Overview

As a community, our ability to understand the terrestrial water budget, and mass and energy fluxes on a river basin scale is limited by the lack of study areas and concerted research efforts designed to address hydrologic science questions across scales and boundaries. Developing an observatory network that provides this crucial data is of the utmost importance and doing so in a manner that is inclusive of all hydrologic disciplines that provide data across scales and boundaries is a daunting task. As members of the Mississippi Embayment Hydrologic Observatory Design Team, we present the conceptual model of a functional hydrologic observatory (HO) designed to specifically focus on science questions and fill gaps in data needed to tackle critical regional/national water science and policy issues in the U.S.

The proposed Mississippi Embayment HO includes the Wolf River Basin and a swath of the Mississippi River extending approximately 10 km on either side of a 200 km reach. The boundary of Mississippi River reach that is to be included in this HO is based on the existence of United States Army Corps of Engineers' (USACE) gaging stations at Osceola, AR, Memphis, TN, and Helena, AR, and a United States Geological Survey (USGS) regional aquifer investigation that indicated lateral influence of the Mississippi River to be as far inland as 10 km. Inclusion of the Mississippi River in the HO is imperative for conducting comparative scale analyses and large river investigations.

The Wolf River is an atypical watershed, evolving from a pristine wetland habitat at the headwaters, to a highly urbanized environment in Memphis, TN. The sole source of drinking water for Memphis and the surrounding communities of over one million citizens is provided from one of the most prolific fresh water aquifer systems in the nation. The Mississippi Embayment Hydrologic Observatory provides the opportunity to address numerous scientific questions in a single basin that otherwise would be addressed at individual locations. This hydrologic observatory provides an enormity of diverse and interrelated topics. A few of these topics include the following: floodplain aggradation/denudation; urban sprawl impacts on surface water runoff quantity and quality; reduction in ground water recharge by urbanization; atmospheric/land-surface interactions and contributions; ground water/surface water interactions; river geomorphology; liquefaction susceptibility of floodplain sediments and the implied impact to man-made structures; age-dating of mixing waters and source identification; and contaminant migration in both the unsaturated and saturated zones.

Site Introduction

<u>Mississippi Embayment: Structure and Features</u>

Structure

The Mississippi Embayment is a southward dipping syncline; its geologic units thicken toward the embayment axis, which roughly parallels the course of the Mississippi River, and toward the Gulf of Mexico. Formation of the Mississippi Embayment had its birth from intercontinental seismic activity which still continues today, known as the New Madrid seismic zone.

Rivers

The Wolf River drains a 2100 km^2 area in west Tennessee and northern Mississippi, ultimately contributing its flow to the Mississippi River. The Wolf River traverses through its basin in a sinuous path for much of its length until it reaches Shelby County, Tennessee where channelization by the US Army Corps of Engineers in 1964, expedites flow for the remainder of its length through a straightened channel. Although the purpose of channelization was to reduce flooding along the Wolf's lower length within Memphis, TN and the surrounding communities, the channel has subsequently undergone extensive degradation from the mouth eastward. Currently there is a cooperative program between the Chickasaw Basin Authority (CBA) which represents the citizens of Shelby County and the Memphis District Corps of Engineers to stabilize the channel with grade control structures and fish weirs. Other environmental features are a part of this project.

Memphis, presently one of the top 20 largest municipalities in the nation, accounts for the urbanization of the lower third of the Wolf River basin. This extensive urbanization of the Wolf River's lower third is contrasted by the upstream portions of the basin, eastward into Fayette and Hardeman County, TN and Benton County, Mississippi, where the landuse is primarily agriculture in the uplands regions and bottomland hardwood forests comprise 90% of the floodplain. Recognized as one of the most pristine wetland habitats in the nation, the Ghost River section of the Wolf River is host to threatened, endangered, and rare species of flora and fauna.

Frequent storm events during the wet months of January through March can have a marked impact on the geomorphology of the Wolf River. The Wolf River basin receives approximately 132 cm/yr of rainfall and is considered to be in a humid environment. The river is classified as a sand-bottom stream and the regional geologic material is comprised of unconsolidated sediments, thus they are easily eroded.

As mentioned previously, the Mississippi River receives the waters of the Wolf River and is the ancestral river whose course the Mississippi Embayment axis parallels. The Mississippi River is the fifth largest river in the world whose drainage area encompasses one-third of the United States crossing 33 states and two provinces of Canada. On average, the daily ground-water usage within the Mississippi Embayment accounts for only 2% of the flow in the Mississippi River at Memphis on an average daily basis. It is impressive, however, to note that the average amount of Mississippi River water flowing past Memphis is more than the total combined ground water usage in all 50 United States.

The 200 km stretch of the river from Osceola, Arkansas past Memphis, Tennessee to Helena, Arkansas is chosen as the northern and southern limits, respectively, because gaging stations exist at these locations and the subsurface geologic structure along this length is similar to that traversed by the Wolf River. A 10 km swath on each side of the Mississippi River defines the east and west boundaries. This distance stems from a ground-water modeling effort by the USGS on the Mississippi Embayment thus indicating that this 10 km distance was the furthest influence the Mississippi River had on ground water.

Aquifers

The upper two-thirds of the Wolf River basin lies within a region where the Memphis Sand outcrops. The Memphis Sand is a hydrogeologic unit within the Mississippi

Embayment that provides good quality drinking water to millions within the region, and is known as the Memphis aquifer in Tennessee or the Sparta aquifer within Mississippi and Arkansas. Ultimately, the Mississippi Embayment hosts a collection of fresh-water, unconsolidated aquifer systems, the delineation of which crosses nine southern states.

The Memphis aquifer is the primary source aquifer for domestic and industrial use in the region. Confinement depth of the Memphis aquifer is approximately 105 m below ground surface in western Shelby County, yet outcrops in eastern Shelby County at a shallow incline of 0.6 m/km. The thickness of the Memphis Sand varies from 240 m in western Shelby County to 0 m in Hardeman County. The Upper Claiborne clay acts as a confining unit to the Memphis aquifer before subcropping along the eastern border of Shelby County. Once believed to be contiguous throughout Shelby County, identification of breaches in this confining unit has changed the perception of this unit's ability to retard contamination of the Memphis aquifer. Once an artesian system, large declines within the Memphis aquifer – as much as 40 m – have created the opportunity for contaminated water from the phreatic aquifer to migrate vertically downward into the Memphis aquifer through breaches in the confining unit. Loss of flow from the Wolf River to the phreatic aquifer within the proximity of these breaches is ultimately mixing with waters of the Memphis aquifer. Once believed to be nearly 2000 years old, modern water as young as 9 years old is now detectable in the Memphis aquifer.

Uniqueness of the HO

A most unique factor of this HO is scale. Not just with respect to comparative scale, but also relating to the magnitude of scaling factors within the HO. Regarding the latter, the Wolf River runs through the heart of Memphis, Tennessee, one of the 20 largest municipalities in the nation. Where the lower one-third of the Wolf River watershed is highly urbanized, the upper third is nationally recognized as one of the most pristine wetland habitats in the nation. Interplay between the Wolf and the region's ground-water systems is only magnified by Memphis and the surrounding communities' sole dependence on ground water, thus making Memphis the largest user of ground-water for drinking water in the nation.

However, the average 800,000 m^3/d used here for drinking water and industrial purposes pales in comparison to the strain on ground-water resources imposed by agriculture in adjoining Arkansas and Mississippi. Total agricultural consumption of ground water by these neighboring states reaches nearly 30,500,000 m^3/d.

The presence of young faulting across the area compounded with evidence of past liquefaction within the Wolf's floodplain is a concern as urban sprawl migrates onto the floodplain. Furthermore, rapid growth into the middle third of the basin is stressing the Wolf's ability to handle flooding, and is impacting the recharge and water quality of the region's drinking water aquifer.

In addition to the Wolf River's research potential, the Mississippi River within this HO provides a unique opportunity to conduct comparative scale studies between the Wolf and Mississippi Rivers as well as investigations into large-river studies. Where the Wolf River takes passage through the outcrop region of the Memphis Sand, passes over the subcrop of the Upper Claiborne confining clay and remains thereafter in contact with the phreatic aquifer, similarly the Mississippi River is in contact with the Memphis Sand near Osceola, Arkansas, passes above the Upper Claiborne by Helena, Arkansas and is in constant contact with the Mississippi River alluvial aquifer along its traverse between Osceola and Helena.

Core data

USGS

The USGS is the main source for historic geologic and hydrologic data, primarily owing to the necessity of addressing the region's ground-water availability and quality. The USGS has investigated the geology of the region since the late 1800's. Geologic data from the USGS exists in two main forms: (1) USGS publications, compilations that are usually in the form of interpolated surfaces or contact boundaries or (2) raw format typically as a geophysical or driller's log. The University of Memphis library hosts a vast number of these USGS publications, both historic and recent, while additional documentation resides in the USGS Memphis field office libraries. Copies of many local USGS geophysical logs are on file at the University of Memphis' Ground Water Institute.

The hydrologic data collected by the USGS includes surface and ground water. Within the Wolf River basin, five stream gages haven been in operation on the Wolf with an additional gage on three individual tributaries. Stage and discharge data are available through the USGS NWSI database. Relative to ground water, the USGS has conducted an annual water level survey of the Memphis aquifer focusing on Shelby County since the 1950's. This data is also being made available through NWSI.

Aside from Shelby County, sparse historic water level data for both the Memphis aquifer and the phreatic aquifer systems exist. Few ground-water observation wells exist in proximity to the Mississippi River in Arkansas, Mississippi, and Tennessee – a majority of those that do exist are screened in the alluvium. Additionally, water level surveys conducted by the three states are not performed in concert, ending at state boundaries.

Water quality investigations have been conducted on both the Wolf and Mississippi rivers. The Wolf River was part of the USGS NAWQA program and water quality data is accessible within NWSI. Through a congressional mandate, the USGS conducted a hydrologic and sedimentological survey of the Mississippi River, including the section between Osceola and Helena, in the late 1980's to early 1990's. During this investigation, contamination of the Mississippi River was addressed and the findings documented.

In addition to these USGS investigations of the area's water and geology, extensive seismic research has been performed within Shelby County - a major population center lying within the New Madrid seismic zone. Interpretation of the subsurface geology of the Wolf River basin within Shelby County has been evaluated and re-interpolated to address concerns regarding ground motion and liquefaction. The re-interpretation of the Shelby County's subsurface stratigraphy from geophysical and geotechnical borings exists in a geographic information system (GIS) database at the University of Memphis.

US Army Corps of Engineers

Stage and discharge data for the Mississippi River is collected by the Memphis District Army Corps of Engineers (USACE) and at the Wolf River at Raleigh, TN. Prior to 1995, discharge was calculated using a velocity meter. Since that time, The Corps of Engineers has employed a Doppler method for measuring discharge. The gaging stations at Osceola, Memphis, and Helena are managed by the Memphis District.

Discharge and stage are calculated daily. These data are made available via the Internet and is published by USACE. Hydrographic surveys that detail the Mississippi River's bed elevations are conducted on a three year cycle. The near subsurface geology directly beneath the river is unknown and existing interpretations are speculative at best.

Other data collection agencies whose data collection and dissemination have a functional role in the area:

National Weather Service – has collected climatic data in the Memphis area since 1941, made available through the Internet hosted by NOAA

Tennessee Wildlife Resources Agency – hosts National Wetland Inventory maps and landuse data maps.

Tennessee Department of Environment and Conservation, Mississippi Department of Environmental Quality, and Arkansas Soil and Water Conservation Commission – are regulatory agencies that collect and distribute data for their state regarding geology, surface water, ground water, pollution, superfund, endangered/rare species, and/or air pollution

University of Memphis – hosts the most extensive borehole GIS database in the region of over 17,000 geophysical and corresponding geologist logs and serves as the largest GIS repository in Shelby County for water and geologic related data in the region.

MLGW - the major utility in the region boasting the largest consumer of ground water for drinking water and industrial use. Pumping records are available back to the early 1940's.

Non-exhaustive list:

US Department of Agriculture, US Fish and Wildlife Service, National Atmospheric Deposition Program, US Forestry Service, St. Francis Levee District

Non-profit Organizations:

Wolf River Conservancy, Sierra Club, The Nature Conservancy, Friends of Shelby Farms, Ducks Unlimited (headquarters)

Land access ownership

These organizations own property along the Wolf River that could be made available to researchers for access and scientific studies.

Tennessee Wildlife Resources Agency, Chickasaw Basin Authority, TN Department of Environment and Conservation Division of Natural Heritage, TN State Parks, and Shelby County government

Example science questions offered by this HO

(1) Recharge (planning and development, ground water, geochemistry)

In a humid environment, determination of infiltration is commonly estimated from a water budget procedure. One of the measured water budget factors is runoff which is generally calculated at a gaged location on a stream. Based on this, the infiltration rate would be an average representation of an area defined by the gage location acting as the pour point. Sparseness of gages can result in a single infiltration rate representing areas of hundreds to thousands of square kilometers.

Additionally, the inability to incorporate a basin's landuse heterogeneity into estimation of infiltration in the water budget can be problematic: this can be prohibitive in making an accurate assessment of the impact urban sprawl has on ground-water recharge. Innovative use of monitoring natural and anthropogenic tracers within the vadose zone would allow for point estimates of infiltration linked to landuse type. The vadose zone on the upland regions of the Wolf River within the Memphis Sand outcrop area can be as thick as 45 m. This thick vadose zone coupled with the varied landuse and presently advancing of urban sprawl into the Memphis aquifer recharge zone makes this an ideal basin for conducting this infiltration research.

<u>(2) Liquefaction susceptibility (geotechnical, ground water)</u>

In some cities, open spaces and floodplains are the last remaining areas available for development. For those cities that experience seismic activity, there is growing concern regarding the liquefaction susceptibility of floodplain sediments and its subsequent impact on man-made structures. Pads are commonly constructed on the floodplain to raise building foundations above the calculated 100 year flood water level. There is not a consensus as to whether these pads reduce or enhance the potential for liquefaction. There are also concerns regarding borrow pits: (1) lateral movement of material back toward onsite borrow pits that are created when supplying media for the pads and (2) the impact these borrow pits have on sustaining localized ground-water levels when they are eventually converted to lakes thereby saturating liquefiable sediment. Evidence of liquefaction has been observed on the Wolf River floodplain within Shelby County. Here, a less permeable layer of alluvium overlying a more sand-based alluvium exists; this provides the opportunity for hydrostatic buildup during a seismic event. Building pads are currently constructed from the alluvium material and the remaining borrow pits are being flooded.

<u>(3) Competition for ground-water resources (ground water, economics)</u>

Groundwater, an invaluable and non-renewable resource, is often taken for granted in the water-rich areas of the United States. Developing a groundwater management plan for an aquifer that is shared by several states is very important for the continuing quality and quantity of water available for domestic, industrial, and agricultural uses. The Memphis area serving a population of over a million citizens is solely dependent on ground water for domestic use. Shelby County pumps nearly 800,000 m^3/d from the Memphis aquifer. This amount from Shelby County alone accounts for 70% of the ground water used for these purposes within the State of Tennessee.

In contrast, nearly 30,500,000 m^3/d is pumped by Arkansas and Mississippi for irrigation and rice farming, primarily from the Mississippi Alluvial aquifer, the fresh water aquifer above the Memphis aquifer in these two states. Significant declines in ground-water levels in the Mississippi Alluvial aquifer has farmers looking to other sources such as surface water and the Memphis/Sparta aquifer. Mining of ground water from the Memphis aquifer at the quantities demanded by agricultural use could have a detrimental impact on domestic and industrial availability of this resource. We do not yet know the specific impact of the Mississippi River on water availability; its role as both a surface water source and as a source or sink to ground water is not well understood.

Industrial usage of ground water is another component that must be considered when assessing competitive use of this nature resource. The abundant supply of pure water from the Memphis aquifer continues to remain a critical element in the economic efforts to attract and retain manufacturing jobs in the area. Most of these jobs represent food processing, chemical production, paper/pulp, and pharmaceutical manufacturing trades, all highly dependent on the water supply. In the Memphis metropolitan area, there are approximately 84 companies with 2,500 jobs with a $1 billion annual economic impact, directly affected by the aquifer. Depletion of the aquifer will require municipalities to resort to surface water treatment to replace unavailable ground water. This would raise treatment costs by approximately $16 million per year. Attracting and retaining manufacturing jobs will become increasingly difficult if faced with this challenge.

<u>(4) Remote sensing (remote sensing, surface water)</u>

Land surface hydrology is by its very nature a distributed, multi-variable process. Therefore, one point observation, namely streamflow cannot adequately characterize the hydrological state of the catchment. Therefore, it becomes imperative to use distributed hydrological modeling as well as observations. Spatially distributed observations are rare, expensive and time-consuming. Remote sensing provides a unique, spatially averaged perspective, given the footprint of the satellite sensor and a temporal repeat associated with the periodicity of the satellite revisit. In this HO, it will be possible to provide (a) historical data and (b) real-time data sets corresponding to precipitation, soil moisture, surface and air temperature and vegetation. The data can be derived from EOS era sensors such as TRMM (Tropical Rainfall Measurement Mission), AVHRR (Advanced Very High Resolution Radiometer), TOVS (TIROS Observing Vertical Sounder) and AMSR (Advanced Microwave Scanning Radiometer) to name a few sensors. It will serve many interesting purposes. The historical data can be analyzed by regular time series methods to understand seasonality, weather phenomenon such as El-Nino and effects of land use change. The real time/present data can be used to study effects of weather and the feedback to the atmospheric system. In addition, all satellite data can be resampled in time and space to fit individual needs as well as used for validation of hydrological, geochemical and bio-geochemical models. Such data can be used to study historical changes in the basin and how these land use changes have impacted hydrology and biogeochemical cycles.

<u>(5) Inter-aquifer leakage (ground water, surface water, geochemical, seismological)</u>

Leakage between aquifers that are separated by a confining unit occurs at a rate that is dependent upon the characteristics of the confining unit and the water levels of the aquifers. However, leakage is exacerbated in areas where the confining unit becomes thin or absent. Variations in the characteristics between two aquifers, such as contamination, water chemistry, influence of surface waters, and seasonal variation of water levels if the upper aquifer is unconfined, influence the way we understand the inter-aquifer transfer through such breaches.

A breach in the confining unit exists in close proximity to the Wolf River – this breach is located approximately 600 m north of the Shelby County landfill, which was opened in 1968 and closed in 1988. The breach can be pinpointed within a 20 km^2 park within Memphis – a landuse that is rather unique for such a heavily urbanized setting. Downward leakage is known to occur from the phreatic aquifer to the Memphis aquifer with the Wolf River locally contributing its flow to the phreatic aquifer. Similarly, another breach exists near the Mississippi River which is in connection at least with the phreatic aquifer with downward leakage into the Memphis aquifer. At both locations, the water of the Memphis aquifer is of higher quality and is being degraded by ground water leaking downward from the phreatic aquifer.

<u>(6) Ground-water/surface water interactions (ground water, surface water, climatology)</u>

Water quantities and water quality of surface water and ground water are jointly impacted when the two interact. Seasonal variations in the water levels of each, atmospheric and land surface interplay, anthropogenic and natural stresses, and geologic heterogeneity complicate our understanding of these interactions. Here are a few scenarios within our proposed HO that are demonstrative of these potential variations and interactions.

Distant from the urbanization of Shelby County, wetlands proximal to the Wolf remain wet year round while those farther away, yet still connected to the Wolf, are absent of water during the drier months. Wetlands within Shelby County, though few, have limited flooding because head cutting in the channelized sections has caused widening of the river and steepening of the banks and, additionally, the spoil bank left from the 1964 channelization still remains creating a levee of sorts along its length.

The Wolf River is in contact with the Memphis aquifer updip of the Upper Claiborne confining clay. Similarly, the Wolf River is in contact with the phreatic sand/gravel aquifer downdip of the subcropping confining clay. A localized breach in the confining clay just downdip of the subcrop creates a continued loss of water from the Wolf to the phreatic aquifer and into the Memphis aquifer. Exacerbating this problem, downward leakage through the breach is encouraged by a large cone of depression that is created from heavy pumping of the Memphis aquifer. Approaching the mouth of the Wolf River, the Hollywood Dump superfund site has contaminated the phreatic aquifer which is in contact with the Wolf River. However, monitoring Wolf River discharge has proven difficult as variations in the stage of the Mississippi River create a backwater effect approximately 3.2 km upstream on the Wolf.

To our knowledge, investigations of the impacts on ground water by large river – particularly of a magnitude afforded by a river with the scale of the Mississippi River – have not been conducted. Researchers will find that the size of the Mississippi River requires innovative thinking on determining the geologic structure beneath the river as the river is approximately 1.6 km wide and the closest borehole data exists 1.6 km from the river. Further complicating the interaction between the Mississippi River and the ground-water systems is the levee system. The Mississippi River is constrained by these levees, which focus the erosive power of the river through a stationary channel. Also, should the Mississippi River be considered a source for irrigation water, can the raw water be used directly or is pre-treatment a priority (e.g., uptake of heavy metals by plants).

Within the context of groundwater-surface water interactions the MS Embayment HO provides a unique opportunity to study the processes occurring within the hyporheic zone across boundaries and scales. The hyporheic zone influences stream ecosystems through solute-substrate contact and consequent chemical changes. Thus the hyporheic zone can be considered a fundamental boundary controlling the biochemistry of stream ecosystems. As a part of the hydrologic continuum between stream water and soil water, root zone water, riparian water, quick flow, delayed flow, macropore flow to, finally, baseflow, the energy and mass balance within the hyporheic zone is of fundamental importance to hydrologic studies. Within the MS Embayment HO opportunities abound to study fundamental processes occurring in the hyporheic zone across a variety of scales. Within the northern Wolf River Basin exists a pristine wetland where researchers can assess chemical fate and transport under permanently wet conditions providing unique insights into small scale mass fluctuations throughout the hydrologic continuum. In addition the large scale study of the hyporheic zone within the MS River segment will allow researchers across hydrologic disciplines to characterize large scale mass and energy balance within the hyporheic zone and the impact of perturbation on this important region of streams.

<u>(7) Unsaturated/saturated and solute transport/remediation (surface water</u>

The transport and fate of contaminants in the environment can be at the same time the most and least understood phenomena. A contaminant is known to originate at point A, has traveled to point B in a measurable block of time, and poses known health risks at certain concentrations. However, contaminant residual in the vadose zone, dilution (especially in the Mississippi River), natural attenuation by microbes, sorption to/desorption from the geologic media (both aquifer and that transported in river systems), and geochemical reactions add complexity to understanding contaminant fate and migration. Linked to contamination of the environment are the remediation methodologies employed to reduce the risk to humans and the environment. Many current and developing technologies must be applied at field-scale operation to gain exposure and acceptance in the academia, regulatory agencies, and industry. The potential for conducting field scale remediation demonstrations at contaminated sites associated with urbanization and industrial operations of the Memphis area could be numerous with cooperation and participation of industry and regulatory agencies. Additional contamination topics include surface-groundwater interactions, gas-phase contaminant transport in the vadose zone, subsurface characterization (hydraulic conductivity, contaminants, moisture content, tracer experiments), metal and inorganic transport in the subsurface, regional and local groundwater and mass transport models, biodegradation, and agricultural inputs and transport to the groundwater and surface water systems (fertilizers/nitrates, salinity, herbicides/pesticides,).

Comparative investigations regarding…

(1) Geomorphology: The Wolf River traverses a sinuous path through pristine wetland habitat in the middle to upper section of the basin yet is constrained to a straightened channel in the lower third owing to channelization.

(2) Landuse: Landuse along the Wolf includes wetland habitat, agriculture, industrial, commercial (strip malls), and residential. Landuse along the Mississippi River from Osceola to Helena, AR includes wetland habitat, agriculture, urban areas (Memphis being the largest), and industry. **note there is the possibility for a scale comparison here between the Wolf and Mississippi Rivers*

(3) Ground-water/surface water interactions (scale comparison): The Wolf River takes passage through the outcrop region of the Memphis Sand, passes over the subcrop of the Upper Claiborne confining clay and remains thereafter in contact with the phreatic aquifer. Similarly the Mississippi River is in contact with the Memphis Sand near Osceola, Arkansas, passes above the Upper Claiborne by

Helena, Arkansas and is in constant contact with the Mississippi River alluvial aquifer along its traverse between Osceola and Helena.

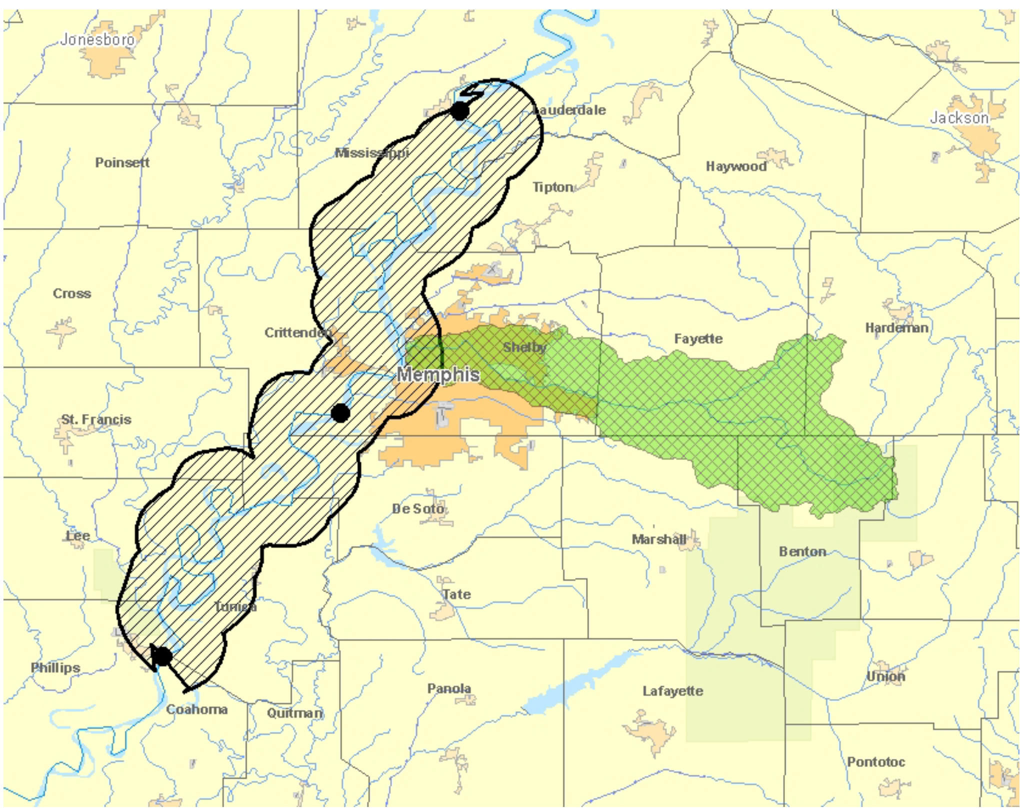
(4) Inter-aquifer transfer (scale comparison): A breach in the Upper Claiborne confining unit exists proximal to the Wolf River and one near the Mississippi River allowing losses of water from the rivers that enter the phreatic aquifer to migrate vertically downward to the Memphis aquifer.

Contributing/Interested CUAHSI institutions

Arkansas State University
Louisiana State University
Southern Illinois University
University of Alabama
University of Kentucky
University of Memphis
University of Texas-Arlington

Other Non-CUAHSI Academic Institutions

University of Arkansas at Pine Bluff
Rhodes College
University of Rochester
University of Alaska-Fairbanks (Fisheries)
Morgan State University



Mississippi Hydrologic Observatory – boundary of the Wolf River basin (green hatched) and the Mississippi River (black hatched).