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

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I. Introduction

Groundwater Management Associates (GMA) was retained by the firm of Daniel Coker Horton & Bell, P.A. (DCH&B) to provide expert geologic and hydrogeologic consulting regarding the origin and distribution of groundwater, interactions between surface water and groundwater, natural and man-induced migration patterns of groundwater, and specific topics regarding the geology and hydrogeology of predominantly sandy sediments 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.

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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

16 miles/day). Another way to look at this generic comparison is that the 'fast' groundwater flow would require roughly 230 years to travel the same 16 miles that the hypothetical stream could transport water during one day.

Groundwater hydrogeology employs unique terms and concepts. To simplify the discussion provided below, the following are some (modified) definitions of terminology from a well-known USGS primer (Heath, 1983).

AQUIFER: A water-bearing layer of rock (or sediment) that will yield water in a usable quantity to a well or spring.

CONE OF DEPRESSION: The depression of (hydraulic) heads around a pumping well caused by the withdrawal of water.

CONFINING BED: A layer of rock (or sediment) having very low hydraulic conductivity that hampers the movement of water into and out of an aquifer.

DRAWDOWN: The reduction in head at a point caused by the withdrawal of water from an aquifer.

EQUIPOTENTIAL LINE: A line on a map or cross section along which total heads are the same.

FLOW LINE: The idealized path followed by particles of water.

GROUND WATER: Water in the saturated zone that is under a pressure equal to or greater than atmospheric pressure.

(HYDRAULIC) HEAD See TOTAL HEAD

HYDRAULIC CONDUCTIVITY: The capacity of a rock (or sediment) to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

HYDRAULIC GRADIENT: Change in head per unit of distance measured in the direction of the steepest change.

POROSITY: The voids or openings in a rock (or sediment). Porosity may be expressed quantitatively as the ratio of the volume or openings in a rock (or sediment) to the total volume of the rock (or sediment).

POTENTIOMETRIC SURFACE: A surface that represents the total head in an aquifer; that is, it represents the height above a datum plane (such as sea level) at which the water level stands in tightly cased wells that penetrate the aquifer.

SATURATED ZONE: The subsurface zone in which all openings are full of water.

SPECIFIC CAPACITY: The yield of a well per unit drawdown (commonly expressed as gallons per minute per foot of drawdown).

STORAGE COEFFICIENT: The volume of water released from storage in a unit prism of an aquifer when the head is lowered a unit distance.

STRATIFICATION: The layered structure of sedimentary rocks.

TOTAL (HYDRAULIC) HEAD: The height above a datum plane of a column of water. In a ground-water system, it is composed of elevation head and pressure head.

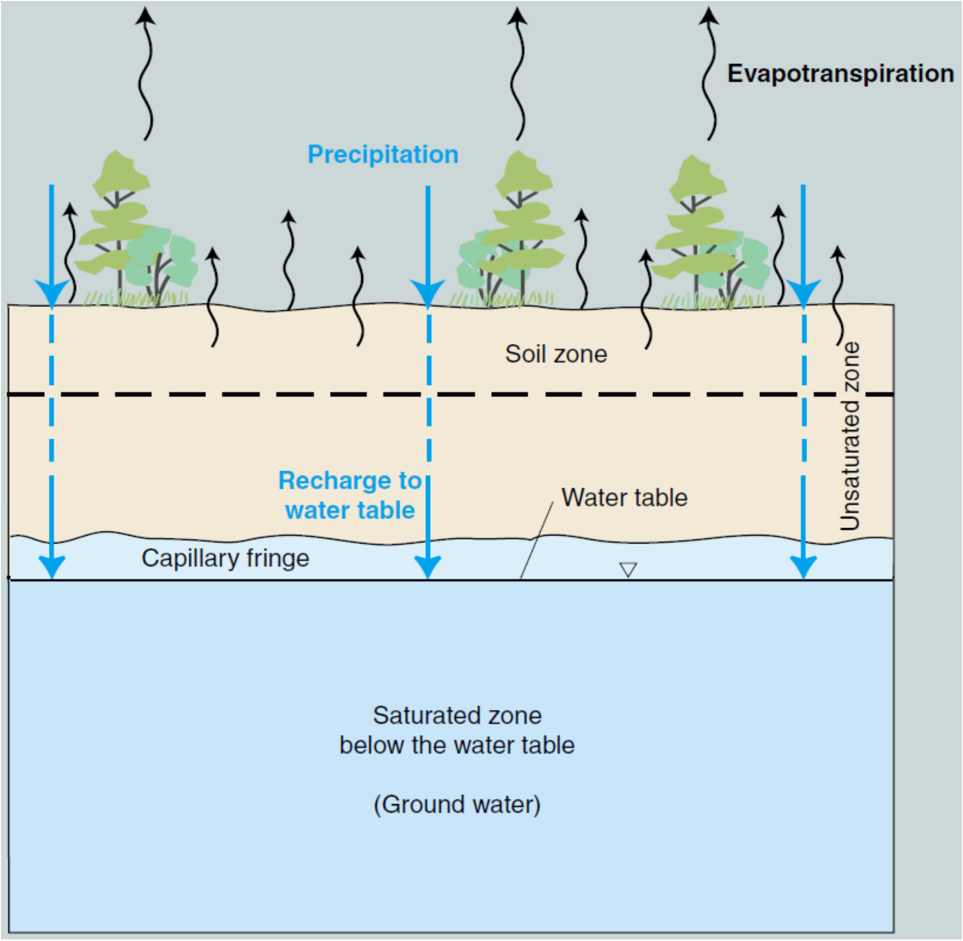
TRANSMISSIVITY: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness.

UNSATURATED ZONE: The subsurface zone, usually starting at the land surface, that contains both water and air.

WATER TABLE: The level in the saturated zone at which the pressure is equal to the atmospheric pressure.

Groundwater occurs in two basic zones that are defined by the degree of water saturation (Figure 1). The unsaturated zone occurs below the land surface where the primary and secondary porosity of the earth materials present will contain both air and water. Groundwater in the unsaturated zone is not available for extraction or exploitation by people. All porosity is filled with water in the saturated zone (Figure 1), and the boundary between the saturated zone and the overlying unsaturated zone is called the water table (discounting the capillary fringe where groundwater is at less than atmospheric pressure). Groundwater in the saturated zone is potentially recoverable, although there may be practical or financial limitations that preclude extraction.

Figure 1: Groundwater Distribution in the Shallow Subsurface (modified from Alley et al., 1999)

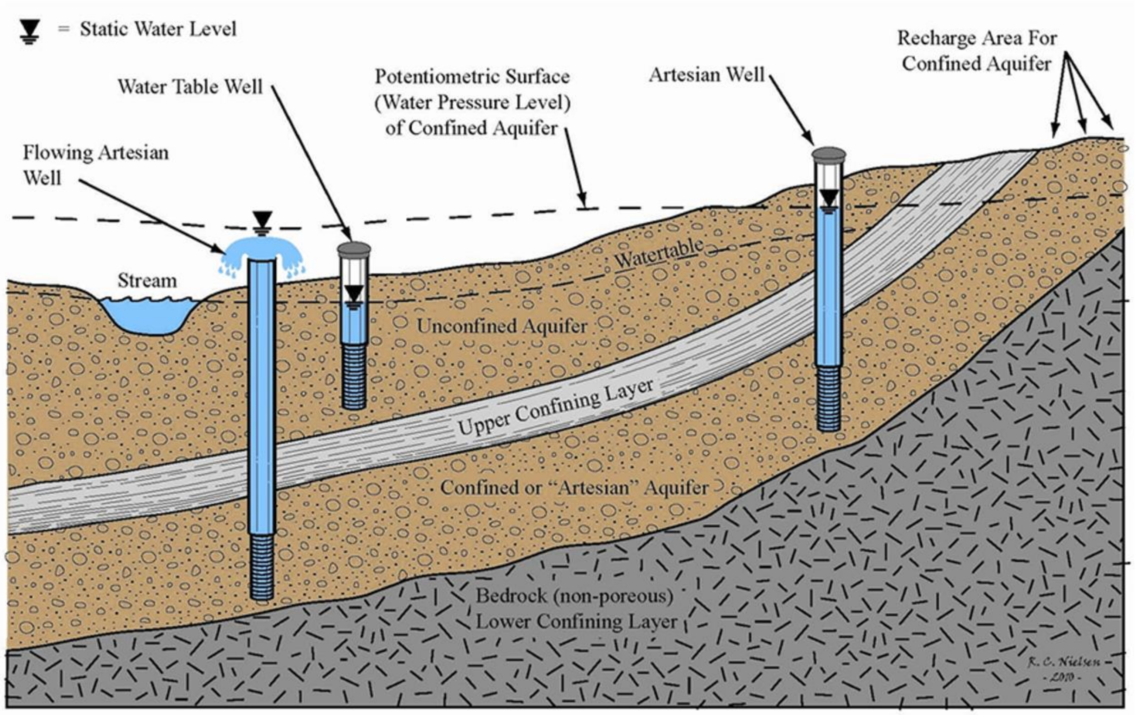


Aquifers consist of groundwater hosted by unconsolidated sedimentary deposits (e.g., sand) or consolidated rocks. To be considered an aquifer, there must be adequate interconnection of the primary and/or secondary porosity such that the geologic materials can hold, transmit, and release groundwater in sufficient volumes for some purpose (e.g., a water-supply well). There is no minimum area, thickness, or quantity of groundwater potentially ‘useable’ or ‘extractable’ by people that must exist before a mass of groundwater-bearing geologic material can be termed an aquifer. Water-bearing sediments or rocks may be exploited by people as a significant source of water in one place, thus constituting an aquifer, but the same combination of water and solid materials might not constitute a viable aquifer at a different place or time.

Aquifers can be classified by the degree of hydraulic confinement (pressurization). The water table scenario described above represents an unconfined aquifer, and an unconfined aquifer may also be referred to as a water table aquifer. New water additions to an unconfined aquifer originate directly above the aquifer at the land surface. A confined aquifer is fully saturated, and it is enclosed above and below by materials with relatively low permeability (e.g., clay). Groundwater in a confined aquifer is typically pressurized, and the degree of pressurization (hydraulic head) can be measured directly in a well open only to the confined aquifer. The hydraulic head is measured inside the well as the elevation of the water at a position above (more shallow than) the top of the aquifer's upper surface. Laymen often refer to such aquifers as "artesian", and a well tapping a confined aquifer will flow freely at the surface without pumping if the hydraulic head is at an elevation above the land surface. Most wells tapping a confined aquifer do not flow freely at the surface, or they may flow until the elevation of the hydraulic head decreases to an elevation below the land surface. These terms and scenarios are illustrated in Figure 2.

Movement of groundwater in the subsurface can be complex, but some basic patterns are common. Groundwater will flow in response to local and regional pressure distributions, and specifically toward areas with lower hydraulic pressure. A common scenario is that groundwater migrates from areas of aquifer recharge toward areas of groundwater discharge. For an unconfined aquifer, these two areas generally correspond to upland areas and surface water (e.g., a river), respectively. In the case of simple porous materials, such as a well-sorted sand, flow occurs around the individual sand grains and through the interconnected pore spaces. Flow occurs in pathways that are perpendicular to decreases in the local hydraulic gradient. Contouring the distribution head on an equipotential map will illustrate the aquifer's pressure distribution, and the associated groundwater-flow pattern can be deduced from that head distribution.

Figure 2: Confined versus Unconfined Aquifers and Artesian Wells



http://www.health.state.mn.us/divs/eh/wells/flowing/flowingwell.jpg

Likewise, flow through fractured geologic materials will occur in direct response to hydraulic pressure distributions, but the actual pathways are dictated by the orientations, lengths, and apertures (widths) of multiple, intersecting fractures. The resulting flow patterns in fractured-rock aquifers can be very complex, and flow may occur in directions that may appear unrelated to indicators commonly used for simple porous media flow (e.g., relative positions of aquifer recharge and discharge areas).

Although groundwater flow in the real world is often complex, even in the case of simple porous media such as a sand aquifer, groundwater generally migrates along curving pathways that display pronounced downward or upward flow components in aquifer recharge areas and discharge areas, respectively. These curved pathways are pronounced, and may be complex, in unconfined aquifers because they reflect local flow systems controlled by proximity of recharge and discharge areas. In contrast, flow pathways in confined aquifers are typically controlled by more regional recharge and discharge features, and flow internal to the confined aquifer can be simple relative to the same aquifer material in an unconfined aquifer.

To further simplify the concept of groundwater flow, one can focus on two primary vectors, the horizontal component of flow and the vertical component of flow. In reality, groundwater flows in response to the net influence of both components, and not merely the horizontal component that is often assumed by examining an equipotential map. The velocity of groundwater flow in a particular area of interest can be described by the relationship between the hydraulic gradient (dh/dl), the aquifer's porosity (n), and the permeability (hydraulic conductivity, or k) of the aquifer. The velocity of the horizontal component of groundwater flow (V_h) can be calculated as $V_h = (k/n)*(dh/dl)$. For a well-sorted sand aquifer with 25% porosity, a k of 10 feet/day, and a hydraulic gradient (pressure difference) of 0.001 feet/foot, the V_h is calculated to be 0.04 feet/day, or 14.6 feet/year. If (only) the porosity in this example is reduced to 1%, a value typical of fractured rock aquifers, the V_h <u>increases</u> to 1 foot/day, or 365 feet/year.

Three aspects of groundwater flow and calculated groundwater velocity are highlighted by the example provided above. First, the values assigned to an aquifer (e.g., k) must be determined as carefully as possible and be representative of the aquifer across the area of interest. Second, increasing or decreasing the porosity assigned to the aquifer will produce large variations in calculated groundwater velocity. Finally, groundwater generally does not move very far during a typical American's lifetime, roughly on the order of 1,000 to 3,000 feet for most aquifers. In contrast, low-permeability materials enclosing a confined aquifer may have groundwater-flow velocities that are several orders of magnitude slower than flow in the adjacent aquifer.

The natural hydraulic gradients and flow patterns within an aquifer are disrupted by pumping groundwater from a well, but the degree of change produced is determined by aquifer characteristics and the rate and duration of pumping. Adjacent to the pumping well, the flow pattern is redirected toward the well, commonly in a radial pattern centered on the well. With increasing distance from the pumping well, the effects of decreasing pressure (drawdown) dissipate, and the result is a cone-shaped area of depressed hydraulic head. The diameter and vertical depth of the cone of depression are manifestations of the inherent physical characteristics of the aquifer and the pumping well. In an unconfined aquifer, physical drainage of pore spaces occurs within the cone of depression. In a confined aquifer, the cone of depression is manifest in the reduction of hydraulic pressure about the well, and the aquifer remains fully saturated as long as the total hydraulic head remains above the top of the aquifer. The cone of depression caused by pumping from a confined aquifer can be very large, thus reducing the quantity of water available to other users. Multiple pumping wells will have coalescing cones of depression that have an additive effect that enlarges the area of the aquifer that experiences declining pressure. This additive impact on water levels in wells is exemplified by excessive pumping of the Sparta-Memphis Sand aquifer in the Memphis metropolitan area that has caused water levels in northwestern Mississippi to decline. This subject is addressed more fully in Section V of this expert report.

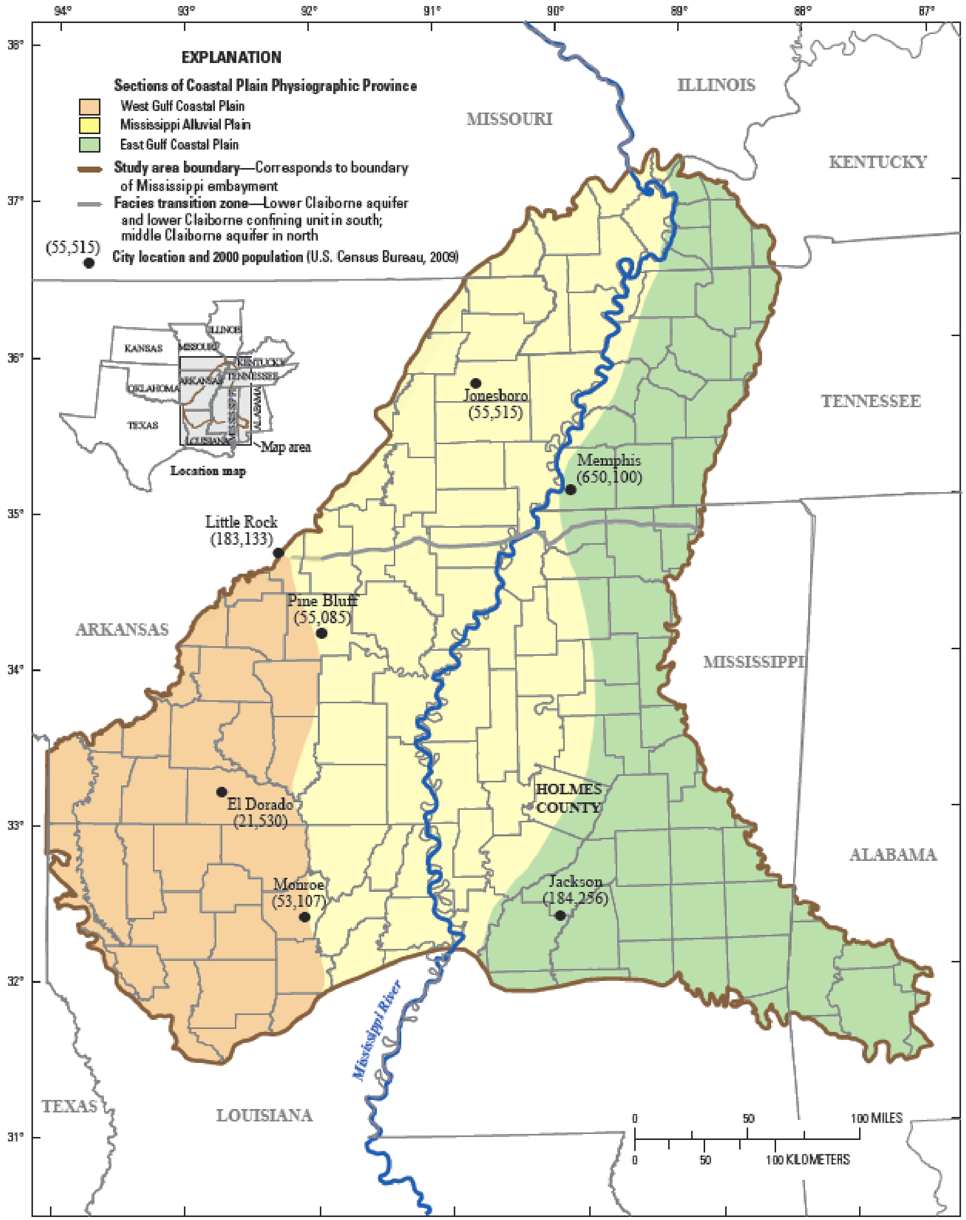
V. Geology and Hydrogeology of the Mississippi Embayment

This section of the expert report provides an introduction to the regional geologic origin and setting of the major basin (i.e., the Mississippi Embayment) that hosts the Sparta-Memphis Sand in northwestern Mississippi and southwestern Tennessee. Geologic and hydrogeologic aspects of the SMS are also described here and elsewhere in the report.

V.1 Introduction to the Origin of the Mississippi Embayment

The Mississippi Embayment is present in portions of eight states: Tennessee, Mississippi, Louisiana, Alabama, Illinois, Missouri, Arkansas, and Texas. The Embayment encompasses three physiographic provinces (Figure 3): the West Gulf Coastal Plain, the East Gulf Coastal Plain, and the Mississippi River Alluvial Plain. The Mississippi Alluvial Plain and East Gulf Coastal Plain are the provinces located in Tennessee and Mississippi, and these areas are the focus of this report.

Figure 3: Physiographic Provinces of the Mississippi Embayment (Clark et al., 2011, Figure 1)



Base from U.S. Geological Survey digital data, 1:100,000

Physiographic province sections from Fenneman and Johnson, 1946
City populations from U.S. Census Bureau, 2009

Around 300 million years ago, the Appalachian Mountains and the Ouachita Mountains formed a single, long mountain chain. There was no break in the Appalachian-Ouachita mountain range where the Mississippi Embayment and the Mississippi River exist today. This mountain range was formed when different continental masses collided and formed a geologic 'supercontinent' called Pangea. The Mississippi Embayment began forming about 230 million years ago in the Triassic Period at the time that dinosaurs were first beginning to appear and when Pangea began to fracture and fragment. The Appalachian-Ouachita range formed the southern margin of the North American tectonic plate, and the area south of the range would become the South American tectonic plate and the Gulf of Mexico. The most common explanation for the Mississippi Embayment involves movement and interactions between these tectonic plates that caused down-warping and fracturing (rifting) of the earth's crust to create a deep basin that collected the sediments eroding from the adjacent highlands (Clark et al., 2011). However, the origin of the Embayment may be more complicated than originally thought, and a combination of moving tectonic plates and local uplift over unusually-hot portions (hot spots) of the earth's mantle may have shaped the surface (Van Arsdale and Cox, 2007).

The Appalachian-Ouachita mountain range has moved slowly and (relatively) westward with time. At about 95 million years ago, in the Cretaceous Period, the Mississippi Embayment was located over a hot spot in the earth's mantle that today is known as the Bermuda hot spot. The crust of the earth rose in elevation in response magma that moved upward toward the surface at the hot spot, and associated fractures and faulting created linear zones of weakness in the crust. Preferential weathering of that fractured crust resulted in erosion and removal of much of the Appalachian-Ouachita mountain range in the vicinity of the hot spot. Within a few million years, the hot spot activity had decreased to the extent that the crust and underlying mantle became cooler and contracted. The once-elevated and eroding mountain range decreased significantly in elevation, thus forming a trough (basin) that accumulated both terrestrial (e.g., stream) and marine sedimentary deposits within the Mississippi Embayment.

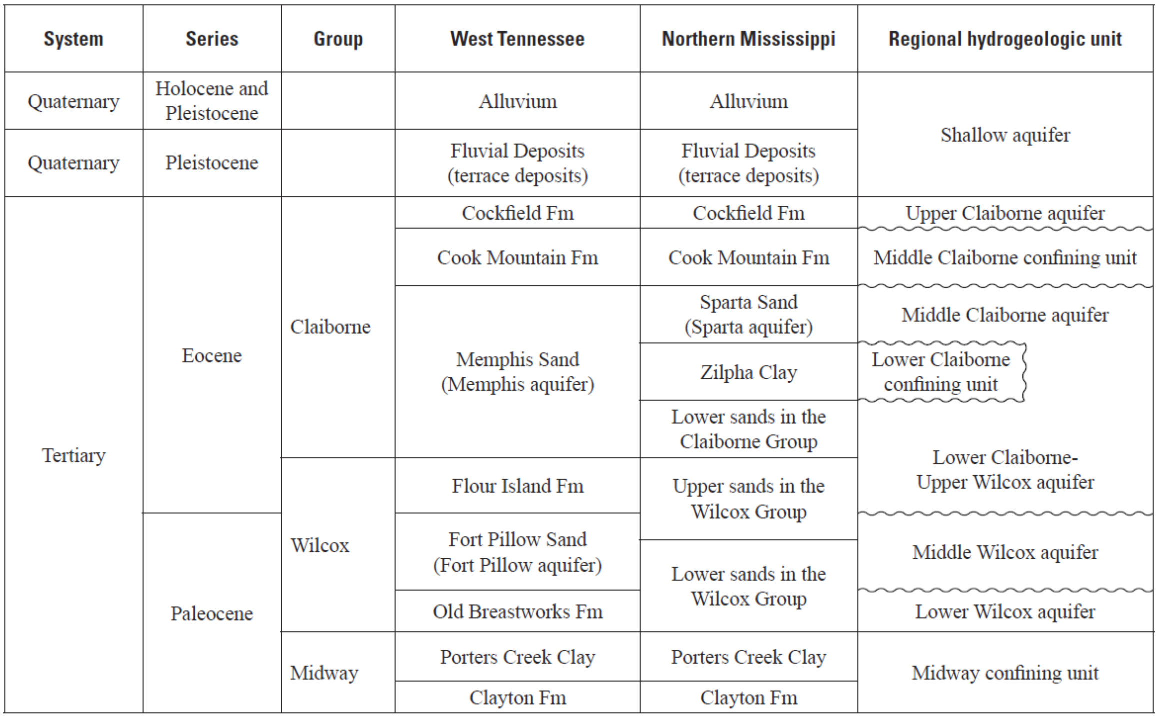
V.2 General Sedimentary Stratigraphy of the Mississippi Embayment

Sediments accumulating in the nascent Mississippi Embayment were deposited on the ancient Paleozoic Era bedrock of the eroded and subsided Appalachian-Ouachita mountain range. The oldest deposits known from the basin are marine sediments deposited in the Late Cretaceous (~95 million years ago to 65 million years ago), and they are predominantly calcareous sands, chalks, marls, and clay that are grouped together as the McNairy-Nacatoch Formations (Grubb, 1998; Cushing et al., 1964).

Cenozoic Era sediments that overly the McNairy-Nacatoch Formations were deposited in the Tertiary Period between 65 million years ago and approximately 3 million years ago. From oldest to youngest, these deposits are subdivided into the Midway, Wilcox, Claiborne, and the Jackson-Vicksburg groups (Grubb, 1998). Thick sand beds characterize the Wilcox and Claiborne groups (Figure 4), while finer grained deposits of clay and silt dominate the Midway and Jackson-Vicksburg groups. Sediments deposited during the Quaternary Period are less than approximately 3 million years old, and are predominantly sands, silts, and clays deposited by the Mississippi River (Figure 4).

Figure 4: Stratigraphic Correlation of Paleocene and Younger Sedimentary Units and Aquifers in Northern Mississippi and Western Tennessee

(Haugh, 2016, Table 1)

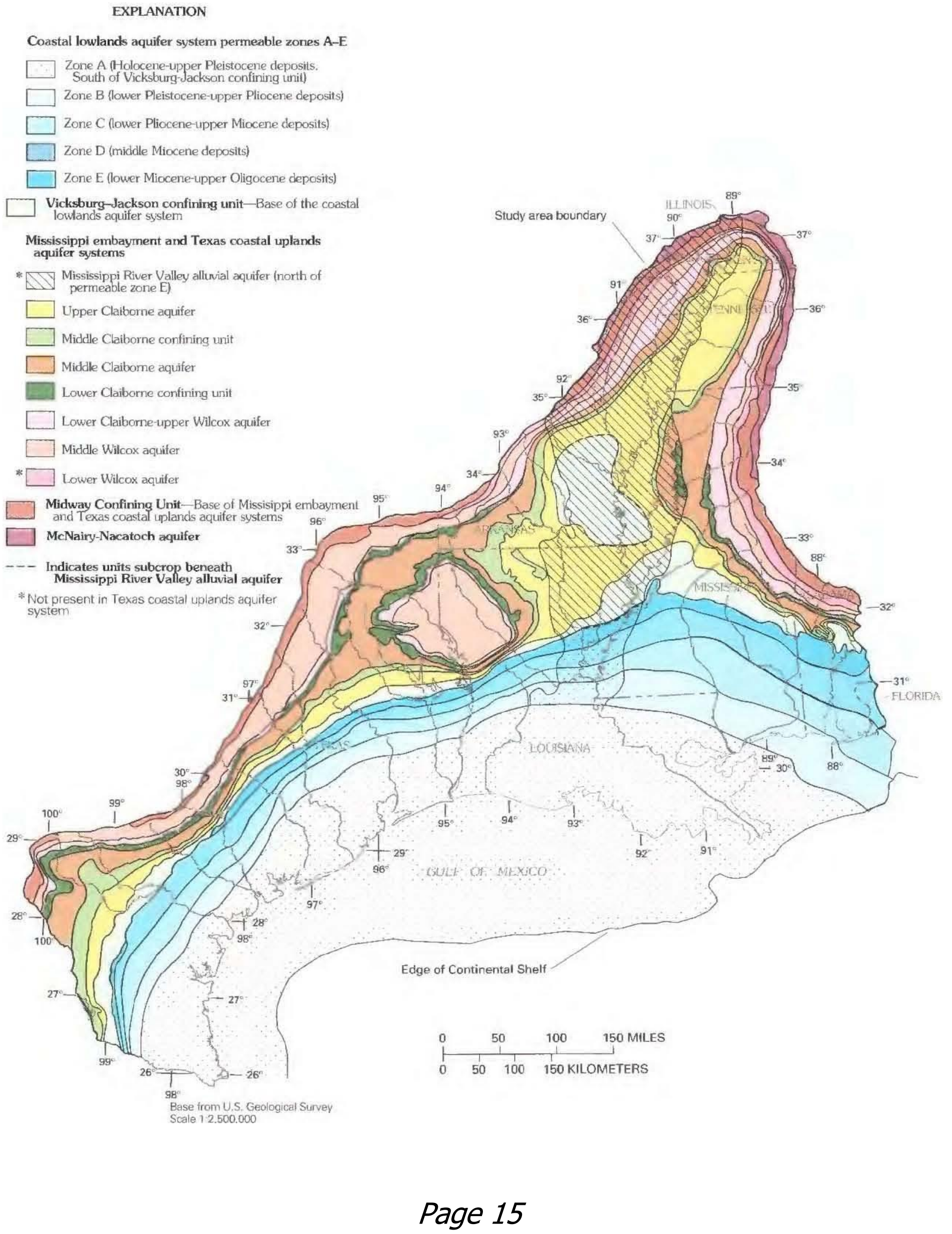


System	Series	Group	West Tennessee	Northern Mississippi	Regional hydrogeologic unit
Quaternary	Holocene and Pleistocene		Alluvium	Alluvium	Shallow aquifer
Quaternary	Pleistocene		Fluvial Deposits (terrace deposits)	Fluvial Deposits (terrace deposits)	
Tertiary	Eocene	Claiborne	Cockfield Fm	Cockfield Fm	Upper Claiborne aquifer
			Cook Mountain Fm	Cook Mountain Fm	Middle Claiborne confining unit
			Memphis Sand (Memphis aquifer)	Sparta Sand (Sparta aquifer)	Middle Claiborne aquifer
				Zilpha Clay	Lower Claiborne confining unit
				Lower sands in the Claiborne Group	Lower Claiborne-Upper Wilcox aquifer
		Wilcox	Flour Island Fm	Upper sands in the Wilcox Group	
	Paleocene		Fort Pillow Sand (Fort Pillow aquifer)	Lower sands in the Wilcox Group	Middle Wilcox aquifer
			Old Breastworks Fm		Lower Wilcox aquifer
		Midway	Porters Creek Clay	Porters Creek Clay	Midway confining unit
			Clayton Fm	Clayton Fm	

V.3 General Hydrogeology of the Mississippi Embayment

There are three major aquifer systems in the Mississippi Embayment recognized in the vicinity of southwestern Tennessee and northwestern Mississippi (Figure 4): The Wilcox System (composed of the lower, middle, and upper Wilcox Aquifers), the Claiborne System (composed of the lower, middle, and upper Claiborne Aquifers), and the shallow alluvial aquifer system located within the Mississippi River valley. Figure 5 shows the areal exposures of these aquifers at the land surface.

Figure 5: Surface Distribution of Regional Aquifers and Confining Units in the Mississippi Embayment and Gulf Coastal Plain **(Grubb, 1998, Figure 7)**



In northwestern Mississippi and western Tennessee, most of the Lower Claiborne and Upper Wilcox Aquifers are confined (i.e., are 'artesian' aquifers). The Lower Claiborne Aquifer and the Upper Wilcox Aquifer are often considered to form one aquifer, and they are separated by a confining layer from the overlying Middle Claiborne Aquifer.

The Claiborne Group is a package of sediments deposited in the Mississippi Embayment approximately 40 million years ago during the middle of the Eocene Epoch of the Cenozoic Era. Historically, the Middle Claiborne Aquifer was called the 500 Foot Sand to reflect the typical depth of the sands being targeted for water-supply wells in the Mississippi-Tennessee border area (Criner et al., 1964). In Tennessee, the names Memphis Sand or Memphis Aquifer (Figure 4) are synonymous with the Middle Claiborne Aquifer. In Mississippi, the upper part of the Middle Claiborne Aquifer is called the Sparta Sand (e.g., Clark et al., 2011), which is correlative with the upper part of the Memphis Sand (Figure 4). The Claiborne and Wilcox Aquifer Systems are the major sources of public water supply in the vicinity of the City of Memphis, both north and south of the Mississippi-Tennessee border. Of these, the Middle Claiborne Aquifer is the primary source of water used to supply municipalities and individual home owners, and that aquifer has experienced the most obvious impacts from extensive pumping in Shelby County, Tennessee. The Middle Claiborne Aquifer in western Tennessee and northwestern Mississippi is inclined (dips) generally westward from where the sand deposits crop out to beneath the Mississippi River.

The upper part of the Middle Claiborne Aquifer (i.e., the Sparta Sand) is the primary water-producing zone exploited by municipal well fields (Clark et al., 2011), and the name Sparta-Memphis Sand is employed in this expert report to refer to the Middle Claiborne Aquifer that is being pumped extensively in Shelby County, Tennessee. The terms Middle Claiborne Aquifer or Memphis Aquifer are considered synonymous with the SMS for purposes of this expert report. It is important to recognize that pumping has also impacted the Lower Claiborne-Upper Wilcox Aquifer, and focus on the SMS is <u>not</u> intended to discount pumping impacts on that deeper aquifer system.

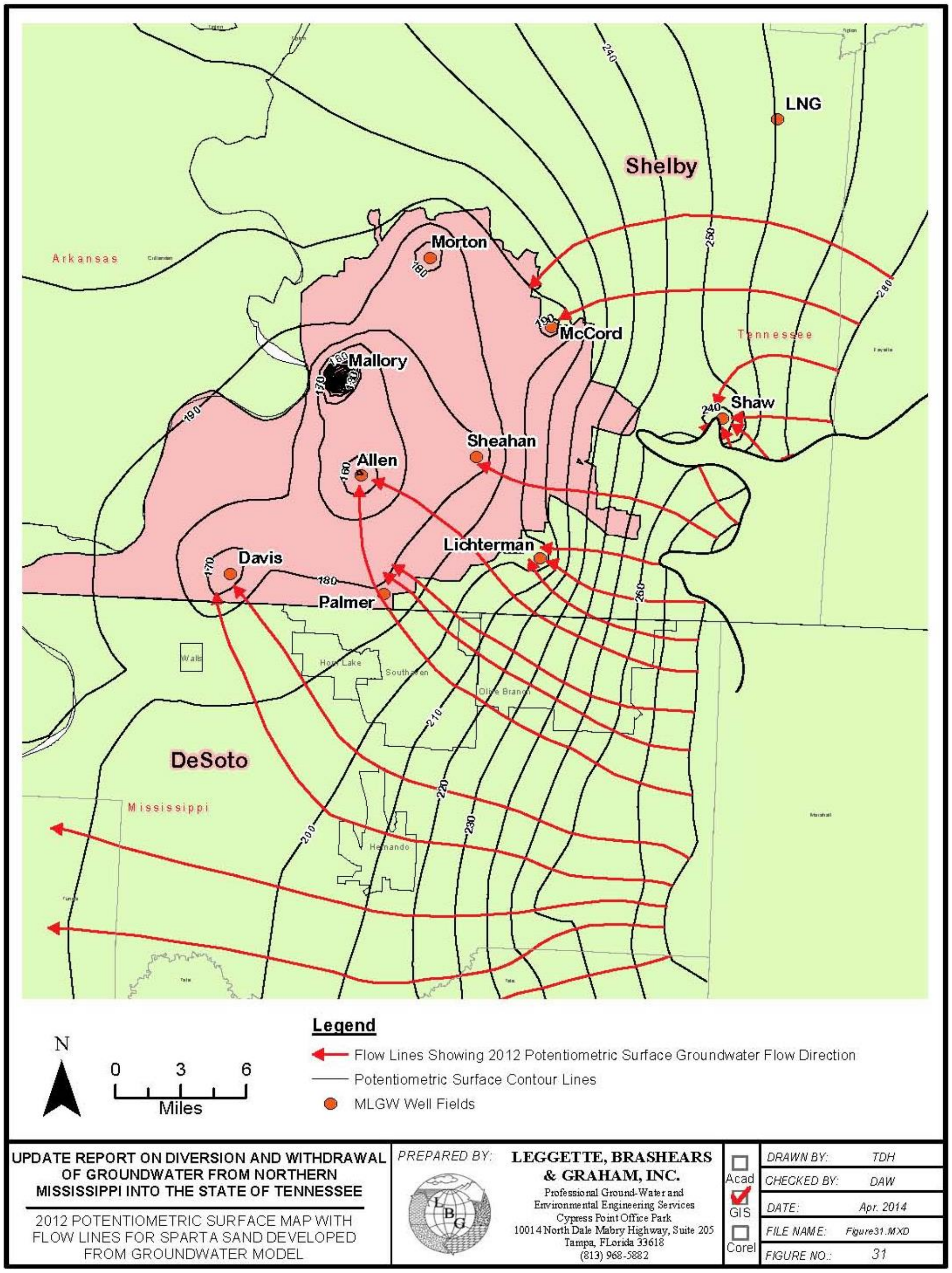
The Mississippi River Alluvial Aquifer (aka, Surficial Aquifer) lies atop these mostly-buried Eocene-age aquifers, and the Surficial Aquifer is exposed at the surface within the Mississippi River floodplain. This aquifer is generally unconfined, and consists of sands, silts, and clays deposited by the Mississippi River during the Quaternary Period (Clark et al., 2011). The Surficial Aquifer is the primary groundwater source used by agriculture throughout much of the Mississippi Embayment.

V.4 Groundwater Withdrawals and Impacts

Groundwater withdrawals within the Mississippi Embayment are used primarily for public consumption and agriculture (Clark et al., 2011). The largest population center in the Mississippi Embayment area is the City of Memphis in Shelby County, Tennessee, and the county has an approximate population of 900,000. In the vicinity of the Mississippi-Tennessee border and generally near the City of Memphis, the middle of the Claiborne Group is dominated by sand deposits that are identified as the Sparta-Memphis Sand. Memphis withdraws water primarily from the SMS (aka, Middle Claiborne Aquifer or Memphis Aquifer). The SMS is a confined aquifer in the vicinity of Memphis, so withdrawal of up to 162 million gallons per day from more than 170 production wells operated by Memphis Light, Gas and Water (MLGW) has produced a large, composite cone of depression (an area of lower pressure) centered on MLGW's 10 well fields.

MLGW is one of the world's largest groundwater-based water-supply systems. Groundwater from the Mississippi Embayment aquifers in Tennessee and Mississippi has been used since the late 1800's. Water service for Memphis began in 1870, and Memphis withdrew approximately 30 million gallons of water per day (mgd) from 1895 to 1900 (Grubb, 1998). Withdrawals increased to over 180 mgd by 2005 (Clark et al., 2011), and the predictable result is that MLGW's withdrawals have produced a broad, coalesced cone of depression centered on Shelby County (Figure 6). The cone(s) of depression result in changes in the pattern of the horizontal component of groundwater flow within the SMS and in the underlying Lower Claiborne-Upper Wilcox Aquifer system, as well as inducing or accelerating vertical flow across confining units separating the SMS from overlying and underlying aquifers.

Figure 6: Cones of Depression and Groundwater Flow Paths Associated with Municipal Well Fields in Shelby County, Tennessee (LB&G, 2014, Figure 31)



Groundwater generally flows from recharge areas toward discharge areas. Significant recharge for the SMS occurs where the sand deposits are exposed (and unconfined) at the land surface in the eastern portion of the Mississippi Embayment in Tennessee and Mississippi (Figure 7), as well as vertical recharge from the overlying Surficial Aquifer.

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)

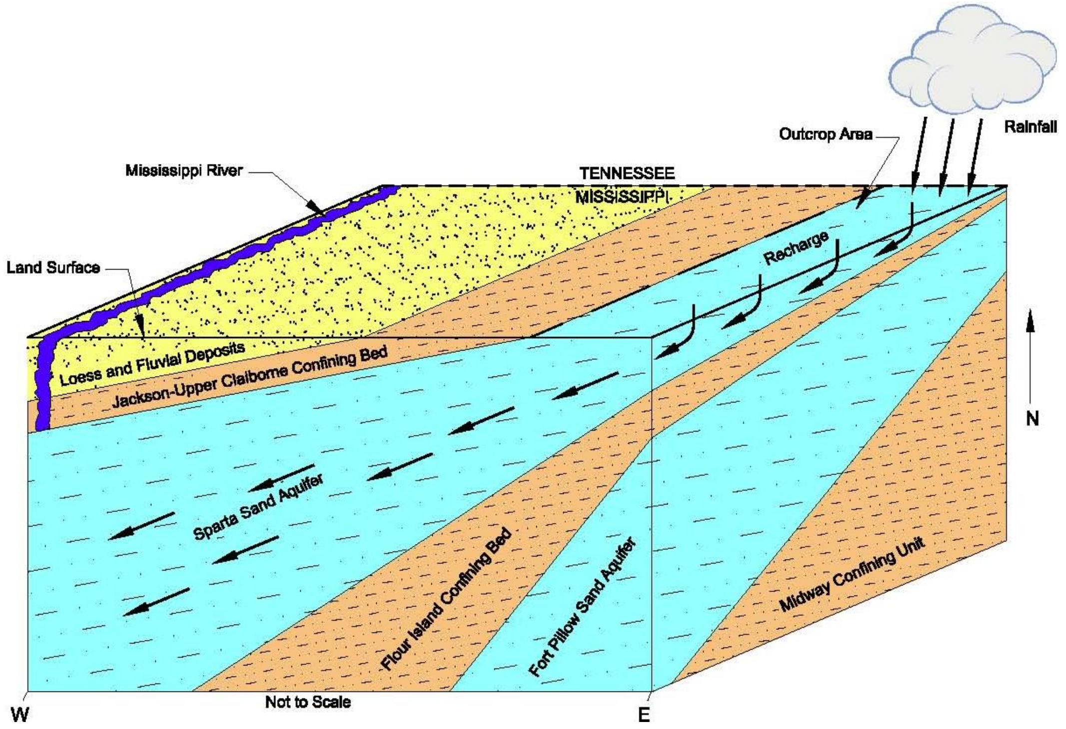
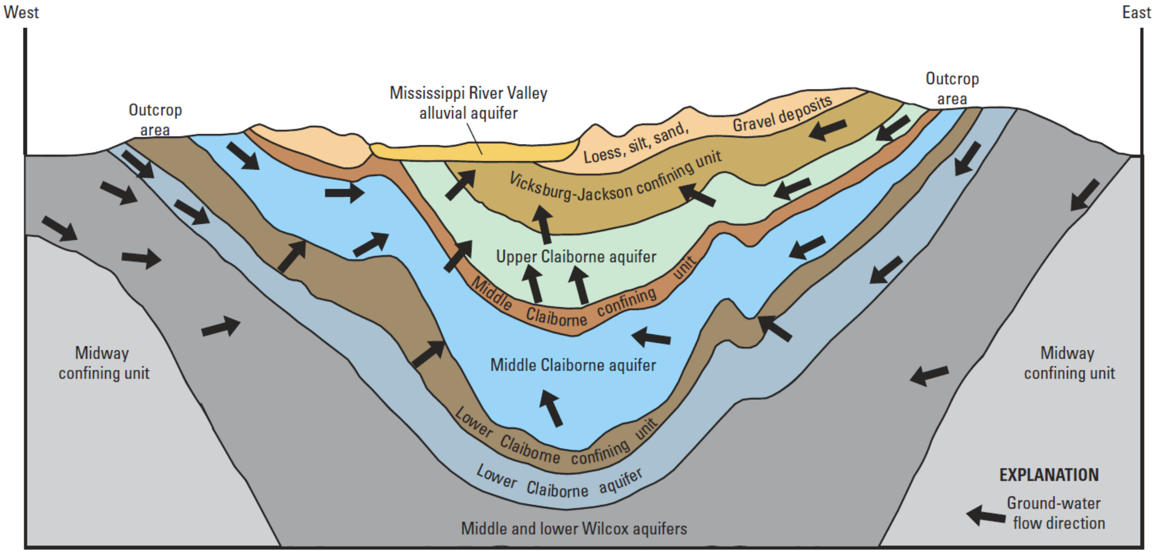


Figure 8 is a schematic east-west cross section (side view) through the Mississippi Embayment that includes arrows depicting the general pattern of groundwater flow before development began in the late 1800s. Some regional flow paths for water movement were as long as 200 miles from the recharge area 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).

Figure 8: Schematic West-East Cross-Section of the Geology of the Mississippi Embayment and Generalized Pre-Development Groundwater Flow Patterns (modified from Figure 4 of Hart et al., 2008)



The natural patterns of groundwater flow have been transformed as a result of extensive pumping (Arthur and Taylor, 1998; Grubb, 1998; Clark et al., 2011). Withdrawal of groundwater from wells has lowered the pressure in the Sparta-Memphis Sand, causing water in higher pressure areas to move within the SMS toward the lower pressure area of the pumping wells. Individual cones of depression centered on MLGW's well fields in Shelby County have coalesced to create a broad area of depressed hydraulic pressure within the SMS (see Figure 6). Not only do withdrawals change the natural directions of the horizontal component of groundwater flow within the aquifer, but water can be induced to flow vertically across confining units from one aquifer to another. Figure 10 presents a map by Arthur and Tayler (1998) showing the potentiometric surface of the Middle Claiborne Aquifer (SMS) in 1987, long after intense exploitation of this aquifer began. Arrows show the direction of groundwater flow in the vicinity of Tennessee and Mississippi, with obvious flow being directed toward the municipal well fields in Shelby County, Tennessee.

Figure 9: Pre-Development Groundwater Equipotential Map and Flow Patterns in the Middle Claiborne Aquifer (modified from Plate 5 of Arthur and Taylor, 1998)

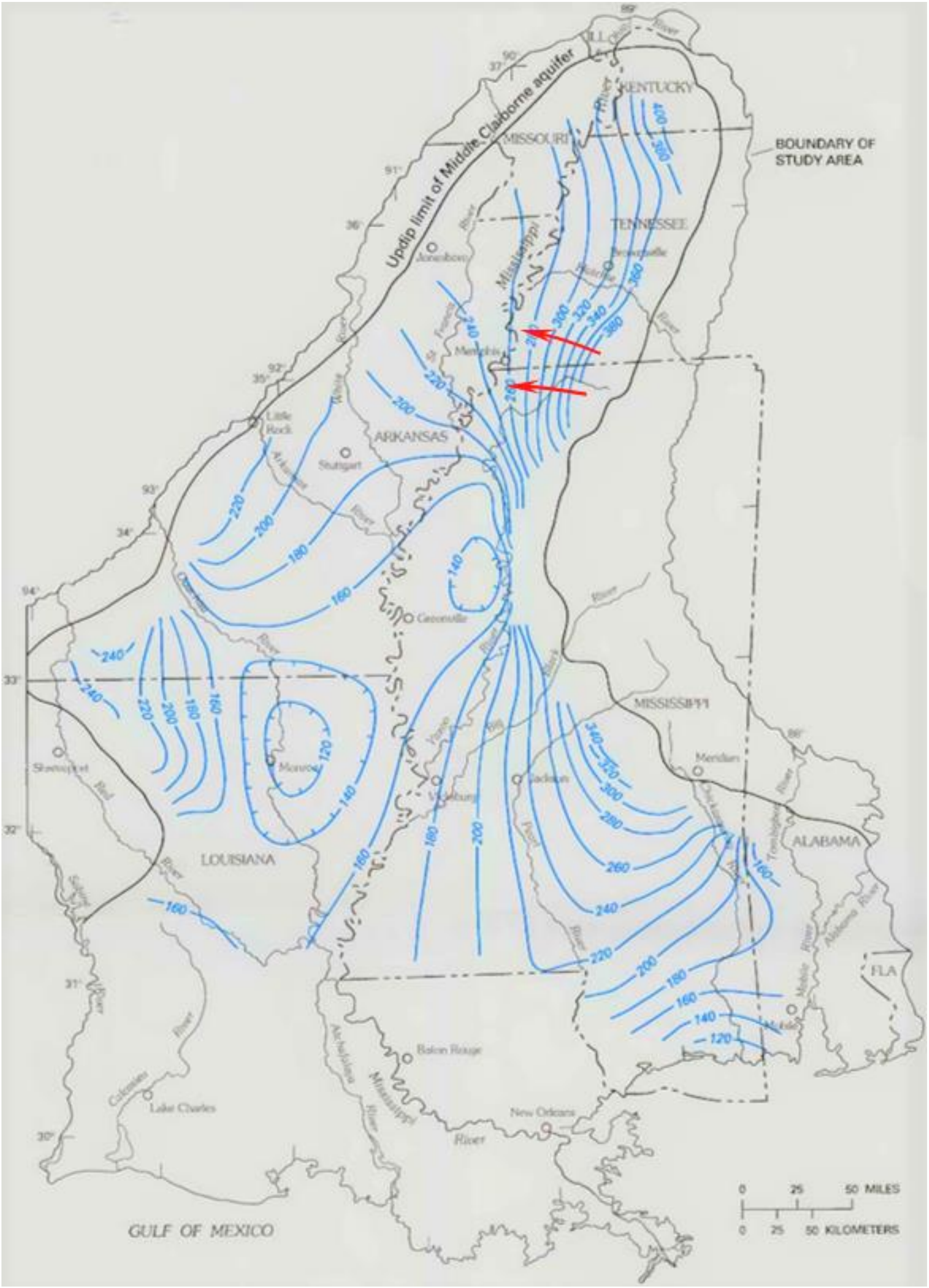
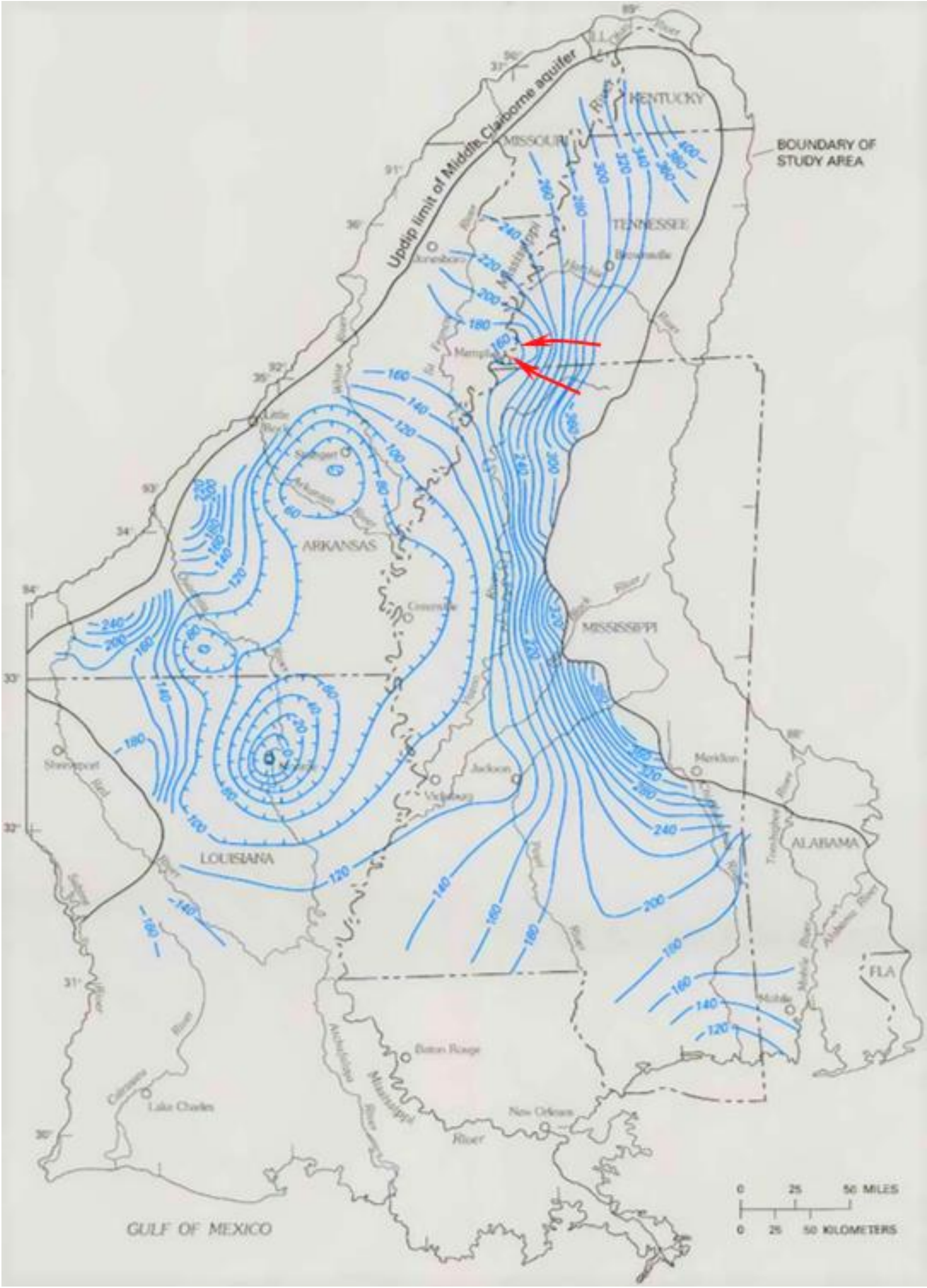


Figure 10: Post-Development Groundwater Equipotential Map and Flow Patterns in the Middle Claiborne Aquifer (modified from Plate 7 of Arthur and Taylor, 1998)



Even after extensive and protracted well-field withdrawals, recharge to the aquifer system will still occur through the Surficial Aquifer and the aquifer outcrop areas in the 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 at a given location. In general, the major water-producing aquifer systems in the Mississippi-Tennessee border region are heterogeneous and anisotropic.

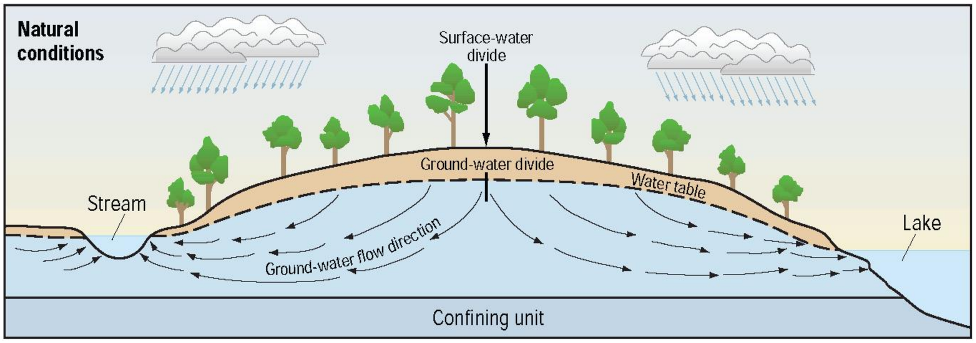
Transmissivity is used to describe the flow of groundwater through aquifers, and it is defined as the hydraulic conductivity multiplied by the thickness of the aquifer. Transmissivity is a property that is commonly determined to understand and quantify how much water moves through, and thus can be recovered from, an aquifer.

Storage coefficient is a measure of the volume of water taken into, or released from, the pore spaces in a unit volume of the aquifer material per foot of head change. The actual value of the storage coefficient of confined and unconfined aquifers is significantly different, and the actual value is used by hydrogeologists to distinguish between the two types of aquifers. Although aquifers are often subdivided as confined or unconfined, the actual degree of confinement can vary and is based on storage coefficient.

VI.1 Unconfined Aquifers

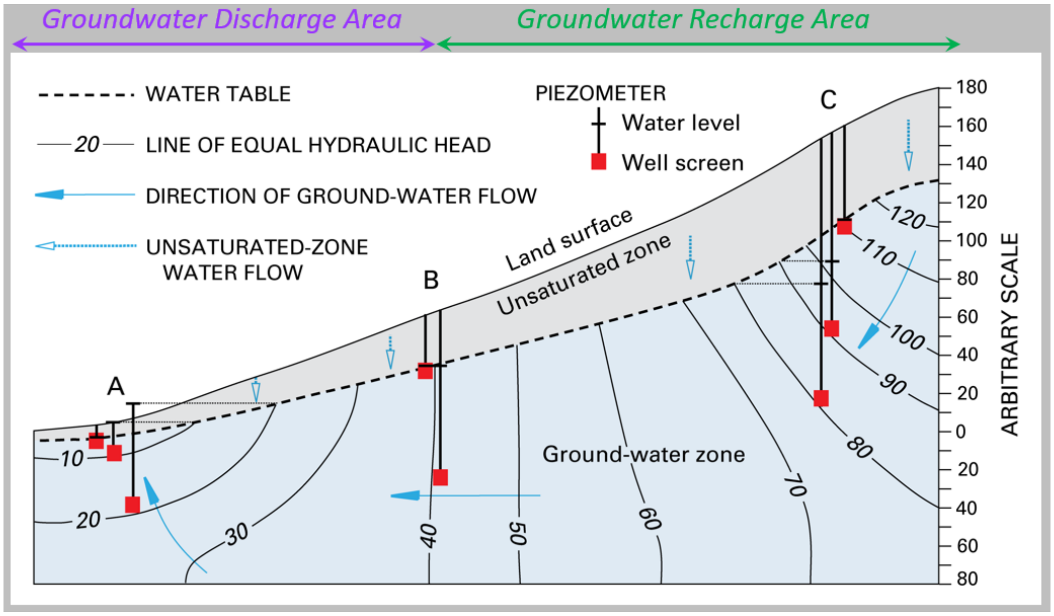
Groundwater flow patterns in unconfined portions of the groundwater system are extremely complex. To illustrate these patterns, Figure 11 is a generalized groundwater illustration that depicts flow in the shallow groundwater system from a groundwater divide in an elevated area to the location of a stream or lake located at lower elevations. Groundwater flow in this system follows a circuitous path from upland areas to lowland areas where groundwater ultimately discharges to the surface water body.

Figure 11: Unconfined Aquifers and Local Flow Systems (Modified from Grannemann et al., 2000)



Hydrogeologists have documented this pattern of circuitous groundwater flow in numerous unconfined aquifers by installing nested piezometers. Piezometers are specially designed wells with short intake areas (screens) which can be used to measure the water level, and hence the pressure, in the aquifer at specific depths. Note the locations and depths of the piezometers in Figure 12, and the value of pressure (head) illustrated with small triangles for each piezometer. Based on these types of studies in numerous locations, hydrogeologists have determined that groundwater flows with a downward-directed component in upland areas (called recharge areas), then it flows horizontally before changing to flow direction that is directed upward in low-lying areas (called discharge areas).

Figure 12: Piezometers are used to define Groundwater Recharge, Discharge, and Flow Patterns in Unconfined Aquifers (modified from Winter et al., 1998)



There are two important points to emphasize regarding the concept of recharge and discharge areas. First, groundwater flow patterns in unconfined areas <u>cannot</u> be determined unless wells are installed to different depths and the screen intervals are short and installed precisely. Wells with long screens <u>cannot</u> be used to evaluate depth-

specific head changes. Wells with short screens with unknown depths cannot be used to evaluate groundwater flow patterns in unconfined aquifer systems
Second, recharge areas in unconfined aquifer systems are based on downward-directed flow patterns and a decrease in total hydraulic head with increasing depth. Discharge areas in unconfined aquifer systems are based on upward-directed flow patterns and an increase in total hydraulic head with increasing depth. The boundary between recharge and discharge areas must be determined using nested piezometers which do not show a change in head with increasing depth. It is a common misconception that recharge and discharge areas can be determined by casual observation of differences in the elevation of the land surface (i.e., topography).

The unconfined groundwater system response to withdrawal of water from water-supply wells is complex. Withdrawal of groundwater from wells reduces the pressure in the aquifer in and near the well, resulting in a 'cone of depression' centered on the well. In unconfined aquifers, there is slow gravity drainage of water from the pore spaces in the aquifer above the developing cone of depression. Two important changes result from this gravity drainage within the cone: (1) the thickness of the unconfined portion of the aquifer is reduced within the cone, and (2) the transmissivity of the unconfined aquifer is reduced because of the reduction in thickness of the saturated portion of the aquifer.

Groundwater in the unconfined portions of most groundwater systems is often characterized by poor water quality relative to confined aquifer systems. For a variety of reasons, wells often produce lower yields from unconfined aquifers than do wells in confined aquifers. This is true in many areas of northwestern Mississippi and western Tennessee, where most water-supply wells do not tap the unconfined portions of the groundwater system.

VI.2 Confined Aquifers

Confined aquifers, such as major portions of the Wilcox and Claiborne Aquifer Systems, are characterized by beds or layers of material that have the ability to yield useable quantities of groundwater to wells open to these layers. In most cases, these aquifers are overlain and underlain by layers of material with reduced ability to transmit useable quantities of groundwater water (i.e., confining layers). Thus, hydrogeologists define aquifers and confining layers in terms of the relative ability of these materials to transmit groundwater, but non-technical individuals often assume incorrectly that confining beds are incapable of transmitting and producing groundwater. This ability of confining layers to transmit groundwater, even at significantly reduced rates relative to aquifers, is important because the slow movement of groundwater across confining layers is a significant component of the natural recharge for confined aquifer systems.

By definition, the pressure in a confined aquifer, under natural conditions, is such that the water level in a well tapping the confined aquifer will rise above the top of the aquifer at the well. In some aquifers, the water level in the well will rise above the land surface, and the well can be constructed in a manner that will allow the well to flow freely. In other instances, the water level in the well is below the land surface, but above the top of the aquifer. Hydrogeologists will often describe these as either a free flowing or non-free flowing well in a confined aquifer (see Figure 2).

Groundwater flow in confined aquifers is often less complex than in the unconfined portions of the groundwater system. For example, in major portions of the confined groundwater system, groundwater flow is often parallel with the top and/or bottom of the aquifer for significant horizontal distances, equipotential lines are often near-vertical in orientations, and withdrawals of groundwater from wells tapping these aquifers does not cause a reduction in thickness of the aquifer. Therefore, the transmissivity of confined aquifers is not reduced by groundwater withdrawals from wells unless the water level in the aquifer is lowered below the upper surface of the aquifer.

Many municipalities prefer to use groundwater from confined aquifers for three reasons: (1) water quality in confined aquifers is generally better than in unconfined aquifers, (2) the transmissivity of confined aquifer is not reduced by reduction in head (unlike unconfined aquifers), and (3) the total available drawdown, a measure of the number of feet that the water level in an aquifer can be reduced without harm to the aquifer, is generally greater in a confined aquifer than in an unconfined aquifer.

VI.3 Total Available Drawdown and Specific Capacity of Wells

The discussion of total available drawdown provided here refers only to the response of water levels in wells in confined aquifers. Pumps installed in wells constructed in confined aquifers will typically have the pump intakes located above the top of the confined aquifer so that the pumping water level cannot be lowered below the top of the aquifer. Hydrogeologists define total available drawdown as the number of feet (or meters) between the top of the aquifer and the water level in a non-pumping well tapping the aquifer (i.e., the static water level). For example, consider a confined aquifer with a top of aquifer elevation of 400 feet above mean sea level (AMSL) and a static water level of 600 feet AMSL. The aquifer has 200 feet of total available drawdown. That aquifer parameter can be used, in conjunction with the measurement called specific capacity of a well, to determine a <u>theoretical maximum yield</u> of a well.

Specific capacity is a term used extensively in the water-supply industry to evaluate the yield potential of a water-supply well. Specific capacity is the withdrawal rate of a well (measured in gallons per minute), divided by the amount of water level change (total drawdown) which occurs during a specific period of withdrawal. A common period for reporting specific capacity is 24 hours of pumping, but there is no fixed time requirement for reporting specific capacity.

The specific capacity of a well pumped at 1,000 gallons per minute (gpm) for 24 hours with 40 feet of drawdown is reported as $(25 \text{ gpm/foot of drawdown})_{24 \text{ hours}}$. Specific capacity is an important aspect of water-supply well hydraulics because it can be combined with total available drawdown to calculate a well’s (theoretical) maximum yield. For example, the confined aquifer well described previously with 200 feet of total available drawdown and a 24-hour specific capacity of 25 gpm/foot of drawdown can (theoretically) produce 5,000 gpm.

Reductions in total available drawdown will reduce the theoretical maximum yield of a well. A variety of factors can reduce the total available drawdown, including regional decline in water levels due to changes in precipitation or recharge rates, and the impacts of other pumping wells in the area. In the example well described above, every foot of reduction of the total available drawdown results in a corresponding loss of 25 gpm. If 100 feet of total available drawdown is lost due to impacts from nearby pumping wells, then 2,500 gpm are no longer available to be pumped from the impacted well.

The example provided here is modeled on an evaluation of municipal wells in the northern part of Mississippi that tap the Claiborne Aquifer. The City of Southaven water-supply well No. 2 (also called the Airways Well) had a reported specific capacity of approximately 20 gpm/foot of drawdown when it was completed in 2002 (LGS, 2002). For every foot of reduction in the total available drawdown caused by external factors, such as withdrawals from other wells operating in the area, the theoretical maximum yield of the Airways Well decreases by 20 gpm.

VI.4 Size of the Cone of Depression Surrounding a Confined Aquifer Well

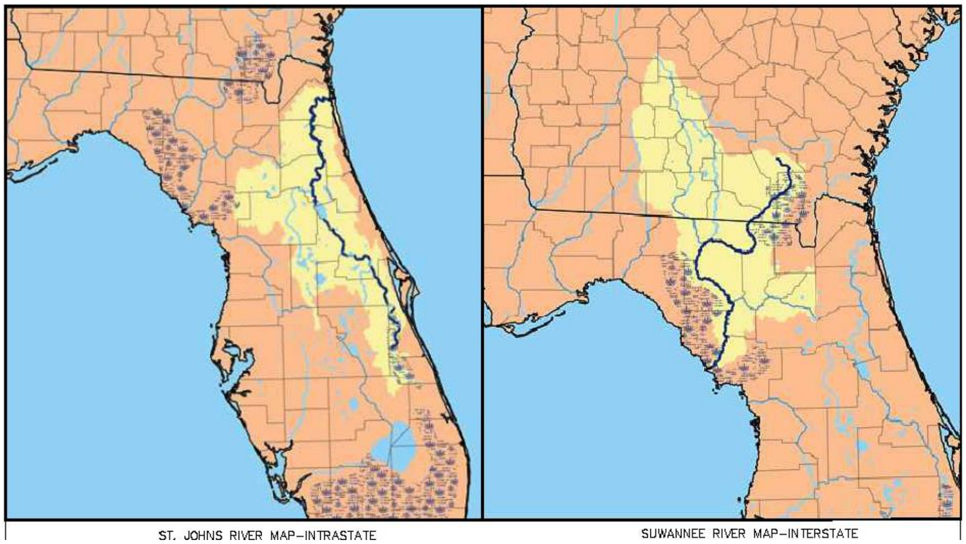
The shape of the cone of depression associated with a pumping well in a confined aquifer has two important aspects. First, the depth of the cone adjacent to the well is controlled by the hydraulic properties of the aquifer, the pumping rate, and the pumping period. The theoretical lateral limit of the cone of depression is independent of the pumping rate, and is instead a function of the hydraulic properties of the aquifer and the amount of pumping time. The theoretical limit of the cone of depression of the City of Southaven's well was calculated to be 90,000 feet, or approximately 17 miles (LGS, 2002). While this number may seem large to the casual observer, it should be remembered that this is the distance from the water-supply well beyond which there is theoretically zero water-level impact. The more important calculation for the Southaven well is, that at a distance of 27,000 feet (~5.1 miles) from the production well, the amount of water-level reduction in the cone of depression is 9.5 feet if the well is pumped at a rate of 1,500 gpm (LGS, 2002). Another production well at that location 27,000 feet away from the Southaven well would suffer a loss of theoretical maximum yield of 190 gpm (9.5 feet of loss in head X 20 gpm/foot = 190 gpm). Hydrogeologists commonly produce these types of well-interference calculations to determine the impacts on an aquifer system caused by one or more production wells. The important point here is that wells constructed and operated within the cones of depression of other production wells have significant cumulative impacts on the groundwater system, the most important of which is the ultimate reduction in the theoretical maximum yield of a well at any specific location. Calculations of the impacts of one pumping well at approximately 1,500 gpm on the water-levels should be considered in light of the large-scale impacts resulting from 175 wells pumping 180 million gallons per day along the Mississippi-Tennessee border.

VI.5 Opinions on Availability of Groundwater in the SMS Under Natural Conditions and Territorial Considerations

Aquifers are geological formations composed of naturally-occurring materials (e.g., sand, silt, limestone, etc.) that are capable of transmitting useable quantities of groundwater. Aquifers are essentially just conduits through which groundwater flows as a natural resource under natural conditions. A sand or rock layer with no groundwater moving into and through its pore spaces is not an aquifer any more than a dry river bed is a river. However, when water is added to either system under natural conditions, the forces of nature determine the ultimate availability of the water in both systems. The determination of the source and natural availability of surface water and groundwater within a specific state or territory under natural conditions requires entirely different analyses.

Fresh water is one of our most important natural resources, and its availability has become a major concern in many parts of the United States and elsewhere. Claims to surface water have historically been recognized based on the location and flow path of the water under natural conditions. Figure 13 illustrates this point with two rivers in Florida. The St. Johns River originates in, and resides entirely within, the State of Florida, and it ultimately discharges to the Atlantic Ocean. The Suwannee River originates in Georgia, travels through Florida, and discharges to the Gulf of Mexico. The river water in the first example is a natural resource of Florida, while the water in the second river is a natural resource shared by both states, a well-established concept based on the locations of the respective watersheds (drainage basins) from which the water is derived and the flow paths of the rivers.

Figure 13: Drainage Basin and Channel location of an Intrastate River (left) and an Interstate River (right) in Florida (modified from Wikipedia)

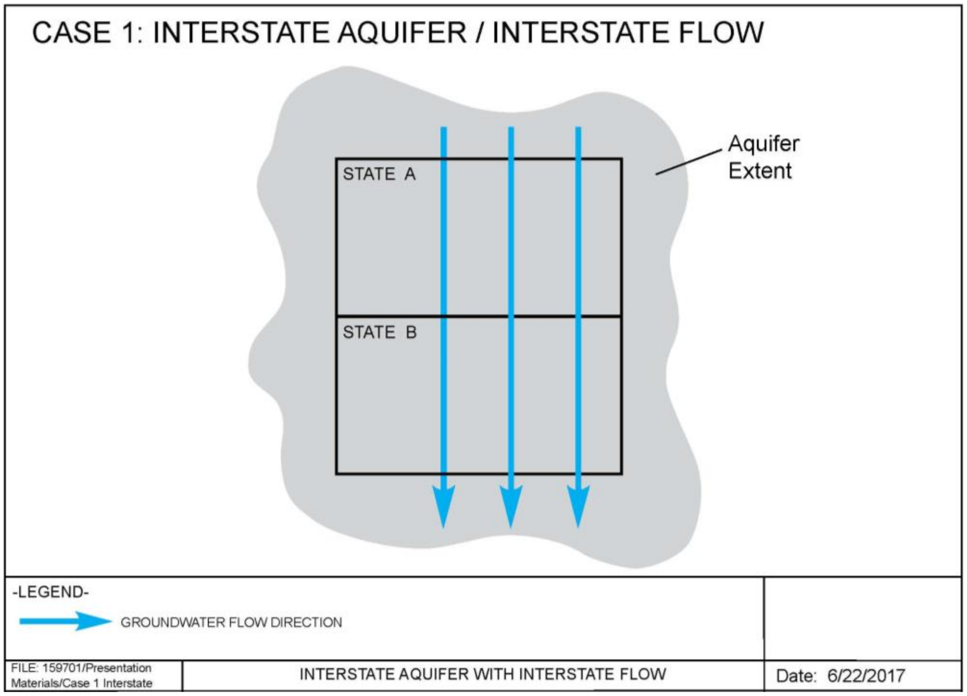


ST. JOHNS RIVER MAP–INTRASTATE

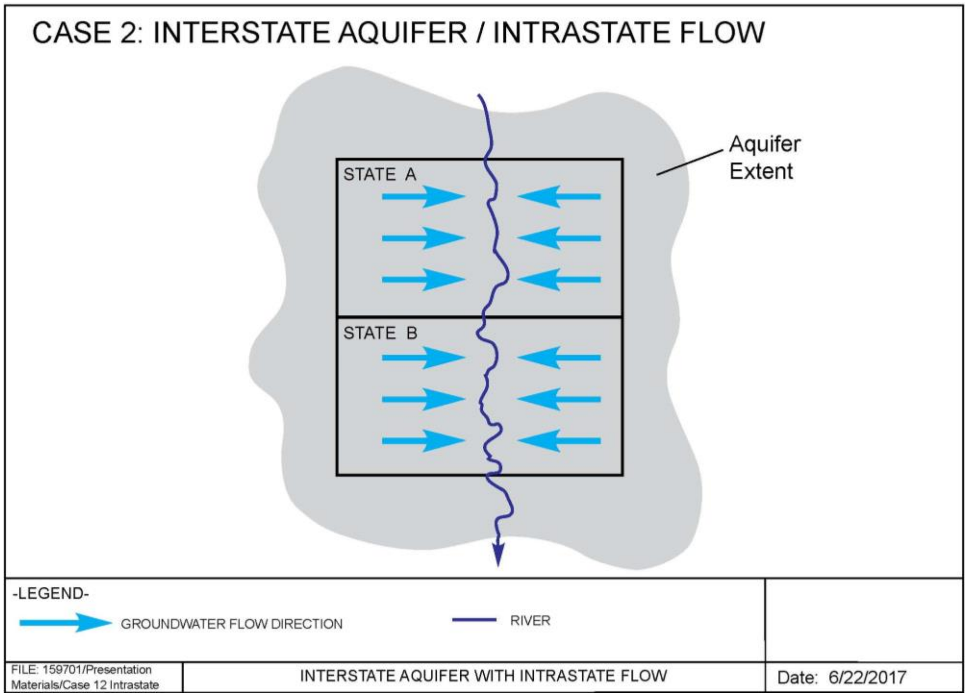
SUWANNEE RIVER MAP–INTERSTATE

The natural territorial accumulation and flow of surface water along the lowest path created by geological processes is visible to the entire world. While it is not as visible, thus making it inherently more complicated, the natural territorial accumulation and flow of groundwater within a confined aquifer is also determined by geological forces and identifiable by application of the concepts described in this expert report. Using my analysis of the Sparta-Memphis Sand Aquifer, I present two hypothetical cases to illustrate how the groundwater within a confined aquifer may or may not be a shared natural resource like the two rivers in Florida illustrated above, and I draw a distinction between Intrastate and Interstate groundwater.

- **Case 1**. Figure 14 is a map of a regionally extensive aquifer, and two states sharing an east-west border lie entirely within the extent of the aquifer. Because of the regional geology, the natural groundwater flow within the aquifer is directed from north to south, and the groundwater flow lines clearly cross the east-west border between the two states. In this case, the groundwater accumulates within, and flows through, both states under natural conditions, thus the groundwater is a shared natural resource under natural conditions analogous to an interstate river.



- **Case 2**. Figure 15 is a map of a regionally extensive aquifer, and two states sharing an east-west border lie entirely within the extent of the aquifer. In this case, a river running southward bisects both states. Because of the geologic conditions, the natural groundwater flow within this aquifer is directed toward the river from both the east and the west. In this case, the groundwater accumulation and flow is confined to each state, as shown by flow lines parallel to the boundary separating the two states. In this example, the groundwater accumulates and flows (for millennia) through one state under natural conditions to its discharge area located within that state. Therefore, the groundwater is that state's natural resource under natural conditions, and the groundwater is analogous to the water in an intrastate river.



Although these hypothetical examples are simple, they are applicable to this litigation. The fundamental question in the specific case of groundwater flow in the northern part of the Mississippian Embayment, and specifically in the Wilcox and Claiborne Aquifer Systems, is: What is the nature of groundwater flow within an aquifer system that is laterally extensive, and what did a groundwater flow net (flow lines and equipotential contours) look like during the pre-development time frame? The only viable way to answer this question is to carefully examine the flow patterns in the confined portions of these aquifer systems prior to any significant development of the groundwater system (i.e., the construction and operation of groundwater production well fields).

Several researchers have produced analyses of the pre-development flow patterns for the Wilcox and/or Claiborne Aquifer Systems for the border region of northwestern Mississippi and southwestern Tennessee, including (1) numerous studies by the United States Geological Survey and (2) investigations by private and academic scientists and engineers. Examples for each group of researchers are described below.

Studies by the United States Geological Survey include the work by Cushing et al. (1964), which provides a good summary of stratigraphy of the Mississippi Embayment.

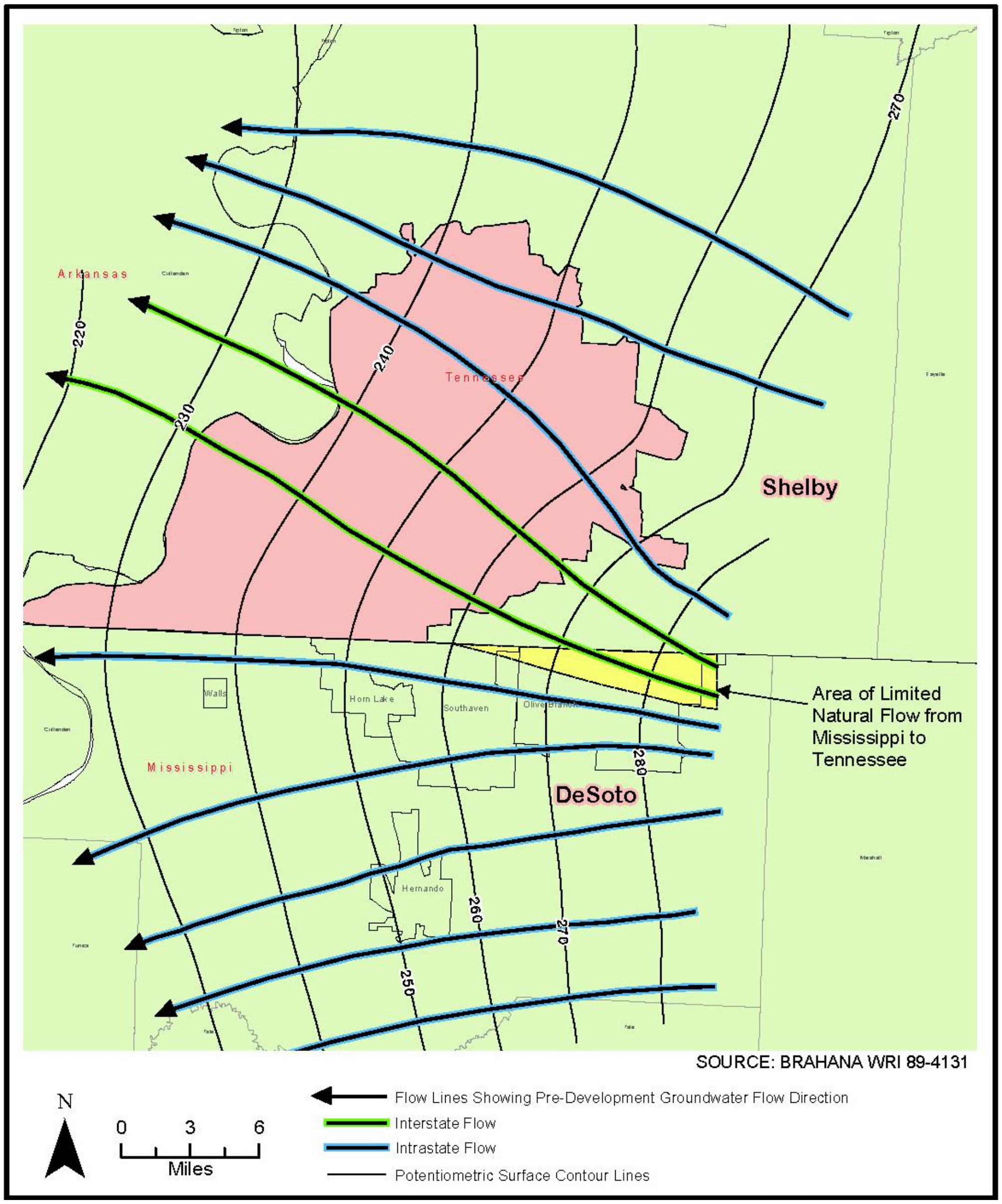
The Cushing et al. report does not include a groundwater flow net, but it does provide important information regarding the orientation and thickness of major Eocene-age deposits within the Mississippi Embayment. Other hydrogeological reports by the USGS include Criner and Parks (1976), Arthur and Taylor (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

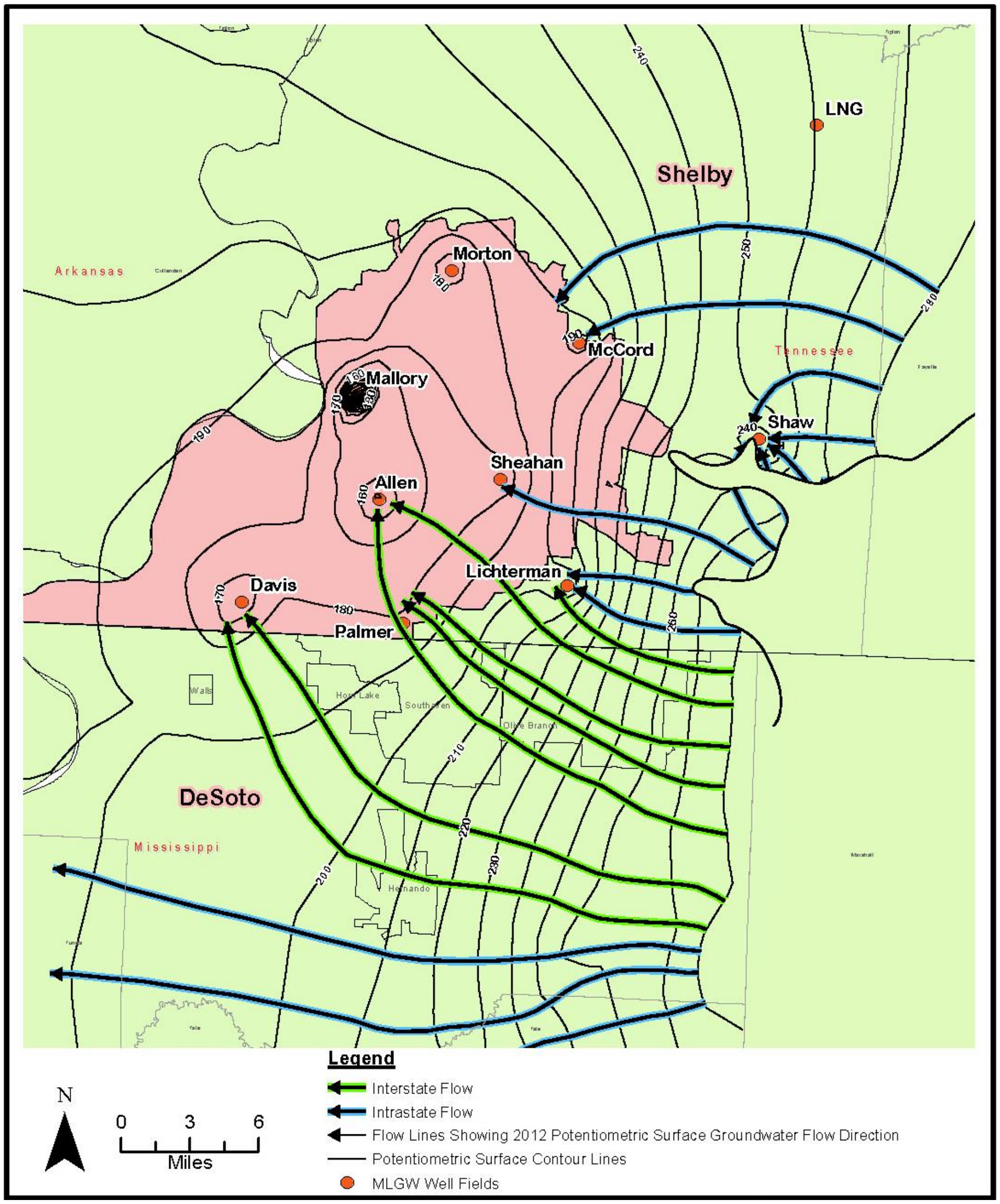
In 2014, Legette, Brashears, and Graham, Inc. (LBG) produced a MODFLOW-based groundwater-flow model for the principal aquifers in the Mississippi-Tennessee border region, specifically in the area that includes the large wellfields operated by the City of Memphis in Shelby County, Tennessee. LBG's pre-development 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)



SOURCE: BRAHANA WRI 89-4131

Figure 18: Legette, Brashears, and Graham, Inc. (2014) Post-Development Equipotential Map for the Sparta-Memphis Sand Aquifer (modified to highlight groundwater-flow paths)



VI.7 The Waldron and Larson (2015) Report

The Waldron and Larsen (2015) report was evaluated in connection with preparation of this expert report. After careful study of the report and their data sources, I did not rely upon the study by Waldron and Larson (2015) because it relies on inaccurate and unreliable data, it does not follow established hydrogeological methodology, and it contains unsupportable conclusions. In my opinion, the Waldron and Larson (2015) report is an unreliable source of information for scientific hydrogeological analysis of, and expert opinion regarding, issues concerning groundwater resources in the Mississippi-Tennessee border area. I reserve the right to offer a response or rebuttal to any opinions that may be provided by Waldron and Larson regarding their work.

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Appendix B: *Curriculum Vitae* for Dr. Richard K. Spruill

Richard K. Spruill, Ph.D, PG
President/Principal Hydrogeologist

Education
Ph.D. Geology, University of North Carolina, Chapel Hill, NC (1980)
M.S. Geology, East Carolina University, Greenville, NC (1978)
B.S. Geology, East Carolina University, Greenville, NC (1974)

Professional Registrations and Service
Professional Geologist in North Carolina (License #942)
Executive Committee member National Association of State Boards of Geology (ASBOG) (2007-2012)
Founding Director of Coastal Water Resources Center, East Carolina Univ. (2010-2013)
Chairman, North Carolina Board for Licensing of Geologists (2006-2010)
Subject Matter Expert, National Association of State Boards of Geology (ASBOG) (2005-2007)

Professional Experience

***Groundwater Management Associates, Inc*.** - Greenville, NC (1986 to Present)

President and Principal Hydrogeologist

Provides technical oversight, directs, and participates in hydrogeological projects, including groundwater resource evaluation and planning, wellfield and well design, borehole logging and evaluation, aquifer test design and interpretation, and other hydrological assessment projects. Clients include engineering firms, municipalities, industry, and attorneys.

Technical Expertise
- Groundwater hydrology
- Surface water hydrology
- Public water supply
- Groundwater resource evaluation and planning
- Wellfield and well design
- Coastal plain, piedmont, and mountain hydrogeology
- Safe yield of aquifers
- Groundwater policy education and implementation
- Aquifer storage and recovery (asr)
- Groundwater chemistry
- Coastal plain geology and geomorphology
- Mineralogy and mineral chemistry
- Igneous and metamorphic petrology
- Isotope geology

East Carolina University - Greenville, NC (1979 to Present)

Associate Professor of Geology, Department of Geological Sciences

Instructor for undergraduate and graduate geology and hydrogeology courses, supervising professor for graduate hydrogeology research projects, groundwater and

Instructor for undergraduate and graduate geology and hydrogeology courses, supervising professor for graduate hydrogeology research projects, groundwater and surface water research, community (local and state) outreach and education concerning hydrological issues.

Graduate-Level Courses Taught at East Carolina University

- Groundwater Hydrology (GEOL 5710/5711)
- Seminar in Computer Applications in Hydrology (GEOL 6522)
- Advanced Groundwater/Surface Water Hydrology (GEOL 7920)
- Geochemistry (GEOL 6400)
- Tectonic Analysis of North America (GEOL 6570)
- Volcanology Seminar (GEOL 5500 and GEOL 6703)
- Readings in Isotope Geochemistry (GEOL 6532)

Teaching Recognition at East Carolina University

- Robert L. Jones Award for Teaching Excellence (1981)
- University-wide Outstanding Teacher Award – Finalist (1989, 1992)

Publications

McCoy, C.A., Corbett, D.R., Cable, J.E., and. Spruill, R.K, 2007. Hydrogeological characterization and quantification of submarine groundwater discharge in the southeast Coastal Plain of North Carolina, Journal of Hydrology, v. 339, p. 159-171

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Litigation Support

2016 Expert witness deposition in the case of State of North Carolina et al. Vs. Duke Energy Progress, LLC, Superior Court for Wake County, North Carolina, File Number 13-CVS-11032 and in the case of State of North Carolina et al. Vs. Duke Energy Carolinas, LLC, Superior Court for Mecklenburg County, North Carolina, File Number 13-CVS-14661.

Retained by John Suttles, Southern Environmental Law Center, Chapel Hill, North Carolina.

2011 Expert witness trial testimony in Onslow Water and Sewer Authority v. Boggs and Rogers, Onslow County Superior Court. Retained by David Nash, Hogue Hill Jones Nash & Lynch, LLP.

2011 Expert witness trial testimony in Michael Allison, et al. v. ExxonMobil Corporation, et al., Circuit Court for Baltimore County, No. 03-C-07-003809. Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2010 Expert witness testimony, Frye-Reed Hearing in Michael Allison, et al. v. ExxonMobil Corporation, et al., Circuit Court for Baltimore County, No. 03-C-07-003809. Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2010 Expert witness deposition in Michael Allison, et al. v. ExxonMobil Corporation, et al., Circuit Court for Baltimore County, No. 03-C-07-003809. Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PCs.

2008 Expert witness trial testimony in Kurt Peterson et al., v. D.R. Horton, Inc., Circuit Court for Montgomery County, Maryland, Case No. 268778-V (Consolidated with cases: 269276-V; 270293-V; 272020-V; 272479-V; 272480-V). Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2007 Expert witness deposition in Kurt Peterson et al., v. D.R. Horton, Inc., Circuit Court for Montgomery County, Maryland, Case No. 268778-V (Consolidated with cases: 269276-V; 270293-V; 272020-V; 272479-V; 272480-V). Retained by Theodore M. Flerlage, Law Office of Peter G. Angelos, PC.

2006 Expert witness deposition in Hope Koch, et al. v. John R. Hicks, et al., United States District Court, Southern District of New York, No. 05-cv-05745-SAS. Retained by Mary V. Koch, Law Office of Peter G. Angelos, PC.

2006 Expert witness deposition in Curl, et al. v. American Multimedia, Inc., et al., and Brown et al. v. American Multimedia, Inc., et al., Superior Court of Alamance County, North Carolina, File Nos. 03 CVS 493 and 03 CVS 663. Retained by Richard Watson and James F. Hopf.

2006 Expert witness deposition in Richard A. Smith and April L. Smith v. Thomas Brothers Oil & Gas, Inc, et al., Superior Court of Caswell County, North Carolina, File No. 03 CVS 226. Retained by James F. Hopf.

2005 Expert witness trial testimony in Ellison v. Gambill Oil Company, Inc., et al., Superior Court of Watauga County, North Carolina, File No. 03 CVS 428. Retained by Warren A. Hutton.

2004 Expert witness deposition in Vines, et al. v. Gambill Oil Company, Inc., et al., Superior Court of Watauga County, North Carolina, File Nos. 02 CVS 467, 02 CVS 498, 02 CVS 776 and 03 CVS 428. Retained by James F. Hopf, Claude D. Smith, Warren A. Hutton and Paul R. Dickinson, Jr.

2003 Expert witness deposition in Joel & Janice Drum v. Schronce and Superior Petroleum and Fuel Company, Inc., Superior Court of Catawba County, North Carolina, File No. 01 CVS 3998. Retained by James F. Hopf.

1999 Expert witness deposition in Robert J. & Kathleen Leary, et al. v. Eastern Fuels, Inc., Superior Court of Currituck County, North Carolina, File No. 97 CVS 326. Retained by James F. Hopf.

1998 Expert witness deposition in King, et al. v. Conoco, Inc., et al., Superior Court of New Hanover County, North Carolina, File Nos. 97 CVS 02670 & 97 CVS 02672. Retained by James F. Hopf.

1998 Expert witness trial testimony in Grant, et al. v. E.I. Dupont, Inc., United States District Court, Eastern District of North Carolina, File No. 4:91-CV-55-H. Retained by Marvin Blount, Jr. and James F. Hopf.

1994 Expert witness trial testimony in Shamrock Fuels, Inc., et al. v. McGraw Edison Company, Cooper Industries, Inc., et al., United States District Court, Eastern District of Kentucky at London, Civil Action No. 92-129. Retained by Marvin Blount, Jr. and James F. Hopf.