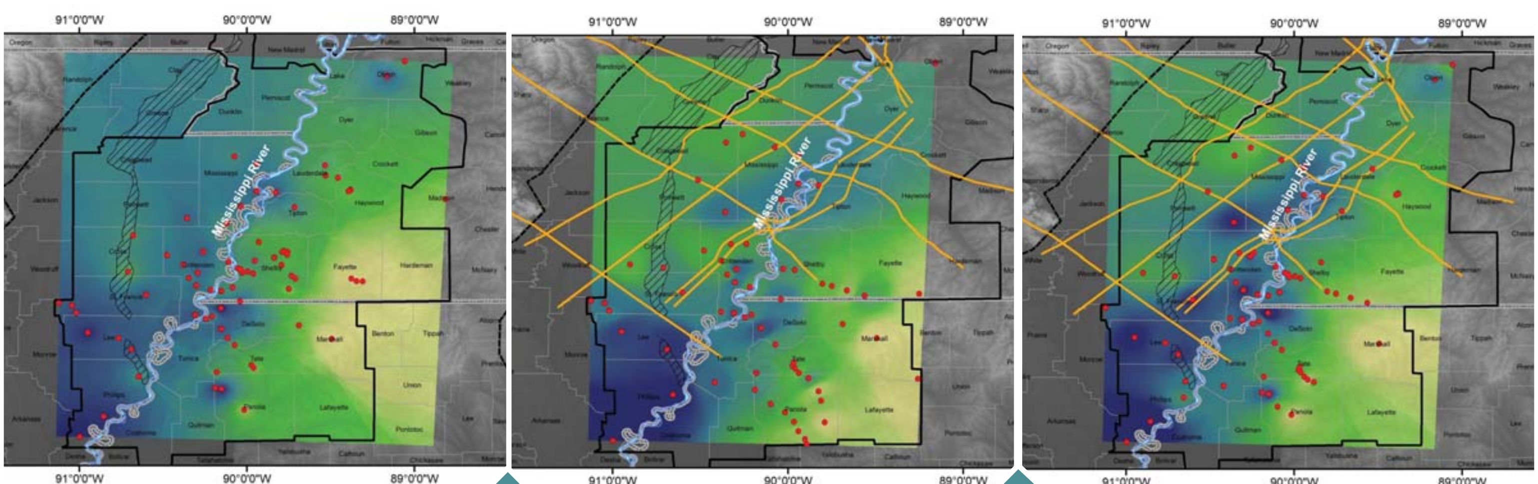
United States
Environmental Protection
Agency

EPA 600/R-10/130 | January 2011 | www.epa.gov/ada

Mississippi Embayment Regional Ground Water Study



Office of Research and Development
National Risk Management Research Laboratory, Ada, Oklahoma 74820

Mississippi Embayment Regional Ground Water Study

Brian Waldron
University of Memphis, Department of Civil Engineering, Ground Water Institute

Daniel Larsen
University of Memphis, Department of Earth Sciences

Robyn Hannigan
University of Massachusetts at Boston, Department of Environmental, Earth and Ocean Sciences

Ryan Csontos
University of Memphis, Department of Civil Engineering, Ground Water Institute

Jerry Anderson
University of Memphis, Department of Civil Engineering, Ground Water Institute

Carolyn Dowling
Ball State University, Department of Geology

Jennifer Bouldin
Arkansas State University, Arkansas Biosciences Institute

Office of Research and Development
National Risk Management Research Laboratory, Ada, Oklahoma 74820

Notice

The U.S. Environmental Protection Agency through its Office of Research and Development funded and managed the research described here under assistance agreement EM833253 to the Ground Water Institute located at the University of Memphis in Memphis, Tennessee. This report has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Increased water usage in the southeastern United States in the tri-state area of Tennessee, Mississippi and Arkansas poses a dilemma to ensuring long-term sustainability of the quantity and quality of ground-water resources that underlie the region. Demand for ground water by agriculture, municipalities and industry are presently stressing the sustainable yield of the fresh water aquifers. Instances of ground-water contamination have closed water-treatment facilities; many other potential contaminant sources could threaten human health. To address these threats, federal, state and local government have initiated a four-phase research effort to understand, model, and suggest best management practices for the ground-water resources in the region.

This report represents the results of the first-phase efforts to address a persistent problem associated with the use of disparate methods and the uncoordinated timing of hydrologic and geologic data collection across state lines, thus creating a disjoint in the regional understanding of aquifer systems, ground-water migration and usage, and potential contamination threats on water resources. Similarly, a communication lapse has existed among the states with regard to ground-water resource planning. By implementing a collaborative, regional approach developed through the first phase, the expectation is to improve the understanding of the ground-water resources – without the constraint of political boundaries and disjointed datasets. This will provide capabilities for stakeholders to begin proactively working toward a common goal of ensuring future ground-water availability without sacrificing the integrity of the regional ground-water resources.

David G. Jewett, Acting Director
Ground Water and Ecosystems Restoration Division
National Risk Management Research Laboratory

Contents

Figures

Tables

1.0 Introduction

Increased water usage in the southeastern United States in the tri-state area of Tennessee, Mississippi and Arkansas poses a dilemma to ensuring long-term sustainability of the quantity and quality of ground-water resources that underlie the region. Demand for ground water by agriculture, municipalities and industry is presently stressing the sustainable yield of the fresh water aquifers. Instances of ground-water contamination have closed water-treatment facilities; many other potential contaminant sources could threaten human health. To address these threats, federal, state and local government have initiated a four-phase research effort to understand, model, and suggest best management practices for the ground-water resources in the region.

Phase I will develop the intellectual, organizational, and methodological foundation for the subsequent three phases. During Phase I, the various stores of hydrogeologic data will be evaluated on their quality and usability to addressing the impact of the surmounting stresses on the regional ground-water system. The area under investigation includes the Tennessee counties of Shelby, Fayette, Hardeman, and Tipton, the Mississippi counties of Desoto, Marshall and Tunica, and the Arkansas county of Crittenden (Figure 1). Standardized and innovative methodologies and technologies will be employed in Phase II to fill the data gaps identified in Phase I. This data gathering will be conducted in such a way as to couple the spatial and temporal components of the hydrologic cycle of atmospheric charging, land surface processes and ground water. In this way, the fluxes and stores can be better represented holistically; an approach not adopted in previous studies thus to their detriment. Guiding the data collection in Phase II and the predictive, analytical and conceptual models constructed during Phase III are the science questions posed by the local stakeholders. These questions are:

1. Can the regional ground-water resources meet the future demands by municipalities, industry and agriculture? If not, what are the expected ground-water shortages and where are they occurring?

2. What are those factors in the regional ground-water system that impact sustainable yield and water quality?

3. Is the Mississippi River a viable alternative water source for agricultural usage?

4. What impact would increased agricultural pumping from the Memphis/Sparta aquifer have on the quantity and quality of ground water necessary to meet the demands by municipalities and industry?

5. To what extent are ground-water withdrawals impacting ecosystems?

Answers to these questions will guide policy makers in Phase IV to make the necessary changes to land use practices and water consumption that, cumulatively over time, will negatively impact the sustainability of the region's ground water as a viable water source.

In 2006, Congress appropriated Phase I dollars within EPA for the study. Phase I specifically addresses EPA's mission of protecting human health and the environment by (1) conducting an assessment of data stores existing at the state and local level, (2) evaluating data needs at the regional scale that will sharpen our understanding of the regional ground-water system and its connection to other environmental processes, and (3) organizing data collection practices on a regional scale that will assist with addressing ground-water resources in a holistic manner. The inherent benefit of this phase is an improved ability to better address issues that threaten regional ground water

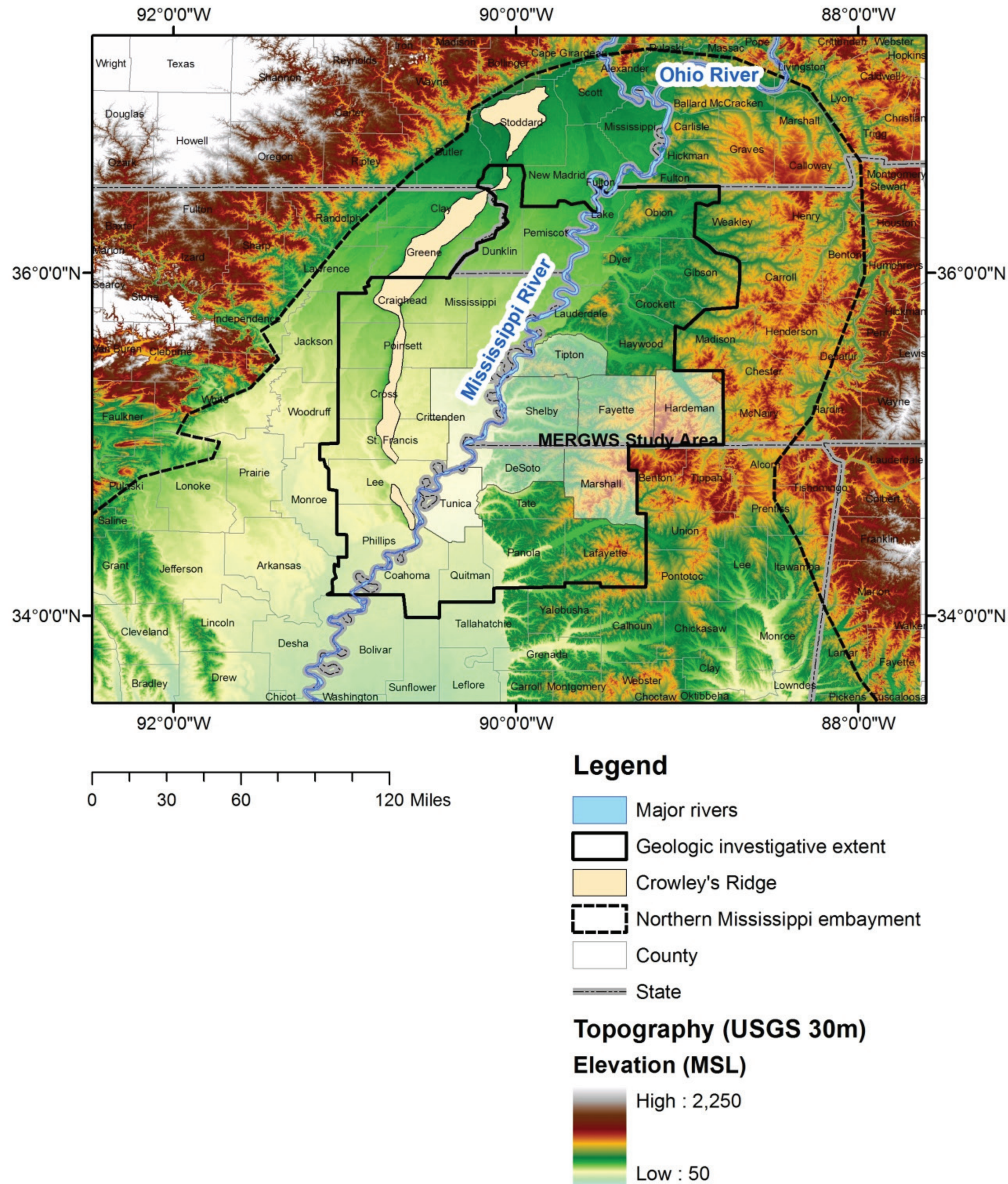


Figure 1. *MERGWS study area (counties in opaque white), geologic investigative boundary and digital elevation model (elevation in feet) of the northern Mississippi embayment.*

resources and ecosystems that depend on these water resources.

In 2000, the local stakeholder community (local, state and federal agencies and academia from Tennessee, Arkansas and Mississippi) formed an informal organization called MAT-RAS, or Mississippi-Arkansas-Tennessee Regional Aquifer Study. This group of stakeholders met annually to discuss the growing threats to the regional ground-water supply and postulate actions to avert further degradation to the system. A persistent problem in the past had been the use of disparate methods and the uncoordinated timing of hydrologic and geologic data collection across state lines, thus creating a disjoint in the regional understanding of aquifer systems, ground-water migration and usage, and potential contamination threats on water resources. Similarly, a communication lapse existed between the states with regard to ground-water resource planning. By implementing a collaborative, regional approach to improve our understanding of the ground-water resources – without the constraint of political boundaries and disjointed datasets – the stakeholders could begin to proactively work toward a common goal of ensuring future ground-water availability without sacrificing the integrity of our water resources. MAT-RAS never formalized into a governing body and eventually stopped meeting, yet the desire of the local stakeholders to do something remained. Phase I of this effort included the formation of a Scientific Advisory Committee (SAC) comprised of the same local stakeholders under MAT-RAS who would oversee the effort.

2.0
Background

Regional overview

The Mid-South region, which includes the tri-state area of Mississippi, Arkansas and Tennessee, is fortunate to have an abundance of fresh water. These water resources include surface water, such the Mississippi River, and ground water. However, because of its generally high quality and relative ease of access, our most valuable water resource is ground water. The ground water resources of the region stem from the formation of the Mississippi Embayment, a geologic extension of the Gulf Coastal Plain province that extends into the mid-section of the United States and terminates at the southern tip of Illinois (Cushing et al., 1964). The ground water consumed within the embayment accounts for nearly 17% of that withdrawn nationally from unconsolidated sand and gravel aquifers, with 90% of this withdrawal coming from Tennessee, Arkansas and Mississippi (Hutson, 1998). Farmers rely heavily upon the quantity of ground water for the irrigation of their crops and water for their livestock. In Eastern Arkansas, ground water consumption for irrigation, primarily for rice crops, is approximately 6500 billion gallons per day (bgd), averaged on an annual scale. Similarly, 1300 bgd is withdrawn in Mississippi for irrigation. Within the embayment, Tennessee's reliance on irrigation use is much less at 3 million gallons per day (mgd); however, ground water usage for public supply and industry is highest among the three states at 258 and 50 mgd, respectively (Hutson, 1998). A majority of the ground water consumed in Tennessee occurs in Shelby County, which is home to Memphis, ranked 17th in overall population among major cities nationwide (Census 2000). In Memphis, Tennessee alone, over 80 industries have located there primarily because of the ground-water quantity and quality; these industries combine to return over a billion dollars per year back into the nation's economy.

Arkansas dilemma

- <u>Issue:</u> *Approximately 90% of ground-water withdrawal in Eastern Arkansas is for agricultural purposes, primarily rice production. A daily average of 6.4 billion gallons per day of ground water is pumped from the Mississippi River alluvial aquifer (Maupin and Barber, 2005); however, this pumping occurs mostly during the growing season. Declines in the Mississippi River alluvial aquifer and concerns about aquifer consolidation have prompted farmers to consider tapping the deeper Memphis/Sparta aquifer for irrigation water. Overuse is the major threat in Arkansas.*

Water levels within the Mississippi River alluvial aquifer in Eastern Arkansas have been on a continual decline in the high production areas such as Poinsett and Lonoke counties, dropping as much as 20 to 25 ft (Westerfield, 1990). Seven identifiable cones of depression have formed in twelve of the twenty-three counties in Eastern Arkansas, and long-term water-level recording in some of these depressions will determine their persistence (Schrader, 2001). Similar to other counties in Eastern Arkansas, alluvial water levels in Crittenden County are lowest in the fall after the growing season, then rebound to some degree by spring after the winter rains (Plafcan, 1985; Plafcan, 1986; Westerfield, 1989; Westerfield, 1990).

Between 1967 and 1986, alluvial water levels in Crittenden County remained relatively level, fluctuating between 200 and 203 ft mean sea level (MSL). Since 1987 water levels have dropped with the most rapid decline occurring after 1995 to about 192 ft MSL. North of Crittenden County in Mississippi County, water levels have fluctuated since 1955, but a sustained decline is not apparent (Ackerman, 1989). St. Francis and Lee counties south of Crittenden have seen water-level declines in the alluvial aquifer with St. Francis County showing a dramatic decline between 1988 and

2001 of nearly 12 ft (Schrader, 2001). The absence of dramatic drops in the alluvial water table in those Arkansas counties bordering the Mississippi River is attributed to the hydraulic connection between the alluvial aquifer and the river. A pressure transducer in the Crittenden County well, AR:H-2A, and operated by the University of Memphis has indicated an immediate response in the alluvial water level as the Mississippi River stage rises and falls.

In the Sparta (Memphis) aquifer, production has been focused in central and southern Eastern Arkansas. Since 1975, withdrawals from the Sparta aquifer have doubled (Hays and Fugitt, 1999). Persistent cones of depression exist at major withdrawal centers in Jefferson, Columbia and Union counties (Edds and Fitzpatrick, 1984; Edds and Fitzpatrick, 1986; Westerfield, 1995; Joseph, 1998). In Columbia and Union counties, the Sparta, originally confined, has since become unconfined with water level dropping below the formation top (Hays and Fugitt, 1999). From 1983 to 1993, as many as three wells tightly cased within the Sparta aquifer within Crittenden County were used for control in developing the potentiometric maps. In 2000, the number of Sparta wells in Crittenden County increased to four (Joseph, 2000). Sparta water levels remained near consistent from 1983 to 2000. In the counties surrounding Crittenden, production from the Sparta increased from 1995 to 2000 with a cone of depression apparent in Poinsett County northwest of Crittenden and growing southward to include Cross County just west of Crittenden (Joseph, 2000). The general trend of the gradient in the Sparta across Crittenden County is toward the southwest. A recent, yet unpublished potentiometric map of the Sparta aquifer conducted by the USGS Tennessee Water Science Center was developed that included water level measurements taken in Tennessee, Mississippi and Arkansas. The suggested gradient trend across Crittenden County was again to the southwest (communication, Michael Bradley USGS TN Water Science Center).

Water use information for the deeper Wilcox group is very limited. Withdrawal from this aquifer is primarily for municipal or industrial use. The depth of the unit limits its use for irrigation, especially when water from the Mississippi River alluvial aquifer is readily available. In Crittenden County, approximately 7.85 million gallons on average each day (MGD) is withdrawn, primarily by West Memphis for drinking water (Holland, 1999). In Mississippi County to the north, 22.3 MGD is withdrawn. Little (<4 MGD) to no water is taken from the Wilcox group in the remaining adjacent counties to Crittenden. Not enough information is available to assess water-use trends in the Wilcox.

Mississippi dilemma

- <u>Issue:</u> *Nearly 65% of ground water withdrawn in Mississippi within the Mississippi Embayment region is for irrigation purposes, primarily rice production. Pumping from the Mississippi River alluvial and Sparta aquifers is prevalent. Development growth in Desoto County directly south of Memphis, Tennessee has made Desoto County the fastest growing county in Mississippi for the last 10 years and is projected to rank highest in future years. Overuse and municipal demands are the greatest concerns in Mississippi.*

In Mississippi, the Mississippi River alluvial aquifer is present only within the northwestern section of the state, bordered to the east by the Bluff Hills. The general alluvial water-level trend is to the south (Goldsmith, 1993). Water levels fluctuate in Desoto and Tunica counties between spring and fall. Declines, some as much as 5 ft, occur across these counties with few exceptions in the fall after the growing season, and then rebound as much as 6 ft by spring after the winter rains (Darden, 1983; Sumner, 1984; Goldsmith, 1993). Water levels within the interior of Tunica County did maintain a decline between 1981 and 1983. Overall, water levels have declined on average less than 0.2 ft per year since 1980 (Arthur, 2001). The largest cones of depression occur in the central and southern portion of the alluvial aquifer in Sunflower, Humphreys and Washington counties where the depth of water, usually 25 ft below ground surface, is commonly 30 to 50 ft

(Sumner and Wasson, 1990; O'Hara and Reed, 1995). Though withdrawal from the Mississippi River alluvial aquifer is large, recharge from precipitation and the rivers has sustained levels and storage still remains at 96 to 99 percent of the aquifer's unconfined capacity (Arthur, 2001). Sumner and Wasson (1990) simulated an increase in pumping from 1983 to 2003 assuming pumpage was 1900 million gallons per day (MGD). Assuming pumpage was distributed uniformly, drawdown in Tunica County was estimated to exceed 10 ft. Estimated ground-water consumption for the Mississippi River alluvial aquifer in 2000 was 6,410 MGD (Maupin and Barber, 2005).

The Sparta aquifer in northwestern Mississippi has major cones of depression that are further south of the alluvial aquifer water-level depressions, occurring in Sharkey, Yazoo and Hinds counties. Smaller cones of depression in the Sparta also exist further north in Sunflower, Bolivar and Coahoma counties. Again, Coahoma County is south of Tunica adjacent to the Mississippi River. Potentiometric water levels in 1984 indicate a west-northwest gradient across Desoto County, and then southwestward through Tunica County (Darden, 1987). Darden (1987) did not show any Sparta observation wells in Marshall County. Arthur and Taylor (1990) indicated that under predevelopment conditions, gradients in the Sparta aquifer were directly toward the west then southwest. Brahana and Broshears (2001) also suggested a western gradient pattern in the Sparta aquifer within Desoto County. Similar to Darden (1987), Oakley and Burt (1994) observed a northwest gradient across Desoto County toward Shelby County. The northwest gradient was still prevalent in Bradley's unpublished contour map of water levels in the Memphis/Sparta aquifer across the tri-state region. Between 1980 and 1989, water levels in the Sparta aquifer in Desoto County have dropped as much as 16 ft (Oakley and Burt, 1994). Observations in Marshall and Desoto were not available. South of Tunica in Coahoma County, water levels have declined as much as 12 ft.

Ground-water production from the Lower Wilcox aquifer in Mississippi is primarily used for municipal and industrial purposes. Water levels across Marshall and Desoto counties were approximated by Oakley et al. (1994), however greater well control in Tunica County and the adjoining Tate and Panola counties allowed for more assured contouring. Some of the largest water level declines in the Wilcox aquifer occurred in Tunica County, decreasing 20 ft between 1979 and 1988 (Oakley et al., 1994). A cone of depression in Panola County has forced the gradient in Tunica toward the southeast.

Population growth in Mississippi has been on the increase since 1990. Only two of Mississippi's 82 counties had a negative percent population change during this time period. Desoto County had the largest percent population change at 66.7%. The next lowest percent change was Rankin County at 41.4%. Marshall and Tunica counties had an increase of 20.6% and 25.2%, respectively, over the same time period. Desoto County is projected to remain the fastest growing county in Mississippi between 2004 and 2009. There are no metro-sized cities in Desoto, Marshall or Tunica counties. Desoto County is directly south of Memphis, Tennessee. Data is courtesy of the Memphis Chamber of Commerce (2005).

Tennessee dilemma

- *Issue: Shelby County is second in the nation in regard to sole dependence on ground water for municipal use. Withdrawals in Shelby County have caused a major cone of depression and reorientation of aquifer gradients in adjacent counties. Growth of Memphis and other municipalities has heightened the concern for urban sprawl impacts to the recharge area. In addition to urban sprawl and sustainability of available water in light of adjacent state's threats, aquitard breaches are posing an increasing contamination threat.*

The total fresh ground water withdrawal on average for the State of Tennessee is approximately 275 MGD. Ground-water withdrawal in

Shelby County, Tennessee accounts for nearly 80% of the total for the state. Therefore, focus on the ground-water system in west Tennessee has been on water use in Shelby County. The Quaternary aquifer in west Tennessee is a remnant of a high level terrace of an ancestral Ohio/Mississippi river system (Austin et al., 1991). Withdrawal from the Quaternary aquifer is minimal, primarily used for irrigation and domestic use. Parks (1990) developed a water table map for Shelby County based on water levels in 1987. This is the sole survey; however, the University of Memphis is revisiting the water table mapping presently. In the fall of 1987, the water table mimicked the topography of the land surface with discharge typically to the local river systems. Five localized depressions in the water table were resolved as areas where the Upper Claiborne confining unit, separating the Quaternary aquifer from the Memphis aquifer, was thin or absent, thus allowing for downward vertical leakage (Parks, 1990).

Exploitation of the ground-water resources of the Memphis aquifer beneath Shelby County began in the late 1880's. The predevelopment gradient of the Memphis aquifer underneath Shelby County was to the west-northwest (Brahana and Broshears, 2001). In 1995, ground-water gradients are toward the major cone of depression beneath downtown Memphis – the origination of the earliest pumping (Kingsbury, 1996). In close proximity to the Shelby County border, Memphis aquifer gradients in Desoto County, Mississippi, Crittenden County, Arkansas and Tipton County, Tennessee are toward Shelby County. Since pumping began from the Memphis aquifer, water levels have dropped nearly 125 ft, however the aquifer remains confined. In northeast Shelby County, just east of the Memphis aquifer outcrop region and within the recharge area, water levels observed in the observation well Fa:R-2 have remained steady since 1950 (Kingsbury, 1996). Memphis aquifer water levels at the county-wide scale have not been recorded for Tipton, Fayette and Hardeman counties. A review by the University of Memphis of measured static water levels by drillers on private wells in Fayette County indicated that the Memphis aquifer water table (Fayette is the recharge area for the Memphis aquifer) mimicked land surface topography with flow toward the alluvial valleys.

The Lower Wilcox, or Fort Pillow aquifer, has limited withdrawal as compared to the Memphis aquifer above it. Across Shelby County gradients are to the southwest toward a major cone of depression beneath West Memphis across the Mississippi River in Crittenden County, Arkansas (Kingsbury, 1996). Smaller, localized water-level depressions in the Fort Pillow aquifer exist in Desoto County, Arkansas and under the City of Millington and below the Shaw wellfield in Shelby County (Kingsbury, 1996). At the same location as Fa:R-2, observation well Fa:R-1 has indicated a near 25 ft decline in the Fort Pillow aquifer between 1950 and 1995.

The Memphis aquifer is the primary water source for municipalities and industry. Replenishment of this vital resource occurs over a 2800 mi^2 area across West Tennessee. Upgradient of the depression beneath Memphis, Tennessee, the recharge area begins along the eastern border of Shelby County and continues eastward across Fayette County and into Hardeman County. Growth in Shelby County has caused urban development to move into the recharge area at an astonishing rate. Increased risk of contamination and an encumbrance to recharge of the Memphis aquifer resulting from urban sprawl has raised considerable concern regarding the sustainability of Memphis aquifer water quality and quantity. In the southeastern corner of Shelby County within the Memphis aquifer outcrop area, one of the Town of Collierville's major water treatment facilities was impacted by two separate industrial contaminant plumes resulting in inoperability of the plant and a near $1 million economic loss (communication, Tim Overly, Town of Collierville).

The Upper Claiborne confining clay overlays much of the Memphis aquifer in Shelby County; however, localized breaches in the clay provide avenues for inter-aquifer exchange of water with the unconfined Quaternary aquifer (Graham and Parks, 1986; Parks 1990). The

Quaternary aquifer is more prone to contamination from sites such as the Bellevue, Hollywood, Brooks, and Jackson Pit waste-disposal dumps (Parks et al., 1981), the Shelby County landfill (Bradley, 1991; Parks and Mirecki, 1992), Memphis Defense Depot (Miller et al., 1994), Mississippi River influence (Brown, 1993; Parks et al., 1995), nearly 1600 underground storage tanks (query Tennessee Department of Environment and Conservation UST program), and the petroleum industry. Due to the extensive pumping from the Memphis aquifer in Shelby County, water levels in the Memphis aquifer have fallen below that of the Quaternary aquifer inducing downward vertical leakage through the confining unit breaches into the Memphis aquifer (Parks, 1990; Brahana and Broshears, 2001; Larsen et al., 2003).

3.0
Project Task Plan

The work plan for Phase I is subdivided into five main topics. These topics are further divided into subtopics as follows:

1. Perform geologic mapping of the region
    - Combine with the University of Memphis geologic borehole database acquired geophysical logs from Tennessee, Mississippi and Arkansas
    - Correlate interpreted geologic picks from the geophysical logs to create cross-sections of formational boundaries and significant intra-bedding facies
    - Construct quasi-3D representation of regional litho-stratigraphy and assess regions of insufficient data
2. Ascertain water quality changes and ground-water contamination threats
    - Catalog water chemistry variables from disparate datasets
    - Ascertain temporal water quality changes and chart statistical variation among measurement geochemical variables
    - Conduct a spatial assessment of contamination threats to the ground water and ascertain chemical signatures and environmental tracers valuable for numerical model calibration and analytical modeling
3. Conduct assessment on aquifer parameter values and measurement methodologies
    - Acquire relevant literature of past investigations into aquifer parameter information
    - Construct aquifer parameter database from historic USGS records
    - Determine the appropriateness of measurement value as a spatially aerial and vertically relevant estimate
4. Catalog surface water sources to ground water
    - Compile information on surface water sources to ground water and evaluate the significance of the sources
    - Form prognosis on lacking surface water property data
5. Diagnose additional sources/sinks of water to the ground-water system
    - Ascertain estimation methodologies for ground-water recharge
    - Evaluate methods for estimating evapotranspiration

4.0

Quality Assurance Project Plan (QAPP) Data Quality Assurance

The final QAPP for this project was accepted on August 20, 2008. Quality assurance visits were accomplished while researchers were actively acquiring and incorporating data for the described tasks. Reports to the primary investigator were completed from these visits and included accomplishments made on each task and descriptions of points of concern. Subsequent quality assurance visits included determination of fulfillment of these points to ensure data quality. Data backup and electronic records of data input and interpretation were the primary points of concern during these visits and deficiencies were satisfied readily. A summary of the data quality assurance for the project is described below, categorized by the five main topics as outlined above.

Task 1: Perform geologic mapping of the region.

<u>Data transcription</u> - to assure the accuracy of data transcription of secondary data sources, the quality assurance of this data transfer included check-print and/or two-person data entry. Signatures (including electronic) were required in the data acquisition of data entry verification form signifying completeness and correctness of the data entry. The record of authentication for each database became part of the data file repository denoting verification, completeness, and correctness of the data entry.

<u>Data quality</u> – was assessed using the following parameters:

- Presence of multiple geophysical logs for the same borehole, consistency and technological reliability of logging instrumentation and protocol, and the presence of a corresponding geologist's or driller's log was required.
- Geologist logs used to assess fine interbedding of sediments and geologic correlation were completed by matching digitized log patterns, representing geologic formations or members among spatially distant boreholes.
- Quality assessment of such data included consistency of formations over the region or average thickness of geological formations, evidence for uplift or subsidence of the top or bottom of formations in multiple correlated sections, seismic cross-sections, and regionally interpolated surfaces were used to assess the presence of fault offsets of the sedimentary package.
- At least two scientists reviewed stratigraphic correlation and fault displacement of strata.
- If final interpretation of these scientists did not correlate, a third opinion was solicited for the final assurance of quality interpretation.

<u>Spatial data quality</u> – was assessed according to the reliability of the source data with a numerical ranking scale for coordinates and recorded within the metadata as described in the QAPP.

Task 2: Ascertain water quality changes and ground-water contamination threats.

All datasets were converted to SI units and outliers were identified utilizing Dixon's and Grubbs outlier tests. Investigators also screened for codependent data to eliminate cross correlation of variables used in models. Data were tested across time and space for normality. A 95% confidence level was set for all statistical tests, resulting in a statistically and chemically robust threat model allowing easy integration of future additional data.

Task 3: Conduct assessment on aquifer parameter values and measurement methodologies.

Data source and location information was incorporated into a Microsoft EXCEL spreadsheet and data quality was ranked for assessment as described in the QAPP and included: published/approved; presence of multiple or observational wells; test duration; supporting information; statistical and repeated analyses; drawdown and recovery analyses.

Task 4: Catalog surface water sources to ground water.

The compilation of existing data for Task 4 incorporated the quality assessment as described for GIS databases (spatial data) in Task 1. Observations from peer reviewed literature were included if determined fit by the Project Manager, QA Manager and Co-managers.

Task 5: Diagnose additional sources/sinks of water to the ground-water system.

Project information was catalogued in Microsoft Word or Excel on the investigator's PC, backed up on separate dedicated storage (i.e. external hard drive) with final compilation housed at the University of Memphis Ground Water Institute.

5.0
Results

Perform geologic mapping of the region

A hydrostratigraphic analysis of an aquifer system aims to identify the extent and hydrologic characteristics of water-bearing rocks and sediments in an aquifer system. Although the hydrostratigraphy of tertiary aquifers in the Mississippi Embayment (ME) has been evaluated on regional (Boswell et al., 1968, Cushing et al., 1964; Hosman et al., 1968; Cushing et al., 1970; Hosman and Weiss, 1991), state and local (Criner et al., 1964; Payne, 1968; 1973; 1975; Parks and Carmichael, 1989; 1990a; 1990b; Brahana and Broshears, 2001) scales, a hydrostratigraphic analysis at a subregional scale in the tri-state region of northern Mississippi, eastern Arkansas, and western Tennessee is needed to address stratigraphic problems and water resource sustainability. Because lithostratigraphic nomenclature and aquifer conceptualization differ among states, careful stratigraphic correlation and detailed aquifer assessment are needed to ensure consistency in hydrogeologic modeling. In addition, hydrostratigraphic subdivisions of aquifers and confining units may be necessary to assess water resources at the subregional scale.

The objectives of this section are outlined as follows:

- Acquire geologic, stratigraphic, and geophysical data in the region that will enable development of a detailed sub-regional model of the major drinking-water aquifers in the region: Memphis and Fort Pillow aquifers.
- Assess the extent, physical characteristics, and connectivity of the Memphis and Fort Pillow aquifers, as well as their relationship to other regional aquifers, such as the Mississippi Alluvial and shallow fluvial/alluvial aquifers, and intervening confining units.
- Assess the quality of existing hydrostratigraphic data and quantitatively assess where the existing data are insufficient in extent or quality to accurately model the aquifer system

These objectives have been addressed by acquiring geologic and geophysical data from state and U.S. Geological Survey offices as well as private data sources and compiling the results into a master database. The geophysical log data, which are the primary sources of stratigraphic information, were evaluated for their quality of log signal, accuracy of well location and number of correlative, useful log plots. Data meeting the quality thresholds were used to evaluate downhole lithologic variations in each borehole. Existing stratigraphic reports and publications were used to correlate lithology to geologic formations and hydrostratigraphic units (aquifers and confining units) and interpret the stratigraphic and structural relationships. The geologic formations were then correlated between individual boreholes to produce regional cross-sections. These regional cross-sections were used to evaluate not only stratigraphic variations in the units but also lithologic variations within the units and probable faults that displace the strata. The idea of this process was not to develop new stratigraphic units, but rather to merge stratigraphic and structural concepts across state boundaries, where different nomenclature and definitions are applied. Quality of the geophysical log data was quantified by ranking the data according to Table App1 (see Appendix Geophysical Logs) from the Project QAPP. Logs were deemed acceptable with a rank of ≥ 6.

The refined stratigraphic cross-sections were then used to interpret well logs that exist between the section lines to improve data coverage across the study area. Following this process, contour surfaces of the stratigraphic bases of formations were created.

The interpolation process involves achieving a best-fit curve between data points to produce the surface. The residual from the best-fit process is used as an indicator of the accuracy of the stratigraphic model. Areas of high residual (high error) are considered areas that require further study to accurately depict the stratigraphic and structural complexities of the associated aquifer systems.

The results of both the cross-section and surface-map studies provide the framework for guiding hydrostratigraphic and hydrologic investigations in subsequent project phases.

Geophysical Log Analysis

Geophysical log analysis involved a review of published literature on Tertiary stratigraphy and hydrostratigraphy of the Mississippi Embayment (ME) region (Figure 1), as well as pertinent studies of correlative Gulf Coast strata. The review of the regional stratigraphy allowed nomenclature across the three states to be correlated and problems identified. A preliminary Tertiary stratigraphic correlation chart was developed and subsequently applied to the interpretation of geophysical log data.

Previous studies have shown that the stratigraphic character of the Claiborne and Wilcox groups changes at approximately the Tennessee-Mississippi state line (Figure 2), which has caused past problems in correlation (Moore, 1965) and assessment of water resources (Hosman and Weiss, 1991; Brahana and Broshears, 2001). In this study, the Fort Pillow Sand, Flour Island, Memphis Sand, Cook Mountain, and Cockfield formations as defined in Moore (1965), Hosman et al. (1968), Moore and Brown (1969), Fredericksen et al. (1982), and Hosman (1996) are mapped in Tennessee and in adjacent regions of Arkansas and Mississippi. Correlative Paleocene and Eocene geologic units (Cushing et al., 1964;

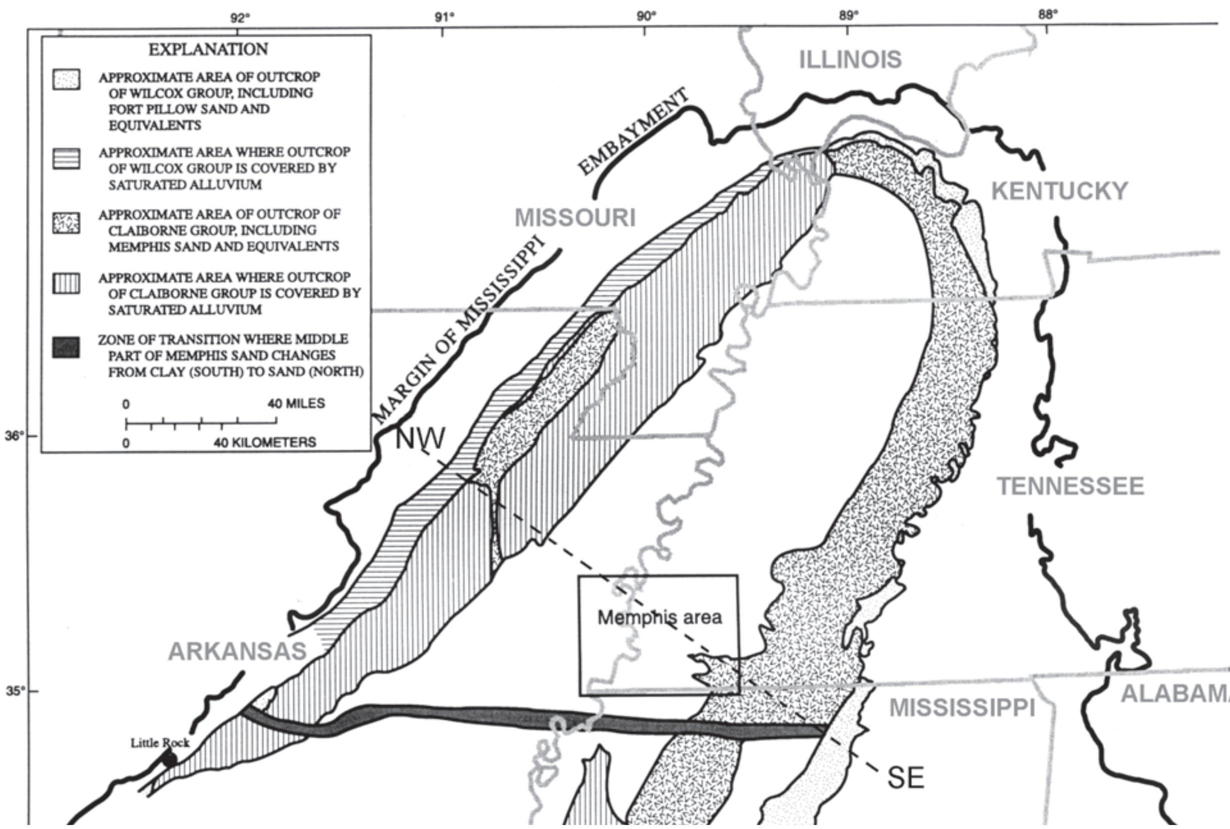


Figure 2. *Map of the northern Mississippi Embayment (NME) showing approximate distribution of outcrop and subcrop of the Wilcox and Claiborne group sediments (From Brahana and Broshears, 2001). Dashed line shows trace of cross-section shown in Figure 3.*

Mancini and Tew, 1991; Dockery, 1996; McFarland, 2004) were mapped in Mississippi and Arkansas where they are well-defined. In general, the stratigraphic nomenclature used in each of the states is used where clear division of geologic formations can be made.

We obtained high-quality geophysical logs from the various log libraries, digitized and scaled the log information, and correlated the known Paleocene- through Holocene-age geologic units within the region. The primary data for this effort exist as paper geophysical and geologic logs obtained during drilling of most water wells and all petroleum exploration wells. Other sources of data (geologic logs, geologic maps, seismic lines, etc.) were used to augment the geophysical log data where available. However, identification of stratigraphic units from geologic logs, unless accompanied by detailed biostratigraphic data or correlative geophysical data, is commonly ambiguous. Geologic units defined in mapping (e.g., Russell and Parks, 1975; Thompson, 2003a, b, c, and d) are difficult to reconcile with downdip subsurface expressions of stratigraphic units observed on geophysical logs. Thus, geologic map data are used to constrain the distribution of stratigraphic units only in outcrop areas. Seismic data are limited in the region and generally do not provide sufficient detail to define individual stratigraphic units within the shallow Tertiary section.

Geophysical logs were obtained from several sources, including the University of Memphis Ground Water Institute (GWI), USGS offices, State Geology offices, and private companies. The GWI houses an extensive log library for western Tennessee and a voluminous exploration geophysical log dataset obtained by North American Coal Company. In addition, geophysical and geologic logs were obtained from the Mississippi Department of Environmental Quality, Arkansas Soil and Water Conservation Commission, and USGS offices in Little Rock and Nashville. The logs utilized by the USGS MERAS study (Hart et al., 2008; Hart and Clark, 2008) in Tennessee and Arkansas were incorporated into our database; however, some of the logs from northern Mississippi were not available at the time of our analysis. In addition, a limited set of industry logs was obtained through the Nashville USGS office (Carmichael, pers. comm., 2007).

Geologic correlation and construction of cross-sections

The lithological variation in the Paleocene through Holocene-age geologic units in the northern Mississippi Embayment is generally limited to various clastic sediments and coal (Cushing et al., 1964). The geophysical log interpretation of these sediments is generally straightforward; however, finely interbedded fine sand, silt and clay are difficult to differentiate. Geologic correlation is completed by matching digitized log patterns, representing geologic formations or members, among spatially distant boreholes. Initial studies indicate that log patterns for several of the geologic formations are not consistent over the region (Owen and Larsen, 2005; Martin, 2008). In this case, marker horizons, such as the Zilpha Shale interval, were used where present to correlate formations. If no marker horizons are evident in the log, then average thicknesses of geologic formations were used to approximate correlations. Observation of evidence for uplift or subsidence of the tops or bottoms of formations in multiple correlated sections was used, along with other information (seismic cross-sections, regionally interpolated surfaces, etc.), to assess the presence of fault offsets of the sedimentary package. Interpreted faults through the sedimentary package were compared to those identified in regional studies of faulting in the Mississippi Embayment (Ervin and McGinnis, 1975; Thomas, 1991; Schweig and Van Arsdale, 1996; Cox et al., 2001; Parrish and Van Arsdale, 2004; Cox et al., 2006; Csontos et al., 2008).

A principle objective of the first phase of the project is to use the available data to construct detailed litho- and hydro-stratigraphic models of the study area and thus determine where existing data are insufficient to constrain the hydrostratigraphic model. In an effort to address this objective, structure contour maps of the stratigraphic units were prepared. These surface maps are a precursor to construction of quasi-three-dimensional litho- and hydro-stratigraphic models. The principle data used to construct the surfaces is the base elevations of stratigraphic units, which are obtained from the interpreted geophysical logs and cross-sections. The structure contour surfaces were constructed using the inverse-distance-weighted

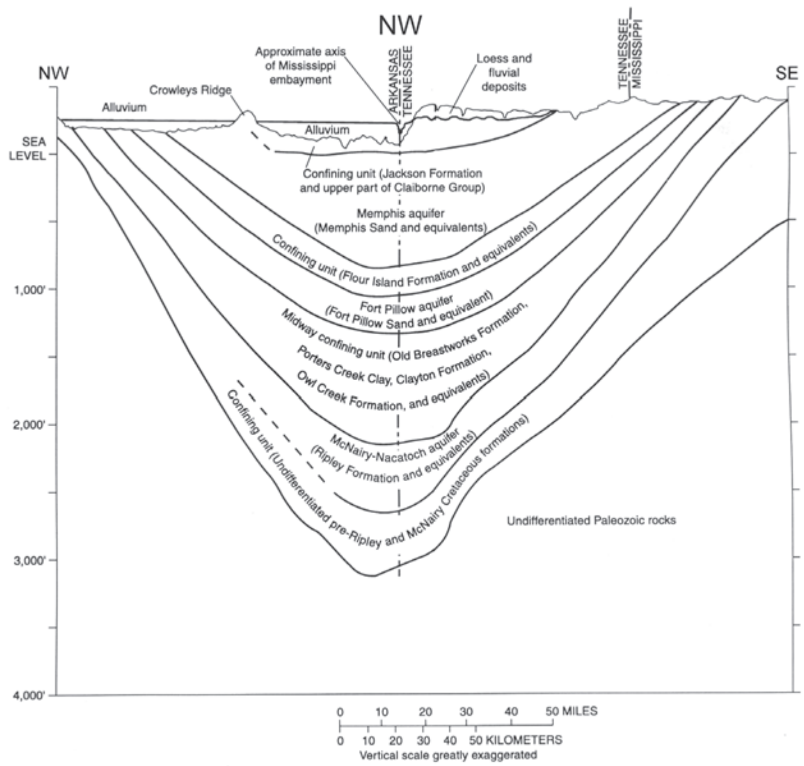


Figure 3. *Cross-section through the northern Mississippi Embayment (NME) showing the generalized stratigraphy (From Brahana and Broshears, 2001). See Figure 2 for location of cross-section.*

(IDW) method. IDW was chosen because it is effective in contouring limited numbers of data points. Best fit was determined by minimization of the root mean square (RMS) error. These interpolated surfaces provide a baseline for determining where additional data are needed to constrain the three-dimensional lithostratigraphic and hydrostratigraphic models necessary in subsequent project phases.

Geologic Background

The Mississippi Embayment

The Mississippi Embayment (ME) is a broad south-plunging trough filled with Upper Cretaceous and Paleogene marine to non-marine sediments overlain by a veneer of Pliocene and Quaternary fluvial sediments and Pleistocene loess (Cushing et al., 1964; Cox and Van Arsdale, 1997). At the southern margin of the ME, where it merges with the Gulf Coast, the post-Cretaceous sedimentary fill is approximately 2 km thick and the embayment is approximately 600 km across from WNW to ESE (Figure 3). The southern margin of the ME also corresponds to the craton-ward limit of the Appalachian-Ouachita detachment (Thomas, 1991). The trend of the trough of the ME roughly follows the ancient Reelfoot Rift (Ervin and McGinnis, 1975), suggesting that Precambrian-early Cambrian extensional structures exert a prominent control on the tectonic evolution of the ME (Howe and Thompson, 1984; Marshak and Paulsen, 1996; Csontos et al., 2008).

The geologic formation and evolution of the Mississippi Embayment was first examined in detail by Stearns (1957) and Stearns and Marcher (1962). Their general interpretation involves structural doming of the northern ME during Early Cretaceous time to form the Pascola Arch followed by deposition of the Upper Cretaceous Tuscaloosa Fm. around the eastern and southern margins of the arch. Subsidence in the region of the Pascola Arch followed, leading to the broad, shallow ME basin. The northern ME was filled subsequently with Upper Cretaceous through upper Eocene strata as well as thin sections of Oligocene and Miocene deposits to the south where the ME merges with the Gulf Coast (Cushing et al., 1964). Formation and subsidence within the ME have been variably interpreted to be related to distal effects of the Appalachian-Ouachita orogenesis (Cushing et al., 1964) or opening of the Gulf of Mexico (Ervin and McGinnis, 1975; Kane et al., 1981; Braile et al., 1986). More recently, Cox and Van Arsdale, 1997; Van Arsdale and Cox, 2007 proposed that the ME formed in response to the track on the Bermuda hot spot beneath the weak crust underlying the Reelfoot Rift. As the hot spot passed beneath the ME it caused magmatism along the ancient rift margins as well as doming and erosion. Following passage of the hot spot, the topographic dome underwent thermal subsidence leading to accommodation space that was filled by the Upper Cretaceous through Eocene succession. The magmatic and exposure history of the ME is consistent with the hot spot migration hypothesis (Cox and Van Arsdale, 1997; Van Arsdale and Cox, 2007); however, detailed stratigraphic tests of the model have yet to be conducted.

Sedimentary deposition within the Mississippi Embayment began in the early Cretaceous, mainly in the southeastern and southwestern portions of the ME where the Gulf Coast system merges with ME strata (Cushing et al., 1964). Lower Cretaceous strata are largely missing in the central ME, where an angular unconformity exists between Upper Cretaceous strata and older deposits (Murray, 1961; Cox and Van Arsdale, 1997). Basal Upper Cretaceous gravels (Tuscaloosa Group) were deposited in a crescent-shaped arc along the eastern margin of the ME (Stearns and Marcher, 1962). These deposits grade upward and westward into the marginal marine and marine strata of the Eutaw Fm. and Selma Group. The Cretaceous deposits within the ME are thickest along the southeastern and southwestern margins and thin substantially in the northern and northwestern ME (Cushing et al., 1964; Hosman, 1996). The upper contact of Cretaceous deposits in the Gulf Coast is locally disturbed and erosional, which has been interpreted to have resulted from tsunami associated with the K-T impact event (Smit et al., 1996). No stratigraphic evidence of tsunami at the K-T boundary is observed in the northern ME (Patterson, 1998), and erosion is consistent with regression associated with relative sea-level fall.

The bulk of sedimentary deposition within the ME occurred during the Paleocene and Eocene, and is recorded in Midway, Wilcox, Claiborne, and Jackson group sediments (Cushing et al., 1964; Hosman, 1996; Van Arsdale and TenBrink, 2000). The Cenozoic stratigraphy is discussed in detail below, with most of the emphasis placed on the Wilcox and Claiborne groups that include the major Tertiary aquifers in the ME (Hosman et al., 1968; Hosman and Weiss, 1991). The post-Jackson sedimentary history of the ME includes minor deposition of Oligocene and Miocene strata in the southern-most part of the ME and wide-spread non-deposition and/or erosion during the Oligocene and Miocene throughout the central and northern ME (Cushing et al., 1964; Hosman, 1996; Van Arsdale and TenBrink, 2000). The Pliocene and Pleistocene depositional history of the ME is mainly that of fluvial incision and terrace formation (Fisk, 1944; Austin et al., 1991; Saucier, 1994; Blum et al., 2000; Rittenour et al., 2005; Van Arsdale et al., 2008).

The structural history of the Mississippi Embayment is strongly influenced by the structural grain of the Reelfoot Rift (Howe and Thompson, 1984; Johnston and Schweig, 1996; Cox et al., 2001a; Parrish and Van Arsdale, 2004; Csontos et al., 2008; Martin, 2008). However, additional structural control is provided by NW-SE-trending lineaments and fault zones (Howe and Thompson, 1984; Stark, 1997; Cox, 1988; Cox et al., 2001b), creating a series of structural blocks that tilt and rotate in response to applied compressional stresses (Csontos, 2007). The effects of these fault structures on the Tertiary stratigraphy in the study area have been studied mostly along the southeastern margin of the Reelfoot rift in Tennessee and Arkansas (Cox et al., 2001a; Parrish and Van Arsdale, 2004; Csontos et al., 2008), but a recent study by Martin extended these investigations into northern Mississippi (Martin, 2008), thus, encompassing the MERGWS study area.

Current seismicity in the northern ME is focused along the NE-trending New Madrid fault system (Schweig and Van Arsdale, 1996), although lesser seismicity also defines the southeastern structural margin of the ancient Reelfoot rift (Chiu et al., 1997; Cox et al., 2001a). During the Holocene, however, both the southeastern structural margin of the Reelfoot rift (Cox et al., 2006) and the NW-SE-trending Sabine and Arkansas River fault zones (Cox et al., 2007) may have defined loci of seismicity, indicating that Holocene seismicity is not confined in time or space to the New Madrid zone.

Tertiary and Quaternary Stratigraphy of the Mississippi Embayment

The Tertiary and Quaternary stratigraphy of the Mississippi Embayment (ME) has been reviewed in several regional papers (Table 1) (Stearns, 1957; Cushing et al., 1964; Hosman, 1996; Van Arsdale and TenBrink, 2000) as well as in state-specific publications (Table 2) (Dockery, 1996; McFarland, 2004). Details of the stratigraphy have been developed in local studies (e.g., Moore and Brown, 1969; Russell and Parks, 1975; Fredericksen et al., 1982; Thompson, 1995) that are not always amenable to regional correlation. To better enable correlation of local geology to the regional scale, it is important to understand the depositional character of the geologic units of interest and use this information as identifiable markers during interpretation. Such information is presented below. The details and associated correlation problems are discussed in the results section.

The basal Midway Group disconformably overlies Cretaceous (Maestrichtian) strata across the entire ME. The Maestrichtian-Danian stage boundary is a type I unconformity (Mancini and Tew, 1991), indicating exposure occurred across most or all of the continental shelf. The basal marine sands of the Paleocene Clayton Formation grade abruptly into marine clay and fine sand of the Porters Creek Clay. The Porters Creek Clay is marine throughout the entire ME (McFarland, 2004;

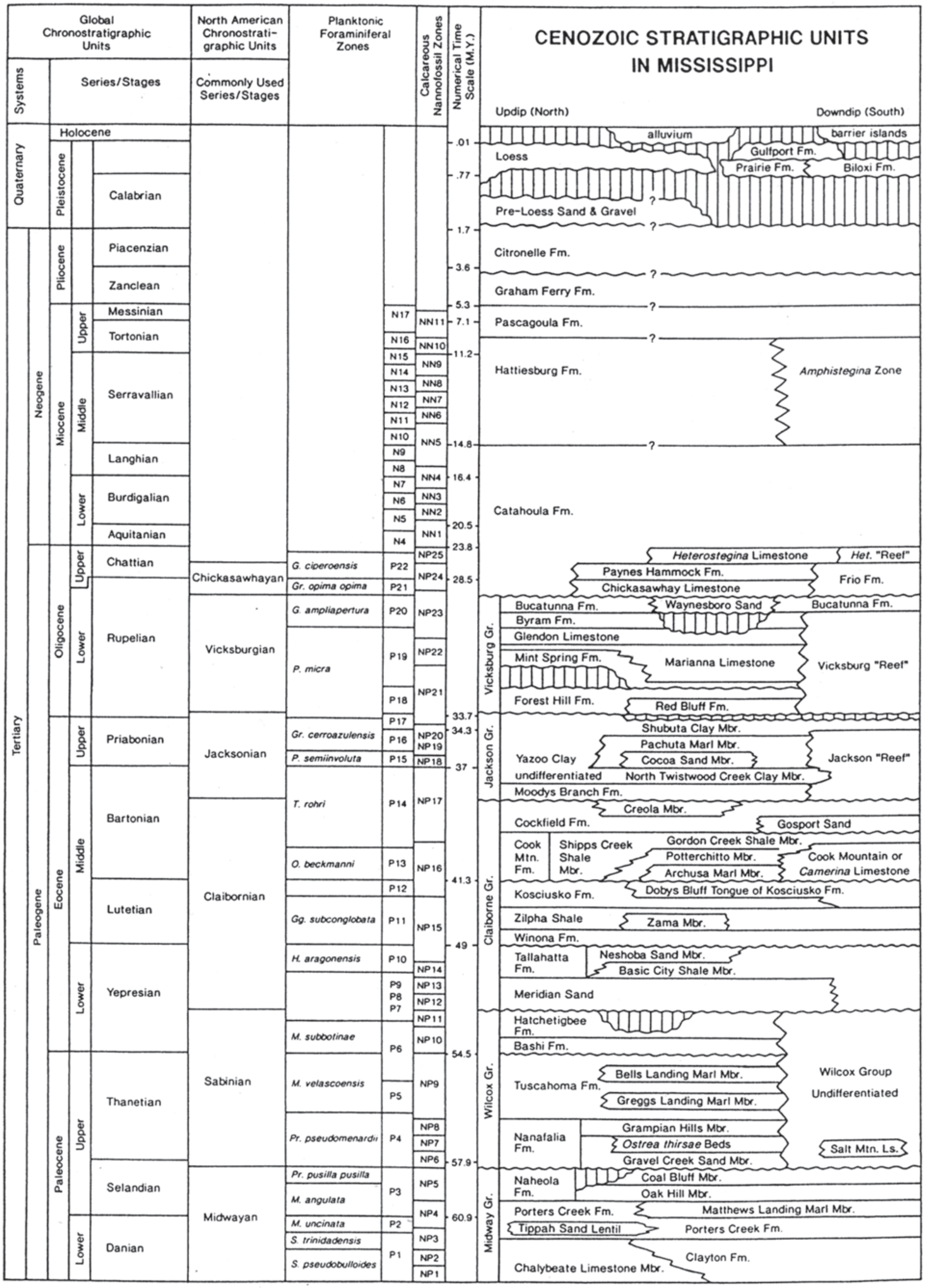
Table 1. Geologic and hydrostratigraphic units correlated throughout the Mississippi Embayment (From Hart et al., 2008).

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

[1]Lower Claiborne aquifer includes the upper Wilcox aquifer in some portions of Mississippi.

Modified from Hosman and Weiss, 1991

Table 2. Geologic correlation diagram for Cenozoic strata in Mississippi (from Dockery, 1996).



Fredericksen et al., 1982; Russell and Parks, 1975), suggesting that its original extent may have been substantially greater. The upper Midway Group in Mississippi includes the Naheola Fm (Dockery, 1996), which is not defined in either Arkansas or Tennessee. The Naheola includes two members, the Oak Hill and the Coal Bluff, which are well-defined in eastern central Mississippi. The Oak Hill rests conformably on the Porters Creek Clay and represents a coarsening-upward sequence that includes interbedded clay, silt, and fine-grained sand (Thompson, 1995). Coal Bluff rests with unconformity on the Oak Hill and includes fine- to coarse-grained sand interbedded with clay, silt, and lignite (Thompson, 1995). The upper part of the Coal Bluff is highly weathered and contains bauxitic to kaolinitic clays. Similar weathered strata are observed in exposures of the basal “Wilcox” Fm. in southwestern Tennessee (Russell and Parks, 1975) suggesting that a Coal Bluff equivalent is present in western Tennessee.

The Wilcox Group rests with unconformity on the underlying Midway Group, although the lithological distinction between Midway and Wilcox strata is locally gradational across the boundary (Hosman, 1996). In eastern central Mississippi, which is the southeastern corner of the ME, four formations define the Wilcox Group: Nanafalia, Tuscahoma, Bashi, and Hatchetigbee formations (Dockery, 1996; Thompson, 1995). The Nanafalia Formation consists of two members, the Gravel Creek Sand and Grampian Hills members. The Gravel Creek Sand contains a prominent sand interval interbedded with clay, silt, sand, and lignite. The Grampian Hills is generally finer grained than the Gravel Creek Sand with a basal sand interval followed by clay, silt and fine- to medium-grained sand interbedded with multiple lignite seams (Thompson, 1995). The overlying Tuscahoma Fm. is lithologically similar to the underlying Grampian Hills member of the Nanafalia Fm.; however, two depositional cycles of basal sand and overlying fine-grained clay, silt, sand, and lignite are observed. Furthermore, the Grampian Hills contains prominent correlative marginal marine intervals (Dockery and Thompson, 1996), whereas the Tuscahoma is almost entirely non-marine, except near the Alabama state line. The Bashi overlies the Tuscahoma Fm. disconformably and represents the basal Eocene strata in the Gulf Coast (Mancini and Tew, 1991). The Bashi Formation is distinctive and mappable in Mississippi only near the Alabama state line where it is a marine interval with glauconitic sands and marls (Thompson, 1995). The Bashi grades laterally into basal sands in the Hatchetigbee Formation in western Alabama (Gibson, 1982), and shows similar relationships in Mississippi (Thompson, 1995; Thompson, 2003a; b; c; d). The Hatchetigbee Fm. contains interbedded clay, silt, sand, and lignite.

The Wilcox Group in the central and northern ME comprises three formations: The Old Breastworks, Fort Pillow Sand, and Flour Island formations (Table 3) (Moore and Brown, 1969; Hosman, 1996; Van Arsdale and TenBrink, 2000; Brahana and Broshears, 2001). Frederiksen et al. (1982), in a biostratigraphic study of the New Madrid test wells in southeastern Missouri, correlate the Old Breastworks to the Naheola Fm (Oak Hill member) based on dinoflagellate species and lithologic similarity, suggesting that the Old Breastworks Fm. belongs to the Midway Group. The Old Breastworks Fm. is not defined in surface exposures in western Tennessee, where the Wilcox Fm. rests directly on Porters Creek Clay (Russell and Parks, 1975). The Fort Pillow Sand is a coarse sand that thickens into the axis of the ME and is roughly correlative to the Nanafalia Fm. (Cushing et al., 1964; Hosman, 1996). The Flour Island Formation is mainly lignitic silt with interbedded clay and fine sand. The lower part of the Flour Island is calcareous and glauconitic at the Fort Pillow test well (Moore and Brown, 1969), but only non-marine strata are present in the New Madrid test wells (Frederiksen et al., 1982).

The Wilcox Group is exposed along Crowley’s Ridge in northeastern Arkansas, but is undivided. The composite thickness is approximately 780 ft thick and composed of sands, silt, clay, and lignite (Meissner, 1984). Significant lignite seams are present only in the upper half of the Wilcox Group.

Table 3. Lithostratigraphy and hydrostratigraphy in the Memphis, Tennessee, area (From Brahana and Broshears, 2001).

System	Series	Group	Stratigraphic unit	Thick-ness	Hydrologic unit	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Surficial Aquifer	Sand, gravel, silt, and clay. Underlies the Mississippi Alluvial Plain and alluvial plains of streams in the Gulf Coastal Plain. Thickest beneath the Alluvial Plain, where commonly between 100 and 150 feet thick; generally less than 50 feet thick elsewhere. Provides water to farm, industrial, and irrigation wells in the Mississippi Alluvial Plain.
	Pleistocene		Loess	0-65		Silt, silty clay, and minor sand. Principal unit at the surface in upland areas of the Gulf Coastal Plain. Thickest on the bluffs that border the Mississippi Alluvial Plain; thinner eastward from the bluffs. Tends to retard downward movement of water-providing recharge to the fluvial deposits.
Quaternary and Tertiary(?)	Pleistocene and Pliocene (?)		Fluvial Deposits (terrace deposits)	0-100		Sand, gravel, minor clay and ferruginous sandstone. Generally underlies the loess in upland areas, but are locally absent. Thickness varies greatly because of erosional surfaces at top and base. Provides water to many domestic and farm wells in rural areas.
Tertiary	Eocene	?	Jackson Formation and upper part of Claiborne Group ("capping clay")	0-370	Confining Unit	Clay, silt, sand, and lignite. Because of similarities in lithology, the Jackson Formation and upper part the Claiborne Group cannot be reliably subdivided based on available information. Most of the preserved sequence is equivalent to the Cook Mountain and overlying Cockfleld Formations, but locally the Cockfield may be overlain by the Jackson Formation. Serves as the upper confining unit for the Memphis Sand.
		Claiborne	Memphis Sand ("500-foot" sand)	500-890	Memphis aquifer	Sand, clay, and minor lignite. Thick body of sand with lenses of clay at various stratigraphic horizons and minor lignite. Thickest in the southwestern part of the Memphis area; thinnest in the northeastern part. Principal aquifer providing water for municipal and industrial supplies east of the Mississippi River; primary source of water for the City of Memphis.
	?	Wilcox	Flour Island Formation	140-310	Confining unit	Clay, silt, sand, and lignite. Consists primarily of silty clays and sandy silts with lenses and interbeds of fine sand and lignite. Serves as the lower confing unit for the Memphis Sand and the upper confining unit for the Fort Pillow Sand.
	Paleocene		Fort Pillow Sand ("1400-foot" sand)	92-305	Fort Pillow aquifer	Sand with minor clay and lignite. Sand is fine to medium. Thickest in the southwestern part of the Memphis area; thinnest in the northern and northeastern parts. Once the second principal aquifer supplying the City of Memphis; still used by an industry. Principal aquifer providing water for municipal and industrial supplies west of the Mississippi River.
			Old Breastworks Formation	180-350	Midway confining unit	Clay, silt, sand, and lignite. Consists primarily of silty clays and clayey silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining unit for the Fort Pillow Sand, along with the underlying Porters Creek Clay, Clayton Formation, and Owl Creek Formation.

The Claiborne Group rests disconformably on the Wilcox Group deposits across the ME, suggesting that a type 1 sequence boundary exists between the units (Mancini and Tew, 1991; Ingram, 1992). In northern Mississippi, the lower and middle Claiborne includes five formations (Dockery, 1996): Meridian Sand, Tallahatta Formation, Winona Sand, Zilpha Shale, and Kosciusko Formation. The Meridian Sand is fine- to coarse-grained sand with characteristic crossbedding (Cushing et al., 1964). Although Thomas (1942) in a comprehensive study of the Claiborne in Mississippi assigned the Meridian to the Wilcox Group, later studies have confirmed its proper inclusion within the Claiborne (Bybell and Gibson, 1985; Hosman, 1996). The Tallahatta Formation consists of dark greenish-gray clay and siliceous to glauconitic siltstone and fine- to coarse-grained sandstone in the Basic City Shale member and generally non-glauconitic fine- to medium-grained sand and gray clay in the Neshoba sand member (Thomas, 1942). The Winona Sand is predominantly medium- to coarse-grained glauconitic sand and is easily identified in surface exposures by its dark red weathering color. The Zilpha Shale is a dark gray, carbonaceous, glauconitic, and sparsely fossiliferous clay (Cushing et al., 1964). The Winona Sand and Zilpha Shale are only observed in central and southern Mississippi, although correlative but lithologically distinct intervals are described in both Arkansas and Tennessee (Moore, 1965; Hosman, 1996). The Kosciusko Fm. consists of medium-grained sand with interbedded light gray, light greenish-gray, and rarely dark gray shale (Thomas, 1942).

The lower and middle Claiborne Group in southeastern Arkansas includes the Carrizo Sand, Cane River Formation, and Sparta Sand (Cushing et al., 1964; Payne, 1968; 1972; 1975). The Carrizo Sand is correlative to the Meridian Sand in Mississippi (Payne, 1975; Hosman, 1996). The Cane River Fm. is roughly equivalent to the Tallahatta Formation, Winona Sand, and Zilpha Shale in Mississippi (Payne, 1972). The Sparta Sand is correlative to the Kosciusko Formation in Mississippi (Hosman, 1996). North of the 35° parallel, the Cane River pinches out and the entire lower and middle Claiborne section is dominated by the Memphis Sand (Hosman, 1996). Similarly in western Tennessee, Moore (1965) correlated the Tallahatta Formation and Sparta Sand to the Memphis ("500-foot") Sand. The Memphis Sand was formally defined in the Fort Pillow test well (Moore and Brown, 1969) in Lauderdale County, Tennessee, and later correlated throughout the northern ME (Frederiksen et al., 1982; Parks and Carmichael, 1990a; Hosman, 1996). The Memphis Sand is predominantly fine- to coarse-grained sand with subordinate carbonaceous and lignitic silt and clay and lignite (Parks and Carmichael, 1990a). Clay intervals correlative to the Basic City Shale and Zilpha Shale are locally identified (Moore, 1965; Parks and Carmichael, 1990a).

Throughout the study area, the Kosciusko Fm., Sparta Sand, and Memphis Sand are overlain with disconformity by the upper Claiborne Cook Mountain and Cockfield Formations (Thomas, 1942; Cushing et al., 1964; Moore and Brown, 1969; Frederiksen et al., 1982). The Cook Mountain Fm. in central Mississippi consists of a lower glauconitic, fossiliferous sandy marl or limestone overlain by sandy carbonaceous clay (Thomas, 1942; Hosman, 1996). However, in western Tennessee the Cook Mountain Fm. is mainly silt and clay with local intervals of fine sand (Parks and Carmichael, 1990a). The contact between the Cook Mountian and Cockfield formations is conformable and transitional. In central Mississippi, the sandy shale of the Cook Mountain Fm. grades upward into sand, lignitic silty shale, and lignite of the Cockfield Formation (Thomas, 1942). The lithology of the Cockfield Fm. is remarkably consistent across the northern ME (Moore and Brown, 1969; Frederiksen et al., 1982; Parks and Carmichael, 1990b; Hosman, 1996).

The Jackson Group has limited extent in the northern and central ME, and is given only formational status in Tennessee. The Jackson Formation crops out along the Mississippi River bluffs in western Tennessee and along the southern part of Crowley's Ridge in Arkansas (Cushing et al., 1964). The Jackson strata overlie the Claiborne Group with disconformity and typically include fossiliferous, glauconitic sandy marl that grades upward into calcareous clay and locally sand in central Mississippi (Hosman, 1996). The Jackson Formation in western Tennessee is lithologically indistinct from the underlying Cockfield Fm. and is typically not differentiated (Parks and Carmichael, 1990b; Moore and Brown, 1969).

The upper surface of the Paleocene-Eocene ME sedimentary system is a time-transgressive erosional surface upon which Pliocene through modern stream deposits and late Pleistocene loess have been laid (Fisk, 1944; Potter, 1955; Austin et al., 1991; Saucier, 1994; Van Arsdale et al., 2008). Because the sequence is associated with the progressive, though punctuated, denudation history of the ME, the oldest deposits are at the highest interfluvial elevations and the youngest deposits are within the modern-day valleys. The Pliocene Upland Complex, also known as the Lafeyette Gravel (Potter, 1955), is present in western Tennessee, northwestern Mississippi, and along Crowley's Ridge in eastern Arkansas (Austin et al., 1991; Van Arsdale et al., 2008). Van Arsdale et al. (2008) used an extensive borehole dataset to map the distribution of the Upland Complex throughout the region and demonstrate its origin as an ancient high-level terrace of the Mississippi River, potentially as much as 5.5 Ma old. Subsequent incision and subsequent terrace formation has led to formation of several terrace levels and associated sand and gravel deposits along the Mississippi River-Ohio River valley system (Austin et al., 1991; Saucier, 1994; Blum et al 2000; Rittenour et al., 2003; 2005) and western Tennessee tributaries (Saucier, 1987; Rodbell, 1996; McClure, 1999). Late Pleistocene terraces were further mantled with loess in the region (Austin et al., 1991; Rodbell et al., 1997; Rutledge et al., 1996; Markewich et al., 1998). The modern Mississippi Valley alluvium consists largely of gravel and sand capped by silt and loess (Saucier, 1994). Pleistocene depositional patterns within the Mississippi Valley appear to be strongly affected not only by glacial processes and climate (Saucier, 1994; Blum et al., 2000; Rittenour et al., 2005), but also tectonic subsidence and uplift along orthogonal Reelfoot Rift faults (Csontos et al., 2008).

Hydrostratigraphic Units within the Central Mississippi Embayment

The lithostratigraphic units described above are divided into a series of hydrostratigraphic units (Tables 1 and 3). Hydrostratigraphic units are defined based on their ability to produce water at an efficient rate. Aquifers are water-producing zones and confining units are generally poor water-producing zones, but more importantly provide confinement to water in underlying and overlying aquifers. The hydrostratigraphic terminology applied to the ME has changed over the past 120 years as stratigraphic studies have better defined the lithology and extent of units, and hydrogeologic studies have better defined the water-producing zones and their hydraulic properties. As mentioned previously, definition of hydrostratigraphic units vary depending on the scale of studies. For example, local studies of ground water tend to use state- or subregion-based nomenclature, such as those applied in the Memphis area (Criner and Parks, 1976; Brahana and Broshears, 2001). Regional scale studies use more generic nomenclature, such as that defined for the ME by the USGS Regional Aquifer-System Analysis (RASA) (Hosman and Weiss, 1991). Most recently, the USGS has completed a regional hydrostratigraphic analysis focusing on the ME (Table 4) (Hart and Clark, 2008; Hart et al., 2008) as a part of the Mississippi Embayment Regional Aquifer Study (MERAS). For the purposes of the present study, which is subregional in scale, the regional hydrostratigraphic terms from Hart et al. (2008) with some modifications discussed below will be applied to the general discussion (Table 1), although the local nomenclature in the Memphis area (Brahana and Broshears, 2001) will be applied to more detailed discussions.

The Tertiary ME aquifer system is confined at the base by the Midway confining unit. The clay-rich nature of this unit limits passage of water; however, water could potentially move through this and other confining units along faults (Kingsbury and Parks, 1993). Regionally, two aquifers are defined within the Wilcox interval, the Lower and Middle (Table 1). However, within the study area the Middle Wilcox aquifer is not distinguished from the lower Memphis aquifer (lower part of Memphis Sand in Table 1) north of the Mississippi-Tennessee state line (Thompson, 2003a, b, c, and d). The Lower Wilcox aquifer is equivalent to Fort Pillow Sand in western Tennessee (Parks and Carmichael, 1989) and northeastern Arkansas (Brahana and Broshears, 2001) and the sandy upper part of the Nanafalia and lower part of the Tuscahoma (Hosman, 1996). The Lower Wilcox is confined by the underlying Midway confining unit and fine-grained intervals within the overlying Flour Island Formation (Tennessee and Arkansas) and Tuscahoma Formation (northern Mississippi). The Flour island is a confining unit within the northern ME.

The Claiborne interval includes three regional aquifers. In northern Mississippi and adjacent Arkansas, the Lower and Middle Claiborne aquifers are separated by the Lower Claiborne confining unit. However, the Lower Claiborne confining unit laterally pinches out near the Tennessee-Mississippi stateline (and in adjacent Arkansas), such that the Lower and Middle Claiborne aquifers merge to form the Memphis aquifer in western Tennessee and adjacent Arkansas (Hart et al., 2008; Hosman and Weiss, 1991; Parks and Carmichael, 1990a). The Middle Claiborne confining unit is equivalent to the Cook Mountain Formation throughout the study area (Hart et al., 2008; Hosman and Weiss, 1991; Parks, 1990). Graham and Parks (1986), Parks (1990), Bradley (1991), Parks and Mirecki (1992), Parks et al. (1995), Larsen et al. (2003), Waldron et al. (2009), and others have noted that the Middle Claiborne confining unit is locally absent or contains transmissive facies which permit vertical recharge to the Memphis aquifer. The Upper Claiborne aquifer, within the Cockfield Formation, is generally thin and discontinuous in the study area and is thickest east of the Mississippi alluvial valley (Parks and Carmichael, 1990b). The Upper Claiborne aquifer is locally unconfined in western

Tennessee, but also has regions of confinement provided by the overlying Jackson confining unit, which is also regionally discontinuous due to late Cenozoic erosion (Hosman and Weiss, 1991).

The upper Cenozoic stratigraphic units represent continental deposits that partially infill valley systems (fluvial terrace and alluvial valley deposits) or mantle regional upland (loess). As such, the correlative hydrogeologic units are present within topographically distinct regions of the study area. The Mississippi Alluvial aquifer is present beneath the modern-day Mississippi River valley (Boswell et al., 1968; Brown, 1947; Arthur and Strom, 1996; Ackerman, 1996; Csontos, 2007; Hart et al., 2008). The surficial (shallow) aquifer beneath the uplands of western Tennessee and northern Mississippi includes several distinct parts (alluvial and fluvial-terrace deposits of tributaries, and the upland gravels), which may or may not be in hydraulic communication. Alluvial deposits in western Tennessee and northern Mississippi tributary valleys are of limited lateral extent and generally thin upstream from confluence with the Mississippi alluvial valley (Saucier, 1994; McClure, 1999; Velasco et al., 2005, 2002; Stevens, 2007; Martin, 2008). The fluvial-terrace deposits are common along the tributary valley margins (Krinitzky, 1949; Saucier, 1987) but also of limited extent. The Upland Complex gravels are present beneath the highest upland surfaces in an extensive, but discontinuous belt in westernmost Tennessee and Kentucky (Van Arsdale et al., 2007; Potter, 1955). Similar deposits are known to exist in northern Mississippi (Dockery, 1996), but have not been well studied. In all cases, the surficial aquifer is overlain by variable thicknesses of either loess or reworked loess (alluvial silt) (Hosman, 1996; Dockery, 1996; Ackerman, 1996), which tends to retard downward infiltration of recharge to the surficial aquifer (Brahana and Broshears, 2001).

Geologic Database

For the hydrostratigraphic analysis, the project footprint was enlarged to include 29 counties (Figure 4); 8 in eastern Arkansas (Mississippi, Craighead, Poinsett, Cross, Crittenden, St. Francis, Lee, and Phillips Counties); 9 in northern Mississippi (Tunica, Coahoma, Benton, Quitman, Panola, Lafayette, Marshall, Tate, and DeSoto Counties); and 12 in western Tennessee (Lake, Obion, Dyer, Gibson, Lauderdale, Crockett, Tipton, Haywood, Fayette, Hardeman, Madison, and Shelby Counties). The combined study area is approximately 16,500 square miles (42,700 square kilometers). It is important to note that consideration of a footprint larger than the eight counties of the overall project is necessary to evaluate subregional trends in stratigraphic variation, as well as local variations.

The main source of data is geophysical logs (also called e-logs or wireline logs) from water wells and, oil and lignite exploration boreholes. Of the 17,000 logs available in the 28 county area, 542 were evaluated (see Appendix Geophysical Logs) and only 378 were deep enough (depth > 500 ft) to be useful in assessing the characteristics of the Memphis aquifer (Figure 4) and even fewer were available for assessing the characteristics of the Fort Pillow aquifer. Most of the logs were obtained from four sources: the GWI log library at The University of Memphis, USGS – Tennessee Water Sciences Center, USGS – Arkansas Water Sciences Center, Mississippi Department of Environmental Quality, and private well drilling contractors. The log quality was generally good; however, most locations and elevations were estimated from topographic maps or UTM coordinates. Any log with an overall rank higher than 5 was included in the project for potential analysis (see Table App4 in Appendix Geophysical Logs).

The geophysical logs commonly included signals from one or more tools: gamma ray, SP, or resistivity (Figure 5). Gamma logs are generally responsive to clay minerals and thus differentiate clay versus sand units; although gamma signals are less responsive to clays in unconsolidated sediments. In addition, substantial kaolinite, which gives a muted gamma signal, is present in the matrix in the sand and many clay intervals (Lumsden et al., 2009). Thus, the most accurate picks could be made from logs with all three signals.

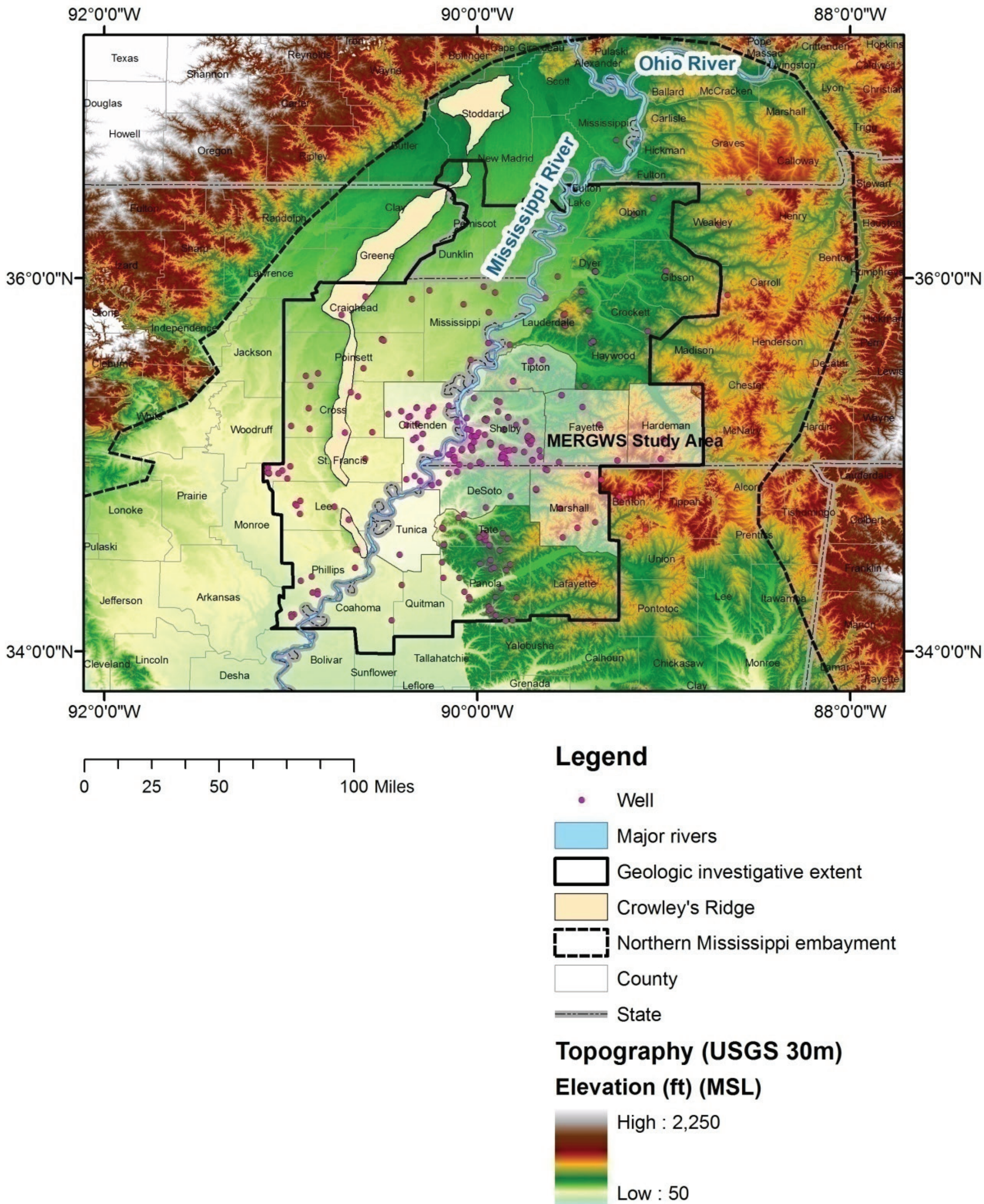


Figure 4. *Map of the study area showing the distribution of wells >500 ft depth used in the study. Elevations are contoured in feet above sea-level.*

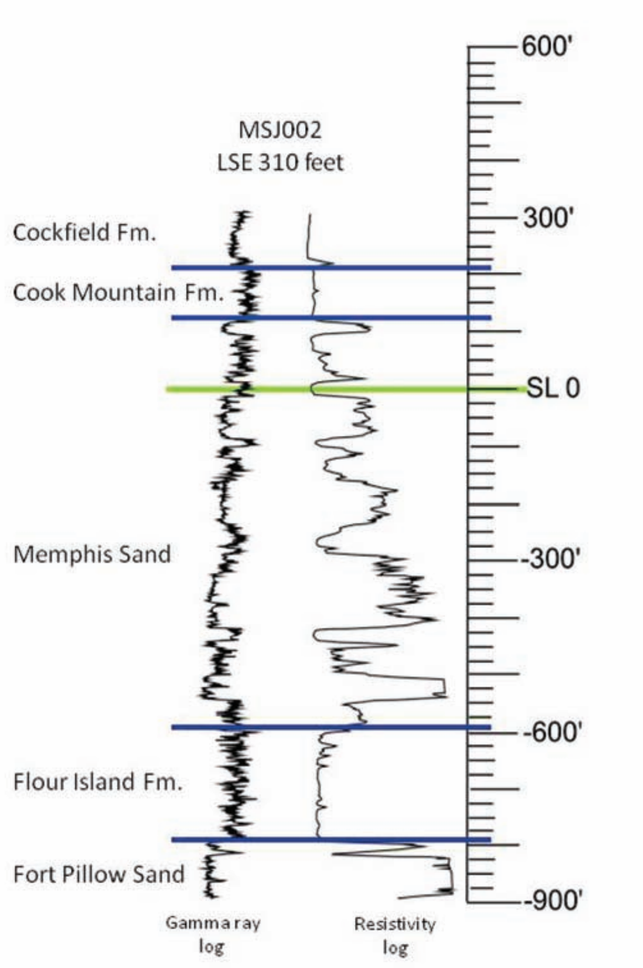


Figure 5. *Example of gamma ray and resistivity borehole log response in the study area. MSJ002 is the well identification; LSE is the land surface elevation; Depths are in feet.*

Stratigraphy

The lithostratigraphic units defined in the study area and identified in the cross-sections are shown in Table 4. The correlations follow Hosman (1996) and Hart et al. (2008) with some minor differences noted below.

The upper units identified in the geophysical logs include the Pleistocene loess, Mississippi Valley alluvium, fluvial terrace gravels, and Eocene Jackson Formation, all of which are discontinuously present across the study area. The Eocene Cockfield and Cook Mountain formations are generally continuous across the study area and dominated by shale with variable thicknesses of sand and silt. Their log response is similar in some cases and clear delineation of each formation was not always possible. The clay-dominated interval, 80 to 100 ft thick, overlying the top of the Memphis Sand was generally assigned to Cook Mountain Formation and overlying strata of variable quantities of sand, silt, and clay as much as 250 ft thick assigned to the Cockfield Formation.

The Memphis Sand and correlative formations in Mississippi and Arkansas are continuous throughout the three-state region (Table 4). The top of the Memphis Sand (or equivalent strata) was typically determined by maintaining the thickness (approx. 700-800 ft from the top of the Flour Island or Hatchetigbee Formation in the center of the ME) observed in neighboring logs and identifying recognizable intervals (e.g., Zilpha Shale and Kosciusko Sand and their correlatives). The base of the Claiborne Group overlies the Flour Island Formation, which is a well-defined fine-grained unit throughout the northern ME. The Memphis Sand in the northern ME is subdivided into three informal members (upper middle, and lower) that correlate to the Carrizo Sand, Cane River Formation, and Sparta Sand in southeastern Arkansas and related strata in northern Mississippi.

The Wilcox Group stratigraphy is continuous throughout the region, although facies changes in northern Mississippi obscure correlations. For example, the correlation between the Flour Island Formation and the Tuscahoma and Hatchetigbee formations in northern Mississippi is not well constrained. For consistency with Thompson's (2003a, b, c, and d) field mapping in northern Mississippi, the uppermost sand of the Wilcox Group is assigned to the Hatchetigbee Formation. The Nanafalia Formation and lowermost sand of the Tuscahoma Formation are correlated to the Fort Pillow Sand, which is lithologically consistent but does not consider disconformities observed within the Wilcox section in Mississippi (Thompson, 1995; Mancini and Tew, 1991).

The Old Breastworks Formation in western Tennessee and northeastern Arkansas is correlated to the Naheola Fm. in northern Mississippi (Figure 4), as suggested by paleontological work by Frederiksen et al. (1982).

Table 4. Proposed lithostratigraphic correlation for the northern and central Mississippi Embayment (modified from Hosman and Weiss, 1991).

ERA	SYSTEM	SERIES	STAGE	Arkansas		Tennessee	Mississippi
				Southern	Northeastern	Western	Northern
Cenozoic	Quaternary	Holocene		Alluvium	Alluvium	Alluvium	Alluvium
					Loess	Loess	Loess
		Pleistocene		Terrace deposits	Terrace deposits	Terrace deposits	Terrace deposits
		Pliocene		Upland Complex	Upland Complex	Upland Complex	Upland Complex
	Tertiary	Eocene	Jackson Group	Jackson Group		Jackson Fm.	Yazoo Clay
							Moody's Branch Fm.
			Claiborne Group	Cockfield Formation		Cockfield Fm.	Cockfield Fm.
				Cook Mountain Formation		Cook Mountain Fm.	Cook Mountain Fm.
				Sparta Sand	upper Memphis Sand		Kosciusko Sand
				Cane River Formation	middle Memphis Sand		Zilpha Shale
							Winona Sand
							Tallahatta Fm.
				Carrizzo Sand	lower Memphis Sand		Meridian Sand
			Wilcox Group	Undifferentiated	Flour Island Formation	Flour Island Formation	Hatchetigbee Fm.
							Bashi Fm.
		Paleocene					Tuscahoma Fm.
					Fort Pillow Sand	Fort Pillow Sand	Nanafalia Fm.
			Midway Group	Porters Creek Fm.	Old Breastworks Formation	Old Breastworks Formation	Naheola Fm.
					Porters Creek Fm.	Porters Creek Clay	Porters Creek Fm.
				Clayton Formation		Clayton Fm.	Clayton Fm.

This correlation brings regional parsimony to the Gulf Coast and northern ME lithostratigraphy and is consistent with weathering horizons observed at the top of the Naheola Fm. in Mississippi (Thompson, 1995) and the basal Wilcox Formation in southwestern Tennessee (Russell and Parks, 1975). The re-assignment is also consistent with the facies changes between the Old Breastworks Formation and Fort Pillow Sand (Moore and Brown, 1969), and phosphatic pebbles, which are commonly associated with transgressive facies above major disconformities, at the base of the Fort Pillow Sand in the Fort Pillow test well.

Cross Sections

Seven cross sections were prepared (Figure 6): one parallel to the Mississippi River (G-G′) (Figure 7), and six perpendicular to the first (A-A′ to F-F′) (Figures 8-13). Because of the size of the cross-sections these are presented as plates at the end of the document. Stratigraphic units from the top of the Cretaceous to the surface were interpreted from the geophysical logs and correlated along the length of the sections, except where removed by erosion. The logs are numbered consecutively on each section from west (or south) to east (or north). The bases of Quaternary formations are designated by red lines and those of Tertiary formations are designated with blue lines. Because of its hydrogeologic significance, the Memphis Sand and correlative formations comprising lower and middle Claiborne aquifers are bound by green lines. Red vertical dashed lines represent faults identified by Csontos (2007). Green vertical dashed lines represent faults inferred based on the present stratigraphic study. The sections are described individually below beginning with section G, followed by sections A through F.

Section G-G′ (Figure 6) serves as a regional key section from southwest to northeast within the northern ME. Sections A, B, D, E, and F are correlated to logs on section G-G′. The

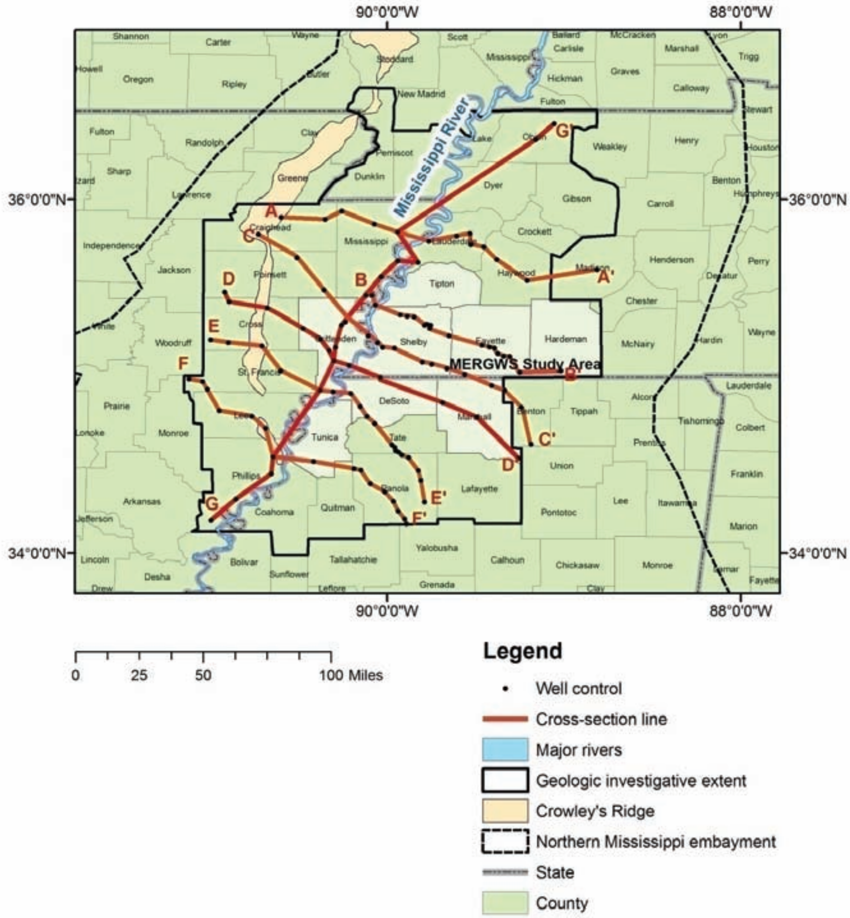


Figure 6. *Locations of cross-section lines A-G in the study area.*

overall trend in section G-G′ is that of progressive thinning of all Tertiary stratigraphic units from southwest to northeast (Plate 1). Faults (green vertical dashed lines) were inserted between logs 3 and 4, 6 and 7, and 13 and 14 to convey inferred offsets. Fault offsets were only considered where multiple formations are offset in a given log, preferably in multiple cross-sections. Log signals for Quaternary units are observed in several logs, but the main constraint on thickness of Quaternary deposits is based on surface elevation and the top of the Tertiary. The Jackson Formation is present as fine-grained deposits only at the Fort Pillow test well (log 11) and to the south of Crowley's Ridge. The Cook Mountain and Cockfield formations are dominated by fine-grained sediments from the south to log 7. To the north of log 7, fining-upward and coarsening-upward sand to mud intervals are present in the Cockfield Formation. Between logs 7 and 10, local sand bodies are present within the fine-grained Cook Mountain deposits. From logs 1 to 5, the lower and middle Claiborne sections show three distinct units, the Carrizo Sand, Cane River Formation, and Sparta Sand. The Carrizo and Sparta are nearly all sand, whereas the Cane River contains numerous sand intervals, none of which are particularly laterally persistent, within an overall mud-rich unit. Winona and Zilpha Shale equivalents are designated; however, they are better conceptualized as comprising a persistent interval rather than as distinct lithologic units. North of log 5, the Memphis Sand is present with two laterally persistent fine-grained intervals (Basic City Shale and Zilpha Shale equivalents) dividing the formation into the three informal members (Table 4). These fine-grained intervals are not single horizons, but rather intervals in which silt and clay are consistently present (although at slightly higher or lower elevations in the formation). The lower and middle Claiborne section thins from 1350 to 600 ft from southwest to northeast. The Flour Island Formation is a laterally persistent fine-grained interval along section G-G′, with thin (10 to 20 ft thick) sand intervals observed throughout the formation. The Flour Island Formation thins from 500 to 75 ft thick from log 1 to 13, respectively. The Fort Pillow Sand varies from a single amalgamated sand interval (e.g., log 5) to comprising two distinct sand intervals with a prominent intervening fine-grained unit (e.g., log 3). It thins from 225 to 125 ft thick from southwest to northeast. The underlying Old Breastworks Formation is observed in only four wells in section G-G′ and shows an overall upward-coarsening character in each; however, it shows the coarsest character in log 13.

Section A-A′ is centered on the Mississippi River and bounded by Crowley's Ridge on the west and Jackson, Tennessee, on the east (Figure 6). Prominent fault offsets are observed east of log 1, along Crowley's Ridge, between sections 4 and 5, and near log 8 (Plate 2). A significant section (120 ft thick) of Jackson Formation is present at log 8, but otherwise the Cockfield and Cook Mountain formations comprise the upper Tertiary sections along most of the section. The Cockfield Formation includes several thick sand intervals, although consistent fining- or coarsening-upward intervals are observed in logs 8 and 10. The Cook Mountain Formation is dominated by fine-grained strata at logs 4 and 5, but contains laterally persistent sand intervals in the upper part of the formation, especially at log 7. The Memphis Sand is dominated by sand east of log 8, with only the Zilpha Shale interval showing potential lateral persistence. However, in logs 2 through 5 the Memphis Sand shows distinct intervals correlative to the Carrizo Sand, Cane River Formation, and Sparta Sand, supporting the correlation in the northwestern ME of the tripartite stratigraphy used in southeastern Arkansas. The Flour Island Formation and Fort Pillow Sand generally show similar characteristics to that observed in section G-G′, with the Flour Island showing substantial thinning toward the eastern and western ME margins. The Flour Island is anomalously thick in log 4, potentially due to the Flour Island interval containing a fault zone.

Section B-B′ was constructed in western Tennessee (Figure 6) mainly utilizing shallow exploration borehole logs (total depth < 300 ft.). The purpose of this section was to assess the utility of the shallow logs. Although the log signals are quite good (Plate 3), the limited depth of most boreholes creates uncertainty in the formation picks; thus, decreasing the value of this cross-section for the overall project goals. However, section B-B′ does illustrate the sand-rich character of the Memphis Sand along the basin margin and need for deep borehole control.

Section C-C′ extends from Crowley's Ridge in Arkansas to northwestern Mississippi, and passes through the Memphis area. Significant fault offsets are inferred between logs 1 and 2, 2 and 3, 4 and 5, 8 and 9, and 10 and 11 (Plate 4). Faults inferred between logs 8 and 9 and 10 and 11 fall along trends identified by Velasco et al. (2005) and Stevens (2007). The Cockfield and Cook Mountain formations are the uppermost Tertiary formations along most of the section with significant subcrop regions of the Memphis Sand and correlative Claiborne strata in Mississippi at the northwestern and southeastern ends of the section, respectively. The Cook Mountain Formation is thin and partially removed by erosion east of the Mississippi River, consistent with studies by Parks (1990) and Kingsbury and Parks (1993). The Memphis Sand is dominated by sand between logs 4 and 6, but shows two or more fine-grained intervals west and east of the central part of the cross-section. Some of the fine-grained intervals appear to correlate to the Basic City Shale and Zilpha Shale intervals; however, others are discontinuous and vary in their stratigraphic level in the Memphis Sand. At the Tennessee-Mississippi state line, the lower part of the Memphis Sand thickens, which is interpreted to reflect the northern extent of the Hatchetigbee Formation as mapped by Thompson (2003a; b; c; and d). The Flour Island Formation in Arkansas and Tennessee is generally fine-grained, but a sandy interval is commonly observed in the middle of the formation (e.g., logs 2, 4, and 9). The Tuscahoma and Hatchetigbee formations are correlated tenuously to the Flour Island Formation and lower Memphis Sand based on lithological studies in central Mississippi by Thompson (1995). The Nanafalia Formation is correlated to the Fort Pillow Sand; however, the interval is more fine-grained at logs 15 and 16 than typically recorded. Furthermore, the Fort Pillow Sand thins extensively from 330 ft at log 4 to 100 ft at log 13. The Old Breastworks Formation and Other Midway Group units are consistent in character along the section, but thin toward the basin margins.

Section D-D′ extends from western Poinsett County (west of Crowley's Ridge) in Arkansas to southeastern Marshall County in Mississippi. Although several faults are shown, the most important offsets exist between logs 2 and 3 (along the eastern margin of Crowley's Ridge), and on either side of log 6, which appears to be on a horst block (Plate 5). The Cook Mountain Formation is present beneath the Quaternary units between logs 3 and 9, with part of the Cockfield Formation present only in logs 4 and 7. The Memphis Sand is present in logs 1 through 9, east of which the Mississippi Claiborne Group formations are assigned. The Memphis Sand is dominantly sand west of the Mississippi River, but the clay intervals within the Tallahatta and Zilpha intervals become increasingly distinct within northern Mississippi. Similar to section C-C′, the lower sandy part of the Claiborne thickens within northern Mississippi as the Hatchetigbee Formation intertongues with the Flour Island Formation. As observed in section C-C′, the Flour Island Formation and Fort Pillow Sand increase in thickness toward the center of the ME in logs 5 through 8 and 10, but thin toward the margins of the basin. Conversely, the Old Breastworks Formation and Porter's Creek Clay retain similar thicknesses in all the Arkansas logs (the interval has limited representation in the Mississippi logs).

Section E-E′ extends from western Cross County (west of Crowley's Ridge) in Arkansas to eastern Panola County in northern Mississippi. Many faults are identified within the section; however, the greatest offsets are observed along the faults between logs 8 and 9, 11 and 12, 12 and 13, and 16 and 17 (Plate 6). The Cook Mountain and Cockfield formations are present to varying degrees between logs 3 and 11, with the Jackson Formation also observed at log 3, which is located on Crowley's Ridge. In contrast to the sections to the north, prominent clay intervals, either within the Cane River Formation (Arkansas) or Tallahatta Formation, Zilpha Shale, and Kosciusko Formation (Mississippi), are present in the lower and middle Claiborne section in all logs except 1 and 2. As observed in sections C-C′ and D-D′, the Flour Island Formation and Fort Pillow Sand thicken toward the center of the ME at logs 5, 6 and 8, but thin toward the margins. The correlative formation to the Fort Pillow Sand (Nanafalia Fm.) in northern Mississippi is finer grained than the Fort Pillow Sand and is likely dominated by silt and clay rather than sand. The underlying Old Breastworks/Naheola Formation and Porters Creek Clay appear to thin toward the margins of the ME, but generally retain similar log signatures throughout their respective extents.

Section F-F′ is the southernmost SE-NW cross-section and extends from western St. Francis County in Arkansas to southern Panola County in Mississippi. Only two faults are identified in this cross-section, between logs 8 and 9 and between 10 and 11, both with significant inferred offsets (Plate 7). The Cook Mountain Formation is present between logs 1 through 7, 9 and 10, with the Cockfield Formation having more limited preservation at logs 4 through 7, 9 and 10. The lower to middle Claiborne section is sandy at logs 1, 2, 6 and 8, but in other logs contains significant clay intervals in the Cane River Formation (Arkansas) and Tallahatta Formation and Zilpha intervals. In general, the lower Claiborne appears to be dominated by silts and clay in logs 11, 12, 13, 15, and 16. The trends in the Flour Island and Fort Pillow Sand intervals are similar to those observed in section E-E′, with limited evidence of the sandy Fort Pillow interval in the correlative Nanafalia Formation at logs 12 and 14. The Old Breastworks/Naheola Formation and Porters Creek Clay appear to be thickest near the center of the ME at log 8 and thin toward the margins of the basin.

Structure Contour Maps

The structure contour maps were made primarily from the high-quality log dataset used in cross-section preparation. Because of limitations in the extent of several formations and the limited well log dataset, maps are presented only for Eocene and Paleocene stratigraphic units. Furthermore, only the following regionally-defined formation or sub-formation boundaries are presented: base of Cook Mountain Formation (Figure 7), base of Kosciusko/ Sparta/ upper Memphis Sand (Figure 8), base of Tallahatta/Cane River/middle Memphis Sand (Figure 9), base of the Meridian/Carrizo/ lower Memphis Sand (Figure 10), base of the Flour Island/Tuscahoma (Figure 11), and base of Fort Pillow/Nanafalia (Figure 12). The major faults identified by Csontos et al. (2008) are also shown on the maps. Although the interpolation algorithm in ArcGIS is applied to an irregular field of data, the resulting output is given as a rectangular region bounded by the longitudinal and latitudinal extents of each data set. Interpretations, however, are limited only to the data-constrained regions of the maps. Interpolation schemes for all points are described in Tables App2 and App3 (see Appendix Geophysical Logs). The location (x,y) numerical rank for lines, polygons and rasters were recorded in the feature class' metadata. For point data, the location (x,y) numerical rank and elevation (z) qualification were stored as attributes for each feature.

The base of the Cook Mountain Formation is shown in Figure 7. Overall, this surface is highest along the eastern side of the ME and is lower in the central southern ME in eastern Arkansas, although few data points constrain the latter trend. The irregular slope of the surface east of the Mississippi River with low areas in Panola (MS), DeSoto (MS), Lauderdale (TN), and Obion (TN) counties has been interpreted by Hundt (2008) to be due to pre-Cook Mountain fluvial erosion; whereas Martin (2008) favors the influence of a series of east-west fault-bounded grabens for the apparent structural lows. Given the limited deep borehole data from which to constrain Martin's proposed fault-bounded structures and the overall lower elevation of the base of the Cook Mountain Formation from east to west, the fluvial-erosion interpretation seems most supported at present.

The base of the Kosciusko/Sparta/upper Memphis Sand is shown in Figure 8. The upper Memphis Sand in northeastern Arkansas and western Tennessee is the correlative upper sand interval to the Kosciusko (MS) and Sparta sands (MS) identified on the cross-sections (Plates 1-5). This surface is highest along the eastern side of the ME, but also shows high areas along the western central part of the ME that follow Reelfoot Rift-bounding faults defined by Csontos (2008). The surface is highly irregular, but generally slopes to the south. Similar to the base of the Cook Mountain Formation, prominent lows are present in Panola (MS), DeSoto (MS), Lauderdale (TN), and Obion (TN) counties; however, lows are also observed in several areas of Arkansas as well.

The base of the Tallahatta/Cane River/middle Memphis Sand is show in Figure 9. Again, the middle Memphis Sand interval is shown in cross-sections in eastern Arkansas and western Tennessee (Plates 1-5). The surface is highest along the eastern side of the ME, but highs are also observed along the western side of the ME and trending east-west in Cross (AR), Crittenden (AR), and Shelby (TN) counties. The latter high area separates the surface into two structural basins, one centered in Mississippi (AR), Lauderdale (TN), and Tipton (TN) counties, and the other centered in the southern central ME. Several of the structural basin boundaries appear to follow major faults within the northern ME.

The base of the Meridian/Carrizo/Memphis Sand is shown in Figure 10. The surface structure generally follows that of the ME, with western margin of the structural basin closely following the central SW-NE fault within the northern ME. The bases of both the Flour Island/Tuscahoma (Figure 11) and Fort Pillow/ Nanafalia (Figure 12) show structural trends nearly identical to that in Figure 10. However, the extent of the Fort Pillow Sand in the northern ME is poorly constrained by the available data.

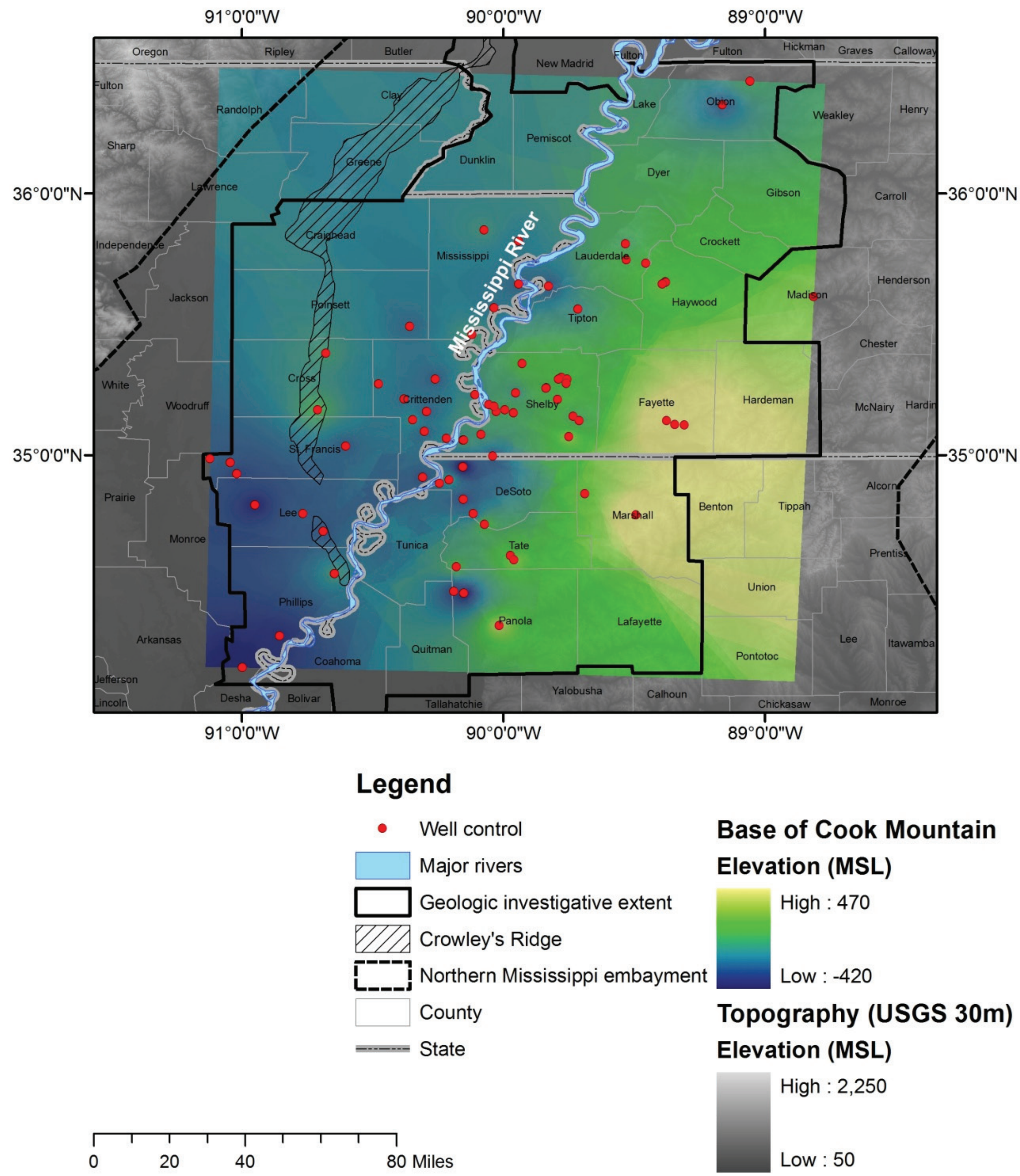


Figure 7. *Structure contour map of the base of the Cook Mountain Formation in the study area. Elevations are in feet.*

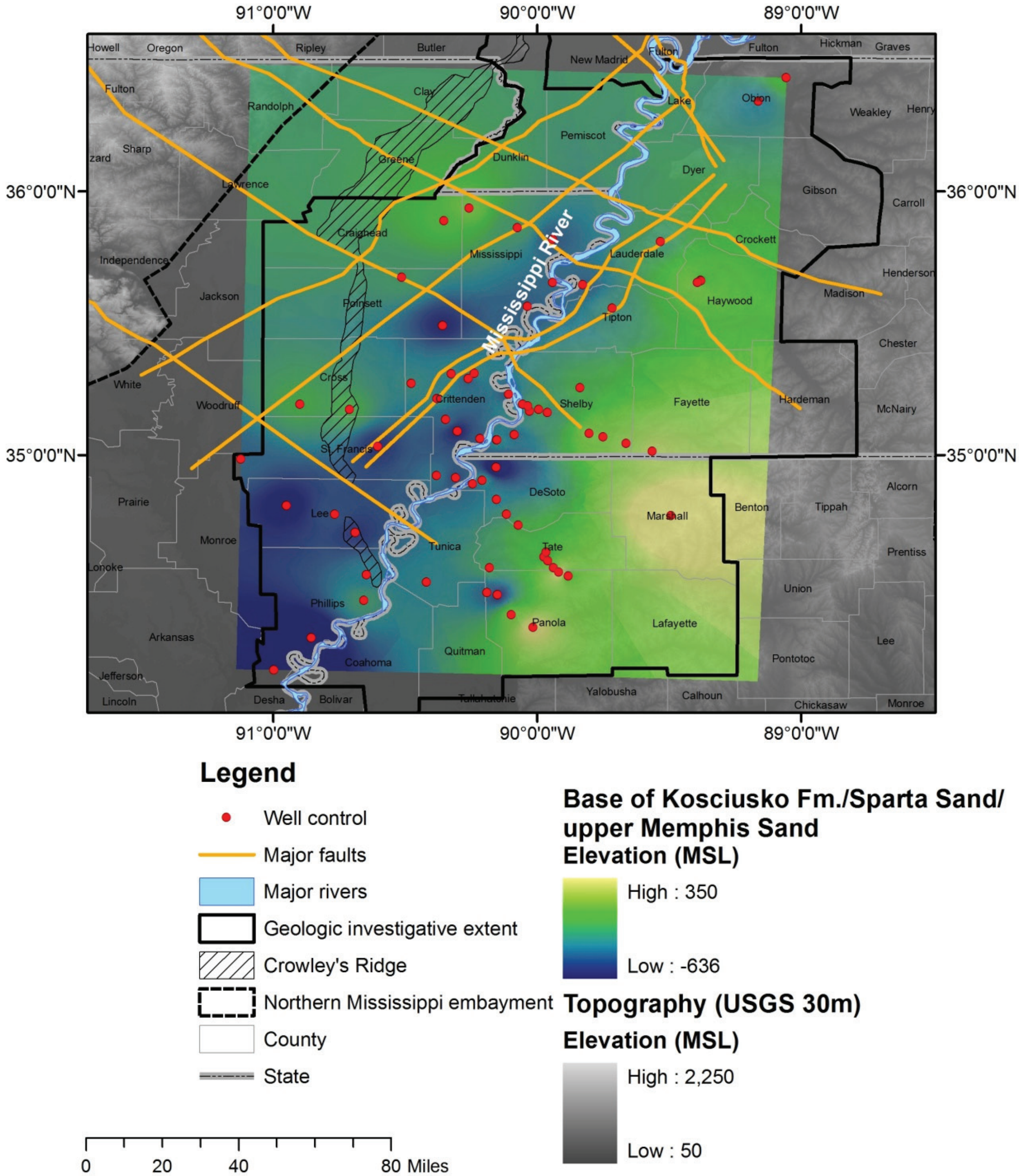


Figure 8. *Structure contour map of the base of the Kosciusko Fm./Sparta Sand/upper Memphis Sand in the study area. Elevations are in feet. Major faults are from Csontos et al. (2008).*

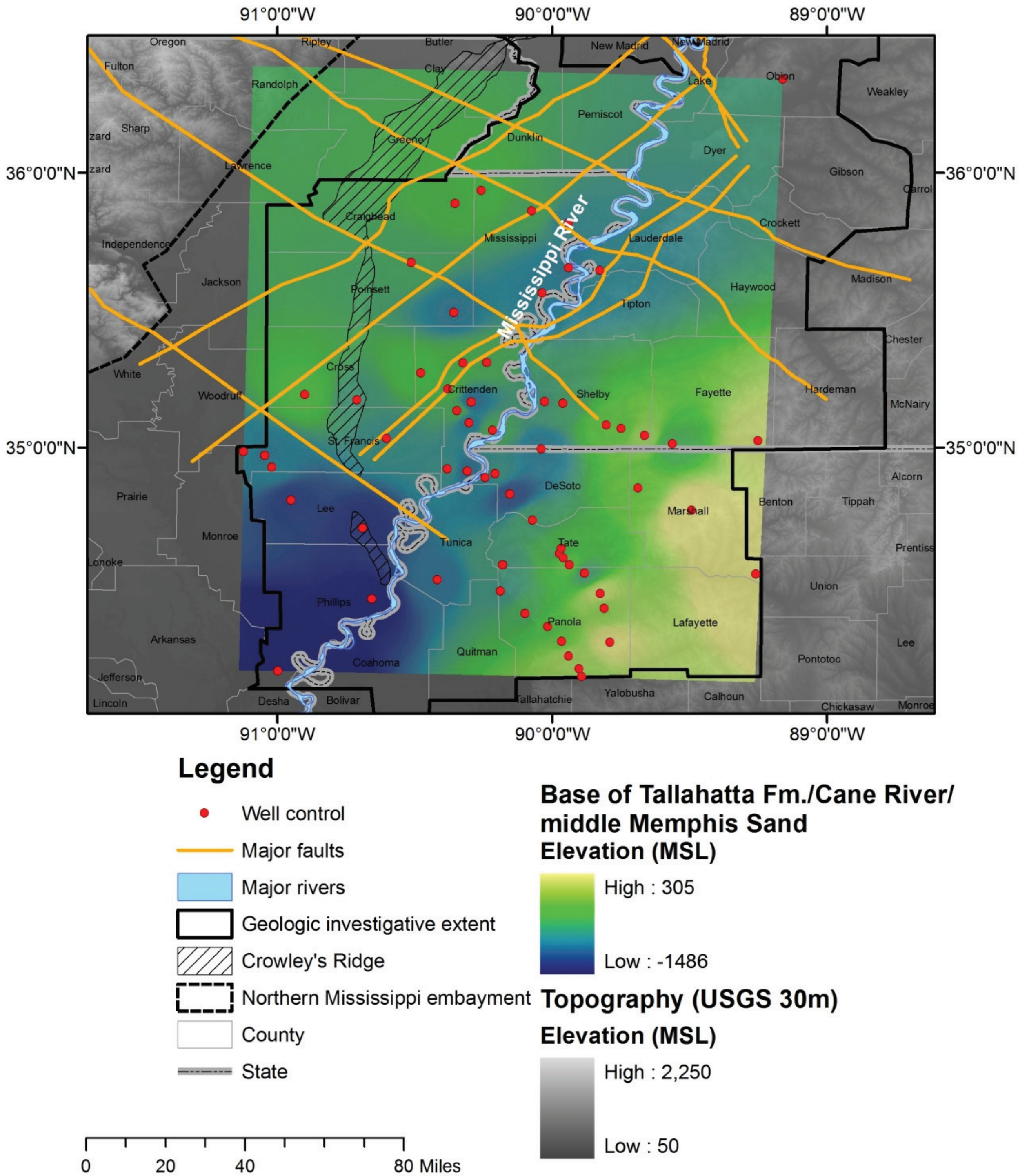


Figure 9. *Structure contour map of the base of the Tallahatta Fm./Cane River Fm./middle Memphis Sand in the study area. Elevations are in feet. Major faults are from Csontos et al. (2008).*

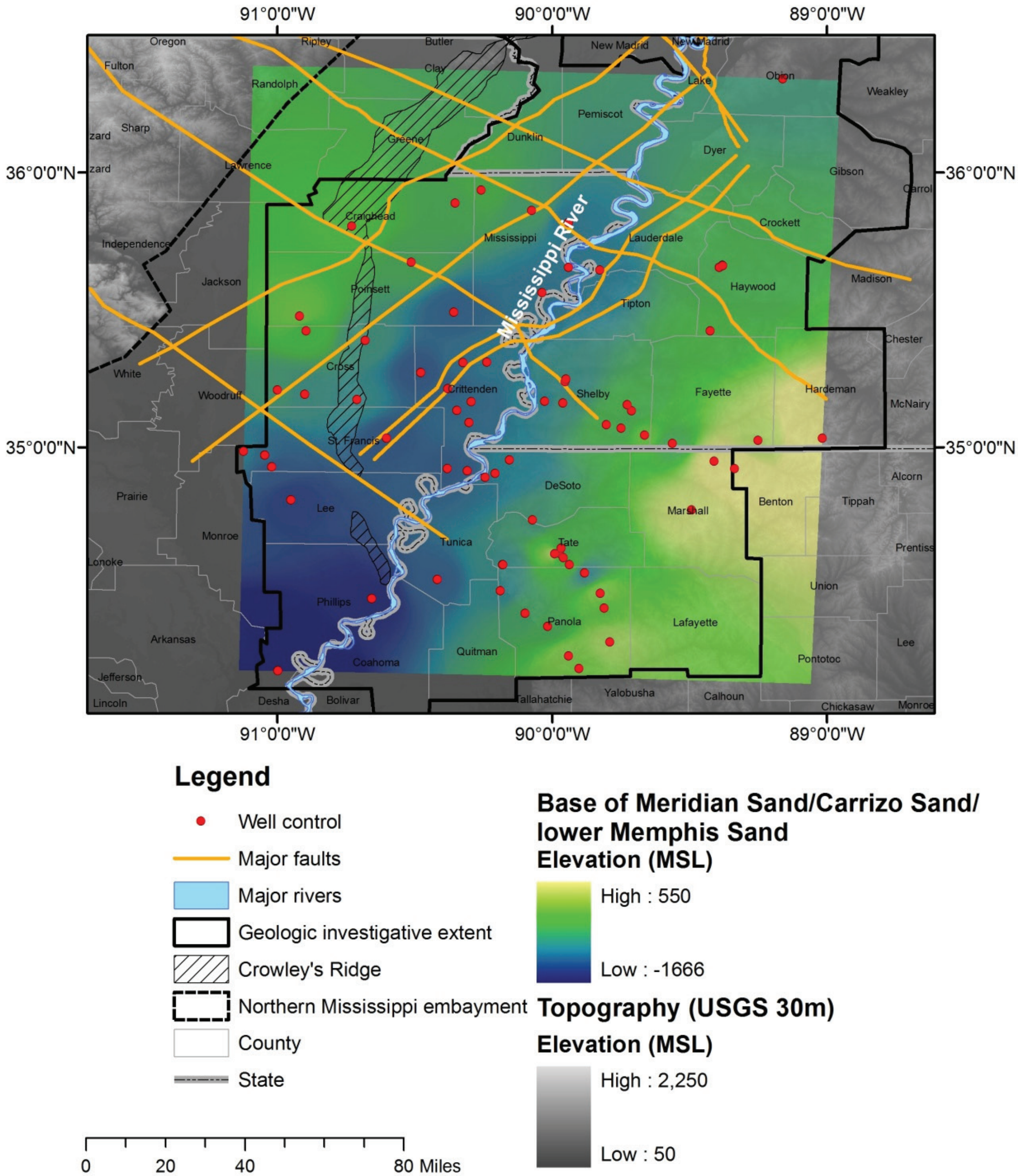


Figure 10. *Structure contour map of the base of the Meridian Sand/Carrizo Sand/lower Memphis Sand in the study area. Elevations are in feet. Major faults are from Csontos et al. (2008).*

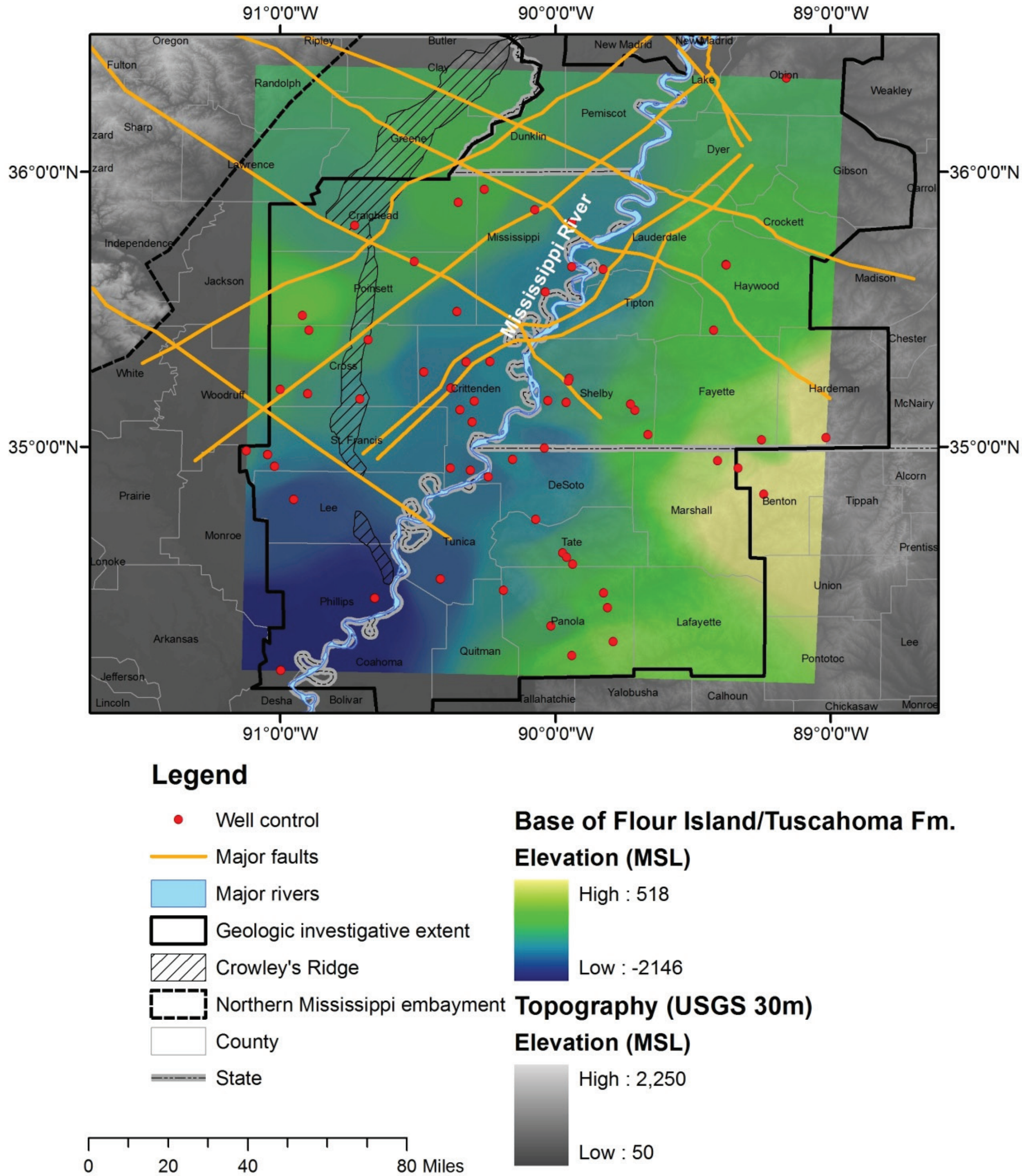


Figure 11. *Structure contour map of the base of the Flour Island/Tuscahoma formations in the study area. Elevations are in feet. Major faults are from Csontos et al. (2008).*

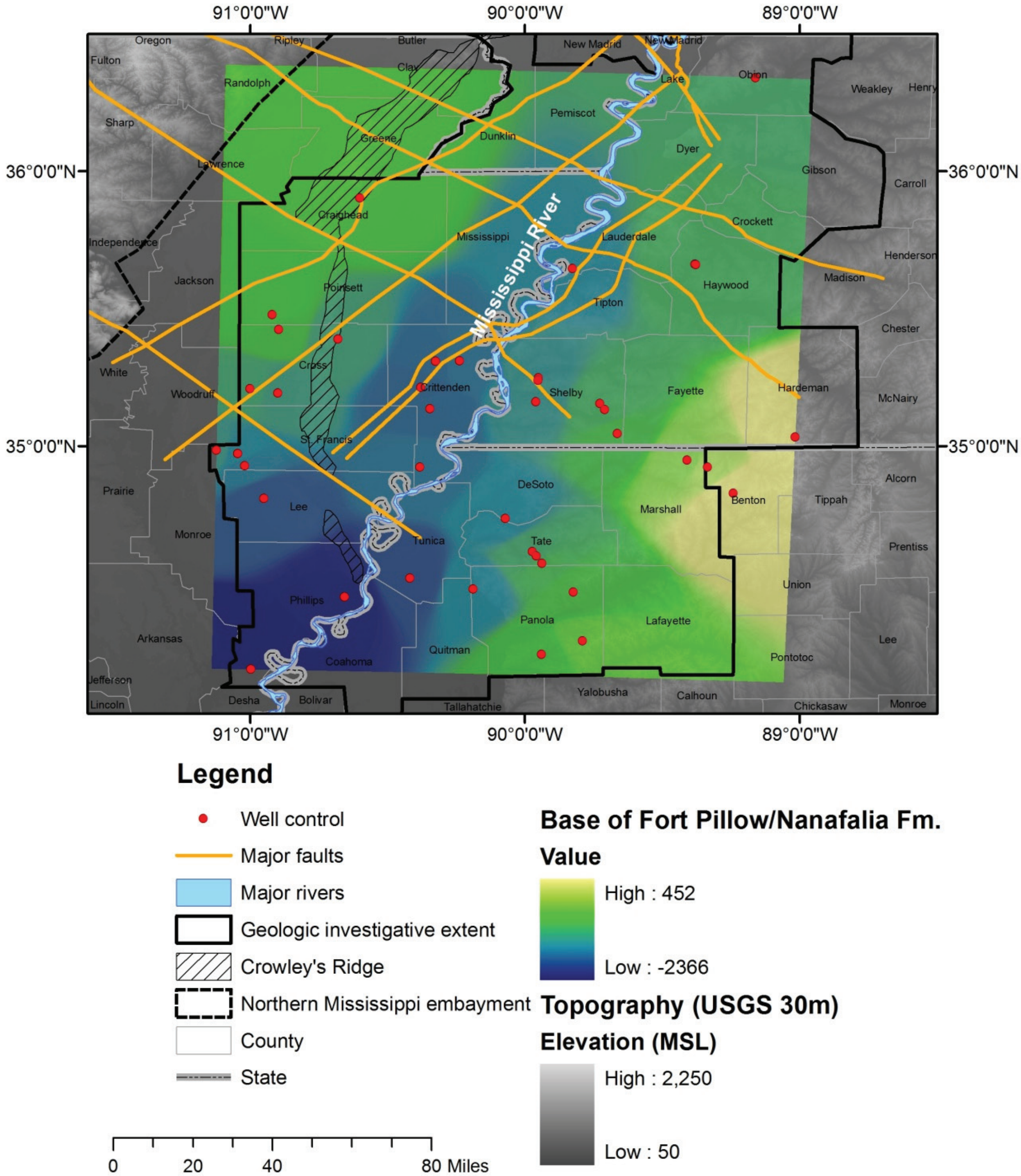


Figure 12. *Structure contour map of the base of the Fort Pillow Sand/Nanafalia Fm. in the study area. Elevations are in feet. Major faults are from Csontos et al. (2008).*

Discussion

Lithostratigraphic correlation and uncertainty

The proposed stratigraphic correlations in the northern ME (Table 4) are reasonably constrained by cross-sections and surface maps presented in this study and surfaces presented in Hart et al. (2008). However, some of the correlations, especially at the Tennessee-Mississippi state line are tenuous and difficult to reconcile. For example, the sandy Hatchetigbee Fm. in northern Mississippi appears to laterally grade into the finer grained Flour Island in the central ME, but what is their contact relationship and how does it relate regionally with the overlying Claiborne Group? A similar type of question could be applied to the basal Wilcox as well. Although parsimonious, the correlation of the Old Breastworks Formations with the Naheola Formation is somewhat speculative and lacks regional paleontological basis. More detailed correlation with geologic and paleontologic control needs to be completed before many of these questions can be addressed.

Another approach to evaluating stratigraphic consistency is to examine the trend of bounding surfaces (i.e., base or top of formations). The presence of sharp or irregular changes in surface elevation may suggest either structural truncation or inconsistent formation picks, which create sharp and erratic breaks in the surface or high error in the surfaces. The IDW interpolation scheme employed by ArcGIS 9.3 provides statistical basis for evaluating errors in the surface interpolation. The results from the surfaces created are shown in Table 5. The nearest neighbor ratio approaches values of one for random distributions of evenly spaced data. Values less than one indicate clustering and those greater than one indicate dispersed, distant data. Most of the nearest neighbor values are slightly less than or slightly more than one, except for the base of the Jackson, Hatchetigbee and Porters Creek surfaces. The nearest neighbor results indicate reasonable but slightly clustered data distributions for the surfaces shown in Figures 7 through 12. In general, values of the Z-scores far from 1 and low values of p (probability) indicate the surface is not a random collection of data. Probabilities less than 95% confidence ($p > 0.05$) or Z-scores close to 1 are observed for the base of the loess, Fort Pillow and Old Breastworks surfaces, suggesting the potential for random distribution and low significance. The optimized polynomial fit was determined using the IDW algorithm in ArcGIS 9.3. The sensitivity of the surface to changes in polynomial fit were addressed by adding and subtracting 1 from the polynomial degree. The optimized polynomial minimized the RMS (root mean square) error. The RMS error evaluates the error in grid and map coordinate transformations in the interpolation process; lower values indicate better point control and lower uncertainty. The highest RMS errors are observed for the base of the Hatchetigbee and Old Breastworks surfaces, suggesting poor control on these

Table 5. Surface interpolation statistics.

Surface	Base Loess	Base Alluvium	Base Jackson	Base Cockfield	Base Cook Mtn	Base Kosiciusko	Base Zilpha	Base Tallahatta	Base Meridian	Base Hatchetigbee	Base Flour Island	Base Ft. Pillow	Base Old Breastworks	Base Porters Creek
Number of Records	23	56	10	51	81	74	45	66	76	10	63	41	20	7
Nearest Neighbor Ratio	1.115	0.828	1.725	0.814	0.695	0.683	1.168	0.870	0.812	1.790	0.867	0.865	1.138	2.166
Z-Score (Std Dev)	1.058	-2.460	4.388	-2.547	-5.249	-5.224	2.159	-2.016	-3.143	4.781	-2.021	-1.653	1.181	5.904
P-Value	0.290	0.014	0.000	0.011	0.000	0.000	0.031	0.044	0.002	0.000	0.043	0.098	0.238	0.000
Optimized polynomial fit (-1)	2.41	2.39	3.48	1.00	1.00	1.39	1.29	3.18	2.92	1.66	4.48	9.21	30.62	-1.00
RMS (-1)	44.73	72.95	59.67	95.87	110.40	129.30	139.40	181.10	180.70	391.60	179.30	184.80	446.70	
mean error	-10.70	-7.54	-4.99	1.12	2.42	0.87	21.61	9.53	9.35	-19.20	10.59	15.20	-92.70	
Optimized polynomial fit	3.46	3.39	4.48	1.38	1.50	2.39	2.29	4.18	3.92	2.66	5.48	10.21	31.62	
RMS	43.70	72.07	58.70	95.10	108.00	125.40	136.20	180.50	179.20	384.20	178.40	184.60	446.70	
mean error	-11.15	-7.06	-1.35	-0.94	1.98	3.06	16.06	9.71	11.62	-31.57	9.04	15.60	-92.77	
Optimized polynomial fit (+1)	4.46	4.39	5.48	2.38	2.50	3.39	3.29	5.18	4.92	3.66	6.48	11.21	32.62	1.00
RMS (+1)	44.23	72.58	58.95	97.87	112.20	127.10	138.30	181.00	179.20	388.80	179.00	184.80	446.70	
mean error	-10.53	-6.80	0.43	-4.95	-1.80	4.34	10.56	9.53	11.62	-40.54	7.86	15.93	-92.83	

RMS – Root Mean Square error

surfaces. Although the statistical results for the major formation and intraformational surfaces are adequate (Figures 7-12), they are far from ideal. Additional data in more evenly spaced distributions are desirable for each of the surfaces shown.

Hydrostratigraphy

The results from this study clarify the extent of hydrostratigraphic units defined in previous studies (Criner and Parks, 1976; Hosman and Weiss, 1991; Brahana and Broshears, 2001; Hart and Clark, 2008; Hart et al., 2008), and constrain the quality of the regional aquifers based on lithologic information. High-production aquifers are considered to be those composed almost exclusively of sand in thicknesses of 100 ft or more. Examples include the Fort Pillow and Memphis aquifers in western Tennessee (Parks and Carmichael, 1989; 1990a). Low- to moderate-production aquifers are considered to be those composed of mixtures of sand, silt, and clay beds, with sand intervals being less than 100 ft thick and discontinuous. An example is the Cockfield aquifer of western Tennessee (Parks and Carmichael, 1990b). Confining units in the study area are generally dominated by silt and clay with thin (generally less than 20 ft thick), discontinuous sand beds. Confinement is hydraulically defined, however, to provide confining pressure to underlying aquifers; thus, any lithologic classification of confinement must be further constrained by hydraulic data. For example, the Flour Island Formation appears to be an effective confining unit in the central ME based on lithology as well as the lateral extent of pumping cones of depression and low storage coefficients in the underlying Fort Pillow aquifer (Parks and Carmichael, 1989).

Regional hydrostratigraphic units are presented in Table 4 and associated surface maps were produced by (Hart et al., 2008). Our results generally confirm the extents of hydrostratigraphic units from Hosman and Weiss (1991), Brahana and Broshears (2001), and Hart et al. (2008); however, the lithologic results suggest that the quality and characteristics of each aquifer change over the study area. For example, the Fort Pillow-Lower Wilcox aquifer are mapped throughout the region by Hart et al. (2008), but fine-grained deposits dominate the Nanafalia Formation (Fort Pillow equivalent) in much of northern Mississippi (Plates 6 and 7) and the Wilcox Formation in the outcrop region of western Tennessee (Russell and Parks, 1975) (Plate 2). These observations along with trends in development of the Fort Pillow and Lower Wilcox aquifers within the central ME (Parks and Carmichael, 1989; Arthur and Taylor, 1998) indicate that the Fort Pillow-Lower Wilcox aquifer has much less regional extent than that illustrated by Hart et al. (2008). In regard to the Lower and Middle Claiborne-Memphis aquifer, fine-grained intervals correlative to the Basic City and Zilpha shales exist throughout the study area (Plates 1-7) suggesting that the Memphis aquifer is better considered as three separate subaquifers. This assertion is supported by tritium and other hydrologic tracer data that indicate the upper, middle, and lower sand intervals within the Memphis aquifer have limited vertical hydraulic connectivity (Larsen et al., 2005; Gentry et al., 2006). The Cockfield Formation in the northern ME locally contains several thick (> 100 ft) sand intervals (Plates 1 and 2) (Parks and Carmichael, 1990b); however, these sands are not laterally continuous and may have limited potential for development.

The lithologic data also suggest that the degree of confinement provided by several of the confining units changes over the study area. The Cook Mountain Formation within the upper Claiborne confining unit contains discontinuous sand intervals, which may provide pathways for leakage into the upper part of the Memphis aquifer in the Memphis area (Parks, 1990; Arthur and Taylor, 1998; Brahana and Broshears, 2001). The basal surface of the Cook Mountain is highly irregular with a deeper section in the south-central ME (Figure 7). This surface bears similarities to that of the Kosciusko/Sparta/upper Memphis Sand (Figure 8), but otherwise does not conform to the shape of underlying surfaces (Figures 9-12). These observations suggest that extensive fluvial erosion occurred prior to and following deposition of the upper Memphis Sand interval (rather than localized growth faults: Martin, 2008), which may further contribute to variations in the thickness and stratigraphy of confining silts and clays in the upper Claiborne confining unit. Persistent sand intervals are also observed in the Flour Island Formation in eastern Arkansas (Plates 2, 4, 5, 6, and 7) and the Old Breastworks Formation in the northern ME (Plate 1).

Regional Structure

The results of the present study generally support the structural interpretations of the northern ME by Kingsbury and Parks (1988), Parrish and Van Arsdale (2004), Stevens (2007), Csontos et al. (2008), and Martin (2008). Many of the faults mapped by Csontos et al. (2008) show clear offsets in the Tertiary stratigraphy. Martin (2008) also mapped several SW-NE trending regional faults, which are consistent with offsets in northern Mississippi and western Tennessee. However, E-W trending grabens described by Martin (2008) based on his surface interpolation of the Memphis Sand are interpreted to be erosional rather structural features.

The amount of offset of Tertiary strata along faults in the study area is generally less than 100 ft, although offsets of several hundred feet are suggested along some regional structures. Determining the amount of fault offset based on geophysical logs is difficult and requires closely spaced well-correlated log sections. Most offsets of Tertiary strata in the study area are less than 100 ft and are difficult to constrain based on the distance between logs. However, offsets of several hundred feet are observed along the margins of Crowley's Ridge (Plate 2), the northern extent of the Southeast margin rift fault (Cox et al., 2006) (Plate 1), and along another SW-NE trending structure in northern Mississippi (Plate 7). Confirmation of significant fault offsets within the Tertiary stratigraphy confirms the potential for vertical inter-aquifer water transfer suggested by Kingsbury and Parks (1993).

Concluding Remarks

The review of the literature and analysis of existing geological and geophysical (borehole) data indicates general continuity of regional lithostratigraphic units throughout the study area in the central and northern Mississippi Embayment (ME). The stratigraphic terminology and units are correlated amongst the three states in the study area (Arkansas, Mississippi, and Tennessee), although some revisions of nomenclature and regional interpretation are necessary. Our analysis suggests that the Old Breastworks Formation of the Wilcox Group in the northern ME is correlated to the Naheola Formation of the Midway Group in Mississippi (as suggested by Frederiksen et al., 1982); however, further paleontological work is required to confirm this parsimonious correlation. The Hatchetigbee Formation of Mississippi likely correlates to the lowermost part of the Memphis Sand in Tennessee, although it is unclear whether the Hatchetigbee pinches out at the state line or is amalgamated into the lower Memphis Sand. The tripartite division of the lower and Middle Claiborne Group defined in Arkansas (Carrizo Sand, Cane River Formation, and Sparta Sand) is mappable over the three state region and provides a useful subdivision of the Memphis Sand in the northern ME. Two regionally observed fine-grained intervals in the Memphis Sand correlate to the Basic City Shale (member of the Tallahatta Formation) and Zilpha Shale in central Mississippi and shales near the base and top of the Cane River Formation in Arkansas. The lower Memphis Sand is essentially equivalent (allowing for some sand equivalent to the Hatchetigbee Formation at the base) to the Meridian Sand in Mississippi and Carrizo Sand in Arkansas. The upper Memphis Sand is equivalent to the Kosciusko Sand in Mississippi and Sparta Sand in Arkansas.

The lithostratigraphic correlation and internal lithological variations in the formations within the study area have implications for the hydrostratigraphy. Lithological variations in the Fort Pillow Sand and Nanafalia Formation from thick clean sand intervals in the central ME to mixtures of sand, silt, and clay in western Tennessee and northwestern Mississippi indicate that the Fort Pillow-Lower Wilcox aquifer is not as extensive as has been mapped by other studies (Hosman and Weiss, 1991; Hart et al., 2008). The Middle Wilcox aquifer, which mainly comprises the Hatchetigbee Formation, is of limited extent in the study area and may be equivalent to the lower Memphis aquifer except in northern Mississippi. Regional continuity of fine-grained intervals correlative to the Basic City and Zilpha shales in Mississippi and other hydrologic information indicate that the Memphis aquifer (Lower and Middle Claiborne aquifer) may be better represented as three subaquifers, with the lower Claiborne confining unit correlating to an interval of discontinuous aquifers between the regional Lower and Middle Claiborne aquifers. Confinement of the Fort Pillow-Lower Wilcox aquifer is provided by fine-grained intervals of the Flour Island Formation and equivalent strata in northern Mississippi throughout most of the study area. The Upper Claiborne confining unit contains sandy intervals and is partially removed by late Cenozoic erosion in the central and eastern ME, which limits confinement of the Memphis (Middle Claiborne) aquifer in part of the study area. The Upper Claiborne aquifer has limited preserved extent in the study area and is comprised of discontinuous sand intervals within the Cockfield Formation.

Faults offset the Tertiary strata throughout the study area, but most offsets are estimated to be less than 100 ft in dip-slip throw. Several regional faults show evidence of greater amounts of dip-slip offset, including faults bounding Crowley's Ridge, and faults defining the southeastern margin of the ancient Reelfoot rift. The latter structures have the potential to influence regional groundwater flow, but all of the faults have potential for inter-aquifer water transfer.

Recommendations

Many of the correlation problems discussed above and the overall limited quality of surface reconstruction from the available data can be addressed by completing several specific data objectives listed below.

Correlation of geologic and hydrostratigraphic unit in the study area is limited by the number of reference sections available. For example, the Fort Pillow (Moore and Brown, 1969) and New Madrid test wells (Frederiksen et al., 1982) provide detailed stratigraphic and paleontological control required for correlation. However, no such reference boreholes exist in northern Mississippi, southwestern Tennesseee, and eastern Arkansas. A well-constrained correlation of the strata in the northern and central ME cannot be completed without this data. Furthermore, the core and cuttings returned from the reference boreholes could more clearly define the compositional, permeability, and porosity characteristics for the hydrostratigraphic units. These data are necessary for accurate groundwater flow modeling within the region.

The data set compiled for this project was admittedly incomplete and the visualization and computational tools applied were readily available software. Acquisition of additional high-quality borehole data and utilization of state-of-the-art geospatial imaging tools, such as those used in the petroleum industry (e.g., Landmark, Petrel, etc.), are needed to develop an accurate three-dimensional hydrostratigraphic model for the study area. The geophysical logs need to be scanned, digitized, and scaled properly to obtain the maximum benefit, and the resulting digital data needs to be projected in fully three-dimension imaging software. Fortunately, the Ground Water Institute has acquired additional log datasets and the necessary equipment, software, and expertise to begin the process of transforming the existing data into a common digital format.

Borehole data provide point observations of vertical stratigraphic relationships; however, all lateral relationships between data points need to be inferred using stratigraphic and structural principles. A true test of stratigraphic and structural relationships can best be made using seismic reflection analysis of the central and northern ME. Multiple seismic lines have been completed within the ME; however, most of these lines emphasize either the very shallow structure (e.g., Cox et al., 2001a; Williams et al., 2001) or the deep crustal structure (e.g., Parrish and Van Arsdale, 2004). Seismic reflection data focused on the Tertiary stratigraphy along the trough of the

ME as well as across the ME are needed to test the stratigraphic concepts developed in this and other regional studies (e.g., Hosman and Weiss, 1991; Hosman, 1996; Hart et al., 2008). Water-based seismic reflection surveys of the Mississippi River channel and underlying stratigraphy recently completed by Magnani et al. (2008) provide a good starting point for this work; however, land-based seismic surveys across the ME are also needed.

Ascertain water quality changes and ground-water contamination threats

Ground water quality is a high priority in the central and northern Mississippi embayment (ME) in the tri-state area of Tennessee, Mississippi and Arkansas. Threats to water quality in the region include nutrients, pesticides, and herbicides from agricultural runoff, industrial pollution, urban runoff, and legacy contamination from past waste disposal practices (Graham, 1982; Parks, 1990; Kleiss et al., 2000; Gonthier, 2000; Gonthier, 2002). The main usage of ground water in the region is irrigation (Holland, 2007) due to the fact that much of the land is used for agriculture. However, urban growth in the tri-state area of Mississippi, Arkansas, and Tennessee has increased the usage of ground water (Webbers, 2000; Holland, 2007), mainly to meet demands for drinking water and industrial supplies.

Past studies of water quality in the Tertiary and Quaternary aquifers within the northern and central ME have established the overall high quality of ground water and regional trends in hydrochemistry (Wells, 1933; Criner and Armstrong, 1958; Bell and Nyman, 1968; Boswell et al., 1965; 1968; Payne, 1968; 1972; 1975; Brahana et al., 1987; Pettijohn, 1996). More recent studies have focused on potential for contamination or degradation in water quality in agricultural (Kleiss et al., 2000), municipal, and industrial water supplies (Parks et al., 1981; Graham and Parks, 1986; Parks, 1990; Bradley, 1991; Parks and Mirecki, 1992; Parks et al. 1995; Larsen et al., 2003; Gentry et al., 2005; Ivey et al. 2008). Declines in the potentiometric surfaces of regional aquifers (Criner and Parks, 1976; Kingsbury, 1996; Schrader, 2008a) create the potential for vertical leakage of poor quality or contaminated waters from surface and shallow ground water sources, especially in areas where regional confining units may be thin or missing (Graham and Parks, 1986; Parks, 1990).

In this study hydrogeochemical data were obtained from historical records to statistically analyze variations and groupings in water quality, and prepare contour maps of geochemical constituents to identify spatial controls on water quality. These observations date from the late 1920s to the mid 2000s, and vary in regard to completeness and quality of chemical analysis. To place the water quality variations in a regional context, data were collected and analyzed from wells throughout the ME and into the Gulf Coast region. This analysis allowed assessment of large-scale influences, such as physiographic region, fault systems, and basin-scale groundwater flow, on water quality. The data were obtained from wells screened in four aquifers: Quaternary Alluvial (Mississippi River and tributary alluvium), Upper Claiborne (Cockfield Formation and equivalents), Middle Claiborne (Kosciusko Formation, Memphis Sand, and Sparta Sand), and Lower Claiborne-Wilcox (Cane River Formation, Carrizo Sand, Meridian Sand, Hatchetigbee Formation, and Fort Pillow Sand) (Hosman and Weiss, 1991; Brahana and Broshears, 2001). The analysis focuses on seven counties in the central and northern ME: Shelby County (TN), Tipton County (TN), Hardeman County (TN), Fayette County (TN), Crittenden County (AR), DeSoto County (MS), Benton County (MS), and Marshall County (MS). However, statistical analysis and mapping incorporated a greater region including much of the central and northern ME. Pettijohn (1996) conducted a similar analysis of water quality data in the ME and Gulf Coast; however, our effort focuses on a smaller geographic region and the water data are grouped differently. The land use in the investigated area includes urban land use in the Memphis metropolitan area and agricultural use in the surrounding areas. The objectives for assessing the water quality are to:

1. *Catalog water chemistry variables from disparate datasets.* Query the USGS, EPA, state environmental agencies, and published research literature for chemical data available for ground water and surface water in the region. The goal is to collate data within a database to allow for assessment of spatial and temporal variability in ground-water chemistry.

2. *Ascertain temporal ground water quality changes and chart statistical variation among measured geochemical variables.* Filter the cataloged water quality data for accuracy, classify based on water quality characteristics, and evaluate trends and data groupings using statistical models.

3. *Conduct a spatial assessment of contamination threats to the ground water and ascertain chemical signatures and environmental tracers valuable for numerical model calibration and analytical modeling*. Identify the spatial distribution of threats and data gaps through time series assessments of specific constituents. Identify environmental tracers that have potential application in evaluating ground-water flow paths and rates of recharge, especially with regard to potential threats.

Catalog water chemistry variables from disparate datasets

We assembled ground-water and surface-water quality data from a variety of sources (e.g., USGS, publications, and unpublished reports as well as from federal, state and local agencies, Native American tribes, volunteers, academics and others). These data are presented in electronic form within the supplementary documentation of this report. The USGS data were obtained from the National Water Information System (NWIS; EarthInfo Inc, 2005). Surface water data were organized by stations, analysis and observation (Table 6, Figures 13-17). Although surface water data were identified and cataloged, no hydrochemical analysis was completed on those data. Ground water data were organized by stations, analysis and observation. Each station was connected to data for state, hydrogeologic unit, county, analysis (pH, DOC, etc.) and observation (time and datum value; Figures 18-20). Sample site distributions within aquifer units are shown in the appendices.

Table 6. Surface water database contents.

State	Station	County	Stations per county	Observations	Analyses
Arkansas	1182	Crittenden	8	3899	167
Mississippi	1478	Marshall	9	234	16
		DeSoto	8	706	29
		Tunica	4	109	8
Tennessee	1554	Fayette	6	11496	1185
		Hardeman	9	5947	302
		Tipton	7	10352	1377
		Shelby	42	31225	3294
TOTAL	**4214**		**93**	**63968**	**6378**

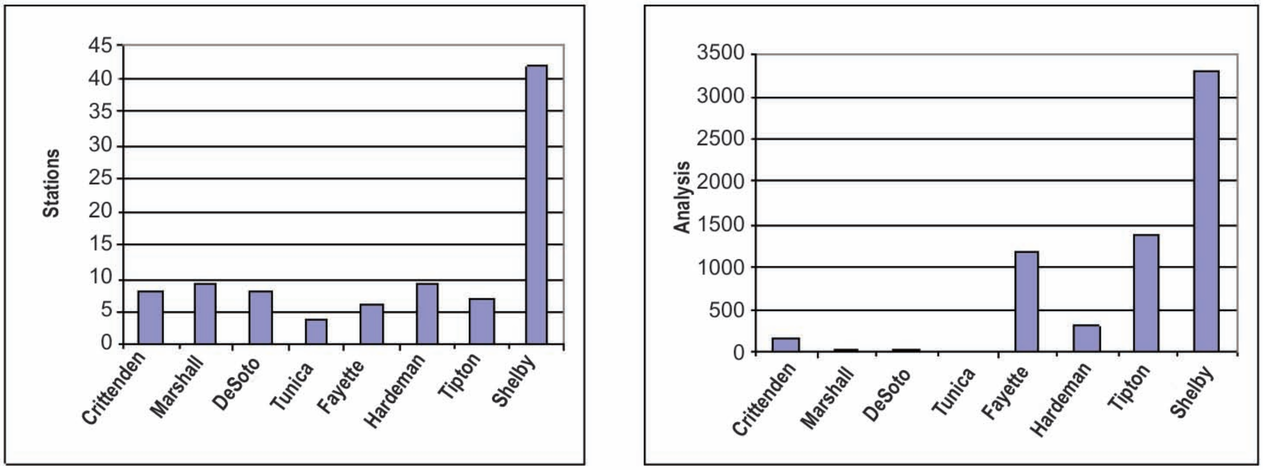


Figure 13. *Stations and Analyses within surface water database.*

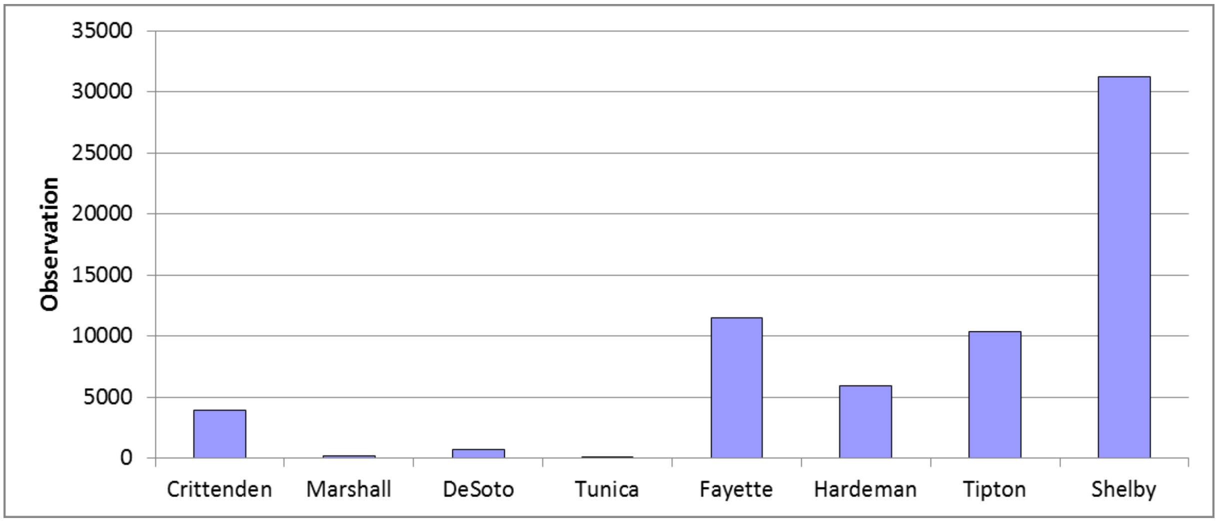


Figure 14. *Number of observations by county in surface water database.*

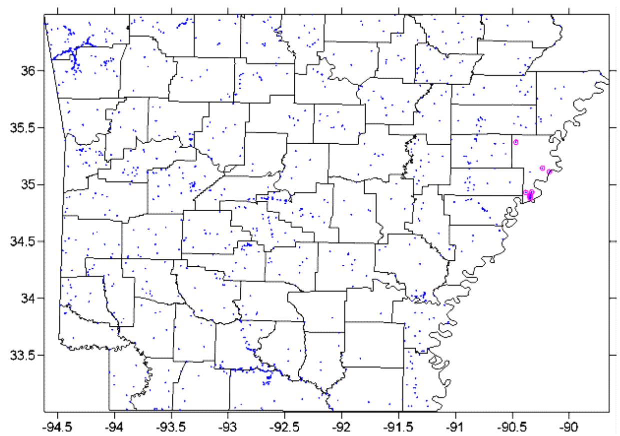


Figure 15. *Map of surface water station locations in AR. Pink stations shown in Crittenden county. Database contains observations 1911-2003.*

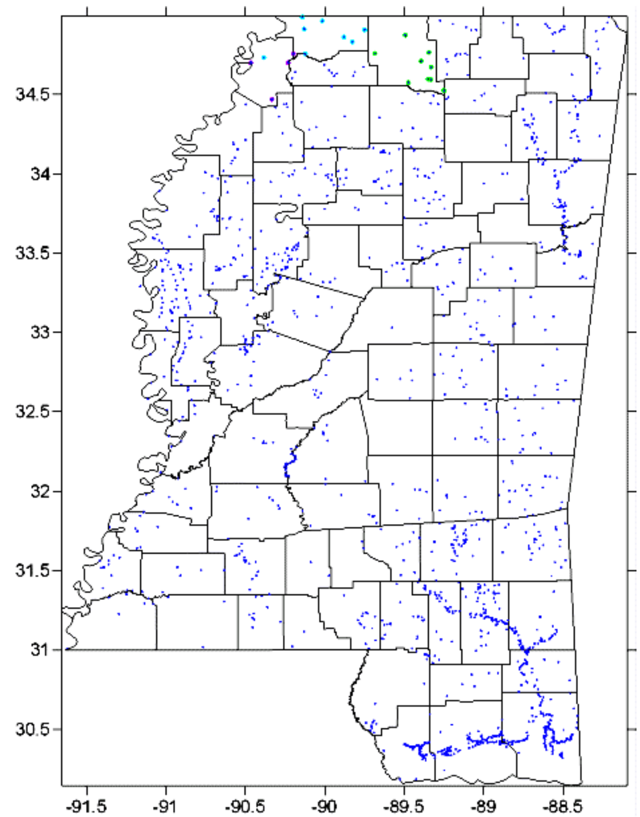


Figure 16. *Map of surface water station locations in Mississippi. Database contains observations 1911-2003 for Marshall, DeSoto and Tunica counties.*

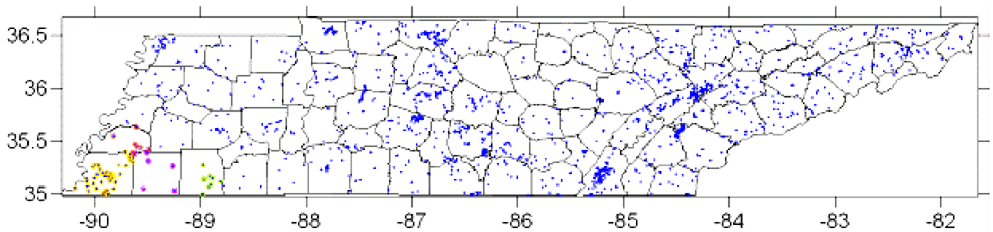


Figure 17. *Map of surface water station locations in Tennessee. Database contains observations 1911-2003 for Fayette, Hardeman, Tipton and Shelby counties.*

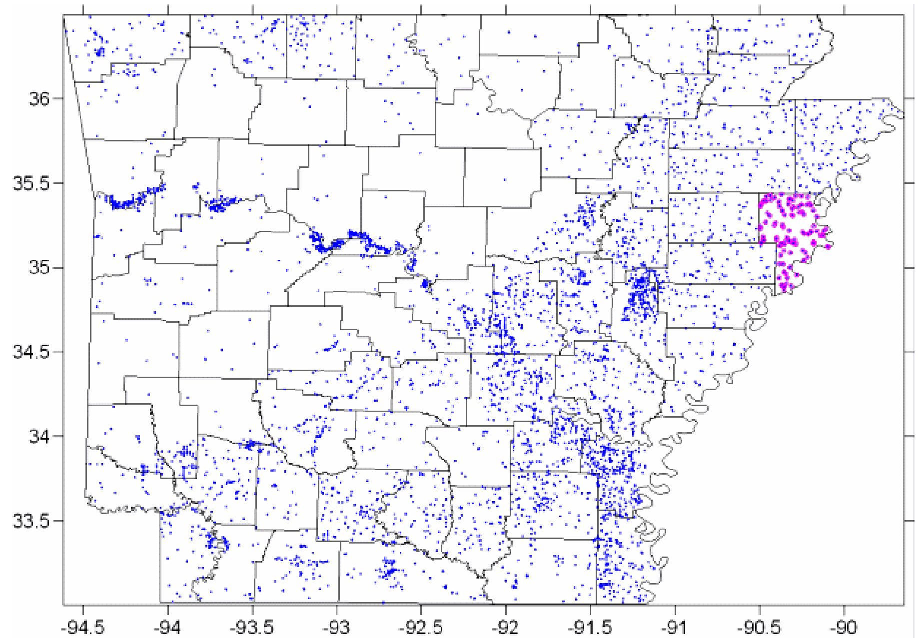


Figure 18. *Map of ground water station locations in AR. Pink stations shown in Crittenden County, Mississippi. Database contains observations 1911-2003.*

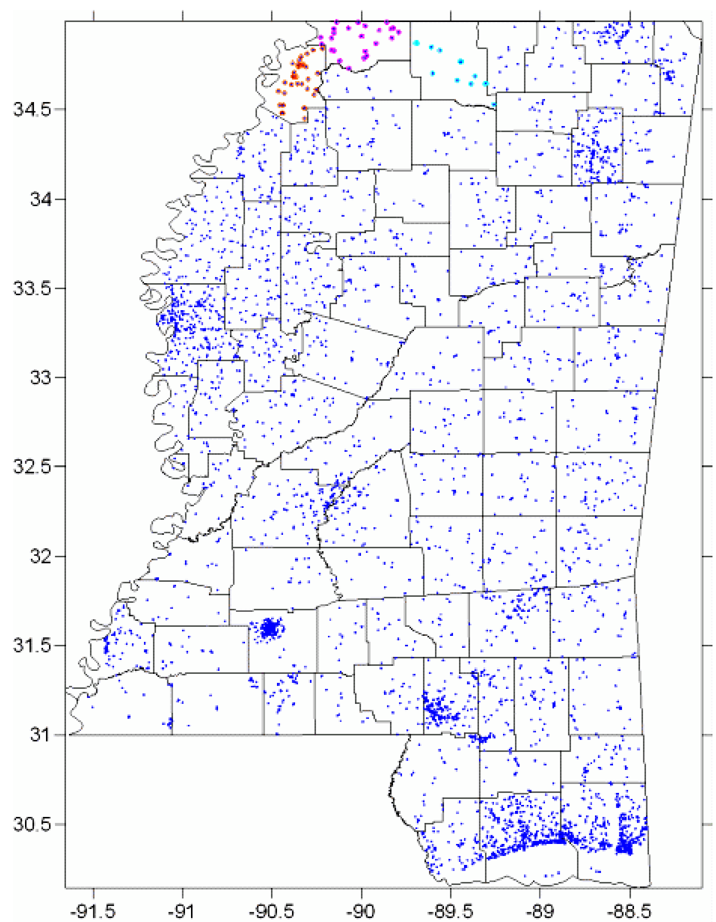


Figure 19. *Map of ground water station locations in Mississippi. Database contains observations 1911-2003 for Marshall, DeSoto and Tunica counties, Mississippi.*

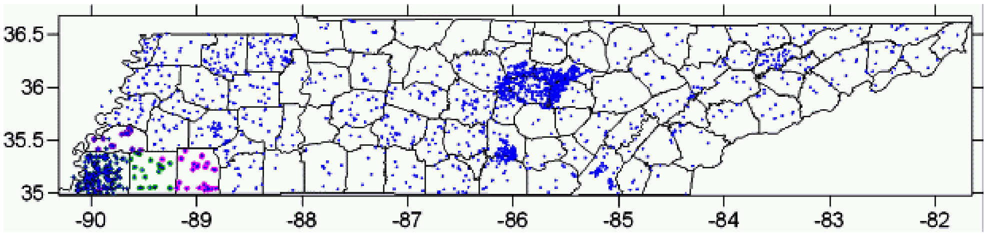


Figure 20. *Map of ground water station locations in Tennessee. Database contains observations 1911-2003 for Fayette, Hardeman, Tipton and Shelby counties. Note that stations (blue crosses) that are identified as Shelby county actually plot in AR.*

Ascertain temporal ground water quality changes and chart statistical variation among measured geochemical variables

From an analytical perspective, the ground water quality data were, at times, inaccurate or incomplete. Consistency in the analyses between boreholes and across time was lacking. We found that some samples for which there were sufficient data were not electrically neutral (an inequality between sum of anions and cations in milligram equivalents per liter or meq/L). We therefore used AquaChem 5.0 (Waterloo Hydrologic, Inc, 2005) to compute missing values of some major ions in those samples that were otherwise complete in terms of parameters of interest.

Accuracy of the chemical analyses was estimated by calculating the electrical neutrality (E.N.; Figure 21) (Eq. 1).

Equation 1:

$$E.N.(\%) = \frac{(\text{Sum C - Sum A})}{(\text{Sum C + Sum A})} \times 100$$

where A is individual anion species (meq/l) and C is individual cation species (meq/l). If E.N. is greater than or equal to 2% (absolute value), then the accuracy of the data for that sample is considered good. E.N. values between 2 and 5% (absolute value) are considered acceptable. Samples with values in excess of 5% were removed from the data set. Approximately 20% of the data were eliminated because of E.N. greater than 5%. The main factors reducing the accuracy of chemical analyses are absence of two and more anions or cations and poor quality of analytical measurements. Accuracy of geochemical data for the Quaternary Aquifer Complex is presented in Figure 21.

Hydrochemical classifications of the ground water based on the filtered geochemical data were performed using AquaChem following the Piper, Durov and Wilcox methods. AquaChem was used to determine the water type using a trilinear Piper diagram (Kehew, 2001). Hydrogeochemical maps were constructed using Surfer 7.0 (Golden Software, Inc., 1999). Shape maps for Arkansas, Tennessee, Mississippi and Louisiana were downloaded from the U.S. Census Bureau. In Surfer 7.0, the grid size was 87 rows and 100 columns; the contour of hydrostratigraphic units was approximated by option breaklines, which were digitized using geological maps; the fault option was used to delineate the influence of the Mississippi River. Inverse Distance to a Power was used for data interpolation. Surfer 7.0 also was used to display and separately analyze well locations for states and aquifers.

For each aquifer unit we performed both univariate and multivariate statistical analysis of the data used SPSS statistical software (SPSS, 2000). Univariate analyses were limited to descriptive statistics, linear (Pearson's) correlation coefficients, histogram and box and whisker plots, as well as detection of anomalous chemical concentrations. Pearson's correlation coefficients (r) are considered significant when greater than or equal to 0.5. The coefficient of determination (R^2) would then be greater than 0.25 or 25%, expressing the proportion of data with a significant value of r (Rock, 1988). Cluster analysis used the hierarchical option

Bin	*Frequency*	*Cumulative %*
-5.09	1	17.73%
-4.64	13	2.48%
-4.20	12	4.61%
-3.76	14	7.09%
-3.32	11	9.04%
-2.88	9	10.64%
-2.43	18	13.83%
-1.99	22	17.73%
-1.55	32	23.40%
-1.11	56	33.33%
-0.67	52	42.55%
-0.22	71	55.14%
0.22	44	62.94%
0.66	41	70.21%
1.10	28	75.18%
1.54	20	78.72%
1.99	16	81.56%
2.43	23	85.64%
2.87	16	88.48%
3.31	20	92.02%
3.75	19	95.39%
4.20	8	96.81%
4.64	10	98.58%
More	8	100.00%

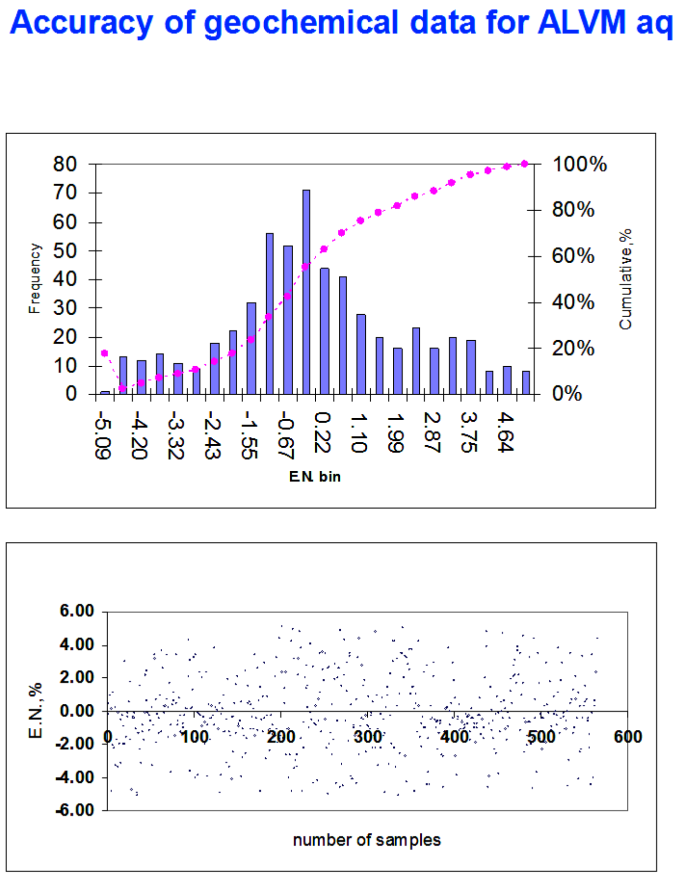


Figure 21. *Data filtered and outliers (E.N. > 5% removed). ALVM is the Mississippi Alluvial Valley aquifer complex.*

and dendrogram graphical representation with average linkage between groups. We also employed squared Euclidean distance with Z scores standardization when exploring geochemical groupings. Factorial analysis used principal components without rotation. We analyzed the correlation matrix, unrotated factor solution and scree plots to identify the two or three most significant factors contributing to the variance in the data.

Throughout the available data sets, few ground water quality time series and limited monitoring data exist. These data are important to understand temporal and spatial water chemistry changes and allow us to map data from different time periods. For example, early studies in the Memphis area argued that the water-quality impacts of ground water extraction are minor in the area (Bell and Nyman, 1968; Graham, 1982). However, more recent studies have shown progressive declines in water quality, especially around pumping centers (Parks et al., 1995; Larsen et al., 2003; Gentry et al., 2005) and waste disposal sites (Parks, 1990; Bradley, 1991; Parks and Mirecki, 1992; Mirecki and Parks, 1994; Gentry et al., 2006). Two groups of monitoring data were used: a) continuous monitoring data for one well and b) monitoring data for a suite of neighboring wells. The use of multiple neighboring wells is justified because the wells are screened in the same hydrostratigraphic unit, the distance between the wells was approximately 1 to 5 km, and the values of monitored parameters were in the same statistical range. Inclusion of both single well and closely spaced wells from the same hydrogeologic unit extended the temporal range of the monitoring investigations. Both single monitoring well and well-suite time series were approximated by polynomial trends of an order of more than two terms of equation.

Results

Water quality characteristics of the Quaternary Alluvial aquifer

The Quaternary Alluvial aquifer includes well locations from mainly the Mississippi Valley Alluvial aquifer as well as additional data points from alluvial aquifers associated with tributaries in the region (Figure 22). Most water-quality threats to regional municipal and industrial water supplies exist from surface or shallow ground water recharge to deeper aquifers (Graham, 1982; Parks, 1990; Parks et al., 1995; Kleiss et al., 2000; Gonthier, 2000; Gonthier, 2002); hence, water quality evaluation of the Quaternary Alluvial aquifer serves to better identify locations where such threats exist. Because few recent evaluations of water quality monitoring data in the Quaternary Alluvial aquifer exist we checked our assumption that aquifer data from different time periods were statistically the same and could be used to characterize regional geochemical properties of the aquifer complex. Changes in chloride (Cl^-) and electric conductivity (EC) over time are not significant, similar to results from other studies (Kresse and Clark, 2008). For Cl^-, variations are within several mg/L to 20 mg/L. EC variation falls between 0.1-0.2 mS/cm. In spite of high human impact in the central ME, time variations of Cl^- and EC are not significant and are characteristic of natural unperturbed water quality conditions in the aquifer. Because the aquifer data from different time periods can characterize regional geochemical properties (e.g., Moraru and Anderson, 2005), the compiled shallow ground water data from the Quaternary Alluvial aquifer were used for detailed analysis of regional water quality trends.

Ground water levels in the Quaternary Alluvial aquifer fluctuate over time. Statistical trends reveal that water levels are generally decreasing, with water level declines of 10 to 66 ft. Similar results have been observed from other studies in the Mississippi Alluvial aquifer (Reed, 2004; Arthur, 2001) and the shallow aquifer system (alluvial and fluvial-terrace deposits) in the Memphis metropolitan area (Parks, 1990). The average ground water level decline is approximately 33 ft, and such changes are characteristic only for specific regions within the central ME (i.e., near multiple wells used for irrigation). Nevertheless, such changes in water level and consequently in water storage do not appear to affect water quality drastically.

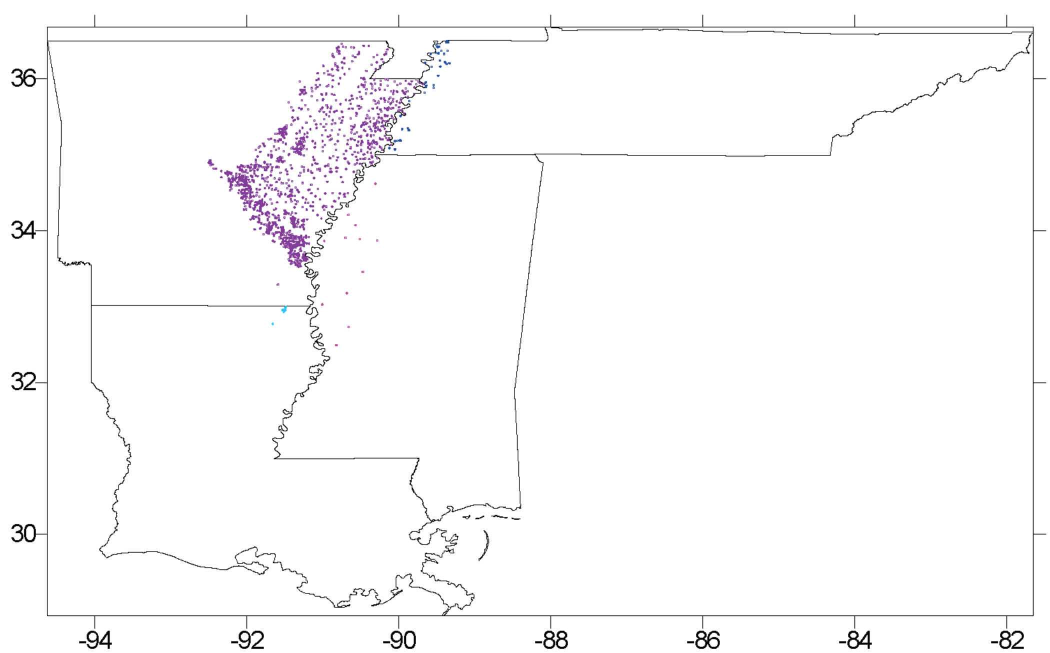


Figure 22. *Well locations in the Quaternary Alluvial aquifer.*

Analyses of descriptive statistics (Table 7) indicate that some of the data are non-normal. Normal sample distributions have similar values of mean, median, and mode, as well as skewness (coarse- or fine-tailing) of 0.0 and kurtosis (peakedness) of approximately 3. Deviations in mean and median from mode may result if many values near the detection limit are observed, as is the case for trace metal analysis. Deviations from normal distributions are also indicated by standard deviation values exceeding the mean values, dominance of positive skew, and kurtosis values much greater than 3. Therefore, for most of the parameters listed in Table 7 the statistical relevance of the mean values is low. In cases where values of the coefficient of variation are greater than or equal to 1.0, mean values are statistically most useful (i.e., K^+, Na^+, SO_4^{2-}, Cl^-, Al^{3+}, As(total), Fe(total), Mn^{2+}, NH_4^+, Ni^+, NO_3^- + NO_2^-, Pb^{2+}, and Zn^{2+}).

Table 7. Descriptive statistical parameters for ground water of the Quaternary Middle Mississippi Embayment (n.d. is non-detect).

Parameter, units	N	Minimum	Maximum	Mean	Std. Deviation	Coefficient of variation	Skewness	Kurtosis
K, mg/l	455	0.08	41	3.450	5.260	1.525	4.618	23.461
Na,mg/l	555	2	140	23.530	23.998	1.020	2.348	6.369
Ca, mg/l	562	0.3	153	62.606	35.422	0.566	0.191	-0.639
Mg,mg/l	569	0.1	84	19.773	12.467	0.630	1.115	2.759
HCO_3, mg/l	556	7	814	305.980	162.840	0.532	0.352	-0.074
SO_4, mg/l	549	0	130	18.288	23.648	1.293	2.365	5.960
Cl, mg/l	554	0.1	190	21.950	35.565	1.620	2.881	8.264
Ag,mg/l	185	0.001	0.003	0.001	0.000	0.175	9.168	90.190
Al,mg/l	109	0	1	0.110	0.218	1.981	2.379	5.111
As,mg/l	173	0.001	0.033	0.005	0.005	1.176	2.438	7.413
Ba,mg/l	144	0	1.3	0.319	0.265	0.832	1.288	1.535
Be,mg/l	76	0.001	0.002	0.001	0.000	0.376	0.991	-0.282
Cd,mg/l	134	0	0.008	0.002	0.002	0.896	1.967	3.729
Co,mg/l	60	0.001	0.015	0.004	0.004	0.880	0.962	-0.371
C org., mg/l	11	1	2	1.580	0.440	0.278	-0.015	-1.518
Cr,mg/l	143	0	0.01	0.005	0.004	0.738	0.362	-1.434
Cu,mg/l	128	0	0.01	0.004	0.004	0.975	0.476	-1.741
F,mg/l	312	0	1.1	0.190	0.135	0.710	2.207	10.776
Fe(II),mg/l	12	0.6	7.6	4.278	2.353	0.550	0.135	-1.145
Fe,mg/l	362	0	31	3.505	5.533	1.579	2.079	4.644
Mn,mg/l	219	0	4.3	0.736	0.781	1.061	1.953	4.831
Mo,mg/l	55	0.001	0.01	0.007	0.004	0.657	-0.454	-1.828
NH_4,mg/l	53	0.01	11	0.971	2.033	2.094	3.781	14.573
Ni,mg/l	53	0.001	0.023	0.005	0.006	1.083	1.29	0.597
NO_3+NO_2,mg/l	106	0	11	0.630	1.764	2.802	3.944	16.594
Pb,mg/l	85	0	0.02	0.003	0.004	1.643	2.519	6.216
Se,mg/l	107	0	0.006	0.001	0.001	0.815	3.532	19.071
Si,mg/l	333	2.4	51	25.902	9.043	0.349	-0.148	-0.542
U,mg/l	15	0.001	0.001	0.001	0.000	n.d.	n.d.	n.d.
Zn,mg/l	151	0	0.27	0.020	0.038	1.946	4.818	26.287
TDS,mg/l	553	41	948	337.270	169.701	0.503	0.961	1.241
pH	534	5.2	8.8	7.095	0.623	0.088	-0.146	0.084
NO_2,mg/l	59	0	0.07	0.016	0.013	0.835	2.068	5.074
O_2,mg/l	12	0.1	0.3	0.125	0.062	0.498	2.555	6.242
Temperature,C	515	11	27.2	17.639	2.160	0.122	1.427	4.494
Tritium,piC/l	26	1	32	10.230	9.705	0.949	1.001	-0.060
EC, uS/cm	537	7	1,620	539.440	289.417	0.537	0.883	1.274

Analysis of the correlation matrix for elements illustrates several geochemical associations. Characteristic correlations between TDS, EC, dissolved O_2, and most major cations and anions are observed. Sodium and chloride are strongly correlated, but show no correlations to other constituents. Calcium (Ca), magnesium (Mg), barium (Ba), and bicarbonate (HCO_3) are all positively correlated, suggesting a common source from dissolved carbonate minerals. Conversely, Cobalt (Co) and Molybdenum (Mo) are negatively correlated to Ca, Mg, Ba, and HCO_3, suggesting different affinities for these elements. Among the trace elements, correlations are commonly observed among the siderophile ("iron-loving") and chalcophile ("sulfide-loving") trace elements, such as chromium (Cr),copper (Cu), and cobalt (Co), lead (Pb), and selenium (Se). Strangely, all of these elements show either no correlation or a significant negative correlation to total iron (Fe) and ferrous iron (Fe^{2+}). The latter relationship may reflect the strong dependence of iron solubility on oxidation-reduction conditions rather than source relationships.

The Piper diagram and scatter plots (Figure 23) reveal key hydrochemical water types found in the Quaternary Alluvial aquifer and their relationship to water-rock interaction. Bicarbonate (HCO_3) is the dominant anion and Ca, Mg, and sodium (Na), respectively, are the most important cations (Figure 23A and B). Average anion and cation compositions of the individual hydrochemical water types are plotted versus TDS in Figures 23C and D. Both anions and cations show systematic changes with increasing TDS that are likely due to a combination of progressive water-rock interaction with the aquifer minerals and mixing of surface waters and shallow groundwater. The HCO_3^- water type is transformed with increasing TDS to HCO_3–SO_4, HCO_3–Cl–SO_4, HCO_3–Cl, SO_4–HCO_3 and Cl –HCO_3, in succession (Figure 23C). For example, bicarbonate water becomes HCO_3–SO_4 at TDS≈500 mg/L and Cl–HCO_3 at TDS≈900 mg/L. The cation values display large variations as well. Overall, calcium (Ca^{2+}) is the dominant cation at TDS $<$ 700 mg/L (Figure 23D). Calcium (Ca^{2+}) contents are roughly constant in waters with TDS≈700 mg/L, presumably due to buffering by calcium carbonate equilibrium. Above TDS≈700 mg/L sodium (Na^+) becomes dominant most likely due to influence of vertical recharge of saline fluids from underlying aquifers (Bryant et al., 1985; Kresse and Clark, 2008). Despite variations in calcium and sodium abundance, the molar Mg/Ca ratio ranges from 0.29 to 0.40, with an average of 0.34. This ratio is consistent with a combination of carbonate mineral sources, such as calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$).

Contour maps of aqueous species concentrations and TDS, EC and hydrochemical water type illustrate the spatial variations in water compositions. The bicarbonate water type is most common throughout the central Mississippi embayment, with subordinate regions of HCO_3-Cl and HCO_3-SO_4 water types along the Arkansas River valley (northern fine dashed line) as well as other locations along the margins of the Mississippi Alluvial valley (Figure 24). The TDS map shows the highest values along the traces of the Mississippi and Arkansas rivers as well as regions of intense groundwater pumping, such as in western-central Mississippi and eastern-central Arkansas (Figure 25). Low TDS values (<400 mg/L) are characteristic for elevated territories; high TDS values (>400 mg/L) are generally located in the river valleys (Mississippi, White, Arkansas and other rivers) and in the Memphis urban area. Although TDS values for stream waters are generally elevated above values in local recharge (Kresse and Clark, 2008), the hydrologic influence of the major streams (Mississippi, Arkansas, and White rivers) diminishes within a couple miles of the stream bank (Ackerman, 1996; Arthur, 2001). Also, high TDS is common for some irrigated regions, where pumping stresses may be inducing intrusion of deeper saline waters (Bryant et al., 1985). Neither water type nor TDS map distributions show relationships to the major structural features in the ME, suggesting little or no fault control of discharge. The maps for Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^- and Ba^{2+} all show similar characteristics to the water type and TDS maps; however, the map for Fe (Figure 26) shows generally low values within the center of the Mississippi Alluvial valley with higher

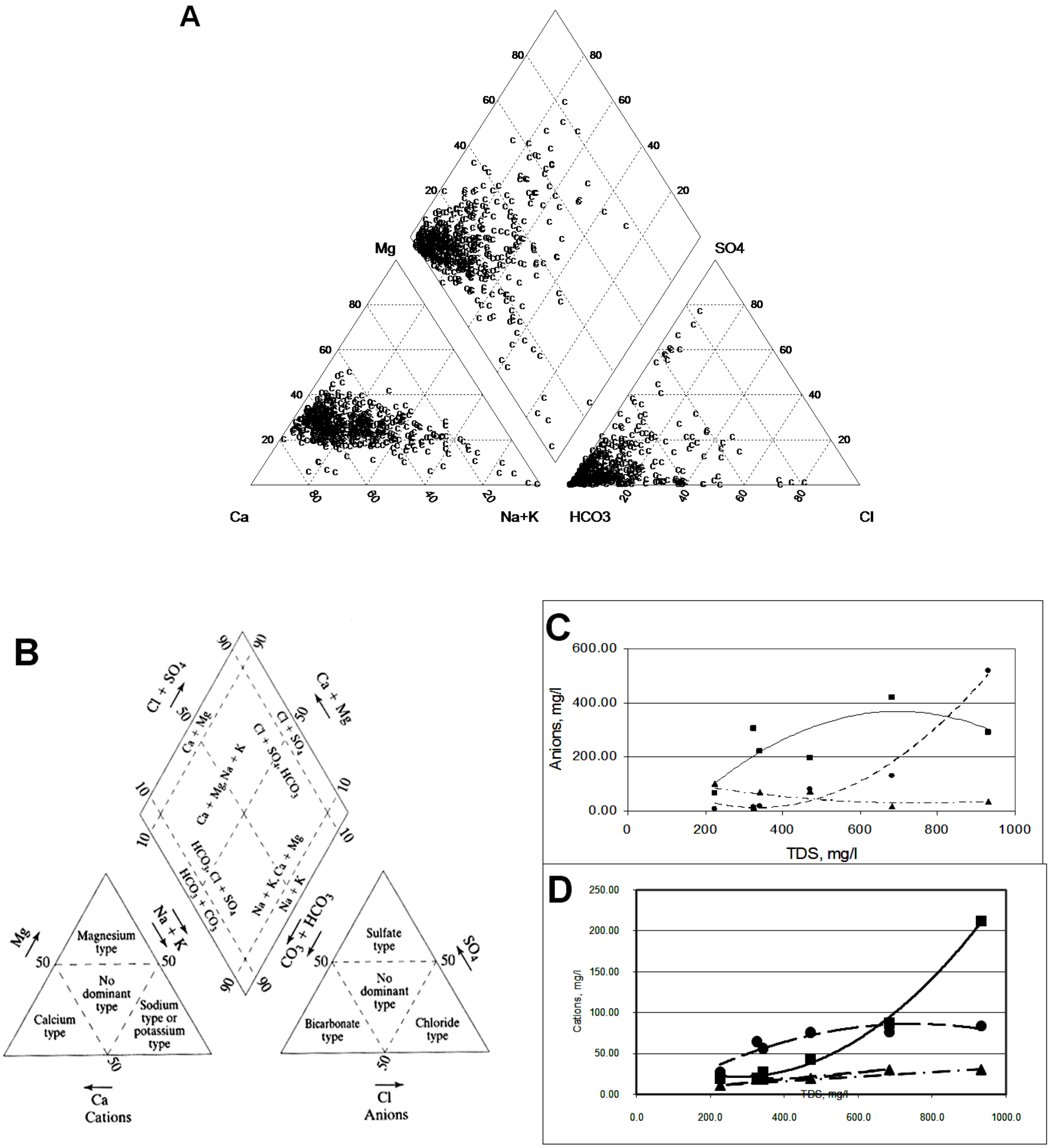


Figure 23. *A) Piper diagram for hydrochemical classification of water compositions in the Mississippi Alluvial aquifer. B) Classification of hydrochemical water types (from Kehew, 2001). Anion (C) and cation (D) contents versus total dissolved solids (TDS) shown with trend lines: (C) - dots and discontinuous line are Cl^-, squares and line are HCO_3^-, triangles and discontinuous line-dots are SO_4^{2-}; (D) dots and discontinuous line are Ca^{2+}, squares and line are Na^+, triangles and discontinuous line-dots are Mg^{2+}.*

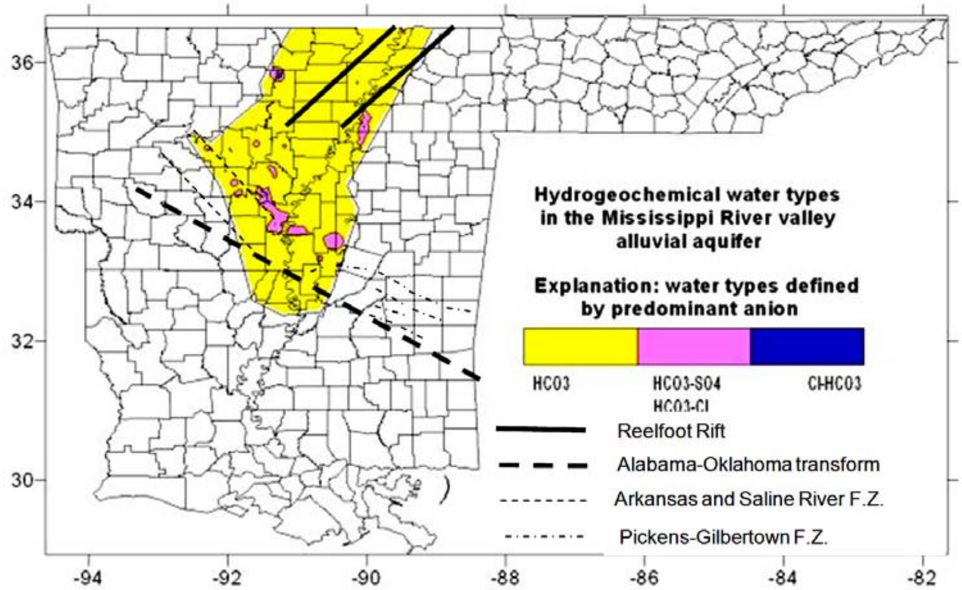


Figure 24. *Map showing distribution of hydrogeochemical water types in the Quaternary Alluvial aquifer, central Mississippi Embayment (county boundaries are shown). Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

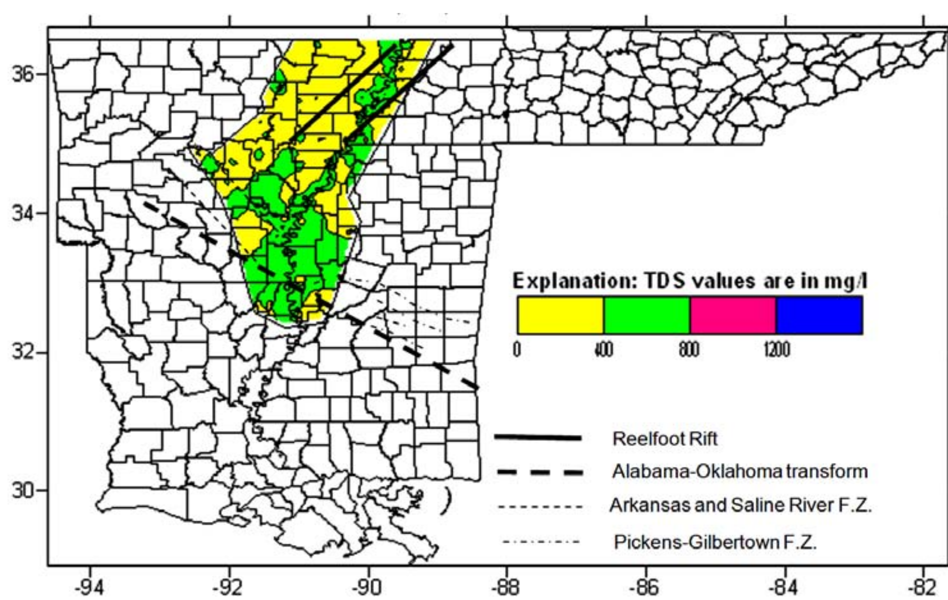


Figure 25. *Map showing TDS distribution, Quaternary Alluvial aquifer, central Mississippi Embayment (county boundaries are shown). Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

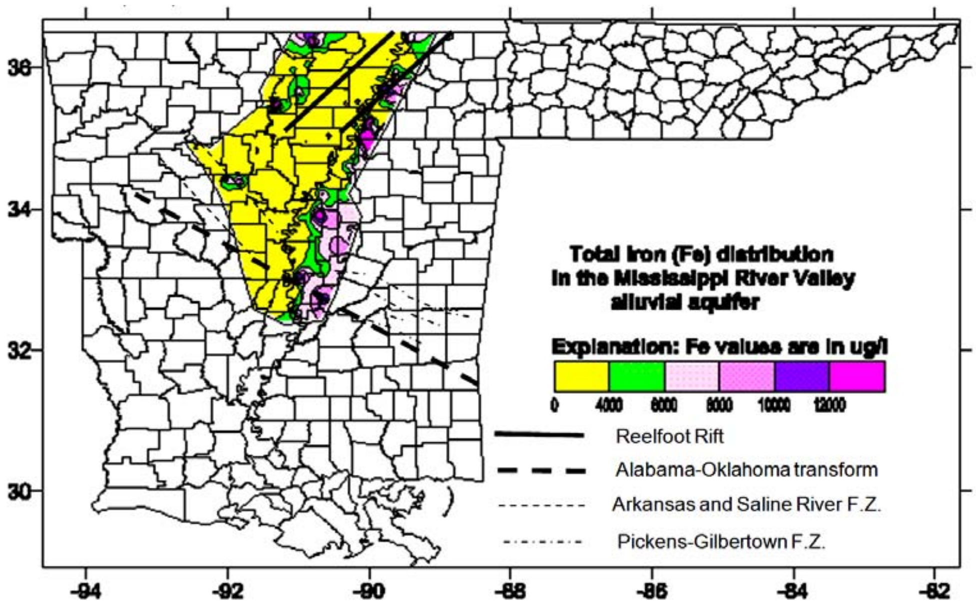


Figure 26. *Map showing the dissolved Fe distribution, Quaternary Alluvial aquifer, central Mississippi Embayment (county boundaries are shown). Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

concentrations mainly along the eastern margin and more erratic locations along the western margin. Thus, iron appears to be associated with recharge along the valley margins and likely oxidation-reduction gradients.

Geochemical associations were further evaluated using cluster and principal component analysis. Three clusters, or groups, were identified on the hierarchical dendrogram (Figure 27) and component analysis (Figure 28). The first group suggests that Fe(total) and Mn(total) have the same origin in shallow ground water, most likely dissolution of dispersed Fe-Mn minerals that were formed during geological deposition and post-depositional weathering reaction of Quaternary sediments in the region, especially along the margins of the Mississippi Alluvial valley. The second group combines SO_4^{2-}, K^+, Cl^- and Na^+. This geochemical association is based on the most soluble salts in ground water. The strong association of Na and Cl may have complex origins, ranging from migration of saline ground waters from depth (Bryant et al., 1985) to infiltration of evaporated irrigation and stream waters (Kresse and Clark, 2008). The third cluster aggregates pH, HCO_3^-, Ca^{2+}, Mg^{2+}, EC and TDS. HCO_3^-, Ca^{2+} and Mg^{2+} form one common sub-cluster because of their dependence on carbonate equilibrium and dissolution of carbonate minerals. TDS and EC functionally depend on each other as well and are shown to be strongly correlated in Mississippi Alluvial aquifer waters (Arthur, 2001). The pH is linked to this cluster as the geochemistry of Ca-Mg-HCO_3 is controlled by the values of hydrogen ion activity and P_{CO2} (e.g., Drever, 1997).

Water quality in the Quaternary Alluvial aquifer in the central ME limits the types of water use. Groundwater in the Alluvial Aquifer is used extensively for irrigation (Ackerman, 1996; Arthur, 2001) and much less for domestic water supplies. Although all salinity hazard categories are encountered in the Mississippi Alluvial Aquifer, the hazard is generally low or medium. The sodium hazard is nearly always low with only few isolated cases of medium and high values. In practice, municipal water use is generally limited due to high iron concentrations and hardness (sum of Ca and Mg). Analysis of the Fe map (Figure 26) shows that all studied regions have concentrations at or above the US EPA secondary drinking water standards maximum level (Fe = 0.3 mg/L). In addition,

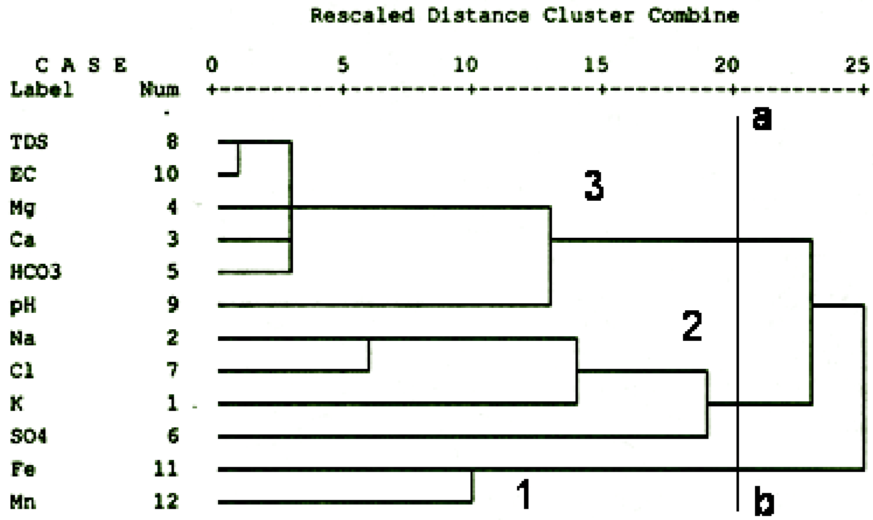


Figure 27. *Hierarchical dendrogram of the geochemical clusters for Quaternary Alluvial aquifer. Line a-b is the value of rescaled distance equal to 20, which mark clusters; 1, 2 and 3 are geochemical clusters shown in Figure 36.*

approximately 10% of the analyses have values that exceed US EPA primary drinking water standards for barium (Ba), fluoride (F^-), or nitrate (NO_3^-).

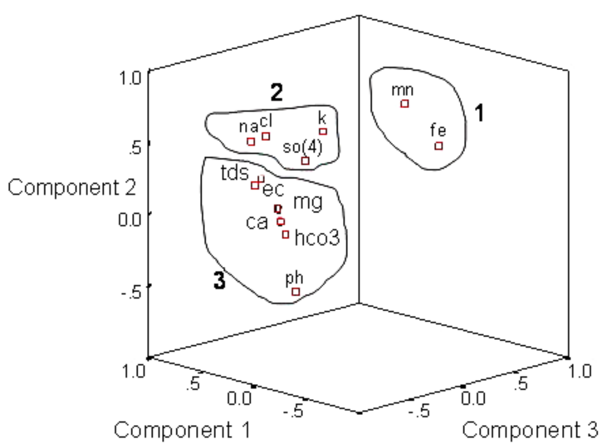


Figure 28. *Component plot of the factorial analysis, Quaternary Alluvial aquifer (ph is pH, hco3 – HCO_3^-, ca – Ca^{2+}, mg – Mg^{2+}, ec – EC, tds – TDS, so(4) – SO_4^{2-}, na – Na^+, cl – Cl^-, k – K^+, mn – Mn(total) and fe – Fe(total); 1, 2 and 3 are geochemical associations).*

Water quality characteristics of the Upper Claiborne aquifer

The Upper Claiborne aquifer comprises sand intervals within the Cockfield Formation and, to a lesser extent, adjacent sand intervals in the underlying Cook Mountain Formation (Hosman and Weiss, 1991). The aquifer is used most extensively in western Tennessee and in the south-central ME, as illustrated by the distribution of wells screened in the aquifer (Figure 29).

Time-plots of dissolved constituents in samples from groups of closely spaced wells screened in the Upper Claiborne aquifer show no consistent trends. Concentration variations from sampling event to event typically exceed the range of values observed in long-term trends. For example, Figure 30 shows trends in Ca^{2+} and TDS in individual and several groups of closely spaced wells. The values of Ca^{2+} commonly vary more between individual sampling events than the variations modeled by the polynomial trend lines.

Descriptive statistics for the analyses from the Upper Claiborne aquifer are given in Table 8. The values of the standard deviation are of similar magnitude or exceed the values of the mean, indicating most parameters have non-normal distributions. Almost all of the parameters are positively skewed, indicating the presence of a tail of larger (outlier) values. Only temperature, which has limited deviation, and pH, which is a log-transformed unit, show negative skew. Most of the data show kurtosis values between 0 and 5, indicating only moderate deviation from normal distributions; however, Cl, F, Mn, NO_3, and PO_4 all show much higher values of kurtosis associated with highly peaked distributions.

Correlation analysis shows that several parameters show significant correlations, beyond expected correlations with specific conductance, TDS, and major constituents (e.g., Ca and Mg, HCO_3 and pH, etc.). The most significant correlations exist amongst (1) sodium, bicarbonate, chlorine, boron, and fluorine, and (2) barium, calcium, magnesium, and bicarbonate. The first grouping appears to reflect a sea-water association, as all of these constituents are concentrated in sea water, whereas the second is most likely from a carbonate mineral source, similar to that described for the Quaternary Alluvial aquifer.

The Piper diagram in Figure 31A reveals several geochemical trends in water composition in the Upper Claiborne aquifer. In general, the upper diamond plot shows complete scatter, suggesting an absence of strong cation-anion associations. However, the trilinear cation (Figure 31A) plot shows a mixing trend between Ca-Mg waters with strongly Na+K waters. The ratio of Mg/Ca ranges from 0.1 to 1.5, with most values following a value of 0.6. The anion trilinear diagram (Figure 31A) and histogram (Figure 31B) illustrate that most waters are dominated by bicarbonate and sulfate with lesser amounts of chloride; however, a limited number of samples also is rich in chloride and bicarbonate with little or no sulfate. The association of chloride with more concentrated waters is illustrated in Figure 32, which further confirms the presence of a saline, alkaline component identified in the correlation analysis.

Trends in water chemistry are further clarified in the contour map distribution hydrochemical water types in Figure 33. The water type observed throughout most of the study area in the Upper Claiborne aquifer is bicarbonate (HCO_3), much like that observed in the Quaternary Alluvial aquifer. However, a northwest-southeast trending region of chloride- and sulfate-bearing bicarbonate waters follows the regional trend of the Oklahoma-Alabama transform fault (Thomas, 1991), which is a zone of tectonic weakness and prone to Quaternary seismicity (Cox et al., 2004; Cox et al., 2006). Furthermore, the chloride- and sulfate-bearing bicarbonate waters fall within two regional fault zones, the Saline and Arkansas River fault zones (Cox et al., 2006) in Arkansas and the Pickens-Gilbertown fault zones (Bicker, 1969) in Mississippi. No obvious recharge or discharge features in the Upper Claiborne aquifer in Arkansas correlate to the water quality changes (Schrader, 2008b). The southern margin of the Pickens-Gilbertown fault zone marks the northern extent of Jurassic salt domes in the Gulf Coast (Ewing, 1991); however, no salt domes are known to exist in the southeastern Arkansas area. Chloride- and sulfate-bearing bicarbonate waters are also observed in the south-central part of the ME and are likely related to fluid-flow associated with salt domes or up-dip flow from the Gulf Coast (Hanor and McIntosh, 2007, McIntosh et al., 2009).

The distribution of wells with high TDS waters (Figure 34) also follows the general trends identified in the hydrochemical water type diagram, especially for the wells in southeastern Arkansas. Lower TDS waters are generally in upland recharge areas, such as those in western Tennessee, south-central Arkansas, and central Mississippi. More localized regions of high TDS are observed in the Memphis area and central Arkansas where extensive pumping may be causing water quality changes. In contrast, the contour map of bicarbonate (HCO_3) values (Figure 35) shows overall increases in central Arkansas and in the southern part of the study area where saline Gulf Coast basin waters are migrating up-dip along aquifer units (Hanor and McIntosh, 2007). Thus, the higher TDS and chloride content waters north of the Gulf Coast basin appear to have a distinctive spatial association.

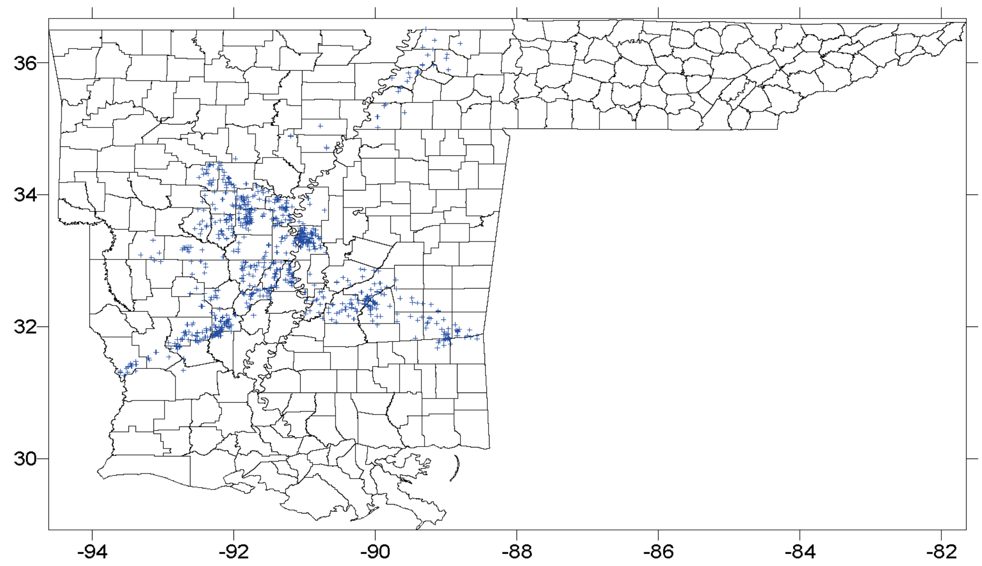


Figure 29. *Well locations in the upper Claiborne aquifer within the study area.*

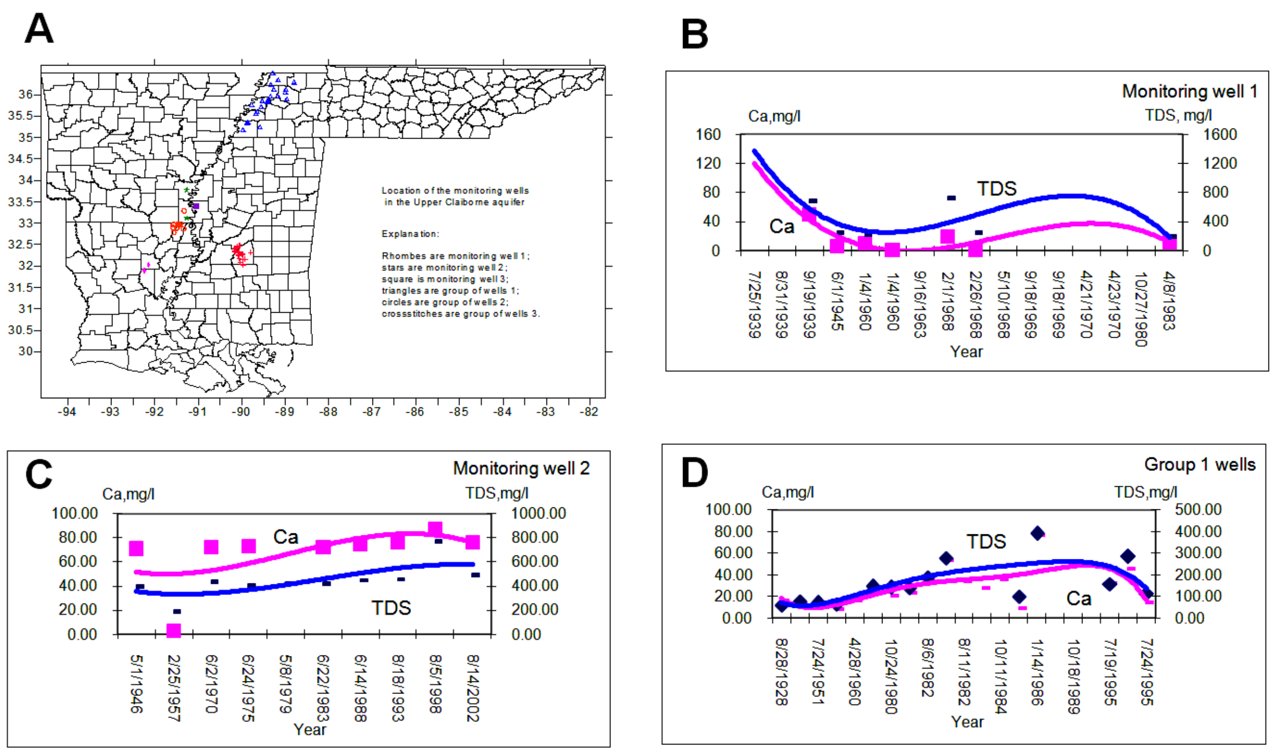


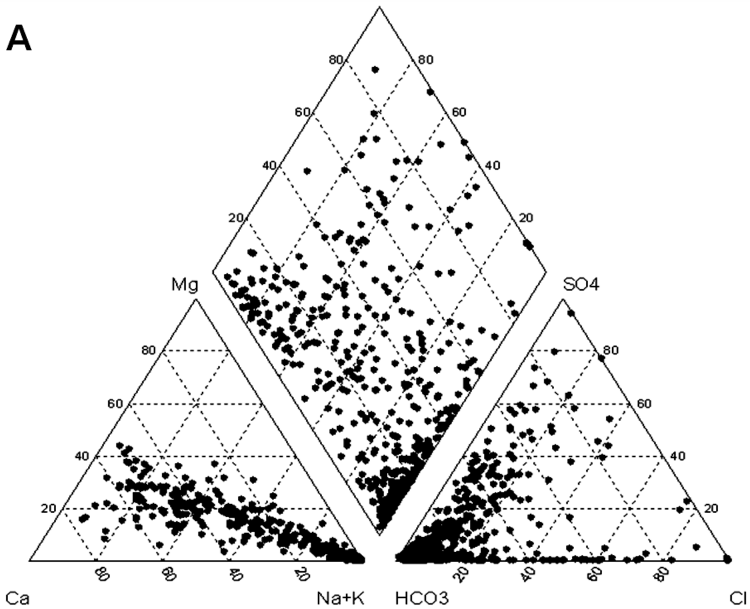
Figure 30. *A) Monitoring well and well group locations in Upper Claiborne aquifer. B) Ca^{2+} and TDS data from 1939 to 1983 for monitoring well 1. C) Ca^{2+} and TDS data from 1946 to 2002 for monitoring well 2. D) Ca^{2+} and TDS data from 1928 to 1995 for monitoring well group 1.*

Table 8. Descriptive statistical parameters for ground water of the Upper Claiborne aquifer in the central and northern Mississippi embayment

Parameter	N	Range	Minimum	Maximum	Mean	Standard Deviation	Variance	Skewness	Kurtosis	Anomaly
Al,ug/l	55	2700	0	2700	611	729.7	532465.89	1.36	1.01	> 2715
B,ug/l	51	2.39	0.01	2.4	0.49	0.56	0.32	1.54	2	> 2.9
Ba,ug/l	28	400	0	400	153.25	105.2	11066.64	0.8	0.21	> 560
Ca,mg/l	715	90	0	90	15.48	20.51	420.71	1.67	2.01	> 96
Cl,mg/l	1116	1099.8	0.2	1100	78.31	147.4	21727.43	3.62	14.71	> 1152
CO_2,mg/l	412	53	0	53	10.74	13.32	177.44	1.55	1.45	> 53
Cond., Us	908	3295	25	3320	741.01	564.94	319158.44	1.84	4.24	> 3360
F,mg/l	585	8.4	0	8.4	0.5	0.8	0.64	4.69	30.13	> 8.3
Fe,ug/l	494	3000	0	3000	446.3	671.94	451498.96	2.07	3.63	> 3000
HCO_3,mg/l	674	572	0	572	245.61	150.25	22575.5	0.17	-0.78	> 571
K,mg/l	616	10.9	0.1	11	2.97	2.01	4.04	1.41	2.36	> 11
Mg,mg/l	727	42	0	42	5.61	8.11	65.7	1.96	3.46	> 47
Mn,ug/l	208	1600	0	1600	114.1	175.72	30877.09	4.77	33.51	> 5577
Na,mg/l	677	785.9	1.1	787	122.86	111.77	12491.85	1.87	5.15	> 847
NO_3,mg/l	484	10	0	10	1.11	1.67	2.78	3.07	11.81	> 10
pH, units	824	6.2	2.9	9.1	7.55	0.97	0.93	-1.45	3.24	> 8.7
PO_4,mg/l	55	7.5	0	7.5	0.93	1.54	2.38	3.05	10.73	> 2.5
Si,mg/l	550	46	0	46	18.82	9.55	91.26	0.69	0.2	> 46
SO_4,mg/l	794	220	0	220	23.87	40.69	1655.37	2.7	7.94	> 220
TDS,mg/l	793	2053	27	2080	446.78	316.39	100101.53	1.91	4.55	> 2263
Temp.,Celsius	577	16	11	27	20.75	2.31	5.33	-0.26	1.1	> 27
Zn,ug/l	28	140	0	140	30.86	41.25	1701.68	1.57	1.35	> 164

Cluster and principal component analysis were used to independently verify water quality relationships identified through spatial and correlation analysis, and further explore geochemical processes. Hierarchical dendrogram and principal component analysis yield three geochemical associations (Figures 36 and 37), similar to those observed in the Mississippi Alluvial aquifer. However, association 1 shows linkage between NaCl, the carbonate system, temperature and TDS/Specific Conductance, suggesting contributions from a more alkaline, saline water source potentially at depth. This component likely integrates the spatially distinct high-TDS, chloride-rich waters identified in Figures 33 and 34. Potassium and sulfate appear to be associated as salt components, perhaps from specific recharge or Gulf Coast sources. Ca, Mg, Mn, and Fe are all associated, either from various carbonate minerals or a combination of carbonate minerals and redox processes affecting Mn and Fe oxides and hydroxides. No obvious spatial relationships are apparent among these quantities.

Water in the Upper Claiborne aquifer in the ME is generally of higher quality than that of the Quaternary Alluvial aquifer, except in regions where high-TDS, chloride- and sulfate-rich waters are observed (see Figures 33 and 34). Groundwater in the Upper Claiborne aquifer is used sparingly for industrial, municipal, and domestic supplies in western Tennessee (Parks and Carmichael, 1990b), but is used more extensively in Arkansas (Holland, 2007) and Mississippi (Wasson, 1980). All salinity and sodium hazard categories are encountered (Figure 38), with most samples low to high sodium hazard and medium to high salinity hazard. Approximately 2% of the analyses have values that exceed US EPA primary



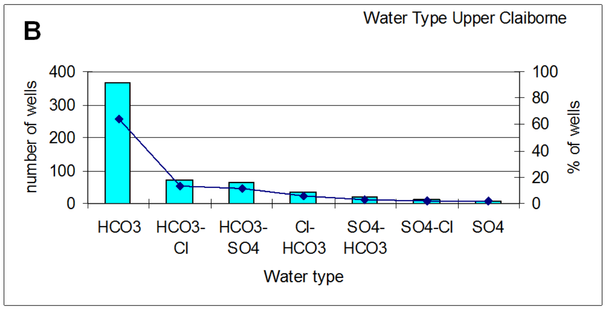


Figure 31. *A) Piper diagram for water chemistry data from the Upper Claiborne aquifer. See Figure 23B for classification fields. B) Total number (in bars) and percentage (points with line) of total samples with differing anion compositions in the Upper Claiborne aquifer.*

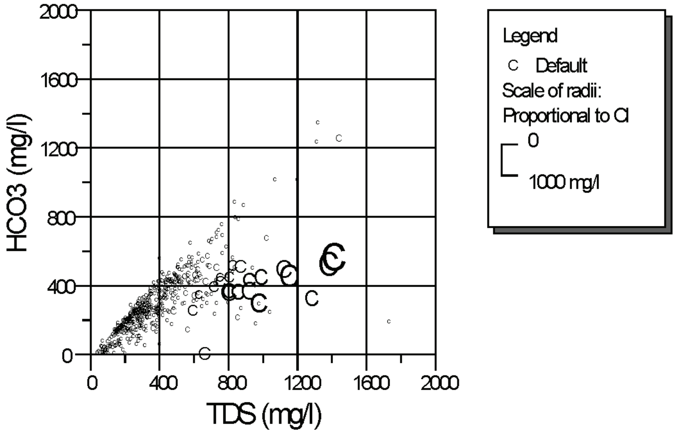


Figure 32. *Scatter plot of bicarbonate (HCO_3) versus total dissolved solids (TDS) data from the upper Claiborne aquifer. Symbol size is scaled to the concentration of chloride. Seven chloride-rich samples with TDS values greater than 1000 mg/L are excluded from the plot.*

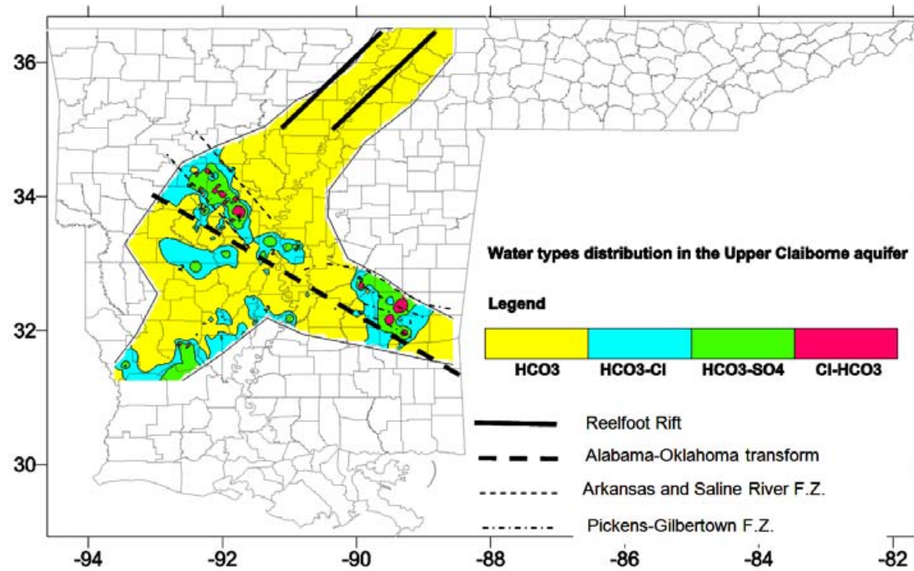


Figure 33. *Distribution of major water types in the Upper Claiborne aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

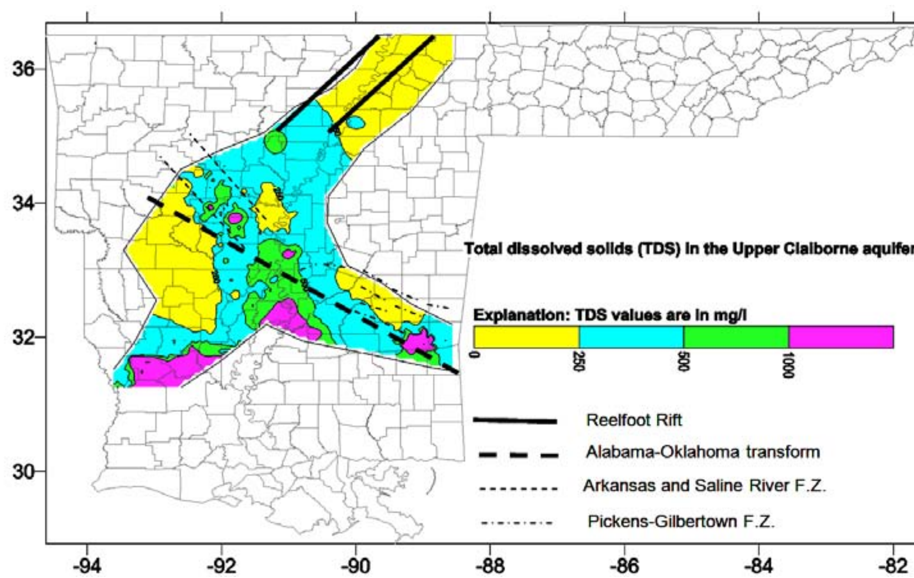


Figure 34. *Contour map of total dissolved solids (TDS) in the Upper Claiborne aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

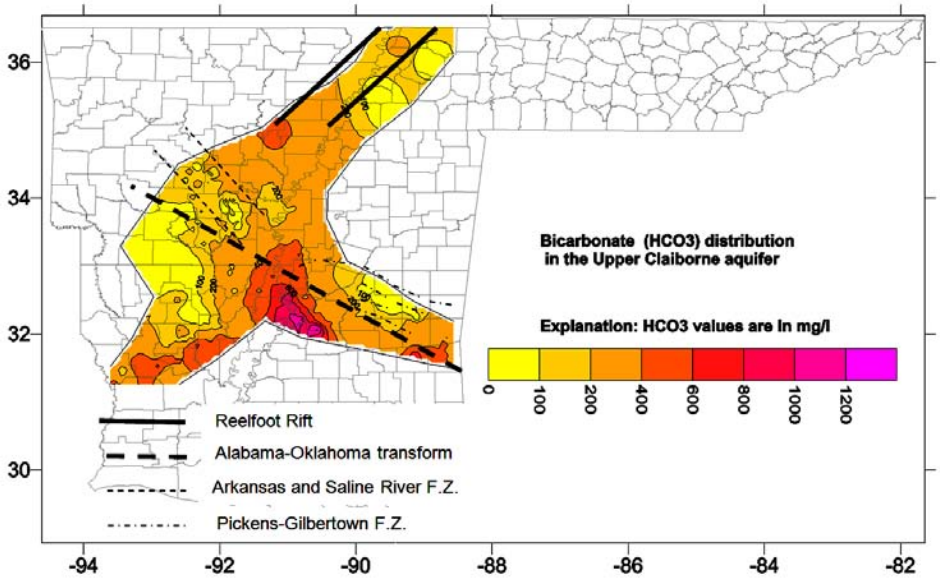


Figure 35. *Contour map of bicarbonate (HCO_3) in the Upper Claiborne aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

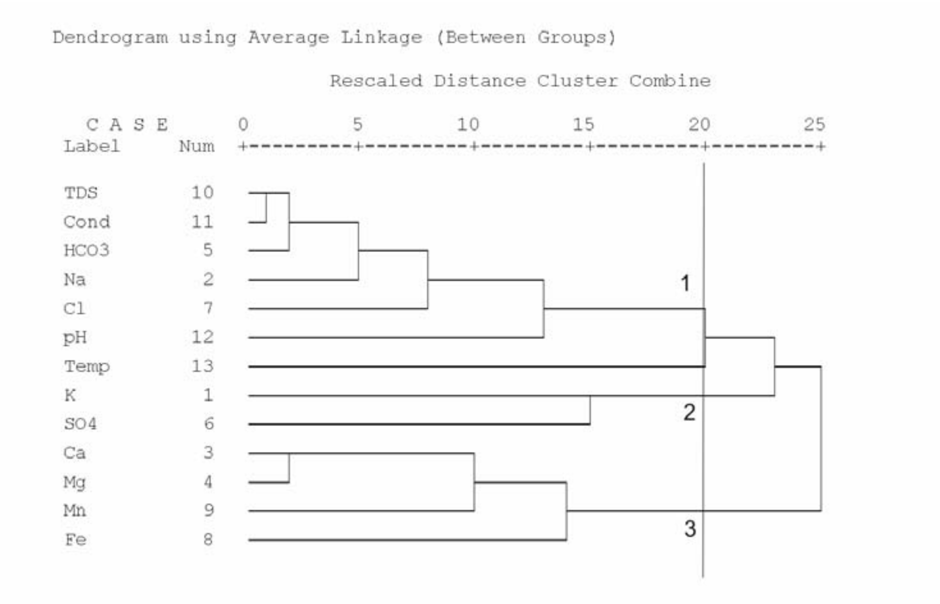


Figure 36. *Hierarchical dendrogram of the geochemical associations for Upper Claiborne aquifer. Line a-b is the value of rescaled distance equal to 20, which mark clusters; 1, 2 and 3 are geochemical clusters shown in Figure 37.*

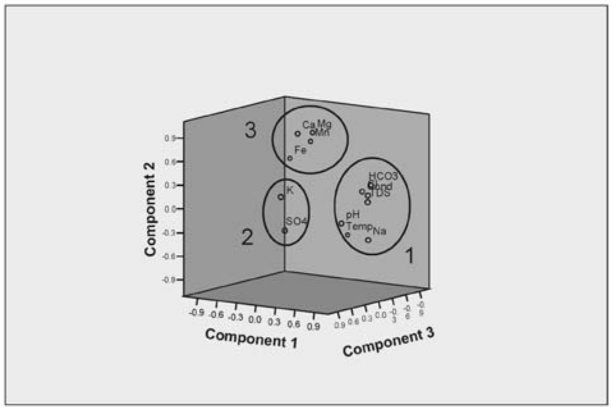


Figure 37. *Component plot of the factorial analysis Upper Claiborne aquifer (HCO3 – HCO_3^-, Ca – Ca^{2+}, Mg – Mg^{2+}, Cond –specific conductance, SO4 – SO_4^{2-}, Na – Na^+, Cl – Cl^-, K – K^+, Mn – Mn(total) and Fe – Fe(total); 1, 2 and 3 are geochemical associations).*

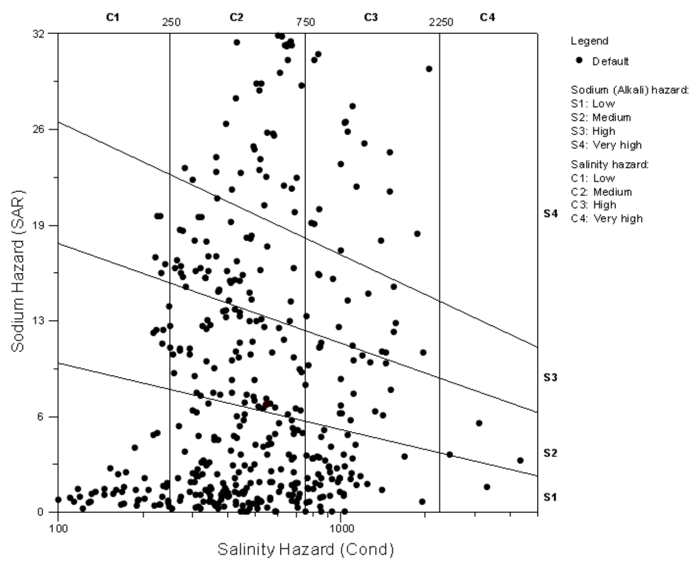


Figure 38. *Wilcox diagram illustrating degree of sodium and salinity hazards in the Upper Claiborne aquifer.*

drinking water standards for fluoride (F^-) or nitrate (NO_3^-). All studied regions have concentrations at or above the US EPA secondary drinking water standards maximum level for iron (Fe = 0.3 mg/L).

Water quality characteristics of the Middle Claiborne aquifer

The Middle Claiborne aquifer comprises sand intervals within the Sparta Sand in southeastern Arkansas, Kosciusko Sand in Mississippi, and Memphis Sand in northeastern Arkansas and western Tennessee (Hosman and Weiss, 1991). Because the Memphis Sand includes stratigraphic equivalents to both the middle and lower Claiborne aquifers (see section on Hydrostratigraphy), water quality assessment in Middle Claiborne aquifer is complicated by inclusion of multiple stratigraphic units that may or may not be hydrogeologically connected. Because the Memphis Sand is relatively shallow in the central and northern ME, water quality characteristics are likely to follow those of the middle rather than lower Claiborne interval. The aquifer is used extensively in western Tennessee and in the south-central ME, as illustrated by the distribution of wells screened in the aquifer (Figure 39).

Time-plots of dissolved constituents in samples from groups of closely spaced wells screened in the Middle Claiborne aquifer show no consistent trends. Concentration variations from sampling event to event typically exceed the range of values observed in long-term trends. For example, Figure 40A shows trends in Ca^{2+} and TDS in a well in Sparta aquifer in Arkansas (Figure 41). The values of both TDS and Ca^{2+} commonly vary more between individual sampling events than the variations modeled by the linear trend lines. Several studies in the Memphis area have demonstrated localized water quality changes in the upper Memphis aquifer (Parks and Mirecki, 1992; Parks et al., 1995; Larsen et al., 2003); however, these reports have investigated wells in the vicinity of either production well fields or waste disposal sites.

Descriptive statistics for the analyses from the Middle Claiborne aquifer are given in Table 9. The values of the standard deviation are of similar magnitude or exceed the values of the mean, indicating most parameters have non-normal distributions. Almost all of the parameters are positively skewed, indicating the presence of a tail of larger (outlier) values. High variance is commonly associated with large anomalous values. Only dissolved oxygen that has limited deviation, and pH that is a log-transformed unit show negative skew. Approximately half of the measured parameters show kurtosis values between 0 and 10, indicating only moderate deviation from normal distributions; however, Br, Cl, E.C., Fe, K, Mg, Mn, Na, NO_3, SO_4 and Sr all show much higher values of kurtosis associated with highly peaked distributions.

Correlation analysis shows that amongst the specific conductance, TDS, and major constituents the most prominent correlations are between pH, TDS, EC, Na, Cl and HCO_3. Of the minor and trace constituents, F, I, Br, and B show significant correlations to Na and/or K and Cl. Iodine also shows strong correlation to SO_4, Mn, Sr, and B. These correlations appear to reflect a sea-water association or that of alkaline brine derived from seawater.

The Piper diagram in Figure 42 reveals several geochemical trends in water composition

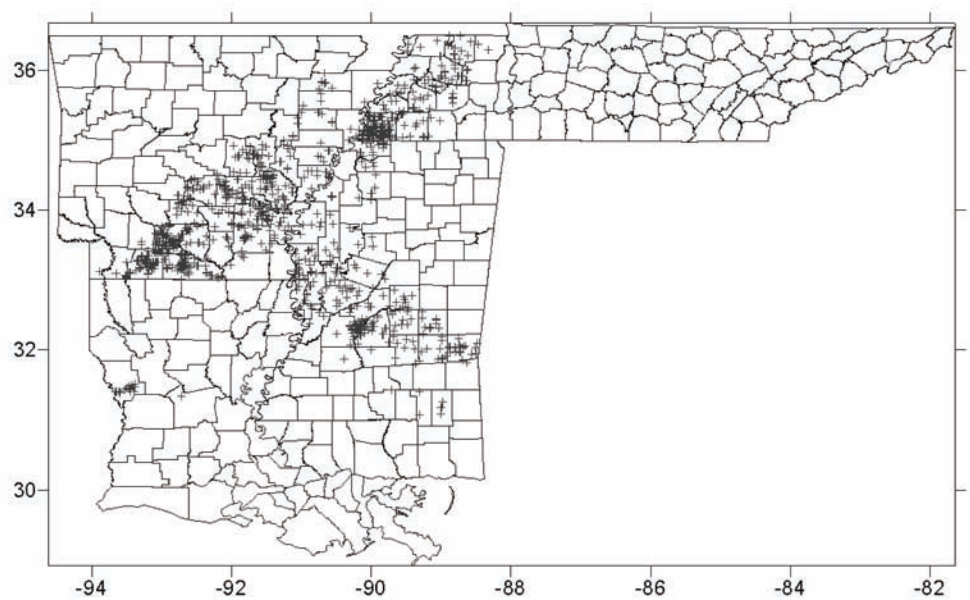
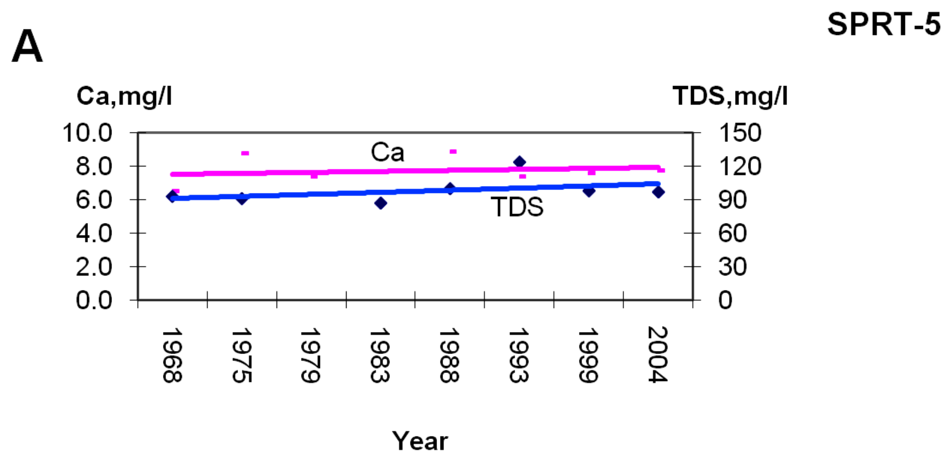


Figure 39. *Well locations in the Middle Claiborne aquifer within the study area.*



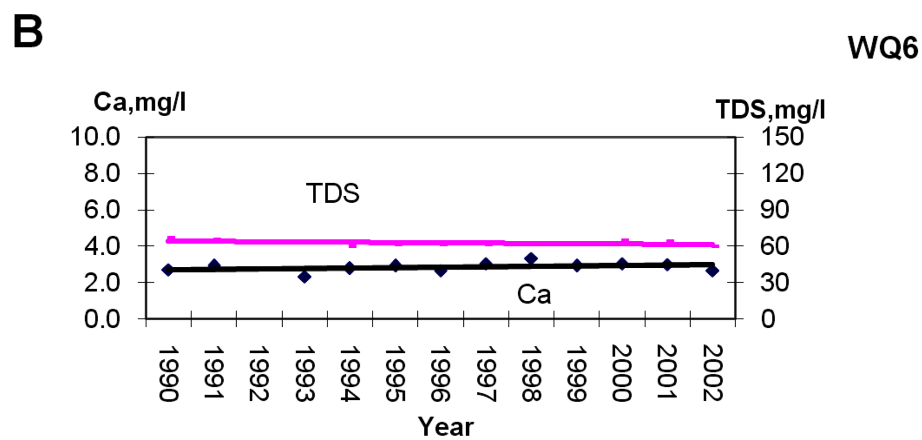


Figure 40. *A) Ca^{2+} and TDS data from 1968 to 2004 for monitoring well 1304 (Figure 41) in the Sparta Sand. B) Ca^{2+} and TDS data from 1990 to 2002 for monitoring well Sh:K-66 in the upper Memphis Sand.*

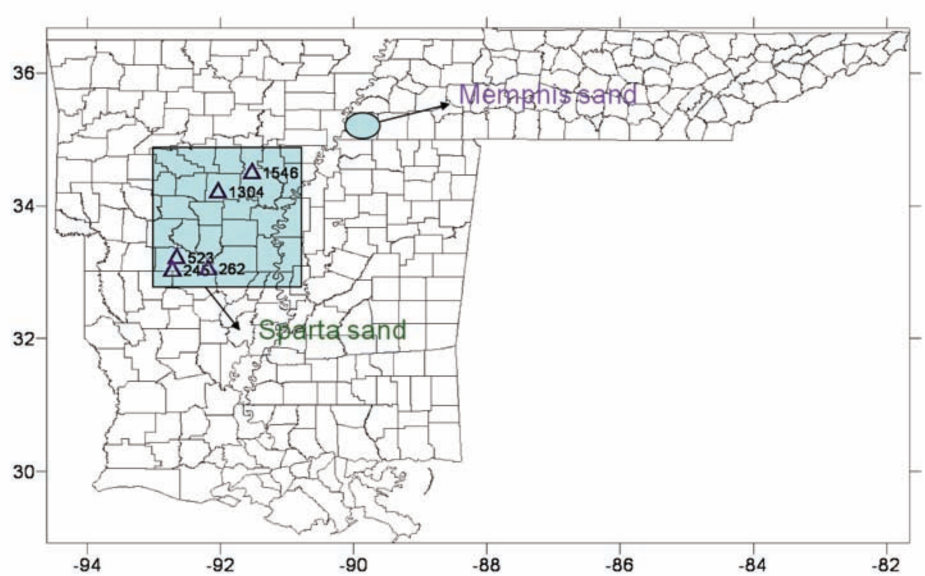


Figure 41. *Locations of monitoring wells in the Middle Claiborne aquifer used for time-series plots of water quality.*

Table 9. Descriptive statistical parameters for ground water of the Middle Claiborne aquifer in the central and northern Mississippi embayment.

Parameter	N	Range	Minimum	Maximum	Mean	Standard Deviation	Variance	Skewness	Kurtosis	Anomaly
Al,ug/l	305	4	0	4	0.3	0.71	0.5	2.83	8.35	>4
B,ug/l	94	4	0	4	0.27	0.83	0.69	3.13	8.71	>4
Ba,ug/l	376									n.d.
Br,mg/l	77	8	0	8	0.16	0.93	0.87	8.07	68.12	>8
Ca,mg/l	1093	87	0	87	12.389	14.13	199.77	2.19	5.36	>100
Cl,mg/l	1087	860	0	860	16.623	62.32	3883.32	8.96	94.28	>1000
CO_2,mg/l	330	97	0	97	11.15	15.11	228.28	2.4	6.59	>100
E.C.,uS/cm	1030	3713	7	3720	299.21	345.45	119338.62	4.68	32.81	>4000
F,mg/l	924	0.9	0	0.9	0.151	0.14	0.02	2.4	7.68	>1
Fe,ug/l	752	27	0	27	1.09	2.31	5.35	4.11	26.64	>30
HCO_3,mg/l	1097	838	0	838	152.48	131.8	17370.8	1.56	2.69	>850
I,mg/l	34	8	0	8	0.85	2.27	5.16	2.68	5.94	>8
K,mg/l	1033	29.9	0.1	30	2.232	2.58	6.66	4.06	27.78	>30
Mg,mg/l	1092	84	0	84	4.554	5.71	32.61	3.94	36.56	>100
Mn,ug/l	526	2	0	2	0.01	0.12	0.01	13.55	201.17	>2
Na,mg/l	1088	774	1	775	48.73	78.65	6185.76	3.82	21.85	>1000
NO_3,mg/l	349	17	0	17	0.97	1.88	3.54	5.48	37.54	>20
O_2,mg/l	71	7	0	7	1.99	2.13	4.53	0.71	-0.86	>7
pH	1041	5	4	9	7.03	0.99	0.98	0.34	-0.91	>9
Si,mg/l	1007	72	0	72	15.65	8.98	80.59	2.63	9.31	>100
SO_4,mg/l	1079	93	0	93	5.92	8.35	69.74	4.99	36.43	>100
Sr,mg/l	217	3	0	3	0.1	0.38	0.15	4.48	22.94	>3
TDS,mg/l	990	984	16	1000	168.96	144.23	20801.73	1.99	5.14	>1000
Temp.,Celsius	918	32	6	38	20.17	4.1	16.83	1.52	2.49	>38
Zn,ug/l	255									n.d.
Remark: n.d. - no data										

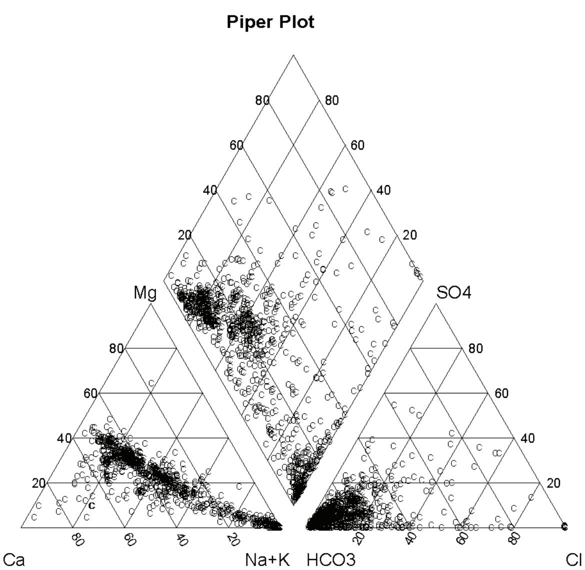


Figure 42. *Piper diagram for water chemistry data from the Middle Claiborne aquifer. See Figure 12B for classification fields.*

in the Middle Claiborne aquifer. The upper diamond plot shows that most of the waters are bicarbonate-rich with either Ca+Mg or Na + K cation compositions; however a variety of other water types are present as well. The trilinear cation (Figure 31A) plot shows a mixing trend between Ca-Mg waters with strongly Na+K waters. The ratio of Mg/Ca ranges from 0.1 to 5.6, with mean value of 0.6. The anion trilinear diagram illustrates that most waters are dominated by bicarbonate and chloride with lesser amounts of sulfate. Figure 43 shows that most data follow a linear correlation of increasing TDS with increasing bicarbonate; however, a highest TDS waters are rich in chloride similar to that observed in the Upper Claiborne aquifer. The association of chloride with more concentrated waters illustrated in Figure 43, confirms the presence of a saline, alkaline component identified in the correlation analysis.

The contour map distribution of hydrochemical water types (Figure 44) shows that bicarbonate waters in the Middle Claiborne aquifer dominate throughout the study area. The distribution of HCO_3-Cl and HCO_3-SO_4 waters is erratic and does not follow tectonic features (Figure 44), recharge, or discharge (cones of depression) patterns (Figure 45) (Schrader, 2008a). The contour map distribution of TDS values (Figure 46) shows that the highest concentrations are toward the center and southern part of the ME, with more dilute waters entering from recharge areas in south-central Arkansas, central Mississippi, northernmost Mississippi, and western Tennessee. The contour maps for sodium, chloride, and bicarbonate show distributions similar to that of the TDS map. The contour map distribution of calcium values (Figure 47) shows the highest values in the northern central ME and around the margins. Although this might result from relationship to bicarbonate and the precipitation of calcium carbonate, a similar map pattern is observed for iron, potassium, and magnesium as well. This pattern suggests distinct spatial distributions of sodium-rich versus calcium-, magnesium-, iron- and potassium-bearing waters.

Cluster and principal component analysis were used to independently verify water quality relationships identified through spatial and correlation analysis, and further explore geochemical processes. Hierarchical

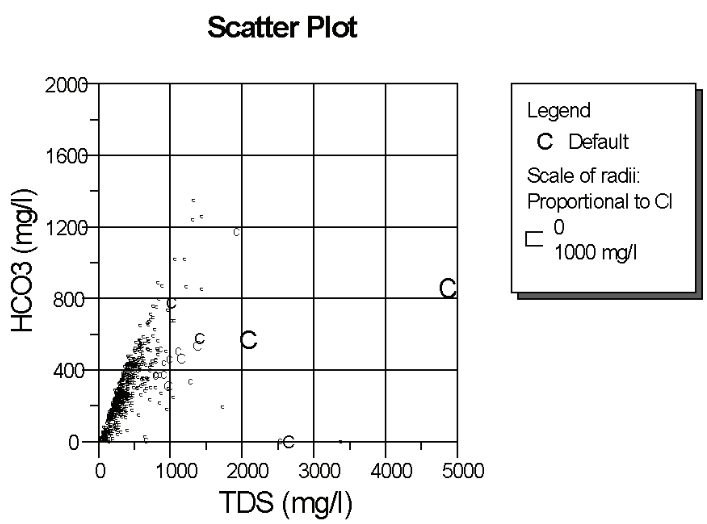


Figure 43. *Scatter plot of bicarbonate (HCO_3) versus total dissolved solids (TDS) data from the Middle Claiborne aquifer. Symbol size is scaled to the concentration of chloride. Eleven chloride-rich samples with TDS values greater than 1000 mg/L are excluded from the plot.*

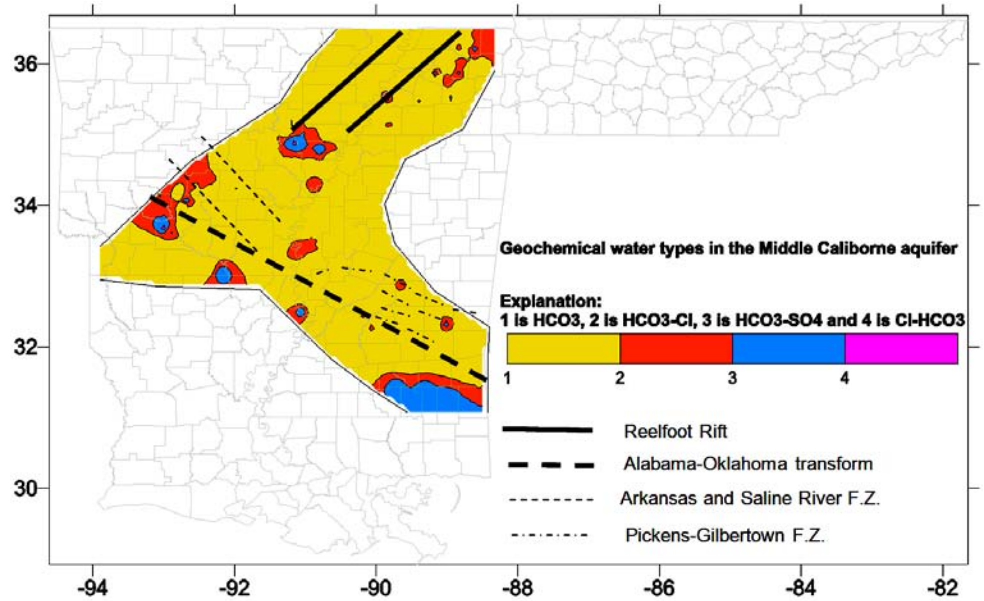


Figure 44. *Distribution of major water types in the Middle Claiborne aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

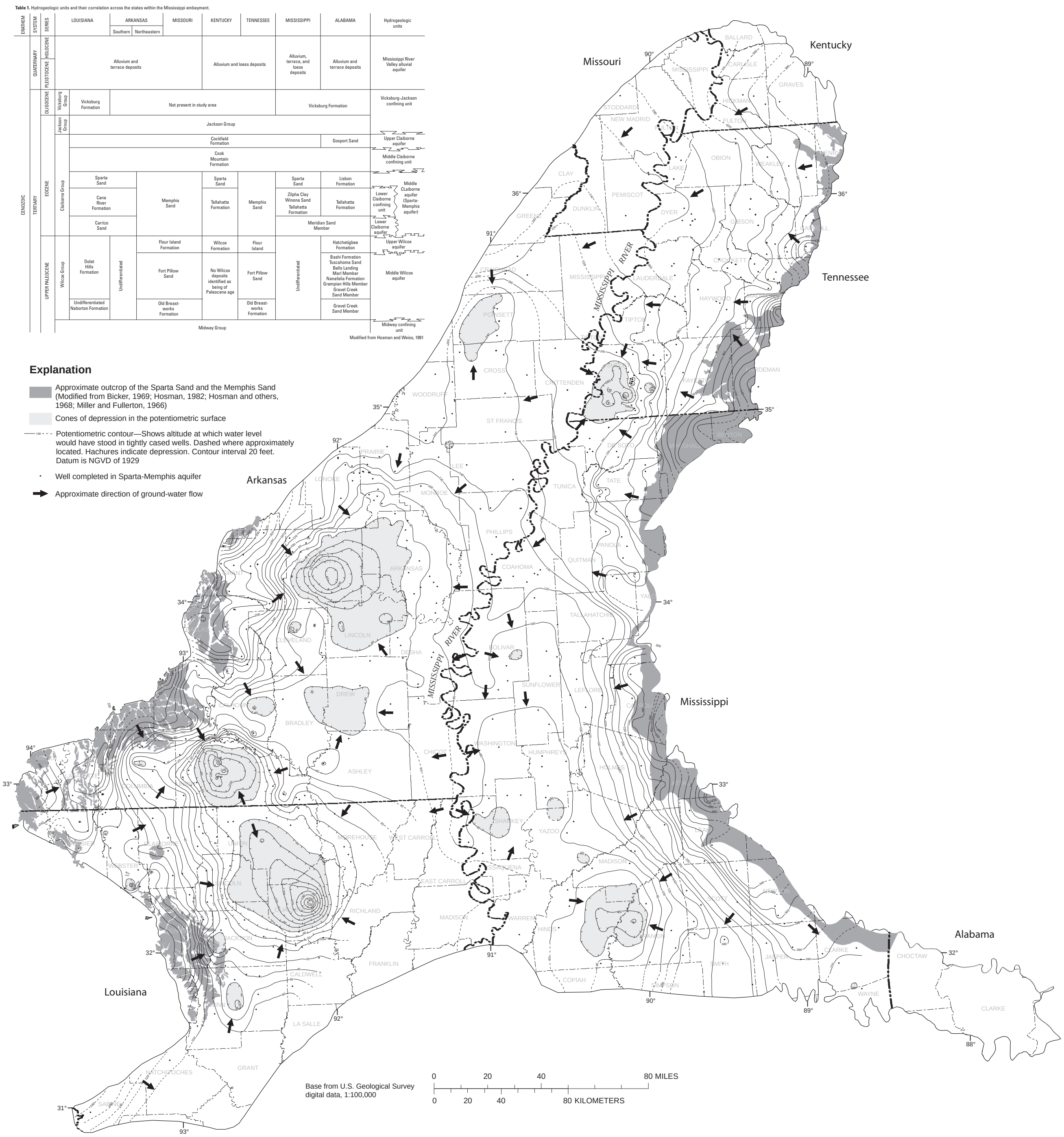


Table 1. Hydrogeologic units and their correlation across the states within the Mississippi embayment.

ERATHEM	SYSTEM	SERIES		LOUISIANA	ARKANSAS Southern	ARKANSAS Northeastern	MISSOURI	KENTUCKY	TENNESSEE	MISSISSIPPI	ALABAMA	Hydrogeologic units
CENOZOIC	QUATERNARY	HOLOCENE / PLEISTOCENE		Alluvium and terrace deposits				Alluvium and loess deposits		Alluvium, terrace, and loess deposits	Alluvium and terrace deposits	Mississippi River Valley alluvial aquifer
	TERTIARY	OLIGOCENE	Vicksburg Group	Vicksburg Formation	Not present in study area					Vicksburg Formation		Vicksburg-Jackson confining unit
		EOCENE	Jackson Group	Jackson Group								
			Claiborne Group	Cockfield Formation							Gosport Sand	Upper Claiborne aquifer
				Cook Mountain Formation								Middle Claiborne confining unit
				Sparta Sand		Memphis Sand		Sparta Sand	Memphis Sand	Sparta Sand	Lisbon Formation	Middle CLaiborne aquifer (Sparta-Memphis aquifer)
				Cane River Formation				Tallahatta Formation		Zilpha Clay Winona Sand Tallahatta Formation	Tallahatta Formation	Lower Claiborne confining unit
				Carrizo Sand						Meridian Sand Member		Lower Claiborne aquifer
		UPPER PALEOCENE	Wilcox Group	Dolet Hills Formation	Undifferentiated	Flour Island Formation		Wilcox Formation	Flour Island	Undifferentiated	Hatchetigbee Formation	Upper Wilcox aquifer
						Fort Pillow Sand		No Wilcox deposits identified as being of Paleocene age	Fort Pillow Sand		Bashi Formation Tuscahoma Sand Bells Landing Marl Member Nanafalia Formation Grampian Hills Member Gravel Creek Sand Member	Middle Wilcox aquifer
				Undifferentiated Naborton Formation		Old Breast-works Formation			Old Breast-works Formation		Gravel Creek Sand Member	
				Midway Group								Midway confining unit

Modified from Hosman and Weiss, 1991

Figure 45. *Potentiometric surface of the Middle Claiborne (Memphis-Sparta) aquifer in the Mississippi embayment (Schrader, 2008a).*

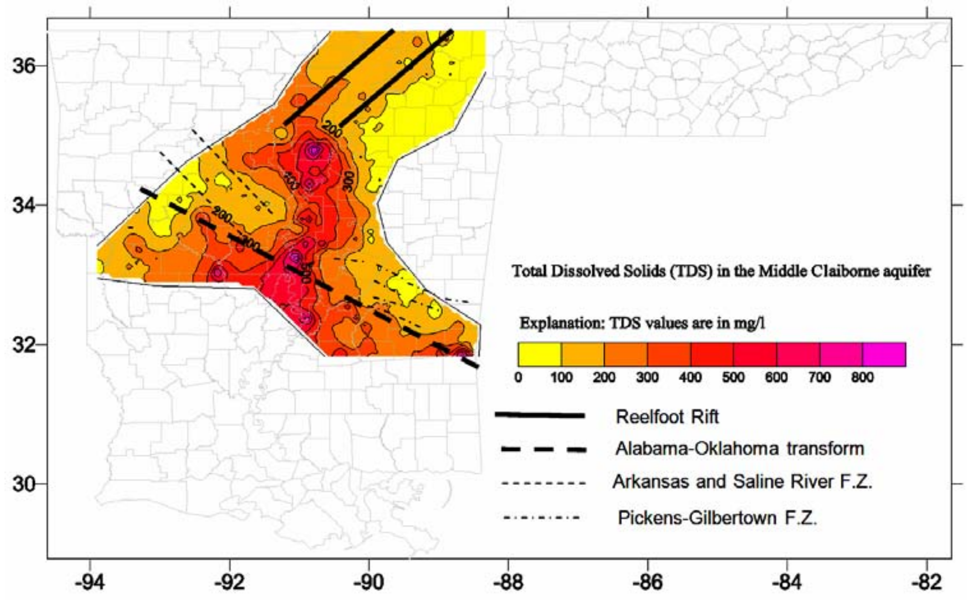


Figure 46. *Distribution of TDS values in the Middle Claiborne aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

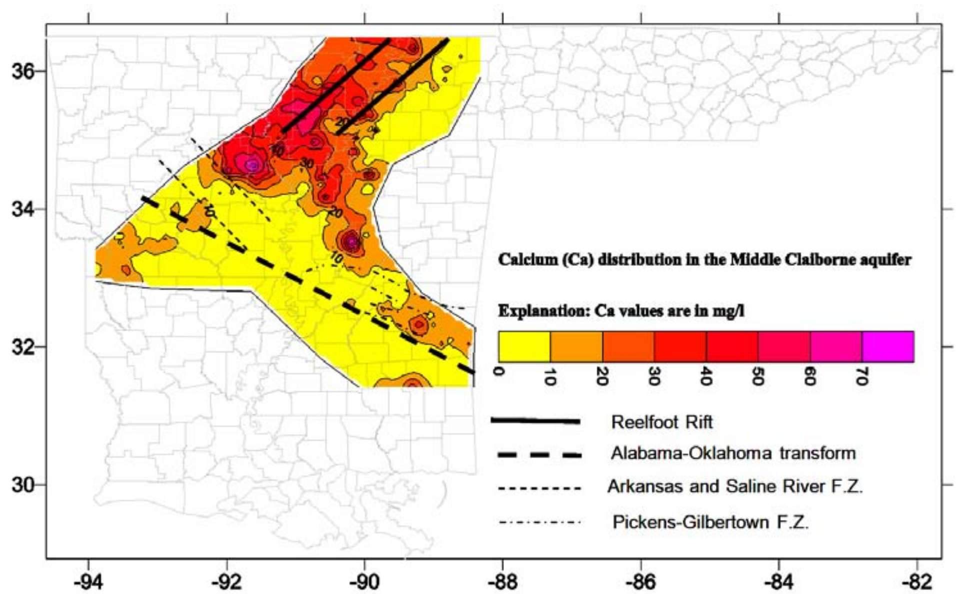


Figure 47. *Distribution of Ca values in the Middle Claiborne aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

dendrogram (Figure 48) and principal component analysis yield two geochemical associations. Association 1 shows linkage between NaCl, HCO_3, temperature and TDS/Specific Conductance, suggesting contributions from an alkaline, saline water source potentially at depth. This component is very similar to that identified in the Upper Claiborne aquifer, but appears to have a more focused distribution in central and ME. Association 2 includes Ca, Mg, Fe, and K, which is also spatially distinct (e.g., Figure 47). Association 2 appears to have some relationship to recharge sources, either directly in the outcrop area (e.g., central Mississippi) or in the subcrop region beneath the Mississippi River Valley alluvium in the northern ME. Because the Middle Claiborne aquifer consists of the entire lower to middle Claiborne interval (i.e., Memphis Sand) north the 35° latitude but only the Sparta interval to the south, it is unclear whether Association 2 represents a hydrochemical signature from two distinct stratigraphic intervals.

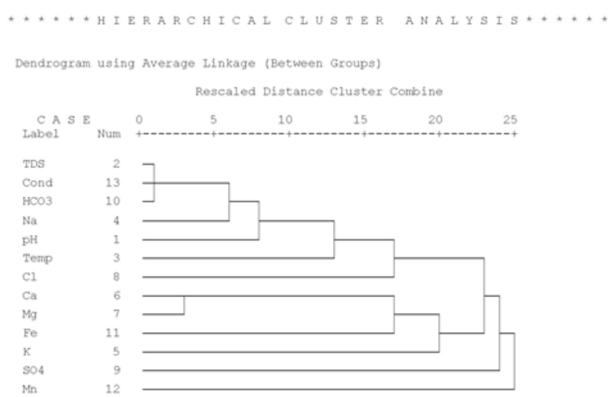


Figure 48. *Hierarchical dendrogram of the geochemical clusters for the Middle Claiborne aquifer.*

Water in the Middle Claiborne aquifer in the ME is generally of high quality, except in regions where high-TDS, sodium-chloride waters are observed (see Figure 46). Groundwater in the Middle Claiborne aquifer is used extensively for industrial, municipal, and domestic supplies in western Tennessee (Parks and Carmichael, 1990a), Arkansas (Holland, 2007) and Mississippi (Wasson, 1986). All sodium hazard categories are encountered (Figure 49), but the samples are dominantly in the low to medium salinity hazard categories. Approximately 2% of the analyses have values that exceed US EPA primary drinking water standards for fluoride (F^-) or nitrate (NO_3^-). All studied regions have concentrations at or above the US EPA secondary drinking water standards maximum level for iron (Fe = 0.3 mg/L), although the highest levels of iron are observed in the northern ME.

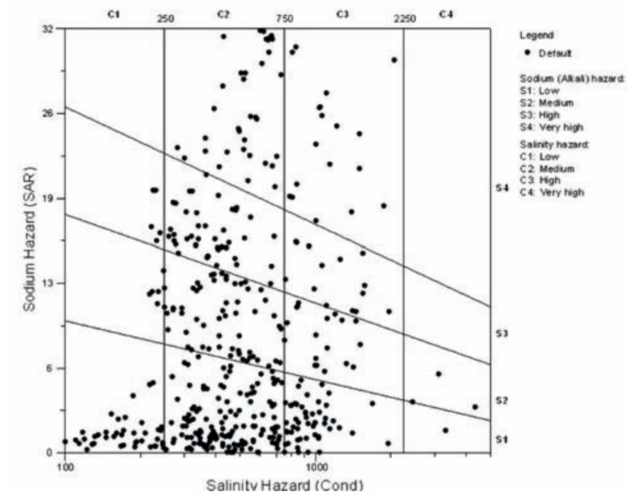


Figure 49. *Wilcox diagram illustrating degree of sodium and salinity hazards in the Middle Claiborne aquifer.*

Water quality characteristics of the Lower Claiborne-Wilcox Aquifer

The Lower Claiborne-Wilcox aquifer comprises sand intervals within the Wilcox Formation and Carrizo Sand in southeastern Arkansas, Nanafalia, Tuscahoma, and Hatchetigbee formations and Meridian Sand in Mississippi, and Fort Pillow Sand in northeastern Arkansas and western Tennessee (Hosman and Weiss, 1991). Because this aquifer interval includes several stratigraphic units that may or may not be hydrologically connected, inferences based on hydrochemical data may be limited. As indicated by the map distribution of wells, the aquifer is used extensively in northern and central Mississippi and northwestern Louisiana and to a lesser extent in western Tennessee and Arkansas (Figure 50).

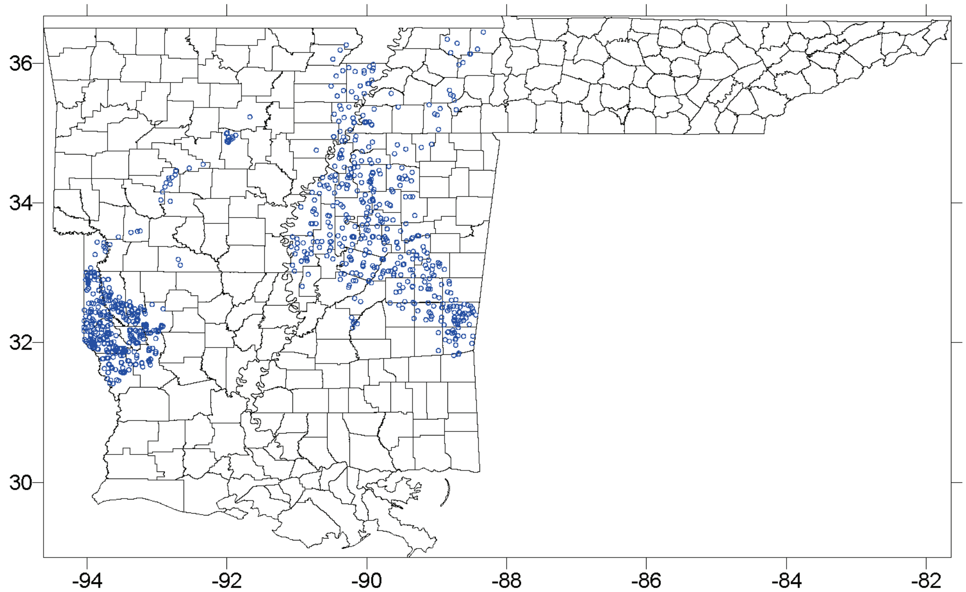


Figure 50. *Well locations in the Lower Claiborne-Wilcox aquifer within the study area.*

Time-plots of dissolved constituents in samples from groups of closely spaced wells screened in the Middle Claiborne aquifer show no consistent trends. Concentration variations from sampling event to event typically exceed the range of values observed in long-term trends. For example, TDS values vary more between individual sampling events than the variations modeled by the linear trend lines (Figure 51).

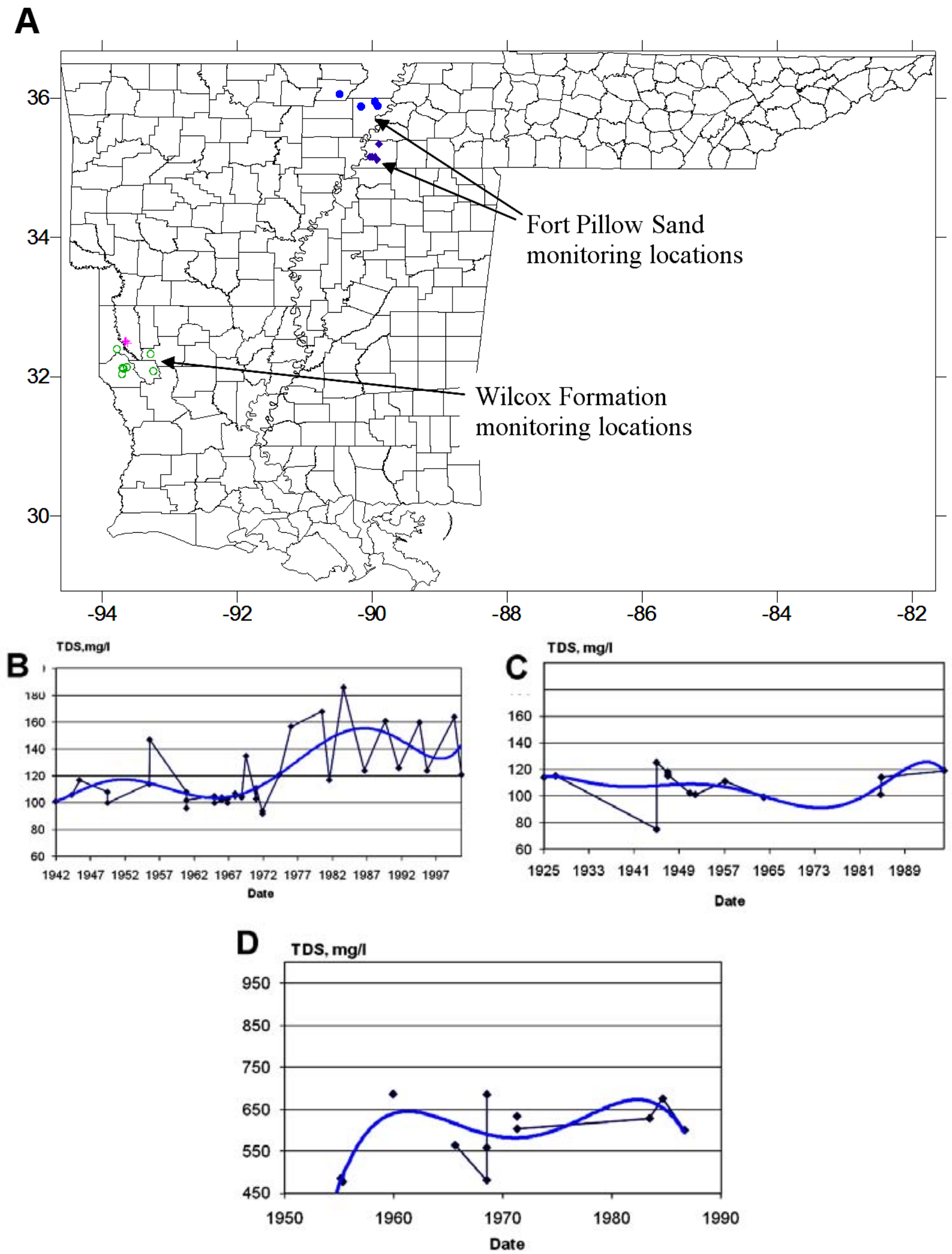


Figure 51. *A) Monitoring well group locations in Lower Claiborne-Wilcox aquifer. B) TDS data from 1942 to 2001 for Arkansas (Fort Pillow Sand) monitoring locations. C) TDS data from 1925 to 1996 for Tennessee (Fort Pillow Sand) monitoring well locations. D) TDS data from 1941 to 1984 for Louisiana (green square symbols) Wilcox Formation monitoring wells.*

Descriptive statistics for the analyses from the Lower Claiborne-Wilcox aquifer are given in Table 10. The values of the standard deviation are of similar magnitude or exceed the values of the mean, indicating most parameters have non-normal distributions. Almost all of the parameters are positively skewed, indicating the presence of a tail of larger (outlier) values. High variance is commonly associated with large anomalous values. Only pH, which is a log-transformed unit, shows negative skew. Two-fifths of the measured parameters show kurtosis values between 0 and 10, indicating only moderate deviation from normal distributions; however, Ba, Br, Ca, Cl, CO_2, F, I, K, Mg, Mn, NO_3, SO_4 Sr, Temperature, and Zn all show much higher values of kurtosis associated with highly peaked distributions.

Table 10. Descriptive statistical parameters for ground water of the Lower Claiborne-Wilcox aquifer in the Mississippi embayment.

Parameter	N	Range	Minimum	Maximum	Mean	Standard Deviation	Variance	Skewness	Kurtosis	Anomaly
Al, ug/l	91	100	0	100	18.6	25.37	643.62	2.02	3.38	> 18.6
B, ug/l	149	4	0	4	0.47	0.9	0.82	2.14	4.07	> 0.47
Ba, ug/l	149	1	0	1	0.01	0.12	0.01	8.54	71.95	> 0.01
Br, ug/l	67	98	0	98	3.43	15.67	245.46	4.96	24.95	> 100
Ca, mg/l	1217	100	0	100	9.2	13.22	174.74	3.08	12.21	> 100
Cl, mg/l	1214	940	0	940	54.73	111.69	12474.54	3.82	18.74	> 1000
CO_2, mg/l	514	364	0	364	14.97	25.63	657.07	6.6	71.75	> 370
El.Cond, uS/cm	1104	4950	10	4960	628.84	658.7	433881.05	2.62	9.84	> 5000
F, mg/l	1152	7	0	7	0.46	0.77	0.6	3.9	19.32	> 0.46
Fe, ug/l	597	1000	0	1000	174.49	224.63	50456.63	1.87	2.92	> 1000
HCO_3, mg/l	1196	987	3	990	262.09	197.19	38883.97	1.12	1.03	> 1000
I, mg/l	40	8	0	8	0.3	1.3	1.7	5.6	33.12	> 0.3
K, mg/l	1181	36	0	36	2.53	2.48	6.18	5.87	56.95	> 36
Mg, mg/l	1224	100	0	100	3.27	7.54	56.79	6.84	62.21	> 100
Mn, ug/l	483	7	0	7	0.03	0.35	0.12	16.92	324.99	> 0.03
Na, mg/l	1212	999	1	1000	125.17	142.61	20337.85	2.24	7.05	> 1000
NO_3, mg/l	581	41	0	41	0.8	2.63	6.9	9.34	115.49	> 50
O_2, mg/l	108	9	0	9	0.76	1.61	2.6	2.96	9.43	> 0.76
pH	1122	6	3	9	7.57	0.88	0.77	-0.66	0.71	> 7.57
Si, mg/l	1155	82	0	82	19.11	12.34	152.33	1.67	2.74	> 100
SO_4, mg/l	1223	740	0	740	14.76	52.31	2736.46	9.02	98.29	> 740
Sr, mg/l	100	8.2	0	8.2	0.29	0.87	0.76	7.94	70.1	> 100
TDS, mg/l	1079	984	16	1000	306.74	230.42	53095.02	1.12	0.4	> 1000
Temp, Celsius	865	66	11	77	22.24	4.34	18.8	3.46	31.69	> 22.24
Zn, ug/l	146	15000	0	15000	142.19	1241.34	1540919.3	11.99	144.46	> 142.19

Correlation analysis shows that amongst the specific conductance, TDS, and major constituents the most prominent correlations are between pH, TDS, EC, Na, Cl and HCO_3. Calcium and Mg, and Mg and SO_4 also show prominent correlations. Of the minor and trace constituents, F, Br, and B show significant correlations to TDS and/or EC, Na, Cl, and HCO_3. Iodine, Sr, and Br also show strong correlations amongst each other and with K, Ca, and Mg. Strontium and Br also correlate well with CO_2. Other strong correlations include Mn to I and Al, and Fe to I. The correlation matrix is seemingly more complex than that of the other three aquifer units, but the presence of a saline, alkaline sea-water like source is evident.

The Piper diagram for the Lower Claiborne-Wilcox aquifer in Figure 52 reveals several geochemical similarities in water composition to that of the Middle Claiborne aquifer. The upper diamond plot shows that most of the waters are bicarbonate-rich with either Ca+Mg or Na + K cation compositions; however, a large number of water samples fall along the Na+K line. The trilinear cation plot shows a mixing trend between Ca-Mg waters with strongly Na+K waters, with most of the waters plotting close to the Na+K apex. The ratio of Mg/Ca ranges from 0.0 to 3.3, with mean value of 0.54 The anion trilinear diagram illustrate that most waters are dominated by bicarbonate and chloride with lesser amounts of sulfate. Figure 34 shows that most data follow a linear correlation of increasing TDS with increasing

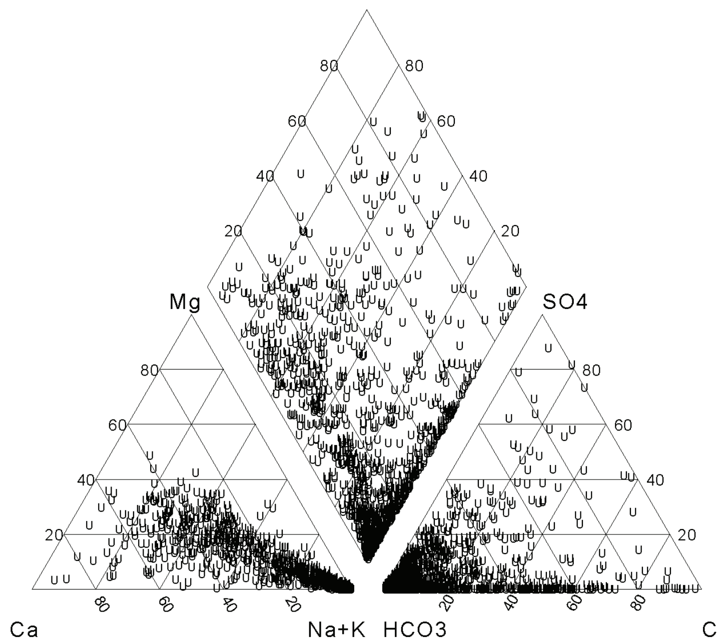


Figure 52. *Piper diagram for water chemistry data from the Lower Claiborne-Wilcox aquifer. See Figure 12B for classification fields.*

bicarbonate; however, the highest TDS waters are rich in chloride similar to that observed in the other Claiborne aquifers. However, no water analyses had chloride contents in excess of 1000 mg/L and numerous waters with anomalously high HCO_3 values are present. The association of chloride with more concentrated waters illustrated in Figure 53 is consistent with the presence of a saline, alkaline component identified in waters from the other Claiborne aquifers. The high bicarbonate waters consistently have little or no SO_4 and are consistent with waters within the Wilcox in Louisiana interpreted by McIntosh et al. (2009) to be dominated by microbial methanogenesis.

The contour map distribution of hydrochemical water types (Figure 54) shows that bicarbonate waters in the Lower Claiborne-Wilcox aquifer dominate throughout the study area. The distribution of HCO_3-Cl and HCO_3-SO_4 waters is generally in the southwestern and central ME, but it does not follow tectonic features (Figure 35), recharge, or discharge (cones of depression) patterns (Schrader, 2008a). An anomalous region of HCO_3-Cl, HCO_3-SO_4, and Cl waters is present in western Tennessee, although these are all dilute waters (Figure 54).

The contour map distribution of TDS values (Figure 55) shows that the highest concentrations are toward the center and southern part of the ME and Gulf Coast. The contour maps for sodium, potassium, chloride, and bicarbonate show distributions similar to that of the TDS map, suggesting up-dip migration mixing with Gulf Coast brines (Hanor and McIntosh, 2007, McIntosh et al., 2009). Calcium, magnesium, and sulfate have limited concentration variance across much of the ME, but show higher values in southern Arkansas and northern Louisiana. The contour map distribution of iron values (Figure 56) shows the highest values in proximity to major pumping centers in western Tennessee (mainly Memphis), central Mississippi, and northwestern Louisiana.

Cluster and principal component analysis for the Lower Claiborne-Wilcox aquifer showed similar relationships to those observed in the Middle Claiborne aquifer. Hierarchical dendrogram and principal component analysis yield two geochemical associations (Figure 57). Association 1 shows linkage between NaCl, HCO_3, Mn, temperature and TDS/Specific Conductance, suggesting contributions from an alkaline, saline water source potentially at

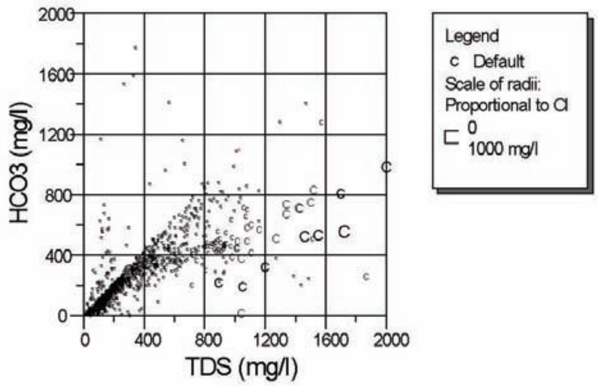


Figure 53. *Scatter plot of bicarbonate (HCO_3) versus total dissolved solids (TDS) data from the Lower Claiborne-Wilcox aquifer. Symbol size is scaled to the concentration of chloride.*

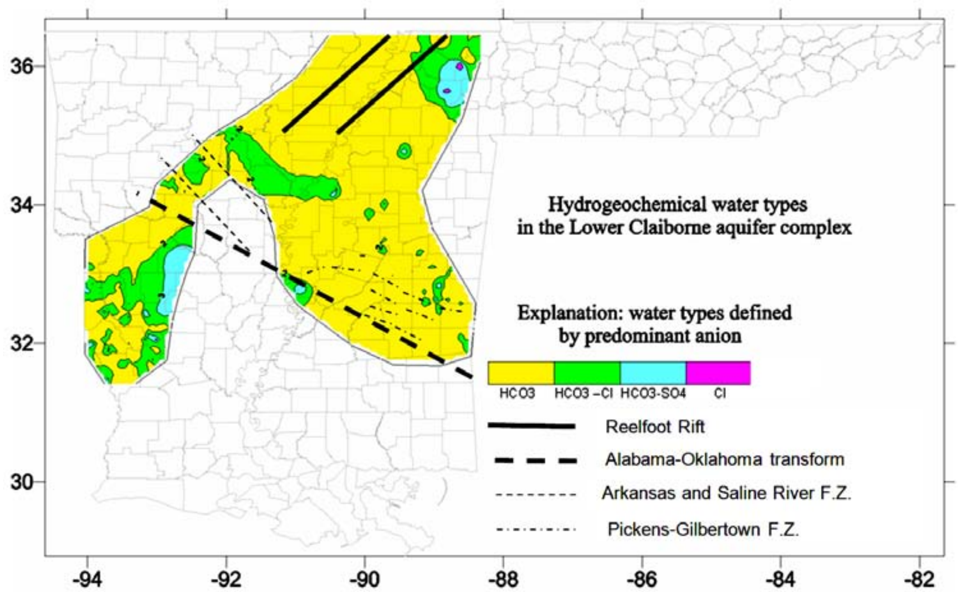


Figure 54. *Distribution of major water types in the Lower Claiborne-Wilcox aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

depth. The inclusion of manganese (Mn) in this association is puzzling; however, it also has the greatest scaled distance from other parameters in the analysis. This component is very similar to that identified in the other Claiborne aquifers, and has a focused distribution in central and southern ME, much like the Middle Claiborne aquifer. Association 2 includes Ca, Mg, SO_4, and K, which is also spatially distinct. Iron has its own distinct behavior and appears to be directly related to pumping centers as illustrated in Figure 56.

Water in the Lower Claiborne-Wilcox aquifer in the ME is generally of high quality, except in regions where high-TDS, sodium-chloride-bicarbonate waters are observed (see Figure 55). Ground water in the Lower Claiborne-Wilcox aquifer is used for industrial, municipal, and domestic supplies in western Tennessee (Parks and Carmichael, 1989), northeastern and southwestern Arkansas (Holland, 2007) and Mississippi (Wasson, 1986). All sodium hazard categories are encountered (Figure 58), but the samples are dominantly in the medium to high salinity hazard categories. Approximately

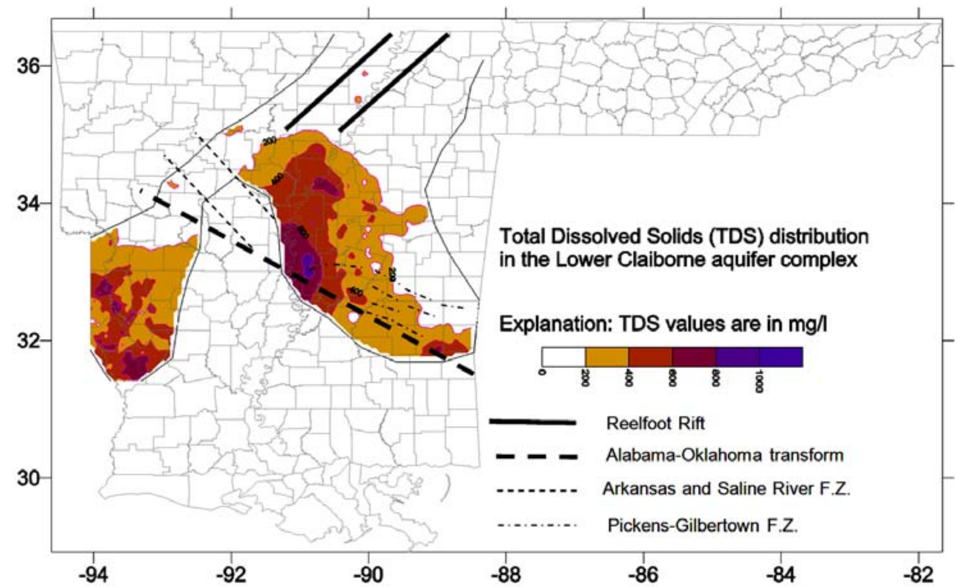


Figure 55. *Distribution of TDS values in the Lower Claiborne-Wilcox aquifer. Reelfoot Rift from Schweig and Van Arsdale (1996). Alabama-Oklahoma transform from Thomas (1991). Arkansas and Saline River fault zones from Cox et al. (2006). Pickens-Gilbertown Fault Zone from Bicker (1969).*

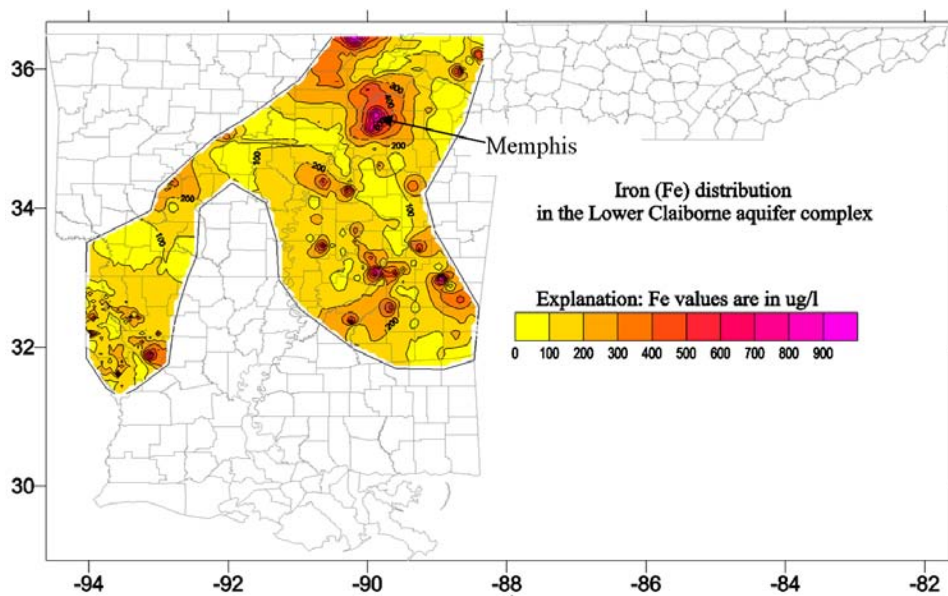


Figure 56. *Distribution of iron values in the Lower Claiborne-Wilcox aquifer.*

2% of the analyses have values that exceed US EPA primary drinking water standards for fluoride (F^-) or nitrate (NO_3^-). Most studied regions have concentrations at or below the US EPA secondary drinking water standards maximum level for iron (Fe = 0.3 mg/L), except near major pumping centers such as Memphis (Figure 56).

Discussion of Water Quality in the Tertiary and Quaternary Aquifers

The results of the present study illustrate the overall water quality and statistical factors controlling water quality in the four main aquifer units defined in the Mississippi embayment. Water from all four aquifers is suitable for consumption; however, the water in the

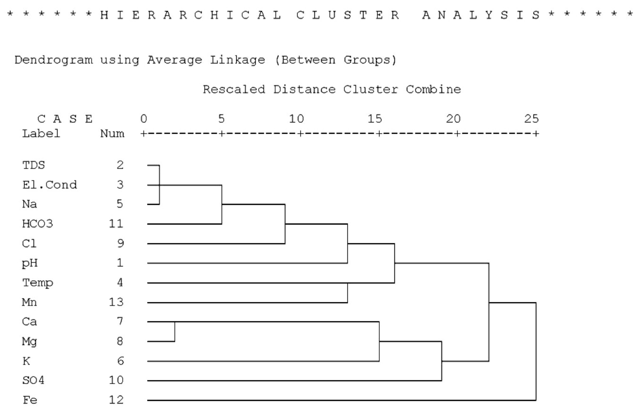


Figure 57. *Hierarchical dendrogram of the geochemical clusters for the Lower Claiborne-Wilcox aquifer.*

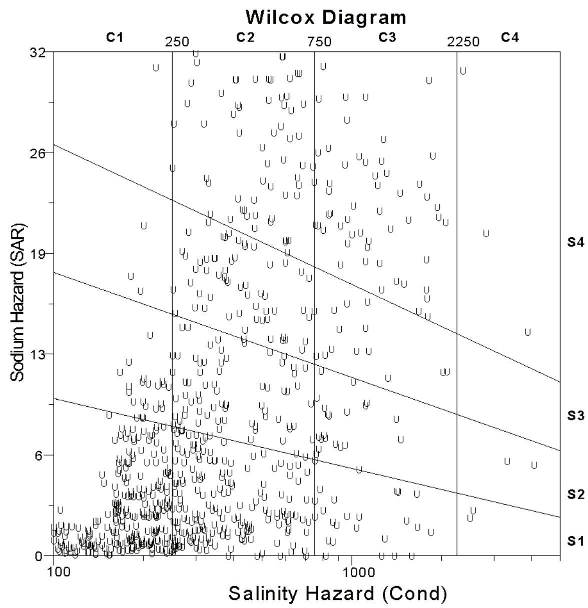


Figure 58. *Wilcox diagram illustrating degree of sodium and salinity hazards in the Lower Claiborne-Wilcox aquifer.*

Quaternary Alluvial aquifer is generally of lower quality (higher TDS, Ca, Mg, and Fe). Water from the Quaternary Alluvial aquifer appears to have hydrochemically distinct origins from the Tertiary aquifers and shows less variation in relation to proximity of the Gulf Coast. The assemblage of factors affecting hydrochemistry in the Quaternary Alluvial aquifer is reaction with Fe-Mn oxides and hydroxides, reaction with carbonate minerals (probably from partially-weathered detritus of glacial origin), and a mixed salt (Na, K, Cl, and SO_4) association that may have geographically distinct and diverse origins (See Kresse and Clark, 2008). Correlations among trace elements, such as Cr, Cu, Co, and Pb, in the Quaternary Alluvial aquifer waters also support origins from partially weathered detritus, and are distinct from trace element associations observed in the deeper aquifers. The overall hydrochemistry is also affected by proximity to the major river systems, where higher TDS, Ca-Mg-HCO_3

waters recharge the aquifer. Prominent regions of higher Na and Cl are observed in southeastern Arkansas and northern Louisiana which may have migrated along faults from underlying aquifers (Bryant et al., 1985; Kresse and Clark, 2008).

In contrast to the Quaternary alluvial aquifer, the underlying Tertiary aquifers have several similarities in water quality and hydrochemistry that are linked to recharge processes, discharge regions, and proximity to the Gulf Coast. Overall water quality in each of the Tertiary aquifers is high and generally increases with depth (in the central and northern Mississippi embayment). Water type generally varies from mixed cation-bicarbonate compositions in the recharge areas to more sodium-rich bicarbonate, bicarbonate-sulfate, or bicarbonate-chloride waters down stratigraphic dip toward the Gulf Coast, similar to interpretations in past studies (Pettijohn, 1996). Correlation and factor analysis consistently shows major and trace element evidence for mixtures of sea-water derived saline; alkaline-waters are common in all three Tertiary aquifers. Vertical increase in salinity is only apparent in the southern ME where saline, alkaline fluids have migrated either up-dip or vertically through the Cenozoic section (Hanor and McIntosh, 2007; McIntosh et al., 2009). All three Tertiary aquifers include a carbonate mineral source, similar to that of the Quaternary Alluvial aquifer, which is focused in recharge areas, especially beneath the Mississippi Alluvial valley. In general, major and trace element hydrochemistry appears to be distinct and more dilute in the recharge areas for the respective Tertiary aquifers.

Some water quality variations in the southern ME appear to relate to migration along fault structures. Kresse and Clark (2008) argue for fault-derived salinity in the Mississippi Alluvial aquifer in southeastern Arkansas near the traces of the Saline and Arkansas River fault zones (Figures 24 and 25) (Cox et al., 2006). Similar association of a saline-alkaline fluid component with regional structures is apparent in the Upper Claiborne aquifer (Figures 33 and 34). Clear evidence of such association, however, appears lacking in the deeper Middle Claiborne and Lower Claiborne-Wilcox aquifers. It is unclear whether this is because these units represent aggregates of several thin or discontinuous aquifers or if other processes are more determinant in the water-quality characteristics.

Water-quality changes over time and due to pumping are limited on a regional basis. The main effects appear to be subtle increases in total dissolved solids (e.g., Quaternary Alluvial aquifer) and changes in oxidation-reduction conditions (Lower Claiborne-Wilcox aquifer). However, the water quality characteristics need to be evaluated in light of regional water-table and potentiometric surfaces. A regional potentiometric surface is only available for the Sparta-Memphis aquifer at present. Although numerous studies have documented local changes in water quality related to pumping and waste-disposal practices (Parks et al., 1981; Graham and Parks, 1986; Parks, 1990; Bradley, 1991; Parks and Mirecki, 1992; Parks et al. 1995; Kleiss et al., 2000; Larsen et al., 2003; Gentry et al., 2005; Ivey et al., 2008), in the regional view these effects appear at present to be localized.

Relationships amongst water sources and processes affecting water quality are most clear in the Quaternary Alluvial and Upper Claiborne aquifers, and less so in the Middle and Lower Claiborne-Wilcox aquifers. This seems likely due to the lumped classification of these aquifer units. More detailed analysis of the water quality trends and factors in the lower Tertiary aquifers will require further subdivision of the aquifers and regional consistency in application (see Hydrostratigraphy section).

Application of environmental tracers in Tertiary and Quaternary aquifers in the Mississippi embayment

Environmental tracers include a variety of chemical and isotopic measurements that provide information on ground water recharge sources, recharge rates, and flow paths (see Cook and Herczeg, 2000 for a review). Recharge areas include locations where water infiltrates from the surface into an aquifer or from a subsurface source (e.g., gap in confinement, fault, etc.) into an aquifer. Surficial recharge areas are inherently vulnerable to pollutants that may infiltrate with the water. Recharge rate is the rate at which the aquifer is replenished from water infiltrating down from the ground surface, which varies with a host of variables, including time, location, land use, and aquifer stress. The recharge area for an unconfined alluvial aquifer is practically everywhere on the surface where water can vertically infiltrate. Recharge areas for confined aquifers are limited to areas where the aquifers crop out or subcrop beneath permeable materials. Recharge areas also identify the locations that are vulnerable to contamination. The shallow aquifer is most susceptible to contamination, such as leaching of fertilizers and pesticides from agricultural fields or trace elements and organic solvents from landfills. For example, in 1997, ~$5.8x10^4$ kg of herbicides, ~$1.18x10^4$ kg of insecticides, and $3.4x10^3$ kg of fungicides were used mostly for cotton and soybean crops in Shelby County, Tennessee (Gonthier, 2002). Many pesticides have been detected in both surface water and shallow ground water in Shelby County (Parks et al., 1981; Gonthier, 2002) and other shallow wells in the region (Fielder et al., 1994; Kleiss et al., 2000). Confined aquifers are especially vulnerable to contamination in recharge areas as well as locations where vertical leakage between aquifers, such as windows in the upper Claiborne confining unit in Shelby County (Parks, 1990; Parks and Mirecki, 1992; Gentry et al., 2006). Thus, the locations as well as rates of recharge to aquifers are critical for assessing vulnerability to contamination.

Environmental tracers are a key tool for assessing locations of recharge and recharge rates. Inorganic chemicals, especially those associated with specific sources, are useful as tracers of ground water recharge pathways and also have potential for evaluating recharge rate (Herczeg and Edmunds, 2000). Contour map distributions of water quality characteristics for each of the Cenozoic aquifer units provide information on likely recharge areas (e.g., locations of dilute water compositions, reduction-oxidation gradients, etc.). Ground water hydrochemistry has been used in several studies within the ME region to identify ground recharge sources and pathways (Mirecki and Parks, 1994; Parks et al., 1995; Larsen et al., 2003; Ivey et al., 2008).

Ground water age, the time since recharge, is important in determining ground water flow velocity and recharge rate (Cook and Solomon, 1997). Ground water age can be determined by using a variety of isotopic tracers, such as tritium-helium ($^3H/^3He$), carbon-14 (^{14}C), chloride-36 (^{36}Cl), and helium-4 (^4He), each with its own dating limitations. Tritium (^3H) provides information on the presence of modern water (<60 years old), but cannot be used under most circumstances to estimate recharge rates. Tritium data exist for many shallow wells throughout the ME region (Brahana et al., 1985; Graham and Parks, 1986; Slack and Oakley, 1989; Bradley, 1991; Parks et al., 1995; Larsen et al., 2005), but the data are generally from study areas of restricted extent or are widely dispersed wells in various geologic units. The $^3H/^3He$ technique is used to date young ground water (less than 60 years) (Cook and Solomon 1997; Solomon et al 1993). The $^3H/^3He$ technique has been used successfully in many studies in the Memphis area (Larsen et al., 2003; Larsen et al., 2005; Gentry et al., 2005; 2006; Ivey et al., 2008) and holds much potential for more regional assessment of recharge locations and rates. Radioactive ^{14}C is useful for dating ground water that has little dissolved carbonate and is between 1,000 and 30,000 years old (Coplen, 1993; Fontes, 1979). Several surveys of radioactive ^{14}C have been done in the ME region (Brahana et al., 1985; Graham and Parks, 1986), but most have focused on study areas of limited extent or widely dispersed wells. Cl-36 is a good indicator of both young waters (bomb-pulse age, Phillips et al., 1988) and waters hundreds of thousands of years old (Phillips et al., 1986; Fehn et al., 1992). Little work with ^{36}Cl has been done in the region (Davis et al., 2003), but it has potential for constraining the age of old and deep ground water. Radiogenic ^{4}He can be used to corroborate ^{14}C (Carey et al., 2004; Dowling et al., 2004; Hendry et al., 2005, Hunt, 2000). Noble and nitrogen (determined during d^{15}N analysis) gas data are used to evaluate recharge temperatures and potential for mixing of gas sources (Aeschbach-Hertig et al., 1999), both of which are important for applying gas-based age models.

Chemical signatures and environmental tracers are invaluable for numerical ground-water flow model calibration and analytical ground-water flow modeling. Measuring geochemical and isotopic characteristics (including apparent ground-water ages) help determine both the source and age of water currently in the aquifer and constrain computer simulations, which will be used to evaluate ground-water apparent age and source distribution. An important component of ground-water flow models is to determine the area and rate of natural replenishment for confined aquifers. Environmental tracers and modeling provide a unique and well-constrained hydrologic characterization of a multiple layered aquifer system, which should serve as a model for developing exploitation strategies in other similar aquifer systems.

Conduct assessment on aquifer parameter values and measurement methodologies

Water production in the region based on historic records has been ongoing since the mid-1800's. Well production capacity and, at the time under artesian conditions, outflow provided insight into the capability of the aquifers to produce sustainable quantities of flow. To quantify this capability, hydraulic conductivity and storage are needed. Additionally, to address contamination potential and fate, porosity of the aquifer material and hydrogeologic characterization of the aquitards will be required. Two information sources were analyzed for measured values of hydraulic conductivity, storage and porosity: (1) published literature and (2) the USGS database.

Literature review

A number of publications were reviewed, but after removing coincident references and following references back to the original source, only thirteen sources could be identified (Table 11). The table shows the hydraulic conductivity, transmissivity, storativity, and permeability values for the three major aquifers in the Memphis area. The values shown were cited from reports that were focused on the aquifers in the Memphis area and the surrounding counties. The majority of studies in the Memphis area cite values given by (Arthur and Taylor, 1990) and (Moore 1965). Two heavily cited papers are a good example of this (Brahana,and Broshears 2001; Parks and Carmichael, 1990a). Slack and Darden (1991) summarized all of the aquifer tests done in Mississippi from June 1942 to May 1988, but none of these test locations were in northern Mississippi counties. Newcome (1971) also reports aquifer test values for Mississippi, but these are not located in northern Mississippi either. Krinitzsky and Wire (1964) report transmissivity values ranging from 12,000 to 54,000 ft^2/day, but this report is out of circulation and the location of these tests could not be confirmed. The values given by Layne Geosciences and EnSafe are unpublished results. Unfortunately for many of the records, location detail below the state or county scale did not exist thus preventing the mapping of the values. The aquifer formation and aquifer name were extracted from the author's description of the units. As will be discussed in the USGS aquifer parameter assessment section, factors such as what aquifer testing method was used, multiple wells pumping during the test, short testing periods, and lack of supporting information may reduce confidence in a recorded value thus warranting caution in its use and the need for more aquifer tests. Without well number identification accompanying the records listed in Table 11, correlation of these values to those assessed in the next section cannot be made, and thus no determination of reliability applied.

USGS historic records

The USGS has the largest public database of aquifer test data in the region. This database includes values for hydraulic conductivity, transmissivity, specific capacity, and storage. The question raised is whether the measured aquifer parameter values are reliable. Reliable in this sense is a qualitative measure that is a function of method(s) used, supporting documentation, and the presence of extraneous factors that might impact an aquifer test like having multiple wells pumping (e.g., well field) or wells turning on and off during testing. For this study, as much information about an aquifer test was compiled and a scoring matrix developed for the assessment tool.

The USGS aquifer parameter data is categorized by aquifer; the naming convention is that used in the USGS database yet correlated as best as possible to that described under the geology section. The aquifer names are: (1) Qal (Quaternary alluvium); (2) Tcf (Tertiary confining unit or Upper Claiborne); (3) Tm (Memphis/Sparta or Lower Claiborne); and

Table 11. Aquifer parameter data from literature review.

Author(s)	K_h (ft/day)	T (ft^2/day)	S	AREA	AQUIFER FORMATION	AQUIFER NAME
(Arthur, J. and Taylor, R.1990)	81	3333	-	TN	Upper Claiborne	Cockfield Formation
	47	25649	-	TN	Middle Claiborne	Upper Memphis Sand
	69	15616	-	TN	Lower Wilcox	Fort Pillow
	69	5358	-	MS	Upper Claiborne	Cockfield Formation
	65	5960	-	MS	Middle Claiborne	Sparta Sand
	63	4754	-	MS	Lower Claiborne-Upper Wilcox	Winona Sand
	42	2536	-	MS	Middle Wilcox	Middle Sand in Wilcox Group
	86	9343	-	MS	Lower Wilcox	Lower Sand in Wilcox Group
	65	6283	-	AR	Upper Claiborne	Cockfield Formation
	172	7668	-	AR	Middle Claiborne	Sparta Sand
	-	486	-	AR	Lower Claiborne-Upper Wilcox	Carrizo Sand
	49	14963	-	AR	Middle Wilcox	Middle Sand in Wilcox Group
	-	17780	-	AR	Lower Wilcox	Lower Sand in Wilcox Group
(Criner, J. et al. 1964)	-	53472	0.003	Memphis	Claiborne Formation	Memphis Sand
	-	16043	0.00028	Memphis	Lower Wilcox	Fort Pillow
(Gentry, et al. 2006)	80-100	-	-	Memphis, TN	Middle Claiborne	Memphis Sand
(Hosman et al. 1968)	23	21390	0.0002	MS Co AR	Lower Wilcox	Fort Pillow
	9	10026	0.0015	Madison Co, TN	Lower Wilcox	Fort Pillow
	-	13102	0.0002	Shelby Co, TN	Lower Wilcox	Fort Pillow
	-	7353	0.0009	St. Francis Co, AR	Middle Claiborne	Memphis Sand
	-	2674	-	Fayette Co, TN	Middle Claiborne	Memphis Sand
	-	26738	0.0001	Haywood Co, TN	Middle Claiborne	Memphis Sand
	11	20053	0.011	Madison Co, TN	Middle Claiborne	Memphis Sand
	-	33422	0.001	Shelby Co, TN	Middle Claiborne	Memphis Sand
	-	29412	-	Tipton Co, TN	Middle Claiborne	Memphis Sand
	22	18717	0.0005	Crittendon Co, AR	Quaternary Aquifer	Shallow or Alluvial
	35	25401	0.0007	MS Co, AR	Quaternary Aquifer	Shallow or Alluvial

Table 11 (cont.). Aquifer parameter data from literature review. Readers are referred to Pugh (2008) for additional values published after the completion of this investigation.

Author(s)	K_h (ft/day)	T (ft²/day)	S	AREA	AQUIFER FORMATION	AQUIFER NAME
	45	40107	0.02	St. Francis Co, AR	Quaternary Aquifer	Shallow or Alluvial
(Mahon and Poynter 1993)	120-390	-	-	Eastern Arkansas	Quaternary	Mississippi River Alluvial
(Moore 1965)	-	18717	0.0004	Dyerburg, TN	Middle Claiborne	Memphis Sand
	-	22326	-	Ripley, TN	Middle Claiborne	Memphis Sand
	-	29411	-	Covington, TN	Middle Claiborne	Memphis Sand
	-	27139	0.0001	Stanton, TN	Middle Claiborne	Memphis Sand
	-	21390	-	Arlington, TN	Middle Claiborne	Memphis Sand
	-	40508	0.0014	Millington, TN	Middle Claiborne	Memphis Sand
	-	2674	-	Somerville, TN	Middle Claiborne	Memphis Sand
	-	42781	0.0002	Mem(McCord)	Middle Claiborne	Memphis Sand
	-	26203	-	Mem(Mallory)	Middle Claiborne	Memphis Sand
	-	45454	-	Memphis, TN	Middle Claiborne	Memphis Sand
	-	35428	-	Mem (Sheahan)	Middle Claiborne	Memphis Sand
	-	31150	-	Mem (Allen)	Middle Claiborne	Memphis Sand
	-	26738	-	Mem (Lichterman)	Middle Claiborne	Memphis Sand
	-	23396	-	Germantown, TN	Middle Claiborne	Memphis Sand
	-	23396	-	Collierville, TN	Middle Claiborne	Memphis Sand
	-	21000	0.002	Blytheville, AR	Lower Wilcox	Fort Pillow
	-	10000	-	Madison Co, TN	Lower Wilcox	Fort Pillow
	-	43000	-	St. Francis Co, AR	Lower Wilcox	Fort Pillow
(Morat, personal communication 2008)	100	-	-	Memphis, TN	Quaternary	Shallow or Alluvial
n = 0.34	40	-	-	Memphis, TN	Middle Claiborne	Memphis Sand
	0.02	-	-	Memphis, TN	Upper Claiborne	Confining Unit
(Parks and Carmichael, 1988)	-	1500-2500	0.0003	Lauderdale Co, TN	Upper Claiborne	Cockfield Formation
(Plebuch et al. 1961)	-	138000	0.00046	Crittendon Co, AR	Quaternary	Shallow or Alluvial
(Robinson et al. 1997)	5-150	-	-	Millington, TN	Alluvial-Fluvial Deposits	Shallow or Alluvial
(Schneider and Cushing 1948)	-	16979	0.00042	Allen Field	Lower Wilcox, 1400 ft sands	Fort Pillow
	-	13636	0.00017	Sheahan Field	Lower Wilcox, 1400 ft sands	Fort Pillow
	-	13369	0.00023	Buckeye Oil Plant	Lower Wilcox, 1400 ft sands	Fort Pillow
	-	18449	0.00038	Sheahan Field	Lower Wilcox, 1400 ft sands	Fort Pillow
	-	15107	0.00021	Sheahan Field	Lower Wilcox, 1400 ft sands	Fort Pillow
(unpublished EnSafe 1992)	60	36216	-	Collierville, TN	Middle Claiborne	Memphis Sand
(unpublished Layne Geosciences 2001)	48	27380	0.0002	Collierville, TN	Middle Claiborne	Memphis Sand

(4) Tfp (Fort Pillow or Wilcox). No aquifer parameter data exists for the remaining geologic units investigated under Topic 2. As shown in Table 12, the vast majority (93.4%) of aquifer test data resides in Shelby County with the larger portion of tests performed within the Memphis/Sparta aquifer. Very few aquifer tests have been recorded outside Shelby County with no tests on record in Hardeman, Marshall and Tunica counties.

Table 12. Breakdown of USGS aquifer parameter tests by county and aquifer.

State	County	Geologic Unit				Percentage of total records
		Qal	Tcf	Tm	Tfp	
Tennessee	Shelby	1	-	85	28	93.4
Tennessee	Fayette	-	1	1	-	1.6
Tennessee	Tipton	-	-	1	-	0.8
Tennessee	Hardeman	-	-	-	-	-
Arkansas	Crittenden	2	-	-	2	3.3
Mississippi	Desoto	-	-	1	-	0.8
Mississippi	Marshall	-	-	-	-	-
Mississippi	Tunica	-	-	-	-	-

A scoring matrix of nine criteria was used to qualitatively assess the reliability of the aquifer parameter data recorded by the USGS (Table 13). Meeting the criteria would either reduce or increase a record's score from its base value of 10. Ten was selected as the initial score so resulting scores would be non-negative (minimum = 0). Determining a threshold score to differentiate between reliable and non-reliable records is difficult. It is recommended that scorings for records be reviewed on an individual basis, guided by the user's intended purpose for using the values.

A general discussion of the scoring is discussed herein following Table 14. With a starting score of 10, the average score for each aquifer was below 5. Only one aquifer parameter test was conducted within the Upper Claiborne confining clay (Tcf), that listing located in eastern Fayette County where according to this investigation this unit is absent. This raises the question of positional accuracy of the data which was not assessed under this investigation. The majority of the records are for the Memphis aquifer in Shelby County. A moderate percentage of the wells (28%) used in aquifer testing are affiliated with well clusters (or well fields), thus accounting for an added increase in the score due to available nearby observation wells. The score is increased further because 47% of the analyses equal or exceed a 24 hour testing period. Yet the influence of multiple pumping wells (i.e., drawback of being in a well cluster), lack of supporting information, no use of multiple analytical methods, and limited drawdown/recovery analyses counter any gain in scores for this aquifer, and similarly for the other units, therefore, resulting in the low average scores.

Table 13. Scoring matrix used to qualitatively assess the reliability of the USGS aquifer parameter data.

Rank Criteria
Published or Approved (yes + 1) Have the test results been published in a USGS report? If yes, plus 1
Multiple pumping wells (yes -2) Are nearby pumping wells affecting the test? If yes, minus 2
Other well on and off (yes -5) Are nearby pumping wells turning on and off? If yes, minus 5
Observation wells (unknown -1, no -2) Were water levels monitored in observation wells for the aquifer test? If unknown, minus 1 If no, minus 2
Test duration (>24 hours +1, unknown -1, <24 hours -2, <1 hour -3) If the pumping duration is more than 23 hours, plus 1 If the pumping duration is unknown, minus 1 If the pumping duration is less than 24 hours, minus 2 If the pumping duration is less than 1 hour, minus 3
Good supporting information (no -2) Do the records provide good supporting information for the test? If not, minus 2
Multiple Analyses (test +1; wells -1; no -2) Were multiple analytical methods used in the analysis? If yes, plus 1 If no, minus 2
Multiple Wells Analyzed (yes +1) Were analysis conducted on multiple wells for the test? If yes, plus 1
Drawdown and recovery analyses (no -2) Were the drawdown and recovery data both analyzed? If not, minus 2

A distribution of the scores aggregated for all of the aquifers is shown in Figure 59. Choosing an arbitrary threshold of seven, only 19% of the records can be considered reliable. This number drops significantly to 7% for scores of eight or greater. Figure 60 shows the distribution of reliable aquifer parameter records with a score of seven or higher. As indicated, reliable aquifer parameter data becomes limited to Shelby County.

Not only is horizontal spatial distribution important, but vertical discretization within the Memphis/Sparta aquifer is equally important for reasons of apparent aquifer compartmentalization as mentioned in Topic 2. Using a threshold score of seven, the records with scores 9 to 11 are clustered in the northern part of Shelby County with the wells screened in the upper section of the Memphis aquifer (Figure 60). Three records (score = 8) are clustered in south middle Shelby County, also representing the upper section of the Memphis aquifer. Nine of the records (score = 7) are screened in the middle to upper section of the Memphis aquifer. The remaining five records (score = 7) are screened within the Fort Pillow aquifer, yet three of the records represent an aquifer test performed on the same well.

Table 14. Number of USGS aquifer parameter records that match the assessment criteria and the average score by aquifer.

Aquifer	Total Number	Published or Approved (yes)	Multiple pumping wells (yes)	Other well on and off (yes)	Observation wells (no)	Test duration (>/=24 hours)	Test duration unknown	Test duration (<24 hours)	Test duration (<1 hour)
Qal	3	1	0	0	2	0	2	1	0
Tcf	1	1	0	1	0	1	0	0	1
Tm	88	20	14	0	19	41	3	44	1
Tfp	32	0	4	0	2	12	1	19	0

Aquifer	Total Number	Good supporting information (no)	Multiple Analytical Methods (yes)	Multiple Analytical Methods (no)	Multiple wells analyzed (yes)	Drawdown and recovery analyses (no)	Average Score	Minimum Score	Maximum Score
Qal	3	2	0	3	0	2	3	1	5
Tcf	1	0	0	1	0	1	4	-	-
Tm	88	56	3	88	25	68	4.1	0	7
Tfp	32	13	0	32	1	30	4.4	0	11

This limited number of aquifer parameter data and weak spatial distribution (i.e., horizontally, vertically within the larger aquifer (e.g., Memphis/Sparta), and vertically inclusive of all the geologic units under investigation) across the study area strongly suggests a major deficiency in the characterization of the aquifers and their confining units, thus, warranting that any future ground-water modeling efforts should include a plan to rectify this data gap.

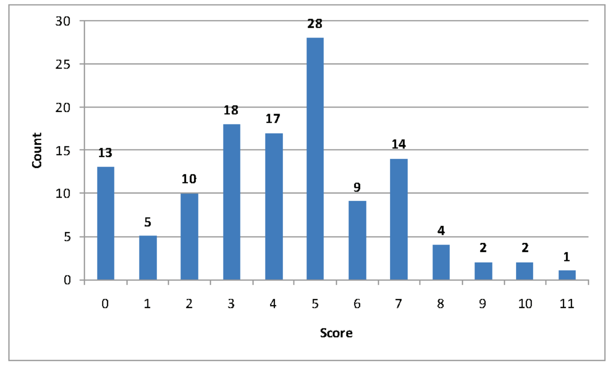


Figure 59. *Distribution of USGS aquifer parameter assessment scores for all geologic units.*

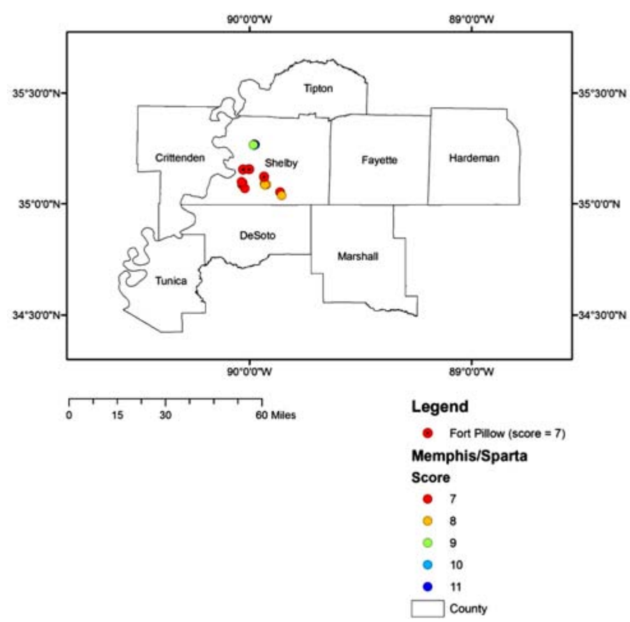


Figure 60. *USGS aquifer parameter records with a score of 7 or greater.*

Catalog surface water sources to ground water

Of the surface water bodies encountered in the study area, rivers are the only system that has historic data associated with them. Lakes and wetlands are recognized as having an impact on the ground water, but have not been investigated beyond identifying their location, size, and in regard to wetlands, their classification. This task is subdivided into five subtasks: (1) gaging station information; (2) assessment of baseflow conditions; (3) availability of digital wetland data; (4) determination of riverbed conductance; and (5) compilation of soils data.

Gaging stations

There are 22 gaging station locations within the study area footprint (Figure 61). Two of these stations are on the Mississippi River, operated by the Memphis district US Army Corps of Engineers (USACE). Stage and discharge are measured at both locations and the records can be found at *http://www.mvm.usace.army.mil/*. There are five main branch channels to the Mississippi River within the study region: (1) Hatchie River (TN); (2) Loosahatchie River (TN); (3) Wolf River (TN); (4) Nonconnah Creek (TN); and (5) Coldwater River (MS). On these branches and their tributaries, there are 20 gage locations, but only 11 are currently active (Figure 61). These 11 gages are maintained by the USGS with the records for each gage available at *http://water.usgs.gov/waterwatch/* or at the links provided in Appendix Gages (the Station ID in Figure 61 is associated to the ID's in the appendix). Also provided in Appendix Gages is the type of data recorded (e.g., real-time, discharge, stage, field measurements, etc.) and date range of activation. Table 15 summarizes the location and activation date range for the gages shown in Figure 61. Data from the monitored tributary gages are used in the next section to assess baseflow conditions.

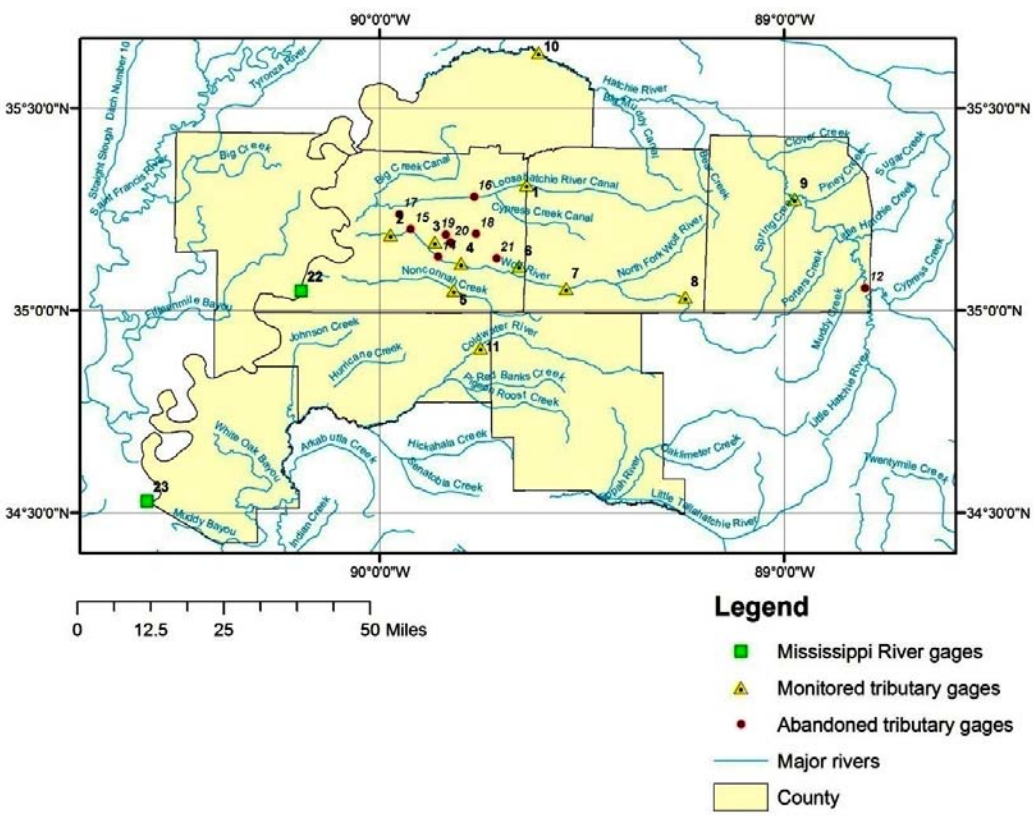


Figure 61. *Monitored and abandoned gaging station locations.*

Table 15. Location and date of activation information for gage stations shown in Figure 61.

Latitude	Longitude	Date range of activation	Drainage area (mi^2)	Station ID	River
35.310863	-89.63948	Oct 1969 to Sep 2008	262	1	Loosahatchie River
35.187777	-89.975555	Feb 1985 to Sep 2008	788	2	Wolf River
35.16928	-89.866038	Apr 1996 to Oct 2008	30.5	3	Fletcher Creek (trib to Wolf River)
35.116388	-89.801388	Oct 1969 to Sep 2008	699	4	Wolf River
35.049722	-89.818888	Oct 1969 to Sep 2008	68.2	5	Nonconnah Creek
35.109444	-89.657777	Nov 2007 to Dec 2008	3.61	6	Mary's Creek (trib to Gray's Creek: Wolf River)
35.054166	-89.541111	Aug 1929 to Sep 2008	503	7	Wolf River
35.0325	-89.246666	Sep 1995 to Sep 2008	210	8	Wolf River
35.275247	-88.976569	Aug 1929 to Sept 2008	1480	9	Hatchie River
35.637255	-89.609377	Jan 1939 to Sep 2008	2308	10	Hatchie River
34.9075	-89.753333	Oct 1954 to Dec 2008	191	11	Coldwater River
35.055672	-88.799277	Nov 1940 to Dec 1969	837	12	Hatchie River
35.13278	-89.854913	Oct 1986 to Dec 1990	709	14	Wolf River
35.201594	-89.922813	Jun 1936 to Dec 1969	771	15	Wolf River
35.281111	-89.765555	Feb 1939 to Dec 1969	505	16	Loosahatchie River
35.237486	-89.951427	Nov 1976 to Sep 1983	1.26	17	Loosahatchie River
35.189166	-89.761666	Jun 1974 to Nov 1983	1.45	18	Fletcher Creek (trib to Wolf River)
35.187777	-89.835833	Nov 1977 to Feb 1982	21.4	19	Fletcher Creek (trib to Wolf River)
35.168583	-89.824297	Dec 1974 to Sep 1977	3.18	20	Fletcher Creek (trib to Wolf River)
35.128888	-89.710277	Oct 1954 to Jun 1957	13.6	21	Gray's Creek (trib to Wolf River)
35.048485	-90.193094		-	22	Mississippi River: Memphis , TN
34.52862	-90.574797		-	23	Mississippi River: Helena, AR

Baseflow conditions

Ground-water recharge can be partitioned into shallow or deep recharge. Shallow recharge as compared to deep recharge has a short residence time in the subsurface and is the contributor to stream baseflow. Deep recharge is a very small fraction (<5-10%) of the total recharge and becomes an important factor in managing ground-water resources in confined aquifer systems. Unfortunately, deep recharge is difficult to quantify (Stricker, 1983). One method of estimating deep recharge is to quantify the other hydrologic cycle components (precipitation, evapotranspiration, runoff (which includes stream baseflow)) over an area and derive deep recharge via a water balance. However, it is recognized that measurement and instrumentation errors are ineluctable and that the magnitude of the accruing error may exceed deep recharge. Though deep recharge may not be able to be determined, stream baseflow (or shallow ground-water recharge) is still an important factor. In a ground-water system, streams are stressors to the system whether as sinks for ground water or contributors to the ground-water regime. Additionally, ground-water contribution to streams can have an impact on water quality and plays a major role in the biogeochemical cycle of the hyporhic zone.

Within the MERGWS study area, there is not enough hydrologic and geochemical information to draw correlations between stream baseflow and deep recharge or water quality/ biogeochemical impacts. Though these analyses cannot be performed, baseflow conditions of four main MERGWS streams and four tributaries were estimated from discharge records from eighteen USGS gaging stations using three techniques: (1) partial duration curves; (2) streamflow partitioning using the PART software package; and (3) hydrograph separation using the USGS WHAT software package.

Three filter techniques were employed with WHAT: (1) local minimum, (2) BFLOW; and (3) Eckhardt. The gaging stations represent a wide range of drainage areas (1.26 to 788 mi^2) and dates of record (1 to 11 years) (see Table 16).

Partial Duration Curves

Various authors have reported that partial duration curves can be used to indicate values of baseflow or groundwater contribution to streamflow. The partial duration flow curve is a cumulative frequency curve that shows the percent of time which specified discharges are equaled or exceeded in a given period. All of the mean daily flows for a given stream at a given gage are used for developing a partial duration flow curve as opposed to the annual maximum flow where the largest mean daily flow to occur in a given year is used to predict frequency events. To assess baseflow conditions, a flow-duration point can be selected representing the percentage of flow that occurs equaled to or greater than a chosen flow rate, the chosen flow rate and percent often labeled as $Q_{\%}$ (e.g., Q_{90}, Q_{65}, etc…). Stricker (1993) investigated streamflow hydrographs for 35 stations in the southeastern coastal plain of South Carolina, Georgia, Alabama, and Mississippi, following the procedure outlined by Riggs (1963) for developing baseflow recession curves. Stricker reported that baseflow values for streams with a mean baseflow ≤ 10 cfs that either the 60 or 65 percent duration flow would

Table 16. Gaged streams investigated for baseflow conditions

Site Number	Site Name	Latitude	Longitude	HUC8	Drainage (mi^2)	Continuous period(s) of record
State of Tennessee						
7030240	Loosahatchie River at Arlington, TN	35°18'39.11"	89°38'22.13"	8010209	262	1970-2006
7030280	Loosahatchie River at Brunswick, TN	35°16'52"	89°45'56"	8010209	505	1940-1949; 1951-1964
7030295	Tributary to Loosahatchie River at New Allen Road	35°14'14.95"	89°57'05.14"	8010209	1.26	1977-1982
7030392	Wolf River at LaGrange, TN	35°01'57"	89°14'48"	8010210	210	1995-2006
7031500	Mary's Creek near Fisherville, TN - tributary to Wolf River	35°07'44"	89°42'37"	8010210	13.6	1955-1956
7031650	Wolf River at Germantown, TN	35°06'59"	89°48'05"	8010210	699	1970-1985; 1991-1995; 1997-2006
7031680	Fletcher Creek at Sycamore View Road - tributary to Wolf River	35°11'21"	89°45'42"	8010210	1.45	1975-1982
7031683	Fletcher Creek at Whitten Road - tributary to Wolf River	35°11'16"	89°50'09"	8010210	21.4	1978-1981
7031685	Fletcher Creek at Charles Bryan Road - tributary to Wolf River	35°10'06.90"	89°49'27.47"	8010210	3.18	1975-1976
7031692	Fletcher Creek at Sycamore View Road - tributary to Wolf River	35°10'09.41"	89°51'57.74"	8010210	30.5	1997-2006
7031700	Wolf River at Raleigh, TN	35°12'05.74"	89°55'22.13"	8010210	771	1937-1962; 1964-1969
7031740	Wolf River at Hollywood Street	35°11'16"	89°58'32"	8010210	788	1997-2006
7032200	Nonconnah Creek near Germantown, TN	35°02'59"	89°49'08"	8010211	68.2	1970-1983; 1986-1994; 1997-2006
7032222	Tributary to Johns Creek at Holmes Road	35°00'20"	89°52'16"	8010211	5.83	1976-1984
7032224	Johns Creek at Raines Road - tributary to Nonconnah Creek	35°02'05"	89°53'10"	8010211	19.4	1976-1981
State of Mississippi						
7275900	Coldwater River near Olive Branch, MS	34°54'27"	89°45'12"	8030204	191	1997-2006
7277700	Hickahala Creek near Senatobia, MS - tributary to Coldwater River	34°37'55"	89°55'28"	8030204	121	1987-2006

give reasonable estimates of the mean annual baseflow. Because of the geologic similarities between Stricker's sites the MERGWS study area, the Q_{60} was used.

The mean daily flows for the river gages listed in Table 16 were downloaded from the USGS National Water Information System (NWIS) database. The data was sorted in descending order from highest daily value, and the Q_{60} determined using the Weibull criteria. The resulting Q_{60} for each stream is listed in Table 17. Calculations of average annual flow rate per square mile and the intensity are also presented. Outlaw and Weaver (1996) prepared a report of flow duration and low flows of Tennessee streams through 1992. Five stations from this study were reported and are listed in Table 17 with the values from the above report shown in parenthesis. The Q_{60} in the report for the 5 stations compared favorably with those calculated in this report. The same analytical procedures were used in the Outlaw and Weaver (1996) report as was used in this report.

Table 17. Baseflow values estimated using partial duration curves.

Site Number	Site Name	Drainage area (mi^2)	Period of record	Q_{60} (cfs)	Intensity (in/yr)
	State of Tennessee				
7030240	Loosahatchie River at Arlington, TN	262	1977-1982	109 (105)	5.65
7030280	Loosahatchie River at Brunswick, TN	505	1951-1962	118 (117)	3.17
7030295	Tributary to Loosahatchie River at New Allen Road	1.26	1977-1982	0.08	0.86
7030392	Wolf River at LaGrange, TN	210	1997-2005	163	10.54
7031500	Mary's Creek near Fisherville, TN - tributary to Wolf River	13.6	1955-1956	1	1.00
7031650	Wolf River at Germantown, TN	699	1997-2005	450 (439)	8.74
7031680	Fletcher Creek at Sycamore View Road - tributary to Wolf River	1.45	1976-1981	0.19	1.78
7031683	Fletcher Creek at Whitten Road - tributary to Wolf River	21.4	1978-1981	1.2	0.76
7031685	Fletcher Creek at Charles Bryan Road - tributary to Wolf River	3.18	1975-1976	0.27	1.15
7031692	Fletcher Creek at Sycamore View Road - tributary to Wolf River	30.5	1997-2005	2.7	1.20
7031700	Wolf River at Raleigh, TN	771	1951-1962	340 (337)	5.99
7031740	Wolf River at Hollywood Street	788	1997-2005	530	9.13
7032200	Nonconnah Creek near Germantown, TN	68.2	1997-2005	3.3 (1.9)	0.66
7032222	Tributary to Johns Creek at Holmes Road	5.83	1976-1981	0.34	0.79
7032224	Johns Creek at Raines Road - tributary to Nonconnah Creek	19.4	1976-1981	1.3	0.91
	State of Mississippi				
7275900	Coldwater River near Olive Branch, MS	191	1997-2005	81	5.76
7277700	Hickahala Creek near Senatobia, MS - tributary to Coldwater River	121	1997-2005	46	5.16

Computer Program PART

PART is a computer program that uses streamflow partitioning to estimate a daily record of baseflow below the streamflow record (Rutledge, 1998). Rutledge contends that the method of baseflow record estimation is a relatively arbitrary procedure of estimating a continuous record of groundwater discharge, or baseflow, under the streamflow hydrograph. If the stream flow record is incremental (such as daily) instead of continuous, estimates of ground water discharge can be made on an incremental basis. Rutledge further notes that the period of analysis is long enough that the effect on the water balance of changes in storage can be considered negligible; hence, the mean groundwater discharge can be considered the effective recharge.

In PART, the program scans the discharge record for days that fit a requirement of antecedent recession, designates baseflow to be equal to streamflow on these days, and performs a linear interpolation to determine the baseflow for days that do not fit the requirement of antecedent recession. The program is commonly applied to a long period of record to give an estimate of the mean rate of ground-water discharge. Because of possible inner-basin climatic variation, PART should be executed using data over a uniform time period. A uniform time period is derived using the program, SCREEN. Rutledge (1998) provides basin size limits for using PART. For estimating recharge or discharge, only drainage areas larger that one square mile should be used so as to meet the requirement of antecedent recession having to exceed the time increment of the data (1 day) – 500 square miles may be used as the drainage basin upper limit.

PART was used to analyze baseflow conditions in streams using 17 gage sites. Table 18 provides the values of annual mean stream flow, annual mean baseflow, and baseflow index for discharge records at these locations. The baseflow index, BFI, represents the mean annual baseflow rate divided by the mean annual stream flow rate. Two values for the Germantown gage on the Wolf River are presented because of two different discharge periods. Loosahatchie station, 0730240, was not included due to irreconcilable data read errors.

Table 18. Baseflow values estimated using PART.

Site Number	Site Name	Drainage area (mi^2)	Period of record	Mean Streamflow Q (cfs)	Mean Streamflow Intensity (in/yr)	Mean Baseflow Q (cfs)	Mean Baseflow Intensity (in/yr)	Baseflow Index (%)
State of Tennessee								
7030280	Loosahatchie River at Arlington, TN	505	1951-1962	666.63	17.93	141.22	3.8	21.2
7030295	Loosahatchie River at Brunswick, TN	1.26	1977-1982	1.69	18.23	0.18	1.98	10.8
7030392	Tributary to Loosahatchie River at New Allen Road	210	1997-2005	318.17	20.58	198.56	12.84	62.4
7031500	Wolf River at LaGrange, TN	13.6	1955-1956	13.15	13.13	1.11	1.11	8.4
7031650	Mary's Creek near Fisherville, TN - tributary to Wolf River	699	1997-2006	1042.51	20.26	645.07	12.54	61.9
7031650	Wolf River at Germantown, TN	699	1997-2005	1080.15	20.99	658.05	12.79	60.9
7031680	Fletcher Creek at Sycamore View Road - tributary to Wolf River	1.45	1976-1981	2.19	20.52	0.15	1.43	7.0
7031683	Fletcher Creek at Whitten Road - tributary to Wolf River	21.4	1978-1981	37.18	23.6	1.68	1.07	4.5
7031685	Fletcher Creek at Charles Bryan Road - tributary to Wolf River	3.18	1975-1976	5.24	22.4	0.41	1.75	7.8
7031692	Fletcher Creek at Sycamore View Road - tributary to Wolf River	30.5	1997-2005	58.89	26.23	4.07	1.81	6.9
7031700	Wolf River at Raleigh, TN	771	1951-1962	972.11	17.13	533.09	9.39	54.8
7031740	Wolf River at Hollywood Street	788	1997-2005	1286.25	22.17	773.19	13.33	60.1
7032200	Nonconnah Creek near Germantown, TN	68.2	1997-2005	116.49	23.2	9.28	1.85	8.0
7032222	Tributary to Johns Creek at Holmes Road	5.83	1976-1981	7.91	18.43	0.79	1.84	10.0
7032224	Johns Creek at Raines Road - tributary to Nonconnah Creek	19.4	1976-1981	30.92	21.65	2.25	1.58	7.3
State of Mississippi								
7275900	Coldwater River near Olive Branch, MS	191	1997-2005	247.33	17.59	103.49	7.36	41.8
7277700	Hickahala Creek near Senatobia, MS - tributary to Coldwater River	121	1997-2005	182.5	20.49	61.88	6.95	33.9

Program WHAT

Web-Based Hydrograph Analysis Tool (WHAT) is a compilation of computer programs that perform hydrograph separation using three techniques: (1) local minimum method; (2) BFLOW filter; and (3) Eckhardt filter (Lim, et al, 2005). Each of these techniques is applied to discharge records for the stream gages listed in Table 16 for the determination of baseflow conditions. Details of these techniques and results follow.

Local Minimum Method (LMM)

Sloto and Crouse (1996) discuss three methods of hydrograph separation used in the HYSEP (HYdrograph SEParation), a baseflow separation computer package provided by the USGS. The three methods used in HYSEP to separate the base flow from the surface runoff component in a runoff hydrograph are (1) fixed interval, (2) sliding interval, and (3) local minimum. Of these three methods, the local minimum method (LMM), which linearly connects non-adjacent local minimums of discharge to derive baseflow, was selected for the WHAT program. Calculation of the local minimums is based on a single parameter that is solely dependent on the drainage area; hence, hydrogeologic and hydrologic basin characteristics are not properly accounted for and thus may limit the accuracy of this method (Stewart et al, 2007; Lim et al, 2005). However, this method is still accepted and is used here. Results for the selected basins are shown in Table 19.

Table 19. Baseflow values estimated with the WHAT model using the LMM, BFLOW and Ekhardt techniques.

Site Number	Site Name	Drainage area (mi^2)	Period of record	Local Minimum		BFLOW-single filter		Eckhardt – dual filter	
				Baseflow Index (BFI)	Baseflow (in/yr)	Baseflow Index (BFI)	Baseflow (in/yr)	Baseflow Index (BFI)	Baseflow (in/yr)
State of Tennessee									
7030240	Loosahatchie River at Arlington, TN	262	1977-1982	0.36	6.39	0.43	7.64	0.43	7.61
7030280	Loosahatchie River at Brunswick, TN	505	1951-1962	0.31	5.49	0.35	6.35	0.36	6.53
7030295	Tributary to Loosahatchie River at New Allen Road	1.26	1977-1982	0.11	2.07	0.19	3.42	0.12	2.13
7030392	Wolf River at LaGrange, TN	210	1997-2005	0.62	12.82	0.67	13.74	0.64	13.15
7031500	Mary's Creek near Fisherville, TN - tributary to Wolf River	13.6	1955-1956	0.12	1.54	0.15	1.98	0.09	1.14
7031650	Wolf River at Germantown, TN	699	1997-2005	0.64	13.45	0.65	13.71	0.63	13.15
7031680	Fletcher Creek at Sycamore View Road - tributary to Wolf River	1.45	1976-1981	0.08	1.73	0.15	2.99	0.08	1.74
7031683	Fletcher Creek at Whitten Road - tributary to Wolf River	21.4	1978-1981	0.09	2.02	0.15	3.54	0.09	2.05
7031685	Fletcher Creek at Charles Bryan Road - tributary to Wolf River	3.18	1975-1976	0.12	2.64	0.15	3.44	0.18	4.05
7031692	Fletcher Creek at Sycamore View Road - tributary to Wolf River	30.5	1997-2005	0.11	2.79	0.16	4.27	0.19	5.03
7031700	Wolf River at Raleigh, TN	771	1951-1962	0.66	11.29	0.62	10.69	0.60	10.23
7031740	Wolf River at Hollywood Street	788	1997-2005	0.64	14.14	0.64	14.17	0.62	13.66
7032200	Nonconnah Creek near Germantown, TN	68.2	1997-2005	0.16	2.58	0.21	3.40	0.12	1.92
7032222	Tributary to Johns Creek at Holmes Road	5.83	1976-1981	0.12	2.14	0.19	3.44	0.12	2.23
7032224	Johns Creek at Raines Road - tributary to Nonconnah Creek	19.4	1976-1981	0.09	1.88	0.17	3.69	0.20	4.32
State of Mississippi									
7275900	Coldwater River near Olive Branch, MS	191	1997-2005	0.44	7.71	0.51	8.95	0.50	8.81
7277700	Hickahala Creek near Senatobia, MS - tributary to Coldwater River	121	1997-2005	0.37	7.51	0.42	8.62	0.43	8.73

BFLOW Filter Technique

Lyne and Hollick (1979) proposed a baseflow separation technique using low-pass filtering. Arnold and Allen (1999) subsequently migrated this technique to a DOS-based program, BFLOW, later to be incorporated into WHAT (Lim, et al, 2005). In BFLOW, baseflow is determined by subtracting a calculated filtered surface runoff value from the stream discharge quantity using one day increments. Calculation of surface runoff requires only one filter parameter (Lyne and Hollick, 1979). Nathan and McMahon (1990) found that a filter parameter of 0.925 gave realistic results when compared to manual separation; hence, this value is used in this study. Baseflow rates using the BFLOW technique are shown in Table 19.

Eckhardt Filter Technique

Chapman (1991) contends that the recursive low-pass filter proposed by Lyne and Hollick (1979), though fast and objective, does not model well baseflow after cessation of direct runoff. Chapman also suggests that the filter constant should expectedly vary by catchment area. Eckhardt (2005) showed that the filter proposed by Chapman (1991) is a special case of a dual parameter filter that accounts aquifer and stream type. Eckhardt (2005) proposed filter values of 0.80 for perennial streams in porous aquifers, 0.50 for ephemeral streams in porous aquifers, and 0.25 for perennial streams in hard rock aquifers. Ekhardt (2008) conducted a baseflow technique comparison on a random selection of 65 USGS gages previously analyzed in a larger baseflow technique comparison study by Neff et al. (2005), but here also compared to the technique proposed by Ekhardt (2005). The streams were perennial in porous aquifers; therefore, the BFI_{max} filter parameter was set to 0.80. Ekhardt (2008) suggestes that the BFLOW and Ekhardt baseflow estimate technique produce more realistic results (baseflow time series is smooth) than that by UKIH, a local minima technique, and PART (hydrograph characteristics points are connected by straight lines). Ekhardt (2008) goes on to say that his technique as compared to BFLOW produces more hydrologically plausible results.

The Ekhardt filtering technique within WHAT is applied to the gages list in Table 16. These streams are perennial and are in connection with the unconsolidated aquifers of the area; hence, a BFI_{max} value of 0.80 is applied. Baseflow calculations and BFI indexes for the 17 stream gages are presented in Table 19.

Five different methods were used to compute stream baseflows within the MERGWS footprint (Table 20). The computer program, Analyse-It™, was used to develop the statistical understanding of the data. Initially a descriptive analysis was performed that calculated the mean and standard deviation for the five values at each gaging station. A box plot analysis was performed to compare the existing data with the median and provide quartile information. This analysis allowed for the determination of outliers within the data. As shown in Table 20, baseflows estimated using partial duration were consistently below the estimates from the other methods with the exception of Fletcher Creek near Cordova; hence, the partial duration values could be classified as outliers as compared to the other baseflow values. Obviously, selection of a Q_{60} for the partial duration analysis does not seem appropriate and possibly an alternate percent flow duration threshold may result in more comparable estimates. Therefore, the remaining analyses will be performed using the remaining four baseflow estimation methods.

The simple statistical analysis was rerun on the baseflow estimates from the remaining methods. Table 21 details the average and standard deviation for each gaging site. The average data values indicate a wide difference in the average baseflows between the drainage basins, yet a moderate consistency within a basin. There are two interesting observations concerning the baseflows. First, the baseflow calculations on the tributaries to the main streams are much smaller than the calculations for the main stream. The primary difference in the smaller drainage basins that were studied is that they are in the developing urban areas and have been subjected to radical clearing and development during the overall period of study. Also, the time period for the analysis was much smaller on the tributaries than on the

Table 20. Summarization of baseflow intensities.

Site Number	Site Name	Drainage area (mi^2)	Period of record	Partial Duration	PART	Local minimum	BFLOW (single filter)	Eckhardt (dual filter)
				Intensity (in/yr)				
State of Tennessee								
7030240	Loosahatchie River at Arlington, TN	262	1977-1982	5.647	-	6.391	7.64	7.609
7030280	Loosahatchie River at Brunswick, TN	505	1951-1962	3.172	3.8	5.493	6.354	6.533
7030295	Tributary to Loosahatchie River at New Allen Road	1.26	1977-1982	0.862	1.98	2.068	3.415	2.13
7030392	Wolf River at LaGrange, TN	210	1997-2005	10.536	12.84	12.815	13.741	13.154
7031500	Mary's Creek near Fisherville, TN - tributary to Wolf River	13.6	1955-1956	0.998	1.11	1.544	1.978	1.142
7031650	Wolf River at Germantown, TN	699	1997-2005	8.739	12.54	13.452	13.708	13.149
7031680	Fletcher Creek at Sycamore View Road - tributary to Wolf River	1.45	1976-1981	1.779	1.43	1.727	2.993	1.735
7031683	Fletcher Creek at Whitten Road - tributary to Wolf River	21.4	1978-1981	0.761	1.07	2.018	3.535	2.047
7031685	Fletcher Creek at Charles Bryan Road - tributary to Wolf River	3.18	1975-1976	1.153	1.75	2.643	3.439	4.046
7031692	Fletcher Creek at Sycamore View Road - tributary to Wolf River	30.5	1997-2005	1.202	1.81	2.792	4.27	5.033
7031700	Wolf River at Raleigh, TN	771	1951-1962	5.986	9.39	11.294	10.688	10.233
7031740	Wolf River at Hollywood Street	788	1997-2005	9.13	13.33	14.143	14.173	13.664
7032200	Nonconnah Creek near Germantown, TN	68.2	1997-2005	0.657	1.85	2.579	3.399	1.92
7032222	Tributary to Johns Creek at Holmes Road	5.83	1976-1981	0.792	1.84	2.139	3.441	2.23
7032224	Johns Creek at Raines Road - tributary to Nonconnah Creek	19.4	1976-1981	0.91	1.58	1.875	3.689	4.316
State of Mississippi								
7275900	Coldwater River near Olive Branch, MS	191	1997-2005	5.757	7.36	7.708	8.95	8.811
7277700	Hickahala Creek near Senatobia, MS - tributary to Coldwater River	121	1997-2005	5.161	6.95	7.513	8.618	8.731

main streams; however, no cause and effect relationship is obvious.

Secondly, the baseflow on the main tributary of the Wolf River presents some interesting results. As shown in Table 21, Station Average Baseflows with Standard Deviations, the typical baseflow for three of the gages on the Wolf River, namely LaGrange, Germantown, and Hollywood gages, presents the baseflow at approximately 13+ inches/year. However the Raleigh gage, which is immediately upstream of the Hollywood gage, has an average baseflow of 10.4 inches/year. Bradley (1991) discusses the loss of streamflow to the alluvial aquifer proximal to the intersection of Walnut Grove and the Wolf River; however, the decline in discharge falls within measurement error and remains invalidated. Konduru (2007) found similar results as Bradley, yet was plagued with the same issue of discharge values falling with measurement error. The suggested baseflow decline at Raleigh on the Wolf River may be better attributed not to discharge losses, but be reflective of the basin's landuse condition during the time of analysis (see Table 16). In the early 1950's, Memphis and Shelby County had yet to undergo much urban development and most of the area was agricultural. A factor that complicates the estimation of baseflow also at the Raleigh gage is that the Wolf River was dredged and realigned from 1960 thru 1964. Thus, it seems logical to omit the baseflow value at the Raleigh gage. As a consequence, the average baseflow in the Wolf River is approximately 13.39 inches/year using values from the LaGrange, Germantown, and Hollywood gages.

For the purpose of the MERGWS effort, it will be important to capture the recharge and stream-aquifer interactions across diverse landscapes and varying spatial and temporal scales. Baseflow estimates from this investigation provide insight into the stream/aquifer connection, but on a very general scale and thus should be used with caution. Additional gages should only be installed if included as part of a suite of analysis tools for investigating recharge and stream/aquifer interactions for the purpose of validation and ensuring mass-balance.

Table 21. Average baseflow intensities for MERGWS streams.

Site Number	Site Name	Drainage (mi^2)	Period of record	Average intensity (in/yr)	Standard deviation (in/yr)
	State of Tennessee				
7030240	Loosahatchie River at Arlington, TN	262	1977-1982	7.21	0.71
7030280	Loosahatchie River at Brunswick, TN	505	1951-1962	5.55	1.25
7030295	Tributary to Loosahatchie River at New Allen Road	1.26	1977-1982	2.40	0.68
7030392	Wolf River at LaGrange, TN	210	1997-2005	13.14	0.43
7031500	Mary's Creek near Fisherville, TN - tributary to Wolf River	13.6	1955-1956	1.44	0.41
7031650	Wolf River at Germantown, TN	699	1997-2005	13.21	0.50
7031680	Fletcher Creek at Sycamore View Road - tributary to Wolf River	1.45	1976-1981	1.97	0.70
7031683	Fletcher Creek at Whitten Road - tributary to Wolf River	21.4	1978-1981	2.17	1.02
7031685	Fletcher Creek at Charles Bryan Road - tributary to Wolf River	3.18	1975-1976	2.97	1.00
7031692	Fletcher Creek at Sycamore View Road - tributary to Wolf River	30.5	1997-2005	3.48	1.45
7031700	Wolf River at Raleigh, TN	771	1951-1962	10.40	0.80
7031740	Wolf River at Hollywood Street	788	1997-2005	13.83	0.41
7032200	Nonconnah Creek near Germantown, TN	68.2	1997-2005	2.44	0.72
7032222	Tributary to Johns Creek at Holmes Road	5.83	1976-1981	2.41	0.71
7032224	Johns Creek at Raines Road - tributary to Nonconnah Creek	19.4	1976-1981	2.87	1.34
	State of Mississippi				
7275900	Coldwater River near Olive Branch, MS	191	1997-2005	8.21	0.79
7277700	Hickahala Creek near Senatobia, MS - tributary to Coldwater River	121	1997-2005	7.95	0.87

Riverbed conductance

There are a number of factors that govern the exchange of flow between a river and ground water. Such factors would include ground-water levels, river stage, riverbed conductance, bank storage capacity, throughflow seepage contribution, and others. Past studies in the area have used a combination of ground-water levels, river stage and riverbed conductance to numerically model ground-water/surface water exchange (Arthur and Taylor, 1990; Mahon and Ludwig, 1990; Mahon and Poynter, 1993; Waldron, 1995; Arthur and Taylor, 1998). In these models, riverbed conductance was estimated and set as a constant for the entire river length. Other local studies have used river discharge variation to suggest the exchange of water between the two systems (Bradley, 1991) and ground-water age-dating to suggest leakage (Graham and Parks, 1986). To further our understanding on the potential for ground-water/surface water interaction, we assess riverbed conductance using borehole data from geotechnical logs at bridge/river crossings.

The analysis of riverbed conductivities is limited to bridge crossings over the Loosahatchie and Wolf Rivers and Nonconnah Creek. Due to time constraints, the Hatchie and Clearwater Rivers were not investigated. Data acquisition from the Tennessee Department of Transportation and local engineering firms included sieve analyses, boring logs and locations, and geotechnical reports. Based on the historic records available, eight crossings were identified in Shelby County and four in Fayette County (Figure 62 and Table 22).

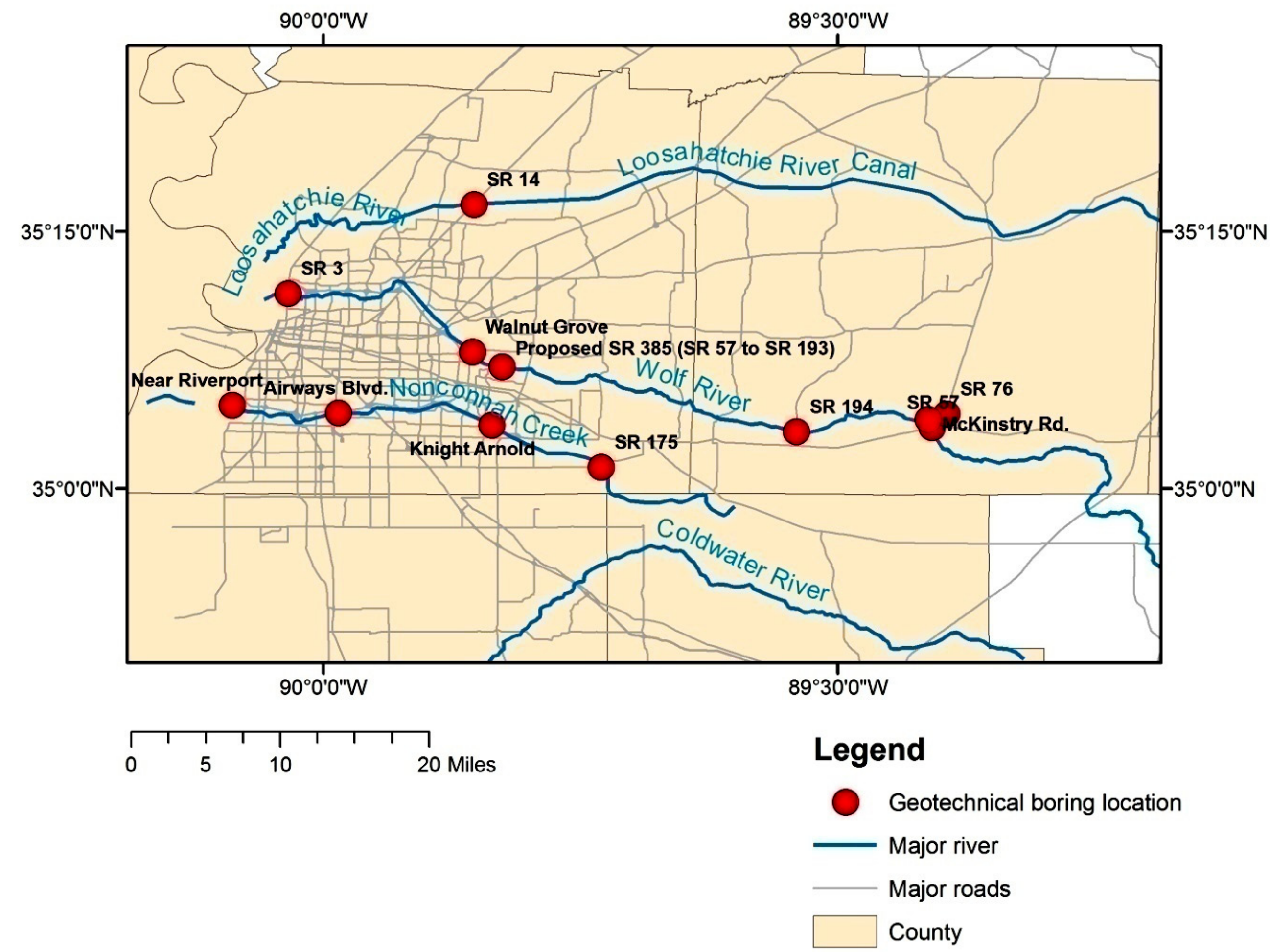


Figure 62. *Bridge crossing locations investigates for geotechnical information on riverbed parameters.*

Table 22. Shelby and Fayette County, Tennessee bridge crossings investigated for geotechnical information on riverbed parameters including an estimation of riverbed conductance.

Crossing	River	County	Boring Logs	Boring Locations	Sieve Analysis	Complete Geotechnical Report	Boring logs used	Estimated K using USCS (m/day)	Estimated K using empirical formulas (m/day)	Comments
SR 14	Loosahatchie	Shelby	Y	Y	N	N	BR-18, BR-19, BR-20, BR-23, BR-24	>0.864 to 0.00000864	N/A	
SR 3	Wolf	Shelby	Y	Y	Gradation Curves	Y	BR-7, BR-8, BR-12, BR-13	0.864 to > 0.864	14.65 to 19.53	Empirical estimate is based on BR-12 and BR-13 gradation curves.
Walnut Grove	Wolf	Shelby	Y	N	N	N	BB-23, BB-26, BB-29	0.000864 to 0.00000864	N/A	
Proposed SR 385 (SR 57 to SR 193)	Wolf	Shelby	Y	N	Gradation Curves	N	N/A	N/A	N/A	Location information on the borings could not be found.
Near Riverport	Nonconnah	Shelby	Y	N	Gradation Curves	N	B-1, B-2, B-12	>0.864 to 0.000864	N/A	Empirical estimate could not be made because the gradation curves were not available at the desired depth
Airways Blvd.	Nonconnah	Shelby	Y	Y	Gradation Curves	N	B-1, B-2	>0.864	N/A	Empirical estimate could not be made because the gradation curves were not available at the desired depth
Knight Arnold	Nonconnah	Shelby	Y	Y	Gradation Curves	N	B-6, B-7, B-8	>0.864 to 0.000864	N/A	Empirical estimate could not be made because the gradation curves were not available at the desired depth
SR 175	Nonconnah	Shelby	Y	N	Y	N	N/A	N/A	N/A	Location information on the borings could not be found.
SR 194	Wolf	Fayette	Y	N	N	N	B-1, B-2	0.864 to 0.00000864	N/A	
SR 57	Wolf	Fayette	Y	N	Y	N	B-1, B-2, B-3	0.864 to 0.000864	1.03 to 1.09	
McKinstry Rd.	North Fork Wolf	Fayette	Y	N	Y	N	B-1, B-2	0.000864 to 0.00000864	1.09 to 2.93	
SR 76	North Fork Wolf	Fayette	Y	N	Gradation Curves	N	B-1, B-2	0.864 to 0.000864	N/A	Empirical estimate could not be made because the gradation curve records were incomplete

Hydraulic conductivity was calculated using the Unified Soil Classification System (USCS) and empirical formulas (Kasenow, 2002) based on soil types and grain size analyses (or gradation curves), respectively. The empirical formulas include Geotechnical reports and supplemental borehole information was used to isolate those boreholes closest to the river. Elevation data from USGS NED's or Lidar was used to ascertain approximate riverbed elevations, unless otherwise stated in reports, to correlate with the corresponding borehole log soil interval depths. It is the soil properties at these depth intervals that an estimate of hydraulic conductivity was calculated.

The six empirical equations used to estimate hydraulic conductivity are Beyer, Hazen, Kozeny, Sauerbrei, USBR (United States Bureau of Reclamation), and Pavchich. Each empirical formula was setup for different conditions but all meant for use with unconsolidated sediment, primarily sand and gravel (Kasenow 2002). In the software package that executes the empirical calculations, the water temperature was set at 10°C. The geotechnical boring records that include sieve analyses show a percent fine for clays. The Number 325 sieve was selected in the software package to represent clay fines as a Number 200 was not an option. The average of the six empirical equations was used to represent the riverbed hydraulic conductivity value.

The estimates of riverbed conductance using the USCS method are not comparable to the estimates obtained from the empirical formulas. This is understandable as the USCS values are generalized, based on the characterization of the soil, and the empirical formulas are tied more closely to the soil composition (grain size). As shown in Table 22, USCS estimates for a single site may vary as much as three to five orders of magnitude (e.g., SR14, Near Riverport, SR 76). To explain this varied range in USCS estimates, one must realize that: (1) the geotechnical boring locations are all proximal to the river, but not in the river; (2) riverbed elevation is projected horizontally to the boring and intersected with the soil stratification column (see Appendix Geo-sites); and (3) all of the boring locations fall within the alluvial plain which results in a complex buried stratigraphy comprised of point bars, oxbows, channel infill, etc.

Only three sites had enough information to estimate riverbed conductance using the empirical formulas (Table 22). SR 3 is close to the confluence of the Wolf River and the Mississippi River (Figure 62). The correlated stratigraphy of two SR 3 borings, BR-7 and BR-8, with the riverbed elevation is near surface resulting in loose, medium grain sand and some rip-rap (excluded from the grain size analysis) (see Appendix Geo-sites). BR-12 indicates sand with gravel, and BR-13 shows sand with some silt. These conditions explain the high riverbed conductance as compared to the other two sites, SR 57 and McKinstry Road. At SR 57, the correlated soils of B-1, B-2 and B-3 with the riverbed elevation are all near surface, resulting in a silty soil. In this area, the Memphis Sand outcrops thus explaining the prevalence of sand beneath the surface (see SR 57 in Appendix Geo-sites). The estimate of riverbed conductance at SR 57 (1.03 to 1.09 m/day) is comparable to that estimated at McKinstry Rd. (1.09 to 2.93 m/day) using the empirical formulas. The estimates can be considered to be comparable due to their close proximity to one another and because the correlated stratigraphy intervals are all near surface and thus may be representative of similar geomorphologic processes and deposition. The correlated soil type for BR-1 at McKinstry is clay with a description of gray/silty (Appendix Geo-sites). Using the USCS method, the riverbed conductance is estimated to be between 0.000864 and 0.00000864 m/day. However determining the conductance using the empirical formulas and the grain size data resulted in a much higher estimate, 1.09 m/day. This discrepancy between these two methods illustrates the importance of using detailed soil data (e.g., grain size analysis) versus generalizing conductance from soil type. The estimate at BR-1 closely approximates the estimate at BR-2 of 2.93 m/day.

Use of the USCS method to estimate riverbed conductance should be used with caution. Obtaining grain size analyses of the riverbed bottom should provide a close estimate of conductance; however, the boundary conditions and initial assumptions for the equations were assumed and the authors of the formulas do not normally recommend criteria for their use (Vukovic and Soro, 1992). This adds to the uncertainty of the estimated riverbed conductance values derived from the empirical formulas. *In situ* measurements of riverbed conductance would provide a better estimate of conductance, and the results can be supplemented with those estimates derived from grain size analyses provided assumptions can be justified. We speculate that determination of a static riverbed conductance may prove difficult as geomorphic processes are constantly changing the river structure, especially in the channelized sections of river where bank failure is common. Where *in situ* measurements are useful for a site specific investigation, a range of conductance values will better serve large-scale applications such as when developing a regional ground-water model.

Wetlands

Wetlands are known to have an interactive role with the local ground-water and other surface water systems; however, specifically what that connection is, is unknown due to the lack of research on this topic in this area. Therefore this subtask focuses specifically on the availability of digital wetland mapping for the area. Here, digital data is considered to be in GIS format, not scanned images of maps or spreadsheet data.

Wetland information is available through the US Fish and Wildlife (FWS) National Wetland Inventory (NWI) program. The FWS office in each state is responsible for the digitization of wetland data into a digital format, this format often being in a GIS. Figure 63 shows the NWI digitization status across the study area. This information is available through the FWS NWI metadata listing at *http://www.fws.gov/wetlands/data/Mapper.html*. Though the metadata layer in Figure 63 does not extend into the northern section of Tipton County, TN, and the eastern section of Hardeman County, TN, these areas are listed as non-digital on the FWS NWI metadata website.

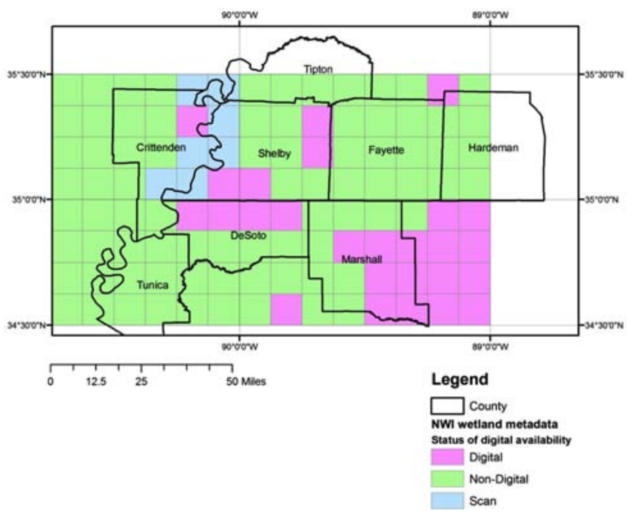


Figure 63. *Status of wetland digitization based on NWI metadata from the US FWS.*

Wetland data was downloaded from the national US FWS website (*http://www.fws.gov/wetlands/index.html*) for Mississippi and Arkansas. Wetland data for Tennessee was accessible through this same site; however, the FWS office in Tennessee hosted digital wetland data for the four counties in Tennessee for areas listed as non-digital on the national FWS website. This discrepancy between the national and Tennessee FWS office on available digital wetland data can be seen in Figure 64 where non-digital and scanned areas (national FWS) overlap areas where wetland data exists (state FWS office). Reasons for this discrepancy are unknown. Wetland classification for the digital data collected follows the National Wetlands Classification standard (Cowardin et al., 1979). A timeline for converting the non-digital and scanned area wetland data into GIS is unknown.

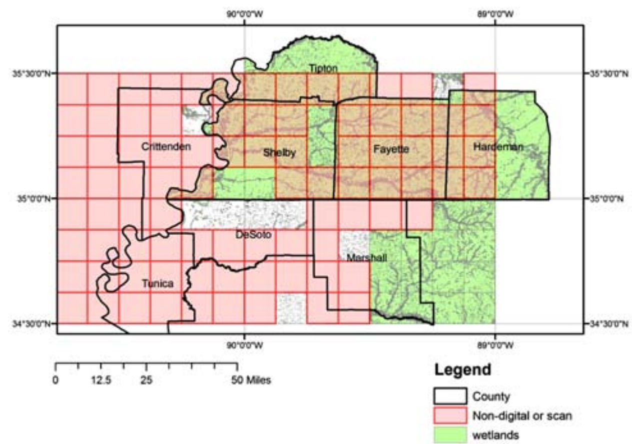


Figure 64. *Discrepancy between the national and Tennessee FWS office on available digital wetland data.*

Soil data

Soil survey maps and data may be important and useful with regards to assessing aquifer recharge, water infiltration, and site location information. Soils are typically derived *in situ* from the materials in place, so that soils may be reflective of the underlying materials and indicative of material property. Utilizing soil survey data may aid in several aspects of this project in the future by providing indicators that may help in quantifying infiltration rates, identifying variability in underlying geologic formations, identifying sites that could be useful for field study, and a variety of other applications. These data sets may also yield proxy information about the aquifers themselves, indicating changes in grain size, distribution, extents, latent heat assessment, and other pertinent information. Data assessments are made from two scales, 1:12,000 and 1: 1:250,000.

For each county, soils data comprised of ArcGIS® shapefiles and Microsoft Access®

tabular databases were acquired from the United States Department of Agriculture (USDA) through the Natural Resources Conservation Service (NRCS) (*http://soildatamart.nrcs.usda.gov*).

Pertinent data to the study within the tabular data were exported by generating a series of reports from within the Microsoft Access databases. These tabular reports, in the form of individual Microsoft Excel sheets, were joined with their corresponding shapefile using the identifier keys within each dataset. The shapefile contained only the shape of the unit and a unique identifier. The tabular dataset contained all available information about the units and types correlated to the soil name and a unique identifier. The unique identifiers were used to join the tabular data to the shapefile data. The resulting dataset has both the spatial extent of the data as well as all the tabular data available for query and interpretation. The data from each county were imported into a single GIS environment for display and interpretation.

Soil survey data is typically generated by a group of individuals that combine field-based and aerial photography (remote sensing) mapping. Field investigation provides for soil pit analyses, determination of the proper soil class, taxonomic characterization, grain size, and other characteristics of the soil and flora. Typically, counties are not mapped by the same individuals, and mapping differences can lead to significant variability between county soil maps when performing detailed analyses. Examples of this variability include delineation of a particular unit in one county that is not identified in an adjacent county despite its presence.

Given the differences in the soil survey mapping techniques, the county data was not merged into a single shapefile database. This was done to preserve the individual county data integrity and to make management for visual investigation and manipulation more simplified. The county datasets can be merged at a later data upon further analysis. The data analyzed describe taxonomic characterization of particle size and soil names. Soil names were not modified, but presented as found within the soil survey tabular data. Joining or displaying tables directly by their original descriptions was impractical as no apparent continuity of data was present and the variable nomenclature increased mapping complexity. Thus, edge matching between counties of the grain size polygons was performed visually to enhance continuity of similar textures and soil units.

The 1:12,000 scale maps at the county level provide high resolution data that may be useful in assessing potential ground water recharge areas. These datasets may provide information relating to recharge and infiltration rates of the aquifer, as well as land cover and land use practices. The derived surface area of infiltration may also allow significant interpretation with regard to ground water recharge and sedimentary unit (aquifer) distribution. Ground-truthing of these data should be conducted to assess their accuracy and hence, their utility. Dissected Loess overlies the primary recharge location of the Memphis Sand aquifer (Plate 8). The impact of this dissected loess blanket over such a broad region of the Memphis aquifer recharge area on ground-water recharge will need to be investigated further. Additionally, distribution of sandy soils may be used as a proxy for outcrop of the Memphis Sand aquifer and direct recharge to the ground water. Correlation of soil type and soil property with MODIS and Landsat data may be helpful in determining evapotranspiration and recharge factors.

The 1:250,000 scale maps are based upon the statewide maps. Though not as detailed as the 1:12,000 scale county soil maps, the regional data provides a general description of the soil properties. This more generalized data may be useful in assigning parameters to a broader region that is useful at the map scale of the geology and aquifer maps/models. The soils maps may help refine the surface geology maps providing contact information and further sedimentary facies information (Plate 9). As expected based on analysis of the 1:12,000 scale soil maps, combination of the state soil maps for Arkansas, Mississippi, and Tennessee yielded inconsistencies in the naming and distribution of materials that will require further work to correct.

Diagnose additional sources/sinks of water to the ground-water system

Two additional stressors to the ground-water system are assessed under this effort, they being recharge and evapotranspiration. Recharge is defined as the natural process of infiltrating rainwater replenishing the ground-water system. Recharge, in a broader sense, can include contributions from surface water and aquifer leakage through aquitards; however, these mechanisms of recharge have been addressed in prior sections. Evapotranspiration represents a loss of water from the system through the combined effect of evaporation and plant transpiration.

Ascertain estimation methodologies for ground-water recharge

Recharge is a critical variable for water-balance within a hydrologic basin, and is thus an essential quantity for evaluating long-term ground-water resource sustainability and quality. Recharge studies have generally focused on arid and semi-arid regions, where water resources are most scarce and recharge is most influenced by near-surface conditions (de Vries and Simmers, 2002). Recharge processes have been addressed to a lesser degree in humid regions (Rushton and Ward, 1979; Sophocleus and Perry, 1985; Wu et al., 1996). Furthermore, recharge estimation in humid regions has focused more on regional-scale estimates, either from water-balance models (see review in Lerner et al., 1990) or ground-water flow models (see review in Sanford, 2002). However, to address issues such as focused recharge and land-use impacts on recharge, point or local-scale values of recharge integrated over varying time intervals are necessary (Scanlon et al., 2002). Common point-methods of recharge estimation employed in humid environments include: Soil-water balance (e.g., Richards et al., 1956; Rushton and Ward, 1979), Lysimeter measurements (e.g., Kitching and Shearer, 1982), Darcy flux (e.g., Steenhuis et al., 1985), environmental tracers (Allison and Hughes, 1978; Edmunds et al., 1988), historical tracers (see review in Cook and Bohlke, 2000), and water-table fluctuation methods (see review in Healy and Cook, 2002). Each of these methods has specific spatial and temporal sensitivity; however, environmental tracers, especially chloride, offer great promise for resolving recharge at a wide range of spatial and temporal scales (Scanlon et al., 2002) and have been underutilized in humid settings.

Environmental tracers offer the opportunity to finely quantify recharge spatially and temporally over an area. The utility of tracers in estimating recharge has been demonstrated in arid and semi-arid environments, where the water-balance approaches are inapplicable (Allison and Hughes, 1983; Gaye and Edmunds, 1996). In this setting, recharge rates are relatively small compared to the measurements of precipitation (P) and evapotranspiration (ET). As a result, small errors associated with measurement of P and ET lead to large recharge estimation errors (Gee and Hillel, 1988; Walker et al., 1991; Phillips, 1994; Wood, 1999) and limit the utility of soil-water balance methods. Application of environmental tracers to determine recharge through the vadose zone have included chloride, ^{18}O and ^{2}H, and the radioactive isotopes, tritium and ^{36}Cl (Allison and Hughes, 1978; Sharma and Hughes, 1985; Daniels et al., 1991; Cook et al., 1994; Reilly et al., 1994; Lui et al., 1995; Wood and Sanford, 1995; O'Brien et al., 1996; Rosen et al., 1999), with chloride and tritium being the most common tracers used.

Defining of aquifer recharge areas within the region is illustrated by Williamson et al (1990) (Figure 65). As seen in Figure 65, West Tennessee is the major recharge zone for the Claiborne and Wilcox aquifers. Unfortunately within the study area, few investigations have estimated the rate of ground-water recharge. Of those estimates that exist, the majority are derived recharge rates from numerical models, but without physical validation. In a numerical modeling study of groundwater flow in the Mississippi embayment, Arthur and Taylor (1998) determined a spatially averaged recharge rate of 1 in/yr. McKee and Clark (2003) simulated aerial recharge rates to the Memphis aquifer in their numerical model of ground-water flow in southeastern Arkansas and north-central Louisiana. Their model calibrated rates ranged between 0.12 and 1.1 in/yr. Brahana and Broshears (2001), using a numerical groundwater flow model in the Memphis, Tennessee area, determined a recharge rate of 0.16 to 1.42 in/yr for the Memphis aquifer recharge area. Bailey et al. (1993), in their numerical ground-water model of Jackson, Tennessee, estimated recharge rates in the Memphis and Fort Pillow aquifers outcrop area using measurements of Q_{60} for two rivers crossing the region. These rates ranged between 5.7 and 8.1 in/yr with model calibrated values averaging around 9.0 in/yr. An investigation by Waldron (personal communication) used meteoric chloride as a tracer within the vadose zone in Fayette County, Tennessee, following recharge estimation procedures commonly implemented in arid environments (Allison and Hughes, 1978; Cook et al., 1994; Sukhija et al., 1996). They estimated recharge to occur at 0.64 in/yr; however, analysis of chloride in ground water resulted in a rate of 5.9 in/yr. Such differences between the two methods are commonly encountered with this method, especially in situations of higher recharge rates (Wood, 1999; Scanlon et al., 2002). Despite the difference in recharge rates obtained by Waldron et al, values are generally within the range of estimates obtained using aforementioned methods in the region. Emphasis should be placed on the need to assess spatial and temporal scales when estimating recharge rates. No one single recharge estimation technique will work in all situations; hence, a suite of methods (water balance, lysimeters, tracers, etc.) should be employed.

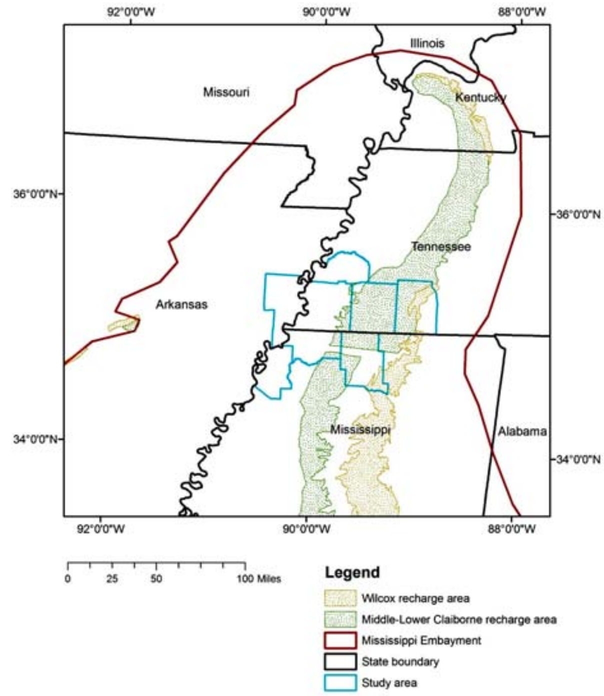


Figure 65. *Delineation of Middle and Lower Claiborne and Wilcox recharge areas within the Mississippi Embayment.*

Evaluate methods for estimating evapotranspiration

Evapotranspiration is the combined sum of evaporation and plant transpiration. Together they represent a significant water loss from a watershed. These two sources account for water reaching the ground that is then lost back into the atmosphere, through soil processes, leaf canopy transpiration, and surface water evaporation. The principal factors affecting and driving evapotranspiration are radiation, air temperature, humidity, and wind speed.

In addition to soil water content and hydraulic conductivity, soil evaporation is mainly determined by the fraction of solar radiation reaching the soil surface. This fraction is decreased by the presence and density of plant cover, which primarily loses water through transpiration, thus both soil and vegetation types significantly impact the relative water loss rates. Accurately gaging ground water recharge and losses requires the quantification of evaporation, transpiration, and infiltration rates, all of which require the measurement of multiple variables.

Water loss due to evapotranspiration is poorly known and quantified within the study area. The variability of this component of the water cycle is of critical importance and needs to be assessed to ensure correct model parameters are used for ground water flow modeling (Brahana and Broshears, 2001). To date, few systems are in place to estimate evapotranspiration within the study area.

Evapotranspiration can be measured, but not directly by any method. Accurate and precise data must be derived from several types of data such as heat flux, soil moisture retention, CO_2, water vapor, and other flux and trace gas measurements (Brotzge and Crawford, 2003). Quantifying evapotranspiration is a complex process requiring a number of factors, algorithms, and assumptions that must be made that vary based upon the estimation or measurement method employed. Regardless of the methodology employed, several empirical relationships and constants must be established and known, given the conditions under which measurements are being made.

There are three general approaches to estimating evapotranspiration: (1) satellite derived; (2) site measurement; and (3) a combination of the two. Assumptions and algorithms vary depending upon the method, equipment, resolution, and datasets used. Two primary methods for calculating (estimating/measuring) evapotranspiration are herein considered for their usefulness and application in this study; these shown in Table 23.

Table 23. List of evapotranspiration estimation methods.

Evapotranspiration Measurement/Estimation Methods	
Point Measurements	Weather station (using Penman-Monteith method (Monteith, 1965)
	Bowen Ratio measurement (Using Bowen Ratio estimation method, Bowen, 1926)
	Eddy Covariant Method (using Eddy Covariant Correlation Coefficient)
Remote Sensing Measurements	MODIS Evapotranspiration estimates
	Landsat Heat Flux Proxies for Evapotranspiration
	rGIS-et GIS tool (using a combination of MODIS and Landsat datasets with ground truthing performed onsite)

Physical sampling methods

Point measurement/estimation systems rely on microclimate towers, typically 2-3 meters in height, prepositioned at a particular location of interest, which can be used to measure some or all of the necessary parameters needed to quantify evapotranspiration at that location. Unmeasured variables are estimated or input from user-defined parameters. Sampling site footprint size will be nearly identical for each method type, as all point measurement systems employing microclimate towers are influenced by similar fetch variations from nearby vegetation. Site variability is important and must be understood and included into the methodologies. Not all sites are applicable to these methodologies as irregular footprints or close proximity to tall forests will impact measurements. Variables such as soil type, solar incidence angle, land cover, microclimate, wind, vegetation type and mass, and other factors can drastically alter evapotranspiration estimates from site to site (Allen et al., 1998). Land cover is important to the measurement as each land cover type or land use type has a different crop coefficient that must be used in the evapotranspiration calculation. Further, each soil type will have different moisture transfer and storativity properties that must be included into the measurements and/or the assumptions used in the equation (Brotzge and Crawford, 2003). Micrometerological sampling methods have significant advantages over lysimeter and soil moisture sampling methods in that they do not require significant manpower and attention, can be employed and readily moved, they can be used for short or long durations, and they provide constant flux measurements (Fritschen, 1965).

Weather Station Derived Penman-Monteith Data

Simple weather station derived evapotranspiration estimates are possible using the Penman-Monteith equation. This method entails the measurement of daily mean temperature, relative humidity, wind speed, and solar radiation (Monteith, 1965). These measurement parameters are sensitive to physical conditions in the area such as land cover, NDVI (normalized difference vegetation index), and vegetative indices (e.g., stomata resistance and conductance). The Penman-Monteith method utilizes the crop coefficient that best emulates vegetation site conditions. This methodology requires assumptions related to the energy heat fluxes to complete the calculation of evapotranspiration, thus forcing closure of the energy budget (Monteith, 1965).

The modified Penman-Monteith equation is a preferred evapotranspiration estimation method by the Food and Agriculture Organization of the United Nations (UN FAO) for estimating cropland evapotranspiration over a wide variety of vegetative indices, available crop types, and instrumentation data on weekly or monthly time steps (Allen, et al., 1998). Allen and others (1998) found that the more simplistic approach and application of the Penman-Monteith equation often produced erroneous results in estimating evapotranspiration in anything other than the reference crop used to parameterize the equation. The usefulness and accuracy of this equation can be improved with the physical measurement of the heat flux variables (Allen, et al., 1998). They realized that the method could be much improved when a local wind calibration was performed, the local aerodynamic term remained relatively small, and where detailed temperature measurements of the near surface ground height and soil were performed. The American Society of Civil Engineers (ASCE), UN FAO, and European counterparts have found that by providing more site specific higher resolution data, the Penman-Monteith equation can be applied successfully (Allen et al., 1998). Benefits of this method include its relatively low cost, ability to account for common different crops and its ease of application.

Bowen Ratio

The Bowen ratio (B) equation is used to estimate evapotranspiration through calculating the ratio of energy fluxes between mediums, specifically sensible (potential energy) and latent (amount of energy released) heating; hence $B = Q_h/Q_e$ where Q_h is sensible heating and Q_e represents latent heating (Bowen, 1926; Lewis, 1995). To estimate evapotranspiration, sensible and latent heat fluxes are derived through measurements of surface net radiation, temperature, total soil heat flux, and vapor pressure between two points. Such measurements are typically conducted at heights of 2 to 3 m; however, up to 10-meter heights can be used for larger site footprints or to reach above forest canopy (McNeil and Shuttleworth, 1975; Brotzge and Crawford, 2003). Rather than measuring all components of the energy cycle, the Bowen ratio method forces closure of the energy budget as the eddy diffusivities of heat and moisture are assumed to be equal. Forced closure of the energy budget makes the Bowen ratio method easier to employ, decreases measurement complexity, increases instrument simplicity, and is typically less expensive than Eddy Covariance methods. Estimates by McNeil and Shuttleworth (1975), Shuttleworth and others (1984), Dugas and others (1991), and Brotzge and Crawford (2003) suggest Bowen ratio measurements may overestimate the evapotranspiration in some environments and vegetation types; the biggest concerns are found within arid environments. Detractions to the method are that closure is forced and the eddy diffusivities of heat and moisture must be assumed equal (Brotzge and Crawford, 2003).

Eddy Covariance

Eddy Covariance is an evapotranspiration measurement technique where the energy balance is closed through flux measurement rather than assumption (Dugas et al., 1991; Brotzge and Crawford, 2003). The Eddy covariance is computed as the covariance between instantaneous variation in vertical wind speed from the mean value and instantaneous deviation in gas concentration mixing ratio from its mean value; these are then multiplied by the mean air density (Burba and Forman, 2008). This technique is extensively employed for validation and tuning of global climate models and regional satellite estimates (Mu et al., 2007). Detractions to the Eddy Covariance method typically include the increased complexity and number of instrumentations and high cost compared to the Bowen ratio method. Continued demand for this technique is resulting in improvements in instrumentation and a reduction in cost.

Eddy covariance is more sensitive to local conditions such as fetch and wind direction (Brotzge and Crawford, 2003). Benefits of the method stem from true closure of the energy budget by measuring the four component fluxes of the energy budget rather than assuming or forcing closure (Brotzge and Crawford, 2003). Another advantage of the method is that failure to close the energy budget through measurements provides a real-time quality control on evapotranspiration values and thus possibly improper working of the instrumentation.

Comparison of Point Measurement Systems

As discussed, there are advantages and disadvantages to each type of point measurement system. There are arguably variations in accuracy and reliability of the methodologies, suggesting each has its place in its intended application. All three proposed methodologies are: (1) accepted within the scientific community; (2) considered reliable; and (3) not cost prohibitive. Comparison of these and other factors for the three point measurement techniques are shown in Table 24. All point measurement systems (microclimate towers) require several design requirements/assumptions: (1) the point measurement represents the upwind area from the instrumentation; (2) measurements are performed within the selected site set to a height above the dominate vegetation type of interest at the site while avoiding influence by nearby vegetation; (3) the fetch terrain is relatively uniform, flat lying or has a consistent slope; and (4) any assumptions made on local variables remain constant throughout the sampling period.

Satellite/Remote Sensing Sampling Methods

Remote sensing is another way to estimate evapotranspiration. Typically this is performed via satellite; however, it may not be solely a satellite derived product and often requires the use of ground-based point measurement data to derive evapotranspiration and other products (Mu et al., 2007). Instrumentation aboard the NASA Aqua AIRS, CERES, and MODIS satellites provides sufficient input data to calculate evapotranspiration.

MODIS/Landsat

Remote sensing estimates of evapotranspiration derived from satellite-based instrumentation are available from the Center for Space and Remote Sensing Research. Evapotranspiration available from MODIS data is processed following Mu et al (2007). Cleugh et al (2007) noted deficiencies in previous satellite derived estimates and generated a new algorithm that better matched ground truthing stations for a variety of land cover types.

Table 24. Comparison of point measurement evapotranspiration methods.

Point Measurement/Estimation Comparison				
Method	**Assumptions**	**Accuracy**	**Cost**	**Pros/Cons**
Weather Station (Penman-Monteith)	Several	Moderate	Low	Easiest, most reliable, and robust least accurate
Bowen Ratio Method	Few	Average to high	Medium	Moderate ease of use, moderate cost, High Accuracy, some assumptions
Eddy Covariance Method	None	High	High	Highest Accuracy, full measurement of the energy budget

Mu et al (2007) based their work on the work of Cleugh et al (2007) to include and calculate canopy conductance and evapotranspiration to generate the current MODIS evapotranspiration data. The MODIS data set utilizes an algorithm that considers both the surface energy partitioning processes and environmental constraints on evapotranspiration. The MODIS dataset also uses 19 ground-based meteorological observations (AmeriFlux Eddy Covariance flux towers) tied to remote sensing data from MODIS to estimate global evapotranspiration. Mu and others (2007) cite an improvement of the correlation coefficients from 0.70 to 0.76 with the inclusion of tower derived meteorological data as opposed to just using satellite-derived data. Evapotranspiration is calculated by Mu and others (2007) by adding vapor pressure deficit and minimum air temperature constraints on stomatal conductance, using leaf area index as a scalar for estimating canopy conductance, replacing the NDVI with the Enhanced Vegetation Index thereby also changing the equation for calculation of the vegetation cover fraction, and adding a calculation for soil evaporation.

The available datasets are eight day averages of the evapotranspiration variations presented within a 1-km (0.62-mile) resolution grid. Benefits to the method are ease of use, the data is available in a GIS projected raster format and no cost. Detractions to utilizing this data are lack of control towers currently available within or near the MERGWS study area (Figure 66), and the evapotranspiration estimate is subject to cloud interference requiring the use of the previous cycle's data to complete the derivation of evapotranspiration.

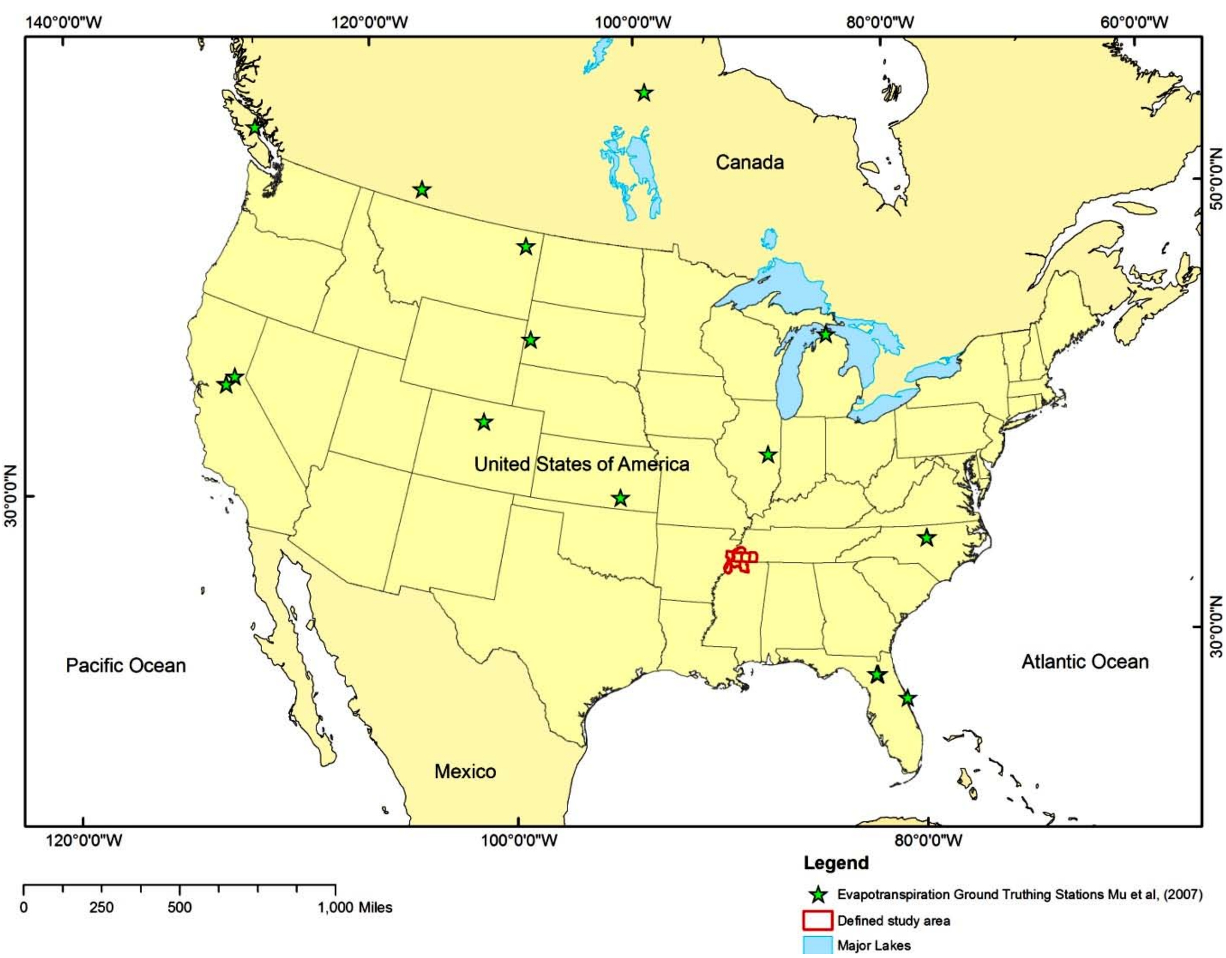


Figure 66. *Location of evapotranspiration control towers proximal to the study area*

Landsat datasets illustrating relative heat flux measurements from a twice-daily pass may also aid in assessing evapotranspiration variability within a small area by measuring heat flux variability before and after storm events. Heat flux variability after storm events may be helpful in assessing where small-scale changes in soil, slope, and land cover variability (including seasonal changes) exist within a particular site or may yield clues as to which sites are intrinsically more variable than others. Applicable Landsat datasets are available at higher resolution (60 m and 250 m) and frequency (daily) than MODIS data. Several European satellites that are taking measurements over the United States may provide additional data toward estimating evapotranspiration across the MERGWS study area. Presently, only MODIS data appears to have evapotranspiration estimates as a product.

rGIS-et

rGIS-et is a GIS-based tool that utilizes both satellite MODIS, Landsat datasets and ground truthing stations of winter wheat and/or summer maize fields to estimate evapotranspiration. This tool is designed to allow the rapid processing of large amounts of satellite data to yield 250 m resolution evapotranspiration raster data sets on a daily basis. The tool is designed to be user friendly and a direct plug-in into ESRI's® ArcGIS Desktop software. Surface temperatures and albedo are key parameters in calculating evapotranspiration utilizing a surface energy balance algorithm (Shu et al., 2006; Yuping et al., 2006). Yuping et al (2006) added a module to rGIS-ET (v2.0) allowing for the adjustment of surface temperature and solar radiance and providing a capacity for terrain correction and shaded relief to improve the estimate of evapotranspiration. Benefits to this method include higher resolution data over shorter time intervals as opposed to eight-day intervals. Ground-truthing will be problematic as these modules are currently tied to the previously mentioned ground-truthed crop types and the climate of present application (southern China); however, the algorithm could be modified to a different latitude and crop type. Detractions also include a non-standard and non-widely accepted methodology for calculating evapotranspiration.

Land Cover

Land cover/vegetation type is a primary factor necessary by design when assessing evapotranspiration for a location. Land cover/vegetation types and their distributions found throughout the study area are displayed in Figure 67. Sampling site locations that are at least 1 km^2 in area and of relatively uniform shape are recommended for successful implementation of the point measurement methods. To employ any point measurement system, it is necessary to understand and quantify the land cover/vegetation distribution and attain evapotranspiration estimates for each land cover subtype based upon distribution and area. A more accurate and complete understanding and assessment of evapotranspiration can be achieved through distributed modeling of evapotranspiration with land cover/vegetation type, which in turn can be used to calculate one of the key factors in the overall hydrologic water cycle budget.

The method employed to identify land cover locations suitable for this study was performed within ESRI's® ArcGIS utilizing 2001 land cover datasets. Given the necessity of a large upwind area of a like vegetation type, polygons of ½ mi^2 and greater were delimited for each land cover type. Refinement of plausible instrumentation deployment sites was performed based on a site's shape uniformity (i.e., elimination of irregularly shaped areas). Irregularly shaped areas were culled out by calculating an ideal perimeter for the land cover polygons by taking the square root of the calculated area and multiplying that value by four. This ideal perimeter was compared to the actual perimeter, and the resulting ratio used to eliminate land cover polygons of irregular shape. Results were verified using aerial photography of the region.

As shown in Figure 68, there is a scattering of possible areas where estimation of evapotranspiration may be made using the point methods discussed. The total available area covers only 18% of the 8-county footprint. Of this 18%, the major land type cover is cultivated crops (74%) with the greatest coverage in Crittenden County, Arkansas, Tunica County, Mississippi and Tipton County, Tennessee. The presence of this land cover type in these areas (see

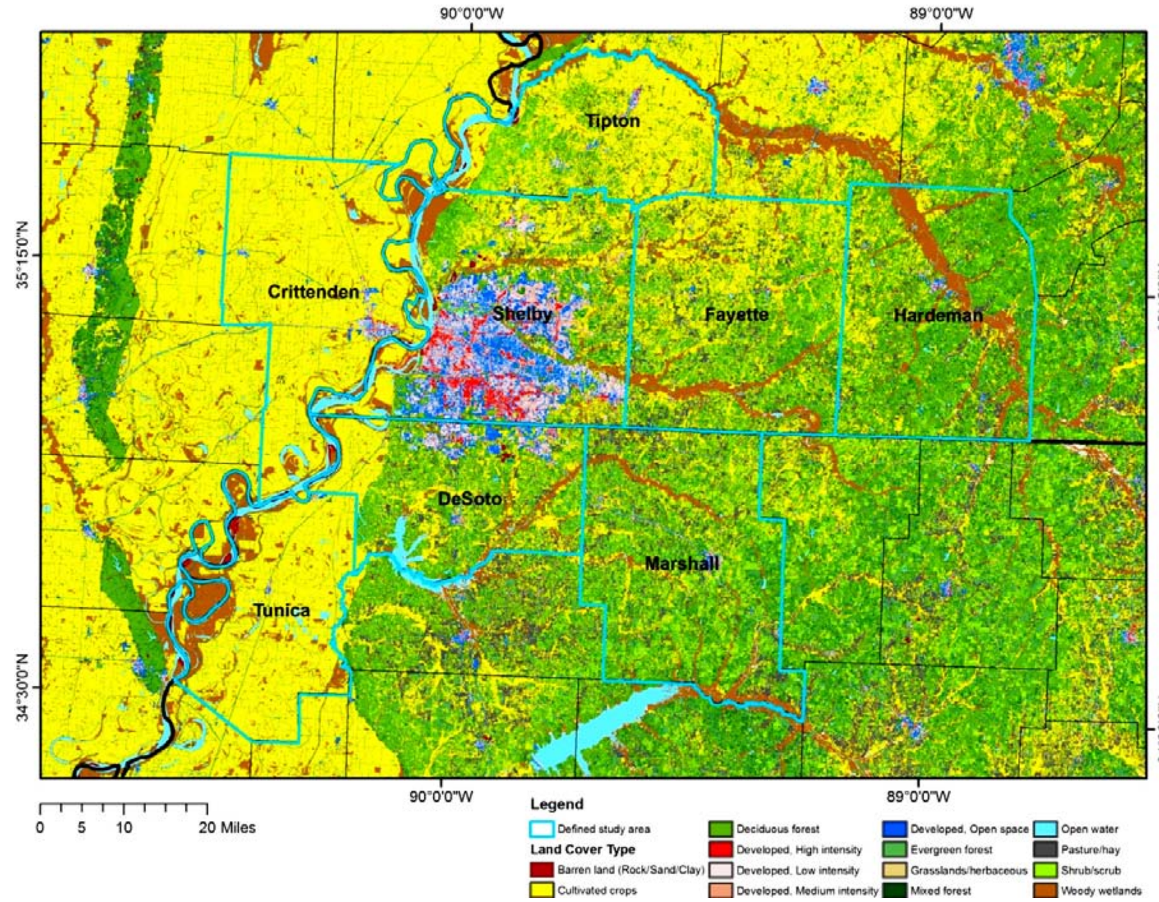


Figure 67. *Land cover types present within the study area at 200 meter resolution (from MRLC consortium 2001 Land Cover Database).*

Figure 67) is understandable based on the amount of rice, cotton and soy agriculture in these counties. Forested areas (< 5%), excluding wetland habitat, was unexpectedly small; however, wetland areas were large (17%) with coverage primarily along the Wolf River in Tennessee, Coldwater River in Mississippi and along the Mississippi River. Not shown in Figure 68 but illustrated in Figure 64 is the developed area of Memphis, Tennessee in Shelby County. Though the high, medium and low developed land cover areas could be lumped into a single "developed" land cover classification, it is unknown if the heterogeneity of the developed areas can be accurately represented using a point measurement method. Certainly combining point measurement data with remote sensed data will offer the greatest means at estimating evapotranspiration contiguously over the MERGWS footprint.

Concluding remarks

There are multiple methods that can be used to estimate evapotranspiration within the study area. Two remote sensing applications and three point measurements methodologies have been proposed. The three point-based measurements (weather station, Bowen ratio towers, and eddy covariance towers) differ in the type of instrumentation being deployed, the number of assumptions, the cost, and the equations being employed. Each point measurement method requires similar, if not identical, local site conditions that enhance sampling accuracy of the evapotranspiration measurement. Those conditions include, fetch, uniform land cover distribution (similar growth height), measurement or estimation of heat flux, uniform slope, and limited microclimate variation. Each of these point measurement/estimation methods is reasonably accurate and locally representative of a similar area of

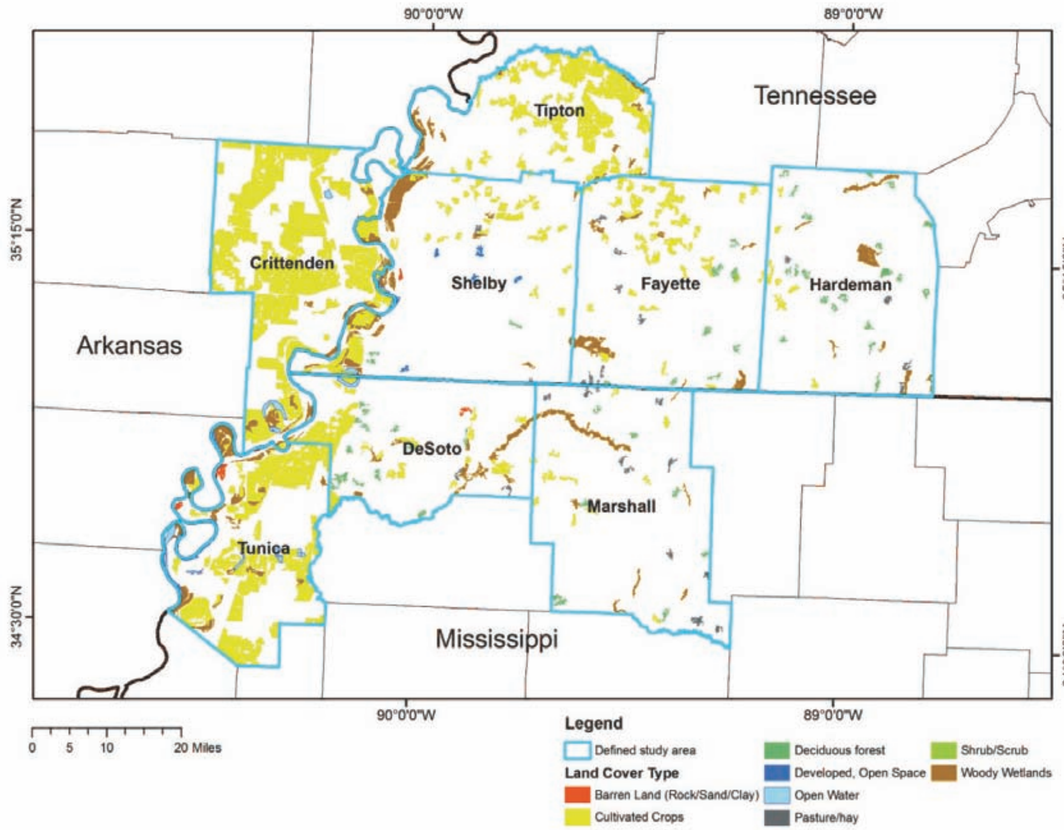


Figure 68. *Depiction of contiguous areas of similar land cover type for possible implementation of evapotranspiration point measurement instrumentation.*

coverage based upon wind speed and tower height. All three methods can be deployed for extended measurement at remote locations.

Bowen ratio and Eddy Covariance methods are most suitable for extended, unmaintained sampling as fewer assumptions are required and local recalculations are not as necessary as with the standard weather station derived Penman-Monteith (Dugas et al., 1998). The Eddy covariance stations are the most accurate, site specific deployable systems which rely upon the fewest number of assumptions, directly measuring the heat flux. Given the available options, the recommendation is to deploy eddy covariance stations alongside basic weather stations calculating evapotranspiration using the Penman-Monteith equation. This setup will provide initial robustness of the calculation and the weather stations can be calibrated alongside the eddy covariance stations, potentially allowing the eddy covariance stations to be moved to new sample locations while the weather station continues to sample and record evapotranspiration at the original site. Additionally, it is recommended that these point measurements be run on identical land cover types to determine if the measurements at similar land cover types are representative and can be applied to the remaining land covers of similar type within the study area, thereby, reducing deployment cost and time.

Remote sensing data allows for evapotranspiration estimation over a broader region than the site measurements. Currently the only scientifically accepted method is to utilize the MODIS datasets with the 1 km resolution. Unfortunately the MODIS data does not allow for local station correction as the data is provided only as a raster output. However, the measurements from the eddy covariance towers could be provided to NASA to be incorporated within the evapotranspiration calculation from the raw MODIS data (Mu, Q., personal communication, 2007). Processing

Landsat data will not net true evapotranspiration rates, yet only indicate where higher variability may exist within the study area. The rGIS-et tool is primarily designed for two crop types, neither of which is used within the study area. This puts limitations on how and where this method can be employed; thus, it seems ill-suited for use within the MERGWS study area.

6.0 Summary and Recommendations

The purpose of this study was to investigate, document, and build a comprehensive database to assess long-term sustainability of the quantity and quality of ground-water resources in the tri-state area of Tennessee, Mississippi and Arkansas. Demand for ground water by agriculture, municipalities and industry is presently stressing the sustainable yield of the aquifers. The stresses on the aquifer systems have led to localized ground-water contamination which in certain instances have closed water-treatment facilities (e.g., Parks, 1990; Bradley, 1991; Parks and Mirecki, 1992; Gentry et al., 2006), declines in the potentiometric surfaces of unconfined and confined aquifers (Parks, 1990; Kingsbury, 1996; Fitzpatrick et al., 1990; Hays and Fugitt, 1999; Arthur, 2001) and localized declines in water quality (Parks et al., 1995; Larsen et al., 2003; Gentry et al., 2005; Schrader, 2001). These problems have the potential to threaten human health as well as impede economic development in the region. This study is the first phase of a four-phase research effort to understand, model, and suggest best management practices for the ground-water resources in the tri-state area of Tennessee, Mississippi, and Arkansas.

The objective of Phase I is to develop the intellectual, organizational, and methodological foundation for the subsequent three phases. Phase I specifically addresses EPA's mission of protecting human health and the environment by (1) conducting an assessment of data stores existing at the state and local level, (2) evaluating data needs at the regional scale that will sharpen our understanding of the regional ground-water system and its connection to other environmental processes, and (3) organizing data collection practices on a regional scale that will assist with addressing ground-water resources in a holistic manner. The work plan for Phase I was subdivided into five main topics: (1) perform geologic mapping of the region; (2) ascertain water quality changes and ground-water contamination threats; (3) conduct assessment on aquifer parameter values and measurement methodologies; (4) catalog surface water sources to ground water; and (5) diagnose additional sources/sinks of water to the ground-water system.

Regarding the geology of the region, the various geologic units of interest (Tertiary and younger) are referred to by many names. This variability in naming convention only scratched the surface of the underlying issue which was the discontinuity in mapping these units at a regional scale with unit delineation often terminating at state boundaries. Additionally, little work had been done prior on identifying and mapping interbedded units of significance, again within a regional framework. Through this investigation, a number of high-quality geophysical logs were analyzed and unit boundaries identified and mapped, this resulting in reducing but not eliminating the aforementioned deficiencies. Further work is still needed to address gaps in our understanding of the geologic framework that will include drilling exploratory boreholes (that can be converted to observation wells) and geophysical mapping.

Water quality data availability varied by state and was often greatest within the aquifer of primary use. In Eastern Arkansas and northern Mississippi, water quality data was greatest in the Quaternary Alluvial aquifer. In Tennessee, it was the Middle to Lower Claiborne aquifer. Still, an attempt was made to assess water quality changes over time across the aquifers of interest. Water quality in the Quaternary Alluvial aquifer is suitable for municipal use, yet is widely used for irrigation. Water chemistry in this system is strongly correlated to recharge sources, but also suggests infiltration of waters at depth through faulting. Water usage from the Upper Claiborne aquifer within the study area is limited mostly to West Tennessee, primarily withdrawn for irrigation. With the limited data in the study area, definite associations between water quality and possible sources cannot be easily drawn. Contrary to data availability in the Upper Claiborne, a large amount of water quality data exists for the Middle Claiborne aquifer. This system is relied upon heavily by municipalities and industry because of its high quality. Changes in water chemistry are due to recharging water in the unconfined areas (outer aquifer margins) and localized upwelling of deeper water as well as water exchange from upper aquifers. The Lower Claiborne - Wilcox aquifer is also of high quality, yet is subject to deeper water intrusion, thus increasing salinity in place, especially south toward the Gulf of Mexico. Relationships amongst water sources and processes affecting water quality are most clear in the Quaternary Alluvial and Upper Claiborne aquifers, and less so in the Middle and Lower Claiborne-Wilcox aquifers. This seems likely due to the lumped classification of these aquifer units. More detailed analysis of the water quality trends and factors in the lower Tertiary aquifers will require further subdivision of the aquifers and regional consistency in application.

A hidden or out-of-sight impact to water quality is a reduction in the integrity of aquitards to prohibit ready exchange of vertically adjacent ground waters. Often called breaches or windows, the presence of these features, whether geomorphic or tectonic in origin, have resulted in the exchange of younger more contaminant prone ground water to leak into deeper, more pristine ground water reservoirs. Though these breaches are local in scale, the capacity for ground water exchange through them can have a regional and possibly costly impact on water quality. Understanding the originating processes that formed these breaches and their extent and characteristics should be a major driver for future investigation, especially since many of the breaches identified occur in heavy urban areas.

Critical components that should be well understood and quantified to address the long-term sustainability of the quantity and quality of ground-water resources in the tri-state area are the inputs and outputs to the ground-water system and the characteristics of the geology through which the water flows. Regarding the latter, no comprehensive effort has been performed to regionally assess aquifer parameters such as hydraulic conductivity and storativity – porosity can also be added to this list though not analyzed in this study, yet is important for contaminant transport. Additionally, the hydraulic conductivity of aquitards is also important. Greater aquifer parameter data exist than that for aquitards; however, a data confidence analysis on the available data suggests that only 23 of 122 aquifer tests are reliable; these 23 tests all within Shelby County for the Lower Claiborne and Upper Wilcox aquifers. A concerted effort to quantify aquifer/aquitard parameters over the seven-county study area and bordering counties should be included in any future work. As part of this recommendation, assessment of parameters for the Lower Claiborne aquifer over its larger thickness should be considered as the interbedding of significant clay units within this aquifer may compartmentalize flow and thus result in a possible differentiation of water quality within the aquifer.

Surface water sources to the ground water system include rivers and wetlands. There are five major river systems in the study area - the largest of which is the Mississippi River; however, the four investigated as part of this study are tributaries to the Mississippi River. Of these four tributaries, three were investigated for riverbed hydraulic conductivity, yet all four and some of their tributaries were analyzed for baseflow conditions. Results from the conductivity assessment indicated that USCS soil classification did not provide reliable results as conductivity values could vary as much as five orders of magnitude. Determination of riverbed conductance by empirical means did provide a smaller range of values; however, the number of grain size analyses available for analysis is very limited. Obtaining good estimates of riverbed conductance is necessary to properly model ground water/surface water interaction. To this end, it is recommended that *in situ* determination of riverbed conductance through additional grain size analyses (none of those available were actually taken from the river channel) or from falling head permeameters be deployed within the stream channel.

Baseflow conditions for 17 gages within the study area were assessed. Period of record for the gages range from 1 to 11 years with the average period of record around 5 years. Unfortunately, the number of river gages is limited, discontinued over time either because the project for which the gage was installed ended or they were simply discontinued due to budgetary constraints. The greatest number of gages exists on the Wolf River and its tributaries. A comparison of baseflow conditions along the Wolf River shows a change in baseflow between the period of 1951-1962 and more recently 1997-2005. This change is attributed to land use change of the area; however, this assessment is complicated by the fact that the Wolf River was dredged and channelized in the early 1960's. The remaining river systems have either a single gage or the period of record for multiple gages on the same river system do not correlate; hence, few conclusions can be drawn. Should river gages be reinstituted at a greater density in Phase II of this effort? We recognize that gaging will be required to provide closure to the water balance budget, but whether or not permanent gages are needed has yet to be determined. Accessibility and safety are two important factors that should play a role in this decision.

For this investigation, wetland data was compiled for the seven-county study region. No assessment was planned for determining the impact of the wetlands to ground water quantity and quality. Wetland information was obtained in GIS format from the US Fish and Wildlife (FWS) National Wetland Inventory (NWI) program. Wetland coverage for the four study area counties in Tennessee is complete, yet dated. Mississippi has partial coverage (~50%) in two of the three investigated counties while Crittenden County, Arkansas has less than 10% coverage. Wetlands are expected to have an interactive role with the local ground-water and other surface water systems; however, specifically what that connection and their importance are will need to be determined during Phases II and III.

Two additional processes that will play a critical role in assessing the sustainable yield and quality of ground water in the region are evapotranspiration and recharge. Evapotranspiration will be important for closing the water balance, especially in Arkansas and Mississippi where flooding of rice fields is most predominant. A variety of techniques are available for estimating evapotranspiration that range in price and accuracy; however, determination of the most appropriate method will depend on site scale and its characteristics. Where smaller, mobile evapotranspiration towers may be used more extensively; we recommend that at least three Eddie covariant towers be installed in dominant landscapes that represent agriculture, urban and forest environments. Though these towers are expensive, there could be cost savings with installation/ maintenance should these towers be incorporated into the national evapotranspiration ground-truth network. Modeling evapotranspiration on a regional scale can be accomplished by using the ground towers to validate and correct MODIS satellite measurements. Soils data acquired and compiled from the NRCS as part of this project as well as land cover data through the MRLC can supplement evapotranspiration measurements. They can also be used to supplement recharge estimation.

Recharge is a critical component to the hydrologic cycle, one that has been generalized, via numerical ground water models, or simply overlooked in the region until recently. Estimation of recharge will include a suite of tools and methods that could include the water balance approach, quantifying river baseflow, mapping vadose zone and ground water tracers, or employing physical measurement using lysimeters, soil moisture probes, neutron density probes, or correlating temperature changes along fiber optic cable to water migration. We anticipate recharge to be the driver of water supply to a regional ground water numerical model. This suite of tools to estimate recharge will result in a range of rates that, depending on the tools used, could be linked to land use and thus provide a heterogeneous distribution of recharge rates across the region. This range of recharge rates can also be used to bound parameter estimation schemes often applied to ground water models.

This phase of the Mississippi Embayment Regional Ground Water Study was to compile the enormity of hydrogeologic data available. Much of this data existed in a variety of formats with varying quality. A valiant attempt was made to unify these dataset so comparisons at a regional, multi-state scale could be performed. Just as ground water knows no political boundaries, so must the data describing the ground water system also follow this principle. With this reconnaissance phase complete, Phase II of the effort can build from the foundation developed herein and we can proceed forward with improving our understanding of this important regional ground-water system.

7.0 References

Ackerman, D.J., 1989. Potentiometric surfaces of the Mississippi River Valley alluvial aquifer in eastern Arkansas, spring 1972 and 1980, *U.S. Geological Survey Water Resources Investigation Report* 88-4075, Plate 1.

Ackerman, D.J., 1996. Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States, *U.S. Geological Survey Professional Paper* 1416-D, 56 p.

Aeschbach-Hertig, W., Peeters, F., Beyerle, U., and Kipfer, R., 1999. Interpretation of dissolved atmospheric noble gases in natural waters, *Water Resources Research*, 35: 2779-2792.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998. Crop evaporation - Guidelines for computing crop water requirements- FAO Irrigation and Drainage paper 56: *FAO - Food and Agriculture Organization of the United Nations*, Rome, 300 p.

Allison, G.B., and Hughes, M.W., 1978. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer, Australian Journal of Soil Research, 16: 181-195.

Allison, G.B., and Hughes, M.W., 1983. The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region, *Journal of Hydrology*, 60: 157-173.

Arnold, J.G., and Allen, P.M., 1999, Validation of Automated Methods for Estimating Baseflow and Groundwater Recharge from Stream Flow Records, *Journal of American Water Resources Association*, 35(2): 411-424.

Arthur, J.K., and Taylor, R.E., 1990. Definition of the geohydrologic framework and preliminary simulation of ground-water flow in the Mississippi Embayment aquifer system, Gulf Coastal Plain, United States, *U.S. Geological Survey Water Resources Investigation Report* 86-4364, 97 p.

Arthur, J.K., and Taylor, R.E., 1998. Ground-water flow analysis of the Mississippi Embayment aquifer system, South-central United States, *U.S. Geological Survey Professional Paper* 1416-I, 48 p.

Arthur, J.K., and Strom, E.W., 1996. Thickness of the Mississippi River alluvium and thickness of the coarse sand and gravel in the Mississippi River alluvium in northwestern Mississippi, *U.S. Geological Survey Water Resources Investigation Report* 96-4305, 1 sheet.

Arthur, J.K., 2001. Hydrogeology, model description, and flow analysis of the Mississippi River Alluvial aquifer in northwestern Mississippi, *U.S. Geological Survey Water-Resources Investigations Report* 01-4035, 47 p.

Austin, W.J., Burns, S.F., Miller, B.J., Saucier, R.T., and Snead, J.I., 1991. Quaternary geology of the Lower Mississippi Valley. In Morrison, R.B., ed., *Quaternary Nonglacial Geology; Conterminous U.S.* Geological Society of America, The Geology of North America, K-2, 547-582.

Bailey, Z.C., 1993. Hydrology of the Jackson, Tennessee, area and delineation of areas contributing ground water to the Jackson well fields, *U.S. Geological Survey Water Resources Investigations Report* 92-4146, 54 p.

Bell, E.A., and Nyman, D.J., 1968. Flow pattern and related chemical quality of ground water in the “500-foot” sand in the Memphis area, Tennessee, *U.S. Geological Survey Water Supply Paper* 1853, 27 p.

Bicker, A.R., comp., 1969, Geologic map of Mississippi: [Jackson], Mississippi Geological Survey, scale 1:500,000.

Bicker, A.R., Jr., 1969. *Geologic Map of Mississippi*, Mississippi Geological Survey.

Blum, M.D., Guccione, M.J., Wysocki, D.A., Robnett, P.C., and Rutledge, E.M., 2000. Late Pleistocene evolution of the lower Mississippi River valley, southern Missouri to Arkansas. *Geological Society of America Bulletin*, 112: 221-235.

Boswell, E.H., Cushing, E.M., and Hosman, R.L., 1968. Quaternary aquifers in the Mississippi embayment, with a discussion of Quality of water by H.G. Jeffery. *U.S. Geological Survey Professional Paper* 448-E, 15 p.

Boswell, E.H., Moore, G.K., MacCary, L.M., Jeffery, H.G., and others, 1965. Cretaceous aquifers in the Mississippi embayment, with discussions of Quality of the water by H.G. Jeffery, *U.S. Geological Survey Professional Paper* 448-C, 37 p.

Bowen, I.S., 1926: The ratio of heat losses by conduction and by evaporation from any water surface, *Physics Review*, 27: 779-787.

Bradley, M.W., 1991. Ground-water hydrology and the effects of vertical leakage and leachate migration on ground-water quality near the Shelby County landfill, Memphis, Tennessee, *U.S. Geological Survey Water-Resources Investigations Report* 90-4075, 42 p.

Brahana, J.V., and Broshears, R.E., 2001. Hydrogeology and ground-water flow in the Memphis and Fort Pillow aquifers in the Memphis area, Tennessee, *U.S. Geological Survey Water Resource Investigation Report* 89-4131, 56 p.

Brahana, J.V., Mesko, T.O., Busby, J.F., and Kraemer, T.F., 1985. Ground-water quality data from the northern Mississippi embayment--Arkansas, Missouri, Kentucky, Tennessee, and Mississippi, *U.S. Geological Survey Open-File Report* 85-683, 15 p.

Brahana, J.V., Parks, W.S., and Gaydos, M.W., 1987. Quality of water from freshwater aquifers and principal well fields in the Memphis area, Tennessee, *U.S. Geological Survey Water Resources Investigations Report* 87-4052, 22 p.

Braile, L.W., Hinze, W.J., Keller, G.R., Lidiak, E.G., and Sexton, J.L., 1986. Tectonic Development of the New Madrid complex, Mississippi Embayment, North America, *Tectonophysics*, 131: 1-21.

Brotzge, J.A., and Crawford, K.C., 2003. Examination of the surface energy budget: A comparison of Eddy Correlation and Bowen Ratio measurement systems, *Journal of Hydrometeorology*, 4: 160-178.

Brown, G.F., 1947. Geology and artesian water of the alluvial plain in northwestern Mississippi, *Mississippi State Geological Survey Bulletin* 65, 424 p.

Brown, M.C., 1993. A study of the aquifer system at the Davis well field, University of Memphis thesis, 169 p. [unpublished]

Bryant, C.T., Ludwig, A.H., and Morris, E.E., 1985. Ground water problems in Arkansas, *U.S. Geological Survey Water-Resources Investigations Report* 85-4010, 24 p.

Burba, George (Contributing Author); Steven L. Forman (Topic Editor). 2008. "Eddy Covariance Method." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment).

Bybell, L.M., and Gibson, T.G., 1985. The Eocene Tallahatta Formation of Alabama and Georgia: Its lithostratigraphy, biostratigraphy, and bearing on the age of the Clairbornian Stage, *U.S. Geological Survey Bulletin* 1615, 20 p.

Carey, A.E., Dowling, C.B., and Poreda, R.J., 2004. Alabama Gulf Coast groundwaters: He-4 and C-14 as groundwater-dating tools, *Geology*, 32(4) 289-292.

Chapman, T.G., 1991. Comment on “Evaluation of automated techniques for base flow and recession analyses” by R.J. Nathan and T.A. McMahon, *Water Resources Research* 27, 1783-1784.

Chiu, S.C., Chiu, J.-M., and Johnston, A.C., 1997. Seismicity of the southeastern margin of Reelfoot rift, central United States, *Seismological Research Letters*, 68: 785-796.

Cleugh, H., Leuning, R., Mu, Q., and Running, S., 2007. Regional evaporation estimates from flux tower and MODIS satellite data, *Remote Sensing of Environment*, 106: 285-304.

Cook, P.G., and Bohlke, J.K., 2000. Determining timescales for groundwater flow and solute transport. In: Cook, P.G., Herczeg, A.L. (Eds.), *Environmental tracers in subsurface hydrology*, Kluwer, Boston, pp. 1-30.

Cook, P.G., and Herczeg, A.L., eds., 2000. *Environmental Tracers in Subsurface Hydrology*. Kluwer Academic, Boston, 529 p.

Cook, P.G., and Solomon, D.K., 1997. Recent advances in dating young groundwater: Chlorofluorocarbons, $^{3}H/^{3}He$ and ^{85}Kr, *Journal of Hydrology*, 191: 245-265.

Cook, P.G., Jolly, I.D., Leaney, F.W., Walker, G.R., Allan, G.L., Fifield, L.K., and Allison, G.B., 1994. Unsaturated zone tritium and chlorine 36 profiles from southern Australia: their use as tracers of soil water movement, *Water Resources Research*, 30(6): 1709-1719.

Coplen, T.B., 1993. Uses of Environmental Isotopes. In: Alley, W.M., ed., *Regional Ground-Water Quality*, Van Nostrand Reinhold Publisher, NY, 227-254.

Cowardin, L.M., Carter, V., Golet, F.C., and LaRoe, E.T., 1979. Classification of Wetlands and Deepwater Habitats of the United States, U.S. Fish and Wildlife Service, FWS/OBS – 79/31, 47 p.

Cox, R.T., and Van Arsdale, R.B., 1997. Hotspot origin of the Mississippi Embayment and it's possible impact on contemporary seismicity, *Engineering Geology*, 46: 201-216.

Cox, R.T., 1988. Evidence of late Cenozoic activity along the Bolivar-Mansfield tectonic zone, Midcontinent, USA, *The Compass*, 65: 207-213.

Cox, R.T., Cherryhomes, J., Harris, J.B., Larsen, D., Van Arsdale, R.B., and Forman, S.L., 2006. Paleoseismology of the southeastern Reelfoot Rift in western Tennessee, U.S.A., *Tectonics*, 25: 3019-3036.

Cox, R.T., Hill, A.A., Larsen, D., Holzer, T., Forman, S.L., Noce, T., Gardner, C., and Morat, J., 2007. Seismotectonic implication of sand blows in the southern Mississippi Embayment, *Engineering Geology*, 89: 278-299.

Cox, R.T., Larsen, D., Forman, S.L., Woods, J., Morat, J., and Galluzzi, J., 2004. Preliminary assessment of sand blows in the southern Mississippi Embayment, *Bulletin of the Seismological Society of America*, 94: 1125-1142.

Cox, R.T., Van Arsdale, R.B., and Harris, J.B., 2001. Identification of possible Quaternary deformation in the northeastern Mississippi Embayment using quantitative geomorphic analysis of drainage-basin symmetry, *Geological Society of America Bulletin*, 113: 615-624.

Cox, R.T., Van Arsdale, R.B., Harris, J. B., and Larsen, D., 2001. Neotectonics of the southeastern Reelfoot rift zone margin, central United States, and implications for regional strain accommodation, *Geology*, 29, 419-422.

Criner, J.H., and Armstrong, C.A., 1958. Groundwater supply of the Memphis area, *U.S. Geological Survey Circular* 408, 20 p.

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

Criner, J.H., Sun, P-C. P., and Nyman, D.J., 1964. Hydrology of the aquifer systems in the Memphis area, Tennessee, *U.S. Geological Survey Water-Supply Paper* 1779-O, 54 p.

Csontos, R., Van Arsdale, R., Cox, R., and Waldron, B., 2008. Reelfoot rift and its impact on Quaternary deformation in the central Mississippi River valley, *Geosphere*, 4(1): 145-158.

Csontos, R.M., 2007. Three dimensional modeling of the Reelfoot Rift and the New Madrid seismic zone. Ph.D. dissertation, University of Memphis, 92 p.

Cushing, E.M., Boswell, E.H., and Hosman, R.L., 1964. General geology of the Mississippi embayment, *U.S. Geological Survey Professional Paper* 448-B, 28 p.

Cushing, E.M., Boswell, E.H., Speer, P.R., Hosman, R.L., and others, 1970. Availability of water in the Mississippi embayment, *U.S. Geological Survey Professional Paper* 448-A, 13 p.

Daniels, D.P., Fritz, S.J., and Leap, D.I., 1991. Estimating recharge rates through unsaturated glacial till by tritium tracing, *Ground Water* 29(1): 26-34.

Darden, D., 1983. Water-level maps of the alluvial aquifer, northwestern Mississippi, September 1982, *U.S. Geological Survey Water Resources Investigation Report* 83-4133, Plate 1.

Darden, D., 1987. Potentiometric map of the Sparta Aquifer system in Mississippi, fall 1984, *U.S. Geological Survey Water Resources Investigation Report* 86-4206, Plate 1.

Davis, S.N., Moysey, S., Cecil, and Zreda, M., 2003. Chlorine-36 in groundwater of the United States: empirical data, *Hydrogeology Journal*, 11: 217-227.

De Vries, J.J., and Simmers, I., 2002. Groundwater recharge: An overview of processes and challenges, *Hydrogeology Journal* 10(1): 5-17.

Dockery, D.T., and Thompson, D.E., 1996. *Ostrea Arrosis* from the Nanafalia Formation of Mississippi, *Mississippi Geology*, 17(3): 59-63.

Dockery, D.T., III, 1996. Toward a revision of the generalized stratigraphic column of Mississippi, *Mississippi Geology*, 17(1) 1-9.

Dowling, C.B., Poreda, R.J., Hunt, A.G., and Carey, A.E., 2004. Ground water discharge and nitrate flux to the Gulf of Mexico, *Ground Water* 42(3): 401-417.

Drever, J.I., 1997. *The Geochemistry of Natural Waters: Surface and Groundwater Environments.* Prentice-Hall, Upper Saddle River, N.J., 436 p.

Dugas, W.A., L.J. Fritschen, L.W. Gay, A.A. Held, A.D. Matthias, D.C. Reicosky, P. Steduto, and J.L. Steiner, 1991. Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat, *Agric. For. Meteor.*, 56: 1–20.

Dugas, W.A., Hicks, R.A., and Wright, P., 1998. Effect of removal of Juniperus ashei on evapotranspiration and runoff in the Seco Creek watershed, *Water Resources Research,* 34(6): 1499-1506.

EarthInfo. Environmental databases, Web. 2005 http://www.earthinfo.com/.

Eckhardt, K., 2005. How to construct recursive digital filters for baseflow separation, *Hydrological Processes*, 19(2): 507-515.

Edds, J., and Fitzpatrick, D.J., 1984. Maps showing altitude of the potentiometric surface and changes in water levels of the alluvial aquifer in eastern Arkansas, Spring 1983, *U.S. Geological Survey Water Resources Investigation Report* 84-4264, Plate 1.

Edds, J., and Fitzpatrick, D.J., 1984. Maps showing altitude of the potentiometric surface and changes in water level of the Sparta sand and Memphis sand aquifers in Eastern Arkansas, spring 1983, *U.S. Geological Survey Water Resources Investigation Report* 84-4265, Plate 1.

Edds, J., and Fitzpatrick, D.J., 1986. Maps showing altitude of the potentiometric surface and changes in water levels in the aquifer in the Sparta and Memphis Sands in eastern Arkansas, spring 1985, *U.S. Geological Survey Water Resources Investigation Report* 86-4084, Plate 1.

Edmunds, W.M., Darling, W.G., and Kinneburgh, D.G., 1988. Solute profile techniques for recharge estimation in semi-arid and arid terrain. In: Simmers, I. (Ed.), *Estimation of Natural Groundwater Recharge*, D. Reidel Publishing Company, Dordrecht, The Netherlands, pp. 139-157.

Ekhardt, K., 2008. A comparison of baseflow indices, which were calculated with seven different baseflow separation methods, *Journal of Hydrology*, 352: 168-173.

Ervin, P.C., and McGinnis, L.D., 1975. Reelfoot rift, reactivated precursor to the Mississippi Embayment, *Geological Society of America Bulletin*, 86: 1287-1295.

Ewing, T.E., 1991. Structural Framework. In: Salvador, A., Ed., *The Gulf of Mexico Basin, The Geology of North America*, The Geological Society of America, Boulder, CO, p.31-52.

Fehn, U., Peters, E.K., Tullai-Fitzpatrick, S., Kubik, P.W., Sharma, P., Teng, R.T.D., Gove, H. E. and Elmore, D., 1992. ^{129}I and ^{36}Cl concentrations in waters of the eastern Clear Lake area, California: Residence times and source ages of hydrothermal fluids, *Geochimica et Cosmochimica Acta*, 56: 2069-2079.

Fielder, A.M., Roman-Mas, A., and Bennett, M.W., 1994. Reconnaissance of ground-water quality at selected wells in the Beaver Creek watershed, Shelby, Fayette, Tipton, and Haywood counties, west Tennessee, July and August 1992, *U.S. Geological Survey Open-File Report* 93-366, 28 p.

Fisk, H.N., 1944. Geological investigation of the alluvial valley of the lower Mississippi River. *U.S. Department of the Army*, Mississippi River Commission, 78 p.

Fitzpatrick, D., Kilpartrick, J., and McWreath, H., 1990. Geohydrologic characteristics and simulated response to pumping stresses in the Sparta aquifer in East-Central Arkansas, *U.S. Geological Survey Water-Resources Investigations Report* 88-4201, 50 p.

Fontes, J.C., and Garnier, J.M., 1979. Determination of the initial C-14 activity of the total dissolved carbon: Review of the existing models and a new approach, *Water Resources Research*, 15(2): 399-413.

Frederiksen, N.O., Bybell, L.M., Christopher, R.A., Crone, A.J., Edwards, L.E., Gibson, T.G., Hazel, J.E., Repetski, J.E., Russ, D.P., Smith, C.C., and Ward, L.W., 1982. Biostratigraphy and paleo-ecology of lower Paleozoic, Upper Cretaceous, and lower Tertiary rocks, in U.S. Geological Survey New Madrid test wells, southeastern Missouri, *Tulane Studies in Geology and Paleontology*, 17(2): 23-45.

Fritschen, L.J., 1965. Accuracy of evapotranspira-tion determinations by the Bowen Ratio meth-ods, *Bulletin of the International Association of Scientific Hydrology*, 12(2): 38-48.

Gaye, C.B., and Edmunds, W.M., 1996. Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in sands of northwestern Senegal. *Environmental Geology*, 27: 246-251.

Gee, G.W., and Hillel, D., 1988. Groundwater recharge in arid regions: review and critique of estimation methods, *Hydrological Processes*, 2: 255-266.

Gentry, R.W., McKay, L., Thonnard, N., Anderson, J.L., Larsen, D., Carmichael, J.K., and Soloman, K., 2006. Novel Techniques for Investigating Recharge to the Memphis Aquifer. AWWARF Report 91137, *American Water Works Association*, Denver, Colorado, 97 p.

Gentry, R.W., Ku, T.-L., Luo, S., Todd, V., Larsen, D., and McCarthy, J., 2005. Resolving aquifer behavior near a focused recharge feature based upon synoptic wellfield hydrogeochemical tracer results, *Journal of Hydrology*, 323: 387-403.

Gibson, T.G., 1982. Revision of the Hatchetigbee and Bashi Formations (Lower Eocene) in the eastern Gulf Coast Plain, *U.S. Geological Survey Bulletin* 1529-H, p. H33-H41.

Golden Software, Inc., 1999. *Surfer 7.0 User's Guide*. Golden Software, Golden, CO, 619 p.

Goldsmith, G., 1993. Potentiometric-surface map, October through December 1988, and water-level change map, 1983-88, of the Mississippi River alluvial aquifer in northwestern Mississippi, *U.S. Geological Survey Water Resources Investigation Report* 92-4176, Sheet 1.

Gonthier, G.J., 2002. Quality of shallow ground water in recently developed residential and commercial areas, Memphis vicinity, Tennessee, 1997, *U.S. Geological Survey Water-Resources Investigations Report* 2002-4294, 105 p.

Gonthier, G.J., 2000. Water quality in the deep tertiary aquifers of the Mississippi Embayment, 1996, *U.S. Geological Survey Water-Resources Investigations Report* 99-4131, 91 p.

Graham, D.D., and Parks, W.S., 1986. Potential for leakage among principal aquifers in the Memphis area, Tennessee, *U.S. Geological Survey Water-Resources Investigations Report* 85-4295, 46 p.

Graham, D.D., 1982. Effects of urban develop-ment on the aquifers in the Memphis area, Tennessee, *U.S. Geological Survey Water-Resources Investigations Report* 82-4024, 20 p.

Hanor, J.S., and McIntosh, J.C., 2007. Diverse origins and timing of formation of basinal brines in the Gulf of Mexico sedimentary basin, *Geofluids*, 7: 227-237.

Hart, R.M., and Clark, B.R., 2008. Geophysical Log Database for the Mississippi Embayment Regional Aquifer Study (MERAS), *U.S. Geological Survey Scientific Investigations Report* 2008-5192, 8 p.

Hart, R.M., Clark, B.R., and Bolyard, S.E., 2008. Digital Surfaces and Thicknesses of Selected Hydrostratigraphic Units within the Mississippi Embayment Regional Aquifer Study (MERAS), *U.S. Geological Survey Scientific Investigations Report* 2008-5098, 33 p.

Hays, P.D., and Fugitt, D.T., 1999. The Sparta aquifer in Arkansas' critical ground-water areas: response of the aquifer to supplying future water needs, *U.S. Geological Survey Water Resources Investigation Report* 99-4075, 6 p.

Healy, R.W., Cook P.G., 2002. Using groundwa-ter levels to estimate recharge, *Journal of Hydrogeology* 10(2): 91-109.

Hendry, M.J., Kotzer, T.G., and Solomon, D.K., 2005. Sources of radiogenic helium in a clay till aquitard and its use to evaluate the timing of geologic events, *Geochimica et Cosmochimica Acta*, 69(2): 475-483.

Herczeg, A.L., and Edmunds, W.M., 2000. Inorganic ions as tracers. In Cook, P. and Herczeg, A.L., eds., *Environmental Tracers in Subsurface Hydrology*. Kluwer Academic, Boston, 31-77.

Holland, T.W., 1999. Water use in Arkansas, 1995, *U.S. Geological Survey Open File Report* 99-188, Plate 1.

Holland, T.W., 2007. Water use in Arkansas, 2005, *U.S. Geological Survey Scientific Investigations Report* 2007–5241, 32 p.

Hosman, R.L. 1982, Outcropping Tertiary units in southern Arkansas, *U.S. Geological Survey Miscellaneous Investigations Series* I-1405, 1 sheet.

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

Hosman, R.L., 1996. Regional stratigraphy and subsurface geology of Cenozoic deposits, Gulf Coastal Plain, South-Central United States, *U.S. Geological Survey Professional Paper* 1416-G, 35 p.

Hosman, R.L., Long, A.T., Lambert, T.W., and others, 1968. Tertiary aquifers in the Mississippi embayment, with discussions of Quality of water by H.G. Jeffery. *U.S. Geological Survey Professional Paper* 448-D, 29 p.

Howe, J.R., and Thompson, T.L., 1984. Tectonics, sedimentation, and hydrocarbon potential of the Reelfoot Rift, *Oil and Gas Journal*, 82: 179-190.

Hundt, K.R., 2008. Regional lithostratigraphic study of the Memphis Sand in the northern Mississippi Embayment. Master's Thesis, University of Memphis, 102 p.

Hunt, A.G., 2000. Diffusional release of helium-4 from mineral phases as indicators of groundwater age and depositional history. PhD dissertation, University of Rochester, NY.

Hutson, S., 1998. Ground-water use by public-supply systems in Tennessee, 1995, *U.S. Geological Survey Open-file Report* 95-98, Sheet 1.

Ingram, S.L., 1992. Meridian Sand paleochannel at Meridian, Mississippi, *Journal of the Mississippi Academy of Sciences*, 37(1): 40.

Ivey, S.S., Gentry, R, Larsen, D., and Anderson, J., 2008. 2. Case study of the inverse application of age distribution modeling using $^3H/^3He$: MLGW Sheahan Wellfield , Memphis, TN. *Journal of Hydrologic Engineering*, 13, 1011-1020.

Johnston, A.C., and Schweig E.S., 1996. The enigma of the New Madrid earthquakes of 1811-1812. *Annual Review of Earth and Planetary Science Letters*, 24: 339-384.

Joseph, R.L., 1998. Potentiometric surface of the Sparta aquifer in eastern and south-central Arkansas and north-central Louisiana, and the Memphis Aquifer in east-central Arkansas, October 1996-July 1997, *U.S. Geological Survey Water Resources Investigation Report* 97-4282, 19 p.

Joseph, R.L., 2000. Status of water levels and selected water-quality conditions in the Sparta and Memphis aquifers in eastern and south-central Arkansas, 1999, *U.S. Geological Survey Water Resources Investigation Report* 00-4009, 34 p.

Kane, M. F., Hildenbrand, T.G., and Hendricks, J.D., 1981. Model for the tectonic evolution of the Mississippi Embayment and its contemporary seismicity, *Geology*, 9: 563-568.

Kasenow, Michael, 2002. Determination of Hydraulic Conductivity from Grain Size Analysis. Water Resources Publications, LLC, Highland Ranch, Colorado.

Kehew, A.E., 2001. *Applied Chemical Hydrogeology*. Prentice-Hall, Upper Saddle River, NJ, 368 p.

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

Kingsbury, J.A., 1996. Altitude of the potentiometric surface, September, 1995, and historic water-level changes in the Memphis and Fort Pillow aquifers in the Memphis area, Tennessee, *U.S. Geological Survey Water-Resources Investigations Report* 96-4278, 1 sheet.

Kitching, R., and Shearer, T.R., 1982. Construction and operation of a large undisturbed lysimeter to measure recharge to the Chalk aquifer, England, *Journal of Hydrology* 58, 267-277.

Kleiss, B.A., Coupe, R.H., Gonthier, G.J., and Justus, B.J., 2000. Water Quality in the Mississippi Embayment, Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky, 1995–98, *U.S. Geological Survey Circular* 1208, 36 p.

Konduru, V.K., 2007. Altitudes of ground water levels for 2005 and historic water level change in surficial and Memphis aquifers, Shelby County, Tennessee, University of Memphis thesis, 95 p.

Kresse, T.M., and Clark, B.R., 2008. Occurrence, distribution, sources, and trends of elevated chloride concentrations in the Mississippi River Valley alluvial aquifer in southeastern Arkansas, *U.S. Geological Survey Scientific Investigations Report* 2008-5193, 34 p.

Krinitzsky, E.L., and Wire, J.C., 1964. Ground water in the alluvium of the Lower Mississippi Valley (upper and central areas), *U.S. Army Engineer Waterways Experiment Station Technical Report* no. 3-658, 100 p.

Krinitzsky, E.L., 1949. Geological investigation of gravel deposits in the Lower Mississippi Valley and adjacent uplands, *U.S. Army Corps of Engineers, Waterways Experiment Station Technical Memorandum* no. 3-273, 58 p.

Larsen, D., Gentry, R.W., and Solomon, D.K., 2003. The geochemistry and mixing of leakage in a semi-confined aquifer at a municipal well field, Memphis, Tennessee, USA, *Applied Geochemistry*, 18: 1043-1063.

Larsen, D., Waldron, B., Anderson, J., Gentry, R., Ivey, S., Owen, A., and Morat, J., 2005. Insights into groundwater recharge processes and pathways based on hydrochemical and tritium data from municipal well fields in Shelby County, Tennessee, USA, *Geological Society of America Abstracts with Programs*, 37(2): 47.

Lerner, D.N., Issar, A.S., and Simmers, I., 1990. *Groundwater recharge, International Contributions to Hydrogeology*, 8, Verlag Heinz Heise, 345 p.

Lewis, J.M., 1995. The Story behind the Bowen Ratio, *Bulletin of the American Meterological Society*, 76: 2433-2443.

Lim, K.J., Engel, B.A., Tang, Z, Choi, J., Kim, K., Muthukrishnan, S., and Tripathy, D., 2005. Automated web GIS based hydrograph analysis tool, WHAT, *Journal of American Water Resources Association*, 41(6): 1407-1416.

Liu, B., Phillips, F., Hoines, S., Campbell, A.R., and Sharma, P., 1995. Water movement in desert soil traced by hydrogen and oxygen isotopes, chloride, and chlorine-36, southern Arizona, *Journal of Hydrology*, 168: 91-110.

Lumsden, D.N., Hundt, K.R., and Larsen, D., 2009, Petrology of the Memphis Sand in the Northern Mississippi Embayment, *Southeastern Geology*, 46: 121-133.

Lyne, V.D., and Hollick, M., 1979, Stochastic time-variable rainfall-runoff modeling, Hydrology and Water Resources Symposium, Institution of Engineers, Perth, Australia, p 89-92

Mahon, G.L., and Ludwig, A.H., 1990. Simulation of ground-water flow in the Mississippi River valley alluvial aquifer in Eastern Arkansas, *U.S. Geological Survey Water-Resources Investigations Report* 89-4145.

Mahon, G.L., and Poynter, D.T., 1993. Development, calibration, and testing of groundwater flow models for the Mississippi River valley alluvial aquifer in Eastern Arkansas using one-square-mile cells, *U.S. Geological Survey Water-Resources Investigations Report* 92-4106.

Mancini, E.A., and Tew, B.H., 1991. Relationships of Paleogene stage and planktonic foraminiferal zone boundaries to the lithostratigraphic and allostratigraphic contacts in the eastern Gulf Coastal Plain, *Journal of Foraminiferal Research*, 21(1): 48-66.

Markewich, H.W., Wysocki, D.A., Pavich, M.J., Rutledge, E.M., Millard, H.T., Rich, F.J., Maat, P.B., Rubin, M., and McGeehin, J.P., 1998. Paleopedology plus TL, ^{10}Be, and ^{14}C dating as tools in stratigraphic and paleoclimatic investigations, Mississippi River valley, U.S.A., *Quaternary International*, 51/52: 143-167.

Marshak, S., and Paulsen, T., 1996. Midcontinent U.S. fault and fold zones: a legacy of Proterozoic intracratonic extensional tectonism?, *Geology*, 24: 151-154.

Martin, R., 2008, Shallow faulting of the southeast Reelfoot rift margin. Ph.D. dissertation, University of Memphis, 126 p.

Maupin, M.A. and Barber, N.L., 2005. Estimated withdrawals from principal aquifers in the United

States, 2000, *U.S. Geological Survey Circular* 1279, 52 p.

McClure, D., 1999. The Distribution, Stratigraphic Characteristics, and Origin of Late Cenozoic Alluvial Deposits in Shelby County, Tennessee. M.S. Thesis, University of Memphis, 112 p.

McFarland, J.D., 2004. Stratigraphic summary of Arkansas: *Arkansas Geological Commission Information Circular* 36, 39 p.

McIntosh, J.C., Warwick, P.D., Martini, A.M., and Osborn, S.G., 2010. Coupled hydrology and biogeochemistry of Paleocene-Eocene coal beds, northern Gulf of Mexico. Geological Society of America Bulletin, 122: 1248-1264.

McKee, P.W., and Clark, B.R., 2003. Development and calibration of a ground-water flow model for the Sparta aquifer of southeastern Arkansas and north-central Louisiana and simulated response to withdrawals, 1998-2027, *U.S. Geological Survey Water Resources Investigations Report* 03-4132, 71 p.

McNeil, D.D., and Shuttleworth, W.J., 1975. Comparative measurements of the energy fluxes over a pine forest, Boundary-Layer *Meteorology*, 9: 297-313.

Meissner, C.R., 1984. Stratigraphic framework and distribution of lignite on Crowley's Ridge, Arkansas, *Arkansas Geologic Commission Information Circular* 28-B, 39 p.

Miller, R.A., Harderman, W.D., and Fullerton, D.S., 1966, Geologic map of Tennessee, west sheet: [Nashville], *Tennessee Department of Conservation*, *Division of Geology*, scale 1:250,000.

Miller, R.D., Xia, J., Deane, J.W., Anderson, J.M., Laflen, D.R., Acker, P.M., and Brohammer, M.C., 1994. High resolution seismic reflection survey to image the top and bottom of a shallow clay layer at the Memphis Defense Depot, Memphis, Tennessee, *U.S. Army Corps of Engineers, Open File Report* 94-18, 17 p.

Mirecki, J.E., and Parks W.S., 1994. Leachate geochemistry at a municipal landfill, Memphis, Tennessee, *Ground Water*, 32: 390-398.

Monteith, J.L., 1965. Evaporation and the environment. *The State and Movement of Water in Living Organisms XIX Symposium Society for Experimental Biology, Swansea*, Cambridge University Press, Cambridge.

Moore, G.K., and Brown, D.L., 1969. Stratigraphy of the Fort Pillow test well Lauderdale County, Tennessee*, Tennessee Division of Geology Report of Investigations* 26, 1 sheet.

Moore, G.K., 1965. Geology and hydrology of the Claiborne Group in western Tennessee, *U.S. Geological Survey Water-Supply Paper* 1809-F, 44 p.

Moraru, C., and Anderson, J.A., 2005. *A Comparative Assessment of the Ground Water Quality of the Republic of Moldova and the Memphis, TN Area of the United States of America.* Ground Water Institute, Memphis, TN, 188 p.

Mu, Q., Heinsch, F.A., Maosheng, Z., and Running, S., 2007. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data, *Remote Sensing of Environment*, 111(4): 519-536.

Murray, G.E., 1961. *Geology of the Atlantic and Gulf Coastal Province of North America*. Harper and Brothers, New York.

Nathan, R.J., and McMahon, T.A., 1990, Evaluation of automated techniques for baseflow and recession analyses, *Water Resources Research*, 26: 1465-1473.

Neff, B.P., Day, S.M., Piggott, A.R., and Fuller, L.M., 2005. Base Flow in the Great Lakes Basin. *U.S. Geological Survey Scientific Investigations Report* 2005-5217, 23 p.

Newcome, R., 1971. Results of aquifer tests in Mississippi, *Bulletin - Mississippi Board of Water Commissioners* 71-2, 44 p.

O'Brien, R., Keller, C.K., and Smith, J.L., 1996. Multiple tracers of shallow ground-water flow and recharge in hilly loess, *Ground Water* 34(4): 675-682.

O'Hara, C.G., and Reed, T.B., 1995. Depth to the water table in Mississippi, *U.S. Geological Survey Water Resources Investigation Report* 95-4242, Plate 1.

Oakley, W.T., and Burt, D.E., 1994. Potentiometric-surface map of the Sparta aquifer in Mississippi, October through December 1989, *U.S. Geological Survey Water Resources Investigation Report* 94-4048, Plate 1.

Oakley, W.T., Burt, D.E., and Goldsmith, G.D., 1994. Potentiometric-surface map of the lower Wilcox aquifer in Mississippi, October through December 1988, *U.S. Geological Survey Water Resources Investigation Report* 93-4174, Plate 1.

Outlaw, G.S., and Weaver, J.D., 1996, Flow duration and low flows of Tennessee streams through 1992. *U.S. Geological Survey Water Resources Investigation Report* 95-4293, 245 p.

Owen, A., and Larsen, D., 2005. Correlation and sequence stratigraphy of the Claiborne Group in the tri-state area of western Tennessee, eastern Arkansas, and northern Mississippi, *Journal of the Tennessee Academy of Sciences*, 81(1-2): 28-29.

Parks, W.S., and Carmichael, J. K., 1988. Geology and ground-water resources of the Cockfield Formation in western Tennessee, *U.S. Geological Survey Water Resources Investigation Report* 88-4181, 17 p.

Parks, W.S., and Carmichael, J.K., 1989. Geology and ground-water resources of the Fort Pillow Sand in western Tennessee. *U.S. Geological Survey Water-Resources Investigations Report* 89-4120, 20 p.

Parks, W.S., and Carmichael, J.K., 1990a. Geology and ground-water resources of the Memphis Sand in western Tennessee. *U.S. Geological Survey Water-Resources Investigations Report* 88-4182, 30 p.

Parks, W.S., and Carmichael, J.K., 1990b. Geology and ground-water resources of the Cockfield Formation in western Tennessee. *U.S. Geological Survey Water-Resources Investigations Report* 88-4181, 17 p.

Parks, W.S., and Mirecki, J.E., 1992. Hydrology, ground water quality, and potential for water-supply contamination near the Shelby County Landfill in Memphis Tennessee. *U.S. Geological Survey Water Resource Investigation Report* 91-4173, 79 p.

Parks, W.S., 1990. Hydrogeology and preliminary assessment of the potential for contamination of the Memphis aquifer in the Memphis area, Tennessee. *U.S. Geological Survey Water-Resources Investigations Report* 90-4092, 39 p.

Parks, W.S., Graham, D.D., and Lowery, J.F., 1981. Chemical character of ground water in the shallow water-table aquifer at selected localities in the Memphis area, Tennessee. *U.S. Geological Survey Open-File Report* 81-223, 29 p.

Parks, W.S., Mirecki, J.E., and Kingsbury, J.A., 1995. Hydrogeology, ground-water quality, and source of ground water causing water-quality changes in the Davis Well Field at Memphis, Tennessee. *U.S. Geological Survey Water-Resources Investigations Report* 94-4212, 58 p.

Parrish, S., and Van Arsdale, R.B., 2004. Faulting along the southwestern margin of the Reelfoot Rift in northwestern Tennessee revealed in deep seismic reflection profiles. *Seismological Research Letters*, 75: 784-793.

Patterson, G.L., 1998. Cretaceous/Tertiary transition of the northern Mississippi embayment: Evidence for a bolide impact? M.S. Thesis, Memphis State University, 84 p.

Payne, J.N., 1968. Hydrologic significance of the lithofacies of the Sparta Sand in Arkansas, Louisiana, Mississippi, and Texas, *U.S. Geological Survey Professional Paper* 569-A, 17 p.

Payne, J.N., 1972. Hydrologic significance of lithofacies of the Cane River Formation or equivalents of Arkansas, Louisiana, Mississippi, and Texas. *U.S. Geological Survey Professional Paper* 569-C, 17 p.

Payne, J.N., 1973. Geohydrologic significance of lithofacies of the Cane River Formation or equivalents of Arkansas, Louisiana, Mississippi, and Texas. *U.S. Geological Survey Professional Paper* 569-C, 24 p.

Payne, J.N., 1975. Geohydrologic significance of lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas and Meridian Sand of Mississippi, *U.S. Geological Survey Professional Paper* 569-D, 11 p.

Pettijohn, R.A., 1996. Geochemistry of ground water in the Gulf Coast aquifer systems, south-central United States, *U.S. Geological Survey Water-Resources Investigations Report* 96-4107, 158 p.

Phillips, F. M., 1994. Environmental tracers for water movement in desert soils of the American Southwest, *Soil Science Society of America Journal*, 58: 15-24.

Phillips, F.M., Bentley, H.W., Davis, S.N., Elmore, D., and Swannick, G.B., 1986. Chlorine-36 dating of very old ground water II: Milk River aquifer, Alberta, *Water Resources Research*, 22: 2003-2016.

Phillips, F.M., Mattick, J.L., Duval, T.A., Elmore, D., and Kubik, P.W., 1988, Chlorine-36 and tritium from nuclear weapons fallout as tracers for long-term liquid and vapor movement in desert soils, *Water Resources Research*, 24, 1877-1891.

Plafcan, M., 1985. Ground-water levels in the alluvial aquifer in eastern Arkansas, 1984, *U.S. Geological Survey Open File Report* 85-569, 25 p.

Plafcan, M., 1986. Ground-water levels in the alluvial aquifer in eastern Arkansas, 1985, *U.S. Geological Survey Open File Report* 86-242, 29 p.

Plebuch, R.O., 1961. Fresh-water aquifers of Crittenden County, Arkansas, *Arkansas Geological and Conservation Commission, Water Resources Circular No. 8*.

Potter, P.E., 1955. The petrology and origin of the Lafayette gravel. Pt. 2, Geomorphic history. *Journal of Geology*, 63: 115-132.

Pugh, A.L., 2008. Summary of aquifer test data for Arkansas - 1940-2006, *U.S. Geological Survey Scientific Investigations Report* 2008-5149, 34 p.

Reed, T.B., 2004. Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2002. *U.S. Geological Survey Scientific Investigations Report* 2004-5129, 53 p.

Reilly, T.E., Plummer, L.N., Phillips, P.J., and Busenberg, E., 1994. The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. *Water Resources Research*, 30(2): 421-433.

Richards, L.A., Gardner, W.R., Ogata, G., 1956. Physical processes determining water loss from soil, *Soil Science Society American Proceedings*, 20: 310-314.

Riggs, H.C. 1963. The base flow recession curve as an indicator of ground water, *International Association of Scientific Hydrology Publication No.* 63, Berkeley, pp. 352-363.

Rittenour, T.M., Goble, R.J., and Blum, M.D., 2003. An optical age chronology of Late Pleistocene fluvial deposits in the northern lower Mississippi valley, *Quaternary Science Reviews*, 22: 1105-1110.

Rittenour, T.M., Goble, R.J., and Blum, M.D., 2005. Development of an OSL chronology for Late Pleistocene channel belts in the Lower Mississippi valley, *U.S.A, Quaternary Science Reviews*, 24: 2539-2554.

Robinson, J.L., Carmichael, J.K., Halford, K.J., and Ladd, D.E., 1997. Hydrogeologic framework and simulation of ground-water flow and travel time in the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee, *U.S. Geological Survey Water Resources Investigation Report* 97-4228, 56 p.

Rock, N.M.S., 1988. *Numerical Geology*. Berlin, Springer-Verlag, 427 p.

Rodbell, D.T., 1996. Subdivision, subsurface stratigraphy, and estimated age of fluvial-terrace deposits in northwestern Tennessee. *U.S. Geological Survey Bulletin* 2128.

Rodbell, D.T., Forman, S.L., Pierson, J., and Lynn, W.C., 1997. Stratigraphy and chronology of Mississippi Valley loess in western Tennessee. *Geological Society of America Bulletin*, 109: 1141-1146.

Rosen, M.R., Bright, J., Carran, P., Stewart, M.K., and Reeves, R., 1999. Estimating rainfall recharge and soil water residence times in Pukekohe, New Zealand, by combining geophysical, chemical, and isotopic methods. *Ground Water*, 37(6): 836–844.

Rushton, K.R., and Ward, C., 1979. The estimation of groundwater recharge. *Journal of Hydrology*, 41: 345-361.

Russell, E.E., and Parks, W.S., 1975. Stratigraphy of the outcropping Upper Cretaceous, Paleocene, and lower Eocene in western Tennessee (including descriptions of younger fluvial deposits). *Tennessee Division of Geology Bulletin*, 75, 113 p.

Rutledge, A.T., 1998. Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records – update, *U.S. Geological Survey Water-Resources Investigations Report* 98-4148, 43 p.

Rutledge, E.M., Guccione, M.J., Markewich, H.W., Wysocki, D.A., and Ward, L.B., 1996. Loess stratigraphy of the lower Mississippi Valley, *Engineering Geology*, 45: 167-183.

Sanford, W., 2002. Recharge and groundwater models: an overview, *Hydrogeology Journal*, 10: 110-120.

Saucier, R.T., 1994. Geomorphology and Quaternary geologic history of the lower Mississippi Valley, *U.S. Army Corps of Engineers Waterways Experiment Station*, 364 p.

Saucier, R.T., 1987. Geomorphological interpretations of late Quaternary terraces in western Tennessee and their regional tectonic implications. *U.S. Geological Survey Professional Paper* 1336-A, 19 p.

Scanlon, B.R., Healy, R.H., and Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge, *Hydrogeology Journal*, 10(1): 18-39.

Schneider, R., and Cushing, E.M., 1948. Geology and water-bearing properties of the "1,400 foot" sand in the Memphis area, *U.S. Geological Survey Circular* 0033, 13 p.

Schrader, T.P., 2001. Status of water levels and selected water-quality conditions in the Mississippi River valley alluvial aquifer in Eastern Arkansas, 2000, *U.S. Geological Survey Water Resources Investigation Report* 01-4124, 52 p.

Schrader, T.P., 2004. Status of water levels and selected water-quality conditions in the Mississippi River valley aquifer in eastern Arkansas, 2000, *U.S. Geological Survey Water-Resources Investigations Report* 01-4124, 52 p.

Schrader, T.P., 2008a. Potentiometric surface in the Sparta-Memphis aquifer of the Mississippi embayment, Spring 2007, *U.S. Geological Survey Scientific Investigations Map* 3014.

Schrader, T.P., 2008b. Water levels and selected water-quality conditions in the Mississippi River valley alluvial aquifer in eastern Arkansas, 2006. *U.S. Geological Survey Scientific Investigations Report* 2008-5092, 73 p.

Schweig, E.S., and Van Arsdale, R.B., 1996. Neotectonics of the upper Mississippi embayment. *Engineering Geology*, 45: 185-203.

Sharma, M.L., and Hughes, M.W., 1985. Groundwater recharge estimation using chloride, deuterium, and oxygen-18 profiles in the deep coastal sands of Western Australia, *Journal of Hydrology*, 81: 93-109.

Shu, Y., Lei, Y., Zheng, L., and Li, H., 2006. A evapotranspiration (ET) model based GIS using Landsat data and MODIS data with improved resolution. In: *Remote Sensing for Environmental Montitoring*, *GIS Applications, and Geology VI*. Eds. Manfred, E., Michel, U., v. 6366.

Shuttleworth, W.J., Gash, J.H.C., Lloyd, C.R., et al, 1984. Eddy correlation measurements of energy partition for Amazonian forest, *Quart. J. Roy. Meteor. Soc.*, 110: 1143–1162.

Slack, L.J., and Darden, D., 1991. Summary of aquifer tests in Mississippi, June 1942 through May 1988, *U.S. Geological Survey Water Resources Investigation Report* 90-4155, 40 p.

Slack, L.J., and Oakley, W.T., 1989. Tritium analyses of shallow ground water in Mississippi, April 1989. *U.S. Geological Survey Open-File Report* 89-418, 8 p.

Sloto, R.A., and Crouse, M.Y., 1996. HYSEP, A computer program for stream hydrograph separation and analysis. *U.S. Geological Survey Water Resources Investigation Report* 96-4040, 54 p.

Smit, J., Roep, T.B., Alvarez, W., Montanari, A., Claeys, P., Grajales-Nishimura, J.M., and Bermudez, J., 1996. Coarse grained, clastic sandstone complex at the K/T boundary around the Gulf of Mexico: Deposition by tsunami waves induced by the Chicxulub impact? In: Ryder, G., Fastovski, D., and Gartner, S., editors, The Cretaceous-Tertiary Event and Other Catastrophes in Earth History: *Geological Society of America Special Paper* 307: 151-182.

Solomon, D.K., Schiff, S.L., Poreda, R.J., and Clarke, W.B., 1993. A validation of the $^3H/^3He$ method for determining groundwater recharge. *Water Resources Research*, 29: 2951-2962.

Sophocleus, M., and Perry, C.A., 1985. Experimental studies in natural groundwater-recharge dynamics—the analysis of observed recharge events, *Journal of Hydrology*, 81: 287-332.

SPSS, 2000. *SPSS Data Entry Builder 2.0: User's Guide*. SPSS, Chicago, IL, 58 p.

Stark, J.T., 1997. The East Continent Rift Complex: Evidence and Conclusions. In: Ojakangas, R.W., et al., editors, Middle Proterozoic to Cambrian rifting: Mid-North America. *Geological Society of America Special Paper* 312: 253-266.

Stearns, R.G., and Marcher, M.V., 1962. Late Cretaceous and subsequent structural development of the northern Mississippi embayment area, *Geological Society of America Bulletin*, 73, 1387-1394.

Stearns, R.G., 1957. Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi embayment, *Geological Society of America Bulletin*, 68: 1077-1100.

Steenhuis, T.S., Jackson, C.D., Kung, S.K., and Brutsaert, W., 1985. Measurement of groundwater recharge in eastern Long Island, New York, USA, *Journal of Hydrology*, 79: 145-169.

Stevens, K.C., 2007. A structural interpretation of near-surface borehole data in Shelby County, Tennessee. Master's Thesis, University of Memphis.

Stewart, M., Cimino, J., and Ross, M., 2007. Calibration of base flow separation methods with streamflow conductivity, *Ground Water*, 45(1): 17-27.

Stricker, V.A., 1983, Baseflow of streams in the outcrop area of southeastern sand aquifer: South Carolina, Georgia, Alabama, and Mississippi, *U.S. Geological Survey, Water-Resources Investigations Report* 83-4106, 17 p.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P., Hussain, S., Giri, V.Y., and Patil, D.J., 1996. Environmental and injected tracers methodology to estimate direct precipitation recharge to a confined aquifer, *Journal of Hydrology*, 177: 77-97.

Sumner, D.M., and Wasson, B.E., 1990. Geohydrology and simulated effects of large ground-water withdrawals on the Mississippi River alluvial aquifer in northwestern Mississippi, *U.S. Geological Survey Water Supply Paper* 2292, 60 p.

Sumner, D.M., 1984. Water-level maps of the alluvial aquifer, Northwestern Mississippi, April 1983, *U.S. Geological Survey Water Resources Investigation Report* 83-4285, Plate 1.

Thomas, E.P., 1942. The Claiborne. *Mississippi State Geological Survey Bulletin* 48, 96 p.

Thomas, W.A., 1991. The Appalachian-Ouachita rifted margin of southeastern North America, *Geological Society of America Bulletin*, 103: 415-431.

Thompson, D.E., 1995, Stratigraphic framework and lignite occurrence in the Paleocene of the Ackerman Area, *Mississippi Geology*, 16(3): 49-59.

Thompson, D.E., 2003. Geologic Map of the Wyatte Quadrangle, Mississippi Department of Environmental Quality, Office of Geology, *Open File Report* 161.

Thompson, D.E., 2003b. Geologic Map of the Senatobia Quadrangle, Mississippi Department of Environmental Quality, Office of Geology, *Open File Report* 162.

Thompson, D.E., 2003c. Geologic Map of the Looxahoma Quadrangle, Mississippi Department of Environmental Quality, Office of Geology, *Open File Report* 163.

Thompson, D.E., 2003d. Geologic Map of the Tyro Quadrangle, Mississippi Department of Environmental Quality, Office of Geology, *Open File Report* 164.

Van Arsdale, R., Bresnahan, R., McCallister, N., and Waldron, B., 2007. The Upland Complex of the central Mississippi River valley: its origin, denudation, and possible role in reactivation of the New Madrid seismic zone, Geological Society of America books section on *Intraplate Earthquakes*, *Special Paper* 425: 177-192.

Van Arsdale, R.B., and Cox, R.T., 2007. The Mississippi's curious origins. *Scientific American:* 75-82.

Van Arsdale, R.B., and TenBrink, R.K., 2000. Late Cretaceous and Cenozoic Geology of the New Madrid Seismic Zone. *Bulletin of the Seismological Society of America*, 90: 245-356.

Van Arsdale, R.B., Bresnahan, R.P., McCallister, N.S., and Waldron, B., 2008. The Upland Complex of the central Mississippi River valley: Its origin, denudation, and possible role in reactivation of the New Madrid seismic zone.

In: Stein, S. and Mazzotti, S., eds., Continental intraplate earthquakes: Science, hazard, and policy issues. *Geological Society of America Special Paper* 425, 177-192.

Velasco, M., Van Arsdale, R., Waldron, B., Harris, J., and Cox, R., 2005. Quaternary faulting beneath Memphis, Tennessee, *Seismological Research Letters*, 76(5) 598-614.

Vukovic, M., and Soro, A., 1992. Determination of Hydraulic Conductivity of Porous Media from Grain-Size Distribution, Water Resources Publications, LLC, Highlands Ranch, Colorado.

Waldron, B.A., and Anderson, J.L., 1995. Development of a ground water flow model with predictive solution for Grand Prairie project implementation, U.S. Army Corps of Engineers.

Walker, G.R., Jolly, I.D., and Cook, P.G., 1991. A new chloride leaching approach to estimation of diffuse recharge following a change in land use, *Journal of Hydrology*, 128: 49-67.

Wasson, 1986. Sources for water supplies in Mississippi: *Mississippi Research and Development Center Bulletin*, 113 p.

Wasson, B.E., 1980. Sources for water supplies in Mississippi. *Mississippi Research and Development Center Bulletin*, 112 p.

Waterloo Hydrogeologic, Inc., 2005. *AquaChem v.5.0 User's Manual.* Waterloo Hydrogeologic, Waterloo, Ontario, CN, 328 p.

Webbers, A., 2000. Public water-supply systems and associated water use in Tennessee, 2000. *U.S. Geological Survey Water-Resources investigations Report* 03-4264, 90 p.

Wells, F.G., 1933. Ground-water resources of western Tennessee. *U.S. Geological Survey Water-Supply Paper* 656, 319 p.

Westerfield, P.W., 1989. Ground-water levels in the alluvial aquifer in eastern Arkansas, 1987, *U.S. Geological Survey Open File Report* 89-64, 32 p.

Westerfield, P.W., 1990. Water-level maps of the Mississippi River alluvial valley aquifer in Eastern Arkansas, 1987, *U.S. Geological Survey Water Resources Investigation Report* 90-4089, Plate 1.

Westerfield, P.W., 1995. Potentiometric surface of the Sparta and Memphis aquifers in eastern Arkansas, April through July 1993, *U.S. Geological Survey Water Resources Investigation Report* 95-4000, Plate 1.

Westerfield, P.W., 1995. Potentiometric surface of the Sparta and Memphis aquifers in eastern Arkansas, April through July 1993, *U.S. Geological Survey Water Resources Investigation Report* 95-4000, Plate 1.

Williams, R., Stephenson, W., Odum, J., and Worley, D., 2001. Seismic-reflection imaging of Tertiary faulting and related post-Eocene deformation 20 km north of Memphis, Tennessee, *Engineering Geology*, 62: 79-90.

Williamson, A.K., Grubb, H.F., and Weiss, J.S., 1990. Ground-water flow in the Gulf Coast aquifer systems, south central United States - A preliminary analysis, *U.S. Geological Survey Water Resources Investigations Report*, 89-4071, 124 p.

Wood, W.W., 1999. Use and misuse of the chloride-mass balance method in estimating ground water recharge, *Ground Water*, 1: 2-3.

Wood, W.W., and Sanford, W.E., 1995. Chemical and isotopic method for quantifying ground-water recharge in a regional, semiarid environment, *Ground Water*, 33(3): 458-486.

Wu, J., Zhang, R., and Yang, J., 1996. Analysis of rainfall-recharge relationships, *Journal of Hydrology*, 177(1-2): 143-160.

Yuping, L., Shu, Y., Li, H., and Zheng, L., 2006. Integrated remote sensing and hydrological models for water balance in mountain watersheds, remote sensing and hydrological models for water balance in mountain watersheds. In: *Remote Sensing for Agriculture, Ecosystems, and Hydrology VIII*, eds. Owe, M., D'Urso, G, Neale, C., Gouweleeuw, B., 6359.

8.0
Appendix Geophysical Logs

Plate 1: Section G-G'

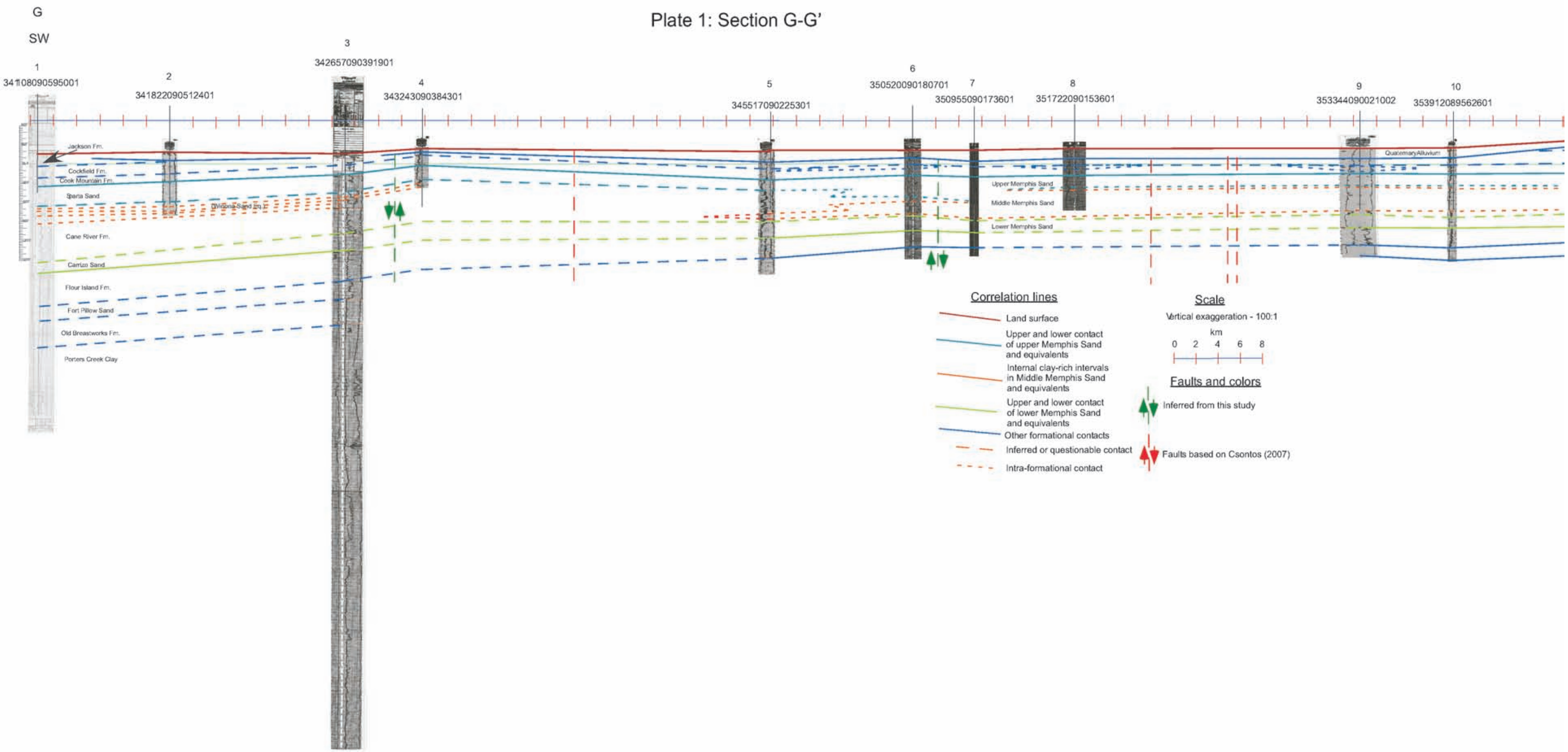


Plate 1: Section G-G'

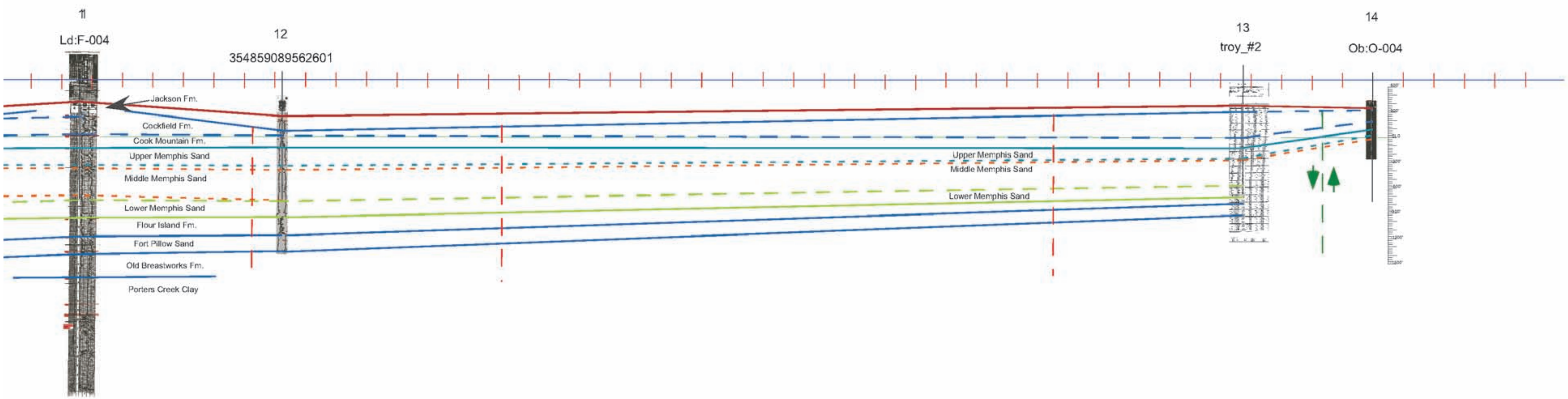
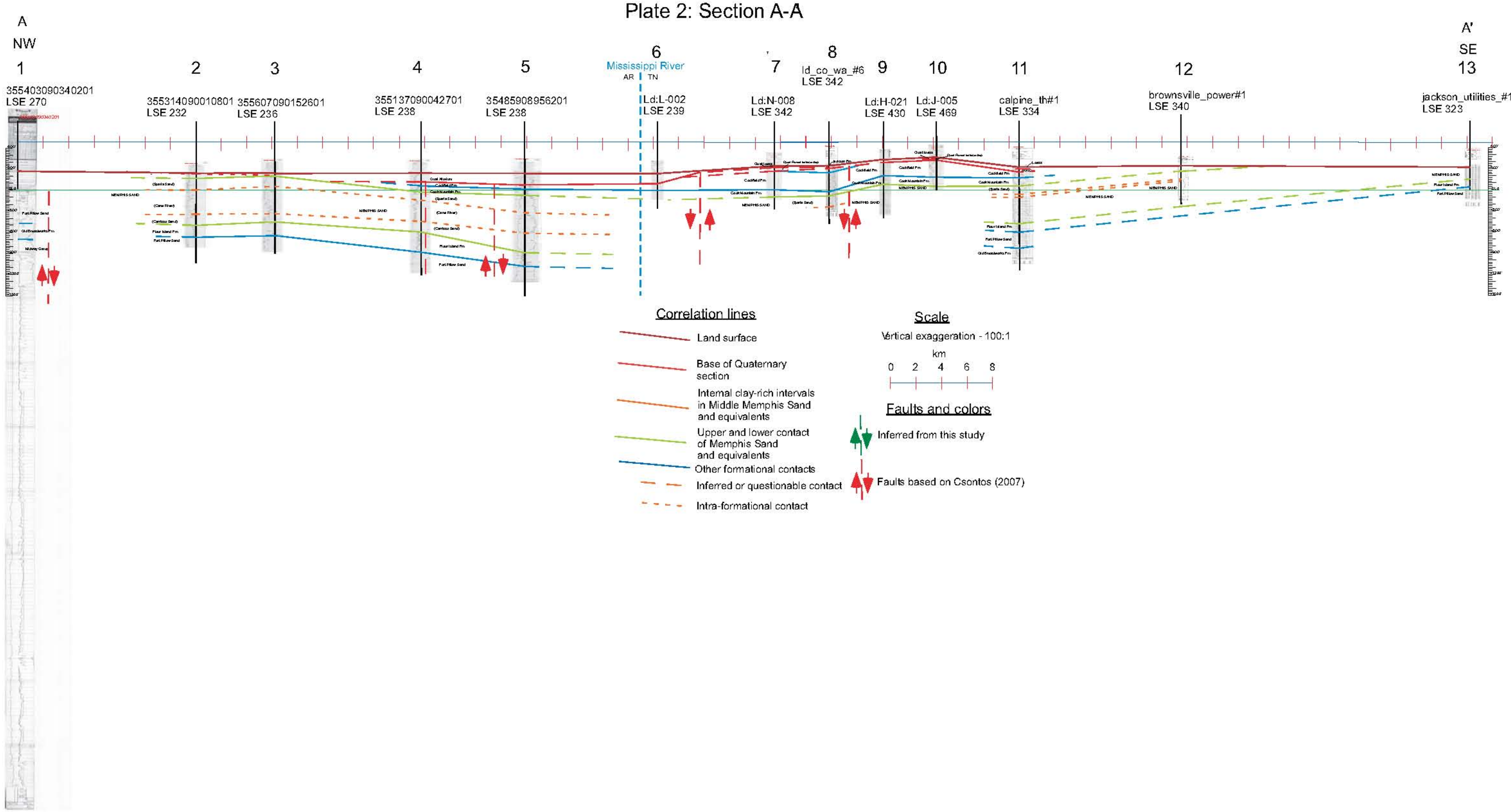


Plate 2: Section A-A



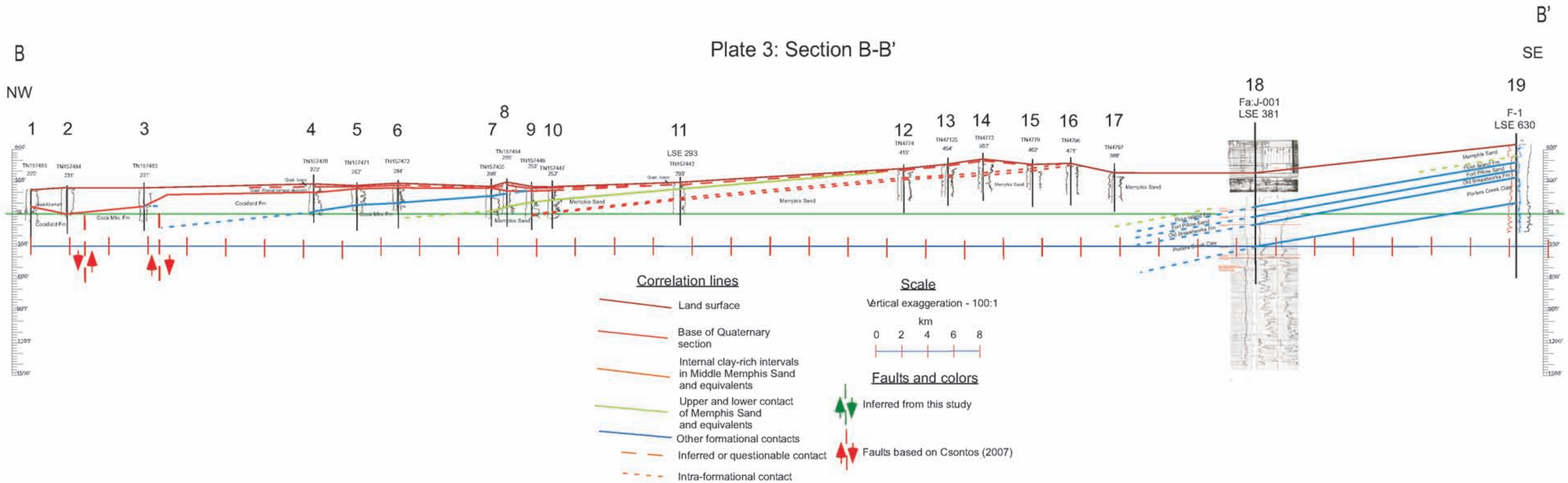


Plate 3: Section B-B'
B
B'
NW
SE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
LSE 293
Fa:J-001
LSE 381
F-1
LSE 630
Cockfield Fm
Cook Mtn. Fm
Memphis Sand
Correlation lines
Land surface
Base of Quaternary section
Internal clay-rich intervals in Middle Memphis Sand and equivalents
Upper and lower contact of Memphis Sand and equivalents
Other formational contacts
Inferred or questionable contact
Intra-formational contact
Scale
Vertical exaggeration - 100:1
km
0 2 4 6 8
Faults and colors
Inferred from this study
Faults based on Csontos (2007)

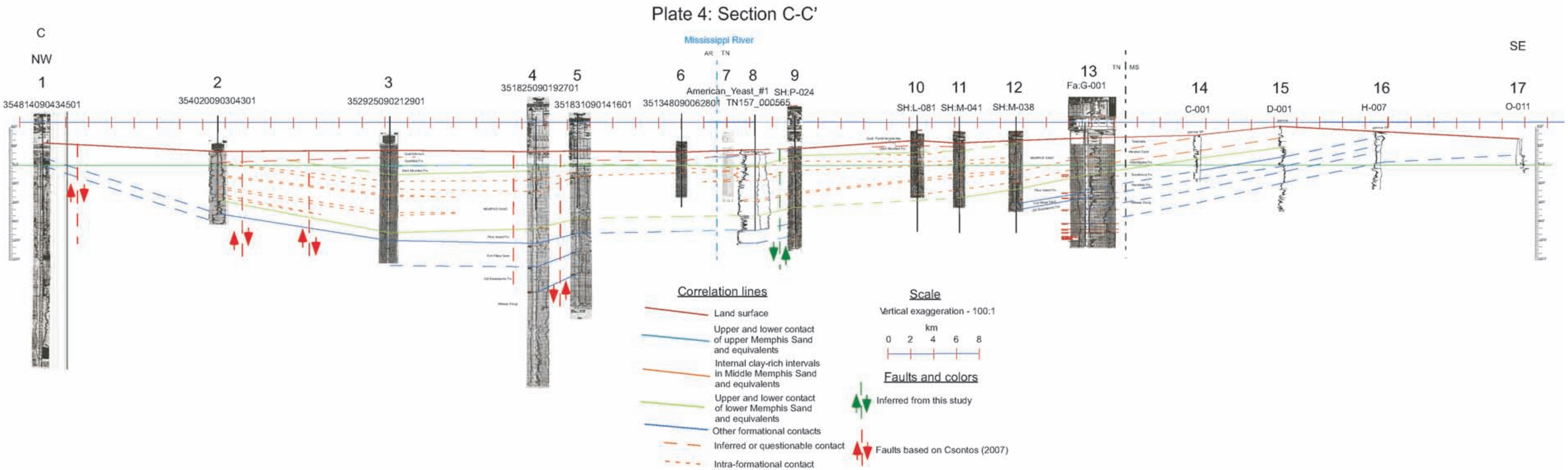


Plate 4: Section C-C'
C
NW
SE
Mississippi River
AR
TN
TN
MS
1
354814090434501
2
354020090304301
3
352925090212901
4
351825090192701
5
351831090141601
6
351348090062801
7
American_Yeast_#1
8
TN157_000565
9
SH:P-024
10
SH:L-081
11
SH:M-041
12
SH:M-038
13
Fa:G-001
14
C-001
15
D-001
16
H-007
17
O-011
Correlation lines
Land surface
Upper and lower contact of upper Memphis Sand and equivalents
Internal clay-rich intervals in Middle Memphis Sand and equivalents
Upper and lower contact of lower Memphis Sand and equivalents
Other formational contacts
Inferred or questionable contact
Intra-formational contact
Scale
Vertical exaggeration - 100:1
km
0 2 4 6 8
Faults and colors
Inferred from this study
Faults based on Csontos (2007)

Plate 5: Section D-D'

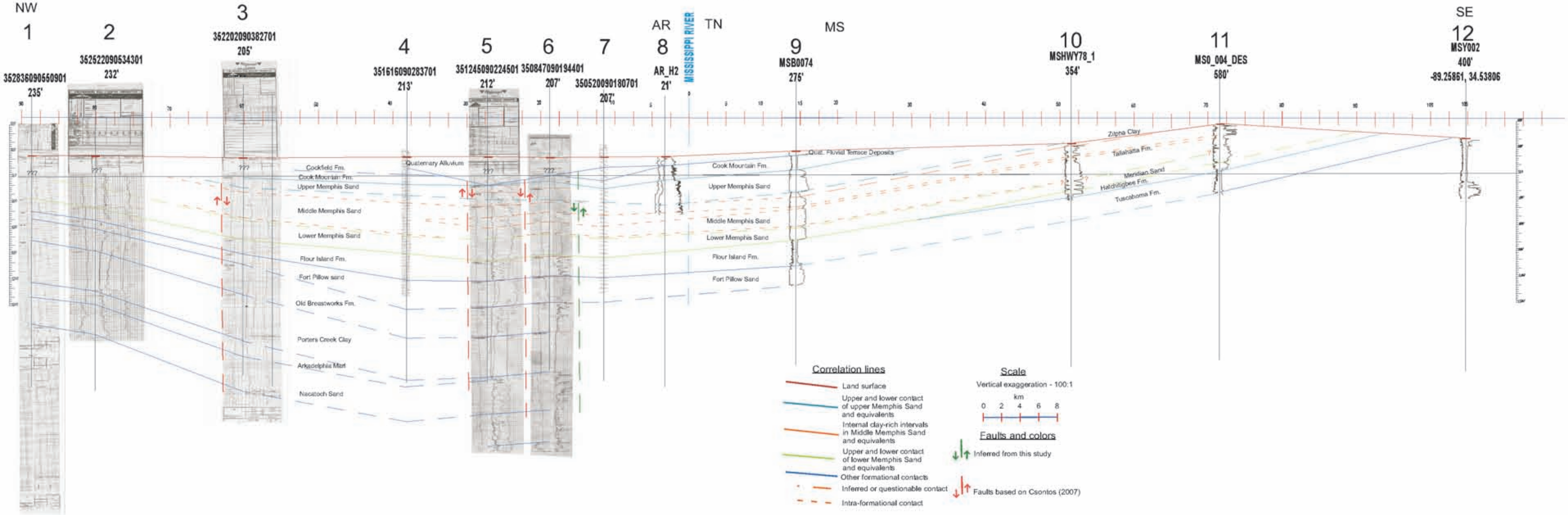
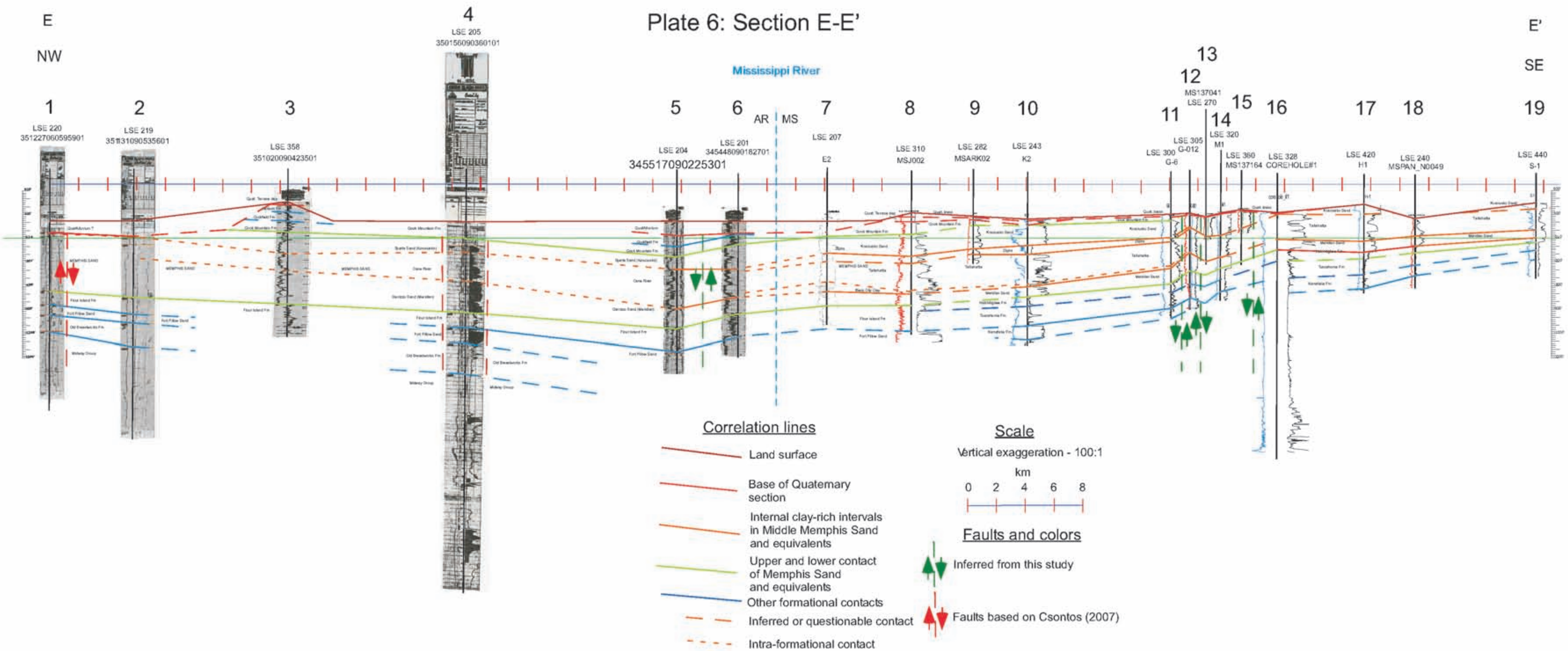
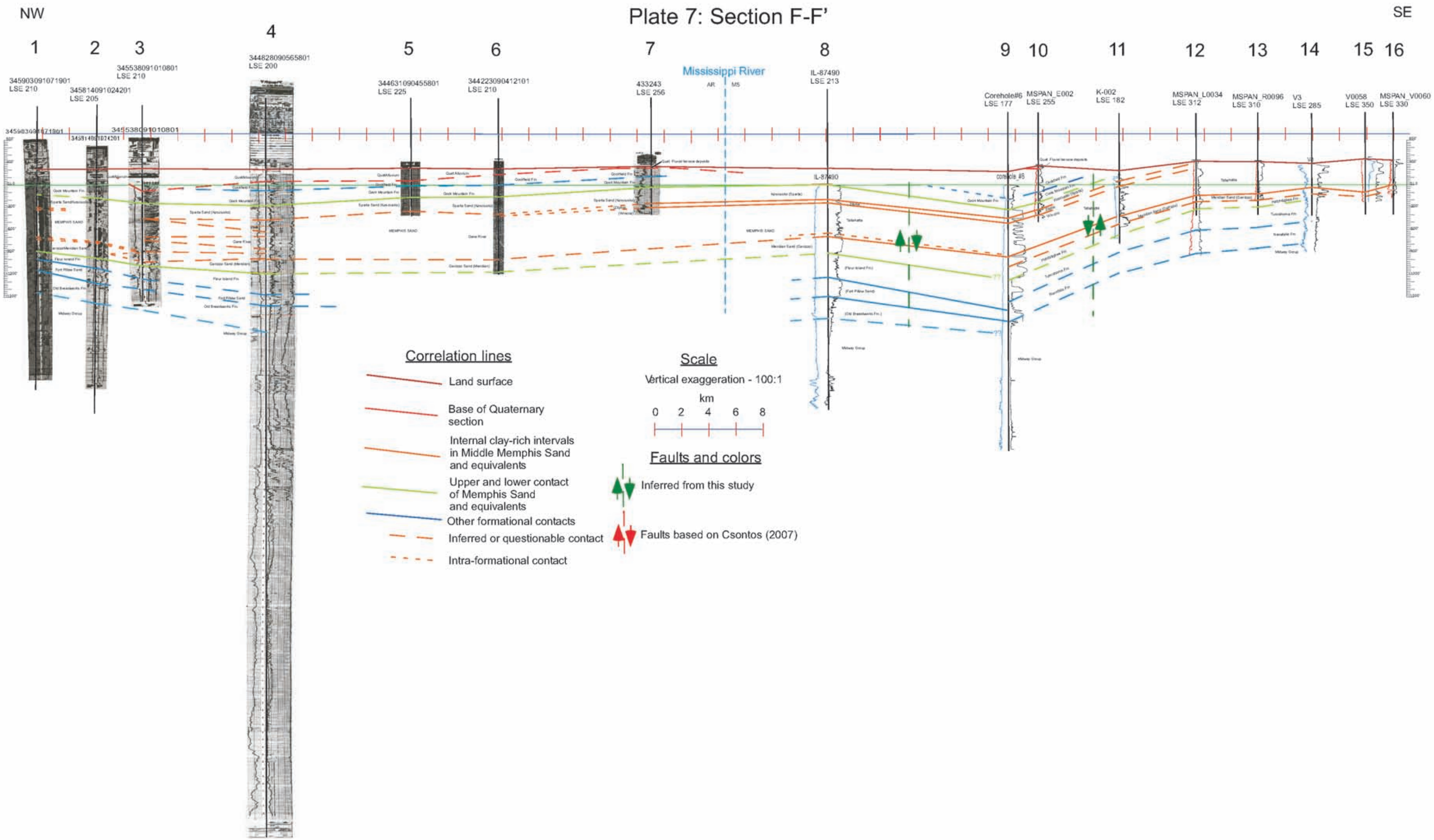


Plate 6: Section E-E'




NW
Plate 7: Section F-F'
SE
1
345903091071901
LSE 210
2
345814091024201
LSE 205
3
345538091010801
LSE 210
4
344828090565801
LSE 200
5
344631090455801
LSE 225
6
344223090412101
LSE 210
7
433243
LSE 256
Mississippi River
AR
MS
8
IL-87490
LSE 213
9
Corehole#6
LSE 177
10
MSPAN_E002
LSE 255
11
K-002
LSE 182
12
MSPAN_L0034
LSE 312
13
MSPAN_R0096
LSE 310
14
V3
LSE 285
15
V0058
LSE 350
16
MSPAN_V0060
LSE 330
Correlation lines
Land surface
Base of Quaternary section
Internal clay-rich intervals in Middle Memphis Sand and equivalents
Upper and lower contact of Memphis Sand and equivalents
Other formational contacts
Inferred or questionable contact
Intra-formational contact
Scale
Vertical exaggeration - 100:1
km
0 2 4 6 8
Faults and colors
Inferred from this study
Faults based on Csontos (2007)

Appendix A

Plates of Cross Sections

Appendix B

Well Log Ranking Chart

Well logs were ranked according to log type, location and elevation accuracy. Log type ranking was determined using the decision matrix below (Table App1). Only logs that had a rank of >6 were used in this report and are provided here in the Appendix.

Table App1. Data ranking system for geophysical log data.

Log type	Rank
Geophysical - Gamma	5[a]
Resistivity	4(+1)[a]
Density	+1
Spontaneous potential	+1
Geologist	4
Drillers	2
Seismic	7
Geophysical log quality	
Readability	
Clear text	+1
Fuzzy text	0
Signal strength	
Strong: facies changes noticeable	+1
Weak: minimal changes in signal over length of log	0
Consistency	
Many groupings of logs drilled by same driller over short time period	+1
Individualized drilling	0

[a] Base ranking with additive ranking possible inclusive of other logs

Well location ranks were determined by the decision matrix illustrated in Table App2.

Table App2. Numerical ranking system for spatial location data (x,y).

Location method	Rank	Accuracy	Additive to Rank
GPS	8	*DMS*	
		no digits after the decimal Second	+0
		1 digit after the decimal Second	+1
		2 or more digits after the decimal Second	+2
		DD	
		4 or less significant digits	+0
		5 to 6 significant digits	+1
		7 or more significant digits	+2
		UTM	+2
		Stateplane	+2
Survey	10		---
Approximation using a reference map			
Graticule grid	6	USGS 1:24000 or smaller scale	+2
		USGS or peer reviewed publication (figure)	+1
		Other publication	+0
Georeference	7		---
Approximation using a reference grid			
TRS	5	Section	+0
		quarter section	+1
		quarter-quarter section	+2
		quarter-quarter-quarter or more section	+3
Scaling	3		---
Geocoding	4		---
N/A	1		---

Lastly, the elevation rank was determined using the ranking matrix shown in Table App3.

Table App3. Ranking system for elevation data (z).

Point elevations	Rank
GPS	Low
Differential GPS	Medium
Survey GPS	High
Barometer-GPS	Medium
Survey	High
Approximation	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation.

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
P-011	-89.098611	34.654722	580	MS	Benton	537	8	14	Low
O-011	-89.186550	34.618022	420	MS	Benton	552	7	8	Low
H-007	-89.242361	34.825961	520	MS	Benton	916	9	8	Low
H-002	-89.235950	34.801131	513	MS	Benton	525	9	8	Low
H1	-89.181281	34.847500	613	MS	Benton	930	6	7	Low
F5	-89.073700	34.894061	620	MS	Benton	1551	6	8	Low
D-001	-89.335833	34.921111	615	MS	Benton	1364	9	14	Low
A-001	-89.635525	34.977311	400	MS	Marshall	694	9	8	Low
S1	-89.463328	34.663781	400	MS	Marshall	1294	6	7	Low
P3	-89.555244	34.766586	513	MS	Marshall	1313	5	8	Low
P1	-89.369031	34.691669	500	MS	Marshall	681	7	8	Low
D-003	-89.684717	34.865525	338	MS	Marshall	1715	5	6	Low
D5	-89.687067	34.870772	360	MS	Marshall	1737	6	8	Low
C-001	-89.410103	34.947600	475	MS	Marshall	737	9	8	Low
A-002	-89.626664	34.971917	420	MS	Marshall	1770	8	5	Low
Withers-001	-90.201217	34.904947	210	MS	DeSoto	3800?	7	5	Low
B-009	-90.037778	34.994722	290	MS	DeSoto	1521	9	8	Low
M1	-89.822533	34.831256	260	MS	DeSoto	646	6	8	Low
L4	-89.954286	34.772264	360	MS	DeSoto	1438	6	8	Low
A1	-90.108453	34.963333	305	MS	DeSoto	1668	7	8	Low
A5	-90.154317	34.953478	210	MS	DeSoto	1614	7	8	Low
E1	-90.243922	34.890117	200	MS	DeSoto	2004	7	8	Low
E2	-90.207100	34.903408	207	MS	DeSoto	1290	7	7	Low
K2	-90.071275	34.734253	243	MS	DeSoto	1589	7	7	Low
G4	-89.968275	34.633056	250	MS	Tate	1268	7	8	Low
M-002	-89.932733	34.566578	320	MS	Tate	1103	9	8	Low
M1	-89.937547	34.571442	320	MS	Tate	1115	7	8	Low
K2	-90.179339	34.572483	320	MS	Tate	1668	8	8	Low
K1	-90.179650	34.572056	320	MS	Tate	1517	8	8	Low
H-001	-89.837481	34.604561	370	MS	Tate	1170	6	8	Low
G-012	-89.958533	34.597731	305	MS	Tate	1212	9	8	Low
G-7	-89.966239	34.631703	250	MS	Tate	1192	7	7	Low
G-6	-89.973192	34.613714	300	MS	Tate	1285	8	8	Low
G-5	-89.956600	34.620919	268	MS	Tate	1197	7	6	Low
G-3	-89.957267	34.620919	260	MS	Tate	1217	7	6	Low
G-1	-89.968047	34.632253	250	MS	Tate	827	7	8	Low
F-2	-89.990597	34.612178	340	MS	Tate	1242	6	8	Low
F-1	-90.081244	34.618983	340	MS	Tate	1518	6	7	Low
E-3	-90.182206	34.656619	210	MS	Tate	1627	8	8	Low
E-1	-90.189292	34.662283	280	MS	Tate	1799	8	8	Low
A-001	-90.101847	34.718042	275	MS	Tate	600	7	8	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
M3	-89.930000	34.490000	320	MS	Panola	1154	7	8	Low
R2	-90.070000	34.320000	210	MS	Panola	805	7	8	Low
S-1	-89.790000	34.290000	440	MS	Panola	928	7	8	Low
S-003	-89.870000	34.340000	250	MS	Panola	555	9	8	Low
V2	-89.940000	34.220000	279	MS	Panola	986	7	8	Low
V3	-89.940000	34.240000	285	MS	Panola	1185	7	8	Low
V-0058	-89.902072	34.194778	350	MS	Panola	581	9	8	Low
W-1	-89.811217	34.166825	330	MS	Panola	625	7	8	Low
W-004	-89.849239	34.164739	330	MS	Panola	1025	6	8	Low
K-002	-90.097406	34.394111	182	MS	Panola	904	7	8	Low
K-5	-90.182994	34.393886	165	MS	Panola	1712	7	8	Low
H-5	-89.847819	34.436256	360	MS	Panola	993	7	8	Low
H1	-89.824503	34.467100	420	MS	Panola	1104	7	8	Low
G-009	-89.926500	34.441631	350	MS	Panola	1415	9	6	Low
G6	-89.912694	34.448089	340	MS	Panola	1152	7	8	Low
Danner #1	-90.153681	35.316008	225	AR	Crittenden	3351	0	0	Low
Sanderson #1	-90.346003	35.133594	207	AR	Crittenden	3504	7	5	Low
Leach #1	-90.370350	35.256622	215	AR	Crittenden	3454	7	5	Low
HaK-012	-89.380833	35.660000	340	TN	Haywood	1102	7	8	Low
HaG-12	0.000000	0.000000	343	TN	Haywood	357	7	2	Low
Q-3	-88.800278	35.303333	510	TN	Hardeman	359	7	6	Low
K-28	-89.005000	35.138611	570	TN	Hardeman	760	6	6	Low
F-1	-89.017500	35.031667	630	TN	Hardeman	819	9	6	Low
G-12	-89.645278	35.699444	360	TN	Lauderdale	427	10	6	Low
J-5	-89.454722	35.732500	469	TN	Lauderdale	452	10	6	Low
N-3	-89.538889	35.804444	491	TN	Lauderdale	583	10	6	Low
N-8	-89.607222	35.794444	342	TN	Lauderdale	333	10	6	Low
N-9	-89.544444	35.795556	387	TN	Lauderdale	406	10	6	Low
R-3	-89.636111	35.894444	258	TN	Lauderdale	252	10	6	Low
S-3	-89.535000	35.885000	279	TN	Lauderdale	465	9	6	Low
U-1	-89.366667	35.883056	273	TN	Lauderdale	408	7	8	Low
O-10	-89.390833	35.821667	308	TN	Lauderdale	416	10	6	Low
H-21	-89.528889	35.745556	430	TN	Lauderdale	773	7	6	Low
H-17	-89.525556	35.660278	325	TN	Lauderdale	297	10	6	Low
F-9	-89.825833	35.644167	437	TN	Lauderdale	352	8	6	Low
H-6	-89.528333	35.745556	420	TN	Lauderdale	755	7	6	Low
H-20	-89.537222	35.632222	305	TN	Lauderdale	443	3	6	Low
U-18	-89.978611	35.266667	246	TN	Shelby	475	7	6	Low
R-45	-89.731389	35.146389	340	TN	Shelby	693	9	6	Low
R-43	-89.720833	35.149167	340	TN	Shelby	1313	9	6	Low
R-47	-89.710278	35.131111	294	TN	Shelby	1319	9	6	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
P-69	-89.923146	35.205644	318	TN	Shelby	346	9	2	Low
P-205	-89.950000	35.246667	258	TN	Shelby	1548	9	6	Low
J-32	-90.073984	35.115924	281	TN	Shelby	422	7	2	Low
Q-62	-89.858333	35.190556	307	TN	Shelby	890	7	6	Low
R-23	-89.731944	35.146667	340	TN	Shelby	758	9	6	Low
R-21	-89.727222	35.153611	305	TN	Shelby	1185	9	6	Low
U-30	-89.972313	35.268698	245	TN	Shelby	496	7	1	Low
U-48	-89.957500	35.353889	267	TN	Shelby	312	7	6	Low
L-17	-89.858421	35.122589	310	TN	Shelby	223	7	2	Low
P-142	-89.961389	35.242222	301	TN	Shelby	850	9	6	Low
P-207	-89.952222	35.236944	246	TN	Shelby	1569	7	6	Low
K-45	-89.933705	35.116201	289	TN	Shelby	1360	7	2	Low
O-143	-90.019257	35.153423	250	TN	Shelby	383	7	2	Low
O-112	-90.022590	35.174256	245	TN	Shelby	483	7	2	Low
Q-3	-89.751195	35.160645	320	TN	Shelby	481	7	2	Low
P-79	-89.942589	35.127034	302	TN	Shelby	374	7	2	Low
P-75	-89.923699	35.212866	330	TN	Shelby	305	7	2	Low
O-113	-90.022868	35.174256	245	TN	Shelby	473	7	2	Low
C-81355	-89.903083	34.291583	360	MS	Panola	3263	7	5	Low
Corehole #1	-89.880731	34.541542	328	MS	Panola	3014	7	5	Low
IE-81357-AL	-89.928444	34.226256	244	MS	Panola	4959	8	5	Low
21-9S-8W	-90.044869	34.292047	205	MS	Panola	2457	7	5	Low
Corehole #5	-89.985794	34.469314	338	MS	Panola	3710	7	5	Low
Corehole #6	-90.188889	34.477583	177	MS	Panola	3530	7	6	Low
Corehole #7	-90.039922	34.279056	219	MS	Panola	3312	7	6	Low
28-29N-2W	-90.405025	34.356042	166	MS	Coahoma	11495	9	6	Low
IL-90319	-90.460758	34.168092	163	MS	Panola	17600	7	6	Low
Johnson #1	-89.542292	34.610228	385	MS	Marshall	4003	7	5	Low
20-5S-6W	-89.864042	34.633875	282	MS	Tate	2880	7	5	Low
IL-87490	-90.417875	34.518164	213	MS	Tunica	11930	7	5	Low
ud-#5	-89.714680	35.556470	387	TN	Tipton	678	9	10	Low
greystone#1	-89.392110	35.652450	318	TN	Haywood	839	10	10	Low
greystone#2	-89.392110	35.652460	318	TN	Haywood	834	10	10	Low
ardie_rd_th_#1	-89.835700	35.255747	290	TN	Shelby	825	9	1	Low
power_#1	-89.209764	35.541828	340	TN	Haywood	441	8	1	Low
dist_pkwy_th_#1	-89.669181	35.033842	370	TN	Shelby	401	9	1	Low
flem_rd_th_#1	-89.705990	35.024920	345	TN	Shelby	537	9	10	Low
flem_rd_th_#2_pie	-89.707000	35.024000	335	TN	Shelby	511	9	1	Low
syc_rd_#1	-89.671800	35.036044	360	TN	Shelby	414	9	1	Low
fleischman_12_05	-90.085017	35.076733	240	TN	Shelby	635	9	10	Low
hunt_wesson_th_#1_well8	-90.017964	35.121755	308	TN	Shelby	528	9	1	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
ld_co_wa_#6	-89.531760	35.807310	431	TN	Lauderdale	613	9	10	Low
mason_11_03	-89.534640	35.411790	310	TN	Tipton	289	9	1	Low
hw_floor_th1_well2	-90.035389	35.185275	240	TN	Shelby	506	9	1	Low
milan_piez_#1	-88.771430	35.921190	466	TN	Gibson	377	9	1	Low
milan_piez_#3	-88.770820	35.921190	460	TN	Gibson	360	9	1	Low
milan_piez_#4	-88.769710	35.921220	454	TN	Gibson	361	9	1	Low
milan_piez_#5	-88.773050	35.921260	487	TN	Gibson	386	9	1	Low
milan_th#1	-88.771090	35.921190	463	TN	Gibson	379	9	1	Low
paris_2_04	-88.327333	36.301567	530	TN	Henry	414	9	10	Low
vertex_th1	-90.140000	35.083889	249	TN	Shelby	471	9	1	Low
allegheny_energy_#1	-88.619920	36.222050	421	TN	Weakley	304	9	1	Low
allegheny_energy_#2	-88.620820	36.221540	410	TN	Weakley	320	9	1	Low
american_yeast_#1	-90.054730	35.191060	250	TN	Shelby	704	9	1	Low
bartlett_ardie_rd_963ft	-89.836736	35.254636	287	TN	Shelby	972	9	1	Low
bartlett_gtown_th#1	-89.792425	35.212097	327	TN	Shelby	818	9	1	Low
birmingham_steel_th#1	-90.151620	35.055830	210	TN	Shelby	607	10	1	Low
birmingham_steel_th#2	-90.153820	35.055870	210	TN	Shelby	721	10	1	Low
buckeye#18	-89.993650	35.171530	240	TN	Shelby	620	9	1	Low
calpine_#7	-89.378910	35.658960	323	TN	Haywood	1181	9	10	Low
calpine_th_#1	-89.381000	35.661000	334	TN	Haywood	1292	9	9	Low
dyersburg_fabric_th#1	-89.370430	36.036490	334	TN	Dyer	789	9	1	Low
haywood_energy_#3	-89.425000	35.422800	377	TN	Haywood	1197	9	1	Low
jackson_utilities_th#1	-88.812920	35.604460	373	TN	Madison	431	9	1	Low
mapco_th#1	-90.082310	35.085050	231	TN	Shelby	547	9	1	Low
munford_571ft	-89.809760	35.447770	448	TN	Tipton	692	9	10	Low
troy_#1	-89.161440	36.339810	361	TN	Obion	1403	10	1	Low
troy_#2	-89.161389	36.339444	357	TN	Obion	1417	10	8	Low
dyersburg_#10_th_#3_911ft	-89.368200	36.036810	325	TN	Dyer	908	8	1	Low
dyersburg_#10_th_#3_1075f	-89.368200	36.036810	325	TN	Dyer	1066	10	1	Low
dyersburg_#11_th#1	-89.367590	36.034360	308	TN	Dyer	912	10	1	Low
dyersburg_#12_th#1	-89.367480	36.034600	307	TN	Dyer	932	10	1	Low
AR035_000001	-90.29399	35.16620	211	AR	Crittenden	295	10	8	High
AR035_000002	-90.21676	35.06232	210	AR	Crittenden	295	10	8	High

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
AR035_000003	-90.22982	35.12343	212	AR	Crittenden	295	10	8	High
AR035_000004	-90.10787	35.23037	217	AR	Crittenden	295	10	8	High
AR035_000005	-90.29399	35.16620	205	AR	Crittenden	295	7	8	Low
MSA006	-90.10861	34.96333	302	MS	DeSoto	545	9	14	Low
MSA007	-90.10861	34.96333	308	MS	DeSoto	1638	9	14	Low
MSB005	-89.99778	34.96750	320	MS	DeSoto	499	9	14	Low
MSB008	-90.04139	34.98139	281	MS	DeSoto	1015	9	14	Low
MSB0074	-90.04000	34.99472	275	MS	DeSoto	1554	9	12	Low
MSC004	-89.92917	34.95000	390	MS	DeSoto	443	9	14	Low
MSD008	-89.77722	34.96778	392	MS	DeSoto	500	9	14	Low
MSD009	-89.86222	34.97222	395	MS	DeSoto	570	9	14	Low
MSF2	-90.03194	34.94361	340	MS	DeSoto	1650	6	13	Low
MSF0113	-90.01611	34.87056	275	MS	DeSoto	1525	9	16	Low
MSG009	-89.99778	34.91750	350	MS	DeSoto	497	9	8	Low
MSJ002	-90.15278	34.83000	310	MS	DeSoto	1609	9	14	Low
MSL005	-89.94444	34.81417	390	MS	DeSoto	405	9	14	Low
MS033_000001	-89.93454	34.83139	298	MS	DeSoto	296	10	7	Low
MS033_000003	-89.89972	34.79732	244	MS	DeSoto	297	10	7	Low
MS033_000004	-89.90754	34.82936	320	MS	DeSoto	297	10	7	Low
MS033_000007	-89.97105	34.82782	340	MS	DeSoto	297	10	7	Low
MS033_000008	-89.93772	34.86096	347	MS	DeSoto	287	10	7	Low
MS033_000014	-89.97559	34.79593	382	MS	DeSoto	296	10	7	Low
MS033_000024	-89.89975	34.86958	301	MS	DeSoto	295	10	7	Low
MS033_000032	-89.92652	34.91848	380	MS	DeSoto	297	10	7	Low
MS033_000033	-89.89733	34.94501	360	MS	DeSoto	296	10	7	Low
MS033_000034	-89.96812	34.91204	340	MS	DeSoto	296	10	7	Low
MS033_000044	-89.96393	34.77358	360	MS	DeSoto	214	10	7	Low
MS033_000050	-89.95020	34.93515	385	MS	DeSoto	276	10	7	Low
MS033_000051	-89.93395	34.89674	385	MS	DeSoto	297	10	7	Low
MS033_000053	-89.90442	34.91821	360	MS	DeSoto	296	10	7	Low
MS033_000054	-89.92212	34.94733	395	MS	DeSoto	297	10	7	Low
MS033_000057	-89.88078	34.98957	350	MS	DeSoto	297	10	7	Low
MS033_000064	-89.96020	34.85969	330	MS	DeSoto	296	10	7	Low
MS033_000066	-89.81980	34.97096	412	MS	DeSoto	418	4	7	Low
MS033_000074	-89.95342	34.97148	380	MS	DeSoto	373	3	8	Low
MS033_000079	-89.79481	34.98426	400	MS	DeSoto	458	4	7	Low
MS137_000037	-89.97986	34.55561	335	MS	Panola	297	10	7	Low
MS137_000039	-89.97121	34.56628	305	MS	Tate	297	10	7	Low
MS137_000040	-89.96684	34.58083	318	MS	Tate	297	9	7	Low
MS137_000041	-89.95329	34.58107	270	MS	Tate	297	10	7	Low
MS137_000042	-89.94875	34.57036	270	MS	Tate	297	10	7	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
MS137_000047	-89.93575	34.56612	320	MS	Tate	297	10	7	Low
MS137_000048	-89.91828	34.57027	265	MS	Tate	297	10	7	Low
MS137_000049	-89.89579	34.57024	310	MS	Tate	297	10	7	Low
MS137_000160	-89.95886	34.69418	315	MS	Tate	297	10	7	Low
MS137_000163	-89.93573	34.55571	342	MS	Panola	296	10	7	Low
MS137_000164	-89.91822	34.55561	360	MS	Panola	297	10	7	Low
MS137_000165	-89.90064	34.55906	261	MS	Panola	296	10	7	Low
MS137_000173	-89.89639	34.64328	310	MS	Tate	297	10	7	Low
MS137_000184	-89.90095	34.67590	361	MS	Tate	297	10	7	Low
MS137_000186	-89.93599	34.64686	323	MS	Tate	297	10	7	Low
MS137_000187	-89.94415	34.66858	340	MS	Tate	247	9	7	Low
MS137_000194	-89.97179	34.68304	270	MS	Tate	296	10	7	Low
MS137_000195	-89.95821	34.66162	322	MS	Tate	270	10	7	Low
TN047_000007	-89.60340	35.11488	433	TN	Fayette	295	10	2	Low
TN047_000009	-89.62420	35.15328	402	TN	Fayette	295	10	2	Low
TN047_000021	-89.59341	35.17209	369	TN	Fayette	285	10	2	Low
TN047_000022	-89.53063	35.11101	385	TN	Fayette	297	10	2	Low
TN047_000023	-89.55657	35.11876	342	TN	Fayette	295	10	2	Low
TN047_000024	-89.55778	35.15762	371	TN	Fayette	296	10	2	Low
TN047_000025	-89.51272	35.17202	408	TN	Fayette	297	10	2	Low
TN047_000072	-89.39422	35.16061	502	TN	Fayette	271	10	2	Low
TN047_000074	-89.46487	35.17658	415	TN	Fayette	297	10	2	Low
TN047_000075	-89.49398	35.11828	430	TN	Fayette	297	10	2	Low
TN047_000076	-89.36118	35.17886	479	TN	Fayette	211	10	2	Low
TN047_000079	-89.37618	35.12964	462	TN	Fayette	217	10	2	Low
TN047_000084	-89.31719	35.15962	468	TN	Fayette	281	10	2	Low
TN047_000096	-89.34315	35.11587	471	TN	Fayette	297	10	2	Low
TN047_000097	-89.30729	35.11426	388	TN	Fayette	244	10	2	Low
TN047_000098	-89.29310	35.17623	527	TN	Fayette	295	10	2	Low
TN047_000099	-89.26024	35.17493	559	TN	Fayette	295	10	2	Low
TN047_000125	-89.42246	35.16623	454	TN	Fayette	297	10	2	Low
TN157_000025	-90.00561	35.15558	252	TN	West Shelby	1422	9	6	Low
TN157_000026	-90.05398	35.14620	268	TN	West Shelby	514	8	6	Low
TN157_000027	-90.02695	35.15438	255	TN	West Shelby	552	8	6	Low
TN157_000034	-90.03454	35.13481	272	TN	West Shelby	451	8	6	Low
TN157_000035	-89.99996	35.15671	251	TN	West Shelby	751	8	6	Low
TN157_000039	-90.00844	35.15442	250	TN	West Shelby	750	8	6	Low
TN157_000044	-90.01323	35.15322	249	TN	West Shelby	830	8	6	Low
TN157_000046	-90.02431	35.15414	259	TN	West Shelby	733	8	6	Low
TN157_000047	-90.00620	35.13565	280	TN	West Shelby	540	10	6	Low
TN157_000085	-89.89592	35.11454	315	TN	East Shelby	232	8	1	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
TN157_000086	-89.93508	35.12385	305	TN	Central Shelby	538	10	6	Low
TN157_000088	-89.92898	35.08842	265	TN	Central Shelby	915	7	2	Low
TN157_000104	-89.93022	35.10700	280	TN	Central Shelby	1226	10	6	Low
TN157_000105	-89.92464	35.11391	295	TN	Central Shelby	870	10	6	Low
TN157_000106	-89.93051	35.11172	278	TN	Central Shelby	860	10	6	Low
TN157_000107	-89.93148	35.12342	311	TN	Central Shelby	340	10	6	Low
TN157_000108	-89.92761	35.10693	300	TN	Central Shelby	557	10	6	Low
TN157_000109	-89.92472	35.09965	285	TN	Central Shelby	914	10	6	Low
TN157_000110	-89.92938	35.10275	278	TN	Central Shelby	943	10	6	Low
TN157_000111	-89.91064	35.10926	312	TN	Central Shelby	619	8	6	Low
TN157_000112	-89.92592	35.10759	285	TN	Central Shelby	618	8	6	Low
TN157_000113	-89.92990	35.10002	273	TN	Central Shelby	912	10	6	Low
TN157_000114	-89.92215	35.11452	297	TN	Central Shelby	865	10	6	Low
TN157_000116	-89.92627	35.11726	305	TN	Central Shelby	622	10	6	Low
TN157_000119	-89.93066	35.12530	260	TN	Central Shelby	428	8	6	Low
TN157_000122	-89.92870	35.11704	308	TN	Central Shelby	855	10	6	Low
TN157_000123	-89.97731	35.00676	320	TN	Central Shelby	1250	9	6	Low
TN157_000124	-89.87580	35.04180	300	TN	East Shelby	1278	10	6	Low
TN157_000125	-89.99398	35.04259	281	TN	South Shelby	408	10	6	Low
TN157_000128	-89.97287	35.02065	311	TN	Central Shelby	816	10	6	Low
TN157_000129	-89.92990	35.12023	295	TN	Central Shelby	595	10	6	Low
TN157_000130	-89.93308	35.12035	285	TN	Central Shelby	1560	10	6	Low
TN157_000272	-89.96704	35.17315	248	TN	Central Shelby	472	7	1	Low
TN157_000273	-89.94315	35.12759	275	TN	Central Shelby	586	6	2	Low
TN157_000275	-89.93473	35.12611	305	TN	Central Shelby	551	7	1	Low
TN157_000276	-89.96120	35.15398	248	TN	Central Shelby	1440	7	6	Low
TN157_000278	-89.99732	35.15759	258	TN	West Shelby	744	7	6	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
TN157_000280	-89.95625	35.24430	300	TN	Central Shelby	904	9	6	Low
TN157_000281	-89.94658	35.24698	232	TN	Central Shelby	1500	7	6	Low
TN157_000310	-89.85370	35.15037	270	TN	East Shelby	267	8	6	Low
TN157_000315	-89.84564	35.19564	305	TN	East Shelby	587	7	2	Low
TN157_000343	-89.80703	35.15953	295	TN	East Shelby	512	9	6	Low
TN157_000355	-89.71764	35.14887	349	TN	East Shelby	1238	9	6	Low
TN157_000357	-89.71104	35.14268	362	TN	East Shelby	1219	9	6	Low
TN157_000358	-89.72454	35.14606	343	TN	East Shelby	1210	9	6	Low
TN157_000359	-89.72070	35.14658	360	TN	East Shelby	1291	9	6	Low
TN157_000363	-89.72802	35.14315	315	TN	East Shelby	1213	9	6	Low
TN157_000364	-89.71925	35.13648	325	TN	East Shelby	1276	9	6	Low
TN157_000374	-89.71107	35.14000	352	TN	East Shelby	1216	10	6	Low
TN157_000375	-89.72842	35.12703	276	TN	East Shelby	824	10	6	Low
TN157_000376	-89.71119	35.14537	370	TN	East Shelby	792	10	6	Low
TN157_000377	-89.72842	35.12704	330	TN	East Shelby	1200	10	6	Low
TN157_000378	-89.71675	35.11176	335	TN	East Shelby	815	10	6	Low
TN157_000393	-89.97870	35.27064	240	TN	Central Shelby	490	9	2	Low
TN157_000431	-89.65867	35.04652	390	TN	SouthEast Shelby	295	9	2	Low
TN157_000432 REF2	-89.74035	35.29335	269	TN	NorthEast Shelby	297	9	2	Low
TN157_000433	-89.72146	35.05956	321	TN	SouthEast Shelby	296	9	2	Low
TN157_000434	-89.75080	35.06496	371	TN	SouthEast Shelby	296	9	2	Low
TN157_000435	-89.71230	35.11840	331	TN	East Shelby	263	9	2	Low
TN157_000436	-89.68036	35.11500	350	TN	East Shelby	297	9	2	Low
TN157_000437	-89.74553	35.12781	305	TN	East Shelby	295	9	2	Low
TN157_000438	-89.74156	35.17550	302	TN	East Shelby	256	9	2	Low
TN157_000439	-89.70852	35.14890	381	TN	East Shelby	237	9	2	Low
TN157_000440	-89.67937	35.16286	375	TN	East Shelby	296	9	2	Low
TN157_000441	-89.65817	35.28545	324	TN	NorthEast Shelby	297	9	2	Low
TN157_000442	-89.65066	35.23097	293	TN	East Shelby	297	9	2	Low
TN157_000445	-89.76705	35.22267	394	TN	NorthEast Shelby	264	9	2	Low
TN157_000446	-89.68680	35.28470	282	TN	NorthEast Shelby	297	9	2	Low
TN157_000447	-89.75971	35.27349	252	TN	NorthEast Shelby	297	9	2	Low
TN157_000448	-89.69565	35.04730	361	TN	SouthEast Shelby	297	9	2	Low
TN157_000449	-89.75574	35.28901	253	TN	NorthEast Shelby	296	9	2	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
TN157_000450	-89.72847	35.29386	272	TN	NorthEast Shelby	297	9	2	Low
TN157_000451	-89.70903	35.30133	285	TN	NorthEast Shelby	297	9	2	Low
TN157_000452	-89.72801	35.30555	355	TN	NorthEast Shelby	287	9	2	Low
TN157_000453	-89.75613	35.30453	269	TN	NorthEast Shelby	297	9	2	Low
TN157_000454	-89.77766	35.29519	295	TN	NorthEast Shelby	297	9	2	Low
TN157_000455	-89.78946	35.28932	260	TN	North Shelby	297	9	2	Low
TN157_000456	-89.67992	35.00669	375	TN	SouthEast Shelby	216	9	2	Low
TN157_000457	-89.75722	35.00565	345	TN	SouthEast Shelby	296	9	2	Low
TN157_000458	-89.82419	35.28986	275	TN	North Shelby	205	9	2	Low
TN157_000459	-89.86174	35.28975	246	TN	North Shelby	295	9	2	Low
TN157_000460	-89.90719	35.29693	289	TN	NorthCentral Shelby	255	9	2	Low
TN157_000461	-89.74303	35.31127	330	TN	NorthEast Shelby	297	9	2	Low
TN157_000462	-89.94329	35.31142	300	TN	NorthCentral Shelby	295	9	2	Low
TN157_000463	-89.72196	35.31976	375	TN	NorthEast Shelby	297	9	2	Low
TN157_000464	-89.97755	35.28540	292	TN	NorthCentral Shelby	235	9	2	Low
TN157_000465	-89.99427	35.29103	245	TN	NorthCentral Shelby	295	9	2	Low
TN157_000466	-90.04175	35.28819	322	TN	NorthWest Shelby	295	9	2	Low
TN157_000467	-90.03102	35.34162	402	TN	NorthWest Shelby	295	9	2	Low
TN157_000468	-89.99742	35.34083	320	TN	NorthWest Shelby	295	9	2	Low
TN157_000469	-89.96386	35.34071	284	TN	NorthCentral Shelby	297	9	2	Low
TN157_000470	-89.92736	35.34920	278	TN	NorthCentral Shelby	297	9	2	Low
TN157_000472	-89.84858	35.33692	284	TN	NorthCentral Shelby	257	9	2	Low
TN157_000473	-89.89192	35.38652	294	TN	North Shelby	297	9	2	Low
TN157_000474	-89.82190	35.34383	298	TN	North Shelby	297	9	2	Low
TN157_000475	-89.77800	35.34151	312	TN	NorthEast Shelby	267	9	2	Low
TN157_000476	-89.74725	35.34413	308	TN	NorthEast Shelby	297	9	2	Low
TN157_000477	-89.70920	35.31233	281	TN	NorthEast Shelby	297	9	2	Low
TN157_000478	-89.70281	35.33727	341	TN	NorthEast Shelby	295	9	2	Low

Table App4. Rankings of well logs including that for assessing the log, location and elevation (cont.)

Well ID	Longitude	Latitude	Elevation (ft)	State	County	Total Depth	Log Rank	Location Rank	Elevation Rank
TN157_000479	-89.76712	35.39560	412	TN	North Shelby	297	9	2	Low
TN157_000480	-89.72868	35.39571	340	TN	NorthEast Shelby	297	9	2	Low
TN157_000481	-89.67812	35.38051	376	TN	NorthEast Shelby	287	9	2	Low
TN157_000482	-89.67185	35.33891	309	TN	NorthEast Shelby	295	9	2	Low
TN157_000483	-90.06807	35.40388	231	TN	NorthWest Shelby	295	9	2	Low
TN157_000484	-90.08771	35.45958	231	TN	NorthWest Shelby	257	9	2	Low
TN157_000485	-90.12049	35.45983	220	TN	NorthWest Shelby	295	9	2	Low
TN157_000565	-90.02735	35.16560	245	TN	West Shelby	1520	9	6	Low
TN157_002033	-89.76675	35.12509	257	TN	East Shelby	475	10	6	Low
TN157_002054	-89.80703	35.12592	262	TN	East Shelby	295	10	6	Low
TN157_002359	-89.93045	35.11637	297	TN	Central Shelby	1516	7	8	Low

9.0
Appendix Gages

Station ID: 1

DESCRIPTION:
Latitude 35°18'39.11", Longitude 89°38'22.13" NAD27
Shelby County, Tennessee, Hydrologic Unit 08010209
Drainage area: 262 square miles
Datum of gage: 246.43 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1969-10-01	2008-11-25	22419
Gage height, feet	1994-10-01	2008-11-25	20580
Daily Statistics			
Discharge, cubic feet per second	1969-10-01	2007-09-30	13879
Gage height, feet	1994-10-01	2007-09-30	4725
Monthly Statistics			
Discharge, cubic feet per second	1969-10	2007-09	
Gage height, feet	1994-10	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1970	2007	
Gage height, feet	1995	2007	
Peak streamflow	1970-04-26	2007-01-15	38
Field measurements	1983-09-29	2008-10-06	243
Field/Lab water-quality samples	1975-10-17	2005-08-16	171
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07030240 (Dec. 2008)

Station ID: 2

DESCRIPTION:
Latitude 35°11'16", Longitude 89°58'32" NAD27
Shelby County, Tennessee, Hydrologic Unit 08010210
Drainage area: 788 square miles
Datum of gage: 191.2 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1995-02-01	2008-11-25	4820
Gage height, feet	2004-10-01	2008-11-25	1340
Daily Statistics			
Discharge, cubic feet per second	1995-02-01	2007-09-30	4425
Gage height, feet	2004-10-01	2007-09-30	945
Monthly Statistics			
Discharge, cubic feet per second	1995-02	2007-09	
Gage height, feet	2004-10	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1995	2007	
Gage height, feet	2005	2007	
Peak streamflow	2001-02-16	2006-12-31	7
Field measurements	1985-10-29	2008-11-19	126
Field/Lab water-quality samples	1995-04-27	2005-07-25	40
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07031740 (Dec. 2008)

Station ID: 3

DESCRIPTION:
Latitude 35°10'09.41", Longitude 89°51'57.74" NAD27
Shelby County, Tennessee, Hydrologic Unit 08010210
Drainage area: 30.5 square miles

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1996-04-01	2008-11-25	4596
Gage height, feet	1996-04-16	2008-11-25	17748
Daily Statistics			
Discharge, cubic feet per second	1996-04-01	2007-09-30	4200
Gage height, feet	1996-04-16	2007-09-30	4041
Monthly Statistics			
Discharge, cubic feet per second	1996-04	2007-09	
Gage height, feet	1996-04	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1996	2007	
Gage height, feet	1996	2007	
Peak streamflow	1996-06-09	2007-02-24	12
Field measurements	1996-03-07	2008-10-08	128
Field/Lab water-quality samples	1996-02-28	2005-07-21	205
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07031692 (Dec. 2008)

Station ID: 4

DESCRIPTION:
Latitude 35°06'59", Longitude 89°48'05" NAD27
Shelby County, Tennessee, Hydrologic Unit 08010210
Drainage area: 699 square miles
Datum of gage: 235.76 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1969-10-01	2008-11-25	12823
Gage height, feet	1991-01-01	2008-11-25	6320
Daily Statistics			
Discharge, cubic feet per second	1969-10-01	2007-09-30	12416
Gage height, feet	1991-01-01	2007-09-30	5916
Monthly Statistics			
Discharge, cubic feet per second	1969-10	2007-09	
Gage height, feet	1991-01	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1970	2007	
Gage height, feet	1991	2007	
Peak streamflow	1970-04-26	2007-02-23	34
Field measurements	1970-01-02	2008-10-14	184
Field/Lab water-quality samples	1975-10-23	2005-08-23	155
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07031650 (Dec. 2008)

Station ID: 5

DESCRIPTION:
Latitude 35°02'59", Longitude 89°49'08" NAD27
Shelby County, Tennessee, Hydrologic Unit 08010211
Drainage area: 68.2 square miles
Datum of gage: 262.92 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1969-10-01	2007-09-30	13144
Daily Statistics			
Discharge, cubic feet per second	1969-10-01	2007-09-30	13144
Monthly Statistics			
Discharge, cubic feet per second	1969-10	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1970	2007	
Peak streamflow	1970-03-03	2007-02-24	37
Field measurements	1983-09-28	2008-10-14	229
Field/Lab water-quality samples	1975-10-23	2005-08-23	165
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07032200 (Dec. 2008)

Station ID: 6

DESCRIPTION:
Latitude 35°06'34", Longitude 89°39'28" NAD83
Shelby County, Tennessee, Hydrologic Unit 08010210
Drainage area: 3.61 square miles

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Field/Lab water-quality samples	2007-11-23	2008-07-09	55

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07036050 (Dec. 2008)

Station ID: 7

DESCRIPTION:
Latitude 35°03'15", Longitude 89°32'28" NAD27
Fayette County, Tennessee, Hydrologic Unit 08010210
Drainage area: 503 square miles
Datum of gage: 300.74 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1929-08-01	2007-09-30	21177
Gage height, feet	2001-05-25	2008-11-25	7881
Daily Statistics			
Discharge, cubic feet per second	1929-08-02	2007-09-30	17478
Gage height, feet	2001-05-25	2007-09-30	1849
Monthly Statistics			
Discharge, cubic feet per second	1929-08	2007-09	
Gage height, feet	2001-05	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1929	2007	
Gage height, feet	2001	2007	
Peak streamflow	1930-01-09	2006-01-24	47
Field measurements	2001-06-18	2008-10-15	61
Field/Lab water-quality samples	1961-08-16	2006-05-25	65
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07030550 (Dec. 2008)

Station ID: 8

DESCRIPTION:
Latitude 35°01'57", Longitude 89°14'48" NAD27
Fayette County, Tennessee, Hydrologic Unit 08010210
Drainage area: 210 square miles
Contributing drainage area: 210 square miles,

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Temperature, water, degrees Celsius	1996-09-18	2008-11-18	3099
Discharge, cubic feet per second	1995-09-01	2008-11-25	4828
Gage height, feet	1995-08-23	2008-11-25	16515
Daily Statistics			
Temperature, water, degrees Celsius	1996-09-18	2007-09-30	630
Discharge, cubic feet per second	1995-09-01	2007-09-30	4048
Gage height, feet	1995-08-31	2007-09-30	3938
Monthly Statistics			
Temperature, water, degrees Celsius	1996-09	2007-09	
Discharge, cubic feet per second	1995-09	2007-09	
Gage height, feet	1995-08	2007-09	
Annual Statistics			
Temperature, water, degrees Celsius	1996	2007	
Discharge, cubic feet per second	1995	2007	
Gage height, feet	1995	2007	
Peak streamflow	1996-03-27	2007-01-06	12
Field measurements	1995-08-16	2008-10-09	104
Field/Lab water-quality samples	1995-10-04	2008-07-22	241
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07030392 (Dec. 2008)

Station ID: 9

DESCRIPTION:
Latitude 35°16'30.89", Longitude 88°58'35.65" NAD27
Hardeman County, Tennessee, Hydrologic Unit 08010208
Drainage area: 1,480 square miles
Datum of gage: 323.49 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1929-08-01	2008-11-25	28971
Gage height, feet	1989-02-20	2008-11-25	6617
Daily Statistics			
Discharge, cubic feet per second	1929-08-01	2007-09-30	28550
Gage height, feet	1989-02-20	2007-09-30	6196
Monthly Statistics			
Discharge, cubic feet per second	1929-08	2007-09	
Gage height, feet	1989-02	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1929	2007	
Gage height, feet	1989	2007	
Peak streamflow	1930-01-09	2007-01-10	77
Field measurements	1983-09-07	2008-10-03	198
Field/Lab water-quality samples	1964-05-14	2006-05-30	269
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07029500 (Dec. 2008)

Station ID: 10

DESCRIPTION:
Latitude 35°38'14.12", Longitude 89°36'33.76" NAD27
Tipton County, Tennessee, Hydrologic Unit 08010208
Drainage area: 2,308 square miles
Datum of gage: 239.81 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1939-01-07	2008-11-25	19880
Daily Statistics			
Discharge, cubic feet per second	1939-01-07	2007-09-30	19458
Monthly Statistics			
Discharge, cubic feet per second	1939-01	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1939	2007	
Peak streamflow	1937-00-00	2007-01-17	44
Field measurements	2003-02-27	2008-10-15	44
Field/Lab water-quality samples	1977-02-10	2008-07-11	68
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2006	1

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07030050
(Dec. 2008)

Station ID: 11

DESCRIPTION:
Latitude 34°54'27", Longitude 89°45'12" NAD83
De Soto County, Mississippi, Hydrologic Unit 08030204
Drainage area: 191 square miles
Contributing drainage area: 191 square miles,
Datum of gage: 280 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	-- Previous 60 days --		
Daily Data			
Discharge, cubic feet per second	1996-06-13	2008-11-25	4540
Gage height, feet	1996-06-13	2008-11-25	4286
Daily Statistics			
Discharge, cubic feet per second	1996-10-01	2007-09-30	4017
Gage height, feet	1996-10-01	2007-09-30	3763
Monthly Statistics			
Discharge, cubic feet per second	1996-10	2007-09	
Gage height, feet	1996-10	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1997	2007	
Gage height, feet	1997	2007	
Peak streamflow	1997-03-03	2006-01-23	10
Field measurements	1954-10-15	2008-11-19	121
Field/Lab water-quality samples	1972-06-14	1972-06-14	1
Additional Data Sources	**Begin Date**	**End Date**	**Count**
Annual Water Data Report (pdf) **offsite**	2006	2007	2

Ref. http://waterdata.usgs.gov/nwis/nwisman/?site_no=07275900
(Dec. 2008)

10.0
Appendix Geo-sites

Table App5. Loosahatchie/SR 14 Hydraulic Conductivity BR-18

Boring (BR-18)						
Drilling Elevation	72.5 m	Boring Station			15+782	
Boring Bottom Elev.	48.1 m	River Center Station			15+910	
Riverbed Elev.	67.2 m					
Ground Water Elev.	N/A	Boring Distance			128 m	
Soil Type	Description	Elevation Range (m)			Layer Thickness (m)	Estimated k (m/day)
Silty Clay	brown and gray, medium to stiff	72.5	to	67.5	5.0	0.0864 to 0.000864
Silty Sand	gray, dense condition	67.5	to	65.1	2.4	0.864 to 0.000864
Silty Clay	gray stiff	65.1	to	64.8	0.3	0.0864 to 0.000864
Sand and Gravel	tan and gray, traces of wood, dense to very dense condition	64.8	to	61.3	3.5	> 8.64
Sandy Clay and Gravel	brown and orange, medium condition	61.3	to	58.5	2.8	0.864 to 0.000864
High Plasticity Clay	gray, contains silt and sand seams, very stiff to hard	58.5	to	48.1	10.4	0.000864 to 0.00000864

Table App6. Loosahatchie/SR 14 Hydraulic Conductivity BR-19

Boring (BR-19)						
Drilling Elevation	72.6 m	Boring St.			15+814	
Boring Bottom Elev.	48.2 m	River Center St.			15+910	
Riverbed Elev.	67.2 m					
Ground Water Elev.	67.4 m	Boring Distance			96 m	
Soil Type	Description	Elevation Range (m)			Layer Thickness (m)	Estimated k (m/day)
Silty Clay	brown and gray, stiff	72.6	to	70.6	2.0	0.0864 to 0.000864
Sand	brown, contains clay seams, medium to very dense condition	70.6	to	66.0	4.6	> 0.864
Sand and Gravel	gray and tan, medium to very dense condition	66.0	to	61.6	4.4	> 8.64
Clay	tan stiff	61.6	to	59.1	2.5	0.0864 to 0.000864
High Plasticity Clay	gray, contains silt and sand seams, stiff to hard	59.1	to	51.6	7.5	0.000864 to 0.00000864
Sandy Clay	gray , very stiff	51.6	to	48.2	3.4	0.000864 to 0.00000865

Table App7. Loosahatchie/SR 14 Hydraulic Conductivity BR-20

Boring (BR-20)				
Drilling Elevation	72.7 m	Boring St.	15+846	
Boring Bottom Elev.	48.3 m	River Center St.	15+910	
Riverbed Elev.	67.2 m			
Ground Water Elev.	N/A	Boring Distance	64 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Silty Sand (SM)	brown and gray, medium to stiff	72.7 to 71.7	1.0	0.864 to 0.000864
Clayey Silt w/ Sand (ML)	gray, dense condition	71.7 to 67.7	4.0	0.864 to 0.000864
Silty Sand (SM)	gray stiff	67.7 to 62.7	5.0	0.864 to 0.000864
Sand and Gravel	gray and brown, very dense condition	62.7 to 60.5	2.2	> 8.64
Sandy Gravel	gray and brown, dense condition	60.5 to 58.7	1.8	> 8.64
High Plasticity Clay w/ Gravel	tan and gray, very stiff	58.7 to 57.0	1.7	0.000864 to 0.00000864
High Plasticity Clay	gray, contains sand and lignite, very stiff to hard	57.0 to 53.7	3.3	0.000864 to 0.00000864

Table App8. Loosahatchie/SR 14 Hydraulic Conductivity BR-23

Boring (BR-23)				
Drilling Elevation	72.8 m	Boring St.	15+944	
Boring Bottom Elev.	48.4 m	River Center St.	15+910	
Riverbed Elev.	67.2 m			
Ground Water Elev.	N/A	Boring Distance	34 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Silty Clay	brown, soft to very stiff, brown and gray	72.8 to 66.8	6.0	0.000864 to 0.00000864
Sandy Clay	gray, dense condition	66.8 to 64.8	2.0	0.000864 to 0.00000864
Sand	gray, medium condition	64.8 to 62.8	2.0	> 8.64
Gravel w/ Sand (GW)	gray, very dense condition	62.8 to 60.0	2.8	> 8.64
Clay	orange and gray, contains gravel, very stiff	60.0 to 58.8	1.2	0.000864 to 0.00000864
High Plasticity Clay	gray, contains silt and sand seams, very stiff to hard	58.8 to 48.4	10.4	0.000864 to 0.00000864

Table App9. Loosahatchie/SR 14 Hydraulic Conductivity BR-24

Boring (BR-24)				
Drilling Elevation	72.5 m	Boring St.	15+980	
Boring Bottom Elev.	48.1 m	River Center St.	15+910	
Riverbed Elev.	67.2 m			
Ground Water Elev.	66.4 m	Boring Distance	70 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Silty Clay (CL-ML)	brown and gray, stiff to very stiff	72.8 to 69.2	3.6	0.864 to 0.00000864
Sandy Clay	brown and gray, stiff	69.2 to 67.8	1.4	0.000864 to 0.00000864
Sand w/ Silt (SP-SM)	gray, medium condition	67.8 to 63.6	4.2	0.864 to 0.000864
Sand and Gravel	gray and tan, dense to very dense condition	63.6 to 60.6	3.0	> 8.64
High Plasticity Clay	gray, stiff to hard, contains sand	60.6 to 49.8	10.8	0.000864 to 0.00000864
Lignitic Silty Clay	dark gray to black, hard	49.8 to 48.1	1.7	0.000864 to 0.00000864

Table App10. Wolf/ SR 3 Hydraulic Conductivity B-7

Boring (B-7)				
Drilling Elevation	58.8 m	Boring St.	5+97	
Boring Bottom Elev.	34.4 m	River Center St.	6+55	
Riverbed Elev.	54.9 m			
Ground Water Elev.	N/A	Boring Distance	58 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Rip-Rap and Sand	N/A	58.8 to 53.5	5.3	> 8.64
Sand and Gravel	tan, dense condition	53.5 to 52.0	1.5	> 8.64
Clay (CL)	Gray, very stiff	52.0 to 49.0	3.0	0.000864 to 0.00000864
High Plasticity Clay	Gray, very stiff	49.0 to 42.0	7.0	0.000864 to 0.00000864
Sandy Silty Clay (CL-ML)	gray, contains lignite, very stiff	42.0 to 39.0	3.0	0.000864 to 0.00000865
High Plasticity Clay	gray contains lignite, hard	39.0 to 36.0	3.0	0.000864 to 0.00000866
Sand	gray, contains lignite, very dense condition	36.0 to 34.4	1.6	> 8.64

Table App11. Wolf/ SR 3 Hydraulic Conductivity B-8

Boring (B-8)					
Drilling Elevation	61.1 m	Boring St.	6+40		
Boring Bottom Elev.	36.7 m	River Center St.	6+55		
Riverbed Elev.	54.9 m				
Ground Water Elev.	55.6 m	Boring Distance	15 m		
Soil Type	Description	Elevation Range (m)		Layer Thickness (m)	Estimated k (m/day)
Rip-Rap and Sand	N/A	61.1 to 55.6		5.5	> 8.64
Sand (SP)	gray, loose to medium condition	55.6 to 53.2		2.4	> 8.64
Silty Sandy Clay	gray, traces of gravel, very stiff	53.2 to 51.4		1.8	0.000864 to 0.00000865
High Plasticity Clay	gray, very stiff	51.4 to 48.4		3.0	0.000864 to 0.00000866
Clayey Silt (ML)	gray, very stiff	48.4 to 47.1		1.3	0.864 to 0.000864
High Plasticity Clay	gray, hard	47.1 to 36.7		10.4	0.000864 to 0.00000866

Table App12. Wolf/ SR 3 Hydraulic Conductivity B-12

Boring (B-12)					
Drilling Elevation	63.4 m	Boring St.	6+71		
Boring Bottom Elev.	39.0 m	River Center St.	6+55		
Riverbed Elev.	54.9 m				
Ground Water Elev.	N/A	Boring Distance	16 m		
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Rip-Rap and Sand	N/A	63.4 to 61.0	2.4	> 8.64	
Clayey Silt	brown, very stiff	61.0 to 59.7	1.3	0.864 to 0.000864	
High Plasticity Clay (CH)	Gray, soft	59.7 to 58.4	1.3	0.000864 to 0.00000866	
Sand	tan, medium to dense condition, clay seams	58.4 to 55.4	3.0	> 8.64	
Sand w/ Gravel (SP)	gray, medium to dense condition	55.4 to 51.3	4.1	> 8.64	14.65
High Plasticity Clay	gray, contains silty sand seams, very stiff to hard	51.3 to 39.0	12.3	0.000864 to 0.00000866	

Table App13. Wolf/ SR 3 Hydraulic Conductivity B-13

Boring (B-13)					
Drilling Elevation	63.4 m	Boring St.	7+16		
Boring Bottom Elev.	39.0 m	River Center St.	6+55		
Riverbed Elev.	54.9 m				
Ground Water Elev.	57.3 m	Boring Distance	61 m		
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Clayey Silt	brown, stiff to very stiff	63.4 to 61.6	1.8	0.864 to 0.000864	
Clay	Brown, stiff	61.6 to 61.0	0.6	0.000864 to 0.00000866	
High Plasticity Clay	gray, silty sand seams, stiff	61.0 to 59.5	1.5	0.000864 to 0.00000866	
Clayey Silty Sand	brown and gray, medium condition	59.5 to 58.3	1.2	0.000864 to 0.00000866	
Sand w/ Silt (SP-SM)	gray, medium to very dense condition	58.3 to 52.5	5.8	> 0.864	19.53
High Plasticity Clay	gray, contains silty sand seams, very stiff to hard	52.5 to 43.7	8.8	0.000864 to 0.00000866	
Sandy Silty Clay	gray, hard	43.7 to 39.1	4.6	0.000864 to 0.00000865	

Table App14. Wolf/ Walnut Grove Hydraulic Conductivity BB-23

Boring (BB-23)				
Drilling Elevation	75.9 m	Boring St.	71+04	
Boring Bottom Elev.	57.4 m	River Center St.	71+37	
Riverbed Elev.	61.0 m			
Ground Water Elev.	70.1 m	Boring Distance	33 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Silty Clay (CL)	brown in color, medium consistency	75.9 to 73.2	2.7	0.000864 to 0.00000864
Clay	gray in color, soft consistency	73.2 to 70.4	2.7	0.000864 to 0.00000864
Silty Sand	gray in color, contains some gravel, medium condition	70.4 to 69.2	1.2	0.864 to 0.000864
Sand	gray in color, medium condition	69.2 to 67.7	1.5	> 0.864
Gravely Sand	gray in color, medium condition	67.7 to 66.5	1.2	> 0.864
Silty Clay	gray in color, contains some traces of sand from 40'; very stiff consistency	66.5 to 61.0	5.5	0.000864 to 0.00000864
Clay	gray in color, contains traces of sand and lignite, very stiff consistency	61.0 to 57.4	3.6	0.000864 to 0.00000864

Table App15. Wolf/ Walnut Grove Hydraulic Conductivity BB-26

Boring (BB-26)					
Drilling Elevation	75.0 m	Boring St.	71+78		
Boring Bottom Elev.	56.7 m	River Center St.	71+37		
Riverbed Elev.	61.0 m				
Ground Water Elev.	70.7 m	Boring Distance	41 m		
Soil Type	Description	Elevation Range (m)		Layer Thickness (m)	Estimated k (m/day)
Silty Clay (CL)	brown in color, contains organic matter, soft consistency	75.0 to 72.7		2.3	0.000864 to 0.00000864
Sand	brown and white in color, loose to medium condition	72.7 to 69.2		3.5	> 0.864
Sandy Clayey Silt	gray in color contains organic matter, medium consistency	69.2 to 68.7		0.5	0.864 to 0.000864
Sand	gray in color, contains occasional gravel, medium condition	68.7 to 64.9		3.8	> 0.864
Clay	gray in color, very stiff to hard consistency	64.9 to 56.7		8.2	0.000864 to 0.00000864

Table App16. Wolf/ Walnut Grove Hydraulic Conductivity BB-29

Boring (BB-29)					
Drilling Elevation	75.6 m	Boring St.			
Boring Bottom Elev.	57.3 m	River Center St.	71+37		
Riverbed Elev.	61.0 m				
Ground Water Elev.	70.1 m	Boring Distance			
Soil Type	Description	Elevation Range (m)		Layer Thickness (m)	Estimated k (m/day)
Silty Sand (SM)	brown in color, loose condition	75.6 to 73.2		2.4	0.864 to 0.000864
Sand	brown in color, medium condition	73.2 to 65.6		7.6	> 0.864
Sand w/ Gravel	brown in color, contains clay seams from 11.6 m, medium condition	65.6 to 62.2		3.4	> 0.864
Sandy Clay	gray in color, very stiff consistency	62.2 to 61.0		1.2	0.000864 to 0.00000864
Clay	gray in color, contains lignite to 17.7 m, very stiff consistency	61.0 to 57.3		3.7	0.000864 to 0.00000864

Table App17. Nonconnah/Near Riverport Hydraulic Conductivity B-1

Boring (B-1)				
Drilling Elevation	68.0 m	Boring Station	N/A	
Boring Bottom Elev.	49.5 m	River Center Station	N/A	
Riverbed Elev.	53.3 m			
Ground Water Elev.	N/A	Boring Distance	115.8 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Clayey Silt (ML)	fill- brown and gray to brown	68.0 to 66.9	1.1	
Silty Clay (CL)	fill- gray	66.9 to 65.4	1.5	
Clayey Silt (ML)	fill- gray	65.4 to 64.2	1.2	
Silty Clay (CL)	fill- gray	64.2 to 59.8	4.4	
N/A (Large amounts of wood were encountered.)	No samples were taken and no tests were run	59.8 to 56.8	3.0	
Sand (SP) w/ gravel	medium dense to very dense tan	56.8 to 53.6	3.2	
Sand (SP)	very dense tan	53.6 to 51.9	1.7	> 0.864
Sand (SP)	medium dense brown	51.9 to 50.5	1.4	
Clayey Gravel (GP-GC)	medium dense reddish brown	50.5 to 49.5	1.0	

Table App18. Nonconnah/Near Riverport Hydraulic Conductivity B-2

Boring (B-2)				
Drilling Elevation	73.2 m	Boring Station	N/A	
Boring Bottom Elev.	50.1 m	River Center Station	N/A	
Riverbed Elev.	53.3 m			
Ground Water Elev.	N/A	Boring Distance	182.9 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Clayey Sand (SC)	medium dense brown	73.2 to 72.6	0.6	
Sand (SP)	medium dense to dense brown, some gravel	72.6 to 69.1	3.5	
Sandy Silt (ML)	firm gray sandy	69.1 to 67.6	1.5	
Sand (SP)	medium dense brown	67.6 to 66.1	1.5	
Silty Clay (CL)	firm gray silty	66.1 to 64.6	1.5	
Sandy Silt (ML)	firm gray sandy	64.6 to 63.1	1.5	
Silty Clay (CL)	soft brown and gray	63.1 to 61.6	1.5	
Clay (CH)	firm gray high plasticity	61.6 to 58.6	3.0	
Sandy Silt (ML)	stiff gray sandy	58.6 to 57.1	1.5	0.864 to 0.000864
Silty Sand (SM)	dense gray silty	57.1 to 55.6	1.5	
Sand (SC) w/ gravel	medium dense brown clayey	55.6 to 54.1	1.5	
Silty Sand (SP-SM)	medium dense brown and gray silty	54.1 to 50.1	4.0	

Table App19. Nonconnah/Near Riverport Hydraulic Conductivity B-12

Boring (B-12)					
Drilling Elevation	70.4 m	Boring Station	N/A		
Boring Bottom Elev.	47.4 m	River Center Station	N/A		
Riverbed Elev.	53.3 m				
Ground Water Elev.	N/A	Boring Distance	274.3 m		

Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Silty Sand (SM)	medium dense brown	70.4 to 69.8	0.6	
Sand (SP)	medium dense brown	69.8 to 69.2	0.6	
Silty Clay (CL)	stiff brown and gray	69.2 to 68.6	0.6	
Silty Sand (SM)	loose gray	68.6 to 67.8	0.8	
Clayey Silt (ML)	soft gray	67.8 to 65.1	2.7	
Clay (CH)	soft to stiff gray high plasticity	65.1 to 60.5	4.6	
Clayey Silt (ML)	firm gray	60.5 to 57.5	3.0	
Sand (SP)	dense brown	57.5 to 56.0	1.5	
Sandy Gravel (GP)	medium dense brown	56.0 to 54.5	1.5	
Silty Sand (SM)	medium dense light gray to brown and light gray	54.5 to 47.4	7.1	0.864 to 0.000864

Table App20. Nonconnah/Airways Blvd Hydraulic Conductivity B-1

Boring (B-1)			
Drilling Elevation	71.0 m	Boring Station	16+29.77
Boring Bottom Elev.	33.1 m	River Center Station	16+13.17
Riverbed Elev.	64.6 m		
Ground Water Elev.	65.5 m	Boring Distance	16.6 m

Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Rip Rap		71.0 to 69.6	1.4	
Silt	brown to gray, stiff	69.6 to 67.8	1.8	
Clayey Sand	gray, contains interbedded clay seams	67.8 to 67.0	0.8	
Sandy Clay	black and gray	67.0 to 66.7	0.3	
Sand	tan, medium dense condition	66.7 to 65.5	1.2	
Gravelly Sand	brown, medium dense condition	65.5 to 64.0	1.5	> 0.864
Sand	brown, medium dense condition, contains gravel	64.0 to 59.4	4.6	
Gravelly Sand	brown, medium dense condition	59.4 to 57.9	1.5	
Lignite/wood		57.9 to 57.0	0.9	
Silty Sand	tan, medium dense to dense condition, contains clay	57.0 to 33.1	23.9	

Table App21. Nonconnah/Airways Blvd Hydraulic Conductivity B-2

Boring (B-2)				
Drilling Elevation	70.4 m	Boring Station	15+96.07	
Boring Bottom Elev.	35.4 m	River Center Station	16+13.17	
Riverbed Elev.	64.6 m			
Ground Water Elev.	66.1 m	Boring Distance	17.1 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Rip Rap		70.4 to 68.9	1.5	
Silty Clay	brown and gray, stiff	68.9 to 68.0	0.9	
Silt (ML)	brown and gray, medium	68.0 to 66.8	1.2	
Sand	brown-gray, contains gravel, dense condition	66.8 to 66.5	0.3	
Sand w/ gravel (SP)	brown and gray, medium dense condition	66.5 to 65.0	1.5	
Gravelly Sand	brown, dense condition	65.0 to 63.5	1.5	> 0.864
Sand (SP)	tan-brown, medium dense condition, contains gravel	63.5 to 42.2	21.3	
Clay	gray, very stiff to hard contains sand	42.2 to 35.4	6.8	

Table App22. Nonconnah/Knight Arnold Hydraulic Conductivity B-6

Boring (B-6)				
Drilling Elevation	84.7 m	Boring Station	5+70	
Boring Bottom Elev.	59.9 m	River Center Station	6+49	
Riverbed Elev.	79.2 m			
Ground Water Elev.	N/A	Boring Distance	79 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Silty Clay	brown	84.7 to 81.0	3.7	
Silty Sand	gray	81.0 to 80.1	0.9	
Clayey Sand	traces of gravel	80.1 to 78.6	1.5	0.864 to 0.000864
Clay	reddish gray	78.6 to 77.1	1.5	
Clay	gray-blue, some lignite	77.1 to 74.1	3.0	
Sandy Clay	gray-yellow	74.1 to 72.6	1.5	
Clay w/ sandy seams	gray and yellow	72.6 to 69.6	3.0	
Sand	clean white	69.6 to 63.5	6.1	
Sand	white and brown	63.5 to 54.4	9.1	

Table App23. Nonconnah/Knight Arnold Hydraulic Conductivity B-7

Boring (B-7)				
Drilling Elevation	82.0 m	Boring Station	6+14	
Boring Bottom Elev.	57.6 m	River Center Station	6+49	
Riverbed Elev.	79.2 m			
Ground Water Elev.	N/A	Boring Distance	35 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Silty Clay	brown	82.0 to 80.6	1.4	
Clayey Sand	brown	80.6 to 79.8	0.8	
Sand and Gravel	brown w/ clay seams	79.8 to 78.4	1.4	> 0.864
Clay	gray, with lignite	78.4 to 73.8	4.6	
Clayey Sand	gray, with lignite	73.8 to 71.2	2.6	
Clayey Sand	brown and gray	71.2 to 69.1	2.1	
Sand	white fine, w/ traces of clay	69.1 to 68.2	0.9	
Sand	white fine	68.2 to 57.6	10.6	

Table App24. Nonconnah/Knight Arnold Hydraulic Conductivity B-8

Boring (B-8)				
Drilling Elevation	86.0 m	Boring Station	7+13	
Boring Bottom Elev.	55.8 m	River Center Station	6+49	
Riverbed Elev.	79.2 m			
Ground Water Elev.	N/A	Boring Distance	64 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Clayey Silt	brown	86.0 to 85.1	0.9	
Silty Clay	gray	85.1 to 84.5	0.6	
Clayey Silt	brown and gray	84.5 to 80.8	3.7	
Sand	white	80.8 to 79.9	0.9	
Sand w/ Gravels	red	79.9 to 78.4	1.5	> 0.864
Sand	clean, white	78.4 to 72.3	6.1	
Clayey Sand	w/ sandy clay seams	72.3 to 70.8	1.5	
Clay	gray	70.8 to 67.8	3.0	
Sand	gray w/ clay lenses	67.8 to 64.8	3.0	
Sand	gray w/ clay seams	64.8 to 58.8	6.0	
Sand	clean, white	58.8 to 55.8	3.0	

Table App25. Wolf/ SR 194 Hydraulic Conductivity B-1

Boring (B-1)				
Drilling Elevation	97.5 m	Boring St.	6+07	
Boring Bottom Elev.	76.0 m	River Center St.	7+39	
Riverbed Elev.	93.3 m			
Ground Water Elev.	93.0 m	Boring Distance	132 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Clay (CL)	stiff brown sandy lean clay with trace gravel	97.5 to 95.2	2.3	0.000864 to 0.00000864
Silty Clay (CL-ML)	stiff brown silty clay with trace organics	95.2 to 93.7	1.5	0.864 to 0.000864
Clayey Sand (CL-ML)	loose brown clayey sand with trace gravel	93.7 to 92.2	1.5	0.864 to 0.000864
Clay (CL)	stiff brown and gray lean clay	92.2 to 90.7	1.5	0.000864 to 0.00000864
Sandy Silt (ML)	very stiff brown sandy silt with trace gravel	90.7 to 89.2	1.5	0.864 to 0.000864
Sand (SP-SC)	medium dense tan sand with clay	89.2 to 87.7	1.5	> 0.864
Sand (SC)	medium dense tan clayey sand	87.7 to 86.2	1.5	0.000864 to 0.00000864
Silt (MH)	firm black elastic silt with sand and trace organics	86.2 to 84.7	1.5	0.0864 to 0.000864
Sand (SP)	dense tan sand, to medium dense tan	84.7 to 81.6	3.1	> 0.864

Table App26. Wolf/ SR 194 Hydraulic Conductivity B-2

Boring (B-2)				
Drilling Elevation	97.5 m	Boring St.	8+74	
Boring Bottom Elev.	76.0 m	River Center St.	7+39	
Riverbed Elev.	93.3 m			
Ground Water Elev.	89.9 m	Boring Distance	135 m	
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)
Clay (CL)	very stiff brown sandy lean clay with trace gravel	97.5 to 95.2	2.3	0.000864 to 0.00000864
Silty Clay (CL-ML)	firm brown silty clay with sand and trace gravel	95.2 to 93.7	1.5	0.000864 to 0.00000864
Clay (CL)	soft gray lean clay with trace gravel	93.7 to 92.2	1.5	0.000864 to 0.00000864
Silty Clay (CL-ML)	stiff brown and gray silty clay	92.2 to 90.7	1.5	0.000864 to 0.00000864
Silty Clayey Sand (SC-SM)	medium dense brown and gray	90.7 to 89.2	1.5	0.864 to 0.000864
Sand (SP)	medium dense tan and gray	89.2 to 87.7	1.5	> 0.864
Clayey Sand (SC)	medium dense brown	87.7 to 86.2	1.5	0.000864 to 0.00000864
Sand (SP)	medium dense brown with trace gravel	86.2 to 84.7	1.5	> 0.864
Clayey Sand (SC)	medium dense tan with trace gravel	84.7 to 83.2	1.5	0.000864 to 0.00000864

Table App27. Wolf/SR 57 Hydraulic Conductivity B-1

Boring (B-1)					
Drilling Elevation	103.2 m	Boring St.	5+68		
Boring Bottom Elev.	80.2 m	River Center St.	5+69		
Riverbed Elev.	103 m				
Ground Water Elev.	N/A	Boring Distance	1 m		
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Silt	wet, moist, brown, clayey and sand	103.2 to 101.4	1.8	0.864 to 0.000864	1.03
Sand	wet, brown, slightly silty wood at tip of spoon	101.4 to 99.9	1.5	> 0.864	
Sand	wet, brown, coarse, quartzite pebbles	99.9 to 98.4	1.5	> 0.864	
Silt	wet, gray, sandy	98.4 to 97.2	1.2	0.864 to 0.000864	
Sand	wet, brown, fine	97.2 to 95.4	1.8	> 0.864	
Sand	coarse, silty	95.4 to 93.9	1.5	> 0.864	
Silt	wet, brown, grayish-white, sandy	93.9 to 89.3	4.6	0.864 to 0.000864	
Sand	wet, gray, fine grain	89.3 to 80.2	9.1	> 0.864	

Table App28. Wolf/SR 57 Hydraulic Conductivity B-2

Boring (B-2)					
Drilling Elevation	104 m	Boring St.	4+58		
Boring Bottom Elev.	82.2 m	River Center St.	5+69		
Riverbed Elev.	103 m				
Ground Water Elev.	N/A	Boring Distance	111 m		
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Silt	wet, moist, brown, moderately clayey and sandy	104.0 to 102.2	1.8	0.864 to 0.000864	1.08
Silt	wet, very soft, gray	102.2 to 100.7	1.5	0.864 to 0.000864	
Sand	wet, brown, very coarse	100.7 to 98.0	2.7	> 0.864	
Sand	coarse to fine	98.0 to 94.5	3.5	> 0.865	
Sand	wet, light gray, silty	94.5 to 91.6	2.9	> 0.866	
Silt	stiff, gray	91.6 to 85.7	5.9	0.0864 to 0.000864	
Sand	wet, gray/rust, fine	85.7 to 82.2	3.5	> 0.864	

Table App29. Wolf/SR 57 Hydraulic Conductivity B-3

Boring (B-3)					
Drilling Elevation	106.3 m	Boring St.	8+68		
Boring Bottom Elev.	84.7 m	River Center St.	5+69		
Riverbed Elev.	103 m				
Ground Water Elev.	N/A	Boring Distance	299 m		
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Silt	moist, brown/gray, sandy	106.3 to 104.5	1.8	0.864 to 0.000864	
Silt	gray	104.5 to 103.0	1.5	0.864 to 0.000864	1.07
Silt	gray, clayey, sand seams	103.0 to 101.5	1.5	0.864 to 0.000864	1.09
Silt	wet, gray, sandy	101.5 to 98.4	3.1	0.864 to 0.000864	
Sand	wet, light brown, coarse	98.4 to 96.9	1.5	> 0.864	
Sand	wet, light brown/ gray, coarse to fine	96.9 to 95.4	1.5	> 0.864	
Sand	coarse	95.4 to 92.3	3.1	> 0.864	
Sand	fine	92.3 to 90.8	1.5	> 0.864	
Silt	wet, rust colored, sandy	90.8 to 87.7	3.1	0.864 to 0.000864	
Sand	wet, gray, fine-grained	87.7 to 84.7	3	> 0.864	

Table App30. Wolf/McKinstry Hydraulic Conductivity B-1

Boring (B-1)							
Drilling Elevation	104.5 m	Boring St.		4+935			
Boring Bottom Elev.	87.4 m	River Center St.		4+967			
Riverbed Elev.	101 m						
Ground Water Elev.	N/A	Boring Distance		32 m			
Soil Type	Description	Elevation Range (m)			Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Clay	brown, silty	104.5	to	102.7	1.83	0.000864 to 0.00000864	
Clay	gray, silty	102.7	to	99.6	3.05	0.000864 to 0.00000864	1.09
Sand	gray, silty, fine-grained	99.6	to	97.3	2.28	> 0.864	
Sand	fine to medium-grained, silty, gray	97.3	to	93.5	3.81	> 0.864	
Sand	fine to medium-grained, silty, gray, with some small gravel	93.5	to	90.5	3.05	> 0.864	
Sand	fine to medium-grained, white, silty	90.5	to	87.4	3.05	> 0.864	

Table App31. Wolf/McKinstry Hydraulic Conductivity B-2

Boring (B-2)							
Drilling Elevation	104.5 m	Boring St.		5+010			
Boring Bottom Elev.	84.4 m	River Center St.		4+967			
Riverbed Elev.	101 m						
Ground Water Elev.	N/A	Boring Distance		43 m			
Soil Type	Description	Elevation Range (m)			Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Clay	brown, silty	104.5	to	102.7	1.83	0.000864 to 0.00000864	
Clay	gray, silty	102.7	to	101.2	1.52	0.000864 to 0.00000864	
Sand	fine-grained, gray, silty	101.2	to	98.1	3.05	> 0.864	2.93
Sand	fine to medium-grained, silty gray	98.1	to	96.6	1.52	> 0.864	
Sand	fine to medium-grained, silty gray, with gravel	96.6	to	95.1	1.52	> 0.864	
Sand	fine to medium-grained, silty, reddish-brown	95.1	to	93.5	1.52	> 0.864	
Sand	fine to medium-grained, silty, reddish-brown, with some small gravel	93.5	to	89.0	4.57	> 0.864	
Sand	fine-grained, silty, reddish-brown	89.0	to	87.5	1.52	> 0.864	
Sand	fine-grained, silty, gray	87.5	to	84.4	3.05	> 0.864	

Table App32. Wolf/SR 76 Hydraulic Conductivity B-1

Boring (B-1)					
Drilling Elevation	106 m	Boring St.	3+722		
Boring Bottom Elev.	84.5 m	River Center St.	3+688		
Riverbed Elev.	102.3 m				
Ground Water Elev.	98.4 m	Boring Distance	34 m		
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Clay	Silty	106.0 to 104.0	1.98	0.000864 to 0.00000864	
Silt	trace wood pieces	104.0 to 102.2	1.83	0.864 to 0.000864	N/A
Clay	lean, sandy	102.2 to 99.1	3.05	0.000864 to 0.00000864	
Sand		99.1 to 96.1	3.05	> 0.864	
Sand	with silt	96.1 to 94.6	1.52	> 0.864	
Sand		94.6 to 93.0	1.53	> 0.864	
Clay	lean	93.0 to 91.5	1.52	0.000864 to 0.00000864	
Sand	with silt	91.5 to 87.0	4.57	> 0.864	
Sand		87.0 to 85.4	1.52	> 0.864	
Sand	Silty	85.4 to 84.5	0.94	> 0.864	

Table App33. Wolf/SR 76 Hydraulic Conductivity B-2

Boring (B-2)					
Drilling Elevation	106 m	Boring St.	3+660		
Boring Bottom Elev.	84.5 m	River Center St.	3+688		
Riverbed Elev.	102.3 m				
Ground Water Elev.	99.9 m	Boring Distance	28 m		
Soil Type	Description	Elevation Range (m)	Layer Thickness (m)	Estimated k (m/day)	Calculated k (m/day)
Gravel	with sand	106.0 to 104.0	1.98	> 8.64	
Sand	with gravel	104.0 to 102.2	1.83	> 0.864	
Clay	lean	102.2 to 100.7	1.52	0.000864 to 0.00000864	
Sand	Clayey	100.7 to 99.2	1.52	> 0.864	N/A
Sand	Silty	99.2 to 97.6	1.52	> 0.864	
Sand		97.6 to 96.1	1.52	> 0.864	
Sand	with silt	96.1 to 94.6	1.52	> 0.864	
Sand		94.6 to 91.5	3.05	> 0.864	
Sand	with silt	91.5 to 87.0	4.57	> 0.864	
Sand	Clayey	87.0 to 85.5	1.52	> 0.864	
Sand	with silt	85.5 to 84.5	0.91	> 0.864	

SCIENCE

United States
Environmental Protection
Agency

PRESORTED STANDARD
POSTAGE & FEES PAID
EPA
PERMIT NO. G-35

Office of Research and Development (8101R)
Washington, DC 20460

Official Business
Penalty for Private Use
$300

EPA 600/R-10/130 Mississippi Embayment Regional Ground Water Study