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Developing a calibrated seepage meter to measure stream-aquifer interaction in the Mississippi delta

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DEVELOPING A CALIBRATED SEEPAGE METER TO MEASURE STREAM-AQUIFER INTERACTION IN THE MISSISSIPPI DELTA

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ABSTRACT

The Mississippi Alluvial Plain (MAP) is a premier region for irrigated agriculture in the United States, producing approximately 9 billion dollars in annual revenues. The region receives around 138 cm of precipitation annually; however, irrigation is necessary to maximize crop yields as most of the precipitation does not occur during the growing season. There are 8 million irrigated acres within the Mississippi Alluvial Plain. The source of most of the irrigated water is the surficial aquifer in the Mississippi Embayment, the Mississippi River Valley Alluvial Aquifer (MRVAA), and due to the reliance on irrigation for maximum crop yields, recent potentiometric surface maps of the MRVAA show 1-1.5 ft/yr declines in groundwater levels. The US Geological Survey and US Department of Agriculture have produced models of the MRVAA to address groundwater sustainability issues. A large source of uncertainty within the Mississippi Embayment Regional Aquifer System (MERAS) and MAP project models is the contribution to groundwater from surface streams. Geophysical data estimating streambed sediment texture has been collected on numerous reaches within the MAP, but physical measurements are still desirable to constrain modeling efforts. Seepage meters are a potential tool for physical measurements of streambed seepage. Like all instruments, seepage meters must be calibrated to validate field measurements. Due to space limitations within the USDA National Sedimentation Laboratory, a tank with sufficient surface area to test a full-scale seepage meter was not feasible. Therefore, a scale-model seepage meter and seepage flux tank were constructed. Any consistent bias, if present, in measured seepage rates through the seepage flux tank could be accounted for by applying a correction coefficient. From the seepage flux tank

data, a 95% confidence interval was calculated for the linear regression trendline through the data. The 1:1 line lies within the 95% confidence interval, indicating there is no need for a correction factor and any bias in measurements is due to installation of the instrument and not to system configuration. A field demonstration of the seepage meter was conducted within Goodwin Creek in Panola County, Mississippi yielding results consistent with estimates of seepage calculated using creek parameters and measured discharges.

LIST OF ABBREVIATIONS

ID ....Inner diameter

MAP ....Mississippi Alluvial Plain

MERAS..Mississippi Embayment Regional Aquifer System

MRVAA...Mississippi River Valley Alluvial Aquifer

OD...Outer diameter

USDA...United States Department of Agriculture

USGS ....United States Geological Survey

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CHAPTER I

INTRODUCTION

Understanding the interactions between groundwater and surface water is critical for modeling water resources and managing sustainable use (Sophocleous, 2002). Rivers and streams may contribute water to aquifers or receive water from aquifers (Doppler et al., 2007). The rate at which water is contributed (infiltration/seepage rate) or received (exfiltration rate) can be substantial and critical to the balance and understanding of the groundwater system.

The rates and direction of groundwater-surface water interaction depend on hydrogeologic parameters such as (1) the distribution and magnitude of the hydraulic conductivity of the aquifer and riverbed; (2) the head distribution of the aquifer; (3) the relationship between the stream gage and the adjacent water level; and (4) the geometry and position of the stream channel within the alluvial plain (Doppler et al., 2007; Sophocleous, 2002). Head levels within an aquifer can be influenced by human processes such as groundwater pumping. When sufficient pumping rates are present, reduced head levels induce seepage from surface water into the aquifer (Sophocleous, 2002). Quantifying the rate of recharge, or seepage, is essential to the understanding of the direction, magnitude, and timing of exchange between aquifers and surface streams.

The Mississippi River Valley Alluvial Aquifer (MRVAA) is the primary supplier of water for irrigation in the Mississippi River Valley Alluvial Plain, locally known as the “Delta”, one of the most productive agricultural regions in the U.S. (Alhassan et al., 2019). Previous research suggests that recharge into the MRVAA could come from: surface hydrologic features such as rivers, streams, and lakes that breach the confining silt-clay unit (Bordonne et al., 2009); direct infiltration of meteoric water and surface runoff where the aquifer units outcrop at the surface; and inflow from the underlying tertiary aquifer (Mason, 2010). In the region of interest, the aquifer is mostly unconfined due to long-term water level declines and a fine-textured surficial layer that limits recharge by infiltration. The numerous rivers and streams that penetrate the MRVAA have become a source of much inflow since the development of the aquifer (Ackerman, 1989); however, the connection between the streams and the MRVAA is uncertain as no physical measurements have been made. A calibrated seepage meter is a potential method to quantify the connection between streams and aquifers within the MRVAA. Physical measurements could validate or change the estimates of stream recharge in the region and better quantify the connection between streams and the aquifer, thus providing critical data for aquifer management and the sustainability of agriculture in the region (Dyer et al., 2015).

The primary objective of this project is to develop a calibrated seepage meter to measure stream-aquifer interaction in the Mississippi Delta. To accomplish this, a seepage flux tank was constructed where a range of known seepage fluxes can be generated across the sediment-water interface to test the efficiency of a seepage meter in a laboratory. A scale-model seepage meter was built for testing within the seepage flux tank and a full-scale seepage meter for field measurements. Testing a range of flux rates through the seepage flux tank will determine whether a correction factor is necessary for field data.

This paper proceeds as follows. In the background section, the study area is described, previous work in the area is discussed, and the importance of my work is identified. Similar research conducted by others is presented along with the theory and design of the seepage meter. The details of the construction of the seepage flux tank are provided. I discuss the results from the seepage flux tank, the functionality and usefulness of seepage meters and their various components, losses associated with the design of the system, and the error associated with seepage meters. Finally, I detail the field demonstration conducted in Goodwin Creek Experimental Watershed.

CHAPTER II

BACKGROUND

The MRVAA is the uppermost aquifer in the Mississippi Embayment Regional Aquifer System (MERAS) (Figure 1*), and it ranks as one of the principal shallow aquifers for agricultural irrigation in the United States, underlying an 85,000 square kilometer area located primarily within Arkansas, Mississippi, Louisiana, and Missouri (Renken, 1998). The MRVAA supplies nearly 9,300 million gallons of water per day (MGal/day), making it the second most productive shallow aquifer in the U.S. behind the Ogallala Aquifer, which provides approximately 17,500 MGal/day (Maupin & Barber, 2005; Barlow & Clark, 2011). Groundwater withdrawals have impacted baseflow throughout the region, and twenty-year net change in groundwater levels shows 1-1.5 ft/year declines in northwestern Mississippi (Barlow & Clark, 2011).

The U.S. Geological Survey (USGS), the U.S. Department of Agriculture (USDA), and many other agencies have been modeling the MRVAA to assess the sustainability of water levels within the aquifer. Data used for modeling includes topographic data; climate data, such as precipitation, runoff, and evapotranspiration; geologic data; hydrogeologic data, such as hydraulic conductivities and total groundwater head; recharge rates (infiltration/seepage rates); and pumping data, including irrigation. The model is calibrated to fit the available data and can be simulated for future scenarios (Clark & Hart, 2009). Stream contributions to recharge were identified as a major source of uncertainty in current models as no physical, or direct, measurements have been made within the MRVAA. Current iterations of the MERAS model

*all figures located in Appendix A

assign a single coefficient to entire rivers through the region based on literature values from other systems (Figure 2) (Clark & Hart, 2009). Riverbed material in Mississippi is often heterogeneous, locally varying from coarse sand to clay. Select rivers in the region are believed to be strongly connected with the MRVAA, many of which would be desirable targets for direct seepage measurements. Direct measurements of seepage would be beneficial to the model, as they would allow for the verification of current seepage estimates or justify necessary adjustments to the estimates.

Direct seepage rate measurements can be obtained by seepage meters (Figure 3). Seepage meters have been in use since the 1940’s and were originally developed to quantify water losses from irrigation canals (Israelson & Reeve, 1944; Warnick, 1951; Robinson & Rohwer, 1952). Seepage meters are designed to measure the rate of flow across a sediment-water interface by isolating an area of the sediment within a cylinder (Martinez, 2013). The base of the cylinder is open to underlying sediment and the top is vented to a collection bag, or bladder. The seepage rate is found by measuring the change in the volume of water within the bladder over a known time interval.

Lee (1977) constructed a seepage meter to measure seepage flux in lakes and estuaries. The seepage meter was built from an end-section of a 57 cm diameter steel drum. A one-hole rubber stopper with a polyethylene tube attached the steel drum to the 0.79 cm ID polyethylene tubing, which connects to a 4 L thin-walled collection membrane. Issues with seepage measurements were reported when the seepage cylinder was improperly placed with the connection hole not at the highest point above the sediment-water interface. Lee (1977) also reported erratic results from blowouts caused by inserting the seepage meter too rapidly into the sediment. Multiple closely placed seepage meters yielded reproducible results in their research.

Landon, Rus, and Harvey (2001) conducted a comparison of instream measurements to determine hydraulic conductivity in sandy streambeds. They tested three seepage meters of the following materials and diameters: 28 cm schedule 80 PVC sealed with sheet metal on one end, an end section of a 61 cm steel drum, and an end from a 91 cm circular livestock watering tank. All tests were conducted with gusseted 4.4 L measurement bags connected via 1.1 cm ID reinforced plastic tubing and a valve to control the measurement period. Bag shelters were used to minimize the effects of stream velocity on the measurement bag. Landon, Rus, and Harvey (2001) reported similar seepage rates with all three sizes of seepage meters where duplicate measurements were successful. However, they also state that individual seepage meter tests coupled with hydraulic gradient measurements were unsuccessful at determining vertical hydraulic conductivity about 40% of the time regardless of seepage meter diameter. According to their results, 58% of failures were caused by groundwater/surface water gradients measured to be opposite the flux direction indicated by the seepage bag, 18% caused by holes in the measurement bag, 11% due to bedload deposition on top of the measurement bag, and 10% due to holes in other parts and procedural errors.

Rosenberry (2005) conducted a study to address local-scale heterogeneity in seepage measurements by linking multiple seepage meters together with a single measurement bladder. Four seepage meters were made using end sections of high-density polyethylene plastic drums ported with garden hose fittings. Standard 1.43 cm ID garden hose and Y-connectors were used to link the seepage meters. A 4 L thin-walled plastic bag served as the measurement bladder by bunching it together at the opening and connecting a garden hose shutoff valve. The focus of the study was to assess whether watershed-scale seepage rates could be estimated through ganged seepage meters, the spatial scale that most water managers are interested in (Rosenberry, 2005).

According to his study, ganged seepage meters have many benefits compared to single seepage meters such as: labor costs reduced, time of testing reduced by a factor of two or more, and the number of bag measurements reduced by like amounts. Shallow, relatively wave-free sites provided an ideal testing environment for the ganged seepage meter concept. Results from Rosenberry's (2005) study indicate that seepage meters can be ganged together to integrate seepage heterogeneity and reduce labor costs with little loss of seepage-meter efficiency. Ganged systems could experience failure in highly permeable substrate due to frictional losses in the garden hose and Y-connectors (Rosenberry, 2005).

CHAPTER III

SEEPAGE METER DESIGN

The efficiency of a seepage meter design can be tested by utilizing a seepage-flux tank, where a range of known seepage fluxes across the sediment-water interface can be generated. By placing manometers on the perimeter of the seepage meter, a comparison can be made between the head inside and outside the seepage meter. The head loss inside the seepage meter can be attributed to frictional losses and inefficiencies of the bladder plumbing. Devices for generating controlled rates of seepage have been described in several reports (Lee, 1977; Erickson, 1981; McBride, 1987; Shaw & Prepas, 1989; Asbury, 1990; Belanger & Montgomery, 1992, Rosenberry & Menheer, 2006). If necessary, a correction factor that compensates for measurement inefficiencies can be found using a seepage-flux tank, which converts seepage flux measured in the field to true seepage flux.

The seepage meter was designed and built based on the “half-barrel” seepage meter (Figure 4) (Lee, 1977). It was constructed out of one-half of a 115-liter Grainger closed-head, steel transport drum. The closed-end of the drum will be vented with two-centimeter latex hose via a quick-connect coupler to a two-liter bladder containing a known volume of water. The two-liter bladder has a shutoff valve to quickly start and stop the flow of water through the seepage meter. A scale-model was constructed out of a 15-centimeter steel pipe (Figure 5) for testing and calibration. The scale model features the same two-centimeter garden hose and two-liter bladder that will be connected to the full-size seepage meter. A parts list for construction of both full-scale and scale-model seepage meters is presented in Appendix B.

CHAPTER IV

SEEPAGE FLUX TANK DESIGN

The seepage-flux tank was constructed using a 380-liter polyethylene open-top tank that is operable with a lid (Figure 6) or with the top open (Figure 7). The tank features a single PVC outlet at its base connected to a high-precision valve to allow for incremental adjustments to the tank discharge. An aluminum flange was attached to the top of the tank for testing with head elevations higher than the top of the tank. Manometer ports were added to determine the pressure gradient within the tank at the following increments measured from the top of the flange: 10 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm, 100 cm, and 116.5 cm. The lowermost manometer at 116.5 cm beneath the tank flange is beneath the porous medium. Three additional manometer ports were added around the perimeter of the tank at 60 cm, 80 cm, and 100 cm below the flange to quantify any spatial variation in pressure. A metal grate was cut and placed at the bottom of the tank to provide a uniform, level base for sediment within the tank (Figure 8). Above the metal grate, there is one sheet of steel mesh (Figure 9), two sheets of window bug screen (Figure 10), a five-centimeter layer of pea-gravel (Figure 11), and a two-centimeter layer of coarse sand (Figure 12).These layers were placed at the bottom to keep the testing medium in place and prevent it from falling to the bottom of the tank. The tank was then filled with the testing medium (Figure 13).

Outside the tank, 0.5 cm ID clear vinyl tubing connected the manometer ports to the manometer board (Figure 14). The tank was filled slowly from the bottom to force out any air trapped in the sediment. Each time the sediment was changed, the tank was filled and drained eight times to remove air from pore spaces. The seepage meter was then placed in the desired location within the tank penetrating the medium such that the seepage meter flange was flush with the medium (Figure 15). The methodology for setup and operation of the seepage flux tank can be found in Appendix C.

CHAPTER V

CALCULATION OF SEEPAGE RATES

Seepage rates were calculated for the seepage flux tank and the seepage meter. To calculate seepage through the meter, discharge through the attached bladder is measured five times ($Q_{B1...}Q_{B5}$) using

$$Q_B = \frac{M_I - M_F}{T}$$

where M_I is the initial weight of the bladder, M_F is the final weight of the bladder, and T is the amount of time that flow from the bladder occurs. Bladder discharge is then converted to seepage through the meter (S_{SM}) using

$$S_{SM} = \frac{Q_{Bmean}}{A_{SM}}$$

where Q_{Bmean} is the mean of $Q_{B1...}Q_{B5}$ and A_{SM} is the cross-sectional area of the seepage meter.

Tank discharge is found mechanically using a graduated cylinder to catch a sample volume from the tank outflow over a known amount of time. A minimum of five sample volumes were taken to minimize the associated error. Tank discharge (Q_T) is calculated using

$$Q_T = \frac{V_{mean}}{T}$$

where V_{mean} is the mean volume of water captured in the graduated cylinder and T is the amount of time used for sample collection. Tank discharge is then converted to tank seepage (S_T) using

$$S_T = \frac{(Q_T - Q_{Bmean})}{A_{EFF}}$$

where Q_{OUT} is tank discharge, Q_{Bmean} is mean bladder discharge when the seepage meter is actively measuring, and A_{EFF} is the effective seepage area within the tank.

CHAPTER VI
METHODS

The efficiency of the scale-model seepage meter was tested using tank flux rates ranging from 60-2300 L/hr/m^2, heads above the sediment-water interface of 0.53-2.1 meters, and through two different porous media M1 (300 μm sand) and M2 (100 μm sand). The seepage meter was tested in two different positions for each testing medium. Tests were run with the lid for M1 and without the lid for M2.

M1 tests were conducted with the machined aluminum lid attached allowing the head to be varied along with the discharge rate from the seepage flux tank. With the lid attached, the head elevation can be varied from a maximum of 2.1 m above the sediment-water interface to a minimum of 1.62 m above the sediment water interface. Higher and lower head elevations can be achieved with longer hoses connecting the constant head reservoir to the tank. M1 tests were conducted at head elevations of 2.1 m, 1.84 m, and 1.62 m above the sediment-water interface. Tank seepage rates ranged from 640 to 2300 L/hr/m^2. Twenty-six measurements were taken with the seepage meter in position 1 and twelve in position 2 (Figure 16). Time of testing with the bladder attached to the seepage meter ranged from 1.5 to 3 minutes due to the high discharge rate through the coarse sand medium.

M2 tests were performed with the lid removed from the seepage flux tank, fixing the head elevation at 0.5 m above the sediment-water interface. Lower head elevations are attainable by adding an outflow valve at a lower point on the tank. Higher elevations cannot be accomplished without major modifications to the seepage flux tank. Five measurements were taken in position

1 and six in position 3 (Figure 16). Due to the low discharge rate through the finer sand medium, time of testing bladder discharge through the seepage meter was increased to 20 minutes.

Losses within the seepage flux tank system were considered using the Darcy-Weisbach equation for head loss due to friction through a known length of pipe. Local losses were determined by subtracting the head loss due to friction through the pipe from the difference in head inside and outside the seepage meter. Formulas used for head loss calculations can be seen in Appendix D.

CHAPTER VII

SEEPAGE FLUX TANK RESULTS

Data from the seepage flux tank indicates a net 0.6% overestimation of true seepage with the seepage meter but varies with positioning of the seepage meter within the seepage flux tank and with the testing medium. Each of the four datasets were fit with a linear trendline with a fixed intercept. M1 center shows a 6% overestimation of seepage (Figure 17), whereas M1 off-center shows a 24% underestimation of true seepage (Figure 18). With the lid removed, the seepage meter overestimates seepage through M2 by 8% in the center (Figure 19) and 0.8% off-center (Figure 20). A linear trendline fit to all data yields a 0.6% underestimation of true seepage through the seepage meter, which is essentially 1:1 (Figure 21). A 95% confidence interval was calculated on the slope of the regression line through all data which reflects the 95% confidence interval for the slope of the regression, not for individual points (Figure 22). Standard error of individual predictions can be seen in Figure 23.

Evaluation of head losses within the system showed a difference in head inside and outside the seepage meter ranging from 0.3 – 2.2 cm with the lid attached and 1.2 – 3.9 cm with the lid removed. The average differences were 0.3 cm and 2.1 cm, respectively. The Darcy-Weisbach head loss calculation yielded average losses of 0.1 cm with the lid and 0.01 cm without. Average local losses with and without the lid were 0.8 cm and 1.7 cm, respectively.

CHAPTER VIII

DISCUSSION

While testing with the lid attached to the tank, and the constant head elevation above the height of the flange, seepage through the meter was inconsistent when compared to tank seepage, which is suspected to be air trapped within the tank underneath the lid. Although the medium was filled from the bottom and drained numerous times to purge air from the medium, the inconsistent data indicates that air is still present within the seepage flux tank. The air release valve shown in Figure 6 was intended to purge all air from the tank when pressurized; however, air could remain pressed against the machined aluminum plate and influence flow within the tank. Air bubbles present in the lines connecting the reservoirs to the tank can be seen through the clear hoses but are not detectable if present in the 2 cm hose from the seepage meter to the bladder. Due to the consistency of the data with the tank lid removed vs data with the tank lid attached, air bubbles remaining inside the tank even after purging the lines and the air release valve, which may explain the inconsistent seepage rates seen in the data from M1. To test the hypothesis of air within the tank, the lid was removed and the constant head level was maintained within the seepage flux tank. To eliminate air from the tank entirely would require pressurization of the tank with CO_2 and subsequent injection of water into the pressurized tank. This is beyond the scope of the current project but planned for future work.

In conjunction with the suspected air uncertainty, the inflow through the hose attached to the tank lid is influencing flow across the sediment-water interface. Inflow occurs through a 7.0 cm vinyl hose oriented perpendicular to the sediment surface. Flow into the tank from the hose leaves a scour hole on the sediment surface on the inlet side of the tank. Due to the scour holes, flow to and through the sediment-water interface is influenced by pressure variations above the sediment surface. Relocation of the inflow pipe to the side of the seepage flux tank would likely minimize the vertical pressure variations and yield more consistent flow through the seepage meter. Also, smaller inflow rates would stabilize the flow above the sediment-water surface and reduce the range of seepage rates measured through the seepage meter.

Tests conducted inside the tank for calibration purposes assume uniform distribution of flow across the sediment water interface; however, seepage heterogeneity was also shown to exist within the seepage flux tank. Differences in seepage rates through the meter compared to seepage through the tank occurred each time the seepage meter was moved to a different position, indicating that spatial heterogeneity of seepage exists even in a homogeneously distributed sand. Shaw and Prepas (1990) indicated that seepage varied by a factor of two or more between two seepage meters spaced only 1.0 m apart. Rosenberry and Menheer (2006) reported similar spatial heterogeneity through a comparable flow system and suggested that several seepage meters or larger diameter seepage meters should be used to average out the effects of heterogeneity during calibration testing.

Although there is a relatively high amount of spread in the data from the seepage flux tank, the linear regression trendline is essentially 1:1. With the 1:1 line lying within the 95% confidence interval for the slope of the regression, no correction factor is needed for the seepage meter as it is currently configured. If there is a bias in data from the seepage meter, it is due to the installation of the device and not to the configuration of the system.

Calculations of head losses within the seepage flux tank system revealed average local losses of 0.8 cm with the lid and 1.7 cm without the lid. Per the Darcy-Weisbach equation, higher velocities within the pipe led to higher head losses due to friction. Efforts were made to minimize frictional losses by increasing the diameter of the pipe from 0.6 cm to 2.0 cm during initial testing of the seepage flux tank system before the collection of data. Frictional losses through the initial tubing were such that there was no measurable seepage through the seepage flux tank. With the lid removed and finer medium in the tank, head readings inside the seepage meter were consistently 0 – 0.1 cm higher than the head outside the seepage meter.

When considering data from the full-scale seepage meter in the field, it is important to consider the effects of the seepage meter on parameters within the stream. The seepage cylinder is affected by local changes in streamflow velocity and pressure due to the diversion of water above and around the seepage cylinder (Rosenberry, 2008). The resulting pressure distribution in the immediate vicinity of the cylinder is complex and temporally variable and can generate hyporheic exchange whose flowpath length is dependent upon streamflow velocity (Cardenas & Wilson, 2007a,b). The integrated pressure-head difference, the resistance to flow presented by stream sediments, and the depth of insertion of the seepage cylinder, determine the rate of streamflow-induced seepage (Rosenberry, 2008). Therefore, streams with low streamflow velocities coupled with a low-profile seepage meter would minimize the local effects of velocity on seepage measurements.

Likewise, the effects of water velocity on the collection bladder must be considered when testing a seepage meter. Effects of bladder-related velocity effects can be negated by utilizing a submerged shelter (Libelo & MacIntyre, 1994; Landon et al., 2001; Murdoch & Kelly, 2003; Schneider et al., 2005). Although the effects of water velocity can be counteracted with a submerged shelter for the bladder, river depth acts as a limiting factor for seepage meter site selection as the shelter and bladder need to be attached to or near the seepage cylinder so the hydraulic heads are the same. If the assumption of equal hydraulic head is not valid, bias is introduced to seepage meter measurements. Rosenberry (2005) found that hose lengths of 10-15 m connecting the bladder to seepage meters does not result in appreciable head loss unless seepage velocity is very fast.

CHAPTER IX
FIELD DEMONSTRATION

A field demonstration of the full-scale seepage meter was conducted within the Goodwin Creek Experimental Watershed (GCEW) in Panola County, Mississippi (Kuhnle et al., 2008). The GCEW lies in the bluff hills physiographic subprovince just east of the Mississippi River alluvial valley in a region with erodible soils, high rainfall (1358 mm/year), and relatively steep slopes in the main channel. Designated as one of twelve benchmark watersheds of the Conservation Effects Assessment Project in 2005, the major focus of research on the watershed is the effect of conservation practices on watershed sediment load. Kuhnle et al. (2008) states that channels in GCEW are deeply incised and generally oversized for their drainage area. These channels contain 14 supercritical flow structures designed and installed by the Vicksburg District of the US Army Corps of Engineers to stabilize the bed elevation of the channels and serve as monitoring sites for stage, discharge, and sediment yield (Figure 24). Streambed material in GCEW is primarily medium sand to gravel but often overlies clay and ironstone. At a depth approximately 0.3 m beneath the streambed exists a relatively uniform clay layer that acts as a confining layer. A hand auger was used to find testing locations within the creek where the clay layer was absent.

Field data was collected from three sites along the main channel within GCEW. Field tests were conducted over three days, May 1, 2019 and June 4-5, 2019. Station 01 data from May 1 indicated an inflow from groundwater to the channel at rates of 1.7, 2.1, and 2.45 L/hr/m^2. Testing at nearly the same location upstream from Station 01 on June 4 showed gaining conditions of 3.87 and 3.26 L/hr/m^2. Data from stations 2 and 3 show inflows of 0.35, 0.61 and 1.12, 1.48 L/hr/m^2, respectively. Insufficient water depths prohibit testing of the seepage meter upstream of Station 3. Methods for operation of the seepage meter can be found in Appendix E.

Seepage rates from each site were averaged and a single value was used for each station (Table 1). Data from Station 2 does not fit within the range expected between Stations 1 and 3, which is believed to be due to subsurface complications at the testing site. Station 2 has a high presence of ironstone and the confining clay unit is more continuous. Assuming linear seepage across the reach between Stations 1 and 3, the average seepage rate, the average cross-sectional area of the creek, and the length of creek between Stations 1 and 3 can be used to find the contribution from seepage between the two stations. The contribution from seepage between Stations 1 and 3 was found to be 0.022 m^3/sec whereas the difference in discharge between the two stations at the time of measurements was 0.023 m^3/sec (Appendix F).

Location	**Measured Seepage Flux Rate (L/hr/m^2)**	**Water Depth (cm)**	**Seepage meter seating depth (cm)**	**Discharge measured at Station (m^3/sec)**
Station 1	3.57	88	18	**0.060**
Station 2	0.48	54	23	0.045
Station 3	1.30	66	20	**0.037**

Table 1. Measured seepage flux rates from Goodwin Creek

CHAPTER X

CONCLUSION

Direct measurements of seepage have proven to be reliable and are very cost-effective compared to other streambed data collection methods. Inefficiencies in seepage meter designs can be accounted for by applying correction factors, when necessary, to account for losses associated with routing water through valves and tubing. A seepage flux tank was designed and constructed that permits the measurement of seepage through a tank and through a seepage meter that covers a small area within the tank. By doing this it was determined that the current configuration of the seepage meter needs no correction factor, and field measurements are accurate to an acceptable degree. Testing with the lid attached to the seepage flux tank yielded a larger range of seepage rates than testing with the lid removed. However, a linear regression trendline through all data was still nearly 1:1. 95% confidence intervals were calculated from the linear regression through the data showing the 1:1 line within the determined interval, meaning any bias in field data is due to installation of the seepage meter and not to the configuration of the system. Field data collected in Goodwin Creek Experimental Watershed all produced gaining conditions; therefore, no field data is available for losing conditions like those recorded using the seepage flux tank. However, seepage meter measurements closely resembled calculated estimates of seepage using the reach and cross-sectional area of the creek and the measured discharge of the creek. Seepage meters, when placed in the proper environments, yield reliable and consistent streambed data. Future work will include deployment of the seepage meter in rivers in the Mississippi Alluvial Plain.

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LIST OF APPENDICES

APPENDIX A

Figures

Figures

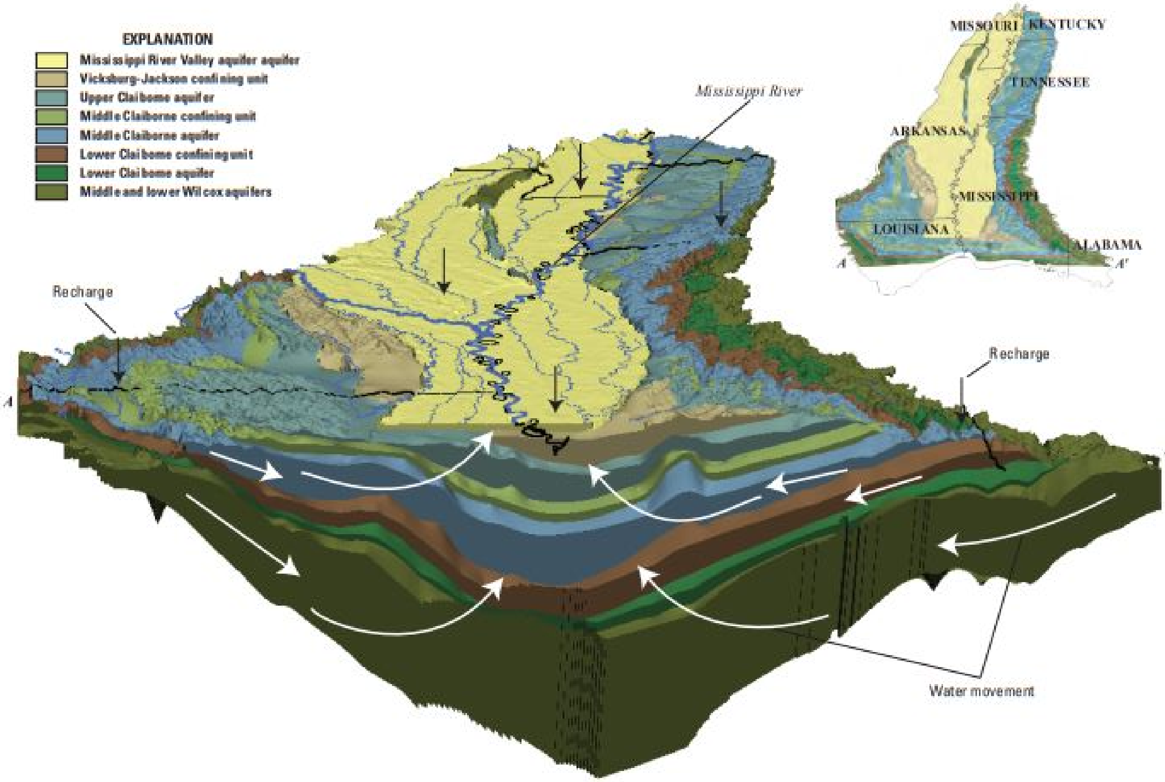

Figure 1. Mississippi Embayment Regional Aquifer System (Clark et al. 2011).

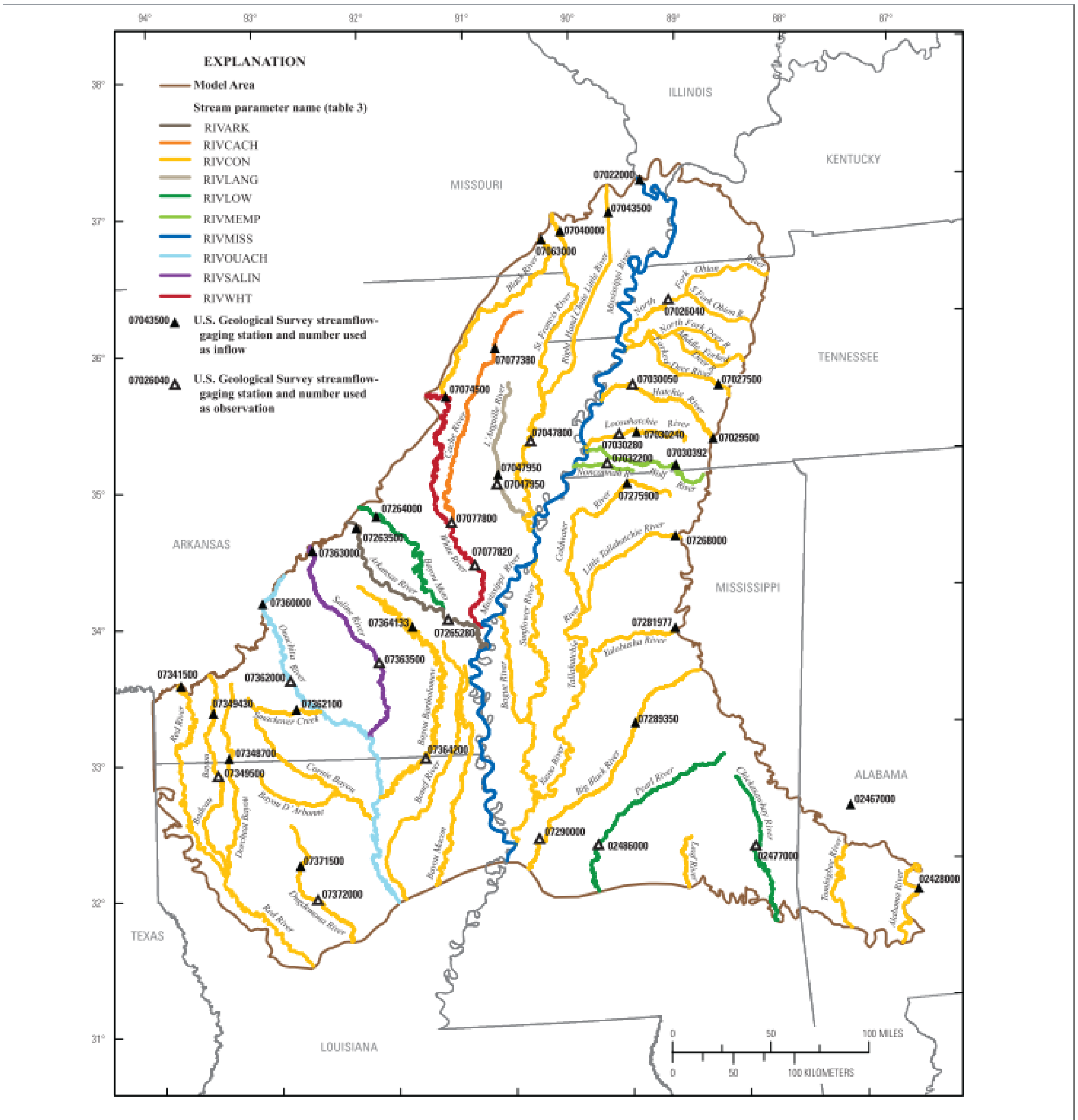

Figure 2. Streams simulated in MERAS model showing single values representing entire reaches of streams (Clark & Hart, 2009).

Figure 3. Half-barrel seepage meter installed in Goodwin Creek, Batesville, MS.

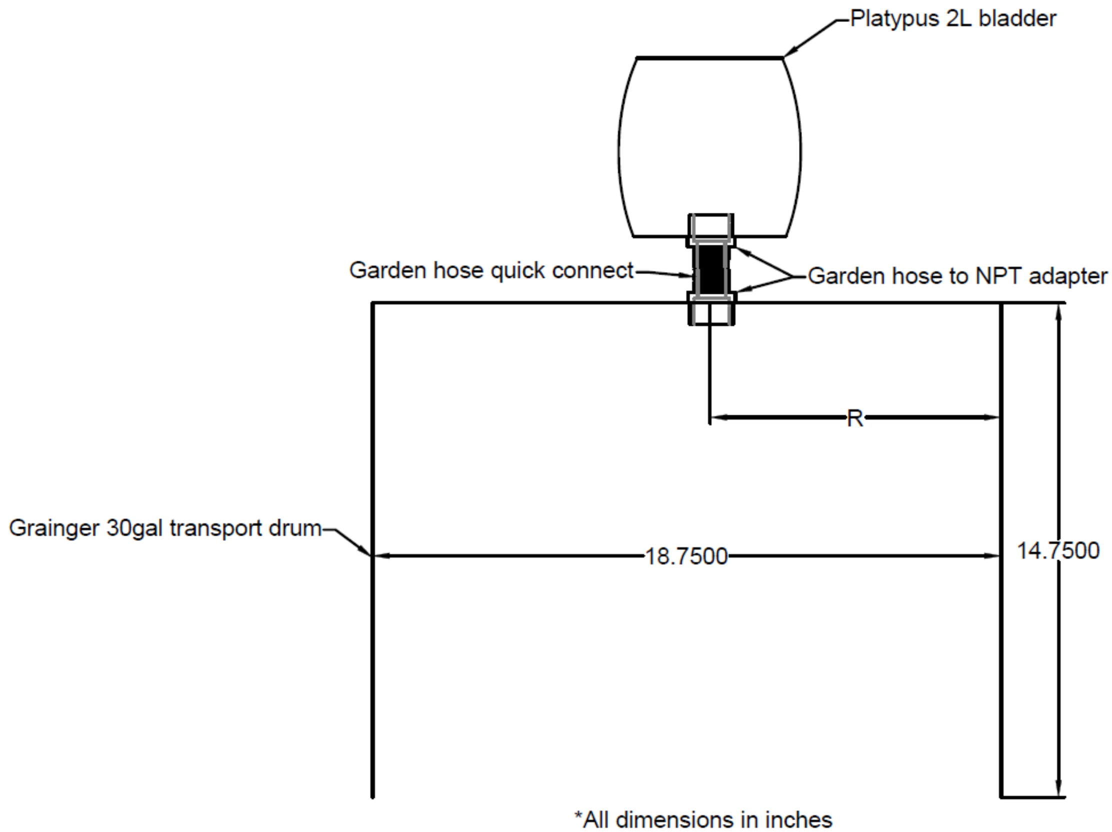

Figure 4. Schematic of full-scale seepage meter.

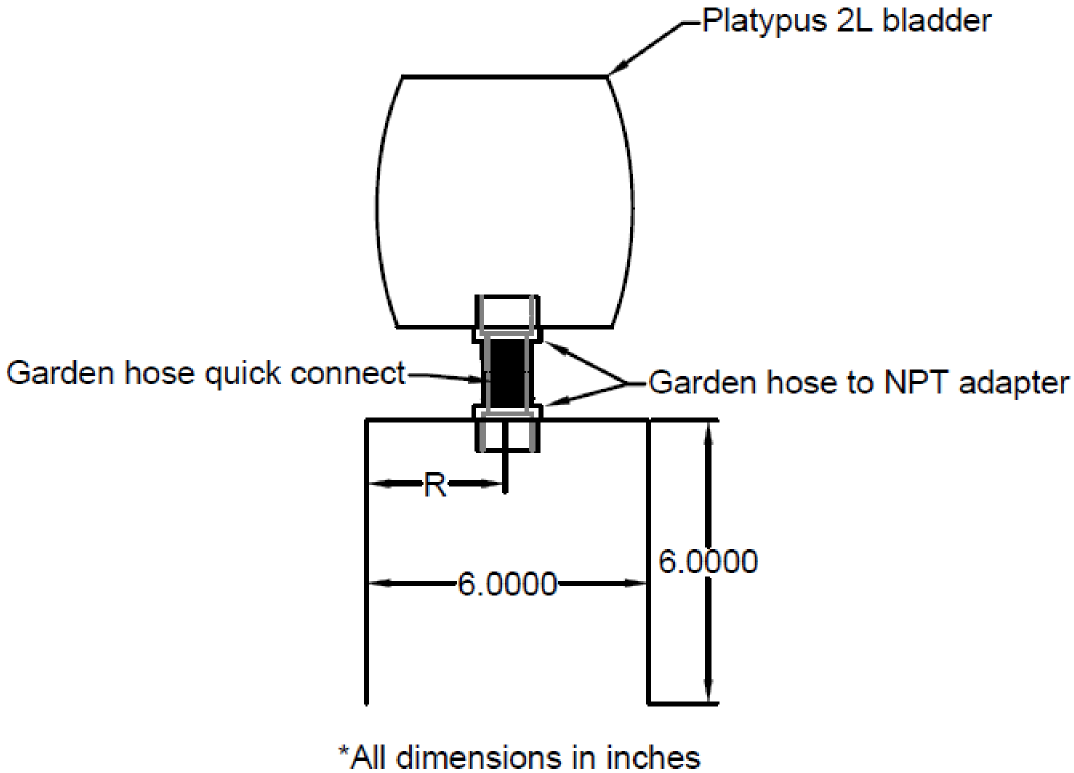

Figure 5. Schematic of scale-model seepage meter.

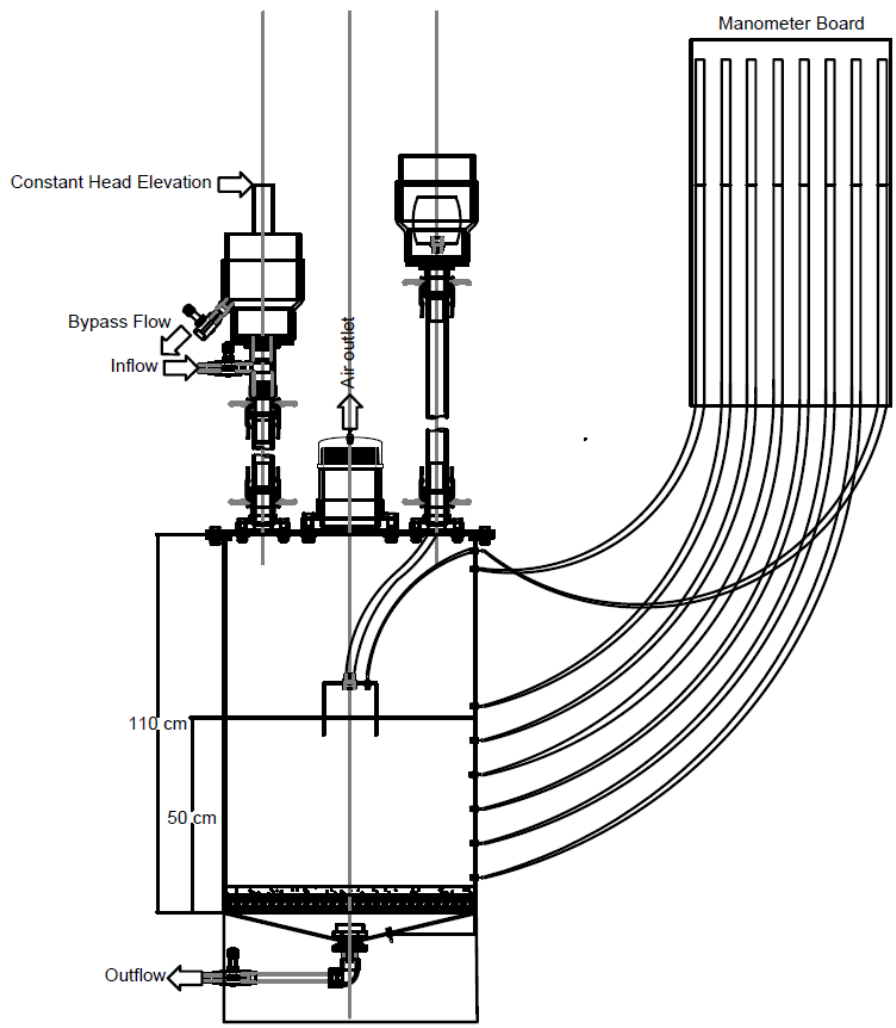

Figure 6. Schematic of seepage flux tank with lid on.

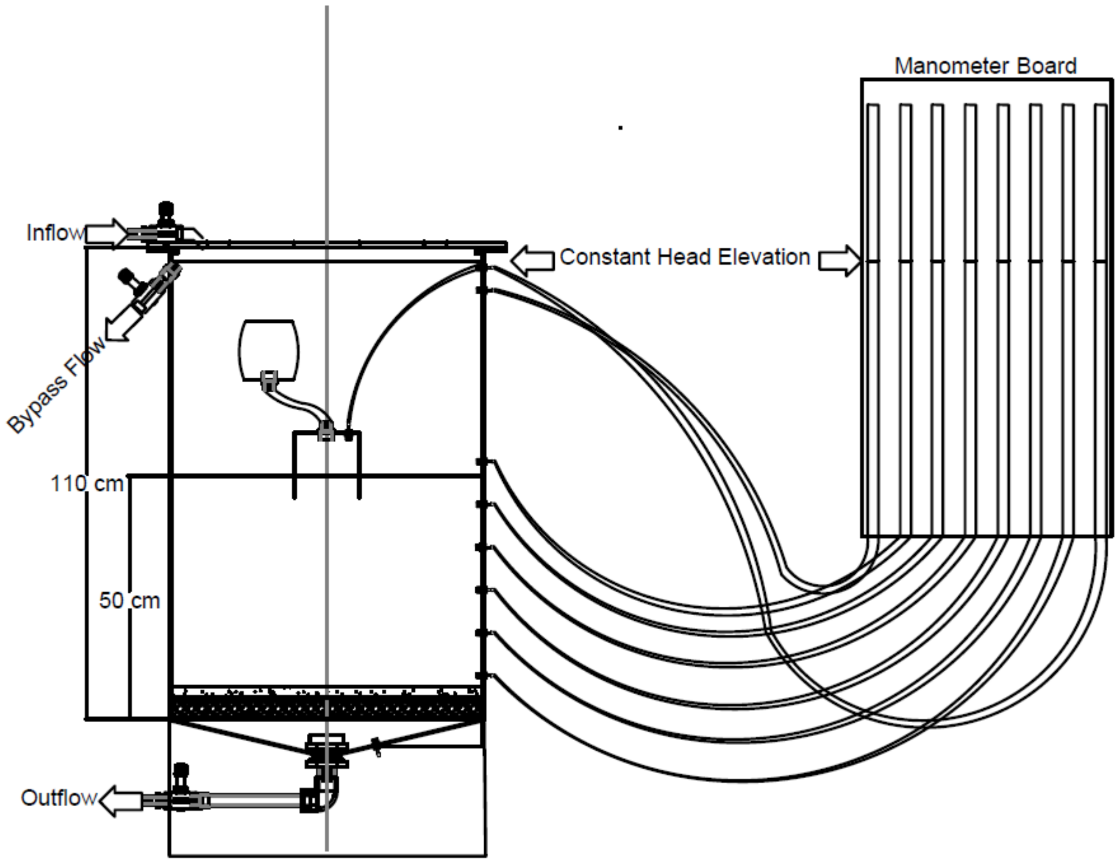

Figure 7. Schematic of Seepage Flux tank with lid off.

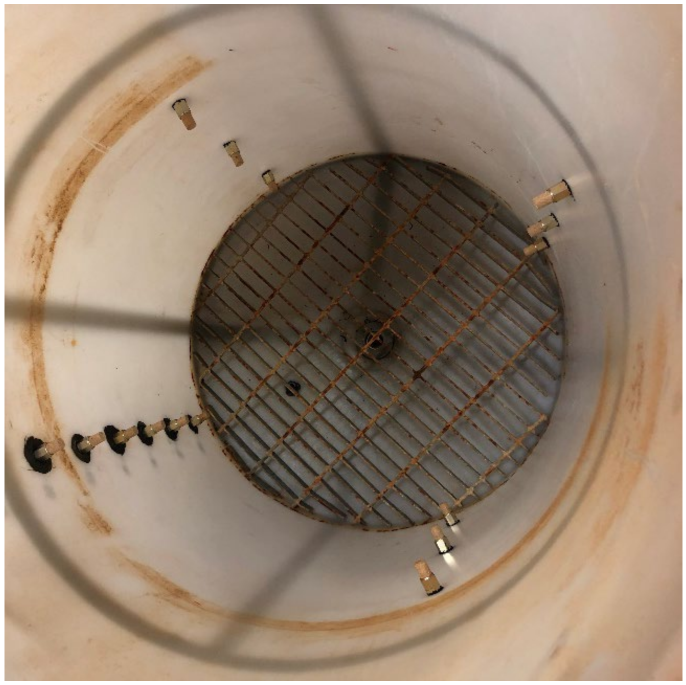

Figure 8. Metal grate placed at the base of the seepage flux tank.

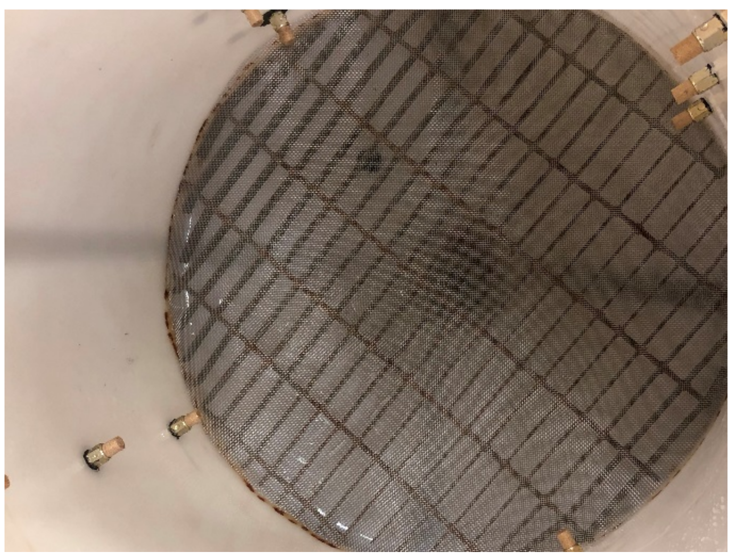

Figure 9. Steel mesh to prevent passing of coarse sediment.

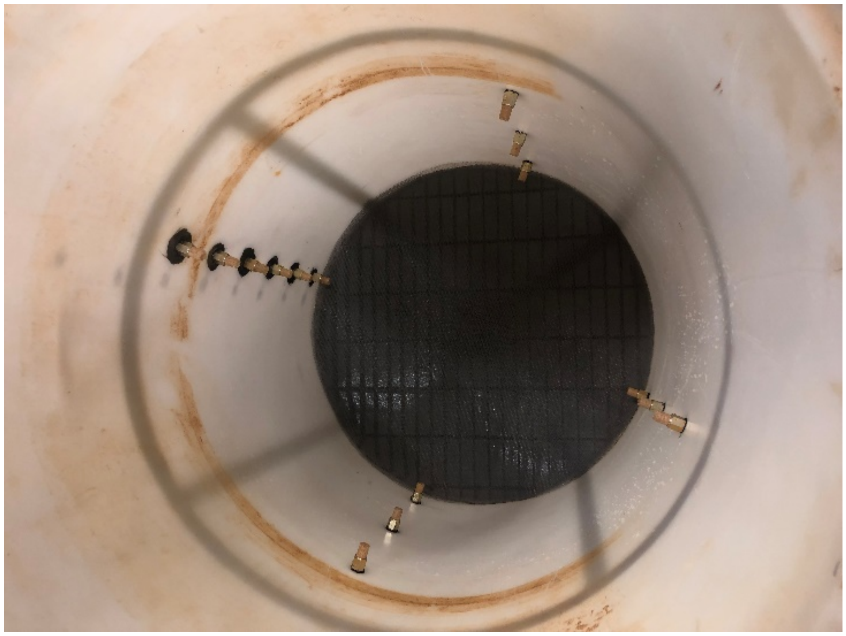

Figure 10. Two layers of bug screen to prevent passing of fine sediment.

Figure 11. Pea-gravel placed to stop passing of coarse sand.

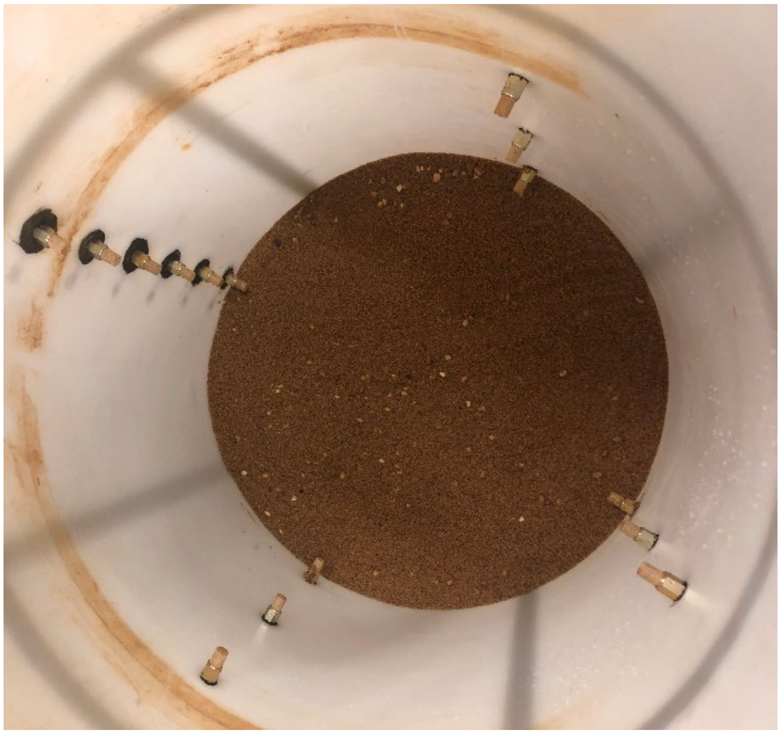

Figure 12. Coarse sand to prevent passing of fine sediment.

Figure 13. Tank filled with testing medium.

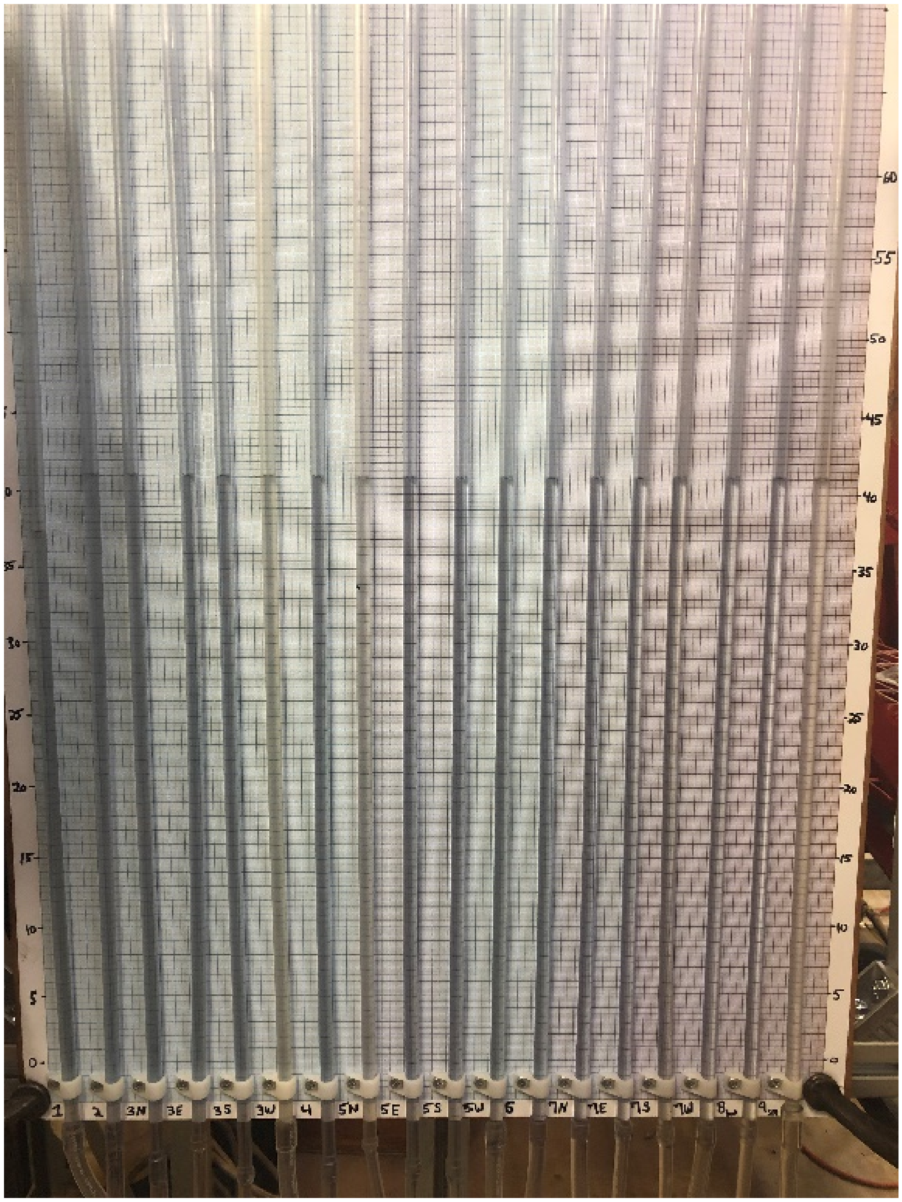

Figure 14. Manometer board attached to seepage flux tank.

Figure 15. Scale model seepage meter placed in seepage flux tank.

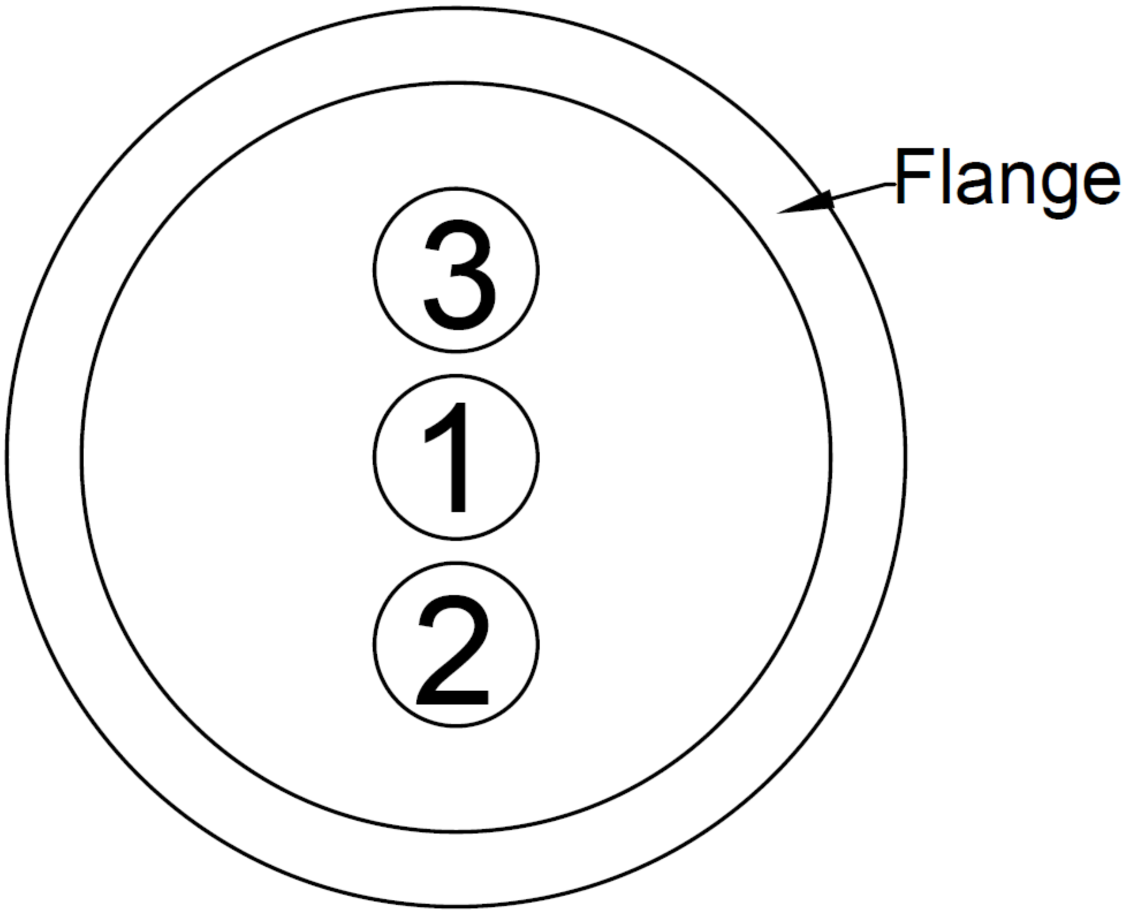

Figure 16. Seepage meter testing locations within the seepage flux tank.

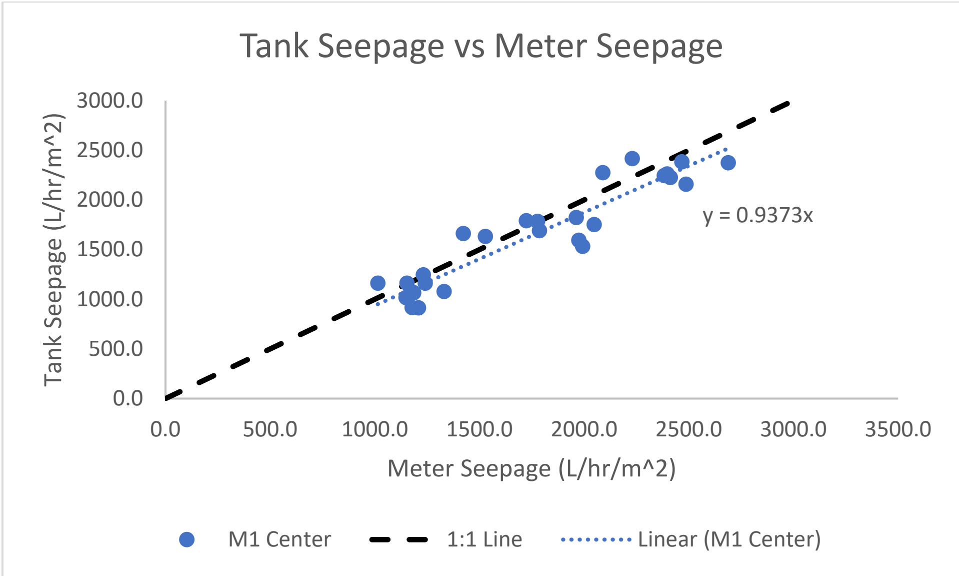

Figure 17. Tank Seepage vs Meter Seepage for M1 center.

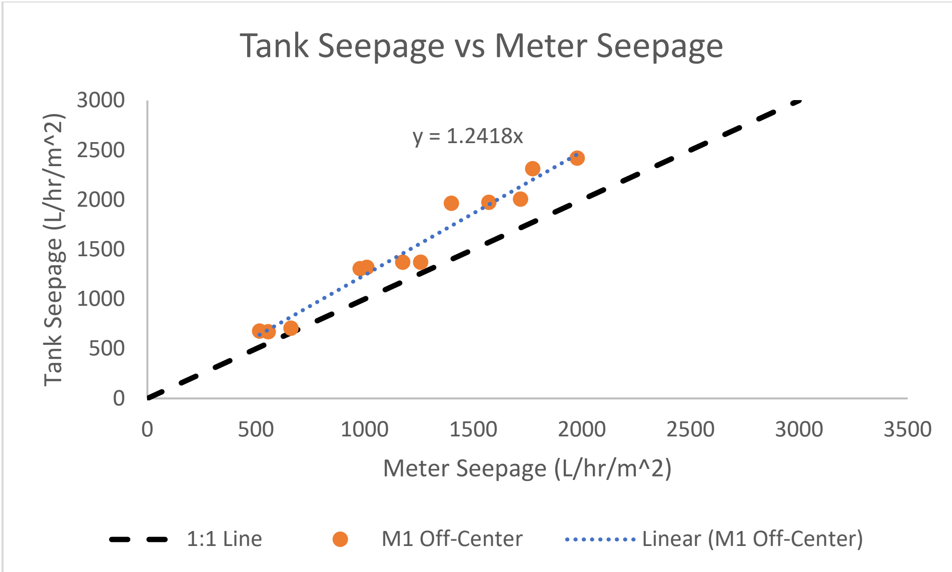

Figure 18. Tank Seepage vs Meter Seepage for M1 off-center.

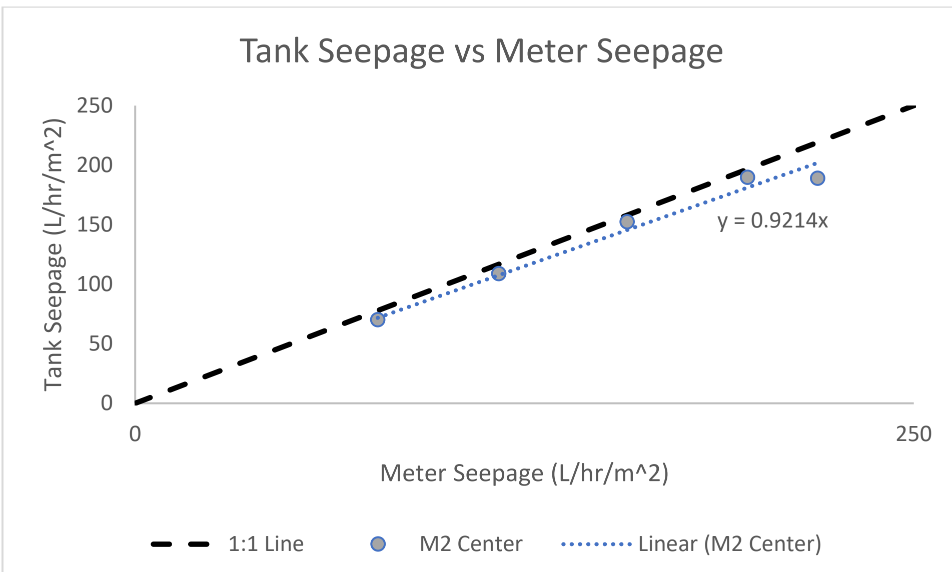

Figure 19. Tank Seepage vs Meter Seepage for M2 center.

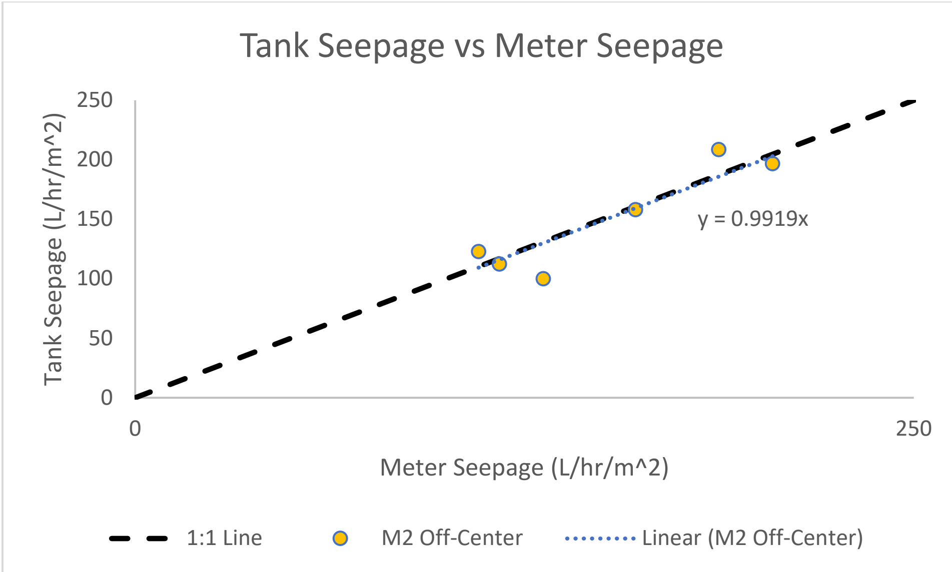

Figure 20. Tank Seepage vs Meter Seepage for M2 off-center.

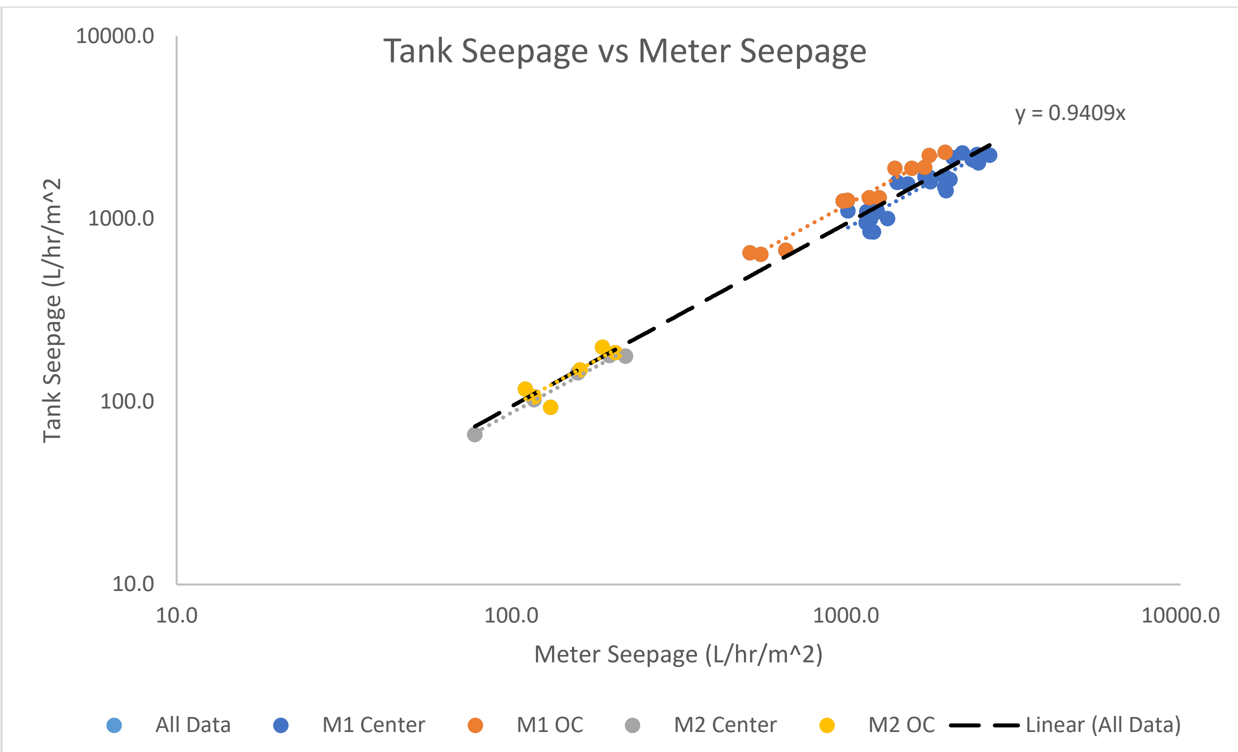

Figure 21. Tank Seepage vs Meter Seepage for All Data.

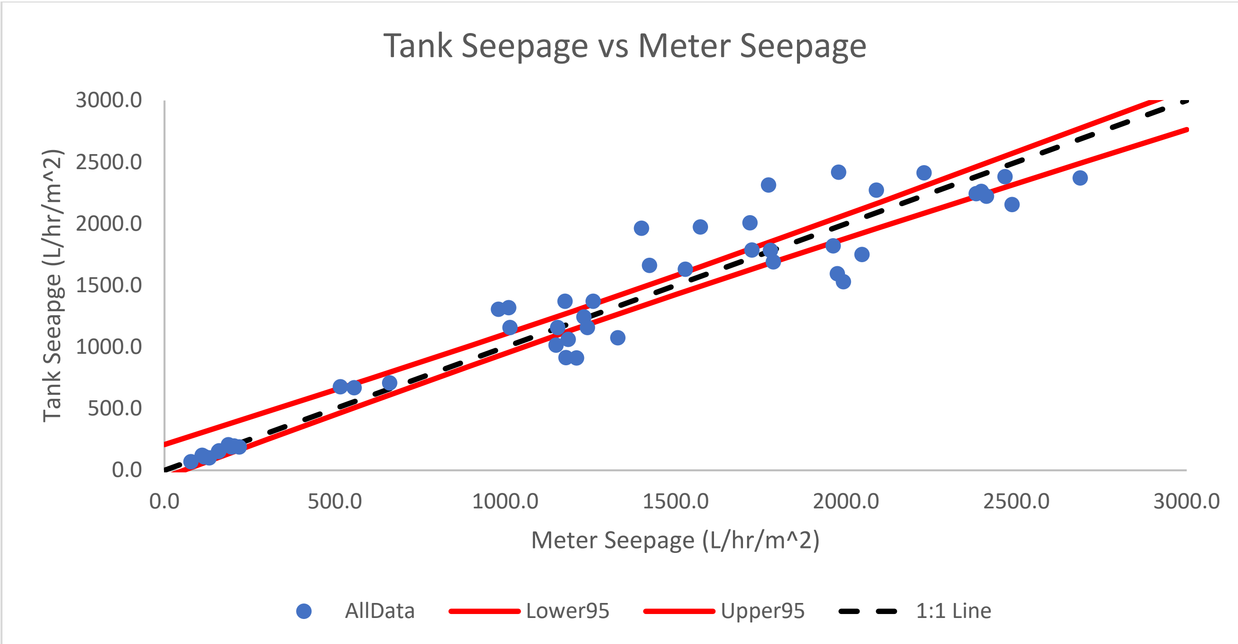

Figure 22. 95% Confidence Interval for the Linear Regression of M2 data forecasted over all data.

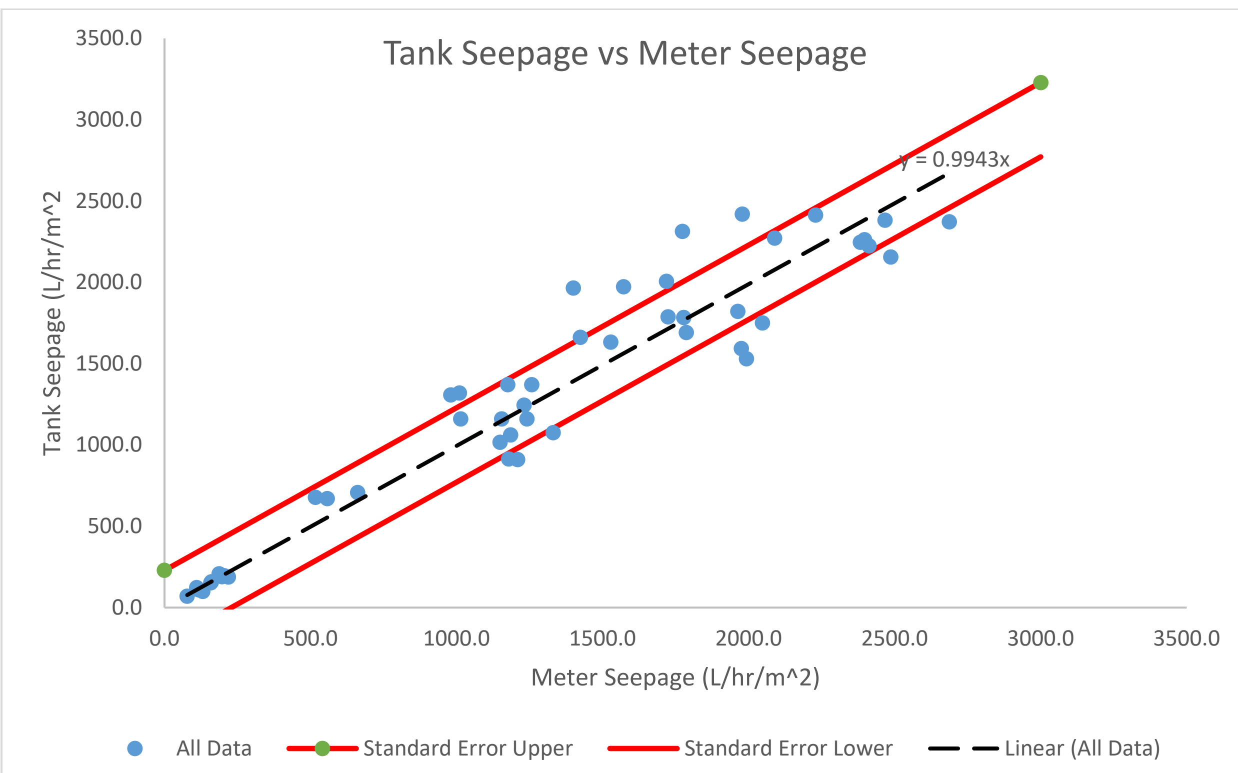

Figure 23. Standard Error of Individual Seepage Measurements.

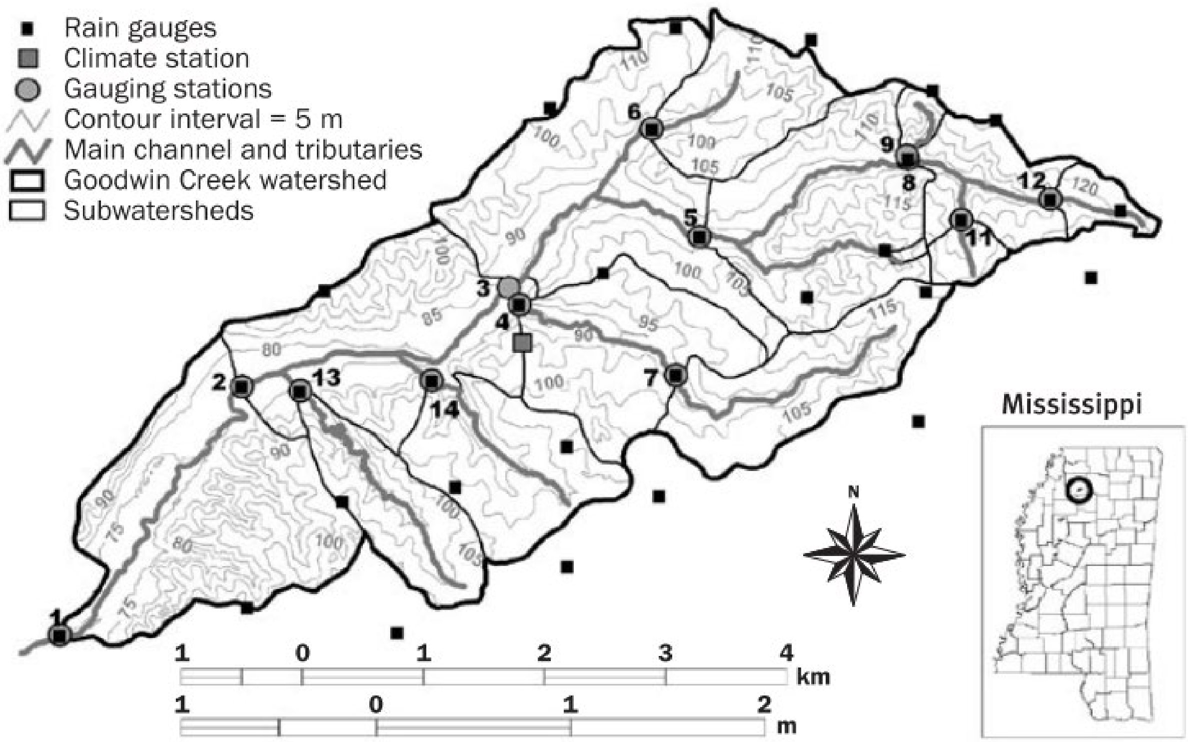

Figure 24. Map of GCEW with elevation contours, station numbers, and rain gauge locations (Kuhnle et al., 2008).

APPENDIX B

Parts List for Seepage Meters

Parts List for Seepage Meters

Full Scale Seepage Meter

1. Grainger 30-gallon steel closed head transport drum
2. Garden hose to National Pipe Thread adapter
3. Garden hose quick connect kit
4. Platypus 2-Liter bladder
5. Brass gooseneck with shutoff valve

Scale-Model Seepage Meter

1. 6-inch thin-walled steel pipe
2. ½-inch sheet of PVC cut to 6-inch circle to cap one end of the steel pipe
3. Garden hose to National Pipe Thread adapter
4. Platypus 2-Liter bladder
5. Brass gooseneck with shutoff valve

APPENDIX C

Setup of the Seepage Flux Tank

Determining Seepage through the Meter (S_{SM})

Determining Tank Seepage (S_T)

Setup of Seepage Flux Tank

1. Set the constant head level at the desired location above the tank flange, verify that all manometers are reading the same head in the tank.
2. Open the valve at the base of the seepage flux tank until you reach the desired head gradient and/or tank discharge.
3. Allow water to flow through the tank for at least 30 minutes prior to testing to allow manometer readings to stabilize.

Determining Seepage through the Meter (S_{SM})

1. Fill the two-liter bladder to or near the two-liter mark and seal it ensuring that no air is present inside. Weigh the bladder and record the initial weight (M_I).
2. Insert the bladder into the reservoir opposite the constant head tank with the nozzle inverted and attach the bladder to the hose.
3. Simultaneously open the valve on the bladder and start a timer.
4. Allow flow through the bladder for 3-20 minutes, depending on the seepage tank discharge, the constant head elevation, and the testing medium.
5. Close the valve on the bladder and stop the timer.
6. Record the amount of time that flow was occurring from the bladder (T).
7. Weigh the bladder and record the final weight (M_F).
8. Repeat at least five times.
9. Calculate bladder discharge ($Q_{B1...}Q_{B5}$) using

$$Q_B = \frac{M_I - M_F}{T}$$

where M_I is the initial weight of the bladder, M_F is the final weight of the bladder, and T is the time of testing.

10. Calculate the mean bladder discharge (Q_{Bmean}) from $Q_{B1}...Q_{B5}$.
11. Convert Q_{Bmean} to meter seepage rate (S_{SM}) using

$$S_{SM} = \frac{Q_{Bmean}}{A_{SM}}$$

where Q_{Bmean} is the mean bladder discharge and A_{SM} is the cross-sectional area of the seepage meter.

Determining Tank Seepage (S_T)

1. Using a graduated cylinder, catch a sample volume from the tank's drain for a known amount of time. Record each sample volume.
2. Repeat at least five times to minimize the error associated with the tank outflow rate.
3. Calculate tank discharge (Q_T) using

$$Q_T = \frac{V_{mean}}{T}$$

where V_{mean} is the mean volume of water captured in the graduated cylinder and T is the amount time the sample was collected.

4. Convert tank discharge (Q_T) to tank seepage (S_T) using

$$S_T = \frac{(Q_T - Q_{Bmean})}{A_{EFF}}$$

where Q_T is tank discharge, Q_{Bmean} is mean bladder discharge, and A_{EFF} is the effective seepage area within the tank.

APPENDIX D

Calculation of Losses within the Seepage Flux Tank

Calculation of Losses within the Seepage Flux Tank

1. Determine difference in head inside the seepage meter using

$$dh = h_O - h_I$$

where h_O and h_I are the heads outside and inside the seepage meter, respectively.

2. Determine the head loss due to friction in the pipe (h_L) using the Darcy-Weisbach equation using

$$h_L = f_D \frac{L}{D} \frac{V^2}{2g}$$

where f_D is the Darcy friction factor, L is the length of pipe in meters, D is the hydraulic diameter in meters, V is the fluid flow velocity through the pipe, and g is acceleration due to gravity.

3. Calculate local losses (L_L) using

$$L_L = dh - h_L$$

where dh is the difference in head inside and outside the seepage meter and h_L is the head loss due to friction in the pipe from the Darcy-Weisbach equation.

APPENDIX E

Operation of Seepage Meter

Operation of Seepage Meter

1. Fill the two-liter bladder approximately half-way with water and record the initial weight (M_I).
2. Seat the seepage meter in the desired location in the bed of a wadable stream.
3. Insert the bladder into the stream with the nozzle inverted and attach the bladder to the seepage meter.
4. Simultaneously open the valve on the bladder and start a timer.
5. Allow flow through the bladder for 30 to 60 minutes.
6. Close the valve on the bladder and stop the timer.
7. Record the amount of time that flow was occurring from the bladder (T).
8. Weigh the bladder and record the final weight (M_F).
9. Calculate the seepage flux rate using

$$Q = \frac{(M_I - M_F)}{T * A} \left[\frac{L}{hr * m^2}\right]$$

   where M_I is the initial weight of the bladder, M_F is the final weight of the bladder, T is the time that flow occurs to/from the bladder, and A is the cross-sectional area of the seepage meter.

10. Apply the correction factor from the laboratory experiments to the seepage flux rate measured in the field.

APPENDIX F

Comparison of Field Seepage Measurements to Seepage Estimates

Comparison of Field Seepage Measurements to Seepage Estimates

Average seepage between Stations 1 and 3 = 2.435 L/hr/m^2

Length of reach between Stations 1 and 3 = 5,400 m

Average width of the channel = 6 m

Seepage contribution between Stations 1 and 3 = 78,894 L/hr or 0.022 m^3/sec

Difference in discharge between Stations 1 and 3 = 0.023 m^3/sec

VITA

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