APPENDIX

TABLE OF CONTENTS

Page

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PRE-DEVELOPMENT GROUNDWATER CONDITIONS SURROUNDING MEMPHIS, TENNESSEE: CONTROVERSY AND UNEXPECTED OUTCOMES[1]

Brian Waldron and Daniel Larsen[2]

ABSTRACT: Reliance on groundwater resources by differing governing bodies can create transboundary disputes raising questions of ownership and apportionment as the resource becomes strained through overuse or threatened by contamination. Transboundary disputes exist at varying scales, from conflicts between countries to smaller disputes between intrastate jurisdictions. In 2005 within the United States, the State of Mississippi filed a lawsuit against its political neighbor and their utility, the City of Memphis and Memphis Light, Gas, and Water, for groundwater deemed owned by the State of Mississippi to be wrongfully diverted across the state line and into Tennessee by the defendants. The

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basis of the 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. The suggested pre-development conditions were derived from limited groundwater level observations between 41 and 74 years post-development. A new pre-development map is constructed using historic records that range 0-17 years post-development that shows the natural flow is northwesterly from Mississippi into Tennessee and transboundary groundwater quantities have actually decreased since pre-development conditions.

(KEY TERMS: water allocation; water law; data management; water supply; Memphis aquifer.)

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INTRODUCTION

Transboundary water disputes are occurring more commonly as freshwater resources become strained. Conflicts, arising when water usage by one party becomes restricted due to the actions of a second party, occur at varying scales, from large international scale to smaller, intrastate jurisdictional scales (Rowland, 2005). A chief concern in assessing solutions to transboundary water disputes is knowledge of not only the total resource availability and quality but also how those resources have been redistributed or otherwise impacted due to human activity (Rowland, 2005). A common approach to water quantity or distribution disputes is to determine the water movement prior to water development, to use quantitative modeling to assess pre- and post-development groundwater budgets, and to apportion the resource according to sustainable yield (e.g., Rainwater *et al.*, 2005; Coes *et al.*, 2010). Significant challenges to establishing pre-development conditions are the lack or inconsistency of historic data and consistency of measurements made in the past as well as natural variability that may or may not be sampled by the available historic record (e.g., Meko *et al.*, 2007). Further complicating the picture is the legal presentation of water resource data that were never intended to be applied to establish pre-development conditions across jurisdictional boundaries. In this contribution, historic data acquisition and verification for rigorously determining pre-development water levels in a regional aquifer subject to a transboundary water dispute are discussed. The revised pre-development water level map is used to estimate pre-development water transfer across the boundary and demonstrate the importance of rigorously establishing pre-development hydrologic conditions in transboundary water disputes.

TRANSBOUNDARY WATER ISSUES AND THE CASE OF THE MEMPHIS AQUIFER

Examples of international transboundary groundwater disputes are numerous. In Western Europe, an inventory of transboundary groundwater conditions was conducted in 1999 by the Core Group Groundwater and the United Nations Economic Commission for Europe (UNECE). Of the 37 countries queried, 25 responded with a total of 89 transboundary aquifers identified (Arnold and Buzas, 2005). The results from the questionnaire indicated that >85% of the transboundary aquifers had groundwater quantity monitoring programs and roughly 80% had groundwater quality monitoring programs. Recognition of transboundary waters between two parties has culminated into joint monitoring agreements, such is the case with the United States (U.S.) and Mexico (1988), Switzerland and France (1978), Germany and Austria (1987), and others (Eckstein and Eckstein, 2005). Yet, interestingly, a conflict between parties is not always recognized among those who utilize the same resource. For example, Arnold and Buzas (2005) point out that one of the discrepancies in the aforementioned survey was that a transboundary aquifer may have been identified by one country but not by its counterpart. Confusion regarding ownership of groundwater beneath one's land owing to the paucity of groundwater law also exacerbates transboundary groundwater conflicts; such is not so much the case with surface water (Matthews, 2005). Surface water, because of its visible passage across the landscape, has a long history of water conflict law and thus the laws are better defined (Arnold and Buzas, 2005). It would seem that at the international scale transboundary groundwater conflicts have had more exposure (U.S.-Mexico Water Treaty, 1994; UNECE Water Convention), yet resolutions are still rarely achieved (Fuentes, 1999; Eckstein and Eckstein, 2005).

In the U.S., recognition of groundwater in transboundary water issues has found substantiation in surface water disputes, primarily in the mid-western and western states. Here, groundwater as early as the late 1800s was considered a tributary to surface water. The two systems have been treated as inseparable such as in Colorado (McClennan v. Hurdle, 1893; Medano Ditch Co. v. Adams, 1902; Comstock v. Ramsay, 1913), New Mexico (Templeton v. Pecos Valley Artesian Conservancy District, 1958; City of Albuquerque v. Reynolds, 1963), Nebraska (Sporhase v. Nebraska, 1982), and Arizona (Maricopa Co. Municipal Water Conservation District v. Southwest Cotton Company, 1931 and 1932).

In the southeastern U.S., the humid-temperate climate and associated precipitation (mean annual precipitation in Memphis is 142 cm/yr) may account for the lack of clarity in water right's law in comparison to the more arid western part of the country, yet groundwater conflict in this water-rich environment does exist. In 2005, the State of Mississippi filed an action lawsuit against the City of Memphis and the major utility, Memphis Light, Gas, and Water (MLGW), in Tennessee, claiming that groundwater withdrawal from the Memphis aquifer by MLGW had caused diversion of groundwater from beneath Mississippi into Tennessee (Hood v. City of Memphis, 2009). The State of Mississippi claims that under pre-development pumping conditions, the groundwater gradient and, hence groundwater flow under homogeneous, isotropic conditions, was east to west (Criner and Parks, 1976) parallel to the Mississippi-Tennessee state boundary. They further contend that since the pre-development period, which is considered to have ended in 1886 with construction of the first commercial well in Memphis, groundwater withdrawals from the Memphis aquifer in Tennessee, primarily within Shelby County, have caused the gradient to reorient to a southeast-northwest direction (Criner and Parks, 1976; Graham and Parks, 1986; Parks and Carmichael, 1990; Kingsbury, 1996; Brahana and Broshears, 2001), thus causing groundwater claimed to be owned by the State of Mississippi to move northward into Tennessee.

The first well drilled and screened in the Memphis aquifer was constructed by R.C. Graves, owner of the Bohlen-Huse Machine and Lake Ice Company (Bohlen-Huse) well in downtown Memphis in 1886. Pumping from this well is considered to mark the beginning of groundwater development from the Memphis aquifer. Of note, the water that issued from the well was abundant and of great quality as described by Safford (1890).

> The water was clear and sparkling, tonic and palatable. People drank of it. Crowds soon collected about the flowing fountain. Policemen were in requisition. The news spread like wildfire. The elixir of life had been found. Memphians of all degrees, high and low, old and young, with buckets and jugs, coffeepots and tin cans, waited in long files to be served, each in turn, from the gushing, hygienic well. And so for days. In good weather there could be seen lines of baby carriages, each with its little occupant, reaching from the well a square or so away. Physicians gave prescriptions: "Let the baby drink artesian water."

Pumping of groundwater from the Memphis aquifer in Shelby County, Tennessee has continued to increase exponentially since 1886 (Criner and Parks, 1976; Hutson and Morris, 1992; Hutson, 1999; Webbers, 2003). With the current groundwater withdrawal at 712,000 m^3/day, pumping has undoubtedly caused changes in groundwater movement from regions in neighboring Mississippi and Arkansas into Tennessee. Of critical importance regarding apportionment, however, are the deviation in hydraulic head from pre-development to current development conditions and availability of water to all potential users. A new pre-development potentiometric surface of the Memphis aquifer is presented based on the historical records between 1886 and 1904 that show the natural hydraulic gradient of groundwater was southeast to northwest, and thus flow was northwestward from Mississippi to Tennessee. The new potentiometric surface map indicates that calculations based on the pre-development conditions suggested by Criner and Parks (1976) would greatly underestimate the natural pre-development interstate water transfer. Determination of total interstate groundwater transfer is further complicated in this case by urban development and associated groundwater pumping in northwestern Mississippi, which was not addressed in the State of Mississippi lawsuit. This case study details the historical approach to determining pre-development conditions and some of the problems attendant to clarifying pre- to post-development changes in transboundary water transfer.

SITE DESCRIPTION

The Eocene Memphis aquifer underlies Shelby County, Tennessee, and the adjoining counties in Tennessee, Mississippi, and Arkansas (Figure 1). The Memphis aquifer is a thick, prolific freshwater aquifer that is part of the Mississippi embayment (ME) aquifer system (Hosman and Weiss, 1991). The ME is a shallow sedimentary basin that spans parts of nine states in the south-central U.S. with an axis that approximately follows the trace of the Mississippi River. The ME is filled with nearly 1,000 m of unconsolidated sand, silt, and clay in the study region (Cushing *et al.*, 1964).

The Memphis aquifer is 250 m thick in Shelby County and tapers to no thickness along the margins of the ME (Waldron *et al.*, 2010). South of the Tennessee-Mississippi state line, multiple thin clay-rich confining units separate the Memphis aquifer interval (the transition zone in Figure 1) into multiple aquifer systems (Brahana and Broshears, 2001), including the Sparta aquifer that is correlative to the upper section of the Memphis aquifer and the Meridian (Mississippi) or Carrizo (Arkansas) Sand that is correlative to the lower section of the Memphis aquifer (Waldron *et al.*, 2010).

The Memphis aquifer in Shelby County is confined above and below by the upper Claiborne confining unit and Flour Island confining unit, respectively. However, the upper Claiborne confining unit in Shelby County is leaky (Parks, 1990) and is known to provide an avenue of recharge from overlying water sources to the Memphis aquifer (e.g., Parks *et al.*, 1995; Brahana and Broshears, 2001; Larsen *et al.*, 2003). East of Shelby County, the Memphis aquifer is unconfined (Figure 1), but generally overlain by a thin (<5 m) veneer of Pleistocene loess. The aquifer comprised mainly of fine to very coarse sand with minor clay lenses, with estimated hydraulic conductivity values of 15-30 m/day (Parks and Carmichael, 1990). The quantity of clay increases and grain size of the sand decreases in the Memphis aquifer south of the Tennessee-Mississippi state line (Waldron *et al.*, 2010); however, the magnitude of the hydraulic impact of these textural changes is not known.

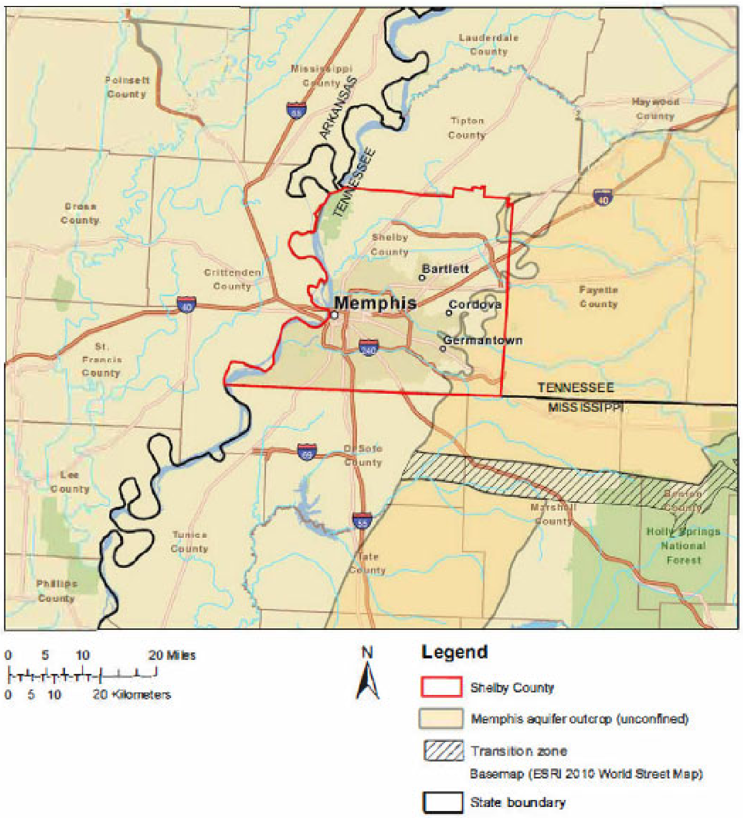

FIGURE 1. Map of the Memphis Area and Surrounding Region, Showing the Estimated Outcrop Zone for the Memphis Aquifer (from Brahana and Broshears, 2001). Transition is approximate southern extent of Memphis aquifer in northern Mississippi, where the regional middle Claiborne is divided into three or more distinct aquifers separated by regional confining units (Waldron *et al.*, 2010).

Criner and Parks (1976) developed a pre-development potentiometric map of the Memphis aquifer beneath Shelby County based on five well locations that depicted groundwater level conditions at the point of discovery of the prolific aquifer system in 1886. They indicate that groundwater generally flowed westward from Fayette County, Tennessee, across Shelby County and into Crittenden County, Arkansas. Although no water level data were presented for locations in northern Mississippi, they showed perpendicular potentiometric contours along the Tennessee-Mississippi state line, suggesting that no flow occurred across the state line prior to groundwater development (Figure 2).

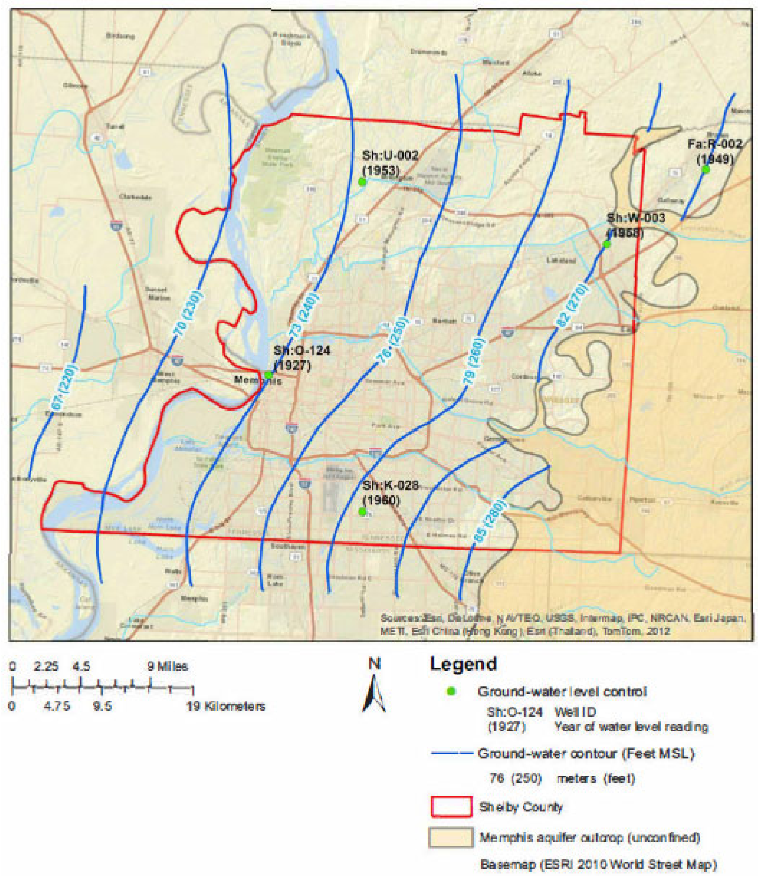

FIGURE 2. Pre-development Potentiometric Surface Map Prepared by Criner and Parks (1976) Showing Wells Used for Control and Dates of Recording Used for Map. Memphis aquifer outcrop pattern from Parks (1990) shown to illustrate region of unconfined conditions.

Since pre-development conditions, pumping in Shelby County has caused groundwater gradients to readjust; hence, the potentiometric contours suggest flow along the Arkansas-Tennessee state line to be more eastward, flow from Fayette and Tipton counties has made a southerly turn and flow along the Tennessee-Mississippi state line is now toward the northwest (Figure 3). This trend has been apparent since the early 1960s (Criner and Parks, 1976; Graham, 1979; Parks and Carmichael, 1990; Kingsbury, 1992). The large cone of depression in western Shelby County centers on downtown where the oldest well fields exist.

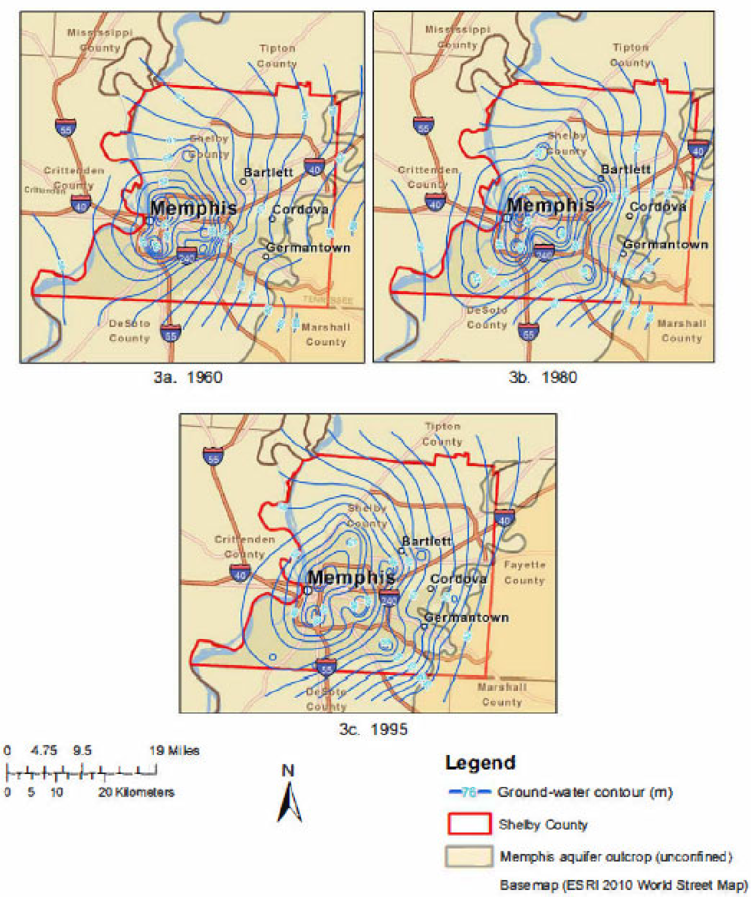

FIGURE 3. Potentiometric Surface Maps for Memphis Aquifer in 1960 (Criner and Parks, 1976), 1980 (Graham, 1982), and 1995 (Kingsbury, 1996). Illustrating changes in water levels in Shelby County, Tennessee as development proceeded during the past century.

In the unconfined regions of the Memphis aquifer, groundwater gradients are expected to be toward the river systems, similar to what is observed in the shallow aquifer beneath Shelby County (Graham and Parks, 1986; Konduru, 2007). Overall, the general flow within the tristate region is toward the embayment axis with a southward trend toward the Gulf of Mexico (Hosman *et al.*, 1968).

Groundwater withdrawal in Shelby has increased exponentially since pre-development. From 1886 to 1975, withdrawals increased from below 38,000 to over 681,000 m^3/day (Criner and Parks, 1976). Over the next 20 years, withdrawals plateaued, averaging 628,000 m^3/day (Hutson and Morris, 1992; Hutson, 1999) before increasing again to a new level of 710,000 m^3/day in 2005 (Webbers, 2003; Kenny *et al.*, 2009).

HISTORY

In 2005, the State of Mississippi filed a lawsuit against the City of Memphis and MLGW in Tennessee, seeking apportionment and compensation (1.3 billion U.S. dollars) for groundwater that has been artificially pulled across the state line between Desoto and Shelby counties due to extensive withdrawals by the defendants. Their claim is based on groundwater flow patterns inferred from the pre-development and post-development potentiometric surface maps of the Memphis aquifer described by Criner and Parks (1976).

In February 2008, Judge Davidson of the U.S. District Court for the Northern District of Mississippi Delta Division ruled that because the Memphis aquifer was an interstate body of water, Tennessee as a sovereign entity should be involved in the lawsuit pursuant to Rule 19 of the U.S. Federal Rules of Civil Procedure (Hood Ex Rel. Mississippi v. City of Memphis, Tenn., 2008). Because Judge Davidson warranted Tennessee's involvement, lawsuits between states must be heard by the U.S. Supreme Court under 28 U.S.C. §1251(a).

The State of Mississippi appealed Judge Davidson's ruling to the Fifth Circuit Court of Appeals. The original ruling by the District Court was affirmed (Hood v. City of Memphis, 2009). The lawsuit was elevated to the U.S. Supreme Court who dismissed the case without opinion; however, by dismissing without prejudice the State of Mississippi can file the original action with the U.S. Supreme Court if the correct parties are involved and injury is quantified. It remains unknown if the State of Mississippi will pursue the lawsuit further. The pre-development map constructed from this research will have direct bearing on what injury, if any, can be substantiated.

PRE-DEVELOPMENT CONDITIONS

Criner and Parks (1976) constructed their depiction of pre-development conditions using five water level measurements as control. Two control points are in northern Shelby County, the third is in northwestern Fayette County, the fourth control is located in downtown Memphis (not the Bohlen-Huse well), and the remaining control point is located in the southern portion of Shelby County (Figure 2); however, no data from northern Mississippi were used. Criner and Parks (1976) state that the groundwater levels at these locations represent pre-development conditions in the Memphis aquifer before pumping began, which is considered to be 1886 (Criner and Parks, 1976; Brahana and Broshears, 2001; Clark and Hart, 2009). Yet, the time between pre-development and the water levels used by Criner and Parks (1976) spans 41-74 years post-pre-development.

Earlier records of groundwater levels in the region by Glenn (1906), Crider and Johnson (1906), and Fuller (1903) tabulate locations of towns or persons and information about their wells including well depth, depth to groundwater, pump rate, and water quality. The earliest Memphis aquifer well is the famous R.C. Graves well in downtown Memphis, Tennessee, marking the 1886 pre-development date. As shown in Table 1, wells in Glenn (1906) place the latest well records only 17 years post-pre-development. Mapping these early, near pre-development period groundwater levels is essential to establishing rigorous control on pre-development groundwater conditions in the region, but required determining or, in some cases, reconstructing the locations, ground surface elevations, and screened intervals of each of these wells.

15a

TABLE 1. Listing of Historic Wells between 1886 and 1906, Used in Developing Memphis Aquifer Pre-development Conditions.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
1	Fuller (1903) p. 378	Turrell	Arkansas	Crittenden	N/A	69	860 ft (262 m)	10 ft (3 m)	66	2.5	Location obtained from Omni Gazetteer (p. 373)	Lumber	1900	Steam pump	Well drilled by the Baker Lumber Company; only Baker in Crittenden County listed in 1910 census was W.R. Baker who lived within the Tyranza township which is proximal to Turrell
2	Fuller (1903) p. 380	Helena	Arkansas	Phillips	N/A	57	543 ft (166 m)	30 ft (9 m)	48	0.0	Located at Helena Water Co., original well site surveyed	Municipal	1890	Air lift	From L.C. Railroad maps (1878), Helena is located in today's location as there is also a West Helena
3	Fuller (1903) p. 380	Forrest City	Arkansas	St. Francis	N/A	77	460 ft (140 m)	160 ft (49 m)	28	0.0	Original well site surveyed	Municipal	1896	Pump	Town report no. 15 from the Arkansas Actuarial Bureau (1916) states location of the pumping station a quarter mile from the mercantile district on the south side of West Front Street, west of South Rosser. (quote)

(continued)

16a

TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
4	Crider and Johnson (1906) p. 30	Hernando	Mississippi	Desoto	N/A	109	165 ft (50 m)	20 ft (6 m)	102	4.2	City center	N/A	1903 pub	Pump	Document states quality is similar to that of Memphis
5	Fuller (1903) p. 346	Holly Springs	Mississippi	Marshall	N/A	180	400 ft (107 m)	175 ft (53 m)	127	2.5	Located in town center	Municipal	1898	Steam pump	
6	Fuller (1903) p. 346	Hudsonville	Mississippi	Marshall	N/A	151	168 ft (51 m)	153 ft (47 m)	104	2.5	E.C. Mahon	N/A	1897	Bucket	E.C. Mahon (Elton C. Mahon (age 17) was the son of Joseph (age 61 — farmer) and Amanda Mahon (age 58 — school teacher) based on 1900 census
7	Glenn (1906) p. 71	Canadaville	Tennessee	Fayette	N/A	121	150 ft (46 m)	125 ft (38 m)	83	2.5	Historic county map shows location at end of dog leg of Canadaville Rd.	Post stop	1895	Pump	James S. Morris is a farmer on Macon Rd. (1910 census)
8	Glenn (1906) p. 71	Claxton	Tennessee	Fayette	N/A	116	85 ft (26 m)	40 ft (12 m)	104	2.5	S.T. Taylor; Claxton was named after the Claxton family. The location of the now gone community was provided by word of mouth. Location was triangulated from a 1895 map of the county	Post stop to Staton on Hwy. 222 (1893 to 1905) and mercantile	1899	Pump	Interviewed elderly lady worked for the Claxton family; said town was located north of the intersection of Stanton Rd., Glade Spring Rd. and Winfrey Rd.

(continued)

17a

TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
9	Fuller (1903) p. 360	Ina	Tennessee	Fayette	N/A	152	110 ft (34 m)	102 ft (31 m)	121	3.8	F.W. Day; Omni Gazetteer of the United State of America, vol. 4 1991 (found on page 976)	N/A	1900	Valve bucket	F.W. Day from 1910 census lived on South Main so inside city limits; Day was the mail carrier
10	Glenn (1906) p. 71	LaGrange	Tennessee	Fayette	532 ft (162 m)	165	175 and 213 ft (53 and 65 m)	194 ft (59 m)	106	3.6	Placed along Main street and 4th and the railroad to the north	N/A	1906 pub	N/A	Town started on Samuel B. Harper's tract of 167 acres, Oct. 1827; 225 town lots laid off south of 4th street with lots 1-14 north of 4th street; Greenhigh Infirmary (Dr. James Nicholson Cocke) offered water cure baths (1855)
11	Glenn (1906) p. 72	Moorman	Tennessee	Fayette	N/A	116	103 ft (31 m)	53 ft (16 m)	100	2.5	Intersection of Hwy 222 and Winfrey	N/A	1897	Windmill	Issac Bowers (farmer listed in 1900 census; no location information)
12	Glenn (1906) p. 72	Moscow	Tennessee	Fayette	354 ft (108 m)	109	95 ft (29 m)	69 ft (21 m)	27	2.5	Placed at present town center	N/A	1906 pub	N/A	Established in 1826 as part of Daniel W. Head's 60.5 acres; D.W. Head appointed overseer to cut road from Head's Ferry (assumed to

(continued)

TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
															be Hwy 76) to Somerville; Railroad leaving town center toward Somerville on 1876 map; town center on 1876 map shown south of Wolf River in present town location
13	Fuller (1903) p. 360	Oakland	Tennessee	Fayette	N/A	116	125 ft (38 m)	75 ft (23 m)	93	2.5	Center of roads Church (west), Oak (north), Hathaway (east), and Yancy (south)	N/A	~1890	Pump	B.J. Flippin (age 58) is a miller and gin in 1900 census; no location information
14	Glenn (1906) p. 72	Rossville	Tennessee	Fayette	311 ft (95 m)	95	N/A	32 ft (10 m)	86	2.5	Placed at intersection of Main and the railroad	N/A	1906 pub	N/A	John F. Robertson had 200 acre plantation — sold 4 acres to railroad ~1837; Came into existence in 1853, built on 25 acres for building of a town at the depot at a place known as Lafett on the Memphis and Charleston railroad. No depth of well was given, but description stated that well screen was below

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19a

TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
															clay and in white sand (consistent with description of Memphis Sand)
15	Glenn (1906) p. 72	Somerville	Tennessee	Fayette	356 ft (109 m)	117	136 ft (41 m)	50 ft (15 m)	102	2.7	C.W. Robertson; placed at courthouse where Main circles and heads north as Hwy 76	Domestic	1898	Hand pump	Well used for gardening
16	Fuller (1903) p. 360	Taylor's Chapel	Tennessee	Fayette	N/A	109	80 ft (24 m)	60 ft (18 m)	91	3.7	R.V. Taylor; Omni Gazetteer of the United State of America, vol. 4 1991 (found on page 1121); Cemetery on USGS Lacona quad (7.5 min)	N/A	1902	Valve bucket	
17	Fuller (1903) p. 362	Belle Eagle	Tennessee	Haywood	N/A	101	70 ft (21 m)	60 ft (18 m)	82	3.5	R.H. Taylor	N/A	1896	Bucket	Not in 1900 nor 1910 census
18	Glenn (1906) p. 82	Brownsville	Tennessee	Haywood	344 ft (105 m)	108	230 ft (70 m)	Avg. 47 ft (14 m)	94	5.5	Centroid of town limits in 1877	Municipal	1895	Compressed air	Water level taken from underground waters of TN and KY 1906 (p. 83 top)
19	Fuller (1903) p. 362	Forked Deer	Tennessee	Haywood	N/A	106	96 ft (29 m)	Artesian	106	3.9	H.A. Rainey	N/A	1900	Pump	Not in 1900 nor 1910 census

(continued)

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TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
20	Glenn (1906) p. 84	Ged	Tennessee	Haywood	N/A	111	247 ft (75 m)	60 ft (18 m)	92	4.2	Triangulation of location from current road intersections to historic location	Domestic	1906 pub	N/A	TN post offices and postmaster appointments 1789-1984, Frazier, D.R. 1984; Ged was a post office from 5/22/1882 to 12/31/1903; post office map shows Ged south and west of Carolina post office on 1877 map; on 1877 map there is a home (Mrs. E.A. Davie) in the approximate location of Ged with a store located a very short distance west of her property; using the intersection of concentric circles from similar road intersections between the 1877 roads and those that exist presently (Jefferson and rail crossing and Old Highway 19 and Elm Tree) Ged was pinpointed

(continued)

21a

TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
21	Glenn (1906) p. 85	Keeling	Tennessee	Haywood	N/A	110	96 ft (29 m)	46 ft (15 m)	95	2.5	Town existed just west of current intersection of Keeling Road and Fredonia Loop Road	N/A	1896	Valve bucket	
22	Glenn (1906) p. 85	Stanton Depot	Tennessee	Haywood	290 ft (88 m)	101	140 ft (43 m)	40 ft (12 m)	88	3.2	Centroid of small parcel north of Main along southwest-northeast dogleg	Railroad	1906 pub	N/A	Haywood County map (1877) included 3 detailed inserts one being Stanton Depot; a spur from the Memphis Division of Louisville-Nashville Great Southern Railroad ran between the north leg of Main Street to the east and Lafayette Street to the west
23	Fuller (1903) p. 362	Arlington	Tennessee	Shelby	N/A	83	228 ft (67 m)	8 ft (2 m)	25	3.3	Located within old section of town's present location	Railroad	1901	Pump	Water used for locomotives and was of fine quality; same depth to water found by Wells, 1932 pub
24	Glenn (1906) p. 107	Bleak	Tennessee	Shelby	N/A	113	176 ft (54 m)	47 ft (14 m)	98	3.5	Located from 1916 U.S. Soils Map	Stagecoach stop and post	1906 pub	N/A	Mail post to Olive Branch, Mississippi; 4 postmen between 1893 and 1905 from Post Office

(continued)

TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
															Department Library Collection of Historic Maps, 1550-1928; town location present on 1916 U.S. Soils Map
25	Glenn (1906) p. 107	Collierville	Tennessee	Shelby	377 ft (115 m)	119	239 and 248 ft (73 and 76 m)	95 ft (29 m)	27	0.6	Fire station on current town square	Municipal	1906 pub	Pump	Original well site was at same location as the fire station presently on the town square northeast corner
26	Fuller (1903) p. 362	Cordova	Tennessee	Shelby	N/A	110	125 and 128 ft (38 and 39 m)	50 ft (15 m)	95	2.5	Intersection of Macon Road and railroad	N/A & N/A	1900	N/A & boiler	J.W. Allen and W.G. Allen owned wells; Allen family identified on 1888 Shelby County map near Dexter railroad stop east of Cheatam Road
27	Fuller (1903) p. 364	Eads	Tennessee	Shelby	N/A	102	100 ft (30 m)	60 ft (18 m)	84	2.6	T.C. Owen; 1910 Census; lived on Front Street in Eads	Domestic	1898	Pump	Eads was a railroad stop on Tennessee Midland Railroad located 40 chains north of Eads

(continued)

23a

TABLE 1. Continued.

ID	Citation	Town	State	County	Published Ground-Surface Elevation (ft and m) (MSL)	Estimated Ground-Surface Elevation (m) (MSL)	Well Depth (ft and m)	Depth to Water (ft and m)	Calculated Water Elevation (m) (MSL)	Estimated Vertical Error (m)	Method of Location	Well Purpose	Year of Installation	Method of Withdrawal	Supplemental Information
28	Fuller (1903) p. 364	Massey	Tennessee	Shelby	N/A	100	200 ft (61 m)	100 ft (30 m)	69	1.3	Original well site found on old Kirby farm	N/A	1899	Gasoline engine	J.A. Kirby; 1900 Tennessee Census (ED 45 Sheet 3 Line 34); north of Nonconnah Creek in 11th district
29	Glenn (1906) p. 110	Memphis	Tennessee	Shelby	N/A	71	354 ft (108 m)	Artesian	71	1.0	Located on R.C. Graves well house property using 1890 Sanborn maps	Municipal	1886	Artesian	1901 map of Memphis, TN; artesian water department shown south of Auction, north of Concord, between Fifth and Fourth just east of Bayou Gayoso Creek
30	Glenn (1906) p. 116	Covington	Tennessee	Tipton	316 ft (96 m)	87	533 ft (162 m)	31 ft (9 m)	77	2.5	ICRR rail depot	Railroad	1906 pub	Pump	On 1909 plate maps, the ICRR Depot is located in Block 8, sheet 8 between Liberty to the west, Pleasant to the south and between the 2nd and 3rd spurs from the west
31	Glenn (1906) p. 117	Tabernacle	Tennessee	Tipton	N/A	101	225 ft (69 m)	106 ft (32 m)	68	3.8	Intersection of Tabernacle and Hwy 179	N/A	1906 pub	N/A	Underground waters of TN KY 1906 (p. 117)

Note: MSL, mean sea level.

APPROACH AND METHODS

Finding Historic Well Locations

As these late 19th and early 20th Century wells no longer exist, determining their location required an extensive analysis of archive records available in county courthouses, libraries, and digital databases. Some well records mention only the town name. In these cases, historic maps were used to place the well in the approximate center of the road network for that town (see id's 1-5, 7, 10-13, 15-21, 24, and 31 in Table 1). In these instances, the spatial error would be at its largest covering multiple city blocks with the largest estimated error at just under 450 m. In many of these instances, the well was used to provide water to steam locomotives; in these cases, the well was placed near the rail yard (see id's 14, 22, 23, and 30 in Table 1). The remainder of the wells were located based on a well owner's name whose location could be determined from either 1900 or 1910 census records (i.e., an address) (see id's 6, 9, and 27), property descriptions, and blueprint drawings (see id's 8, 25, and 29) or their property boundary that was found on historic plats (see id's 18, 26, and 28). In these latter instances, the spatial error would be at its lowest with some well locations mapped direct atop the structure in which they were housed. Spatial error will be incorporated into the analysis of flow across the Tennessee-Mississippi state line in a later section.

Determining Ground Surface Elevations

The water level for each well was recorded as depth to water (Fuller, 1903; Crider and Johnson, 1906; Glenn, 1906). To standardize the water levels, the approximate ground surface elevation of the well was determined in reference to mean sea level (MSL) using the vertical datum of 1988. The most accurate ground surface elevation came from surveying the well. The original well sites at Helena, Arkansas and Forrest City, Arkansas still exist. A survey traverse was performed from a benchmark to the well site and the measured ground surface elevation used.

The second most accurate elevation was from interpolation of elevation contours mapped by the U.S. Army Corps of Engineers (USACE) during the 1930s (USACE, 1932). Using these older elevation contours was critical in downtown Memphis, Tennessee, where growth and development have greatly altered the landscape. The only well located in downtown Memphis was the Bohlen-Huse well drilled by R.C. Graves in 1886. Glenn (1906) stated that the original water level in this well was 68.9 m MSL. Based on the location of the Bohlen-Huse facility from an 1897 Sanborn map, the ground surface elevation as interpolated from a 1932 USACE contour map was approximately 234 ft (71.0 m) MSL. Given that flowing artesian conditions originally existed at the well, the water level for this well was adjusted from 68.9 m to reflect the 71.0 m land surface elevation. Wells (1932, 1933) suggests that the original water level for this well was between 70.1 and 71.6 m MSL.

For the remainder of the wells, the lack of data for original land surface elevations, such as that available for wells mapped in downtown Memphis, required using more recent elevation data: 60-cm resolution LiDAR (2006) and the U.S. Geological Survey (USGS) national elevation dataset (NED) at 30-m spacing. As LiDAR existed only for Shelby County, Tennessee, ground surface elevation estimates for the wells in Shelby County with the exception of the Bohlen-Huse well were determined using this dataset. The USGS NED dataset was used for the remainder of the wells. For wells mapped to a town center, an average ground surface elevation was calculated based on the elevations within the boundary of the town's outskirts as defined by its historic road network. When a town's boundary could not be determined, an elevation was calculated by averaging elevations within a square kilometer area centered on the well point. Fewer elevations were included in the average for those instances where the well was more accurately located to a rail yard or property boundary.

Vertical error is introduced when using the LiDAR and USGS NED with the latter having the largest error of approximately 2.44 m. An estimate of the vertical error was calculated based on comparing the average elevation plus one standard deviation to the NED error; the larger of the two was set as the vertical error. As an estimate of the vertical error for the LiDAR data was not available, those wells whose elevations were measured using LiDAR were assigned a vertical error estimate of 2.44 m. In those instances when the well location and elevation were surveyed, the vertical error was less than 1 cm. Vertical error (see Table 1) will be incorporated into the analysis of flow across the Tennessee-Mississippi state line in a later section.

Validating Well Screen Intervals in the Memphis Aquifer

The final step to assessing wells appropriate for determining pre-development conditions was to ascertain whether the well was screened within the Memphis aquifer. As none of the well records had screen information, it was assumed that the base of the well screen was equal to the well's total depth.

Using the total well depth as a guide, nearby geophysical logs to each well were used to validate proper emplacement in the Memphis aquifer.

Constructing Memphis Aquifer Pre-development Water Levels

The pre-development groundwater level condition for the Memphis aquifer shown in Figure 4 was developed using 27 control points over an 11-county footprint. Water level contouring was a two-part process. First, Delaunay triangulation was performed to obtain a preliminary representation of the water level contours. Using the triangulation results plus the distance measurements from the convex hull, water level contours were adjusted further by hand to smooth jagged contours often associated with this technique and more accurately represent the groundwater/surface water connection in the unconfined area of the Memphis aquifer.

In Fayette and Haywood County, Tennessee where the Memphis aquifer is unconfined, groundwater contours were drawn to depict gaining streams, crossing the streams where the ground surface equaled the groundwater contour elevation (Figure 4). The lack of data control in Mississippi prevented detailing water level conformation to stream valleys. Along the Tennessee-Mississippi border, groundwater gradients are not east to west as suggested by Criner and Parks (1976), but they have a northwest orientation across the state line before turning westward in northern Shelby County and Tipton County toward Arkansas. Once in Arkansas, the gradients turn south following the overall plunge of the ME toward the Gulf of Mexico (Hosman *et al.*, 1968).

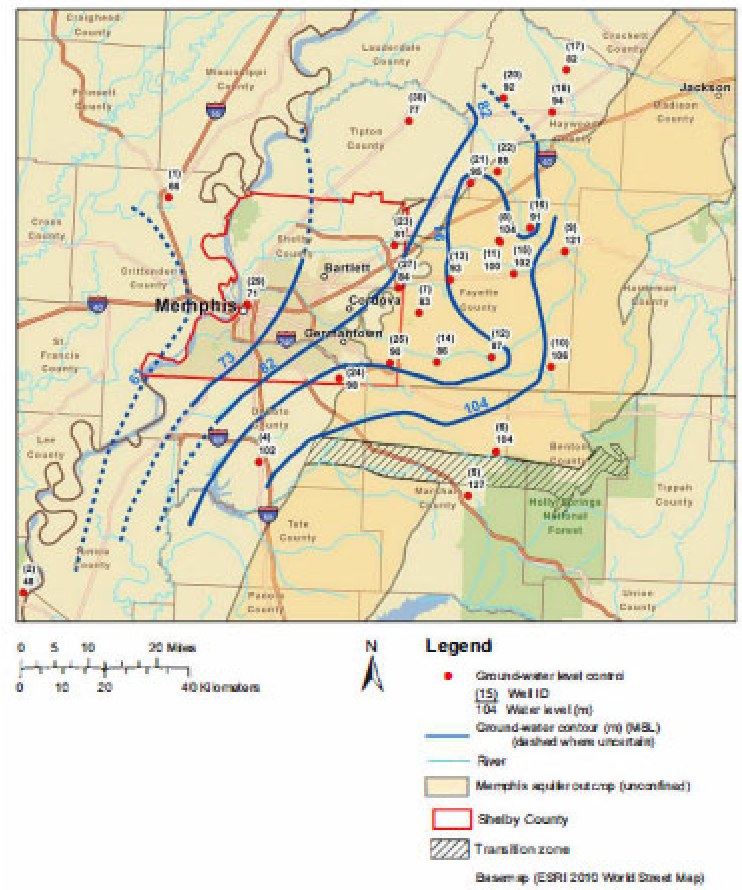

FIGURE 4. Pre-development Potentiometric Surface for the Memphis Aquifer from This Study.

A comparison of groundwater volumes crossing the Tennessee-Mississippi state line, specifically along the Shelby County-Desoto and Marshall County boundary, is made using our proposed pre-development conditions and more recent conditions as mapped by Schrader (2008). To estimate the volumes of flow crossing between Mississippi and Tennessee specifically along the Shelby County border, Darcy's law was employed using a range of saturated thickness of 209-284 m (Gomberg *et al.*, 2003), a range of hydraulic conductivity of 13-18.6 m/day for the Memphis Sand (TN) or Sparta Sand (MS) (Waldron *et al.*, 2010), and calculated hydraulic gradients that vary in magnitude depending upon location along the Shelby County southern border.

For the pre-development condition as shown in Figure 4, volumetric water rates range from 156,292 to 294,378 m^3/day across the range of hydraulic conductivity and aquifer thickness with an average rate of 219,922 m^3/day. A range of hydraulic gradients across the Mississippi-Tennessee state line along Shelby County was derived from the contours where they vary between 0.00034 and 0.00138. Devlin (2003) offers an alternative quantitative method to deriving gradients from the observed point heads in a linear gradient field. Following Devlin's approach, the gradient across the state line is 0.00026, lower than that derived from the contours. As the gradient field, as interpolated from the water level, suggests a non-linear flow pattern across the state line, the gradients derived from the contours will be used. When considering the vertical error (see Table 1), the volumetric flow-rate range expands to be between approximately 139,000 and 331,000 m^3/day with an average rate of 221,000 m^3/day. The spatial location error is not considered as it does not impact the position of the contours.

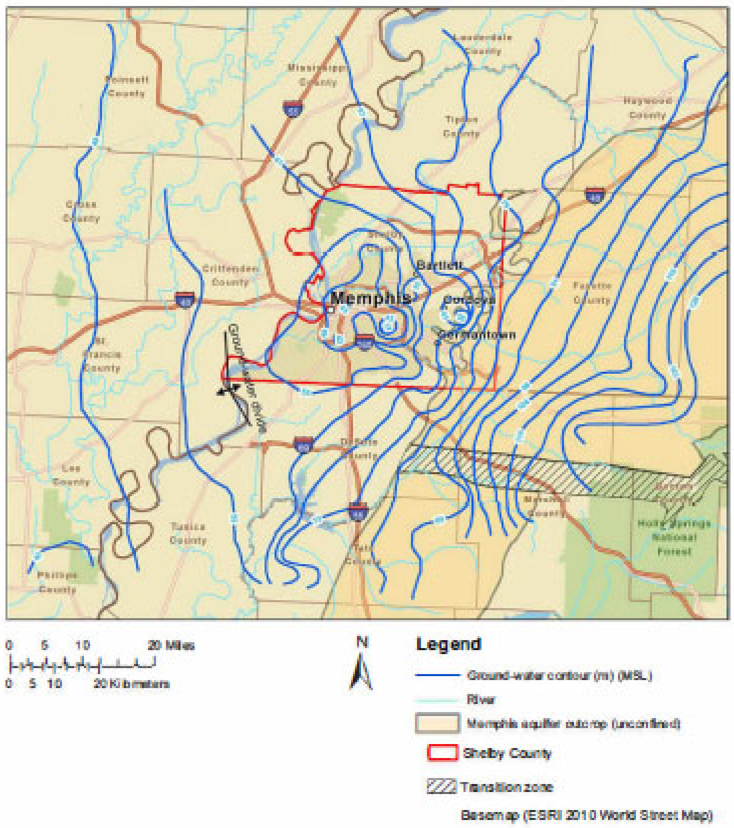

FIGURE 5. Regional Potentiometric Surface for the Memphis Aquifer and Middle Claiborne Aquifer (south of transition zone) Developed by Schrader (2008).

The same calculation was repeated using the same aquifer parameter ranges, but using the 2007 Memphis aquifer potentiometric surface by Schrader (2008) (Figure 5). The groundwater gradient in 2007 is primarily west to northwest from Mississippi into Shelby County except along the western edge where a groundwater divide is present (Figure 5). The range of gradients is 0.000132-0.00170. The estimated quantity of flow crossing into Shelby County from

Mississippi using Schrader's (2008) potentiometric surface is on average 186,000 m^3/day with a range of approximately 132,000-249,000 m^3/day. Without information from Schrader (2008) on the spatial and vertical error of their water levels an analysis of error cannot be performed.

DISCUSSION

The State of Mississippi claimed that pumping in Shelby County, Tennessee caused groundwater from the Memphis aquifer to reorient its original, pre-development direction from east-to-west to northwest across the state line; hence, water that was once the property of the State of Mississippi was now being withdrawn for use in Tennessee. Mississippi based its claim on the pre-development potentiometric surface map presented by Criner and Parks (1976) that was estimated using four control points with no southern control proximal to the state line border. The validity of the downtown control point used by Criner and Parks (1976) is questionable as it was not taken from an actual well screened within the Memphis aquifer, but was a water level extracted from an underground network of tunnels that collected and conveyed groundwater as it rose under pressure into the tunnel network. The three remaining control points are in the northern part of Shelby and Fayette counties. The water levels used for these controls are at least 68 years post-pre-development, which is considered to be 1886. Although Criner and Parks' (1976) map was useful for illustrating the overall pre-development water levels in Shelby County, Tennessee, for the scope of their study, the map is clearly inappropriate for supporting the State of Mississippi's claims.

In cases of transboundary groundwater quantity disputes, such as that between the State of Mississippi and MLGW, preparation of a well constrained water level map based on data approaching pre-development conditions is essential. The pre-development water level map of groundwater conditions in the Memphis aquifer presented in this study uses 27 control points whose latest water level records are only eight years post-pre-development (1886). Six control points are within Shelby County with the remainder scattered throughout the adjoining counties of which three are in Mississippi. This improved pre-development map indicates that groundwater naturally flowed from Mississippi into Tennessee prior to major pumping within Shelby County. The estimated average quantity of flow from Mississippi into Shelby County around the time of pre-development was approximately 220,000 m^3/day as compared to zero or no flow according to Criner and Parks (1976). Accounting for uncertainty in the data, the volumetric flow crossing from Mississippi into Shelby County, Tennessee is still much greater than zero where the range is approximately 139,000 and 331,000 m^3/day with an average rate of 221,000 m^3/day.

Schrader (2008) indicated that in 2007 the Memphis aquifer water levels were oriented toward the pumping centers, causing a large cone of depression under downtown Memphis. Groundwater gradients along the Shelby/Desoto County lines were primarily northwestward into Shelby County. Along the state line near the eastern edge of Shelby County, the gradient (see Figure 5) had a more westward orientation as compared to the northwest direction shown in Figure 3; hence, less groundwater would pass from

Mississippi into Tennessee at this location. Given that urban growth in northwestern Mississippi has increased greatly over the past 20 years and is fastest growing urban area in the State of Mississippi, it is likely that groundwater may in the future move from Tennessee to Mississippi. The lack of well control and thus contours along the southwest corner of Shelby County limits the accuracy of our average estimate crossing the Mississippi state line (186,000 m^3/day) into Shelby County. Adding greater control near the two southern corners of Shelby County on future groundwater level mapping efforts will improve our ability to better estimate the amount of groundwater flowing across the state line.

The results of this study raise concern in the State of Mississippi's claim that MLGW altered a zero-gradient flow condition along the Shelby County to now unrightfully pull groundwater across the county line due to excessive pumping in Shelby County. This study demonstrates the utility of accurate reconstruction of early groundwater conditions in assessing the validity of transboundary water disputes. This research also amplifies the importance of retaining historic groundwater level records and the need for additional groundwater level control along political boundaries that may separate regional groundwater resources.

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Basic Ground-Water Hydrology

Water-Supply Paper 2220

By RALPH C. HEATH

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

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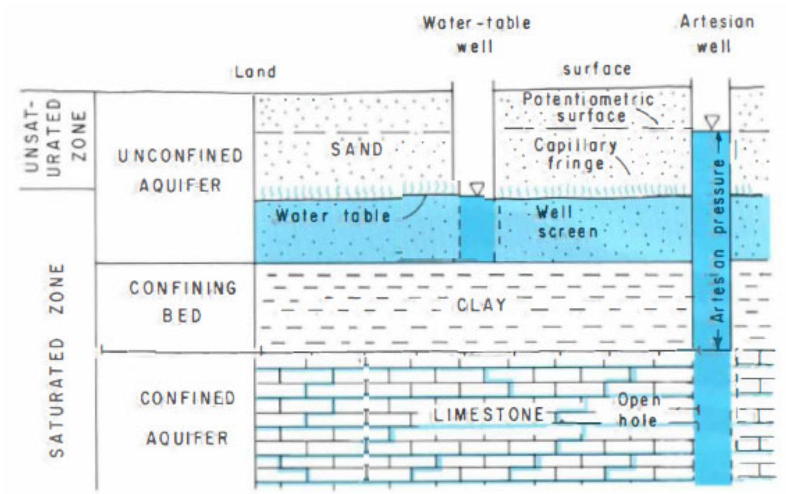
[p. 6; pdf p. 11 of Joint Exhibit 40]



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[p. 35; pdf p. 40 of Joint Exhibit 40]