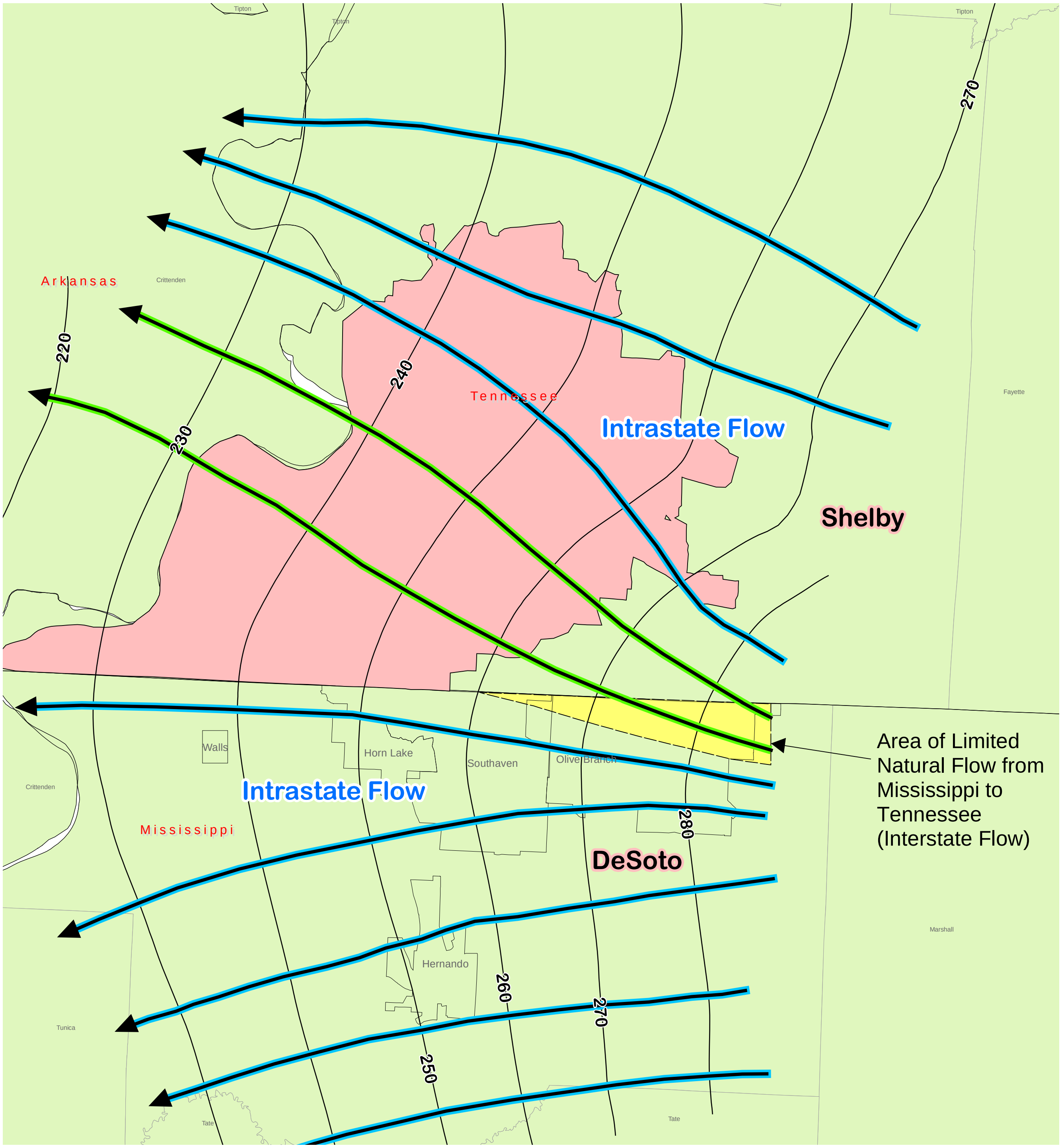

SOURCE: BRAHANA WRI 89-4131

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Flow Lines Showing Pre-Development Groundwater Flow Direction
Interstate Flow
Intrastate Flow
Potentiometric Surface Contour Lines

UPDATE REPORT ON DIVERSION AND WITHDRAWAL OF GROUNDWATER FROM NORTHERN MISSISSIPPI INTO THE STATE OF TENNESSEE

1886 ESTIMATED POTENTIOMETRIC SURFACE MAP FOR PREDEVELOPMENT CONDITIONS

PREPARED BY: **LEGGETTE, BRASHEARS & GRAHAM, INC.**
Professional Ground-Water and Environmental Engineering Services
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Exhibit 6

Excerpts from
Expert Report of Richard K.
Spruill, Ph.D., P.G.
(June 30, 2017)

EXPERT REPORT

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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June 30, 2017

Richard K. Spruill

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

I. Introduction

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

This expert report was produced for DCH&B using information available from publicly-available maps and reports from a variety of sources, including federal agencies such as the United States Geological Survey (USGS). This information was used in combination with the professional training and experience of the report's author, Dr. Richard K. Spruill, to develop opinions about the geologic and hydrogeologic setting of the study area. A partial list of resources and documents that were reviewed or employed to prepare the expert report is provided as Appendix A.

II. Qualifications

Richard K. Spruill, Ph.D, is GMA's Principal Hydrogeologist, president, and co-owner of the firm. Dr. Spruill's professional practice is focused on the hydrogeological exploration, evaluation, development, sustainable management, and protection of groundwater resources. He has been a geologist for over 40 years, and he is licensed in North Carolina as a professional geologist. Since 1979, Dr. Spruill has been a faculty member in the Department of Geological Sciences at East Carolina University (ECU), Greenville, North Carolina. He teaches hydrogeology, mineralogy, petrology, field geology, and physical geology at ECU. Dr. Spruill has provided litigation support and testified previously regarding geology, hydrogeology, water resources, and environmental contamination. His *curriculum vitae* is provided as Appendix B.

I, Dr. Richard K. Spruill, am the author of this expert report. My descriptions, interpretations, conclusions, and professional opinions described within this expert report are subject to revision, expansion, and/or retraction as additional information becomes available.

III Summary of General Opinions

The following is a summary of my opinions provided within this expert report. The opinions itemized below are based on (1) my education, training, experience, (2) detailed study of the geology and hydrogeology of the Mississippi Embayment, (3) evaluation of the specific geological and hydrological characteristics of the pertinent geological formations in north Mississippi and west Tennessee, and, (4) specific resources and materials referred to and identified with this report.

- The Sparta-Memphis Sand, also known as the Middle Claiborne Aquifer or the Memphis Aquifer, is an important source of potable groundwater within northwestern Mississippi and southwestern Tennessee. Most of the Sparta-Memphis Sand is a hydraulically-confined aquifer that consists of geologic deposits that accumulated within the Mississippi Embayment approximately 40 million years ago. The Sparta-Memphis Sand is inclined (dips) toward the west from areas where the unit crop out in both Mississippi and Tennessee. These sandy deposits thicken toward the center of the Embayment, which generally coincides with the present trace of the Mississippi River.
- The Middle Claiborne formation contains several lithologic constituents, including the Sparta Sand, that comprise an aquifer that has accumulated groundwater over many thousands of years. Historically, most of that groundwater originated as surface precipitation that infiltrated the formation where exposed at or near

the surface, and that groundwater migrated generally westward in both states to create a source of high-quality groundwater that did not naturally flow to any significant extent in a northerly direction out of Mississippi and into Tennessee.

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

Richard K Spruill

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

IV. Principles of Groundwater Hydrogeology

This section of the expert report provides an overview of key aspects of groundwater hydrogeology, especially as it pertains to the Sparta-Memphis Sand (aka, Memphis Aquifer or Middle Claiborne Aquifer) in northwestern Mississippi and southwestern Tennessee. Geologic and hydrogeologic details of the Sparta-Memphis Sand (SMS) are described elsewhere in the report.

Because groundwater availability depends on specific aspects of the local and regional geologic setting, it is not found in 'usable' quantities everywhere in the subsurface. The location, age, quality, movement, and availability of groundwater for human exploitation are determined by the actual geologic materials (i.e., aquifer) that host the water (e.g., sand) and the geologic and hydraulic characteristics of the aquifer system. This introduction to the basic principles of groundwater hydrology is generally tailored to be applicable to the groundwater system of the Middle Claiborne Group in northwest Mississippi and southwest Tennessee, and an analysis of the natural characteristics of the groundwater that is in legal dispute.

Groundwater originates as precipitation at the land surface, and some of that precipitation infiltrates the surface and enters the subsurface. In some places, groundwater originates as seepage through the bottoms and sides of surface water channels or basins, as well as by migration from other groundwater-bearing materials (e.g., 'confining units' that enclose some aquifers). Groundwater is located in the subsurface within small pore spaces located between rock and mineral particles and/or within fractures or other types of secondary porosity (e.g., voids in limestone from dissolved shell fragments).

Because groundwater typically moves through the subsurface at a rate of only a few feet or tens of feet per year, the water at a particular location and depth may have been in the subsurface for many years, decades, or millennia. By way of comparison, groundwater flowing at 1 foot per day is generally considered to be fast, while the velocity of water flowing in a stream is typically more than 1 foot per second (more than

The source of recharge water is predominantly rainfall in the areas where the SMS crops out at the surface (Grubb, 1998). Groundwater in the SMS discharges upward to streams (local flow paths) and the Mississippi River (regional flow paths).

Figure 7: Block Diagram Illustrating Surface Recharge and Groundwater Flow Paths within the Sparta-Memphis Sand Aquifer in Northern Mississippi (LB&G, 2014, Figure 6)

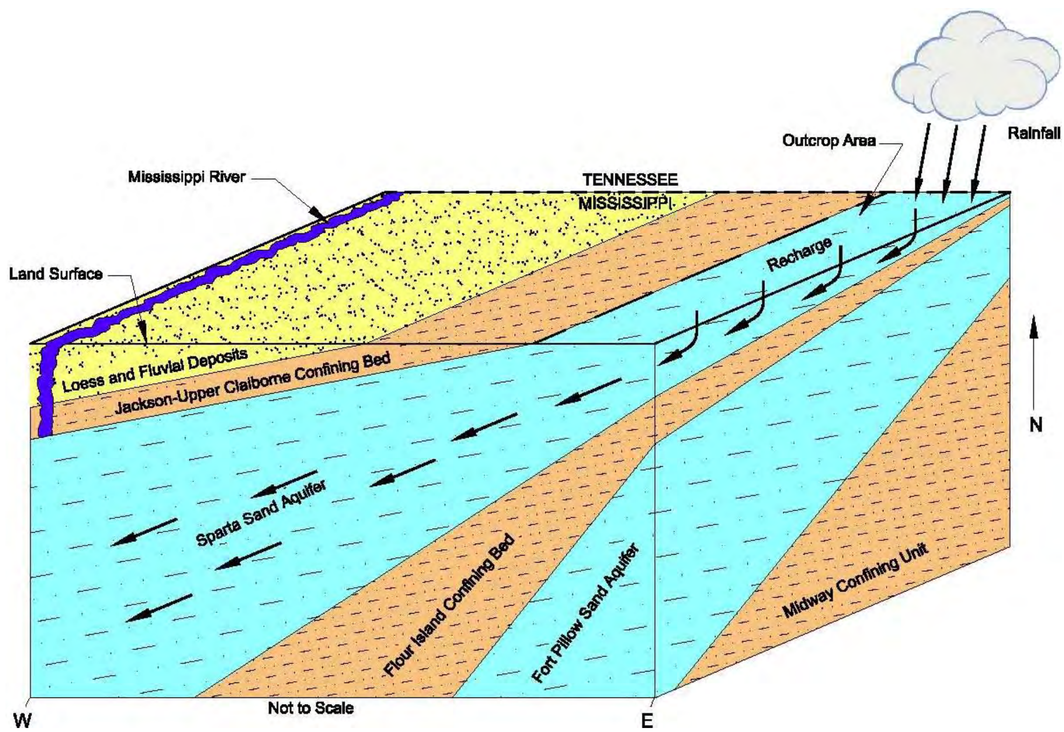


Figure 8 is a schematic east-west cross section (side view) through the Mississippi Embayment that includes arrows depicting the general pattern of groundwater flow before development began in the late 1800s. Some regional flow paths for water movement were as long as 200 miles from the recharge area to the discharge area. However, some local flow paths were shorter and were influenced by local topography and the density of streams and other surface water features in the recharge areas. Figure 9 illustrates the natural pre-development potentiometric (pressure) surface for the confined Middle Claiborne Aquifer. Arrows show that the direction of natural groundwater flow in the SMS in the vicinity of Memphis was generally directed from east to west (Figure 9).

eastern part of the Mississippi Embayment in Tennessee and Mississippi. However, most water recharging the aquifer systems has been diverted to major pumping centers in Shelby County, and discharge is no longer directed upward to the Mississippi River (regional flow paths) and to smaller streams (local flow paths) in the vicinity of the well fields. For example, the USGS has reported that groundwater movement in the summer of 2006 was predominantly directed downward from the channels of rivers and streams to offset the demand from pumping in the deeper confined aquifers (Clark et al., 2011). This change in groundwater discharge patterns resulted in reduced stream flow because the base flow of the streams was being taken indirectly by pumping of the SMS aquifer.

Prior to extensive development of the Middle Claiborne Aquifer in Tennessee, groundwater that existed in the SMS for thousands of years was primarily migrating westward from recharge areas in the eastern outcrop belt of the SMS (Clark et al., 2011). The SMS received relatively small contributions of water from the adjacent Surficial Aquifer and Lower Claiborne Aquifer, and a minor amount of water was also contributed by the Upper Wilcox Aquifer. It has been estimated (Brahana and Broshears, 2001) that roughly half of the groundwater in the Sparta-Memphis Sand being recovered by pumping in Shelby County, Tennessee, originates as predominantly horizontal flow in the SMS, and the other half of the extracted water is derived from vertical leakage across the aquifer's confining layers and the overlying surficial aquifer and underlying confined aquifers.

V.4 Current Groundwater Conditions in the Sparta-Memphis Sand

Voluminous and ongoing withdrawals in the vicinity of Memphis, Tennessee, have changed the pre-development patterns of groundwater flow within the Sparta-Memphis Sand in southwestern Tennessee and northwestern Mississippi. Historically, recharge to the SMS occurred in eastern areas of the Mississippi Embayment where the Eocene-age sand deposits are exposed at the surface. That groundwater moved generally westward until it ultimately discharged upward to the Mississippi River channel thousands of years later. Prior to intense pumping of the SMS, groundwater flowed horizontally from east to west in the regional aquifer systems, essentially parallel to the Tennessee-Mississippi state line. Therefore, the flow of groundwater that had existed within Mississippi's borders for thousands of years was directed from east to west across the state prior to development, so the recharge originating in each state remained within that state.

The withdrawal of large quantities of groundwater from the SMS for many decades by large municipal well fields in Shelby County, Tennessee, has modified significantly the natural east-to-west groundwater-flow pattern, thus diverting large quantities of high-quality groundwater from within Mississippi to Tennessee. The Surficial Aquifer, an important area of groundwater discharge for the Sparta-Memphis Sand prior to intense withdrawals, is now a significant source of recharge water for the SMS. Today, groundwater flows toward MLGW's well fields from multiple directions, as well as vertically across confining units separating the SMS from adjacent aquifers. Specifically, groundwater previously contained within, and moving entirely within, Mississippi now flows interstate toward pumping centers in Tennessee, and the rate of that flow has increased because intense pumping by MLGW has produced substantially steeper hydraulic gradients (e.g., compare Figures 9 and 10). Groundwater that was once part of Mississippi's natural resources long before it became a state has been taken, and is still being taken, by Tennessee for the benefit of its citizens.

VI. Groundwater Flow Patterns in Unconfined Versus Confined Aquifers

Unconfined and confined groundwater systems are fundamentally different in several significant ways. The hydraulic properties of the two systems, such as hydraulic conductivity, transmissivity, and storage coefficient, can vary in different parts of each system. Hydraulic conductivity, often referred to by non-technical individuals as permeability, is a measure of the ability of sediments or rocks to transmit water through a unit cross sectional area, under a unit hydraulic gradient, in a given amount of time, usually one day. Hydrogeologists describe differences in aquifer materials by evaluating the directional and locational differences in hydraulic conductivity. The terms homogeneous, heterogeneous, isotropic, and anisotropic are used to describe variations in hydraulic conductivity within aquifers at different locations, and in different directions

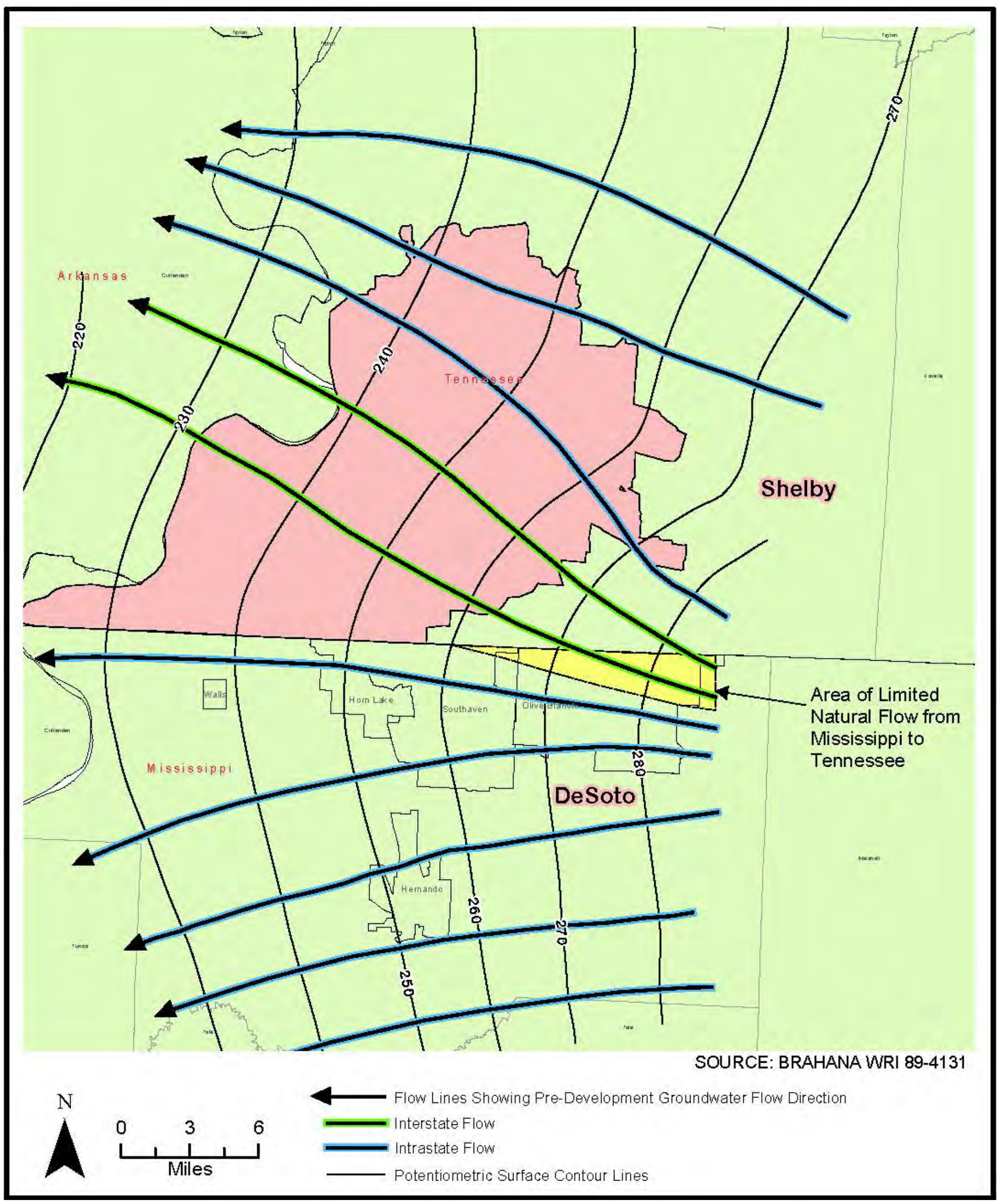
The Cushing et al. report does not include a groundwater flow net, but it does provide important information regarding the orientation and thickness of major Eocene-age deposits within the Mississippi Embayment. Other hydrogeological reports by the USGS include Criner and Parks (1976), Arthur and Taylor (1998), Clark et al. (2011), and Hart et al. (2016). Figure 9 shows the Arthur and Taylor (1998) interpretation of the pre-development equipotential surface for the Middle Claiborne Aquifer, to which I have two representative groundwater-flow lines, one in northwestern Mississippi and another in southwestern Tennessee. Both flow lines indicate that groundwater within each state flows generally westward and away from recharge areas where the Middle Claiborne's sediments crop out. In the case of both states, that groundwater originates in, resides in, travels in, and ultimately discharges from the aquifer system within each state. Figure 10 illustrates the change in hydraulic gradients and flow patterns resulting from extensive pumping in Shelby County, Tennessee.

Notable reports by private and academic scientists and engineers that address the pre-pumping conditions in the Claiborne Aquifer System for the Memphis area include Legette, Brashears, and Graham (2014) and Waldron and Larson (2015). In the next two sections of this expert report, I highlight the pre-development equipotential map produced by Legette, Brashears, and Graham, and I provide my opinions about Waldron and Larson's analysis.

VI.6 The Legette, Brashears, and Graham (2014) Pre-Development Equipotential Map

In 2014, Legette, Brashears, and Graham, Inc. (LBG) produced a MODFLOW-based groundwater-flow model for the principal aquifers in the Mississippi-Tennessee border region, specifically in the area that includes the large wellfields operated by the City of Memphis in Shelby County, Tennessee. LBG's pre-development and post-development equipotential surfaces for the SMS aquifer are shown in Figures 16 and 17, respectively. Figure 17 clearly illustrates the natural groundwater accumulation and flow in both Mississippi and Tennessee prior to intense pumping in the vicinity of Memphis. The groundwater flow lines indicate that almost all groundwater in northern Mississippi originated in Mississippi, flowed within the aquifer in Mississippi, and discharged upward to overlying aquifers and (ultimately) to the Mississippi River within the state of Mississippi. Figure 18 demonstrates that the predominantly eastward flow of Mississippi's groundwater has been converted to a northward-directed flow by intense pumping in Shelby County, Tennessee.

Figure 17: Legette, Brashears, and Graham, Inc. (2014) Pre-Development Equipotential Map for the Sparta-Memphis Sand Aquifer (modified to highlight groundwater-flow paths)



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This is not a comprehensive list of resources and documents that were reviewed or employed in preparation of the expert report, and additional documents and data may be reviewed or considered.

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Exhibit 7

Excerpts from
Deposition of David Wiley
(September 26, 2017)

In the Matter Of:

STATE OF MISSISSIPPI vs

STATE OF TENNESSEE

OF TENNESSEE,

DAVID WILEY

September 26, 2017

Q. (BY MR. DAVID BEARMAN) The final document that I've handed you is your CV that was included with your expert disclosure from the State of Mississippi. Have you looked at that document?
A. Yes. It has been a while, but, yes, I've looked at it.
Q. Is this your current CV?
A. Yes.
MR. DAVID BEARMAN: Let's mark that Exhibit 3.
(The above-mentioned document was marked as Exhibit 3.)
Q. (BY MR. DAVID BEARMAN) Mr. Wiley in your report you use the term "Sparta Sand" and you also use the term "Sparta/Memphis Sand." I want to make sure that we're talking about the same aquifer. Is that right?
A. Yes, we are.
Q. I think on one of your diagrams it is labeled "Middle Claiborne Aquifer." That's the same aquifer also, right?
A. Yes, the Memphis Sparta Sand is in the Middle Claiborne Aquifer.

Q. And you've read the report by David Langseth, and he used the term "Memphis Sparta Sand Aquifer" or "MSSA." Do you remember that?

A. Yes.

Q. That is the same aquifer?

A. Yes.

Q. I think Dr. Spruill wrote a report. Have you read that?

A. Yes.

Q. He used the term "Sparta Memphis Sand." That's the same aquifer also, right?

A. Yes.

Q. During the deposition today, if we talk about the aquifer, can we assume that we're talking about the Memphis Sand Sparta Aquifer or the Sparta Sand, the Sparta Memphis Sand, unless we specify otherwise?

A. Yes, I can agree to that because we're primarily talking about a couple of aquifers here in the area.

Q. One of the other aquifers, for example, would be the Fort Pillow?

A. Fort Pillow.

Q. So for purposes of the deposition we'll assume that the term "aquifer" is the Memphis Sand Sparta Aquifer. Okay?

A. Okay. If I have a question about that to clarify, I'll ask.

Q. Okay. We agree, I think, that the extent of the aquifer is pretty well agreed upon by scientists, don't we?

A. Yes.

Q. And the aquifer is I'll use the term "bell shaped," that starts up around Illinois and coming down east includes a little part of Kentucky, Tennessee and Mississippi. Is that right?

A. The Mississippi Embayment is bell -shaped. The aquifer may not match that perfectly, but it extends in those states.

Q. Let me hand you a diagram here. This is Figure 17 from USGS report authored by Clark and Hart. Is the area that is colored in, I guess you would say here, a different shade of blue and green and a little orange, that is the aquifer, correct?

A. This map is a potentiometric surface simulated water-level map of the Middle

Claiborne Aquifer, as it states at the bottom, and it shows the boundaries of the Middle Claiborne Aquifer in different colors.

Q. There is a black line that kind of outlines the extent of the aquifer, correct?

A. Yes.

Q. Okay. That is not really disputed?

A. No.

MR. DAVID BEARMAN: Let's make that Exhibit 4.

(The above-mentioned document was marked as Exhibit 4.)

Q. (BY MR. DAVID BEARMAN) You agree that the Memphis Sparta Aquifer is a primary source of fresh water for Northwest Mississippi and Shelby County, right?

A. Yes.

Q. And you agree that the Memphis Sparta Aquifer lies beneath several states, right?

A. Yes.

Q. It lies beneath Tennessee?

A. Yes, it does.

Q. Portions lie beneath Mississippi?

A. Yes.

Q. Portions lie beneath Arkansas?
A. Yes.
Q. Portions lie beneath Kentucky?
A. Yes.
Q. Among other, right?
A. The other -- I believe there are several others.
Q. Missouri?
A. Missouri.
Q. I can't remember if I said Louisiana.
MR. ELLINGBURG: Alabama and Louisiana.
A. Louisiana.
Q. (BY MR. DAVID BEARMAN) The Memphis Sparta Aquifer is recharged from outcrop areas in both Tennessee and Mississippi, right?
A. That's right.
Q. And the outcrop area is where the aquifer comes close to the surface or comes to the surface with no confining layer above it, right?
A. That's right.
Q. The outcrop area is sometimes called the recharge area?
A. In this case it is called the recharge

A. Yes.
Q. You said that in your report, correct?
A. Yes.
Q. You agree that pumping groundwater from the Memphis Sparta Aquifer from wells in one state can impact the groundwater in that same aquifer in another state?
A. I agree with that, that's right.
Q. In fact, you say in your report that groundwater pumped from the Memphis Sparta Aquifer in Tennessee impacts that same aquifer in Mississippi, right?
A. That's right.
Q. And you also say in your report that pumping in DeSoto County impacts the groundwater that is available to Shelby County in that same aquifer, right?
A. I believe I said that pumping from DeSoto County has reduced the amount that is diverted into Shelby County due to MLG&W pumpage.
Q. So pumping from DeSoto County from the Memphis Sparta Aquifer is decreasing the amount of water in the aquifer flowing into Shelby

within Tennessee?
A. I'm not following the wells that are "entirely in Tennessee." A well is in one spot. It is not in -- "entirely" makes it sounds like you are inferring that it is not -- that a well can be somewhere else besides one state and it can only be in one spot.
Q. You are not -- you have no knowledge and are not suggesting that a well, for example, in either Mississippi or Tennessee is drilled in such a way that it can be on the surface in one state and it is slanted and the screen of the well is actually in the aquifer under another state?
A. I know no wells like that here, but there are horizontal wells that do exist in other parts of the country.
Q. But not here?
A. Not here.
Q. The wells in this area go straight down?
A. Yes.
Q. A well in Tennessee can access and pump from the Memphis Sparta Aquifer, right?

A. Yes.
Q. A well in DeSoto County can access and pump from a well -- strike that. A well in DeSoto County can access and pump from the Memphis Sparta Aquifer, correct?
A. Yes.
Q. What issue were you asked to address in your June, 2017, report?
A. I was asked to address hydrologic conditions in the Northern Mississippi area with respect to pumpage from MLG&W and to address predevelopment flow conditions in Northern Mississippi.
Q. I think that I may have erred on the date. We're talking about your initial expert report dated June, 2017, correct?
A. Yes.
Q. Exhibit 1. Is that right?
A. Yes.
Q. You were addressed -- could you tell me what you said again? I'm sorry.
A. I was asked to address hydrologic conditions in the Northern Mississippi area around DeSoto County with respect to the pumping

on your map?
A. Yes.
Q. Can you we agree that all three of the flow lines in Mississippi cross into Arkansas?
A. Yes.
Q. So those would also be interstate flow, correct?
A. Once they Leave the State of Tennessee, they would be.
Q. The arrows that you drew right here cross into Arkansas, right?
A. That's right.
Q. So those would be interstate flow?
A. When they cross the Mississippi River.
Q. And it would be true, then, that when the lines you drew in Mississippi cross the Mississippi River or flow out of the state, it would be interstate flow also, then, correct?
A. That's correct. Which would take thousands of years, by the way.
Q. Is there a reason that you -- that the eastern side of your triangle stopped where it is?
A. It is near the outcrop area.

pumping in Northwest Mississippi, right?
A. Since these -- this is a USGS map, then it is based on actual water levels. So whatever is being pumped everywhere is influencing these water levels.
Q. In your report you say "The large cone of depression as seen on Figure 11 has been created by the cumulative groundwater pumping in Tennessee," right?
A. Yes.
Q. But the contours, the equipotential lines, the cone of depression that appears on Figure 11, which you took from the USGS, actually reflects pumping in Tennessee and in Mississippi, right?
A. That's correct.
Q. And to the extent there is any influence from Arkansas, it would include Arkansas also, right?
A. Correct. But my statement says primarily MLG&W wells causes the shape of that cone of depression.
Q. Earlier we had a conversation about the impact of pumping in DeSoto County on the

availability of water in Shelby County. Do you remember that?

A. Yes.

Q. Take a look at Page 15, the last paragraph. The second sentence says "There is a slight decrease in drawdown from 2013 through 2016 as shown in Figures 14 through 17." The slight decrease in drawdown is due to lower pumping in Shelby County and greater pumping over time in DeSoto County, right?

MR. ELLINGBURG: Objection.

A. The slight decrease in drawdown is due to the decrease in pumpage from MLG&W wells.

Q. (BY MR. DAVID BEARMAN) And the increase of pumping from in DeSoto County, right?

A. There was an increase in pumpage in DeSoto County at the same time that DeSoto County -- I mean MLG&W pumpage decreased. That's what went into the decrease in the cone of depression for that period.

Q. (BY MR. DAVID BEARMAN) Your drawdown maps in this report reflect pumping from MLG&W and Shelby County and pumping in DeSoto County, right?

A. That's correct.
Q. All right. Let's talk for a minute about groundwater budget analysis, which starts in your report on Page 16.
(Cell phone ringing.)
MR. ELLINGBURG: Sorry.
(Off-the-record discussion.)
A. The same report?
Q. (BY MR. DAVID BEARMAN) That's right, Exhibit 1.
A. Yes.
Q. When you prepare a groundwater budget, you are looking at all of the in-flows and out-flows of a particular area, correct?
A. That's correct.
Q. And the area that you choose to budget is designed to answer a particular question, right?
A. Yes. I would say yes.
Q. So you can -- if you are asked to prepare a groundwater budget for DeSoto County, you can do that in your model, right?
A. That's right.
Q. And you could also prepare a

A. Correct.
Q. But that's not included in your report?
A. It is irrelevant to the amount that is being -- that moves across the state line to Shelby County. It is taken into account.
Q. In predevelopment times there was actually water flowing from DeSoto County into Shelby County and groundwater flowing from Shelby County into DeSoto County, right?
A. That's right.
Q. All within the Memphis Sparta Aquifer?
A. That's right.
Q. And in predevelopment times there was groundwater flowing out of DeSoto County into Crittenden County, Arkansas, and groundwater flowing from Crittenden County, Arkansas, into DeSoto County, right?
A. Say that again.
Q. In predevelopment times there was groundwater in the Memphis Sparta Aquifer that flowed from DeSoto County, Mississippi, to Crittenden County, Arkansas, correct?
A. There would have been some, yes.
Q. And there was also groundwater in the

Memphis Sand Sparta Aquifer.

Q. What is the true definition of the word "share"?

A. Where two or more parties share something, give and take things together.

Q. You would agree that Shelby County and DeSoto County are both pumping from a common resource, right?

A. Yes, they are pumping from the same aquifer.

Q. Look above that in Section 2.2. You quote Dave Langseth where he said "other intrastate aquifers." Do you see that?

A. Yes.

Q. You say "The phrase, quote, intrastate aquifer, close quote, has no known technical reference in USGS literature or from other scientific professional organizations." Did I read that correctly?

A. Yes.

Q. What does that mean? What are you saying here?

A. I've never heard or read in the literature the term "interstate aquifer."

correct?
A. Yes.
Q. Now, based on that first arrow that you drew, that's certainly an interstate flow path, right?
A. It goes through multiple states.
Q. So it is an interstate flow path?
A. It would -- it is an interstate flow path.
Q. All right. All of the flow paths, if we were going to add more, all of the flow paths between Dr. Langseth's original flow path and the top one that you drew, all of those flow paths would go from Mississippi into Tennessee, correct?
A. The other three flow paths --
Q. Well, take a look at your top flow path.
A. Okay.
Q. Look at the area between the top flow path that you drew, which is one we just talked about, and Dr. Langseth's flow path, which is above it.
A. I see that.

want. Textbooks talk about flow boundaries.

Q. (BY MR. HILL) Just to be clear, I thought you said it was not the same thing as a no-flow boundary, a flow boundary is not the same thing as a no-flow boundary.

MR. ELLINGBURG: Objection to form.

A. I don't recall saying they are the same or different.

Q. (BY MR. HILL) Are they the same thing?

A. A flow boundary is a boundary where flow can either be added -- it can be added in, such as a constant-head boundary. Constant-head boundary is an elevation you put in a groundwater flow model that keeps the elevations at that node constant throughout the model. That's a boundary.

Q. You would agree that the hydrology of the alluvial aquifer affects the Middle Claiborne Aquifer, correct?

MR. ELLINGBURG: Object to form.

A. I've got to think about that. The hydrology of the --

Q. (BY MR. HILL) The alluvial aquifer.

A. Under predevelopment conditions water from the Memphis Sparta Sand Aquifer discharged to the alluvial aquifer. Under stressed conditions in the Memphis Sand Sparta Aquifer now water is discharging from the alluvial aquifer downward toward the Sparta Sand Aquifer. So there is interaction between those two units.

Q. The two are hydrologically connected?

A. Yes, they are.

Q. Is the Fort Pillow Aquifer also hydrologically connected to the Middle Claiborne?

A. Yes. There is a semi-confining layer between, but there is leakance between the two, from one aquifer to the other, through the confining layer.

Q. Are surface waters in the Mississippi Embayment also hydrologically connected to the Middle Claiborne?

A. In the outcrop area.

Q. That was true under predevelopment conditions as well?

A. Yes.

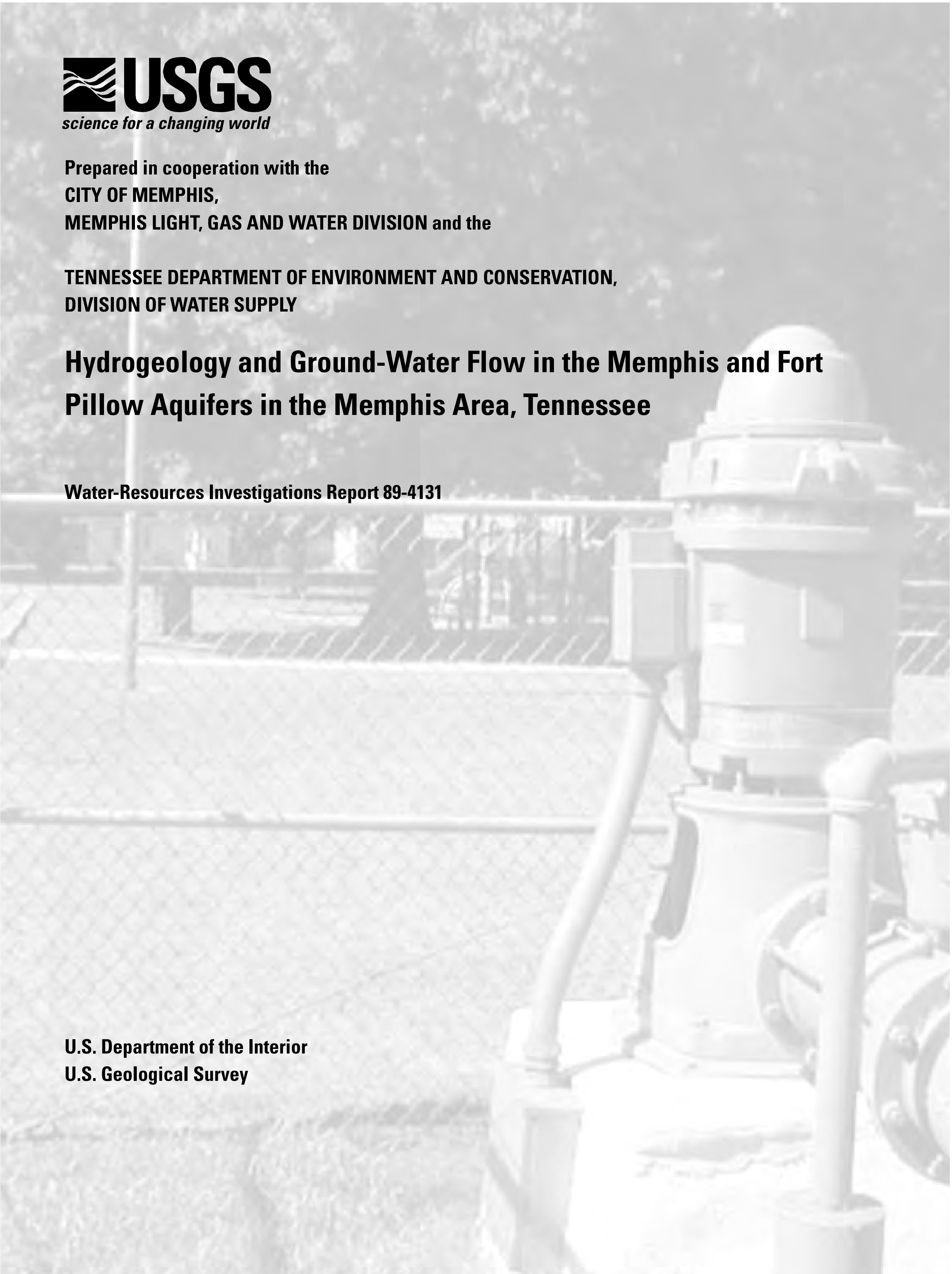
Q. Can you list some streams or rivers that are hydrologically connected to the Middle

Claiborne?
A. I'm trying to think of the name of the river. It is in Northern Mississippi. There is the Wolf River in Tennessee. But there is a river in Northern Mississippi. I can't think of the --
Q. Coldwater?
A. The Coldwater River. They are both in the outcrop. They flow through the outcrop and on.
Q. The Wolf and the Coldwater rivers?
A. Yes.
Q. Any other rivers that jump to mind?
A. That's the only two that I recall. I'm sure there are others, but that's the only two that I recall.
Q. I believe you had also stated that under predevelopment conditions, some water from the Middle Claiborne ultimately is discharged into the Mississippi River?
A. Yes.
Q. If you could turn to Page 8 of your rebuttal report.
A. Okay.

Exhibit 8

Excerpts from
Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee
By J.V. Brahana and R.E. Broshears

(2001)



USGS
science for a changing world

Prepared in cooperation with the
CITY OF MEMPHIS,
MEMPHIS LIGHT, GAS AND WATER DIVISION and the

TENNESSEE DEPARTMENT OF ENVIRONMENT AND CONSERVATION,
DIVISION OF WATER SUPPLY

Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee

Water-Resources Investigations Report 89-4131

U.S. Department of the Interior
U.S. Geological Survey

Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee

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

ABSTRACT

On the basis of known hydrogeology of the Memphis and Fort Pillow aquifers in the Memphis area, a three-layer, finite-difference numerical model was constructed and calibrated as the primary tool to refine understanding of flow in the aquifers. The model was calibrated and tested for accuracy in simulating measured heads for nine periods of transient flow from 1886-1985. Testing and sensitivity analyses indicated that the model accurately simulated observed heads areally as well as through time.

The study indicates that the flow system is currently dominated by the distribution of pumping in relation to the distribution of areally variable confining units. Current withdrawal of about 200 million gallons per day has altered the prepumping flow paths, and effectively captured most of the water flowing through the aquifers. Ground-water flow is controlled by the altitude and location of sources of recharge and discharge, and by the hydraulic characteristics of the hydrogeologic units.

Leakage between the Fort Pillow aquifer and Memphis aquifer, and between the Memphis aquifer and the water-table aquifers (alluvium and fluvial deposits) is a major component of the hydrologic budget. The study indicates that more than 50 percent of the water withdrawn from the Memphis aquifer in 1980 is derived from vertical leakage across confining units, and the leakage from the shallow aquifer (potential source of contamination) is not uniformly distributed. Simulated leakage was concentrated along the upper reaches of the Wolf and Loosahatchie Rivers, along the upper reaches of Nonconnah Creek, and the surficial aquifer of the Mississippi River alluvial plain. These simulations are supported by the geologic and geophysical evidence suggesting relatively thin or sandy confining units in these general locations. Because water from surficial aquifers is inferior in quality and more susceptible to contamination than water in the deeper aquifers, high rates of leakage to the Memphis aquifer may be cause for concern.

A significant component of flow (12 percent) discharging from the Fort Pillow aquifer was calculated as upward leakage to the Memphis aquifer. This upward leakage was generally limited to areas near major pumping centers in the Memphis aquifer, where heads in the Memphis aquifer have been drawn significantly below heads in the Fort Pillow aquifer. Although the Fort Pillow aquifer is not capable of producing as much water as the Memphis aquifer for similar conditions, it is nonetheless a valuable resource throughout the area.

INTRODUCTION

The Memphis area has a plentiful supply of ground water suitable for most uses, but the resource may be vulnerable to pollution. Withdrawal of nearly 200 million gallons per day (Mgal/d) ranks Memphis second only to San Antonio, Texas, among the nation's cities that depend solely on ground water for municipal-water supply. For the past century, most of the city's ground water has been pumped from the Memphis aquifer, a Tertiary sand unit that is confined in most of the Memphis area. Industrial, public supply, and private withdrawals also have been made from the Fort Pillow aquifer, but these generally have amounted to less than 10 percent of the total pumping in the area.

There has been increasing concern that contaminated ground water in the area's surficial aquifers may leak downward to the Memphis aquifer (Parks and others, 1982; Graham and Parks, 1986; M.W. Bradley, U.S. Geological Survey, written commun., 1987). To assess the potential for such leakage, a cooperative investigation was initiated in 1978 between the City of Memphis, Memphis Light, Gas and Water Division (MLGW) and the U.S. Geological Survey. This investigation is part of a series of studies pursuing a more complete understanding of ground-water flow and chemistry in the area. The main tool of this investigation is a ground-water flow model of the major aquifers in the Memphis area. This flow model integrates all available information on the geology, hydrology, and ground-water chemistry of the region. The model has helped to quantify the potential for leakage between principal aquifers, and it may be a valuable predictive tool to assist water managers in managing ground-water resources.

Approach and Scope

The necessary approaches to this investigation were:

1. to describe the hydrogeologic framework of the Memphis area, with emphasis on the Memphis aquifer and Fort Pillow aquifer;
2. to develop a conceptual model of ground-water flow in the Memphis area;
3. to test the conceptual model through the application of a multilayer, finite-difference ground-water flow model.

As defined for this investigation, the Memphis area comprises a rectangular zone of roughly 1,500 square miles (mi^2), measuring about 45 miles from east to west by 35 miles from north to south. The Memphis area lies near the center of the northern part of the Mississippi embayment and includes all of Shelby County, Tennessee, and parts of Fayette and Tipton Counties, Tennessee, DeSoto and Marshall Counties, Mississippi, and Crittenden and Mississippi Counties, Arkansas (fig. 1).

The study area includes all of metropolitan Memphis, as well as undeveloped, outlying areas where ground water is affected by pumping from metropolitan well fields. Although the study focuses on the Memphis area, the aquifers and confining units are regional in occurrence, and extend far beyond the Memphis area boundaries. Descriptions and maps necessary to define the regional hydrogeology are included within this report only as an aid to understanding ground-water flow in the Memphis area. Readers interested in a full discussion of the regional hydrogeology of the Memphis and Fort Pillow aquifers in the northern Mississippi embayment are referred to Arthur and Taylor (1990).

Previous Investigations

A substantial body of literature exists on the hydrology and hydrogeology of aquifer systems in the Memphis area. The most recent, comprehensive studies include those of Graham and Parks (1986), who studied the potential for leakage in the Memphis area, and Parks and Carmichael (1989a, 1989b, 1989c), who described the geology and ground-water resources of three aquifers in West Tennessee. Extensive bibliographies of previous ground-water studies are included in Brahana (1982a, table 2 and p. 35-40) and in Graham and Parks (1986, p. 41-44). A series of potentiometric maps and a description of historic water-level changes and pumpage from the Memphis aquifer and Fort Pillow aquifer in the Memphis area are included in Criner and Parks (1976). Historic water levels in individual wells are also documented by the U.S. Geological Survey (1936-1973). The potentiometric surface in the Memphis aquifer for 1978 and 1980 in the Memphis area is shown in Graham (1979, 1982), and for 1985 for West Tennessee is shown in Parks and Carmichael (1989d). The potentiometric surface of the Fort Pillow aquifer for 1980 for the northern Mississippi embayment is shown in Brahana and Mesko (1988, fig. 11), and for 1985 for West Tennessee is shown in Parks and Carmichael (1989e, fig. 2).

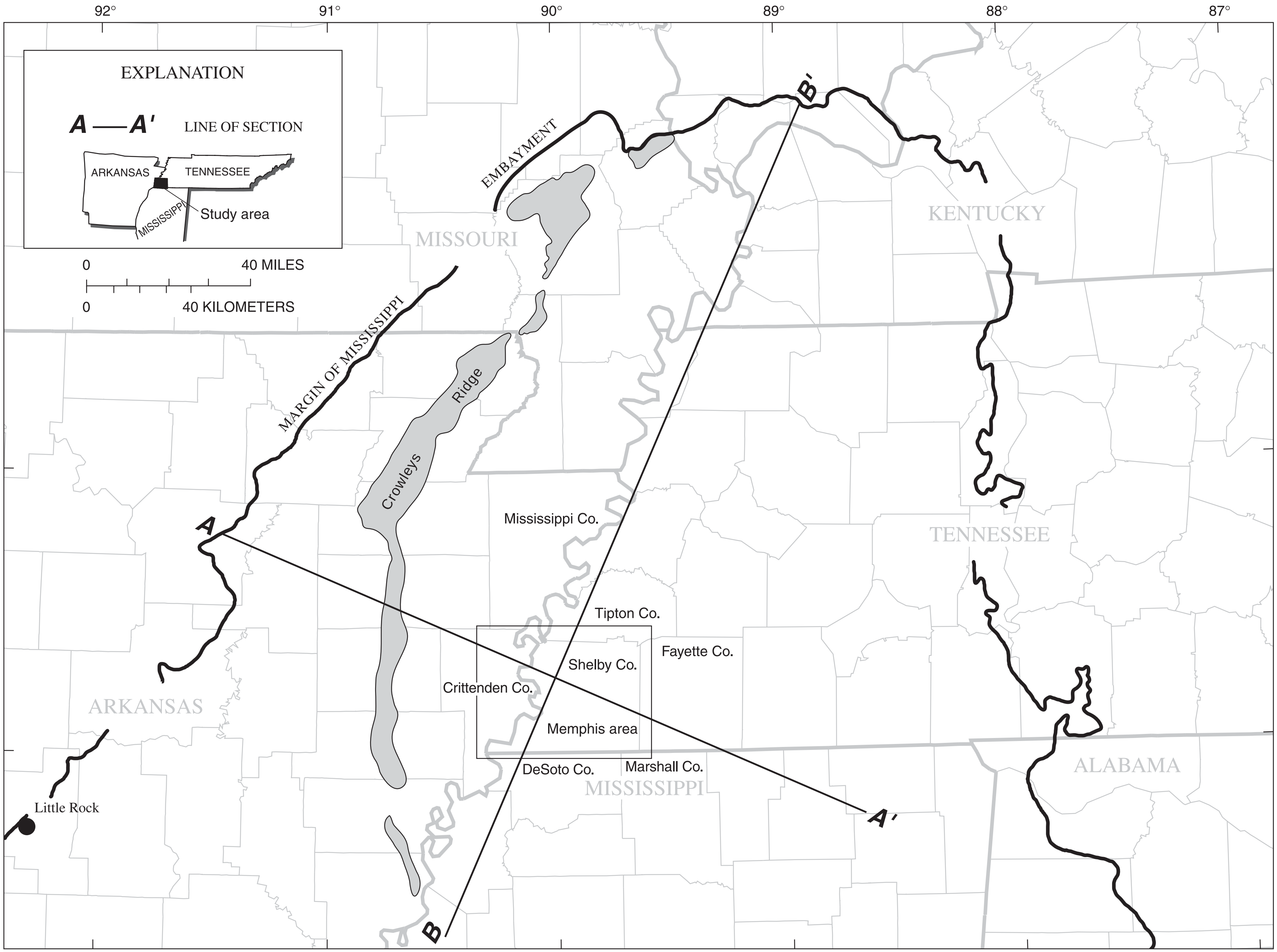


Figure 1. Location of the Memphis area and hydrogeologic sections along lines A-A′ and B-B′ in the Mississippi embayment.

Water quality in aquifers in the Memphis area has been summarized by Brahana and others (1987), and data describing selected water-quality parameters in the water-table aquifers in the Memphis area have been described by McMaster and Parks (1988). Parks (1973, 1974, 1975, 1977b, 1978, 1979a, 1979b) mapped the surface and shallow subsurface geology of the Memphis metropolitan area. A summary of some current and possible future environmental problems related to geology and hydrology in the Memphis area is given in a report by Parks and Lounsbury (1976). Parks and others (1982) described the installation and sampling of observation wells at selected waste-disposal sites.

Analog simulation of water-level declines in the Sparta aquifer (equivalent to the upper part of the Memphis aquifer) in the Mississippi embayment was summarized by Reed (1972). A two-dimensional digital flow model of the Memphis aquifer was described by Brahana (1982a). This model was used as a predictive tool to estimate aquifer response to various hypothetical pumpage projections (Brahana, 1982b). Arthur and Taylor (1990) evaluated the Memphis and Fort Pillow aquifers (as part of the Mississippi embayment aquifer system) in a regional study that encompassed the northern Mississippi embayment. Fitzpatrick and others (1989) described the geohydrologic characteristics and digital model-simulated response to pumping stresses in the Sparta aquifer (equivalent to upper part of Memphis aquifer) in east-central Arkansas.

Reports describing the general geology and ground-water hydrology of the Memphis area include Fisk (1944), Schneider and Blankenship (1950), Caplan (1954), Stearns and Armstrong (1955), Stearns (1957), Cushing and others (1964), Krinitzsky and Wire (1964), Moore (1965), Boswell and others (1965, 1968), Hosman and others (1968), and Cushing and others (1970).

In addition to published reports, there is a substantial body of unpublished hydrogeologic data for the Memphis area. These data include borehole geophysical logs, well-completion data, driller's records, geologic logs, summaries of pumping tests, inventories of pumpage, and individual well records and maps of water levels. Most of these records are located in the files of the U.S. Geological Survey, Water Resources Division; Tennessee Division of Geology; Tennessee Division of Water Resources; and City of Memphis, Memphis Light, Gas and Water Division.

HYDROLOGIC SETTING

Climate and Precipitation

The Memphis metropolitan area is characterized by a temperate climate, with a mean annual air temperature of about 62^{o} F, and abundant precipitation. About 48 inches of precipitation per year is typical, although annual amounts recorded have ranged from 31 to 77 inches.

The distribution of rainfall is nonuniform in space and time. Mean annual precipitation increases approximately 4 inches per year from west to east across the Mississippi embayment (Cushing and others, 1970). The driest part of the year is late summer and fall, and the wettest is late winter.

Topography and Drainage

Land-surface altitudes in the Memphis area range from about 200 feet above sea level on the flat alluvial plain of the Mississippi River to about 400 feet above sea level in the upland hills of eastern Shelby County. A bluff 50 to 150 feet high separates the alluvial plain from the upland. Other than the bluff, local relief seldom exceeds 40 feet.

The Mississippi River dominates surface-water flow in the area. From the upland in the east, it receives drainage from three main tributary streams—Nonconnah Creek, Wolf River, and Loosahatchie River. Along most reaches, these three tributaries flow throughout the year. One notable exception is Nonconnah Creek upstream from the mouth of Johns Creek. Since the 1950's, Nonconnah Creek has been dry in its upstream reaches for short periods during the dry season from July to October (Criner and others, 1964).

Hydrogeologic Framework

The Memphis area is located near the axis of the Mississippi embayment, a regional downwarped trough of Paleozoic rock that has been filled with more than 3,000 feet of unconsolidated sediments (Criner and Parks, 1976). These sediments include uncemented sand, clay, silt, chalk, gravel, and lignite. On a regional scale, the sediments form a sequence of nearly parallel, sheetlike layers of similar lithology. The layers reflect the trough-like shape of the Paleozoic strata (fig. 2).

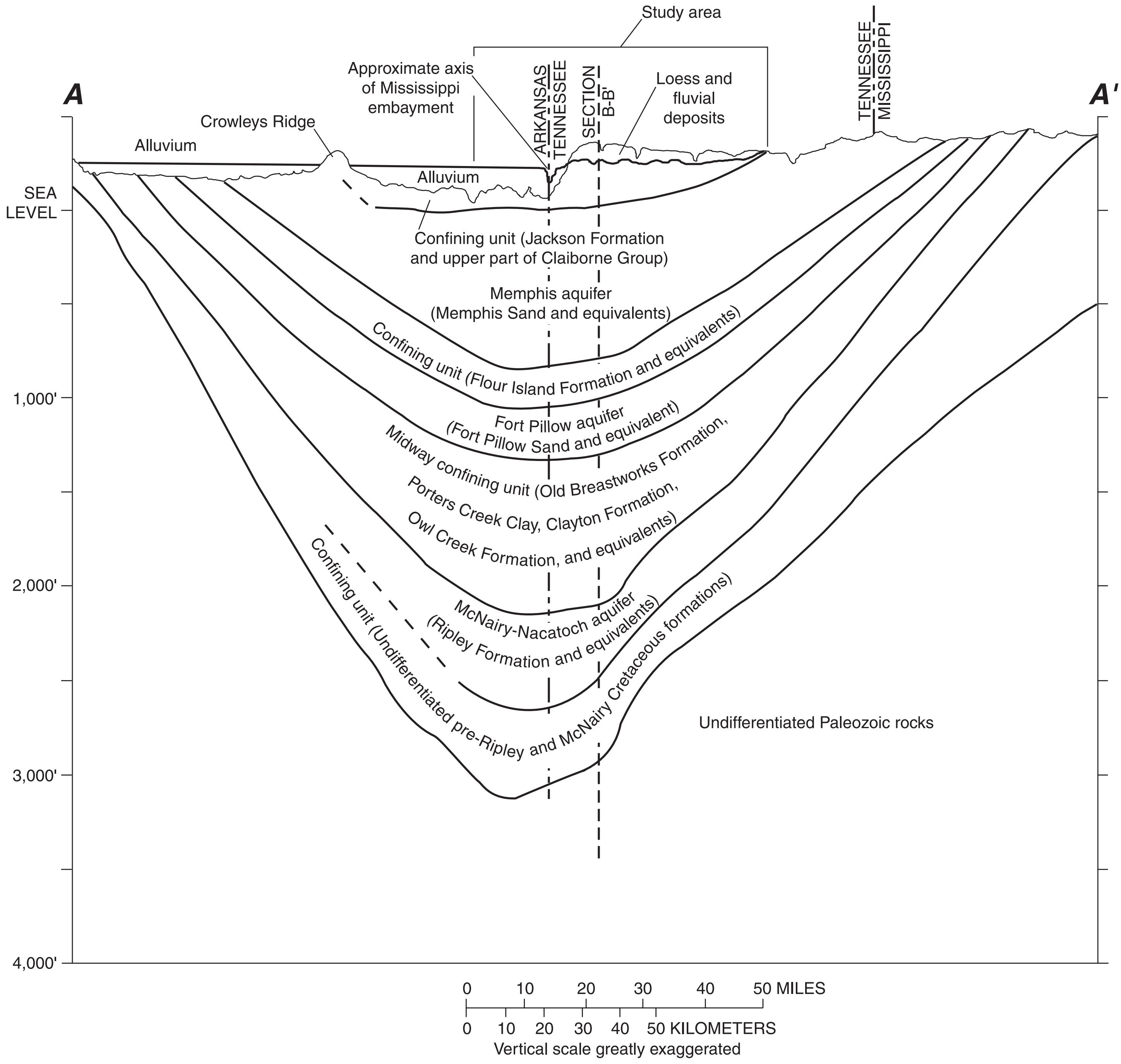
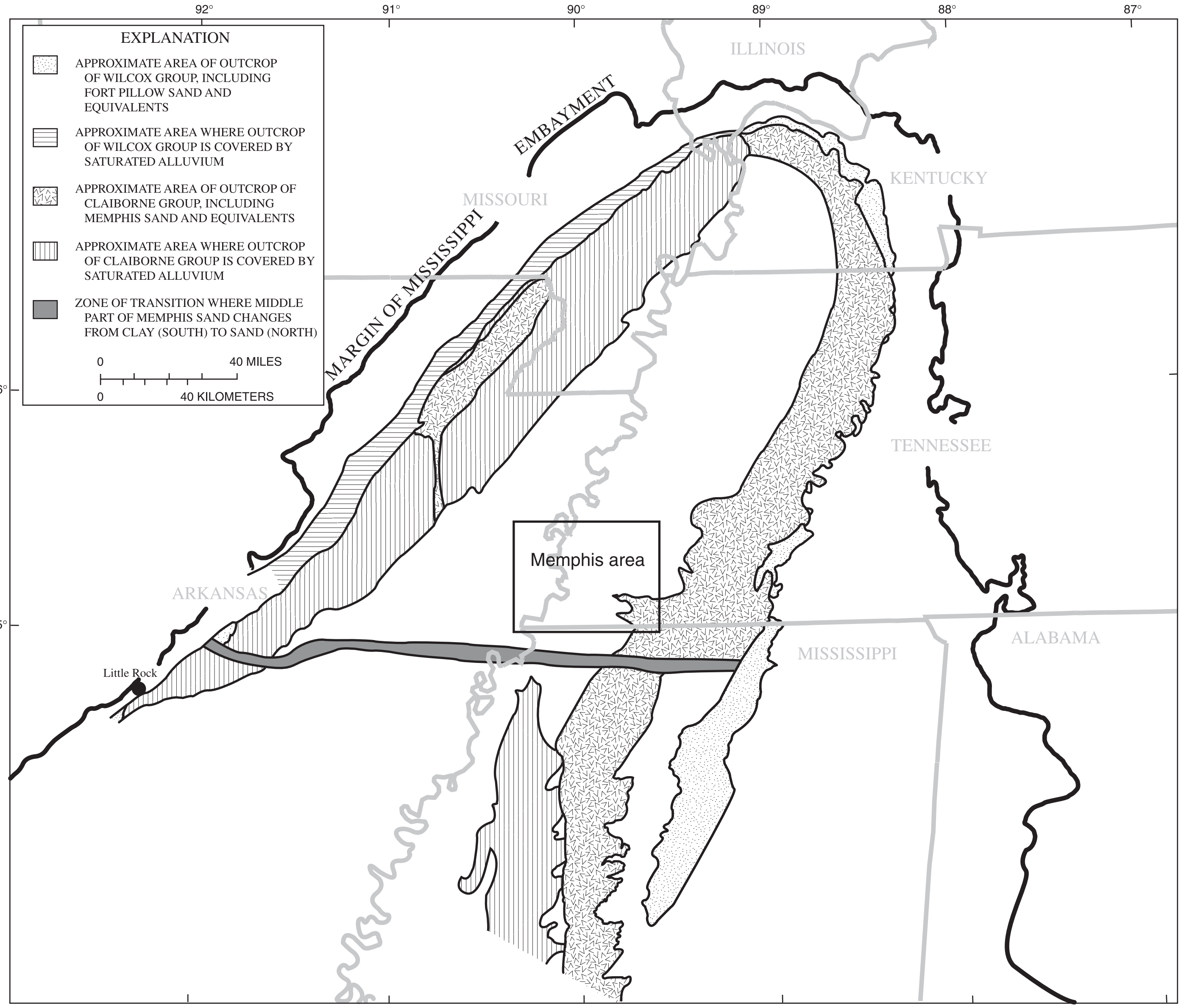


Figure 2. Hydrogeologic section showing principal aquifers and confining units, west to east, through the Mississippi embayment along line A-A'.



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

Figure 13. Areal geology of the northern Mississippi embayment.

Exhibit 9

Excerpts from
The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment
By Brian R. Clark and Rheannon M. Hart

(2009)

The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment

By Brian R. Clark and Rheannon M. Hart

Groundwater Resources Program

Scientific Investigations Report 2009-5172

U.S. Department of the Interior
U.S. Geological Survey

The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment

By Brian R. Clark and Rheannon M. Hart

Abstract

The Mississippi Embayment Regional Aquifer Study (MERAS) was conducted with support from the Groundwater Resources Program of the U.S. Geological Survey Office of Groundwater. This report documents the construction and calibration of a finite-difference groundwater model for use as a tool to quantify groundwater availability within the Mississippi embayment. To approximate the differential equation, the MERAS model was constructed with the U.S. Geological Survey's modular three-dimensional finite-difference code, MODFLOW-2005; the preconditioned conjugate gradient solver within MODFLOW-2005 was used for the numerical solution technique. The model area boundary is approximately 78,000 square miles and includes eight States with approximately 6,900 miles of simulated streams, 70,000 well locations, and 10 primary hydrogeologic units. The finite-difference grid consists of 414 rows, 397 columns, and 13 layers. Each model cell is 1 square mile with varying thickness by cell and by layer. The simulation period extends from January 1, 1870, to April 1, 2007, for a total of 137 years and 69 stress periods. The first stress period is simulated as steady state to represent predevelopment conditions.

Areal recharge is applied throughout the MERAS model area using the MODFLOW-2005 Recharge Package. Irrigation, municipal, and industrial wells are simulated using the Multi-Node Well Package. There are 43 streams simulated by the MERAS model. Each stream or river in the model area was simulated using the Streamflow-Routing Package. The perimeter of the model area and the base of the flow system are represented as no-flow boundaries. The downgradient limit of each model layer is a no-flow boundary, which approximates the extent of water with less than 10,000 milligrams per liter of dissolved solids.

The MERAS model was calibrated by making manual changes to parameter values and examining residuals for hydraulic heads and streamflow. Additional calibration was achieved through alternate use of UCODE-2005 and PEST. Simulated heads were compared to 55,786 hydraulic-head measurements from 3,245 wells in the MERAS model area. Values of root mean square error between simulated and observed hydraulic heads of all observations ranged from 8.33 feet in 1919 to 47.65 feet in 1951, though only six root mean square error values are greater than 40 feet for the entire simulation period. Simulated streamflow generally is lower than measured streamflow for streams with streamflow less than 1,000 cubic feet per second, and greater than measured streamflow for streams with streamflow more than 1,000 cubic feet per second. Simulated streamflow is underpredicted for 18 observations and overpredicted for 10 observations in the model. These differences in streamflow illustrate the large uncertainty in model inputs such as predevelopment recharge, overland flow, pumpage (from stream and aquifer), precipitation, and observation weights.

The groundwater-flow budget indicates changes in flow into (inflows) and out of (outflows) the model area during the pregroundwater-irrigation period (pre-1870) to 2007. Total flow (sum of inflows or outflows) through the model ranged from about 600 million gallons per day prior to development to 18,197 million gallons per day near the end of the simulation. The pumpage from wells represent the largest outflow components with a net rate of 18,197 million gallons per day near the end of the model simulation in 2006. Groundwater outflows are offset primarily by inflow from aquifer storage and recharge.

Introduction

Fresh groundwater in the Mississippi embayment can be found in alternating formations of sand, silt, and clay. The uppermost of these formations is the Mississippi River Valley alluvial aquifer (alluvial aquifer), which can provide well yields of 300 to 2,000 gal/min. The alluvial aquifer exists at land surface and covers much of the embayment area within the Mississippi Alluvial Plain. One of the next most widely used aquifers is the middle Claiborne aquifer, which can provide well yields of 100 to 500 gal/min (up to 1,500 gal/min in the Memphis area). The middle Claiborne aquifer, in some areas, lies several hundred feet beneath land surface. Decades of pumping from the alluvial aquifer for irrigation and from the middle Claiborne aquifer for industry and public-water supply have affected groundwater levels throughout the northern Mississippi Embayment in Arkansas, Louisiana, Mississippi, and Tennessee. Since the Gulf Coast Regional Aquifer System Analysis (GCRASA) study was completed in 1985, groundwater withdrawals have increased ranging from 37 percent at Memphis, Tennessee (17th largest city in the United States), to 132 percent in the agricultural areas of Arkansas from 1985 to 2000. Groundwater withdrawals for agriculture have caused water-level declines in the alluvial aquifer in Arkansas of at least 40 feet in 40 years (Schrader, 2001) while withdrawals from the middle Claiborne aquifer in Arkansas have resulted in declines of more than 360 feet since the 1920's (Scheiderer and Freiwald, 2006). These declines have prompted concerns over water availability and quality for agriculture and industry.

The Mississippi Embayment Regional Aquifer Study (MERAS) was conducted with support from the Groundwater Resources Program of the U.S. Geological Survey (USGS) Office of Groundwater to assess groundwater availability within the Mississippi embayment (fig. 1). The primary tool used in the assessment of groundwater availability is the MERAS groundwater-flow model.

Purpose and Scope

The purpose of this report is to document the construction and calibration of the MERAS groundwater-flow model of the Mississippi embayment. The current purpose of the model is to assist in the estimation of available groundwater in the Mississippi embayment aquifer system. The model was constructed to benefit concurrent and future investigations involving groundwater-withdrawal scenarios, optimization, particle transport, and monitoring network analysis.

Previous Investigations

Previous investigations of groundwater flow in the Mississippi embayment are numerous. Some early examples were the 1906 investigation of the underground waters of northern Louisiana (Veach, 1906) and 1928 investigation of groundwater resources of Mississippi (Stephenson and others, 1928). In the 1980's, the USGS began the GCRASA. The GCRASA compiled data and simulated groundwater flow in three main parts: the Mississippi River Valley alluvial aquifer, the Mississippi embayment aquifer system, and the gulf coastal lowland aquifer system (U.S. Geological Survey, 2008a). Other reports documenting groundwater-flow simulations within the MERAS flow system include Reed (1972), Brahana and Mesko (1988), Fitzpatrick and others (1990), Mahon and Ludwig (1990), Sumner and Wasson (1990), Mahon and Poynter (1993), Ackerman (1996), Arthur and Taylor (1998), Hays and others (1998), Arthur (2001), Brahana and Broshears (2001), McKee and Clark (2003), Stanton and Clark (2003), and Reed (2003).

Methods of Analyses

The primary method used to analyze the groundwater-flow systems is through the use of a numerical model to simulate groundwater flow. The viability of the numerical model is tested by comparing transient, simulated hydraulic-head values and streamflows from the groundwater-flow model with measurements from wells and stream gages. Details of the numerical model are listed in the next section, followed by a description of the limitations and assumptions of the model.

Numerical Model

For the MERAS model, the modular finite-difference code, USGS MODFLOW-2005 (Harbaugh, 2005), was used to approximate the solution of the equations governing three-dimensional (3D) groundwater flow. Because MODFLOW-2005 was used as the model simulation code, an additional advantage is the ability to investigate local areas within MERAS using the Local Grid Refinement package of MODFLOW-2005 (Mehl and Hill, 2007). The preconditioned conjugate gradient solver (Hill, 1990) was used for the numerical solution technique. The groundwater-flow system is represented by a set of grid cells, within which the hydraulic properties are the same. Each cell has three finite-difference equations describing the flow through it, which can be solved for either steady-state or transient conditions to simulate water-level changes within the flow system resulting from pumping stress over discrete periods of time. The model simulates 137 years (1870–2007) of system response to stress by using 69 stress periods.

Study Area Description

The model area encompasses approximately 78,000 mi^2 in an area known as the Mississippi embayment, referred to hereafter as the embayment (fig. 1). The model area boundary crosses eight States and includes approximately 6,900 mi of simulated streams, 70,000 well locations, and 10 primary hydrogeologic units. These hydrogeologic units include two primary aquifers—the Mississippi River Valley alluvial aquifer and the Middle Claiborne aquifer (Hart and others, 2008). The model area lies within parts of three physiographic sections, West Gulf Coastal Plain, East Gulf Coastal Plain, and Mississippi Alluvial Plain sections of the Coastal Plain physiographic province (fig. 1).

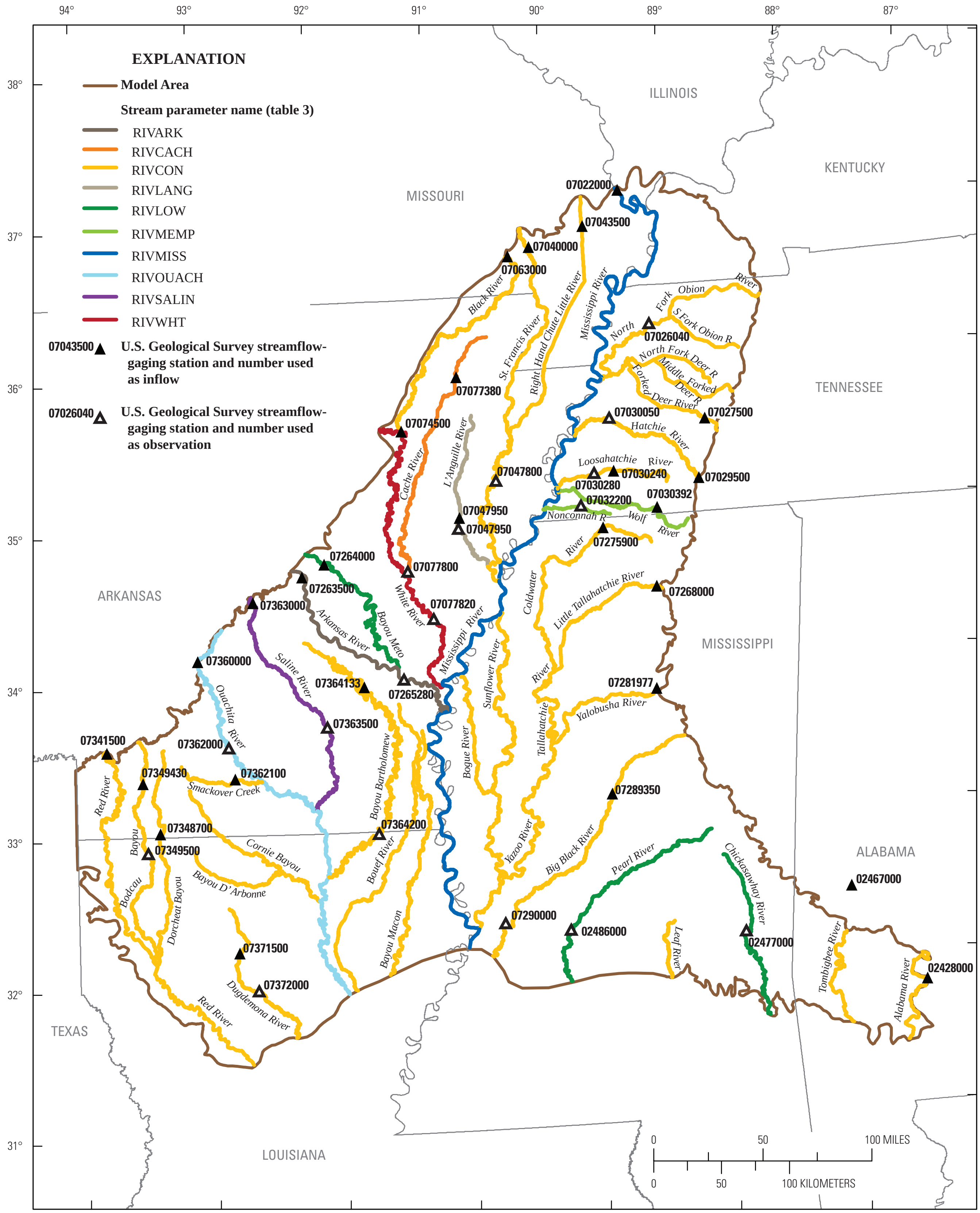


Figure 3. Streams simulated in the model area.

Table 1. Hydrogeologic and geologic units and their correlation across the States within the Mississippi Embayment Regional Aquifer Study.

ERATHEM	SYSTEM	EPOCH	GROUP	LOUISIANA	ARKANSAS Southern	ARKANSAS Northeastern	MISSOURI	KENTUCKY	TENNESSEE	MISSISSIPPI	ALABAMA	Hydrogeologic units	Model layer number
CENOZOIC	QUATERNARY	HOLOCENE / PLEISTOCENE		Alluvium and terrace deposits				Alluvium and loess deposits		Alluvium, terrace, and loess deposits	Alluvium and terrace deposits	Mississippi River Valley alluvial aquifer	1
	TERTIARY	OLIGOCENE	Vicksburg	Vicksburg Formation	Not present in study area					Vicksburg Formation		Vicksburg-Jackson confining unit	2
		EOCENE	Jackson	Jackson Formation									
			Claiborne	Cockfield Formation							Gosport Sand	Upper Claiborne aquifer	3
				Cook Mountain Formation								Middle Claiborne confining unit	4
				Sparta Sand	Memphis Sand			Sparta Sand	Memphis Sand	Sparta Sand	Lisbon Formation	Middle Claiborne aquifer[4]	5–7
				Cane River Formation				Tallahatta Formation		Zilpha Clay Winona Sand Tallahatta Formation	Tallahatta Formation	Lower Claiborne confining unit[2]	8–9
				Carrizo Sand						Meridian Sand Member		Lower Claiborne aquifer[1]	10
		UPPER PALEOCENE	Wilcox	Dolet Hills Formation	Undifferentiated	Flour Island Formation		Wilcox Formation	Flour Island Formation	Undifferentiated	Hatchetigbee Formation	Middle Wilcox aquifer	11
						Fort Pillow Sand		No Wilcox deposits identified as being of Paleocene age	Fort Pillow Sand		Bashi Formation Tuscahoma Sand Nanafalia Formation	Lower Wilcox aquifer[3]	12–13
				Undifferentiated Naborton Formation		Old Breast-works Formation			Old Breast-works Formation				
			Mid-way	Midway Group								Midway confining unit	Base of model

[1] Lower Claiborne aquifer includes the upper Wilcox aquifer in some parts of Mississippi.
[2] Winona-Tallahatta Formation is included with lower Claiborne confining unit in Hart and others (2008).
[3] Old Breastworks confining unit is included with middle Wilcox aquifer in Hart and others (2008).
[4] El Dorado confining unit and El Dorado Sand are included with middle Claiborne aquifer.

Modified from Hosman and Weiss, 1991

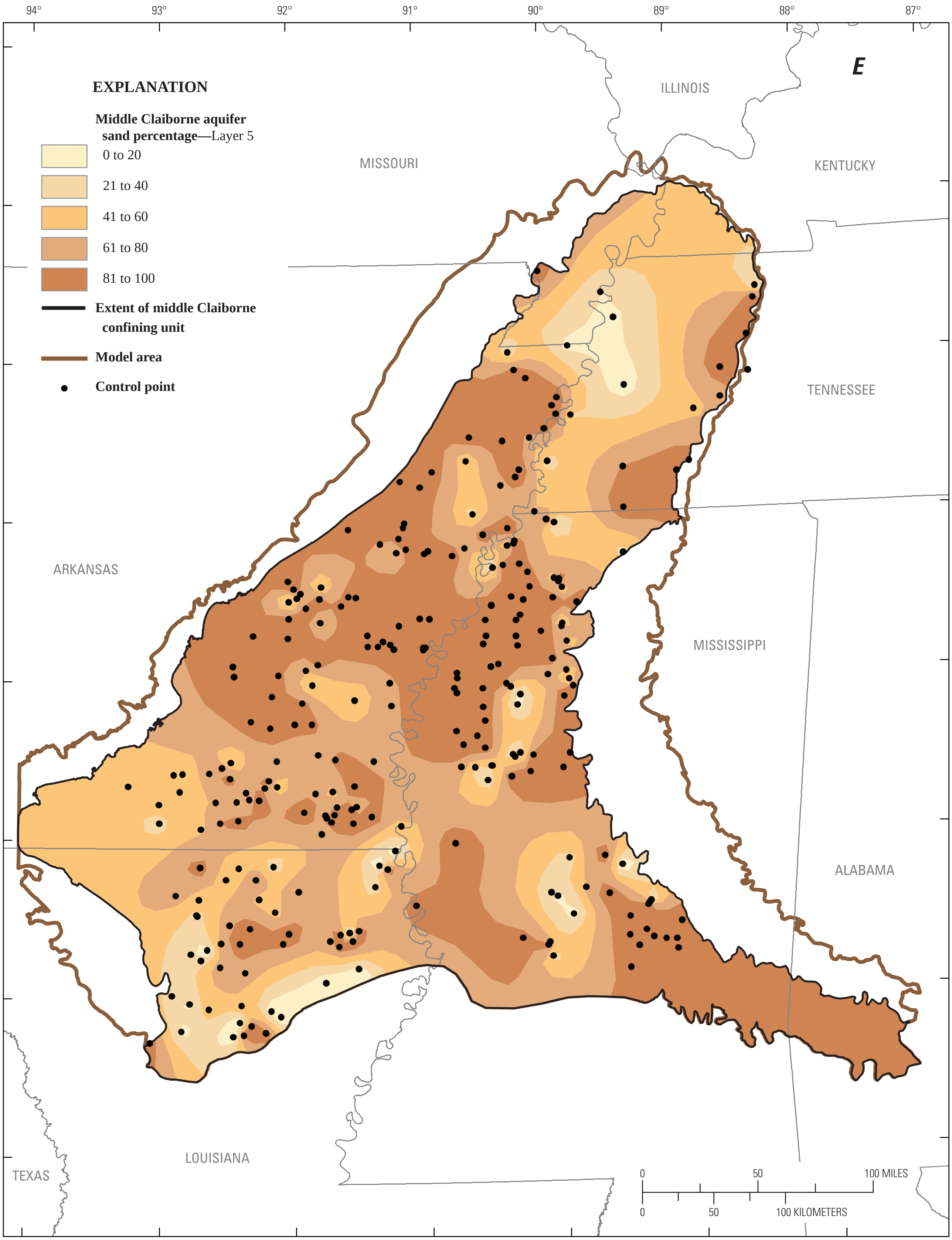


Figure 14. Sand percentage for select hydrogeologic units in the Mississippi Embayment Regional Aquifer Study area.—Continued

Exhibit 10

Analog Simulation of Water-Level Declines in the Sparta Sand, Mississippi Embayment
By J.E. Reed

(1972)

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

HYDROLOGIC INVESTIGATION
ATLAS HA-434

ANALOG SIMULATION OF WATER-LEVEL DECLINES IN THE SPARTA SAND, MISSISSIPPI EMBAYMENT

INTRODUCTION

Large local ground-water withdrawals from several of the aquifers in the Mississippi embayment have caused lowering of water levels that are of regional and interstate significance. The purpose of this study was to determine and evaluate the effects of increasing water withdrawals from the Sparta Sand, with the use of an electrical analog model. The Sparta Sand was chosen from the many aquifers in the Mississippi embayment because the problems associated with ground-water development are more imminent in the Sparta than in other aquifers. The study area is shown in figure 1. The Sparta Sand extends for an indeterminate distance downdip, but the location of the boundary was arbitrarily picked where the transmissivity becomes less than approximately 3,000 sq ft per day (square feet per day). North of the 35th parallel, the Sparta Sand is part of a thick sand section in the middle and lower parts of the Claiborne Group. This sand section, known as the Memphis aquifer, includes in descending order the Sparta Sand, sandy facies equivalents of the Cane River Formation, and the Carrizo Sand (Hosman and others, 1968, p. 20).

POTENTIOMETRIC SURFACE PRIOR TO DEVELOPMENT

The "original" potentiometric surface of the Sparta Sand and the Memphis aquifer (fig. 2) is based on measurements made prior to extensive development. The first significant use of water from the Sparta Sand was at Memphis, Tenn., beginning in 1886.

MEASURED WATER-LEVEL DECLINES

By 1965 approximately 3½ trillion gallons of water had been pumped from the Sparta Sand and the Memphis aquifer in Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. In response to this pumpage, water levels have declined throughout the Sparta Sand and the Memphis aquifer in this six-State area. Cones of depression caused by large withdrawals are of interstate significance in such places as Memphis, Tenn., north-central Louisiana, and south-central Arkansas; the maximum amount of decline reached 300 feet in 1965 in south-central Arkansas (fig. 3).

SIMULATION OF DECLINES BY ANALOG MODEL

The analog model was constructed to analyze water-level changes in the Sparta Sand and in the Memphis aquifer. For readers not familiar with the construction and use of analog models, a general discussion of principles is given by Robinove (1962). The model was constructed with a grid spacing of 4 miles.

Transmissivity of the Sparta Sand south of the 34th parallel is from Payne (1968, pl. 7). North of the 34th parallel, the transmissivity of the analog model, determined by E.M. Cushing from data in files of the U.S. Geological Survey (written commun., 1968), ranged from 7,000 tc 70,000 sq ft per day. The storage coefficient used in the analog model was assumed to be proportional to the thickness of the aquifer and ranged from 0.0001 to 0.001.

Preliminary analysis of water-level declines was made using the analog by assuming that all of the water pumped came from storage in the aquifer. The analog drawdown greatly exceeded that calculated from records of water levels, especially in the Memphis area. Recharge sources were added at the boundaries of the model to represent induced recharge or captured discharge at the outcrop. These sources were located where perennial streams crossed the outcrop, or where the outcrop was covered by alluvial aquifers of Quaternary age. Recharge sources representing vertical leakage were also added within the model. The model was then modified by adjusting the recharge to the aquifer until a similarity between the analog and observed drawdowns was achieved (fig. 4). This analysis assumed that the distributions of transmissivity and storage coefficient are correct as modeled.

The combined pumping rate from the Sparta Sand and the Memphis aquifer in the project area was about 350 million gallons per day in 1965. Analog analysis of the water balance for the Sparta Sand and the Memphis aquifer shows that in 1965 only about 20 percent of the water pumped was depleting storage in the aquifer, and that the other 80 percent was balanced by induced recharge or captured discharge (table 1). Water derived from changes in the rate of vertical leakage was the largest item in the 1965 water balance, amounting to 60 percent of the pumpage. Although large in total amount, when considered as an average throughout the area where the Sparta Sand or the Memphis aquifer occurs, the change in vertical leakage is small, averaging less than 0.1 inch per year. There has also been a change in flow where the outcrop of the Sparta Sand is overlain by Quaternary alluvial deposits. Induced recharge, or captured discharge, at this subcrop was about 20 percent of the pumping rate in 1965.

Table 1.—*Water balance as indicated by analog analyses*

[Rates of water flow in million gallons per day]

	1965	1990
Storage depletion	60	80
Total induced recharge and captured discharge	290	550
Change in vertical leakage	210	350
Change in flow at boundaries	80	200
Pumping rate	350	630

PROJECTED WATER-LEVEL DECLINES

The locations and rates of pumping of present (1970) and proposed new withdrawals were projected to the year 1990. Although the change in pumping rate differs from place to place, the average change in rate was about 80 percent from the period 1961–65 to the period 1966–90. The analog response to this projected pumping rate is shown in figure 5. The analog model indicates that in 1990 about 10 percent of the projected pumpage will be from storage in the aquifer and the rest will be induced recharge or captured discharge (table 1). Changes in vertical flow will account for about 60 percent of the 1990 pumpage, and changes in flow across the horizontal boundaries, about 30 percent. The analog analysis also indicates that in some places the water level will decline below the top of the aquifer (fig. 5), which in turn will cause a reduction in transmissivity and an increase in storage coefficient.

SUMMARY

Because local ground-water withdrawals from several aquifers in the Mississippi embayment have caused water-level declines that are of regional and interstate significance, an analog model of the Sparta Sand was used to predict and evaluate the regional effects of increasing future water withdrawals. The Sparta Sand and the Memphis aquifer were chosen because the problems associated with ground-water development were more imminent in these aquifers than in others.

Although the model was constructed with a coarse grid spacing and although data in some areas were scarce, it nevertheless seems to give reasonable regional values for water levels that may be expected as a result of projected pumping rates and proposed future withdrawals (fig. 5). This model can be useful not only as a starting point in the construction of more detailed models of local problem areas within the Mississippi embayment, but also as a tool in the planned management and wise use of the water resources of the entire region.

REFERENCES

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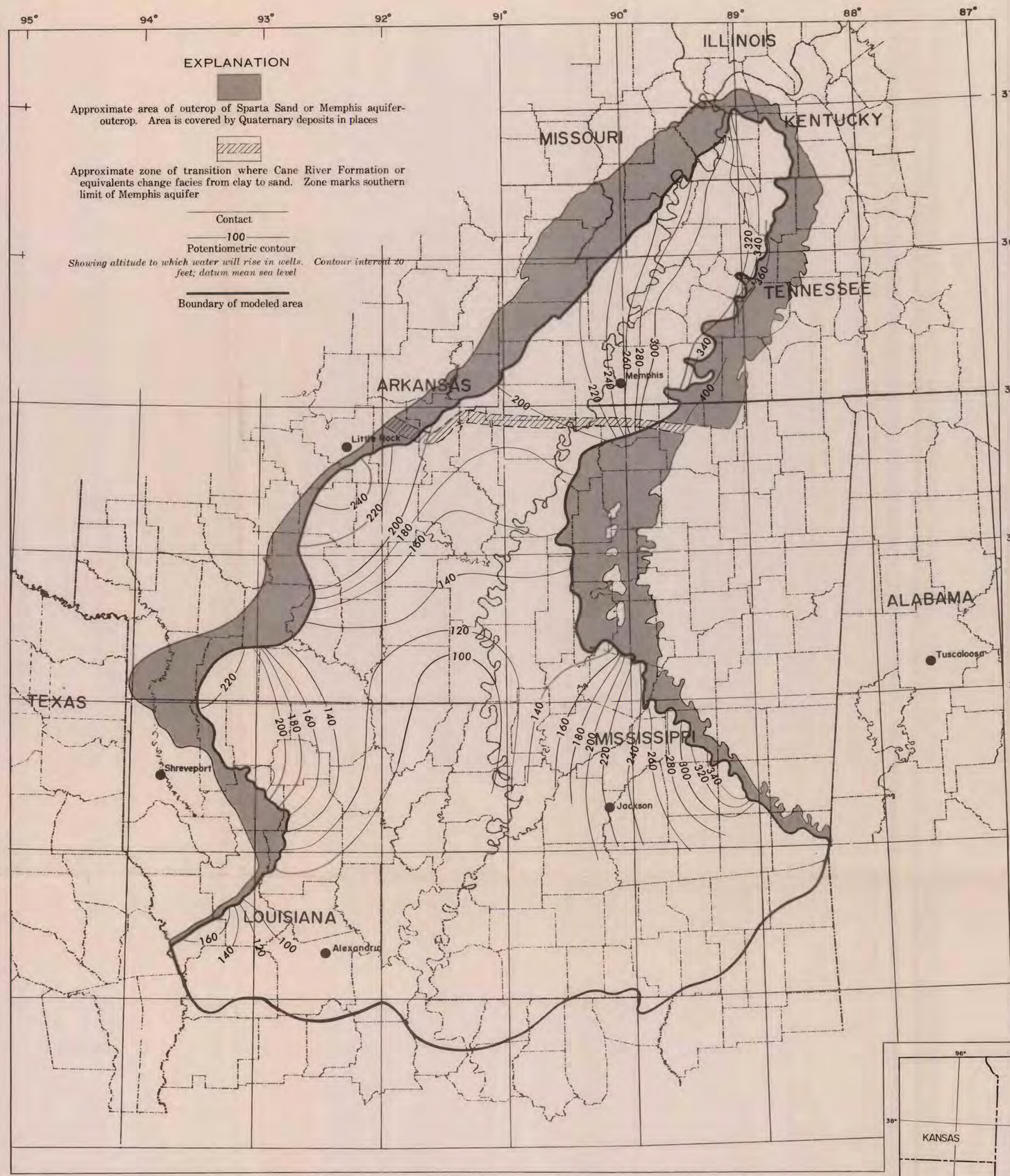


FIGURE 2.—Potentiometric surface of the Sparta Sand and Memphis aquifer in 1886.

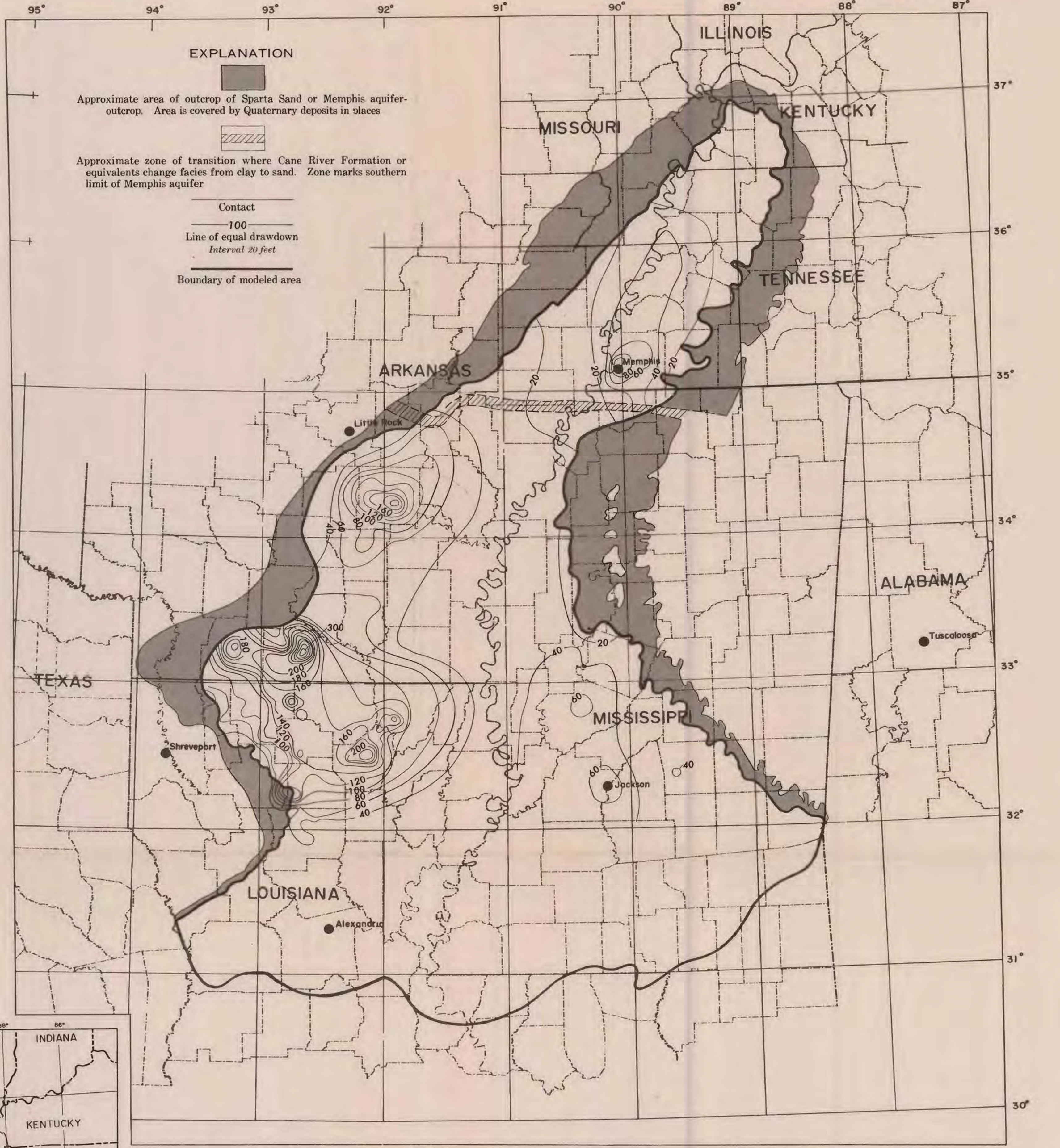
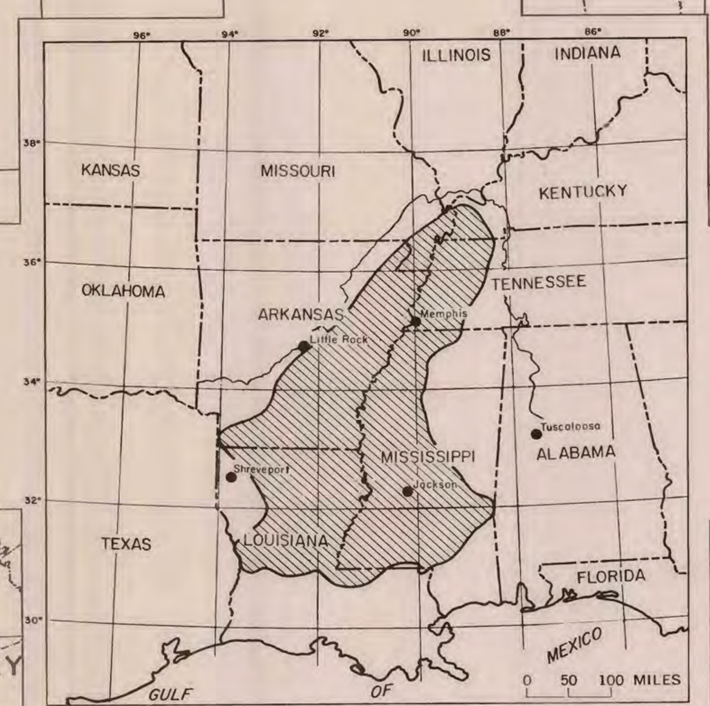


FIGURE 3.—Lowering of water level in the Sparta Sand and Memphis aquifer in the period 1886-1965.



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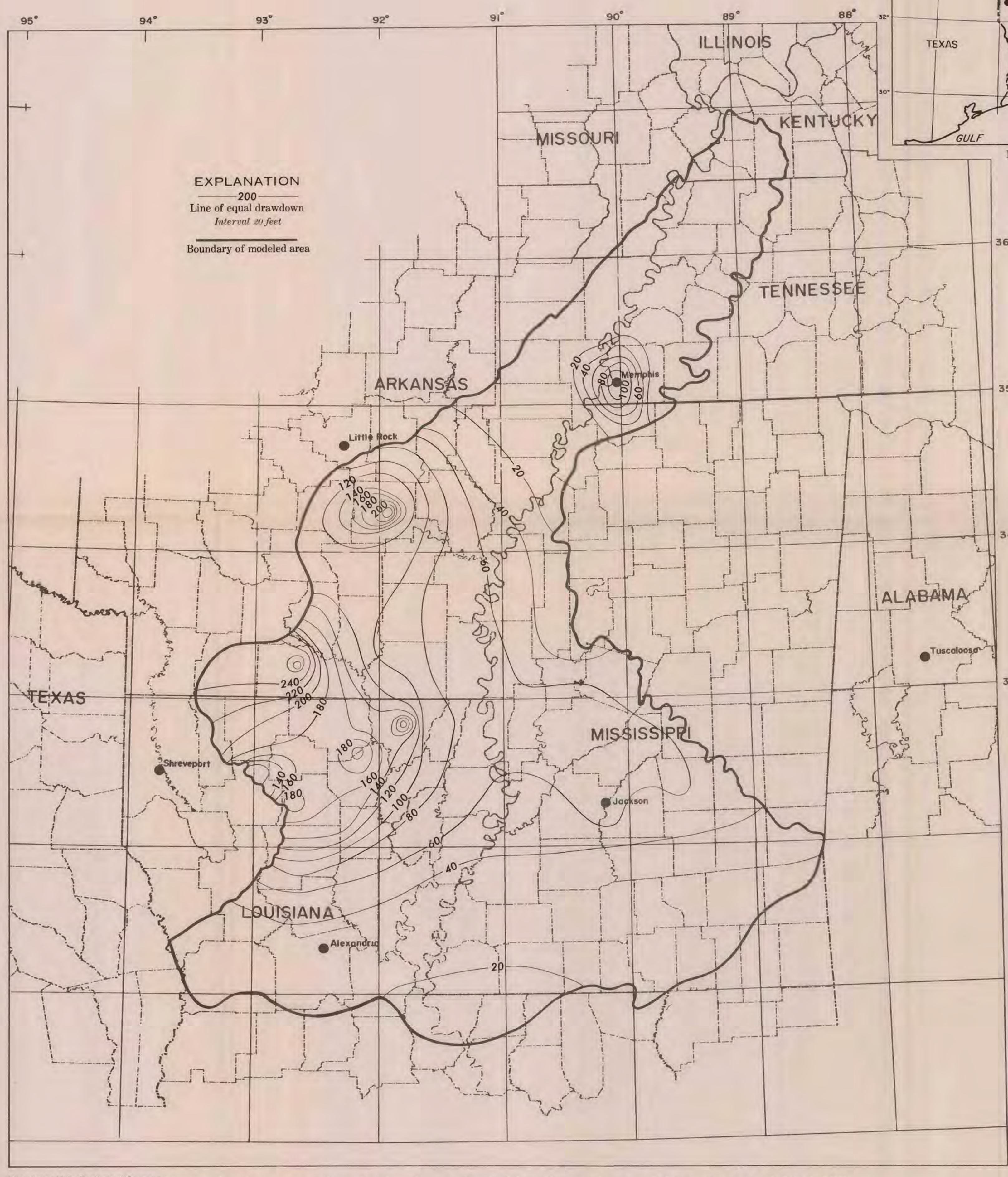
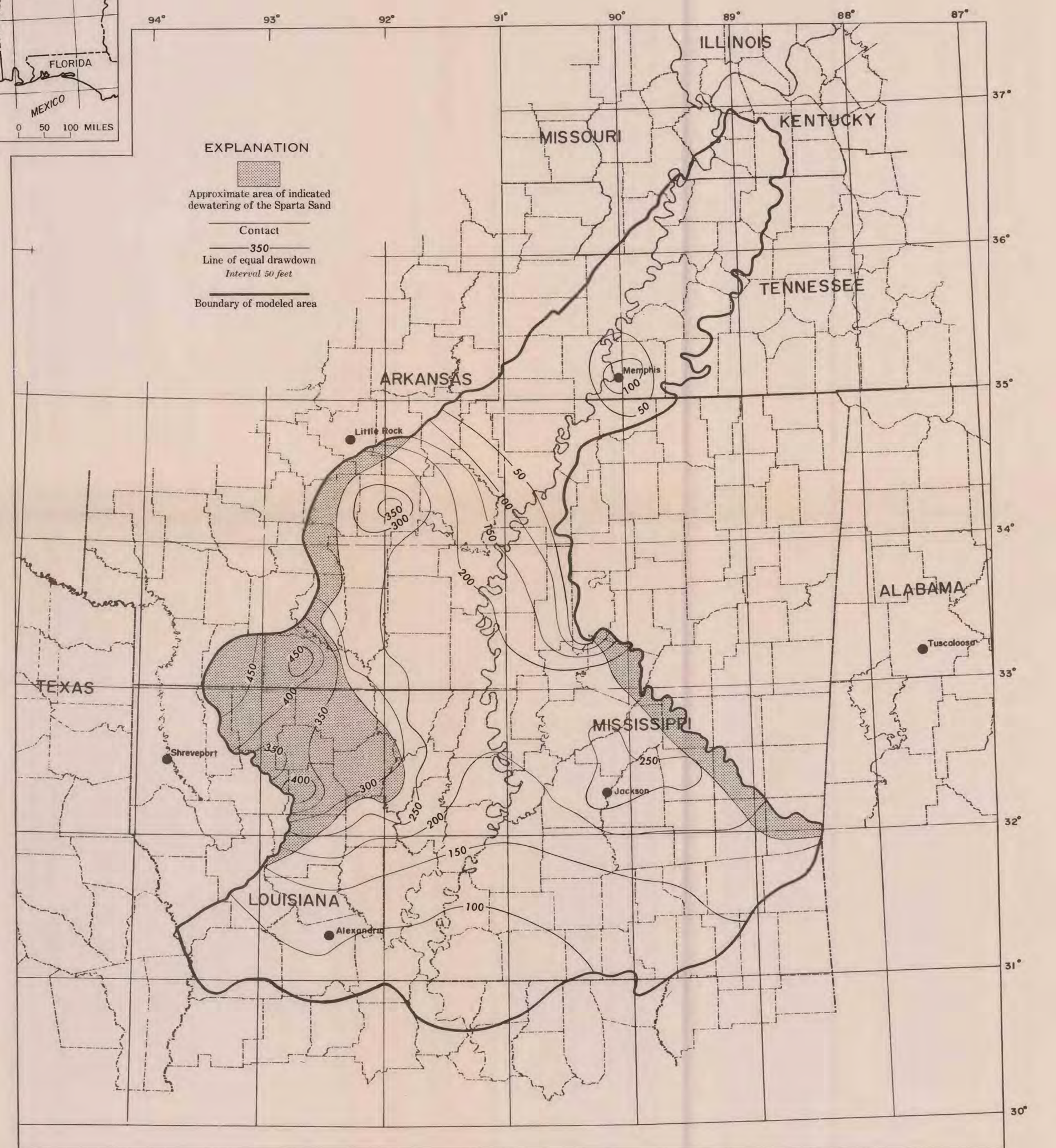


Base from U.S. Geological Survey

FIGURE 4.—Lowering of water level as indicated by the analog model for the period 1886-1965.



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SCALE 1:2 500 000

50 0 50 100 150 200 250 MILES

50 0 50 100 150 200 250 KILOMETERS

ANALOG SIMULATION OF WATER-LEVEL DECLINES IN THE SPARTA SAND, MISSISSIPPI EMBAYMENT

By

J. E. Reed

1972

For sale by U.S. Geological Survey, price 75 cents

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(1972)

DEPARTMENT OF THE INTERIOR
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FIGURE 1.—Location of study area.

FIGURE 4.—Lowering of water level as indicated by the analog model for the period 1886–1965.

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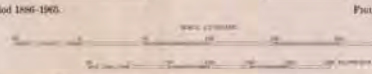


ANALOG SIMULATION OF WATER-LEVEL DECLINES IN THE SPARTA SAND, MISSISSIPPI EMBAYMENT

By
J. E. Reed
1972

Exhibit 11

Excerpts from
Ground-Water Flow Analysis of the Mississippi Embayment Aquifer System, South-Central United States: Regional Aquifer System Analysis – Gulf Coastal Plain
By J. Kerry Arthur and Richard E. Taylor

(1998)

Ground-Water Flow Analysis of the Mississippi Embayment Aquifer System, South-Central United States

By J. KERRY ARTHUR *and* RICHARD E. TAYLOR

REGIONAL AQUIFER-SYSTEM ANALYSIS—GULF COASTAL PLAIN

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1416-I

1998

GROUND-WATER FLOW ANALYSIS OF THE MISSISSIPPI EMBAYMENT AQUIFER SYSTEM, SOUTH-CENTRAL UNITED STATES

By J. KERRY ARTHUR and RICHARD E. TAYLOR

ABSTRACT

The Mississippi embayment aquifer system is composed of six regional aquifers covering about 160,000 square miles in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. The flow analysis presented in this report as part of the Gulf Coast Regional Aquifer-System Analysis study pertains to five aquifers in sediments of the Wilcox and Claiborne Groups of Tertiary age. In descending order, the aquifers are (1) the upper Claiborne, (2) the middle Claiborne, (3) the lower Claiborne–upper Wilcox, (4) the middle Wilcox, and (5) the lower Wilcox. The flow analysis of the sixth aquifer in the aquifer system, the Mississippi River Valley alluvial aquifer in sediments of Holocene and Pleistocene age, is presented in chapter D of this Professional Paper.

In 1886, before ground-water development began, potentiometric surfaces of the Mississippi embayment aquifers sloped from the outcrop areas on the eastern and western sides of the embayment toward the embayment axis in the central and northern parts of the embayment and southward toward the Gulf of Mexico in the southern part of the embayment. The Sabine uplift in northwestern Louisiana interrupted this pattern, and water surfaces in the area of the uplift sloped away from the uplift flanks. In the Mississippi Alluvial Plain in northeastern Louisiana, predevelopment water levels in the upper Claiborne aquifer were 60 to 80 feet lower than water levels in adjacent areas in the upper Claiborne aquifer and the underlying middle Claiborne aquifer, indicating an area of upward flow and predevelopment system discharge.

Simulations indicate that the greatest amount of aquifer recharge under predevelopment conditions was to the middle Claiborne aquifer in northern Mississippi and southern Tennessee where recharge rates exceeded 1 inch per year. The greatest aquifer discharge under predevelopment conditions was to the Mississippi River Valley alluvial aquifer east of Crowleys Ridge and west of the Memphis, Tennessee, area where water moved upward from the subcropping Claiborne and Wilcox aquifers into the alluvial aquifer at a rate of 0.6 inch per year. Large aquifer transmissivity, high heads in outcrop areas, and short flow paths from recharge to discharge areas were factors contributing to the high rates of recharge and discharge in the northern area of the embayment. Total predevelopment discharge to the Mississippi River Valley alluvial aquifer was about 34 million cubic feet per day (254 million gallons per day). The northern area of the embayment (north of the 35th parallel) had the greatest predevelopment discharge to the alluvial aquifer, about 21 million cubic feet per day (157 million gallons per day). The northern area had the greatest predevelopment vertical flow between aquifers; about 11.5 million cubic feet per day (86.0 million gallons per day) flowed upward into the upper Claiborne aquifer from the middle Claiborne aquifer. Predevelopment horizontal flow in the aquifers generally was southward and westward. Total predevelopment horizontal flow southward across the 35th parallel from the northern area was about 0.9 million cubic feet per day (6.7 million gallons per day). Total predevelopment horizontal flow westward across the axis of the embayment south of the 35th parallel was about 2.6 million cubic feet per day (19.4 million gallons per day). Most of the southward predevelopment horizontal flow was in the middle Claiborne aquifer, about 0.5 million cubic feet per day (3.74 million gallons per day). Most of the westward predevelopment horizontal flow was in the upper Claiborne aquifer, about 1.4 million cubic feet per day (10.5 million gallons per day).

Significant ground-water development of the Mississippi embayment aquifer system began in 1886 at Memphis, Tennessee, with pumpage from the middle Claiborne aquifer. During 1985 total pumpage from the five aquifers was about 102.2 million cubic feet per day (764.5 million gallons per day), a decrease of 5 percent from 1980 totals. The greatest pumpage during 1985 was from the middle Claiborne aquifer; about 74.3 million cubic feet per day (556 million gallons per day) was withdrawn. The Memphis, Tennessee, area had the largest ground-water usage during 1985; about 25.5 million cubic feet per day (191 million gallons per day) was pumped from the middle Claiborne aquifer. The least used aquifer in the Mississippi embayment aquifer system is the middle Wilcox; total pumpage during 1985 was about 3.3 million cubic feet per day (24.7 million gallons per day).

Flow analysis simulation indicates that 1987 water levels in the middle Claiborne aquifer were 125 feet below predevelopment levels in the Memphis, Tennessee, area. Water-level declines in the middle Claiborne aquifer of more than 200 feet below predevelopment levels have resulted from heavy pumpage in the Pine Bluff–Stuttgart and El Dorado areas in Arkansas and in the Monroe area in Louisiana.

Recharge to the middle Claiborne aquifer in outcrop areas east and southeast of Memphis under 1987 conditions was more than 1.5 inches per year. In the northern area of the embayment, total recharge to the middle Claiborne aquifer was about 40 million cubic feet per day (299 million gallons per day) during 1987, an increase of about 67 percent over predevelopment rates. Total aquifer-system discharge to the Mississippi River Valley alluvial aquifer was about 1.8 million cubic feet per day (13.5 million gallons per day) by 1987, a decrease of about 95 percent from predevelopment rates. In the northern area, net vertical flow between the upper Claiborne and middle Claiborne aquifers was upward prior to development but changed to downward flow of about 9.2 million cubic feet per day (68.8 million gallons per day) into the heavily pumped middle Claiborne aquifer during 1987.

Ground-water development in the Memphis area changed the direction of net horizontal flow east of the Mississippi River near the 35th parallel from southward before development to a northward flow of about 0.6 million cubic feet per day (4.49 million gallons per day) during 1987. Heavy pumpage from the middle Claiborne aquifer in the Pine Bluff–Stuttgart area in Arkansas increased the net southward horizontal flow on the west side of the Mississippi River to about 2.4 million cubic feet per day (17.2 million gallons per day) during 1987.

Comparison of the predevelopment and 1987 ground-water flow budgets indicates that the current (1985) pumpage from the five regional aquifers is supplied mostly by (1) increased recharge in the outcrop areas of the upper and middle Claiborne aquifers and (2) reduction of discharge from those two aquifers to the Mississippi River alluvial aquifer. Loss of ground water from aquifer storage is very small.

On a regional scale the five aquifers in the Mississippi embayment aquifer system have potential for future ground-water development; the middle Claiborne aquifer has the greatest potential for providing large point sources of water. Simulation results indicate that, by the year 2000, an increase in total pumpage from the aquifer system of 20 percent relative to 1985 rates will produce significant declines in water levels. Declines of about 25 feet below 1987 levels are indicated at the end of the 13-year period in the middle Claiborne aquifer in the Memphis, Tennessee, area and about 30 feet in the middle Claiborne aquifer in the El Dorado, Arkansas, and Monroe, Louisiana, areas. In the Jackson, Mississippi, and Pine Bluff–Stuttgart, Arkansas, areas, simulation results indicate that water levels in this aquifer will be about 20 feet below 1987 levels after 13 years.

Simulated point increases in pumpage of 5.35 million cubic feet per day (40 million gallons per day) added to the 1985 pumpage from the middle Claiborne aquifer at Marianna, Arkansas, south of the lower Claiborne confining unit facies change, would lower water levels in the aquifer at Marianna about 90 feet below 1987 levels by the year 2000. If the simulated increases in pumpage were at Wynne, Arkansas, north of the lower Claiborne confining unit facies change, water levels in the aquifer would be lowered about 30 feet below 1987 levels after 13 years.

INTRODUCTION

BACKGROUND

The Gulf Coast Regional Aquifer-System Analysis project is part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) program that began in 1978 to study the regional aquifers that provide a significant part of the country's freshwater supply (fig. 1). A brief overview of each RASA project is provided by Ren Jen Sun (1986). The Gulf Coast RASA project, which began in November 1980, is a study of regional aquifers that underlie about 230,000 mi^2 (square miles) in all or parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and Texas. The objectives of the project are to define the geohydrologic framework in which the regional aquifers exist, to describe the chemical and physical characteristics of the ground water, and to analyze the flow patterns within the regional ground-water system.

Three regional aquifer systems are delineated in the Gulf Coast RASA study area: the Mississippi embayment aquifer system, the Texas coastal uplands aquifer system, and the coastal lowlands aquifer system (Grubb, 1984). The three systems were delineated on the basis of differences in geologic framework, regional ground-water flow patterns, and distribution of fine-grained sediments. Five subprojects were conducted to study in detail different parts of these aquifer systems. Two of the subprojects focused on the Texas coastal uplands aquifer system and the coastal lowlands aquifer system, and two subprojects focused on two regional aquifers, the Mississippi River Valley alluvial aquifer and the McNairy-Nacatoch aquifer. This report discusses five regional aquifers in the Mississippi embayment aquifer system.

The Mississippi River Valley alluvial aquifer is the uppermost aquifer of the Mississippi embayment aquifer system throughout 33,000 mi^2 in the central part of the Gulf Coast RASA study area (fig. 2). The alluvial aquifer was selected for detailed study because it provides large quantities of water for agriculture, it has been partially dewatered locally, and it has a substantial hydraulic connection with the numerous streams that cross the Mississippi Alluvial Plain. Ackerman (1989, 1996) described the Mississippi River Valley alluvial aquifer and presented an analysis of regional ground-water flow in the aquifer.

The Texas coastal uplands aquifer system has been described by Ryder (1988; Ryder and Ardis, in press) and is laterally equivalent to the Mississippi embayment aquifer system. Both aquifer systems decrease in thickness in the vicinity of the Texas-Louisiana State line.

The Mississippi embayment aquifer system is separated from the coastal lowlands aquifer system by the Vicksburg-Jackson confining unit, which crops out in a narrow band across central Louisiana and central Mississippi. The confining unit overlies the Mississippi embayment aquifer system downdip of its outcrop area. Martin and Whiteman (1989; in press) described the coastal lowlands aquifer system, except that part in Texas, and presented an analysis of regional ground-water flow.

The McNairy-Nacatoch aquifer underlies the Mississippi embayment aquifer system in an area of about 27,000 mi^2 in the northern part of the Mississippi embayment and was chosen for study to investigate flow between aquifers studied in the central midwest RASA and the Mississippi embayment aquifer system (fig. 1). Brahana and Mesko (1988) described the McNairy-Nacatoch aquifer and reported that throughout most of its areal extent it is hydraulically independent of the Mississippi embayment aquifer system.

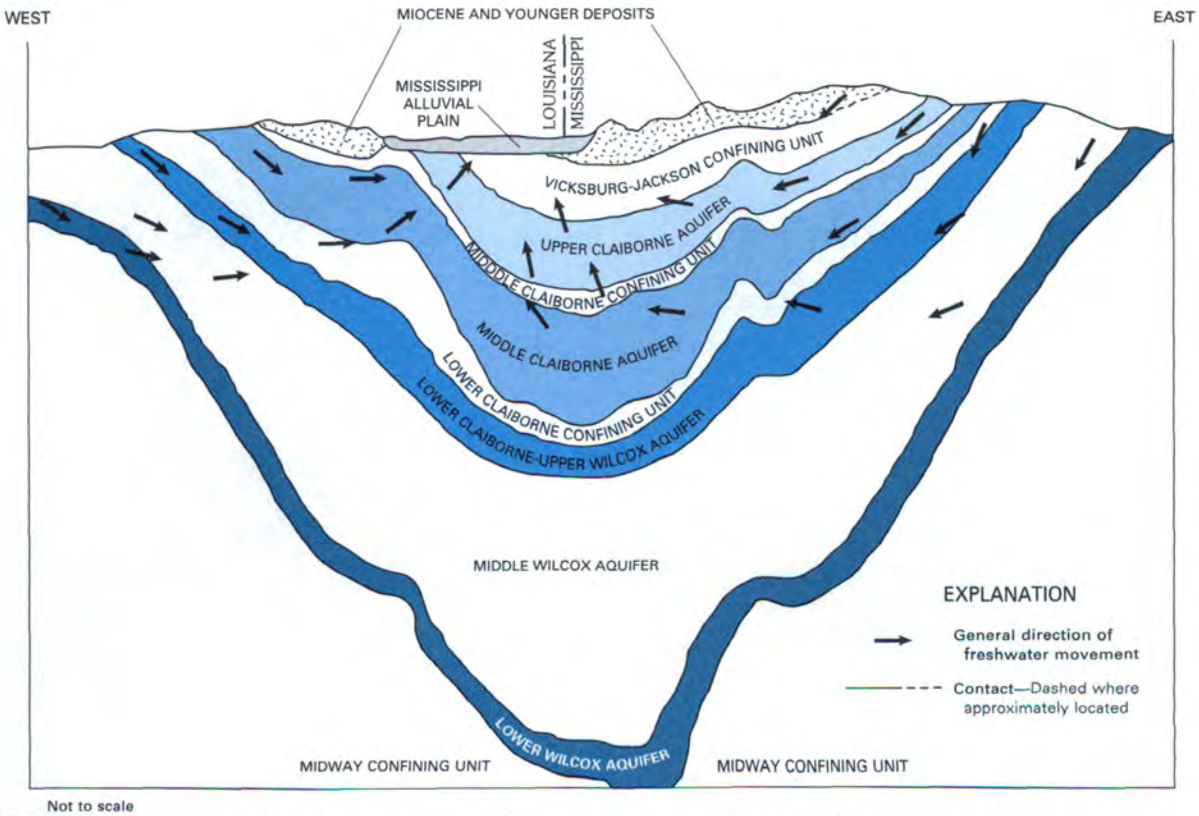


FIGURE 5.—Idealized hydrogeologic section, Louisiana, Mississippi, just south of a line from Monroe, La., to Jackson, Miss. Arrows indicate general direction of freshwater movement. Dashed line indicates contact is approximately located. Modified from Payne (1976, fig. 2).

other parts of the study area except that aquifer outcrops are more nearly parallel with the axis of the Gulf Coast geosyncline.

UPPER CLAIBORNE AQUIFER

The upper Claiborne aquifer is the uppermost of the five aquifers in sediments of Eocene age in the study area (table 1). The upper Claiborne aquifer underlies the Vicksburg-Jackson confining unit that separates the Mississippi embayment aquifer system from the coastal lowlands aquifer system in the southern part of the study area. The aquifer is separated from the older, deeper middle Claiborne aquifer by the middle Claiborne confining unit.

The upper Claiborne aquifer predominantly consists of sand beds in the Cockfield Formation and all sand beds in the Cook Mountain Formation that are in direct contact with the Cockfield sand beds. The aquifer mainly consists of interbedded fine- to medium-grained quartz sand, silt, and carbonaceous clay and averages about 250 feet thick in the subsurface. The aquifer thins downdip toward the Gulf as sediments gradually change to a clay facies. In part of the aquifer that contains freshwater, the total sand bed thickness (the aggregate of sand beds thicker than 20 feet) is from less than 100 feet in the northern part of the area to more than 300 feet in the vicinity of Vicksburg, Miss. (pl. 3). The upper Claiborne aquifer crops out on both sides of the embayment, and the major outcrop areas are in central Mississippi, north-central Louisiana, and south-central Arkansas. The aquifer underlies the Loess Hills in western Tennessee and is the most extensive subcropping aquifer underlying the Mississippi River Valley alluvial aquifer. The aquifer subcrops about 43 percent of the alluvial plain from northeastern Louisiana northward to about the northern extent of the embayment.

MIDDLE CLAIBORNE AQUIFER

The middle Claiborne aquifer, composed mostly of the Sparta Sand in the southern two-thirds of the study area and the Memphis Sand in the northern one-third (Tennessee, east-central Arkansas, southeastern Missouri, southwestern Kentucky, and northwestern Mississippi), is the most extensively developed of the five aquifers. The aquifer is composed of sand, clay, shale, and lignite. It underlies the entire central part of the study area and crops out on both sides of the embayment. It crops out in an arcuate band on the eastern side of the embayment from the northern end of the embayment in Kentucky, through Tennessee, and two-thirds the length of Mississippi. The outcrop band averages about 15 miles wide, with the widest and most extensive part of the band in north-central and northern Mississippi and western Tennessee. The middle Claiborne aquifer does not crop out in the northwestern one-third of the embayment: rather, the aquifer subcrops in a narrow band under the Mississippi River alluvial plain. The aquifer crops out on the western side of the embayment in southwestern Arkansas and northwestern Louisiana on the eastern flank of the Sabine uplift. The aquifer is the second most extensive subcropping aquifer; it underlies about 15 percent of the Mississippi River Valley alluvial aquifer, predominantly in northwestern Mississippi and northeastern Arkansas.

The middle Claiborne aquifer also includes sand beds of the Cook Mountain Formation where the sand beds are in direct contact with sand beds of the Sparta Sand. In some areas, the Cook Mountain Formation is composed of clay, and the top of the Sparta consists of clay. In these places the top of the aquifer is the top of the uppermost sand bed of the Sparta. The base of the middle Claiborne aquifer is the top of the underlying Zilpha Clay, or the Cane River Formation where that formation is clay. Where the basal Sparta consists of clay and overlies clay of the Zilpha or Cane River, the base of the aquifer is at the top of basal Sparta clay. Where the basal Sparta is sandy and the upper part of the underlying geologic unit is also sandy, the base of the aquifer is at the top of the first clay in the underlying unit.

In extreme northwestern Mississippi and east-central Arkansas near the 35th parallel, the underlying lower Claiborne confining unit undergoes a facies change. The predominantly marine clay of the confining unit south of the parallel changes to a massive sand and becomes part of the middle Claiborne aquifer north of the parallel. A hydrogeologic section illustrating this facies change is shown on plate 2. From the facies change northward, the middle Claiborne aquifer includes the stratigraphic interval that is occupied by the lower Claiborne confining unit and the lower Claiborne–upper Wilcox aquifer south of the facies change. In the area north of the facies change, the middle Claiborne aquifer is equivalent to the Memphis Sand. From the facies change southward, where the units exist, the lower Claiborne confining unit separates the middle Claiborne aquifer from the lower Claiborne–upper Wilcox aquifer, and the middle Claiborne confining unit separates the middle Claiborne aquifer from the upper Claiborne aquifer.

Aggregate sand thickness of the middle Claiborne aquifer is from about 100 to more than 700 feet; the aquifer is the thickest in the vicinity of the juncture of Arkansas, Tennessee, and Mississippi (pl. 3). In other areas aggregate sand thickness is commonly several hundred feet. The aquifer increases in thickness from its outcrop area to about 400 feet in the subsurface. Farther downdip the sand beds decrease in thickness until the aquifer pinches out near the Gulf of Mexico.

LOWER CLAIBORNE–UPPER WILCOX AQUIFER

The lower Claiborne–upper Wilcox aquifer underlies the lower Claiborne confining unit and may include all or parts of several stratigraphic units. The aquifer is made up of discontinuous, hydraulically connected sand beds in different geologic units and varies considerably in thickness and lithology. The aquifer includes all sand beds below the clay beds of the lower Claiborne confining unit down to and including the sand beds of the upper part of the Wilcox Group. The aquifer includes the sand beds of the Winona-Tallahatta and Meridian–upper Wilcox in Mississippi, the Carrizo-Wilcox sand in Louisiana, and the Carrizo Sand in Arkansas (table 1). In northwestern Mississippi and east-central Arkansas, where the lower Claiborne confining unit has changed to a sand facies, the lower Claiborne–upper Wilcox sediments are considered to be part of the middle Claiborne aquifer. Aggregate sand thickness of the lower Claiborne–upper Wilcox aquifer is greater east of the Mississippi River; in some areas sand thicknesses are more than 400 feet, as compared to 100–300 feet west of the Mississippi River (pl. 3).

The lower Claiborne–upper Wilcox aquifer crops out on both sides of the embayment and subcrops the Mississippi River valley alluvial aquifer in a small area in east-central Arkansas. The largest outcrop area is on the eastern side of the embayment and extends southward from about the 35th parallel for a distance two-thirds the length of Mississippi and into southwestern Alabama in an arcuate band 10–20 miles wide. The outcrop on the western side of the embayment in southwestern Arkansas and northwestern Louisiana is considerably narrower and shorter.

MIDDLE WILCOX AQUIFER

The middle Wilcox aquifer is the least significant aquifer in the Mississippi embayment aquifer system. The aquifer is composed predominantly of thin interbedded sand, silt, and clay and includes all sand beds of the Wilcox Group between the lower Claiborne–upper Wilcox aquifer and the lower Wilcox aquifer. The aquifer consists of sand beds hydraulically interconnected to varying degrees, and no dominant sand bed is traceable over a large area.

The middle Wilcox aquifer crops out on both sides of the embayment and subcrops the Mississippi River valley alluvial aquifer in northeastern Arkansas and southeastern Missouri. The outcrop area is less than 5 miles wide in the northern end of the embayment, about 10 miles wide in

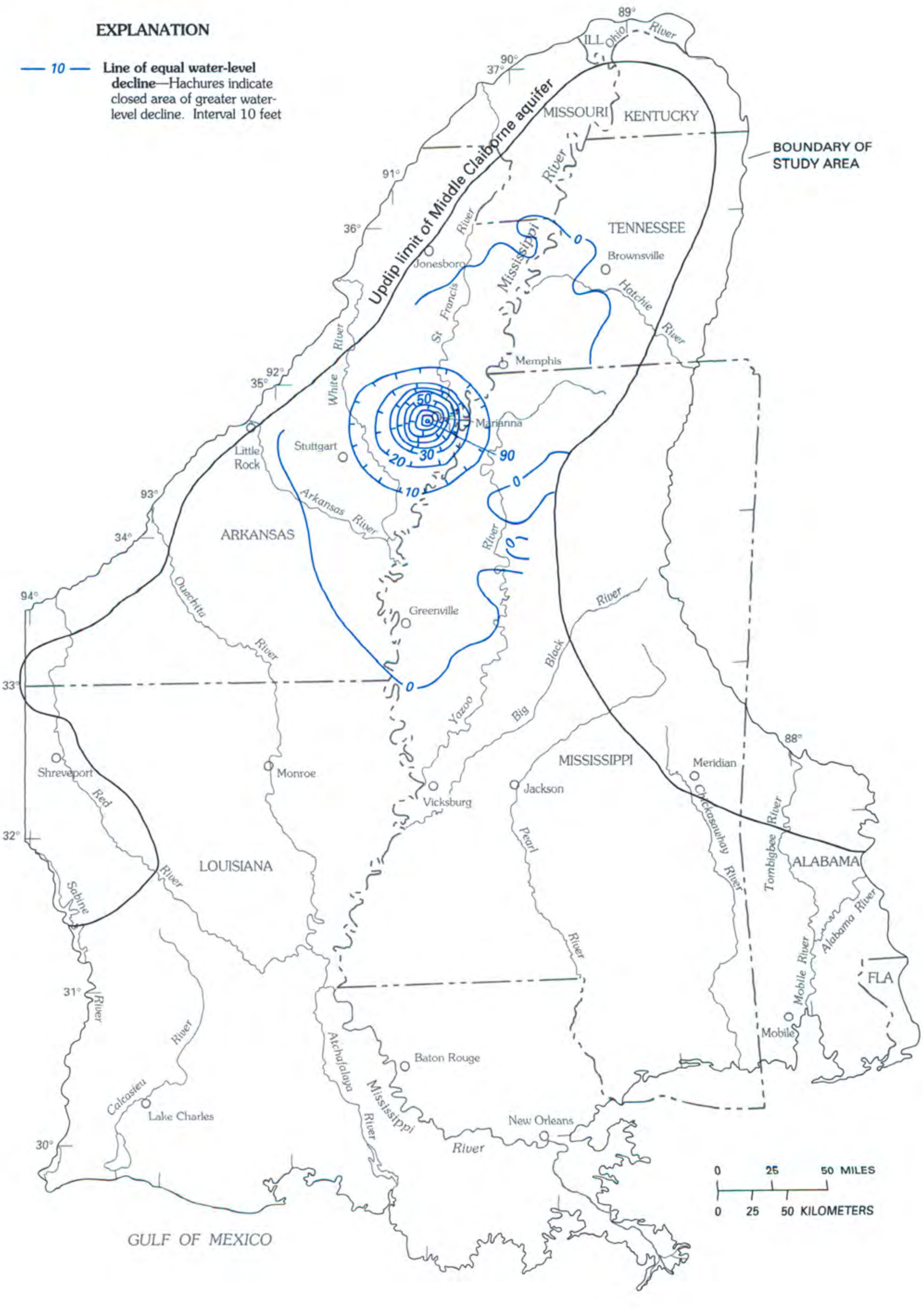

EXPLANATION
— 10 — Line of equal water-level decline—Hachures indicate closed area of greater water-level decline. Interval 10 feet
BOUNDARY OF STUDY AREA
Updip limit of Middle Claiborne aquifer
ILL
MISSOURI
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
FLA
Ohio River
Mississippi River
St Francis River
White River
Arkansas River
Hatchie River
Ouachita River
Yazoo River
Big Black River
Red River
Sabine River
Pearl River
Chickasawhay River
Tombigbee River
Alabama River
Mobile River
Calcasieu River
Atchafalaya River
Jonesboro
Brownsville
Memphis
Marianna
Stuttgart
Little Rock
Greenville
Shreveport
Monroe
Vicksburg
Jackson
Meridian
Mobile
Baton Rouge
Lake Charles
New Orleans
GULF OF MEXICO
89°
90°
37°
91°
36°
92°
35°
93°
34°
94°
33°
32°
31°
30°
88°
0
10
20
30
50
90
0 25 50 MILES
0 25 50 KILOMETERS

Exhibit 12

Excerpts from
Deposition of Jamie Crawford

(July 30, 2007)

UNITED STATES DISTRICT COURT
FOR THE NORTHERN DISTRICT OF MISSISSIPPI
DELTA DIVISION

JIM HOOD, ATTORNEY GENERAL, EX REL., THE STATE OF MISSISSIPPI, ACTING FOR ITSELF AND PARENS PATRIAE FOR AND ON BEHALF OF THE PEOPLE OF THE STATE OF MISSISSIPPI, PLAINTIFF

VS. CIVIL ACTION NO. 2:05CV32-D-B
CONSOLIDATED

THE CITY MEMPHIS, TENNESSEE, AND MEMPHIS LIGHT, GAS & WATER DIVISION, DEFENDANTS

DESOTO COUNTY, MISSISSIPPI PLAINTIFF

VS. CIVIL ACTION NO. 2:05CV085-D-B

THE CITY MEMPHIS, TENNESSEE, AND MEMPHIS LIGHT, GAS & WATER DIVISION, DEFENDANTS

NESBIT WATER ASSOCIATION, INC.; MISSISSIPPI UTILITY COMPANY, INC.; AND BILL J. ROBERSON, ON BEHALF OF THEMSELVES AND ALL OTHER ENTITIES AND PERSONS SIMILARLY SITUATED PLAINTIFFS

VS. CIVIL ACTION NO. 2:05CV108-D-B

THE CITY MEMPHIS, TENNESSEE, AND MEMPHIS LIGHT, GAS & WATER DIVISION DEFENDANTS

ORIGINAL

VIDEOTAPE DEPOSITION OF MDEQ 30(b)(6)
JAMIE CRAWFORD

Taken at Mississippi Department of Environmental Quality, 2380 Highway 80 West, Jackson, Mississippi, on Monday, July 30, 2007, beginning at 9:20 a.m.

1994.

A. That's correct.

Q. This is one of the documents that you found last week.

A. Yes.

Q. All right. Look at this second paragraph. This is your letter to Memphis Light, Gas and Water Company, correct?

A. Yes.

Q. You say: "The Memphis/Southaven area is obviously of interest and concern to all of the various players involved in protecting groundwater quality and availability."

Is that accurately read?

A. Yes.

Q. And you said that because you recognized that everybody in that area, in west Tennessee, northern Mississippi, has an interest in this shared resource, correct?

A. That's correct.

Q. You say next: "It is a forgone conclusion that the delineated WHPA's for the PSW wells/well fields in both states will reach across the Mississippi/Tennessee state boundary."

MDEQ is not part of the state and not part of this lawsuit?

MR. McMULLAN:

No, I'm not saying that at all. I'm just saying I don't think you should lead the witness this way, but I guess if you're treating him adversely. . . I guess I'll withdraw it.

You can treat him adversely, I guess. I guess you consider him to be adverse. But. . . Yeah. I'll withdraw it. You can take it that direction.

MR. BEARMAN:

Q. You're advocating cooperation here; is that correct?

A. Correct.

Q. Because everybody in that area shares this resource, correct? And I'm talking about the area in the Tennessee, Mississippi border area that we're -- that's the subject of this lawsuit. Everybody's got an interest.

A. Well, sure. And everybody -- everybody's using the Sparta.

Q. Southaven, correct?

A. Yes.

Q. Memphis?

A. Yes.

Q. So at least back in 1994, MDEQ was aware of this possibility that water could be coming across the border from Tennessee into Mississippi and from Mississippi into Tennessee, right?

A. Well, I don't know that any of us at the time truly believed that water would be flowing from Tennessee into Mississippi. The conversations that I've had, with the documents that you've been provided, indicate that we were having some discussions with folks, with various parties trying to work up some sort of an investigation that would look at these type things.

Most of my discussions with the folks at MLGW and with the Ground Water Institute during this period, their concern seemed to be mostly pulling contamination from Mississippi into Tennessee. Our --

Q. The concern of the people in Memphis?

A. Yes. Our interest was water -- was simply a water supply, water quantity issue where water was moving from Mississippi into Tennessee.

Exhibit 13

Excerpts from
Deposition of Charles Thomas Branch

(October 1, 2007)

UNITED STATES DISTRICT COURT
FOR THE NORTHERN DISTRICT OF MISSISSIPPI
DELTA DIVISION

JIM HOOD, Attorney General, ex rel.,
THE STATE OF MISSISSIPPI PLAINTIFF

VS. CIVIL ACTION NO: 2:05CV32-D-B
CONSOLIDATED FOR DISCOVERY

THE CITY OF MEMPHIS, TENNESSEE and
MEMPHIS LIGHT, GAS & WATER DIVISION DEFENDANTS

DESOTO COUNTY, MISSISSIPPI PLAINTIFF

VS. CIVIL ACTION NO: 2:05CV085-D-B

THE CITY OF MEMPHIS, TENNESSEE and
MEMPHIS LIGHT, GAS & WATER DIVISION DEFENDANTS

NESBIT WATER ASSOCIATION, INC., et al. PLAINTIFFS

VS. CIVIL ACTION NO: 2:05CV108-D-B

THE CITY OF MEMPHIS, TENNESSEE and
MEMPHIS LIGHT, GAS & WATER DIVISION DEFENDANTS

THE VIDEOTAPED DEPOSITION OF
CHARLES THOMAS BRANCH

Taken on behalf of the Defendants on October 1, 2007, at the Barrett Law Office, 404 Court Square North, Lexington, Mississippi 39095, beginning at approximately 9:36 a.m.

Reported By: Marilyn C. Rea, CSR 1059, RPR 036208

COPY

Q There's a paragraph that says -- that starts with the words, "It's important." Do you see that paragraph, in the far-right column? Right over here on this side, (indicating)?
A Yes, I see it.
Q That paragraph says, "It's important, Branch said, for all the groups having a stake in the aquifer to participate in efforts to protect it." Did I read that correctly?
A Yes, sir.
Q All right. And when it says "Branch said," they are talking about you, correct?
A I believe that's correct.
Q Is there any question in your mind that that's not talking about you?
A No, sir.
Q Okay. And you agree with that statement, right?
A I agree with it.
Q All right. And when you were talking to Tom Charlier about this article -- who wrote the article, correct?
A Uh-hum. Correct.
Q When you say all the groups having a stake in the aquifer, you are talking about

everybody in the region, all the tri-state region; East Arkansas, West Tennessee, North Mississippi, right?
A In this particular case, we were talking about those groups that were utilizing the aquifer right there in the Memphis and adjoining areas; Eastern Arkansas and Northwest Mississippi and, of course, the City of Memphis.
Q Okay. And then I am continuing there, and it says in quotes, 'whatever happens in one area effects people in another' he said. And he said, I am assuming, refers to you; is that correct?
A Correct.
Q "We need to have a more in depth understanding of how this system works," close quotes. Did I read that correctly?
A Correctly.
Q And you still believe that, right?
A I still believe that; that is correct.
Q Okay. And when you talk -- when you are talking to Tom Charlier for this article about "the system," you are talking about the -- in this article -- you are talking about the regional Memphis Sands Sparta aquifer system in this tri-state area that you just mentioned; the Eastern

Exhibit 14

Excerpts from
Basic Ground-Water Hydrology
By Ralph C. Heath

(2004)

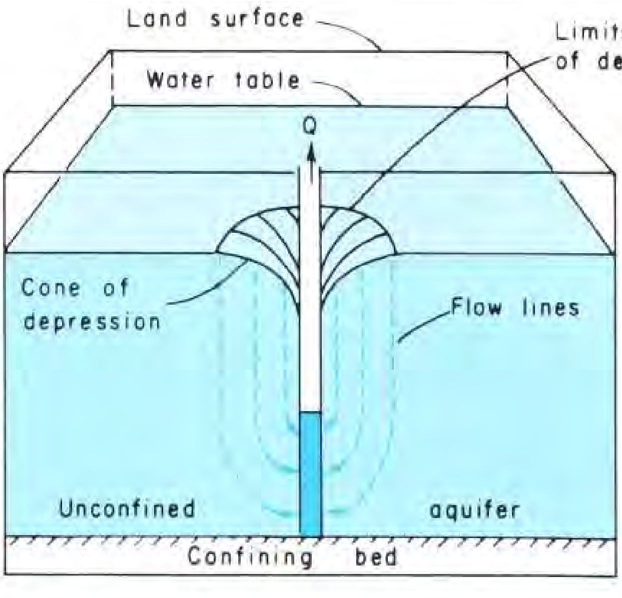
Basic Ground-Water Hydrology

By RALPH C. HEATH

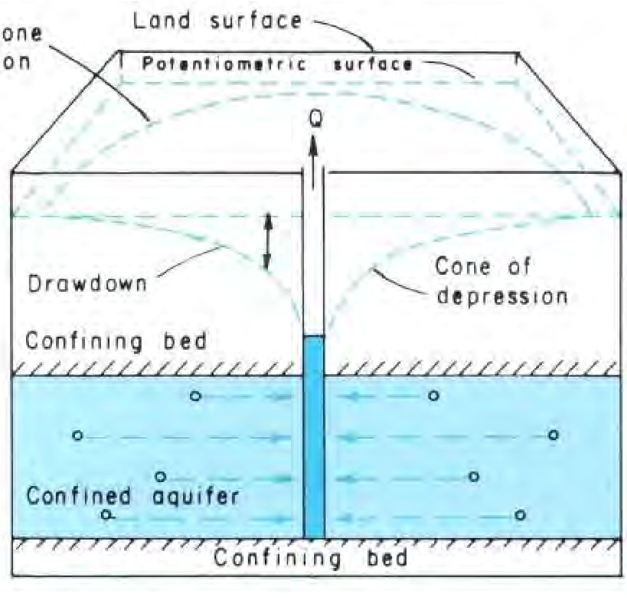
Prepared in cooperation with the
North Carolina Department of
Natural Resources and Community
Development

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2220

CONE OF DEPRESSION



(1)



(2)

Both wells and springs serve as sources of ground-water supply. However, most springs having yields large enough to meet municipal, industrial, and large commercial and agricultural needs occur only in areas underlain by cavernous limestones and lava flows. Therefore, most ground-water needs are met by withdrawals from wells.

The response of aquifers to withdrawals from wells is an important topic in ground-water hydrology. When withdrawals start, the water level in the well begins to decline as water is removed from storage in the well. The head in the well falls below the level in the surrounding aquifer. As a result, water begins to move from the aquifer into the well. As pumping continues, the water level in the well continues to decline, and the rate of flow into the well from the aquifer continues to increase until the rate of inflow equals the rate of withdrawal.

The movement of water from an aquifer into a well results in the formation of a *cone of depression* (1) (2). Because water must converge on the well from all directions and because the area through which the flow occurs decreases toward the well, the hydraulic gradient must get steeper toward the well.

Several important differences exist between the cones of depression in confined and unconfined aquifers. Withdrawals from an unconfined aquifer result in drainage of water from the rocks through which the water table declines as the cone of depression forms (1). Because the storage coefficient of an unconfined aquifer equals the specific yield of the aquifer material, the cone of depression expands very slowly. On the other hand, dewatering of the aquifer results in a decrease in transmissivity, which causes, in turn, an increase in drawdown both in the well and in the aquifer.

Withdrawals from a confined aquifer cause a drawdown in artesian pressure but do not (normally) cause a dewatering of the aquifer (2). The water withdrawn from a confined aquifer is derived from expansion of the water and compression of the rock skeleton of the aquifer. (See "Storage Coefficient.") The very small storage coefficient of confined aquifers results in a very rapid expansion of the cone of depression. Consequently, the mutual interference of expanding cones around adjacent wells occurs more rapidly in confined aquifers than it does in unconfined aquifers.

Cones of depression caused by large withdrawals from extensive confined aquifers can affect very large areas. Sketch 3 shows the overlapping cones of depression that existed in 1981 in an extensive confined aquifer composed of unconsolidated sands and interbedded silt and clay of Cretaceous age in the central part of the Atlantic Coastal Plain. The cones of depression are caused by withdrawals of about 277,000 $m^3\ d^{-1}$ (73,000,000 gal d^{-1}) from well fields in Virginia and North Carolina. (See "Source of Water Derived From Wells.")

Exhibit 15

Excerpts from
The State of Mississippi's Responses to
State of Tennessee's First Set of
Interrogatories

(January 20, 2017)

No. 143, Original

IN THE SUPREME COURT OF THE UNITED STATES

STATE OF MISSISSIPPI,
Plaintiff,

v.

STATE OF TENNESSEE, CITY OF MEMPHIS, TENNESSEE,
AND MEMPHIS LIGHT, GAS & WATER DIVISION,
Defendants.

THE STATE OF MISSISSIPPI'S RESPONSES TO STATE OF TENNESSEE'S FIRST SET OF INTERROGATORIES

COMES NOW, the State of Mississippi and Responds to State of Tennessee's First Set of Interrogatories as follows:

INTERROGATORY NO. 1: Identify each person likely to have information or knowledge that you may use to support your position that the groundwater at issue in this action "is an intrastate natural resource, not a naturally shared resource. Compl. ¶41.

RESPONSE: Individuals likely to have knowledge of this issue are generally found in the discovery materials from the prior district court proceeding which are still under review; however, the following individuals have been identified who have knowledge of this issue at this time:

exempted by this chapter shall use water without having first obtained a permit as provided herein . . . .").

- In determining whether the groundwater at issue is "intrastate" or "interstate," under existing United States Supreme Court precedent, the determination must first be made of the natural movement and storage under the geologic and hydrologic conditions at the time of creation of the states and their boundaries to which the property law within each state applies. The groundwater at issue originated in Mississippi, was stored in the Sparta Sand formation in north Mississippi, and would have, under natural conditions, never been available in Tennessee. This is evidenced and confirmed by the fact that MLGW must mechanically pump the water from underneath Mississippi's borders in order to produce and use it. In the absence of such pumping, the water would have remained in Mississippi.

INTERROGATORY NO. 3: Explain what you mean by your allegation that the groundwater at issue in this action is "confined" (Compl. ¶¶ 17, 47), including whether you mean that this groundwater is: (a) vertically confined in the sense that the Aquifer is sandwiched between layers of less permeable material above and below, or instead (b) horizontally confined with the territory of Mississippi by some physical or hydrological barrier that prevents or impedes the groundwater from flowing across the Mississippi-Tennessee boundary. If you mean "confined" in the latter sense, state the basis for your description of the water at issue as "confined."

<u>**RESPONSE**</u>**:** Mississippi objects to Interrogatory 3 on the grounds that Tennessee improperly defines "Aquifer" to conflate the natural groundwater movement and storage in a deep confined geological formation within each state's borders with generalized geology to erase state boundaries and sovereignty to natural resources residing within their territory under natural conditions.

Without waiving its objection, Mississippi states that the term "confined" in paragraphs 17 and 47 of the Complaint has both vertical and horizontal components as described above. First, groundwater at issue is confined vertically because the Sparta Sand geological formation in Mississippi is sandwiched between upper and lower clay formations which are impermeable, or of very low permeability. Second, the groundwater at issue is also horizontally confined by the natural hydrologic conditions in northwest Mississippi. Under these natural conditions, the groundwater collected in Mississippi could not flow or be stored outside Mississippi's sovereign territory. The sovereignty of each state over the resources naturally residing within its sovereign territory under the Constitution and laws of the United States is not changed by technological advances as Defendants argue.

This, the 20th day of January, 2017.

Respectfully submitted,

JIM HOOD
ATTORNEY GENERAL
STATE OF MISSISSIPPI

BY: ______________________

TITLE: Special Contract Attorney General

STATE OF MISSISSIPPI

COUNTY OF Hinds

PERSONALLY CAME AND APPEARED BEFORE ME, the undersigned authority in and for the state and county aforesaid, the within named George W. Neville who acknowledged that he/she executed the above and foregoing Response to Interrogatories in his/her capacity as SAAG, after first being duly authorized so to do.

____

SWORN TO AND SUBSCRIBED BEFORE ME, this the 20th day of January, 2017.

____
NOTARY PUBLIC

My commission expires:

May 7, 2017

STATE OF MISSISSIPPI
NOTARY PUBLIC
ID # 50224
FONDA I. HELLEN
Commission Expires
May 7, 2019
HINDS COUNTY

Exhibit 16

Excerpts from
Deposition of Richard Spruill

(September 28, 2017)

In the Matter Of:

STATE OF MISSISSIPPI vs

STATE OF TENNESSEE

OF TENNESSEE,

RICHARD SPRUILL

September 28, 2017

---

gradients.

Q. So understanding the point that you just made, generally speaking would you agree that groundwater in the Middle Claiborne is hydrologically connected to other aquifers in the Mississippi Embayment?

A. With the caveat that these aquifers are separated by confining layers that do transmit water under vertical hydraulic gradients and that sometimes the confining layers are absent.

Q. Would you also agree that groundwater in the Middle Claiborne is hydrologically connected to some surface waters in the area?

A. In the unconfined portions of the system I think they are hydrologically connected and some recharge takes place there. I also think they are hydrologically connected throughout the system even in the confined portions of the groundwater system.

Q. Would one of the surface waters to which groundwater in the Middle Claiborne is hydrologically connected include the Wolf River, for instance?

A. It could be.

Q. Any other rivers that you in particular were thinking of when you just answered my last question?

A. The river just to the south of the Mississippi-Tennessee border escapes me.

Q. Coldwater?

A. Yes. Any of the tributaries of the Mississippi, there could be long-term exchange with the aquifer and the Mississippi Embayment and the Mississippi, for example.

Q. Under predevelopment conditions the groundwater in the Middle Claiborne you would agree was not static?

Let me rephrase. The groundwater under natural conditions in the Middle Claiborne was all moving, correct?

A. Yeah. I would want to know your definition of "static." If your definition of "static" is it is not moving, then groundwater flow in all aquifer systems is moving. There is some theoretical spots where you can argue there is no movement, but for all practical purposes it is moving.

Q. So under natural conditions in this

Exhibit 17

Excerpts from
Expert Report Addendum #1 of Richard K. Spruill, Ph.D., P.G.

(July 31, 2017)

EXPERT REPORT
Addendum #1

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

PREPARED FOR:
Daniel Coker Horton & Bell, P.A.
265 North Lamar Boulevard, Suite R
Oxford, Mississippi 38655
Telephone: (662) 232-8979

PREPARED BY:
Groundwater Management Associates, Inc.
4300 Sapphire Court, Suite 100
Greenville, North Carolina 27834
Telephone: (252) 758-3310

GMA

July 31, 2017

Richard K. Spruill

Richard K. Spruill, Ph.D
Principal Hydrogeologist

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 <u>only</u> 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 <u>cannot</u> be quantified or evaluated properly in unconfined aquifers by using data from wells that have long sections of screens and/or have unknown construction details. Examination of the data sources cited by W&L 2015, and the locations assigned for many of their "well" data points used to create their Figure 4, reveals that they elected to combine indiscriminately data from confined and unconfined portions of the Sparta-Memphis Sand aquifer. Waldron and Larson's decision to combine these disparate data, in addition to the fundamentally flawed nature of the data itself, render the interpretation of the SMS' pre-development equipotential surface in W&L 2015 meaningless, and also explains why their interpretation is considerably different from that of USGS researchers (e.g., Reed, 1972; Criner and Parks, 1976).

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

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

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

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

invoking the scientific reputation of the USGS to support an opinion that is not an expert geological or hydrological opinion. Larson actually acknowledges that he is conflating a physical system with a computer simulation to meet his objective by stating that "*The fact that the numerical models of the Middle Claiborne are grounded on interstate connections and intend to simulate interstate conditions further supports my view that the groundwater within the Middle Claiborne aquifer is an interstate resource*." (page 3, paragraph 10).

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

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

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

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

Exhibit 18

Excerpts from
The State of Mississippi's Responses to City of Memphis, Tennessee, and Memphis Light, Gas & Water Division's First Set of Request for Admissions

(January 20, 2017)

No. 143, Original

IN THE SUPREME COURT OF THE UNITED STATES

STATE OF MISSISSIPPI,
Plaintiff,

v.

STATE OF TENNESSEE, CITY OF MEMPHIS, TENNESSEE,
AND MEMPHIS LIGHT, GAS & WATER DIVISION,
Defendants.

THE STATE OF MISSISSIPPI'S RESPONSES TO CITY OF MEMPHIS, TENNESSEE, AND MEMPHIS LIGHT, GAS & WATER DIVISION'S FIRST SET OF REQUEST FOR ADMISSIONS

COMES NOW, the State of Mississippi, by and through counsel, and Responds to City of Memphis, Tennessee, and Memphis Light, Gas & Water Division's First Set of Request for Admissions, as follows:

REQUEST NO. 1: The Aquifer underlies several states including Mississippi, Tennessee, and Arkansas.

RESPONSE: Mississippi objects to Request No. 1 because it improperly defines the "Aquifer" as "the underground hydrogeologic units identified in paragraphs 15 and 41 of the Complaint," and conflates the natural groundwater movement and storage in a deep confined geological formation within each state's borders with generalized geology to erase state boundaries and sovereignty to natural resources residing within their territory under natural conditions. (See

Defendants' "Definitions and Instructions," at paragraph 14.) Mississippi's claims relate solely to groundwater collected and stored in the Sparta Sand within Mississippi and its specific hydrogeology, not in multiple "hydrogeologic units." Further, the proposed definition and Request No. 1 are built on a false premise, as they fail to distinguish between (1) the sandstone geological formation known as the "Sparta Sand within Mississippi territory," and (2) the water naturally collected and stored in Mississippi in the Sparta Sand formation. Mississippi, therefore, denies Request No. 1.

Without waiving its objection, Mississippi states that the general geologic formation known as the Sparta Sand underlies several states, including Mississippi, Tennessee, and Arkansas; and avers that the groundwater at issue in this case underlies and is confined in Mississippi only under natural conditions, and is an intrastate natural resource.

REQUEST NO. 2: Groundwater from the Aquifer is being pumped and has been pumped from wells located in Mississippi and from wells located in Tennessee.

RESPONSE: Mississippi objects to Request No. 2 because it improperly defines the "Aquifer" as "the underground hydrogeologic units identified in paragraphs 15 and 41 of the Complaint," and conflates the natural groundwater movement and storage in a deep confined geological formation within each state's