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Application of Numerical Tools to Investigate a Leaky Aquitard beneath Urban Well Fields

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Abstract

Memphis aquifer is the primary drinking water source in Shelby County (Tennessee, USA) and supplies industrial, commercial, and residential water. Memphis aquifer is separated from the Shallow aquifer by a clayey layer known as Upper Claiborne Confining Unit (UCCU). All of the production wells in the Memphis area are screened in the Memphis aquifer or even deeper in the Fort Pillow aquifer. Traditionally, it was assumed that the UCCU could fully protect the Memphis aquifer from the contaminated Shallow aquifer groundwater. However, recent studies show that at some locations the UCCU is thin or absent which possibly leads to the contribution of Shallow aquifer to the Memphis aquifer. Accurately locating the breaches demands expensive and difficult geological or geochemical investigations, especially within an urban area. Hence, a pre-field investigation to identify the locations where the presence of breaches is likely can significantly reduce the cost of field investigations and improve the their results. In this study, to identify the locations where the presence of breaches in the UCCU is likely we use three different analyses: (1) pilot point calibration (PPC), (2) velocity and flow budget (VFB), and (3) particle tracking (PT) to post-process the developed groundwater results. These pre-field numerical investigations provide relevant and defensible explanations for groundwater flow anomalies in an aquifer system for informed decision-making and future field investigations. In this study, we identify five specific zones within the broad study area which are reasonable candidates for the future field investigations. Finally, we test the results of each analysis against other evidence for breaches to demonstrate that the results of the numerical analyses are reliable and supported by previous studies.

Key words: Groundwater model, well field, pre-field investigation, aquitard breach

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1 Introduction

The City of Memphis (Shelby County, Tennessee, USA) has undergone significant urban development from 1950 to 2000, partially due to the availability of inexpensive, high-quality water from Memphis aquifer, a regional groundwater resource. Local utilities and industries in Shelby County, Tennessee extract more than 680 thousand cubic meter per day of groundwater that requires minimal treatment for municipal use (Dieter et al., 2018). The groundwater quality of Memphis is not only crucial for the general consumption but also for the economy of the region (Staff, 2015). After decades of continues extraction, water quality degradation and contamination of the Memphis aquifer has become a concern leading to local utilities and citizen groups taking a more proactive approach to address these issues rather than the traditional reactive approach.

Memphis is within the Mississippi embayment aquifer system and underlain by approximately one kilometer of unconsolidated sediments (Figure-1). The subsurface is divided into a series of alternating sand and clay layers grouped into hydrostratigraphic units that include several water-bearing units. As shown in Figure-1, four sand aquifers beneath Shelby County, Tennessee include the Shallow aquifer, the Memphis aquifer, the Fort Pillow aquifer, and the Cretaceous aquifer, each of which is separated from adjacent aquifers by aquitard units, known as Upper Claiborne confining unit (UCCU), Flour Island, Tertiary-Cretaceous confining unit, and other Cretaceous units (Brahana and Broshears, 2001; Clark and Hart, 2009). The Shallow aquifer consists of the Mississippi River Valley alluvial (MRVA) aquifer and the Gulf Coastal Plain (GCP) fluvial and alluvial aquifer. The MRVA aquifer serves as a water source for industrial, domestic, and irrigation wells in the Mississippi alluvial valley and typically is not utilized in urban settings. Water from the Shallow aquifer is of poorer quality than that in the underlying Memphis and Fort Pillow aquifers due to the absence of an overlying aquitard; thus, it is locally contaminated in places. The Memphis aquifer serves as the primary source of drinking water in Shelby County, Tennessee with minor withdrawals coming from the deeper Fort Pillow aquifer. The Cretaceous aquifer is not utilized in Shelby County due to the depth and poorer water quality.

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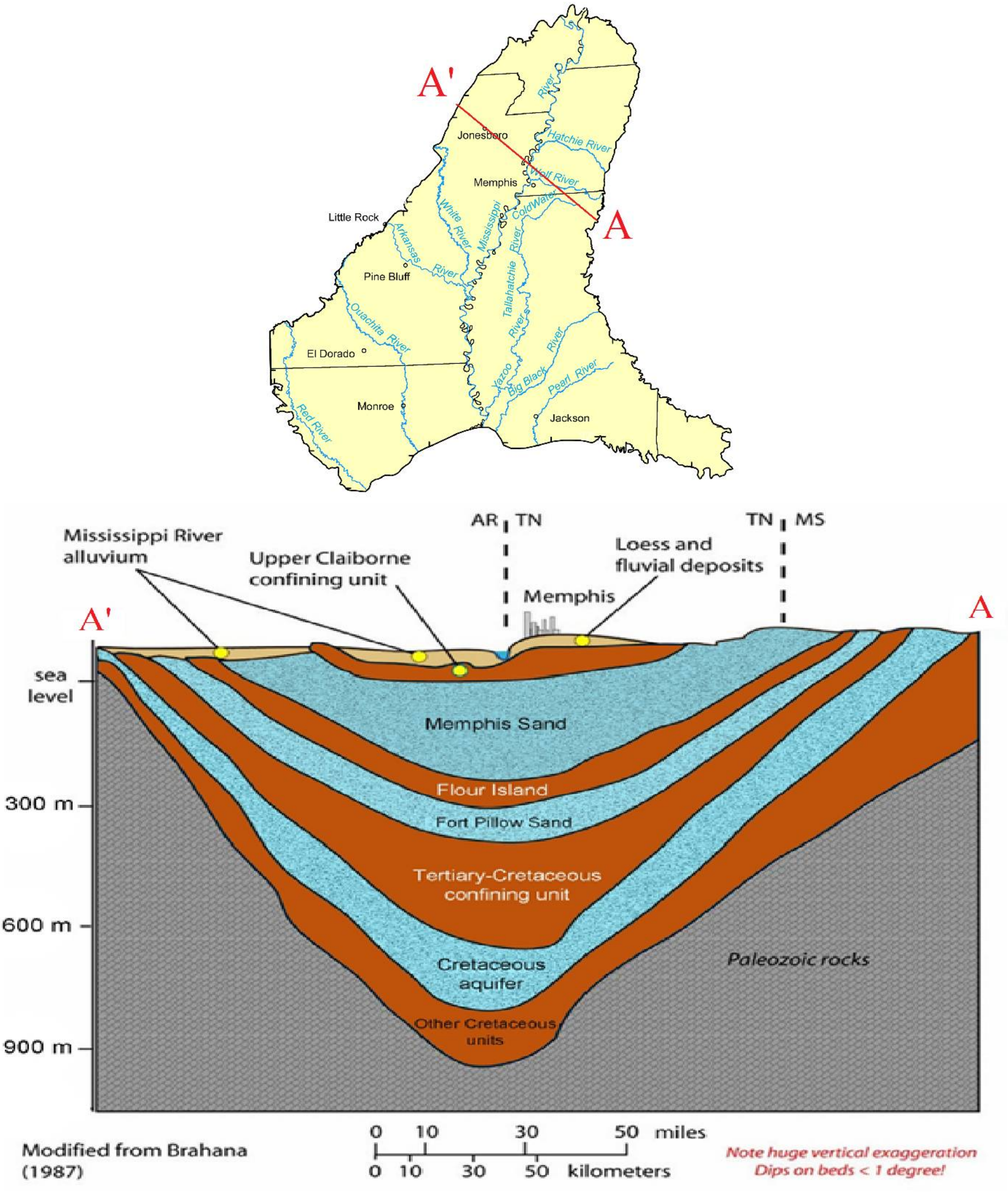

Figure-1 A-A' hydrogeological section of the Memphis groundwater system, through the Mississippi embayment. It represents four aquifers and four confining units. Note that the vertical axis is dramatically exaggerated for visualization purposes.

The UCCU layer separates the Shallow and the Memphis aquifers throughout most of the Shelby County acting as an upper protective layer to the Memphis aquifer. However, hydrogeologic breaches, also termed windows, within the UCCU locally create hydraulic

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connections between these aquifers (Parks, 1990). The quantity of water passing through these hydraulic connections increases with greater groundwater withdrawal and groundwater head depression within the Memphis aquifer (Kingsbury and Parks, 1993). Hence, through these breaches the Shallow aquifer is recharging the Memphis aquifer through the leaky hydrogeologic breaches where the hydraulic conductance is relatively high comparative to the rest of the UCCU. Figure-2 demonstrates a schematic of a breach in the aquitard layer that acts as a preferential flow path from the Shallow aquifer to a screened production well in the Memphis aquifer.

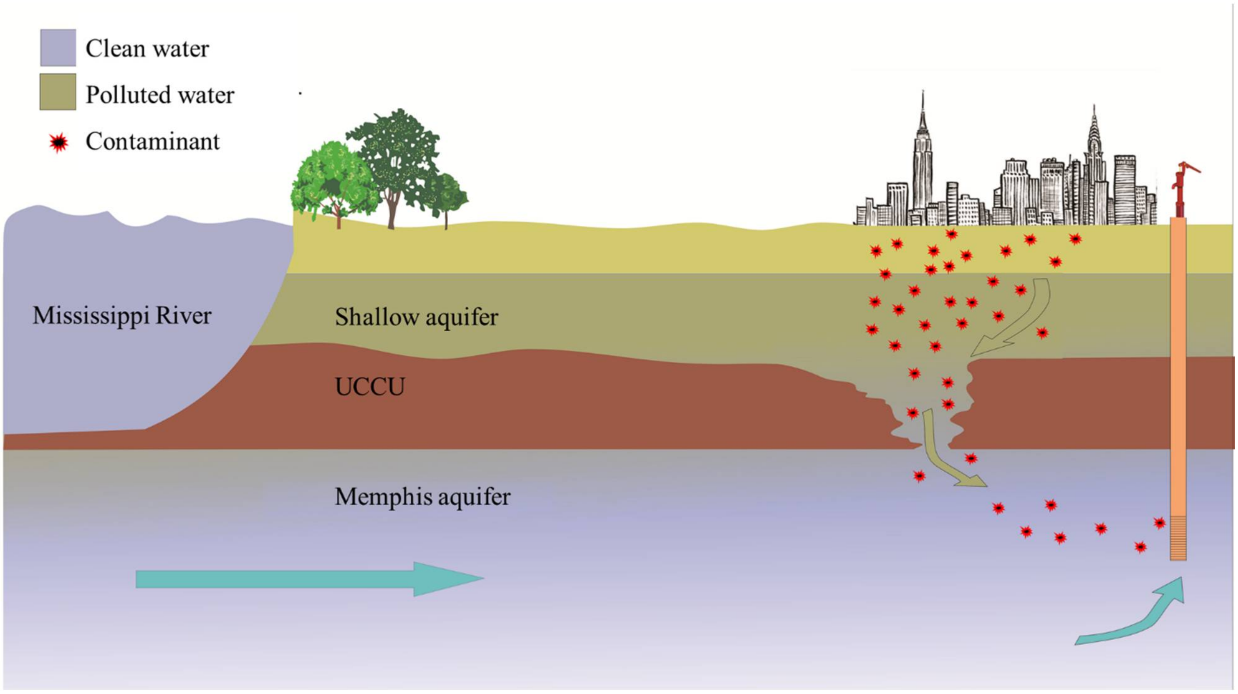

Figure-2 shows how pollution can be transferred from urban activities to the Shallow aquifer, and finally to the Memphis aquifer through a breach.

Breaches in the UCCU aquitard threaten the water quality of the City of Memphis; therefore, identifying locations of the breaches are essential for source-water protection, and the development and implementation of wellhead protection plans. However, the seemingly straightforward question is --Where are the breaches? So far, two different approaches are employed to answer this question. The first approach is the "geochemical investigation" (Neretnieks, 1981; Busenberg et al., 1993; Larsen et al., 2003, 2013, 2016; Ivey et al., 2008; Majidzadeh et al., 2017) where groundwater samples are analyzed to identify geochemical signatures attributed to surface water within the Memphis aquifer water. Within the Memphis area, age-dating of groundwater using tritium-helium-3 and sulfur hexafluoride support geochemical data and reflects the influence of modern water (< 50 years) in the Memphis aquifer. Subsequent studies have shown that modern water contributes up to 40% of groundwater withdrawn from production wells – in one case production water contains as much as 75% modern water (Larsen et al., 2003, 2013, 2016). The second approach is the “geological investigation” in which techniques such as surveying stratigraphic thickness and water table elevation, electrical resistivity surveys, shear-wave seismic reflection, and other geophysical analyses are used to identify gaps in impermeable layers (Parks, 1990; Sutinen, 1992; Besson et al., 2004; Waldron et al., 2009; Schoefernacker, 2018). Geological investigations show how hydrogeologic units are connected in the subsurface and where preferential leakage pathways may exist. Parks (1990) created an isopach map of the UCCU throughout Shelby County and identified several areas where clay layers within the UCCU are thin or absent. Parks (1990) also prepared a water-table elevation map for Shelby County and showed that several areas with anomalous water-table depressions also had thin or absent confining unit clay, consistent with vertical leakage through a breach in the UCCU. Waldron et al. (2009) used an S-wave seismic reflection survey to map the size and the orientation of localized breaches in the UCCU near an unlined landfill.

The abovementioned approaches have several limitations. First, mapping breaches are complicated, costly and time-consuming owing to their depth, unknown location and randomness of origin causality. Second, mapping studies with geophysical methods are technically limited to the small study area and their measuring accuracy dissipates as the study area extends. Third, approaches involving extensive drilling and geophysical studies are inapplicable or prohibitive in urban areas due to infrastructure, and compact residential and commercial areas. Therefore, when the presence of a breach in the aquitard layer is likely, numerical investigations conducted prior to field studies (pre-field investigation) can be extremely helpful to identify locations where a breach is likely to exist. Pre-field numerical investigations provide relevant and defensible explanations for groundwater flow anomalies in an aquifer system for informed decision-making.

Several numerical tools are developed to simulate the groundwater flow within the system. Groundwater models provide invaluable information about what cannot be adequately measured or observed, in both space and time domains (e.g., geological conceptualization, flow rates and flow pathways). Such numerical tools apply mathematical equations to calculate aquifer system responses to forcing conditions such as pumping, stream-stage variation, and rainfall events

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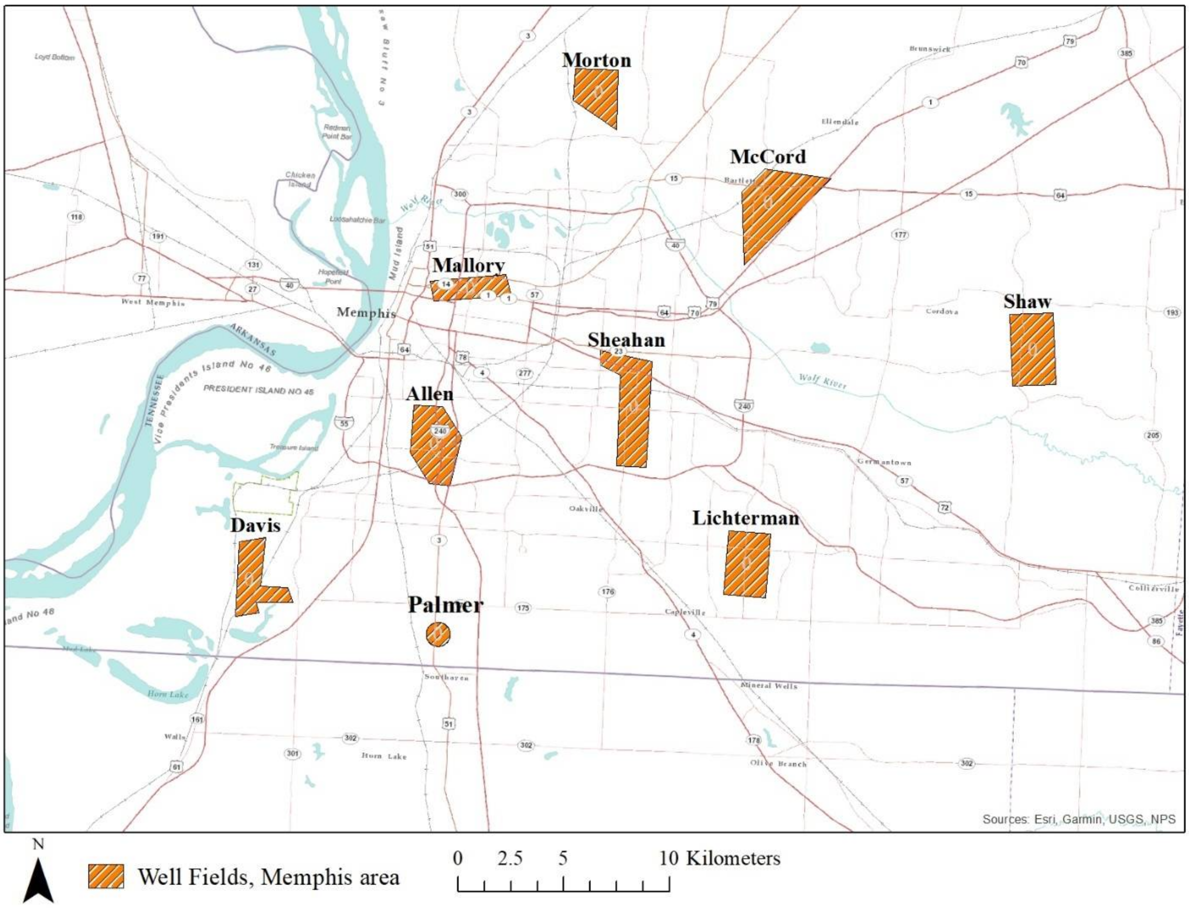
(Anderson et al., 2015). Beside the groundwater models, several other numerical tools and techniques are developed to post-process the flow equations and results of numerical models to improve our understanding of the studying groundwater system (Pollock, 1994; Owen et al., 1996; Zimmerman et al., 1998; Van Dam and Feddes, 2000; Guha, 2008; Simpson et al., 2013; Jazaei et al., 2014, 2016, 2017).

In this work, we show how a combination of forward and backward numerical modeling, and post-processing numerical tools can be used to produce a more satisfactory representation of the groundwater system to make informed field investigation decisions. Herein, three numerical analyses are utilized: (1) pilot point calibration analysis (PPC); (2) velocity and flow budget analyses (VFB); and (3) particle tracking analysis (PT), to reasonably identify the locations where the presence of breaches is likely. Finally, we test the results of each analysis against other evidence for breaches to demonstrate that the results of the numerical analyses are reliable and supported by previous studies.

2 Methodology

This study incorporates multiple Memphis Light, Gas and Water (MLGW) well fields including the Allen, Davis, and Palmer well fields. These three well fields are located east of the Mississippi River bluff line in southwestern Shelby County (Figure-3) that include 49 production wells (26 wells in Allen; 19 wells in Davis, and 4 wells in Palmer) and collectively produce more than 50 million cubic meter per year over 2005 to 2016 (TDEC Dataviewers, n.d.). Herein, we consider only the upper three geological units: (1) Shallow aquifer, (2) UCCU, and (3) Memphis aquifer (Figure-1). This approach is justified because all the production wells within these well fields are screened in the upper and middle Memphis aquifer and little evidence exists for upward flow of water from deeper hydrogeologic units (Brahana and Broshears, 2001). Therefore, we neglect the interaction between the lower Memphis aquifer and the Flour Island aquitard by assuming a no-flow boundary condition at the base of the Memphis aquifer (Figure-1).



Sources: Esri, Garmin, USGS, NPS

Figure-3 shows all active well fields in the Memphis area.

2.1 Extent of the study area

In this study, we first assemble and analyze existing relevant hydrogeological field data to define a proper extent for the study area, and build an advisory conceptual model. In groundwater studies, the delineation of the extent of the study area is quite critical and challenging. To evaluate a proper extent for this study, we use available potentiometric data of the Memphis aquifer in 2005, 2007, 2010 and 2015 ("USGS Water Data for the Nation," n.d.; Kingsbury, 2018). Figure-4 shows the types and locations of boundary conditions which encompass Allen, Davis, and Palmer well fields. The purple, blue, green, and orange lines are associated with the years of 2005, 2007, 2010 and 2015, respectively. Dashed lines symbolize temporally varying boundary conditions in the Memphis aquifer (i.e., the groundwater heads along the dashed lines are spatially constant while their magnitudes vary with time). The solid line symbolizes the no-flow boundary condition at the groundwater divides between Allen, Sheahan and Mallory well fields (Figure-3 and 4). As shown in Figure-4, locations of both no-flow and temporarily varying boundary conditions remain nearly consistent from 2005 to 2015. Hence, we estimate the study area to encompass the average extent of the boundary conditions in different years, which is shown in black in Figure-4. The same extent is delineated for the Shallow aquifer and UCCU; however, with relevant spatially and temporally varying boundary conditions.

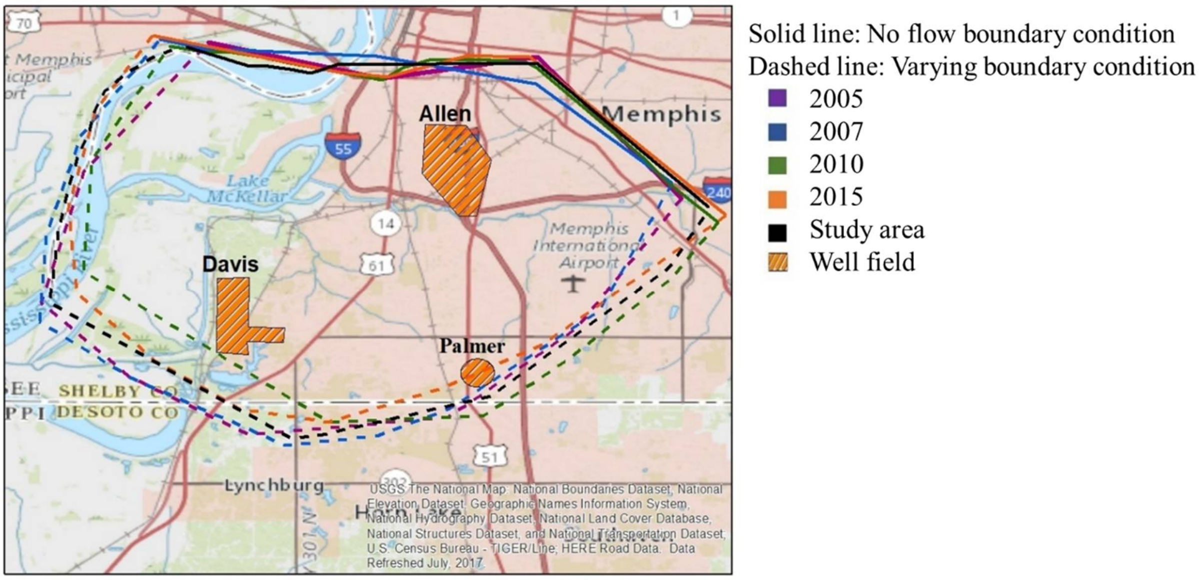


Figure-4 shows the no-flow boundary condition (solid lines) and temporarily varying boundary conditions (dashed lines) of the Memphis aquifer for the years of 2005, 2007, 2010, and 2015. The black line shows the estimated extent of the study area.

2.2 Conceptual model

Figure-5 shows the conceptual model for the site-specific hydrogeological setting. In the conceptual model, we simplify the system conditions and capture the essential features of the site. Figure-5(a) shows a plan view of the conceptual model. A bluff line of 15 to 45 m high separates alluvial and fluvial Shallow aquifers. Consequently, the hydraulic characteristics of the Shallow aquifer vary significantly on either side of the bluff line. Figure-5(b) shows a side view of the conceptual model which is made up of three layers: Shallow aquifer, UCCU, and the Memphis aquifer. Stratigraphic unit elevations were derived from Clark and Hart (2009). Production well screen intervals are illustrated in Figure-5(b), taking note that they vary in depth. This aquifer system conceptualization was very helpful in developing the numerical model.

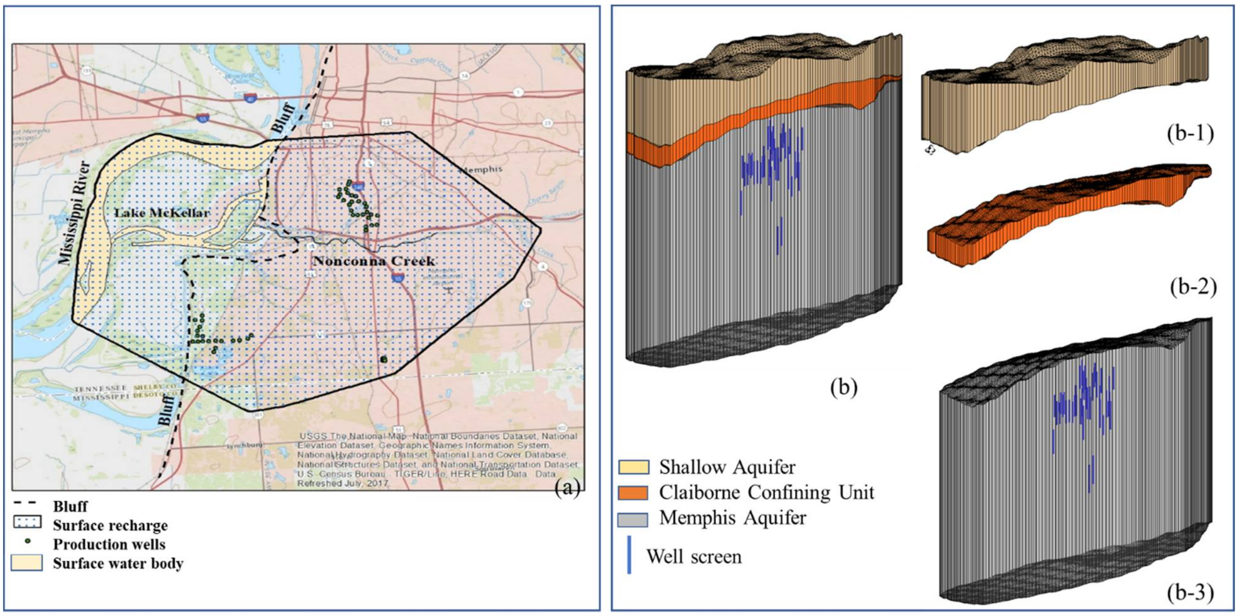


Figure-5 (a) shows a plan view of the conceptual model which includes a part of the Mississippi River, Lake McKellar, Nonconnah Creek, production wells and surface recharge. (b) shows a side view of the conceptual model and the location of production well screens. (b-1), (b-2) and (b-3) separately show the Shallow aquifer, UCCU, and the Memphis aquifer, respectively.

2.3 Groundwater model

To describe the transient groundwater flow in the study area, we develop a high resolution three-dimensional numerical model using (Bear, 2012):

$$S\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) + w, \tag{1}$$

where h [L] is groundwater head, K_x, K_y, and K_z [L/T] are hydraulic conductivity in x, y and z directions, respectively; t is time [T]; S [1/L] is the storage coefficient of the aquifer and w [1/T] is a source and sink parameter (volumetric flux per unit volume). We use MODFLOW-NWT to solve Eq. (1) (Niswonger et al., 2011). The numerical model has 6 layers with a uniform 250×250 m^2 cells, totaling 20,773 active cells. The first and second numerical layers represent the Shallow aquifer and UCCU, respectively. Other four numerical layers uniformly divide the Memphis aquifer. The time domain of the model begins from 2005 to 2015, a span we have relatively sufficient data for Shallow and Memphis aquifer groundwater head within the study

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area. This duration is discretized into 121 monthly stress periods. Each stress period has 5 time steps.

2.4 Initial conditions and boundary conditions

In this study, the initial head conditions of the Shallow aquifer are set to the water-table surface (Shallow aquifer) measured in 2005. There are no information regarding the groundwater head in UCCU. Therefore, we assume the same initial condition within the UCCU in 2005 (Narsimha, 2007). The initial head conditions for the Memphis aquifer are derived from the 2005 Memphis aquifer potentiometric surface (Kingsbury, 2018). Boundary conditions of the Shallow, UCCU, and Memphis aquifer are estimated using available potentiometric surfaces during 2005 to 2015. The boundary condition of the Shallow aquifer is assumed to be spatially and temporally varying during 2005-2015 except beneath the Mississippi River where it is controlled by the river stage variations. Therefore, the boundary condition under the Mississippi River is estimated according to the monthly measurements of river stage at the nearby Beale Street gage during the period of 2005 to 2015 (“Rivergages.com: Providing River Gage Data for Rivers, Streams and Tributaries,” n.d.). We neglect the horizontal inflow and outflow at the UCCU boundary condition; therefore, the boundary condition of the UCCU is assumed to be a no-flow boundary condition. Two boundary conditions are applied to the Memphis aquifer: no-flow (boundary is perpendicular to equipotential lines) and temporarily varying boundary conditions (Figure-3). The Memphis aquifer head variation at the varying boundary condition, at many points, remains in relatively small range of fluctuation during 2005 to 2015. Tehrefore, the temporally varying boundary condition of the Memphis aquifer is estimated by interpolating available 2005 to 2015 Memphis aquifer heads (Kingsbury, 2018).

2.5 Internal forcing conditions

Internal forcing conditions within the study area include McKellar Lake, Nonconnah Creek, production wells, and surface recharge. Since McKellar Lake has an open connection to the Mississippi River, lake stage follows Mississippi River stages. The Nonconnah Creek stage variation is modeled using monthly mean stages measured at an upstream and downstream stations, Farris View Drive stage and Riverport stage, during the period 2011 to 2017 when the stage data were recorded (“Rivergages.com: Providing River Gage Data for Rivers, Streams and Tributaries,” n.d.). The exact withdrawal rates of the production wells are unavailable. Therefore,

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monthly production for the entire well field is uniformly distributed to each active well during that month (Tennessee Department of Environment and Conservation (TDEC) "Upon request: TDEC Dataviewers," n.d.). Precipitation recharge is applied to the upper layer representing the Shallow aquifer surface recharge. Unfortunately, recharge rates are unknown and must be inferred from available precipitation records. However, since precipitation events occur almost in all months of each year we assume a constant but spatially varying recharge rate over the study area (See Appendix-3).

3 Numerical analysis results

In this study, we locate zones where the presence of leaky aquitard (UCCU) breaches is likely by applying three numerical analyses: (1) pilot point calibration (PPC) performed against horizontal and vertical hydraulic conductivities, (2) velocity and flow budget (VFB), and (3) particle tracking (PT). As it pertains the identifying plausible aquitard breach locations, the following observances are assumed: (1) hydraulic conductivities at breaches are expected to be locally high, (2) convergence of flow to a specific area is a sign of the presence of a breach, and (3) vertical flow at breaches is expectedly high compared with other parts of the study area. These conditions will be derived from the PPC and VFB. In contrast, PT should show that groundwater particles at the breaches vertically transport further than in the surrounding area.

3.1 Pilot point calibration analyses (PPC)

Although the boundary conditions and withdrawal rates are estimated, several required parameters for groundwater modeling including horizontal and vertical hydraulic conductivities, storage coefficients, surface recharge, and the conductance of the hyporheic zone at Nonconnah Creek bed are remained unknown. To estimate the unknowns we use an advanced nonlinear method of spatial parameter characterization to develop an inverse groundwater model (Doherty, 2003). We first use uniform properties for each layer to estimate proper starting calibration values within a meaningful range of parameters reported in previous studies conducted in the Mississippi embayment area (Moore, 1965; Brahana and Broshears, 2001). In the groundwater literature, this approach is known as zonal calibration (Park et al., 2014; Jiménez et al., 2016). We consider two zones at the east and west of the bluff for Shallow aquifer. Similarly, we consider two zones at either side of the bluff for UCCU. Finally, we consider one zone for each numerical layer (four layers) of the Memphis aquifer. Parameters used for this pre-calibration process are horizontal and

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vertical hydraulic conductivities, storage coefficients, the Nonconnah Creek bed conductance, and surface recharge. To describe the heterogeneity in hydraulic conductivity and surface recharge within each zone we use "pilot points" accompanied by advanced regularization functionality available through PEST (Doherty, 2003, 2002). This model includes 69 pilot points distributed in all layers. The inverse distance weighted method is used to spatially distribute pilot points values to each cell of the model. We use PEST to estimate a new set of the model parameters (i.e., horizontal and vertical hydraulic conductivities, storage coefficients, the Nonconnah Creek bed conductance, and surface recharge) using a robust mathematical technique by comparing simulation results to a set of observations (Doherty, 2003, 2002). Observation points are derived from the available Shallow and Memphis aquifers potentiometric surfaces maps (Narsimha, 2007; Kingsbury, 2018). To evaluate the calibration results, we compare the simulated transient groundwater head with the observed data at 31 observation points within the Shallow and Memphis aquifers. Shallow aquifer observation data includ water levels collected in 2005 and 2015. The Memphis aquifer observation data include groundwater heads collected during 2005 to 2015. Groundwater head fluctuation in each observation point was not high; therefore, the monthly varying head at each observation point is estimated by linear interpolation between years when the observation data are available. The observed versus simulated groundwater heads are shown in Figure-6. The goodness of fit coefficients between the simulated and calibrated results of the model are computed for all observation points within the Shallow and the Memphis aquifers (Glantz and Slinker, 1990). R^2 values of Shallow and Memphis aquifers are estimated 0.98 and 0.84, respectively, which indicate a satisfactory goodness of fit.

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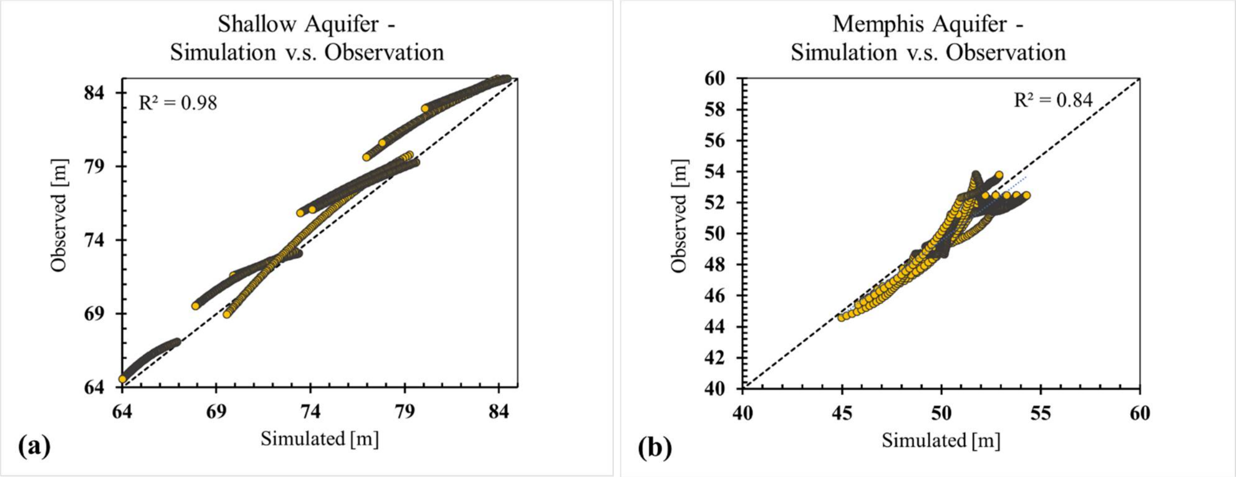

Figure-6 (a) and (b) show observed vs simulated results of the model for the Shallow and Memphis aquifers, respectively. The goodness of fit coefficients for the Shallow and Memphis aquifers are estimated as 0.98 and 0.84, respectively.

The calibrated horizontal and vertical hydraulic conductivities of the UCCU are shown in Figure-7(a) and (b), respectively. Figure-7 shows that the patterns of the distribution of horizontal and vertical hydraulic conductivities are quite similar however with different values (see Appendix-1, 2 and 3 which summarize all six numerical layers' calibrated hydraulic conductivities, storage coefficients and surface recharge, respectively). As shown in Figure-7, PPC reveals three major zones (dashed lines) in which the vertical and horizontal hydraulic conductivities of the UCCU are relatively high. Since we expect locally high hydraulic conductivity at the breaches, we concluded that the presence of breaches at these three zones is more probable than other parts of the study area.

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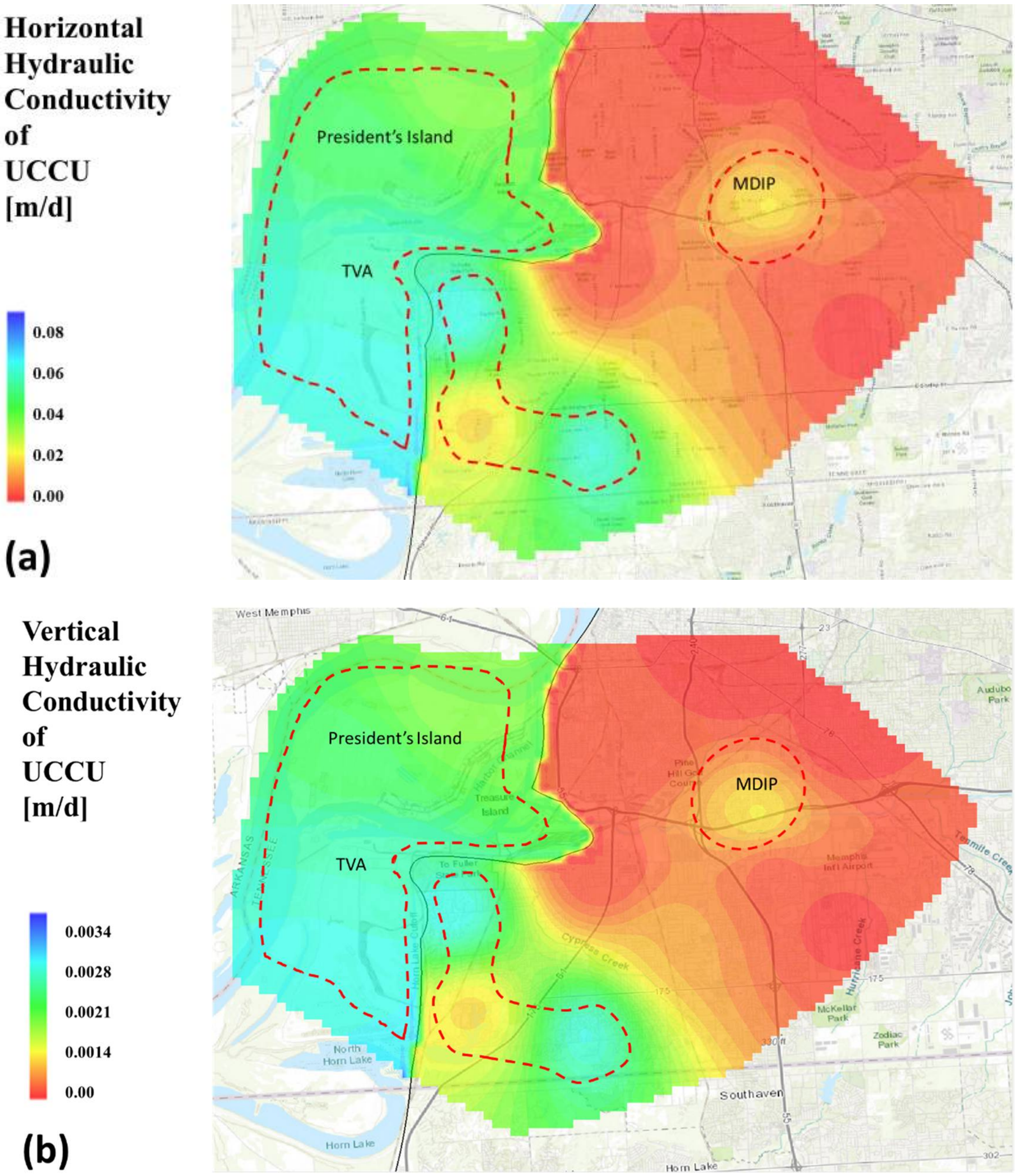

Figures-7(a) and (b) maps show calibrated horizontal and vertical hydraulic conductivities of UCCU, respectively. They show relatively higher hydraulic conductivities in three zones: Memphis Depot Industrial Park (MDIP), Tennessee Valley Authority (TVA) and President's Island, and the south of the study area.

3.1.1 Validation of PPC results

The increase of hydraulic conductivities represented within the three identified zones (Figure-7) likely exist due to lithologic variation or erosion of the UCCU with an increase of coarser grained sediments (Ebina et al., 2004; Alakayleh et al., 2018). The first identified area by PPC is located in the Memphis Depot Industrial Park (MDIP) (Figure-7). Recent investigations have already indicated that the Shallow groundwater level in this area is locally lower than that in the surrounding areas (Bradshaw, 2011; Narsimha, 2007). Figure-8 shows the approximate flow directions of Shallow aquifer in 2005 and 2015, which converge from the surrounding areas toward the MDIP. There are no pumping wells in this area which otherwise would have resulted in such local cone of depression.

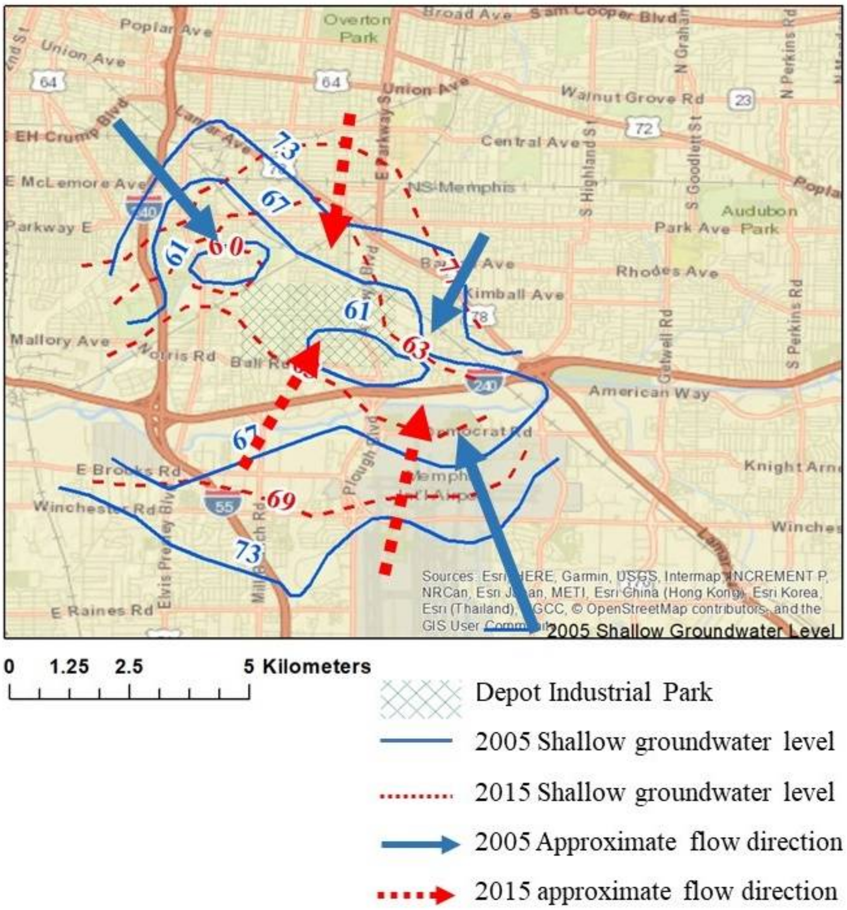

Figure-8 map shows Shallow aquifer groundwater level and approximate flow directions in 2005 (blue arrow) and 2015 (red arrow) at the MDIP area

The second zone is located on President's Island (Figure-7). Previous study and field investigation in this area have indicated that the thickness of the UCCU beneath President's Island significantly thins (Parks, 1990). Calibration results in the President's Island area affirm the suspicion of the thinning or absence of the UCCU. Moreover, in the area immediately south of President's Island that includes the Tennessee Valley Authority (TVA) combined cycle plant a

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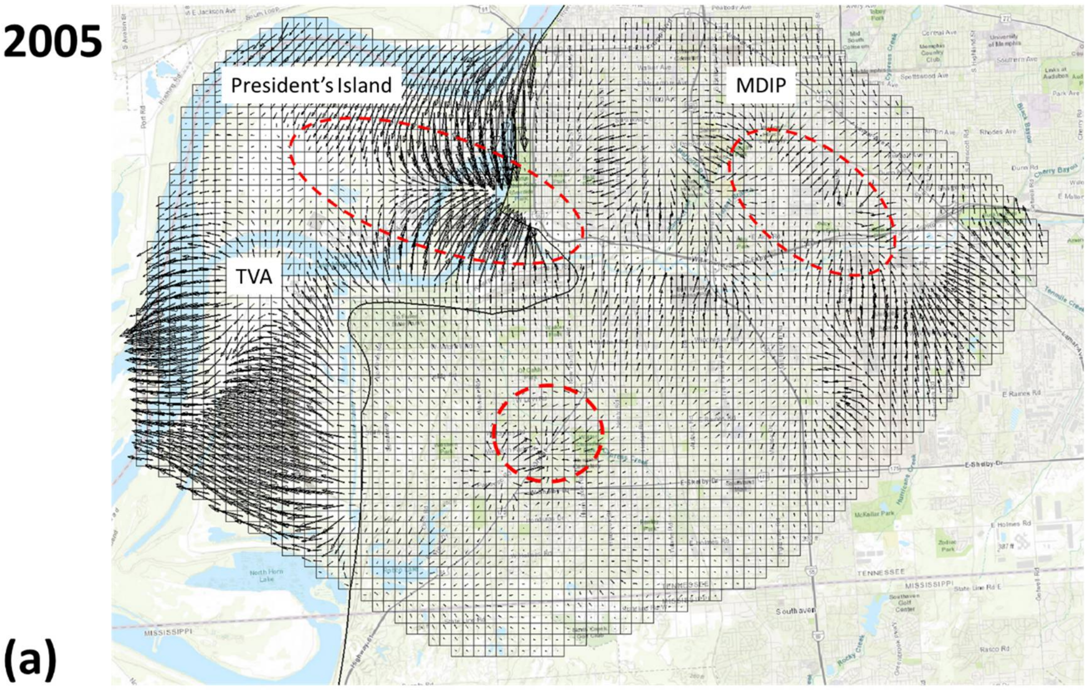
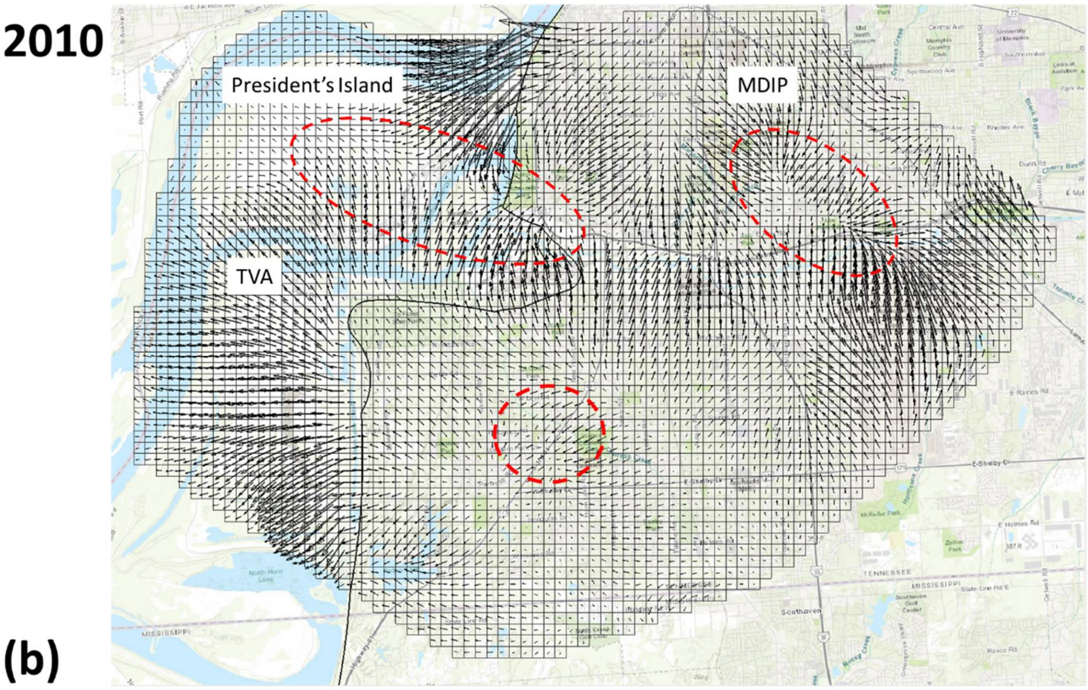
hydraulic connection of the Shallow and Memphis aquifer is identified (Carmichael et al., 2018) (Figure-7). This recent study supports the likely presence of a breach in that area.

The third identified zone is located at the southern part of the study area adjacent to the bluff line. This area is an undiscovered zone where field investigations are lacking. Therefore, this area is considered an area of interest where further investigations are required to validate the PPC results.

3.2 Velocity and flow budget analyses (VFB)

High hydraulic conductivity alone at a breach does not necessarily lead to a vertical flow and needs sufficient vertical gradient to create flow. Determining the velocity and flow directions of the Shallow aquifer can provide valuable information regarding the likely presence of a breach. Figures-9(a-c) show the horizontal velocity vector of the Shallow aquifer in the study area in 2005, 2010 and 2015 derived from the developed numerical model. The magnitude of the velocity is proportional to the arrows lengths. A longer arrow refers to a higher horizontal velocity. As shown in Figure-9(a-c), the VFB approach identifies three zones where the velocity vectors converge to specific areas. The horizontal velocity of groundwater decreases inside the convergence zones, suggesting downward flow (assuming upward flow is negligible due to the regional downward vertical gradient). As shown in Figure-10(a-c), VFB analyses also show vertical downward flow budgets at the bottom of the Shallow aquifer in 2005, 2010, and 2015, respectively. Negative values refer to an upward flow and positive value refers to a downward flow. As shown, the vertical flows in all three identified zones by VFB are locally high. The main difference between the results of the PPC and VFB analyses is that VFB does not show any local flow convergence and an increase in vertical flow budget at the TVA area. Using this approach, we can conclude that the presence of breaches at the three identified zones is more likely than other parts of the study area.


2005
President's Island
MDIP
TVA
(a)


2010
President's Island
MDIP
TVA
(b)

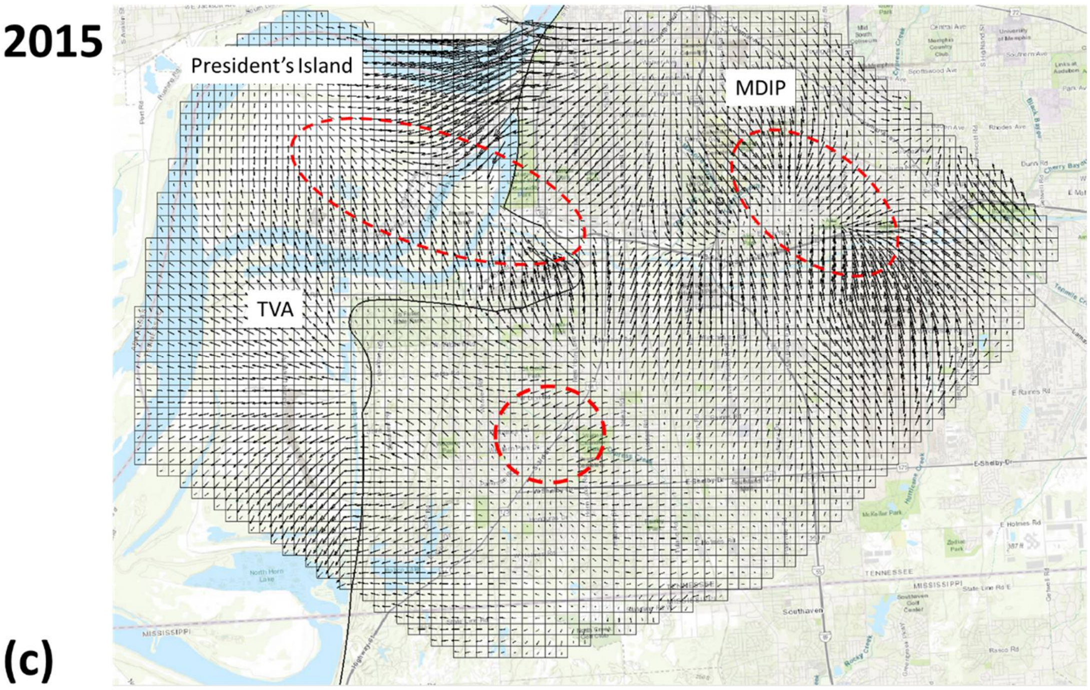
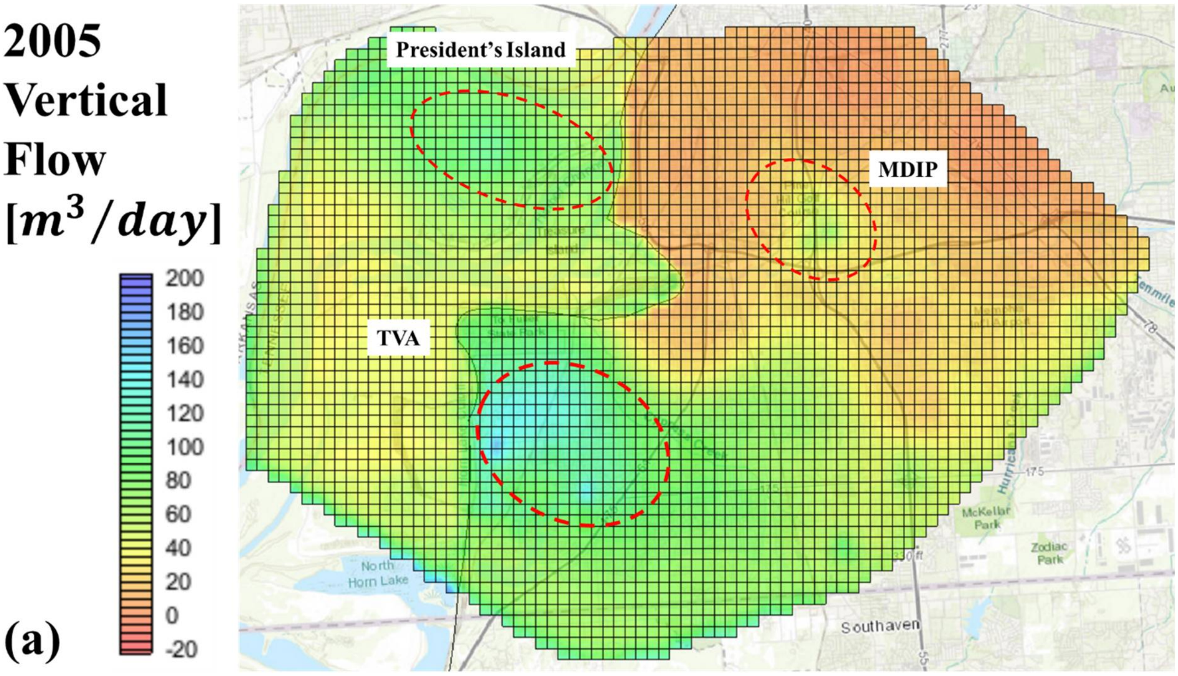


Figure-9(a-c) maps show the Shallow aquifer groundwater velocity vectors for 2005, 2010 and 2015, respectively. Magnitude of velocities are proportional to the length of arrows. Three zones where the groundwater velocity vectors are converged are shown. The probability of the presence of a breach in these zones are more probable than that of the surrounding areas.



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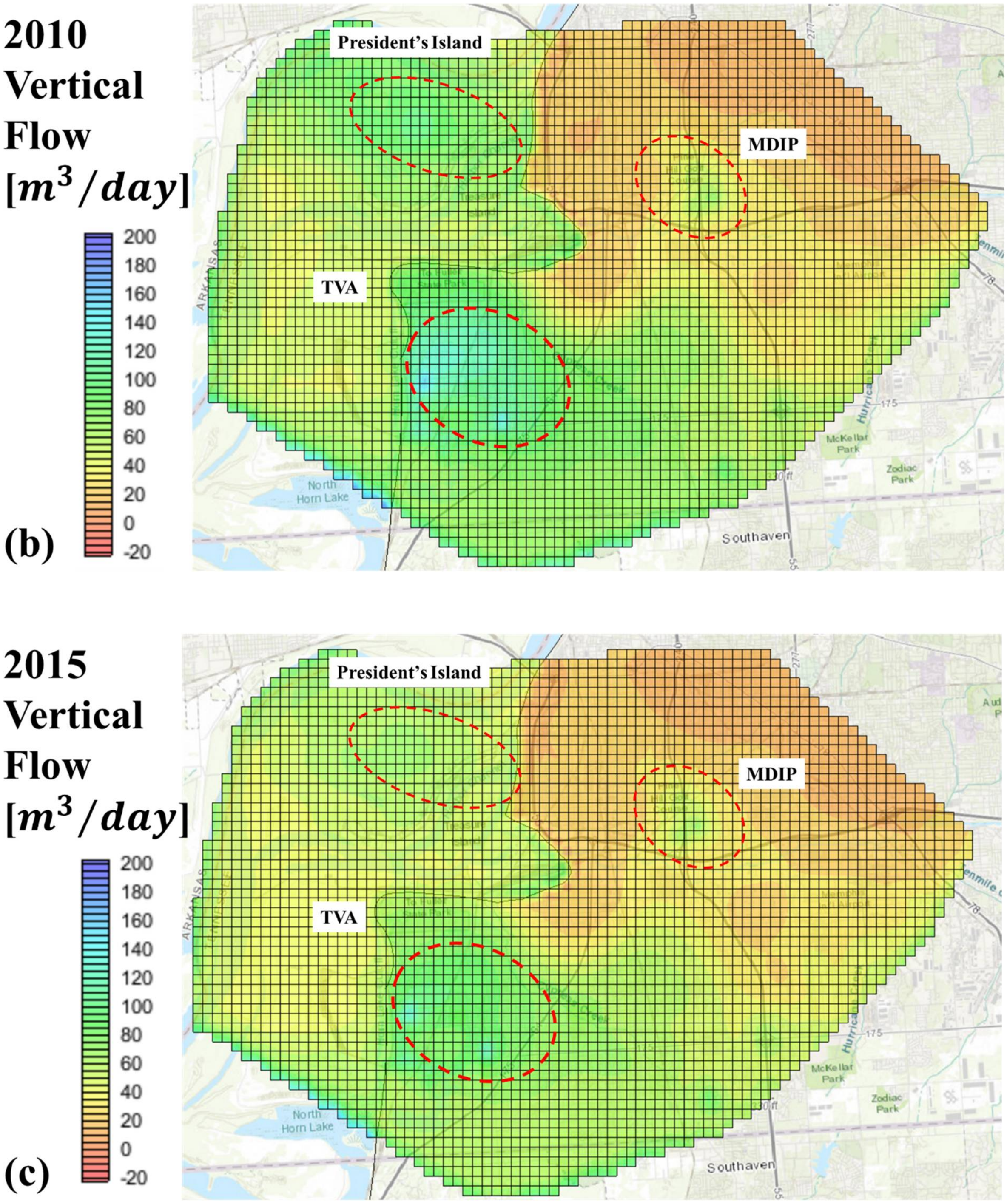

Figure-10(a-c) maps show vertical flow budgets at the bottom of the Shallow aquifer in 2005, 2010, and 2015, respectively. Negative values refer to upward flow and positive values refer to downward flows.

3.2.1 Validation of VFB results

As shown in Figure-9, the velocity vectors converge and focalize to three specific zones. These zones are almost the same as the three zones identified by PPC analysis except in the TVA area; therefore, VFB analysis only verifies the previous findings in the MDIP and President's Island. However, it should be noted that VFB identifies smaller breach areas compared with PPC. The third identified zone at the southern part of the study area is an undiscovered zone where further local and detailed investigations are required for verification. It should be noted that the convergence of the flow near the Nonconnah Creek is not necessarily because of the presence of a breach in this area. Flow budget analysis shows that the convergence of the flow in this area is mainly because of the drainage of the Shallow aquifer to the creek.

3.3 Particle tracking analyses (PT)

In this approach, we use the numerical tool, MODPATH (Pollock, 1994), to conduct forward particle tracking. Figure-11(a) shows cross-section A-A’ of the Shallow aquifer and UCCU, an east to west transect of the study area that is shown in context in Figure-11(b). Forward particle tracking represents the location of imaginary particles at the Shallow aquifer surface and top of the UCCU from 2005 (green marks) to 2015 (red marks). Figure-11(a) shows vertical downward flow transport from the Shallow aquifer and UCCU to the Memphis aquifer. A sudden change is observed at the bluff line due to differences in alluvial (west of the bluff) and fluvial (east of the bluff) deposits characteristics. The particles in the MDIP area also locally penetrate further from 2005 to 2015. As shown, particles west of the bluff within the President's Island move downward significantly faster than the east of the bluff, consistent with higher hydraulic conductivity of the MRVA and fluvial deposits at either side of the bluff line.

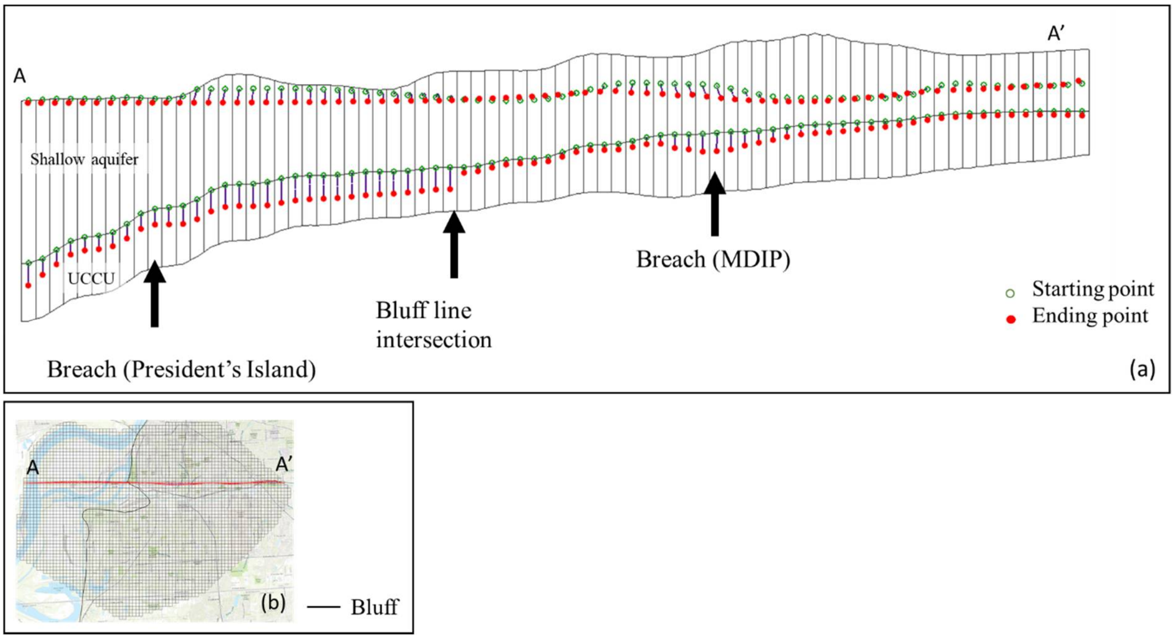

Figure-11 shows the A-A' cross section of the Shallow aquifer and the UCCU used for particle tracking. (a) shows the Shallow aquifer and the UCCU at the cross section. (b) shows the plan view of the cross section. Particles are placed on top of the groundwater in the shallow aquifer and top of the UCCU in 2005 (Green mark). Forward particle tracking shows the transport of the particles within the layers (blue line) and the position of each particle at the end of simulation in 2015 (Red mark).

Figure-12(a) shows placement of north-south cross-section B-B' of the Shallow aquifer and UCCU that is shown in context in Figure-12(b). Cross-section B-B' intersects the bluff at three points. Figure-12(a) shows a sudden change in particle migration proximal to the bluff due to hydraulic characteristics differences in alluvial and fluvial deposits at either side of the bluff line. Particles at the southern part of the cross-section B-B' transport further at depth from 2005 to 2015, compared with particles at the northern part of the cross-section.

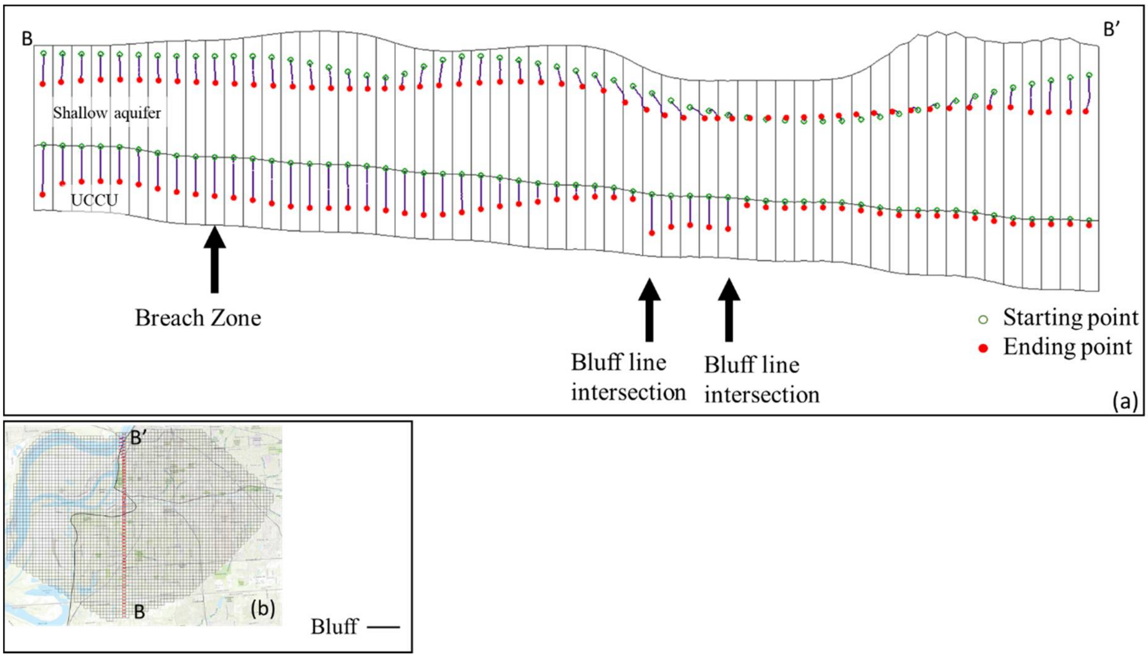

Figure-12 B-B' cross section of the shallow aquifer and the UCCU showing particle tracking results. (a) Cross-section of the shallow aquifer and the UCCU along B-B'. Particles are placed on top of the groundwater in the shallow aquifer and top of the UCCU in the year of 2005 (Green mark). Forward particle tracking shows the transport of the particles within the layers (blue line) and the position of each particle at the end of the simulation in 2015 (Red mark).

Figure-13(a) shows cross-section C-C' of the Shallow aquifer and UCCU, an east to west transect of the study area that is shown in context in Figure-13(b). The cross-section intersects the bluff at one point. Similarly, we place imaginary particles on the Shallow aquifer and top of UCCU in the year of 2005 (green marks). Forward particle tracking represents the location of each particle in 2015 (red marks). Same as cross-section A-A', an abrupt change is observed at the bluff; however, PPT results show a relatively high interaction between layers adjacent the bluff line. As shown in Figure-13(a), PPT shows no sign of a breach at the TVA area. However, there is a broad area east of the bluff where particles transport paths are relatively long. Therefore, there is a high possibility for the presence of a breach in this area.

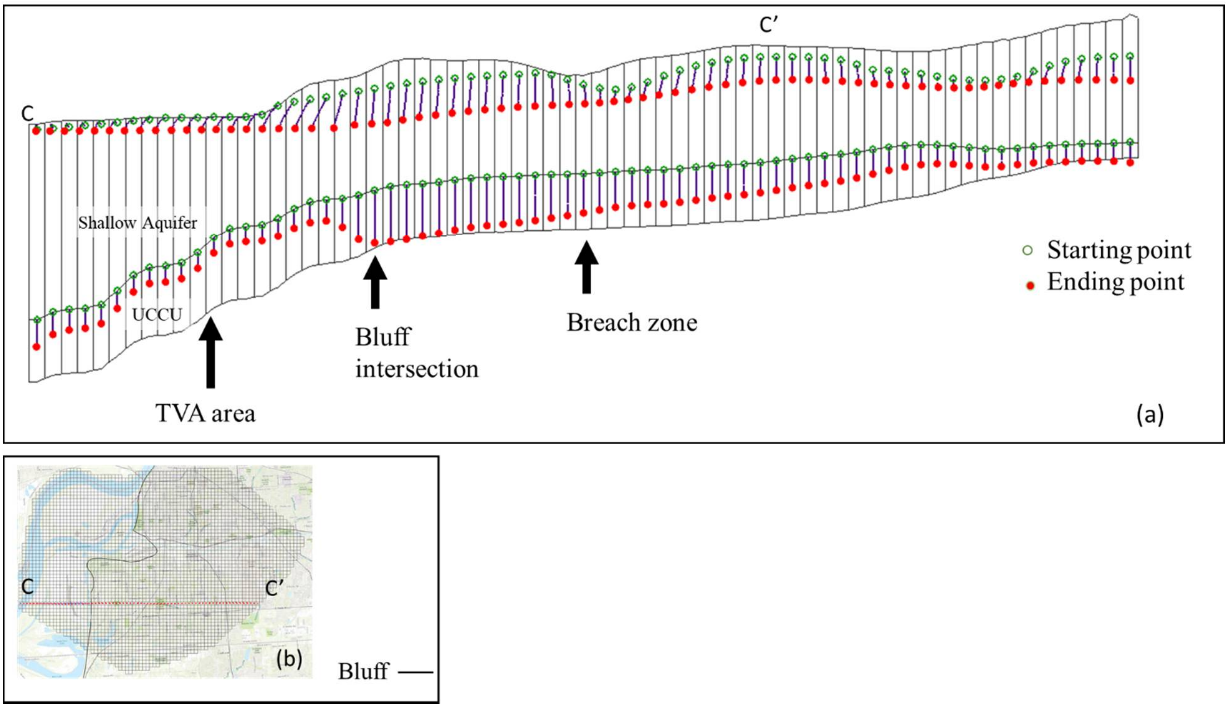

Figure-13 C-C' cross section of the shallow aquifer and the UCCU showing particle tracking results. (a) Cross-section of the shallow aquifer and the UCCU along C-C'. Particles are placed on top of the groundwater in the shallow aquifer and top of the UCCU in the year of 2005 (Green mark). Forward particle tracking shows the transport of the particles in the layers (blue line) and the position of each particle at the end of simulation in 2015 (Red mark).

3.3.1 Validation of PT results

PT results confirm all the zones identified by PPC and VFB analyses. The results show that the particles in the President's Island and MDIP transport locally further which is consistent with previous studies (Parks, 1990; Narsimha, 2007; Bradshaw, 2011) in these areas. PT shows that particles in the TVA area transport slowly downward excep adjacent the bluf line. This finding is consistent with a recent study (Carmichael et al., 2018). However, similar to PPC analysis, there is an undiscovered area in the southern part of the study area where PT identifies it as the locations where the presence of breaches is likely.

4 Summary and Conclusion

The Memphis aquifer is the primary drinking water source in the Shelby County (Tennessee, USA), and supplies industrial, commercial, and residential water. Memphis aquifer is one of several deep sand aquifers separated from the Shallow aquifer by a clayey confining layer, UCCU. All of the production wells in the Memphis area are screened in the Memphis aquifer or even deeper in Fort Pillow aquifer to avoid Shallow aquifer contamination. Traditionally, the

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public water supply authority in the Memphis area assumed that the UCCU could fully protect the water in the Memphis aquifer from downward leakage of the contaminated or poor-quality groundwater from overlying Shallow aquifer. However, recent studies show that at some locations the UCCU is thin or absent which leads to the contribution of water from the Shallow aquifer to the Memphis aquifer (Parks, 1990; Larsen et al., 2003, 2013, 2016). Hence, sustainable water management in the Memphis area requires locations of breaches in the UCCU to ensure protection of water pumped from the production wells. Locating breaches demands expensive geological or geochemical investigations. These studies are even more costly and complicated in densely developed urban areas. Therefore, other techniques are desired that can help determine the locations of breaches so that complicated and costly field investigations can be focused in limited areas.

In this study, to identify the locations where the presence of breaches in the UCCU is likely we use three different analyses: (1) pilot point calibration (PPC), (2) velocity and flow budget (VFB), and (3) particle tracking (PT). As shown in Figure-14, these approaches identify five zones where the presence of breaches is expected. As summarized in Table-1, all three approaches distinguish Zone-1, 2, and 3 from other parts of the study area. However, VFB does not identify Zone-4 and 5 as the locations of possible breaches. Previous investigations results are concurrent with this study in that the presence of breaches in Zone 1, 2, and 4 is likely. These findings validate the reliability of the numerical model. However, the presence of breaches in Zone 3 and 5 have never been explored and need further investigation. Five zones identified in this study are reasonable candidates for the future field investigations based on the current understanding of the study area. The results of this study can reduce the cost and increase the efficiency of investigations all over the broad study area, by directing future studies.

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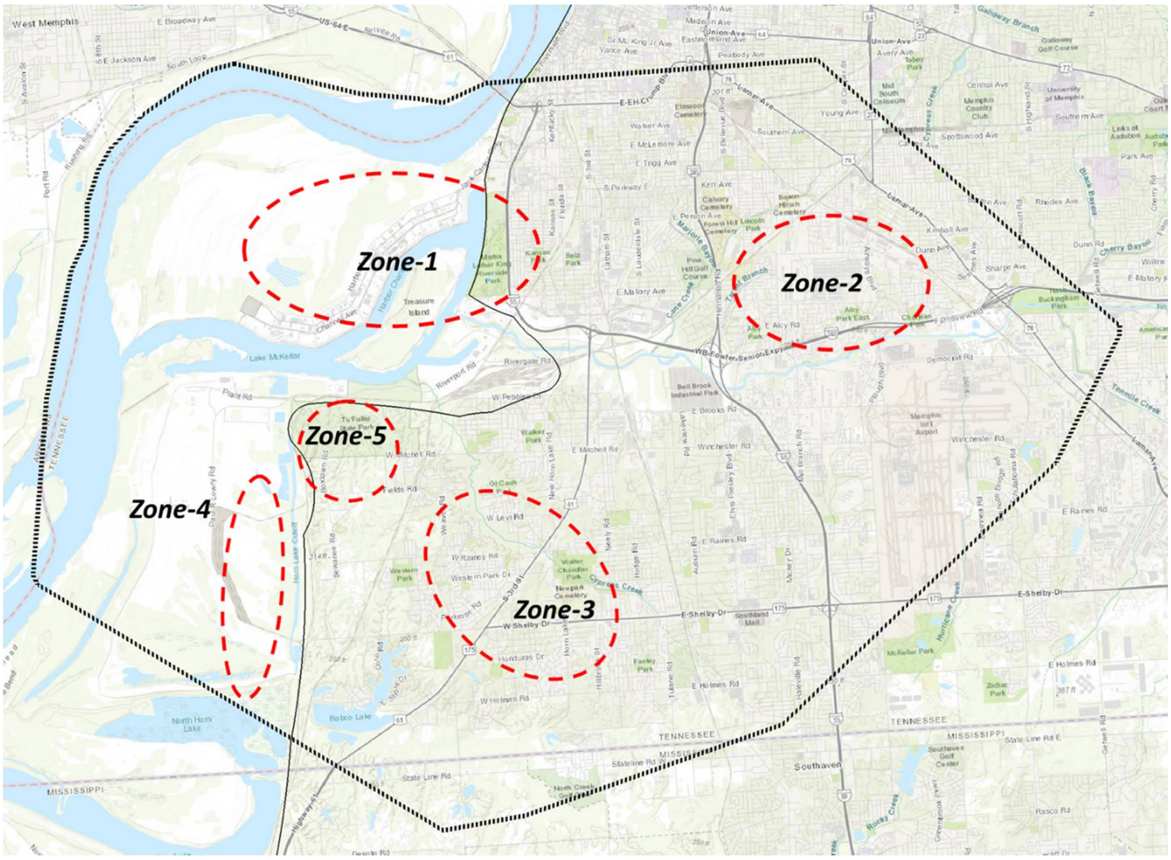
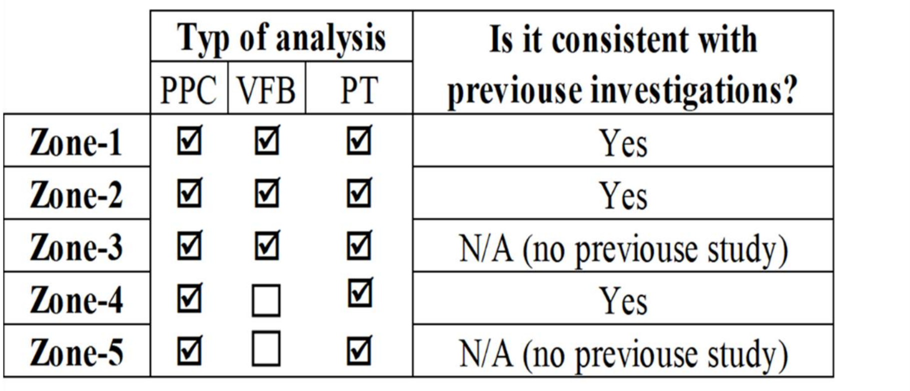


Figure 14 shows five zones identified by PPC, VFB and PT where further field investigations are required.

Table-1 summarizes the PPC, VFB and PT analyses identified zones.



	Typ of analysis			Is it consistent with previouse investigations?
	PPC	VFB	PT	
Zone-1	☑	☑	☑	Yes
Zone-2	☑	☑	☑	Yes
Zone-3	☑	☑	☑	N/A (no previouse study)
Zone-4	☑	☐	☑	Yes
Zone-5	☑	☐	☑	N/A (no previouse study)

5 Acknowledgment

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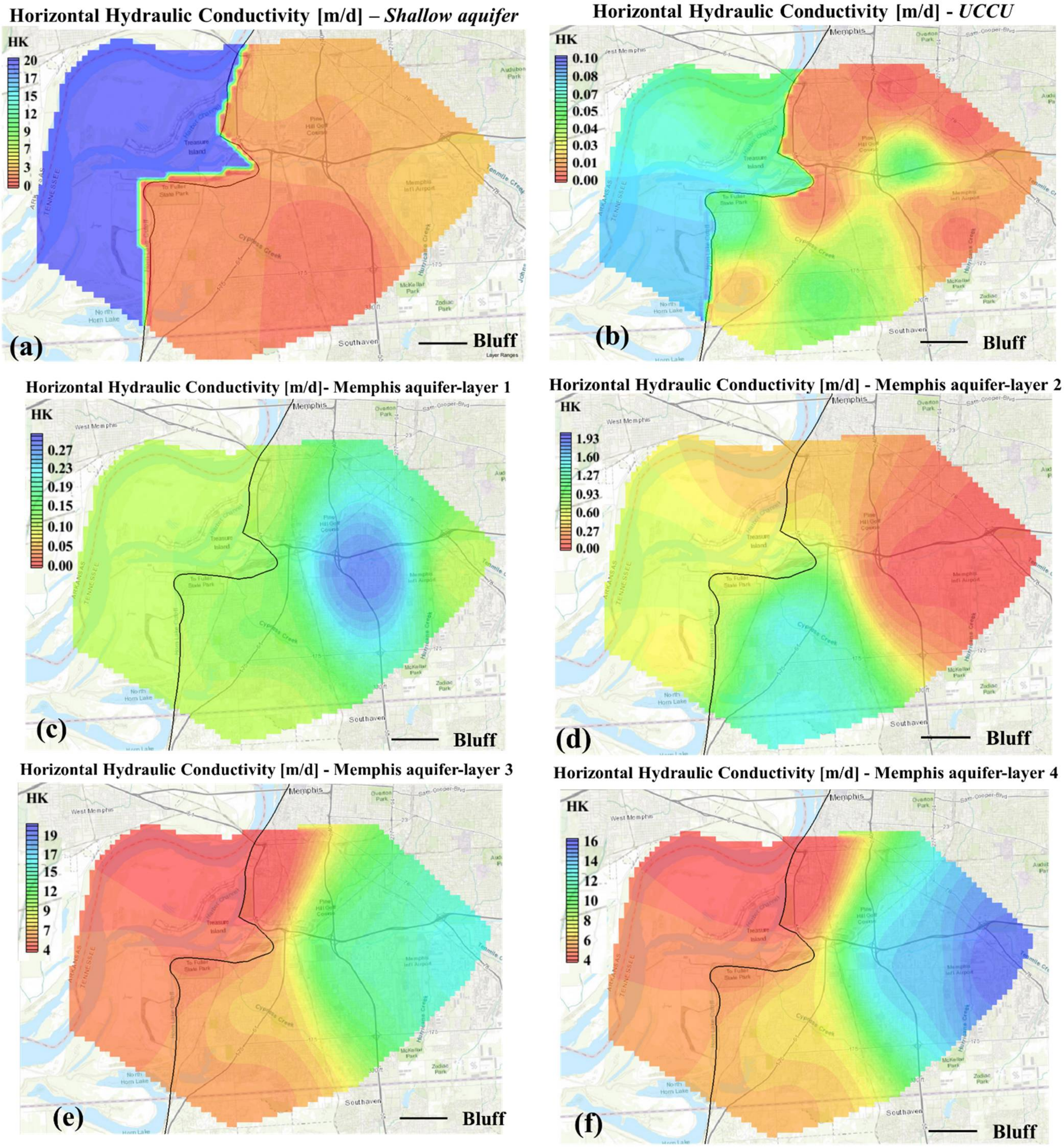
Appendix-1


Horizontal Hydraulic Conductivity [m/d] – *Shallow aquifer*

Horizontal Hydraulic Conductivity [m/d] - *UCCU*

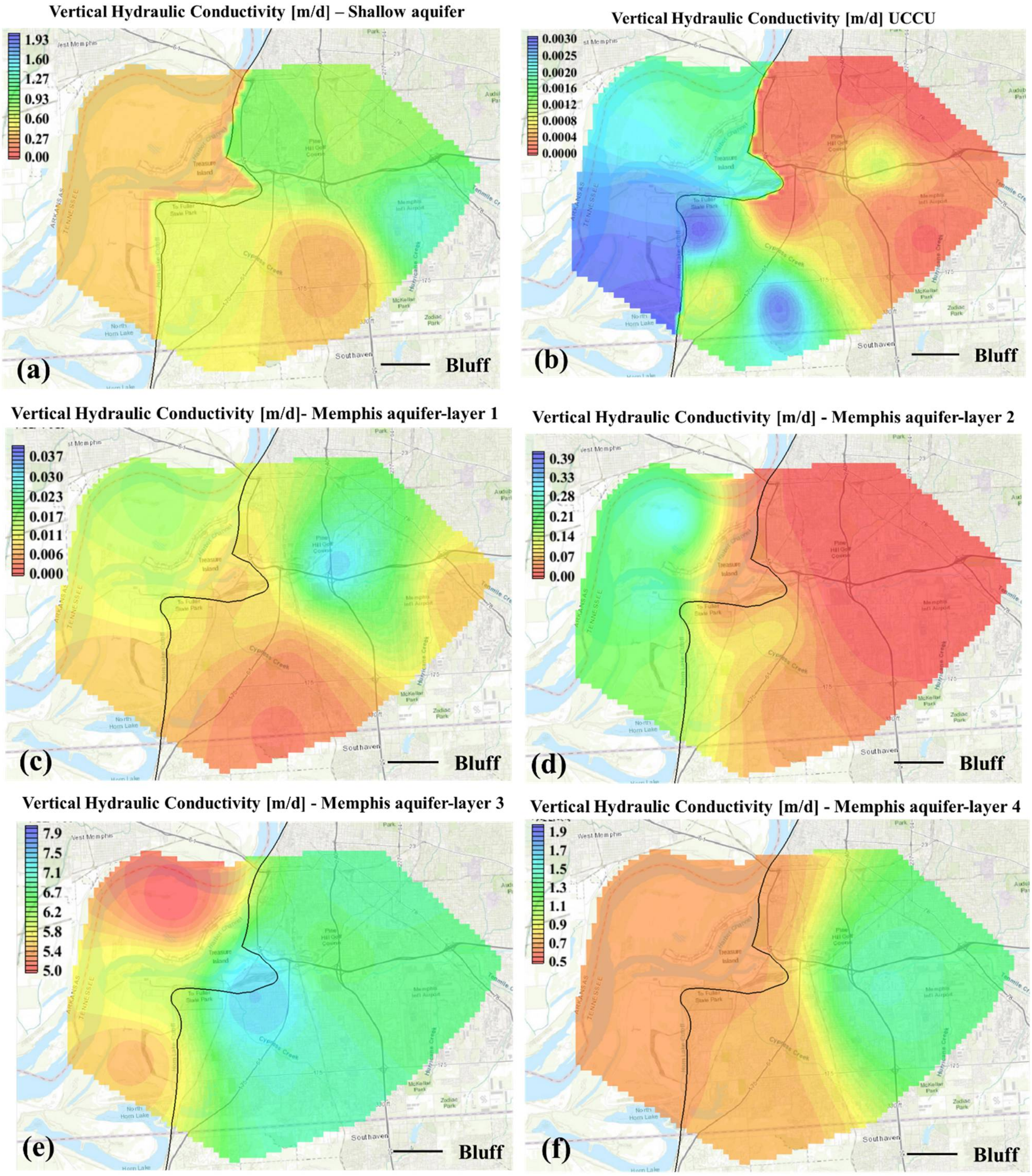
Horizontal Hydraulic Conductivity [m/d]- Memphis aquifer-layer 1

Horizontal Hydraulic Conductivity [m/d] - Memphis aquifer-layer 2

Horizontal Hydraulic Conductivity [m/d] - Memphis aquifer-layer 3

Horizontal Hydraulic Conductivity [m/d] - Memphis aquifer-layer 4

Figure 15- Figures (a-f) shows the horizontal hydraulic conductivity of each numerical layer.


Vertical Hydraulic Conductivity [m/d] – Shallow aquifer

Vertical Hydraulic Conductivity [m/d] UCCU

Vertical Hydraulic Conductivity [m/d]- Memphis aquifer-layer 1

Vertical Hydraulic Conductivity [m/d] - Memphis aquifer-layer 2

Vertical Hydraulic Conductivity [m/d] - Memphis aquifer-layer 3

Vertical Hydraulic Conductivity [m/d] - Memphis aquifer-layer 4

Figure-16 (a-f) show the vertical hydraulic conductivity of each numerical layer.

Appendix-2

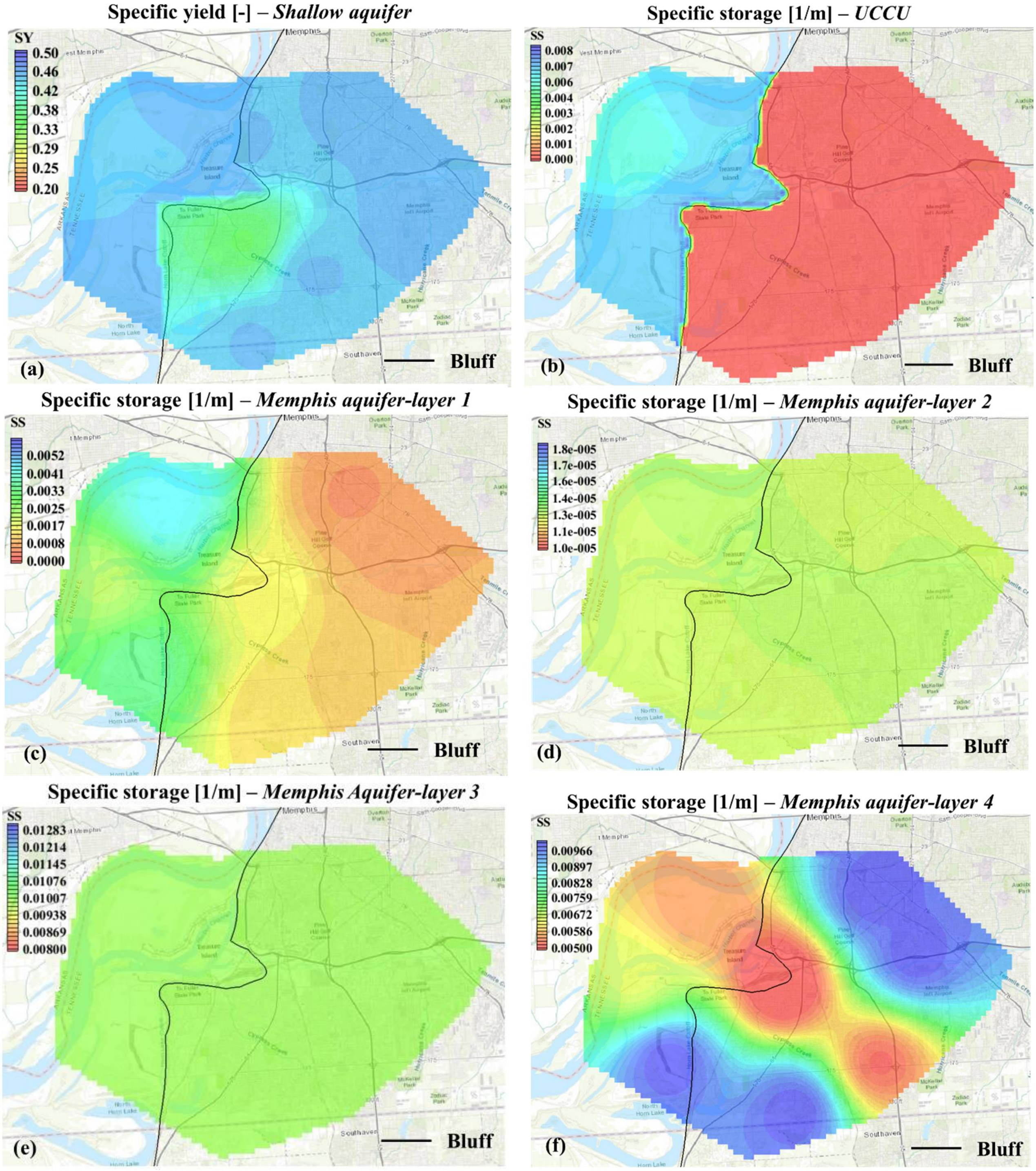


Figure-17 (a) shows the specific yield coefficient of the Shallow aquifer. Figures-17(b-f) shoes specific storage of UCCU and Memphis aquifer, respectively.

Appendix-3

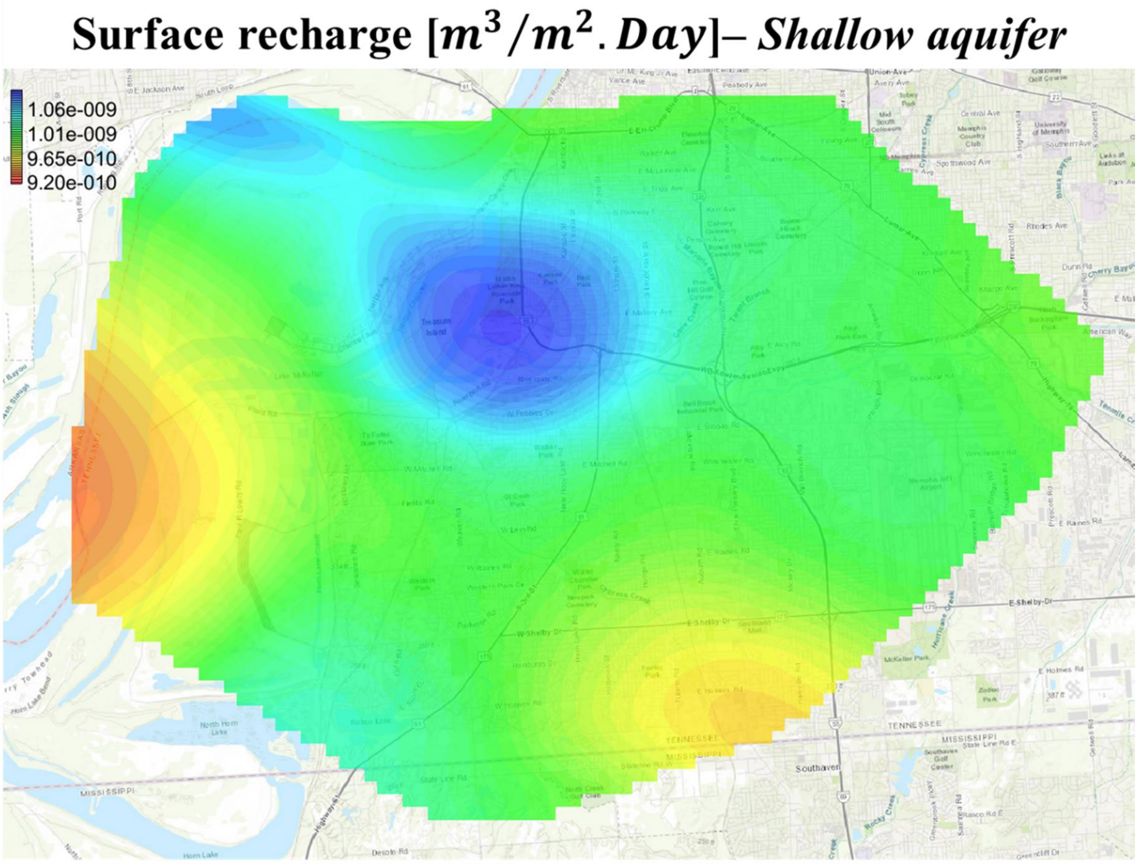


Figure-18 shows the calibrated surface recharge to the Shallow aquifer.