ABSTRACT

Interaction Between Floodplain Groundwater and a Constructed Wetland,
North Central Texas

Laura K. Foss, M.S.

Thesis Chairperson: Joe C. Yelderman, Jr., PhD.

The primary goal of this study was to investigate the groundwater conditions and the potential for interaction between groundwater and surface water at the East Fork Wetland Project. In order to prepare for that investigation, a study of the water budget was conducted to gain an understanding of the wetland system as a surface water system. Infiltration became both a term in the water budget and also a measurable aspect of interaction between groundwater and surface water. The water budget was found to balance in confined timeframes, but discrepancies compounded as the timeframe was extended. Groundwater was found to have a west to east gradient and the subsurface investigation indicated discontinuous lenses of more permeable (sandy) materials than the clays typical of the floodplain. Interaction between groundwater and surface water is supported by water chemistry analysis, evidence of groundwater recharge, and seepage events measured in the field.

Interaction Between Floodplain Groundwater and a Constructed Wetland, North Central Texas

by

Laura K. Foss, B.A., M.A.

A Thesis

Approved by the Department of Geology

Steven G. Driese, Ph.D., Chairperson

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Approved by the Thesis Committee

Joe C. Yelderman, Jr., PhD., Chairperson

Peter M. Allen, PhD.

Joseph D. White, PhD.

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J. Larry Lyon, Ph.D., Dean

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CHAPTER ONE

Introduction

From Kansas south into Mexico and from the Mississippi River west to California the U.S. is experiencing a series of severe droughts that are expected to continue for several years. Because of this, the need for a source of clean and plentiful water has rarely been of such concern to citizens in both urban and rural communities. One answer to this problem is found in the use of constructed wetlands to pretreat and reuse water from existing sources. Water from effluent dominated stream flow is diverted into a wetland where it first flows through settling basins that provide initial sedimentation, followed by passage through vegetated cells that filter the water with natural biological and chemical processes. Constructed treatment wetlands are intended to improve raw water quality with this filtration process which polishes the water by removing contaminants, thereby providing a cleaner source for final stage municipal treatment and eventual public consumption.

The constructed wetland at the East Fork Wetland Project (EFWP) was designed for the North Texas Municipal Water District (NTMWD) for just such a purpose: to provide partially treated water for a municipal water supply system. Water from the East Fork of the Trinity River is pumped into the wetland where it travels south by gravity flow through settling basins and a series of vegetated cells. At the completion of the wetland process the now polished water is piped north to a water treatment facility for final purification, storage, and distribution for public consumption in north central Texas. While the idea of improving upon stabilization ponds and lagoons with wetlands as a sink for contaminated water is not new (Brix, 1994; Kadlec and Knight, 1996), the construction of vegetated wetlands is becoming more feasible and more common as their success improves with public perception and with predicted savings.

Key to the efficient management of a constructed wetland is a balanced water budget (Kadlec and Wallace, 2009). The water budget is necessary to calculate flow residence time and water volume produced (as is the wetland's main purpose), and the budget is also important to monitor and possibly adjust due to changes in potential interaction between surface water and groundwater. The water budget of a constructed wetlands system consists primarily of a well-controlled inflow and a somewhat less controlled outflow. The uncontrolled aspect of outflow as evaporation, transpiration, and infiltration combined can be a significant quantity. Evaporation and transpiration are influenced by weather (seasonal conditions of wind, precipitation, temperature), vegetation (type and quantity, presence and absence); and diel fluctuations (changes during the day compared to night). Infiltration – the interaction between surface water and groundwater – is influenced by soils and underlying sediments; infiltration is both a term in the water budget and also a measurable aspect of interaction between groundwater and surface water. Water budgets are studied and planned during initial wetland construction, but they tend to change over time as the wetland becomes an established feature of the local environment (Nungesser and Chimney, 2006; Favero and others, 2007).

The East Fork Wetlands Project is recently operational (as of 2009) and its day to day management and efficiency with water flow and volume produced depend on a clear understanding of the water budget. Currently evaporation and transpiration are assumed to be the two primary components of the uncontrolled outflow and are accounted for in the monitoring of productivity at EFWP. Transpiration and evaporation are notoriously difficult to measure due to issues with logistics and equipment, oftentimes estimates made for water budgets rely on off-site fixtures such as lysimeters or applying back-calculation for evapotranspiration (Lott and Hunt, 2001). Infiltration, or seepage, is considered to be nonexistent or negligible because of the thick layer of naturally occurring low permeability clay soils that lie below the wetland cells. Shallow groundwater occurs in the Trinity River alluvial sediments but it not considered an aquifer by the state of Texas (Texas Water Development Board, 2009) and is poorly understood. Studies that have been conducted on the lower Trinity River (mainstem) suggest thick continuous soils deposited throughout its floodplains, but also imply that the depositional patterns (specifically noted on the lower Trinity) were also influenced by channel migration and shifting point bar deposition, extensive erosion that shifted alluvial materials collected previously, and increased sediment load due to human activity (Phillips and others, 2004). These observations may be generalized to some effect to the upper river system in that the upper river system experienced a similar geologic history as the lower Trinity due to its geographic confinement to the 18,000 square miles of the Trinity River watershed (see Figure 1, below). The EFWP was constructed in the floodplain of the East Fork and overlies Trinity Clay soil, but borings completed prior to this construction (Geotech Report, property of NTMWD) indicate layers of more permeable and larger sized sediments below the soil that could affect seepage. The water budget at this wetland is an ongoing concern, with the surface water to groundwater exchange also being of interest now that the project has been in use for its first few years.

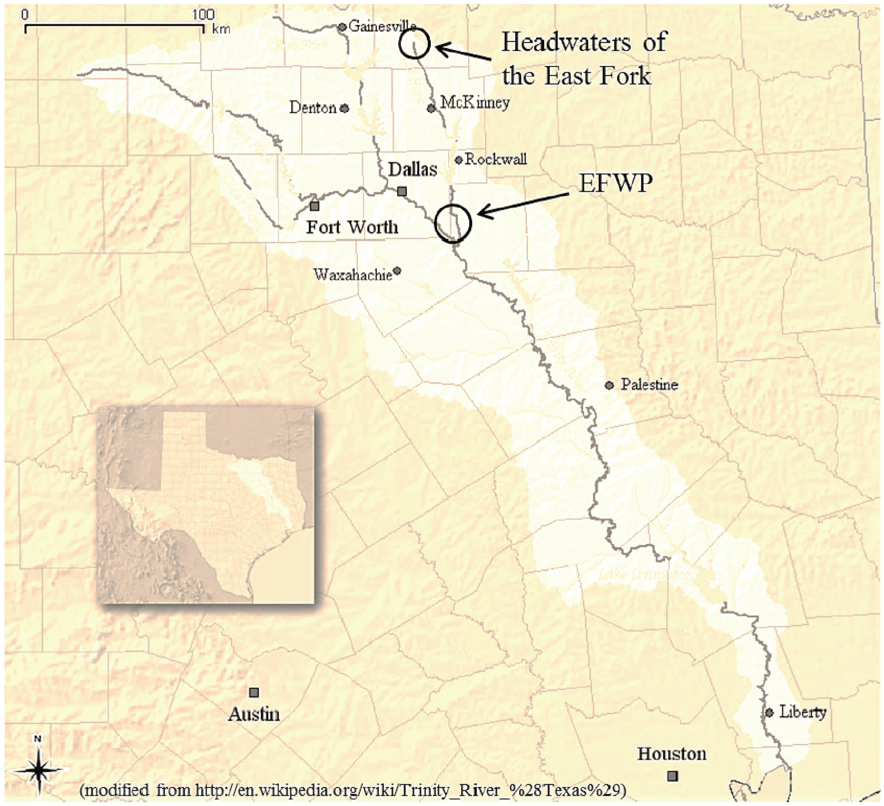


Figure 1. Trinity River, basin and location of EFWP.

This study investigated the water budget and hydrogeologic conditions of the wetland. The hydrogeologic portion of the study site was intended to increase baseline information regarding groundwater and its interaction with the wetland surface waters in terms of recharge, leakage, and water quality. The hydrogeologic investigation required installing piezometers throughout the wetland area to observe groundwater flow through the alluvial sediments. This shallow groundwater flow system may have an impact on the relationship of the wetland to the floodplain and the infiltration term of the water budget. For the water budget portion of the study there is evaporation which may be monitored within the cell water; there is transpiration that can be measured; infiltration detection may be gained with use of a seepage meter; and there is a gaged flow in from the river and out to the reservoir. These physical aspects of a water budget may be measured in terms of seasonal and diel differences as well as differences between vegetated and non-vegetated coverage in the cells. The information from the water budget and hydrogeologic study combine to provide further understanding for improved efficacy of the constructed wetland water. The EFWP currently serves as a water source for a rapidly growing population and is one of several wetland water treatment projects applying the basic ideas behind this innovative approach to limited water resources. Currently, a study is being conducted at Richland-Chambers reservoir to the south of EWTP and it confirms the importance of a careful water budget as crucial to success (Kadlec and others, 2011).

The measurements taken for this study required a set of fixtures to be designed, built, and deployed. All supplies were clean, primary source materials; metal staking and protective measures were used throughout the study to mitigate damage from/to wildlife; and a decommission plan was designed to remove all fixtures from the site. Care was taken to minimize impact on the environment as it eventually serves as a municipal water source. Field work and data collection were conducted between December 2011 and September 2012.

CHAPTER TWO

Site Description

The study site is a 1840 acre constructed wetland in north Texas (see Figure 2, below). Its geomorphologic setting is within the East Fork Trinity floodplain and local hydrology consists of drainage ditches that protect the wetland from upslope drainage and several stock ponds that were in use into the 1980s. The wetland is comprised of three sets of cells (26 total cells) that are fed by diverting river water through canals inter-connected with sluice gates and agri-drains. The land is privately owned; wetland management is under the supervision of a local environmental consulting group; and water management is on the authority of the North Texas Municipal Water District.

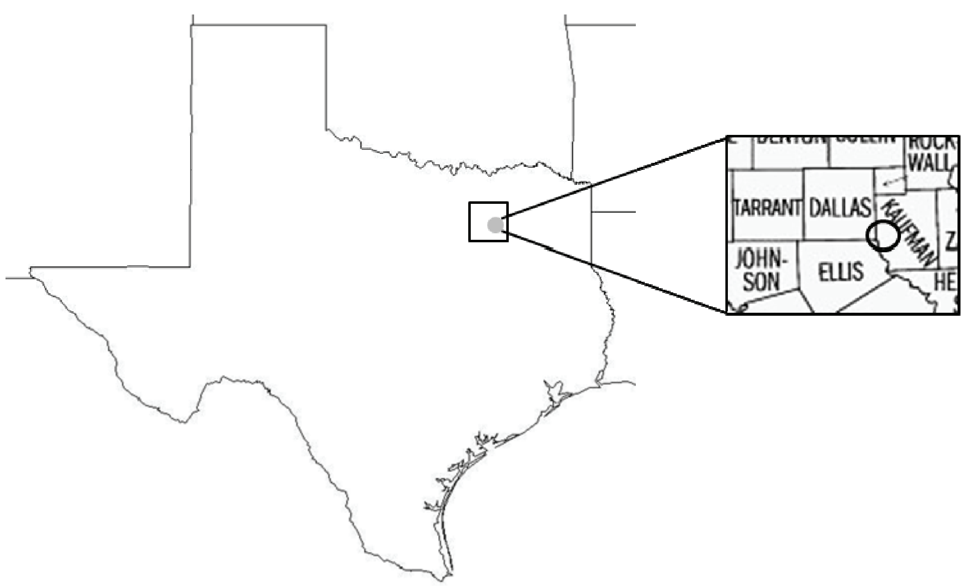


Figure 2. Regional location map for EFWP.

Source waters for the wetland originate in Grayson County Texas at the headwaters of the East Fork of the Trinity River, approximately 60 miles north of the East Fork Wetland Project. The East Fork of the Trinity River travels south out of Grayson County and flows into and out of Lavon and Ray Hubbard reservoirs; there are six wastewater treatment plant inflow points in the watershed. The East Fork passes through Late Cretaceous formations Woodbine Sand, Austin Chalk limestone, and Eagle Ford shale. Approximately 10 miles south of Ray Hubbard a portion of the river is diverted into the wetland project in Kaufman County.

The wetland, although designed to be a water polishing system, has also become a refuge for resident and migratory birds and for animal populations both terrestrial and aquatic. The wetlands has a public center (the John Bunker Sands Wetland Center) for outreach and education, which has been instrumental in creating a positive relationship with the surrounding communities. The EFWP overlies the floodplain of the East Fork of the Trinity River which, prior to the rapid growth of north Texas urban development, was an ephemeral stream but is now perennial, supplied primarily with secondary-treatment effluent from the Dallas metroplex area. Historically the surrounding plain experienced seasonal flooding; appropriately, the EFWP was constructed on the footprint of the floodplain. The predominant soils in the floodplain are very deep, moderately well drained Trinity Clay (very fine, smectitic, thermic Typic Hapluderts) on a very slight slope, on average 1% (USDA, 2012). The surrounding, original vegetation is bottomland scrub and grassland and local agriculture is typically row crops and cattle. Construction of the wetland was complete in 2009 and has been in operation continually since that time, supplying water as is-needed per height of local lake levels.

CHAPTER THREE

Methods

The EFWP is considered an emergent macrophyte system with free-water surface flow. Constructed wetlands that are free-water surface by definition depend on an intentionally flooded area where the water surface is exposed. Therefore free-water surface wetlands require a sound understanding of the water budget and the impact of the wetland interaction to the groundwater must be carefully studied (USEPA, 2000). Data are available from U.S. Geological Survey (USGS) regarding precipitation and stream discharge (USGS, 2012); from Texas Water Development Board regarding lake evaporation rates (TWDB, 2009); and from the USDA regarding infiltration rates for the local Trinity Clay and transpiration rates for major macrophyte species (USDA, 2012). Therefore a wetland water budget can be considered using generalized historic data to fit the standard water budget equation: INFLOW = OUTFLOW ± STORAGE where INFLOW consists of diversion source water, precipitation and runoff, and where OUTFLOW consists of evaporation, transpiration, infiltration, and water conveyance. Storage is that quantity within the cells during residence time. But there is also value found in direct access measurements independently taken on site with a focused and specific perspective in order to mitigate erroneous application of the generalized information. This study applied the direct measurement approach using fixtures built to fit the environment and deployed to measure evaporation, groundwater fluctuation, and seepage detection; with standard fixtures that can be purchased for field studies such as weather monitoring, surveying and in situ gas exchange monitoring; and establishing permanent groundwater monitoring piezometers that may be either passively logged with a pressure transducer or actively bailed and developed for chemical analysis and flow studies.

Weather conditions were monitored with a Davis Vantage Pro2 weather station placed at the Wetland Center campus. The station began collecting data in December of 2011 and was in operation throughout this study. Precipitation, wind speed, and temperature were measured and recorded, and then reported through a link to a console residing in the center. Seasonal weather patterns were documented throughout the duration of the study and combined with each aspect of the investigation. Precipitation was the primary focus of the station; the mechanical parts of the station rain collector were checked periodically with a known volume of water released into the tipping buckets and verified for accuracy on the recording console.

Evaporation was measured in the wetland cells winter through summer. Evaporation is typically measured with land pans set on dry land or modified to float (Masoner and others, 2008), but cost and logistics were somewhat prohibitive for Class A pans in this environment. Also, wildlife interference and open water combined with winter and spring storms could potentially result in damaged and/or overturned fixtures. For these conditions, the data were collected using a 5-gallon utility bucket. Four stakes were driven into the cell floor to surround the bucket and ties were attached through the handle, thereby assuring some measure of stability in the wetland environment (see Figure 3, below). The bucket contained a known volume of water and it floated with rising or falling cell water levels to gain a similar exposure to that of the wetland cell water surface. A pressure transducer (Global Water WL16) was placed in the water inside the bucket to monitor fluctuations in the volume of water as it was influenced by the surrounding conditions of wind, sun, temperature, and humidity. Confirmation of the recorded fluctuations were made with direct manual measurements. Initial quantity of water in the bucket was 4 gallons and depth to water surface consistently measured at the same marked place on the bucket. Another pressure sensor was placed into the main wetland cell water to record fluctuations in water level per inflow/outflow; all data were recorded with battery operated data loggers sleeved and staked on the cell bank. Evaporation rates were monitored in three different settings within the wetland cells: in open water, in partially vegetated areas and in densely vegetated areas.

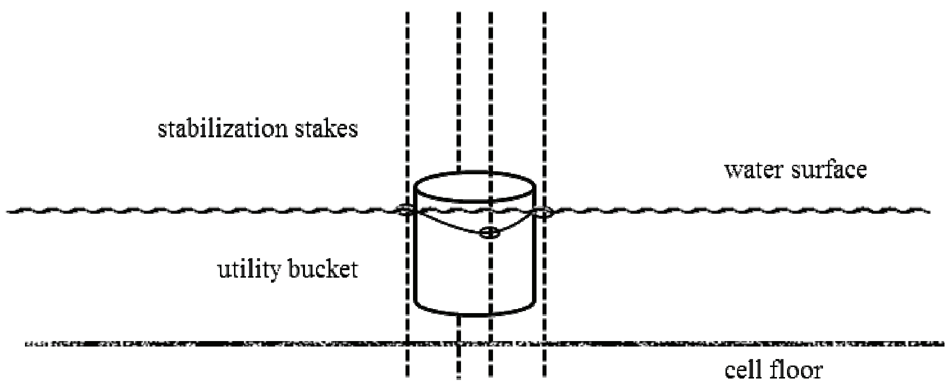


Figure 3. Evaporation station set-up.

Light readings were taken with a handheld photosynthetically active radiation (PAR) meter (Apogee BQM) in cold season (February) and in hot season (June) on cloudless days at the selected locations monitored for evaporation rates. Six readings above the evaporation set-up, at vegetation tips, and six readings at the water surface (both in a roughly hexagonal pattern) were taken for each of the evaporation stations. Vegetation counts were taken at the same time light readings were taken using a 1 m^2

quadrat. At the time the buckets were emplaced (January, February) the only intact vegetation was giant bulrush (in overwinter dormancy), the vegetation counts at this time are therefore entirely of this species.

Transpiration rates were measured directly on site with a CO_2/H_2O gas analyzer (CI-340 Handheld Photosynthesis System by CID). Six species of emergent vegetation were selected as the most abundant wetland plants (*Pontederia cordata*, pickerel weed; *Typha domingensis*, cattail; *Schoenoplectus californicus*, giant bulrush; *Schoenoplectus tabernaemontani*, softstem bulrush; *Nelumbo lutea*, american lotus, and arrowhead *Sagittaria spp*.) and were measured both at first appearance in spring and in mature growth in the summer. The number of trials to establish stratified sampling was decided upon by local abundance of each plant. Transpiration rates were used to scale up from individual leaves to vegetation coverage over the entire wetland.

Field recording of gas exchange rates (E) were reported from the device and were used with the actual leaf sections enclosed in the cuvette which were clipped and returned to the lab, scanned and measured for area of the exposed leaf (A). Area is adjusted per device default

$$A_{adj} = A_l/2 \qquad (1)$$

Where both values are in cm^2 and A_{adj} is now unitless. E is adjusted with A_{adj} and averaged

$$E_{adj} = A_{adj}*E \qquad (2)$$

$$\bar{E}_{adj} = \sum(E_{adj\ 1}+ E_{adj\ 2}+ \dots E_{adj\ 10})/10 \qquad (3)$$

Where E_{adj} is in $mmol/m^2/s$. $\bar{E}_{adj}$ is scaled up for E values of an entire species leaf

$$\bar{E}_{adj\ (leaf)} = (\bar{E}_{adj} * A_{leaf}) \quad (4)$$

Where $\bar{E}_l$ is in mmol/s. $\bar{E}_l$ is scaled up with mean leaf quantity of individual species per 1 m^2 (as determined by quadrat in the field)

$$\bar{E}_i = \bar{E}_l * N_i \quad (5)$$

Where $\bar{E}_i$ is now in mmol/s per one square meter. Transpiration is calculated for milliliters per second

$$\bar{E}_i * (0.001) * (18.01528 \text{ g } H_2O/1 \text{ mol } H_2O) \quad (6)$$

Where $\bar{E}_i$ is now represented as loss in ml/s. $\bar{E}_i$ may now be considered in terms of daylight hours per season; in terms of days, weeks, or months; and scaled to liters, gallons, or acre-feet as is appropriate. For this study, a rate of liters/day was used to determine a rate for a million gallons per day (mgd) measurement, as this is the rate used by management at the wetland. For example, flow into and out of the wetland was measured and reported by NTMWD in mgd.

The foregoing accounts for individual leaf measurement. However, leaves compound into canopy which creates error in the calculations because of changes to air current, humidity levels, and energy exchange among and between individual leaves. To accommodate for the error in the equations a de-coupling coefficient, omega, was used to correct for leaf scale to canopy scale (McNaughton and Jarvis, 1983).

$$\Omega = (E + 1)/((E + 1 + (ga/ge)) \quad (7)$$

Where E (epsilon) is a seasonally given constant dependent on temperature (the slope of vapor pressure curve / psychrometric constant or s/γ); ga (0.1) is aerodynamic conductance (Jones, 1983) and ge (0.0025) is the leaf conductance (Koch and Rawlik, 1983). For these calculations, epsilon as 2.84 (per 25 °C for spring) and 5.84 (per 40 °C for summer) were used (McNaughton and Jarvis, 1983).

Daily values calculated (ml/s) were then multiplied by Ω for the canopy scale transpiration rate.

Aerial photos (property of Alan Plummer and Associates) and a vegetation survey on site were used for an areal interpretation of the wetland surficial condition, to separate vegetated and non-vegetated spaces; to determine percentage or extent of vegetation coverage, species and growth patterns; and to differentiate between seasonal coverage. These interpreted percentages were then used to scale up transpiration values to the entire wetland. Total acreage for the wetland is published at 1840, measurement of the cells' footprint was calculated to 1636 acres. The figure of 1636 acres used in this study does not include the channeling canals, roads, etc.

Infiltration or seepage flux, is the exchange of water at the interface of groundwater and surface water. Infiltration was monitored and measured with the use of seepage meters. Seepage meters may be constructed using a wide range of quality and sized components, but are basically determined by a chamber to achieve a seal with the sediments connected to a collection bag to monitor the communication between groundwater and surface water (Brodie and others 2009; Lee and Cherry 1978). For this study, seepage meters consisting of a half barrel (55 gallon drum cut in half), connecters (½ inch hose, threaded barbs and ball valve) and a 2.8 liter flexible bag (coffee catering bag with screw lid) were built to withstand long term immersion in the wetland cell (see Figure 4, below). Because of biogenic gas production in the wetland sediments, a gas release tube was attached to the top of the barrel and staked into the cell floor.

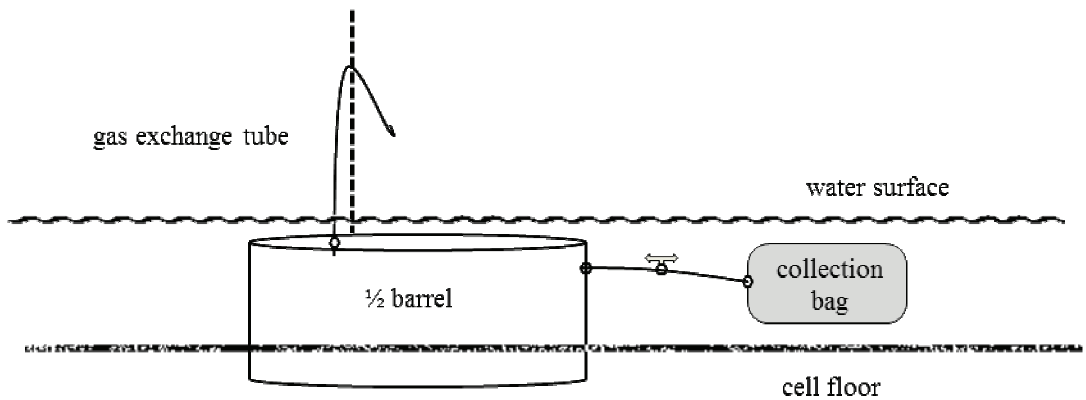


Figure 4. Seepage meter set into wetland cell sediments.

The seepage meter barrel was placed cut edge down and pushed into the sediments 4-6 inches; the hose/valve/hose/bag fixture, with the ball valve closed and the bag protected by a wire mesh basket, extends out into the water. Once the seepage meter was deployed and the seal with sediments secured, the ball valve was opened and the water (one liter) in the bag was in communication with the wetland waters in the barrel. Volume of water in the bag was measured at varying intervals of time to record the interaction of wetland cell waters with the underlying sediments. Infiltration is measured with a general equation

$$Q = (v_t - v_i)/tA \qquad (8)$$

Where Q is seepage flux flow, v_t is volume of water in the collection bag after some time, v_i is initial volume, t is time elapsed and A is the area of the chamber, the ½ barrel. Calculations result in a measure of volume of water exchanged per chamber area over time. This rate was used to scale up from chamber area to areas corresponding to cell size. As with the evaporation sets, seepage meters were also placed variously in densely and partially vegetated areas as well as in open water sets to explore the possibility of differences between disturbed and non-disturbed sediments.

Groundwater was monitored with the use of piezometers; drilling was conducted in eight locations on the perimeter of the wetland boundaries. Piezometers were drilled with a trailer mount rig (SIMCO 2400SK-1) using 4 ½-inch solid stem auger. Depth of piezometers was determined both from previously drilled well logs and concurrently with drilling according to materials encountered. Environmental grade schedule 40, 2-inch PVC was set into the 4 ½-inch hole: five feet screened (0.010) at the bottom and solid risers throughout the remainder. Completion was consistent for each of the eight with 20/40 grade sand to cover the depth of screened pipe; remaining annulus fill consisted of alternating layers of bentonite with layers of commercial grade play sand; and mounding at the surface with drill cuttings. Completed wells were developed through initial bailing prior to setting pipe and periodic (weekly) bailing of water from full depth of the screened pipe to extract murky or muddy water residual from drilling activity, until the water cleared. Bailed groundwater and recovery water levels were measured each time to demonstrate individual well response times.

Minipiezometers were used to characterize the sediment immediately underlying the wetland cells. A 5-foot long, ½ inch diameter PVC pipe was inserted into a steel pipe and driven into the sediments approximately 20 inches into the bottom of the cell; the pipe was slotted at alternating ½ inch intervals for three inches at the bottom of the pipe to allow water in but restrict sediment entry. Two minipiezometers were placed near the seepage meter sets in both the west and the east cells for a total of four minipiezometers. A staff gage was used to determine relative fluctuation in the cells, also in proximity to the seepage meters.

Water samples were collected for chemical analysis after the piezometer had been developed and established. Groundwater from the eight piezometers was sampled 24 hours after being bailed extensively to ensure the sample contained fresh groundwater. Groundwater was removed with a standard PVC bailer and care was taken to eliminate cross contamination between sampling by rinsing the bailer and bailer cord several times with deionized (DI) water. Sediment water was sampled from the minipiezometers residing in the midcells (west side and east side) using a flexible tube and a syringe. Water samples were taken from four surface-water locations: from a settling basin, two from the midcells (west side and east side), and one from the south cells near the conveyance station. Each sample was tested in the field for electrical conductance, pH and temperature. The samples were returned to the lab, diluted and prepared for analysis of anions and cations in a capillary electrophoresis (CE) instrument (Waters Quanta 4000). Dilutions of sample water for CE analysis were based on EC readings as a measure of the ionic content of the samples. The CE system is designed to separate and identify constituents (anions and cations) in a water sample by the various size-to-charge ratios of species present. Bicarbonate was determined using a charge-balance equation when all results had been reported.

The study site was surveyed using a Trimble GeoXM GPS in conjunction with a high precision antenna and Pro XH receiver. Each of the piezometers, the river, and the midcells were surveyed to establish elevations Height Above Ellipsoid (HAE). The receiving equipment was set to an accuracy of 0.4 meters and the survey was completed during favorable weather (cloud cover) conditions. The surveyed information was used throughout the study to gain information on gradient both surficial and hydrogeologic.

Figure 5. Aerial view of EFWP with fixtures as mentioned above.

CHAPTER FOUR

Results and Discussion

Precipitation in the winter months (December to March) at the Center was recorded at 0.24 meters and that of summer (April to July) was recorded at 0.15 meters. While the recorded results were checked for equipment accuracy, the catchment volume for an area as large as EFWP cannot be known exactly due to variation of rainfall over a larger area. The quantities acquired from the Davis were used to approximate precipitation inputs into the budget (see Table 1, below) over the entire wetland area.

Table 1. Precipitation rates measured by weather station Dec 2011 – Jul 2012

Month	Precipitation (m)	
DEC	0.043	
JAN	0.054	
FEB	0.014	
MAR	0.131	
APR	0.031	
MAY	0.027	
JUN	0.050	
JUL	0.040	
	Total Precipitation (m)	Volume (million gallons)
Winter (Dec-Mar)	0.24	423
Summer (April-July)	0.15	263

The measured monthly rainfall amounts given in Table 1 are lower overall than the those provided by the 30 year averages (US NOAA, 2011). The 30 year average in the north Texas area for the month of January was 0.07 meters and for the month of July was 0.06 meters compared to 0.05 and 0.04 meters for those individual months measured by the

Davis station at the Center in 2012. These measurements suggest a lower than average rainfall for the area, during this study. Given the recorded measurements and the measured area of the wetland cells as 1636 acres, precipitation contributes 423 million gallons during winter months and 263 million gallons in summer months.

Evaporation was monitored 24 hours a day, in both winter and summer months. Winter evaporation rates taken during January and February for data loggers placed in buckets in the midcells ranged from 0.00013 meters per hour (m/hr) to 0.00254 m/hr, and averaged 0.00048 m/hr. These rates were compiled from two placements, one in the northwest corner of the cells and one in the southwest corner. The rates assessed for the northwest corner ranged from 0.00013 m/hr to 0.00254 m/hr, and averaged 0.00098 m/hr. The rates assessed for the southwest corner ranged from 0.00013 m/hr to 0.00076 m/hr, and averaged of 0.00031 m/hr (see Table 2, below).

Table 2. Evaporation rates monitored by pressure sensor data; 1/17-2/24

Cold Weather Evaporation				
Measure	Cell Location	MIN	MAX	MEAN
Rate (m/hr)	4B_SW	0.00013	0.00076	0.00031
Rate (m/hr)	4B_NW	0.00013	0.00254	0.00098
Rate (m/hr)	4B	0.00013	0.00254	0.00048
Loss (mgd)	4B	2.5	50.7	9.5

Summer evaporation rates taken in May and June for data loggers placed in the midcells ranged from 0.00006 m/hr to 0.00381, and averaged 0.00097 m/hr. These rates were also compiled from the two corner placements in the midcells. The rates assessed for the northwest corner ranged from 0.00013 m/hr to 0.00381 m/hr, and averaged 0.00140 m/hr. The rates assessed for the southwest corner ranged from 0.00006 m/hr to 0.00241 m/hr, and averaged of 0.00046 m/hr (see Table 3, below). The winter rates were lower than the summer rates, as expected. The rates recorded for the northwest corner were significantly greater than for the southwest corner. This variation may be the result of predominantly north wind directions and indicates there is potential for error in these measurements.

A midpoint between evaporation rates measured at the two sites was used to extrapolate to the overall wetland area. Calculations for evaporation on open water, winter months, suggest losses of a minimum 2.5 million gallons per day (mgd), maximum 50.7 mgd, and an average of 9.5 mgd. Calculations for evaporation on open water, for summer months, suggest losses of minimum 0.8 mgd, maximum of 48.0 mgd, and an average of 12.3 mgd. Calculated losses for vegetated areas were less than for open water, on average 3.0 mgd for winter and 8.0 for summer. Losses in cold weather months, while less than that of warm weather months on average, have higher potential losses. This may be attributed to decreased amount of open water exposed to evaporative forces due to increasing vegetation coverage in summer months (May, June, July), and to the low humidity and high winds that occur during winter months (January, February).

Table 3. Evaporation rates monitored by pressure sensor data; 5/12-7/12

Warm Weather Evaporation				
Measure	Cell Location	MIN	MAX	MEAN
Rate (m/hr)	4B_SW	0.00006	0.00241	0.00046
Rate (m/hr)	4B_NW	0.00013	0.00381	0.00140
Rate (m/hr)	4B	0.00006	0.00381	0.00097
Loss (mgd)	4B	0.8	48.0	12.3

Evaporation was also monitored manually (see Table 4, below), both in locations with pressure sensors deployed, using manual measurement for calibration, and in those places that were not appropriate for pressure sensor and data logging equipment. In cold weather months, evaporation rates at locations in dense vegetation indicate loss of 0.00008 m/hr while stations in partially vegetated locations indicate loss of 0.00020 m/hr. Partially vegetated stations registered greater loss than those in densely vegetated locations. There were no stations for dense and partial in the northwest location during cold weather measurements. In warm weather months, stations in dense vegetation at the southwest location indicate loss of 0.00008 m/hr. Stations in partial vegetation at the southwest location indicate loss of 0.00023 m/hr. Stations in dense vegetation at the northwest location indicate loss of 0.00043 m/hr. Stations in partially vegetated areas at the northwest location indicate loss of 0.00035 m/hr. Densely vegetated northwest stations registered greater loss than those in partially vegetated locations.

Table 4. Evaporation rates direct measurement

Location	Jan-Feb	May-Jun
SW DENSE	0.00008	0.00008
SW PARTIAL	0.00020	0.00023
NW DENSE		0.00043
NW PARTIAL		0.00035

During cold weather the only available vegetation was giant bulrush. Giant bulrush (round bulrush) is row-planted at EFWP, remains all year, and is dormant in the winter. Evaporation sets placed in densely vegetated locations in the southwest corner were therefore entirely surrounded by giant bulrush in both summer and winter although in the warmer weather there was an increase in bulrush density and height.

Dense vegetation stations in the southwest recorded the least amount of evaporation (both seasons, 0.00008 m/hr) as they had greater protection from wind and sun exposure. Evaporation sets placed in partially vegetated locations in the southwest corner were initially set in winter and therefore were also in giant bulrush, but the vegetation was on one side of the set, which was in a line roughly northwest to southeast so that evaporation stations were south of the vegetation coverage.

Partially vegetated stations that recorded greater losses in cold weather (0.00020 m/hr) compared to open water stations (0.00012 m/hr) were positioned to the south of the vegetation cover and may have been subject to air movement patterns that were more circular or swirling as they traveled over open water to the north. These locations also became more densely vegetated during summer although they maintained a section of open water to their immediate south so that they were in a space of open water approximately 3 meters lengthwise and 1 meter wide, surrounded by giant bulrush. Warm weather evaporation levels at partially vegetated stations were only slightly higher than cold weather measurements (0.00023 compared to 0.00020 m/hr) suggesting that thickening density of vegetation provided shade and windbreak during summer months.

The northwest stations (set in early spring) were surrounded by a greater variety of vegetation in summer than those of the southwest station, including giant bulrush, softstem bulrush, and pickerel weed. Vegetation collapsed after a strong wind storm and the stations were somewhat covered instead of being surrounded at the partially vegetated station, suggesting a possible explanation for the lower evaporation rate as compared to that of the densely vegetated location in warm weather measurements (0.00035 in the partial, 0.00043 in the dense).

During cold weather, stations in open water areas recorded less evaporation than in the partially vegetated locations though slightly more than those in the densely vegetated areas. Open water stations were placed at the north bank in the northwest corner and on the south bank in the southwest corner. The water level in the bucket was stations was exposed to full sun and ambient temperatures. Wind exposure at these stations may have been buffered by the bank of the cell; the bank was within 3 meters of the perimeter road and 1 meter below that road. Both locations faced deep open water that runs the length of the cell and then a large area of planted giant bulrush, into which were placed the partially and densely vegetated stations. Some protective windbreak aspect may have limited evaporation in comparison to heightened wind action on the partially vegetated stations. During warm weather, open water stations record substantially greater evaporation than any stations at vegetated stations due to their direct exposure to wind, sun, and heat.

Light readings were taken to support evaporation measurements and to schedule transpiration measurements. Light readings for cold season were 1138 µmol/m/s for open water and top tips of vegetation; 507 µmol/m/s for water level spaces in partially vegetated stations and 448 µmol/m/s for densely vegetated spaces at water level. Light readings for warm season were 2006 µmol/m/s for open water and top tips of vegetation; 494 µmol/m/s for water level spaces in partially vegetated stations and 271 µmol/m/s for densely vegetated spaces at water level. Light readings in summer were lower in dense and partial vegetation than light readings in winter due to the shading created by thickening vegetation; light readings in open areas were higher in summer than in winter. These readings compare to geographic standards of 1900 µmol/m/s for sunlight maximum in March and 2200 µmol/m/s for sunlight in July (USNREL, 2009). Solar radiation is key to transpiration because of its role in; light readings taken for this study confirmed the presence or absence of sunlight and suggested transpiration measurement opportunities.

Transpiration was measured twice for this study, once in the last week of March and once in the last week of June (see Table 5, below), both on fully sunlit days. Transpiration measurements were taken with a handheld device that recorded gas exchange on individual leaves. In the cold weather, when plants first began greening, measurement of gas exchange provided rates for bulrush (giant and softstem) that were 1482.3 and 1696.2 liters per day (respectively) and the rate for cattail was 17929.2 l/day. Arrowhead was not yet present and lotus was barely beginning to leaf out at this time. Measurements taken in full growing season provided rates for bulrush, 4192.2 and 18334.7 l/day; 143078.2 for cattail; 14874.3 for arrowhead; and 2138.4 l/day for lotus. These evaporation rates were used to scale up, to the entire wetland area based on percent coverage of individual species.

Table 5. Transpiration rates, direct measurement CI-340

Measurements taken 3/28/2012		Measurements taken 6/26/2012	
Vegetation Species	Rate (L/day)	Vegetation Species	Rate (L/day)
Giant Bulrush	1482	Giant Bulrush	4192
Softstem Bulrush	1696	Softstem Bulrush	18335
Cattail	17929	Cattail	143078
		Arrowhead	14874
		Lotus	2138

Transpiration rates for a wetland this size are approachable only at a level of approximation but contribute to the water budget. Quantities of water lost to the photosynthetic process of gas exchange are determined primarily by the stomatal structures (number and size) and surface area on the leaves. Round and softstem bulrush have a substantial surface area as does cattail, which also have stomata on both sides of the leaf; all three possess large leaves and all three are abundant at the EFWP. The cattail transpired more than the bulrush at a ratio of ten to one even in the early season. During the warmer season of full growth (June) the round bulrush increased by four times the quantity of transpiration measured in late March. The softstem bulrush increased by a factor of ten from March to June, and the cattail transpired at the greatest rate of all the vegetation in the study.

Transpiration rates provided by this study for cattail would appear to be extremely high (at 4.4-35.4 mm/day), but compare to reported rates from a study in Utah (colder climate) of 4-14 mm/day (Martin and others, 2003) Transpiration rates for arrowhead (both duck potato and grassy) are of value due to their spreading growth pattern and proliferation in and among other types of vegetation. They continue to spread throughout the summer and are found on the banks and in the planted vegetation, wherever the water is shallow enough to support them. The transpiration rates of lotus are extremely low as compared to the other species. While the leaf area of the cattail is 0.19 m^2 (calculating for both sides of the leaf) and that of the lotus is similar, at 0.13 m^2 (for the top surface only) the difference in transpiration suggests that the cattail transpires at nearly 67 times that of lotus. The low transpiration rate is accompanied by the lotus leaf area coverage of the water surface, spreading sometimes 16-18 inches across, that ultimately limits evaporative forces and therefore slows water losses in both aspects of the water budget (Takagi and others, 2006). As scaled up, transpiration contributes losses of 2.1 mgd in the early growing season and 17.8 mgd in full growing season. These calculations do not include all vegetation species present at the wetland, but the remaining species are thought to contribute an insignificant amount to the total transpiration due to limited coverage.

Seepage rates were assessed with the use of seepage meters built for this study. During winter the meters were placed in densely vegetated areas, partially vegetated areas, and in open water; measurements taken during the summer were taken from placement in open water (see Table 6, below).

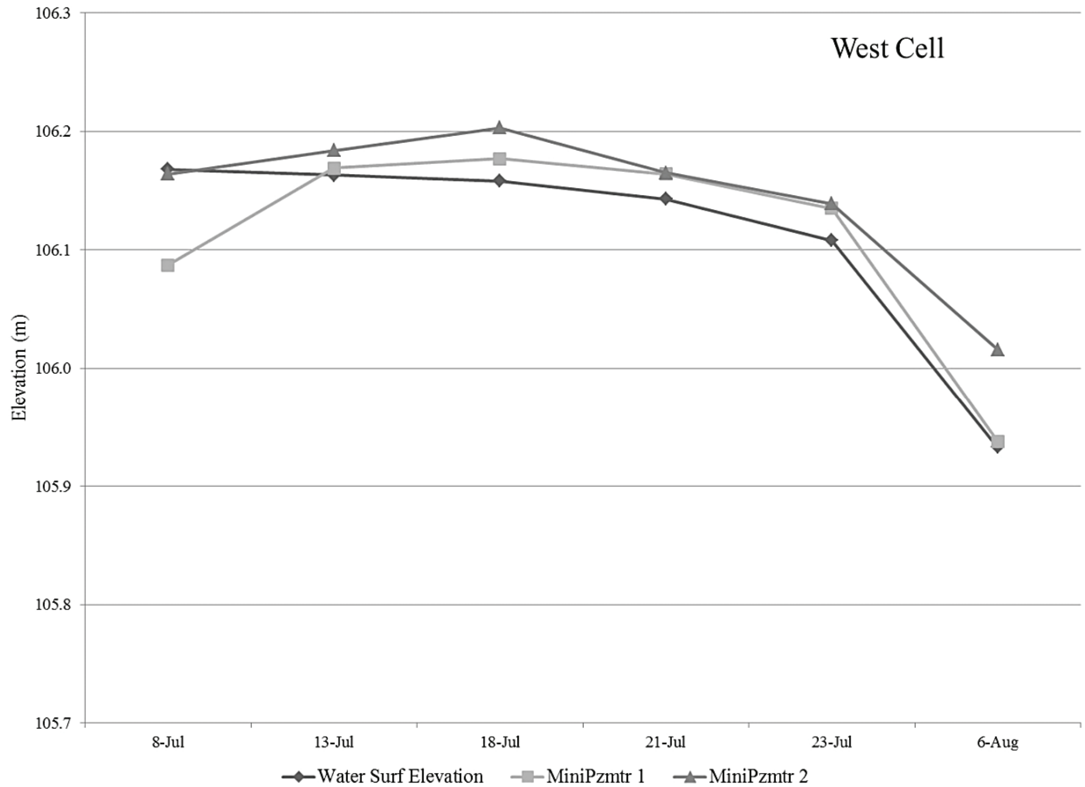
Table 6. Rates as measured with use of seepage meters placed in cell bottom

Season	Condition	Location	Seepage (m/hr)
Winter	Dense	Southwest	0.0000062
Winter	Partial	Southwest	0.0000046
Winter	Open	Southwest	-0.0000023
Summer	Open	Southwest	0.0000233
Summer	Open	Southeast	0.0000234

Meters placed in proximity to vegetation were placed in areas planted with giant bulrush. The meters in open water were placed near the bank of the cell. In cold season, average exfiltration rates were measured to be 0.0000062 m/hr for meters placed in dense vegetation. Rates for partially vegetated areas were somewhat less at 0.0000046 m/hr. During this same time the meters placed in open water gave an average infiltration of rate of 0.0000023 m/hr. Rates assessed during summer season were calculated from placement of three meters in the southwest corner midcell area and three meters placed in the southeast corner midcell area. Rates were averaged from two trials, one conducted in late May, early June and the second one in mid-July. Rates for meters placed in the west of the wetland were 0.0000233 m/hr and those from the east side of the wetland were 0.0000234. These two locations are an approximate midpoint in the wetland.

Exfiltration rates for the summer, open water placements were similar on average from west placement to east placement although there were marked differences between the first and second trials with the rates for trial one being 0.000037 in the west and 0.000032 m/hr in the east and the rates for trial two being 0.0000074 in the west and 0.0000148 m/hr in the east. Seepage from the sediments into the wetland cell may reflect a general pattern of equilibration of saturation levels as the summer season passed with decreasing rainfall; flow through of resident water from the river that increased/decreased cell capacity; topographic trend from upslope in the west toward the river in the east. The small quantities measured in the cell were confirmed by placement of minipiezometers.

Minipiezometers are designed to characterize the water bearing sediments underlying a body of water (Lee and Cherry, 1978). For this study pipes were driven into the cell floor and used to measure small differences in hydraulic head as relates to the surrounding surface water. Measurements were taken concurrently with the summer seepage meter trials. Depth to sediment waters within the PVC was measured from the pipe top and a comparative measurement made in relation to the pipe from the top to the surface water. As illustrated in Figure 6, below, measurements make clear the slight change in head demonstrating that groundwater was slightly elevated compared to the surface water in the west cell, but somewhat below the surface water elevation in the east cell.



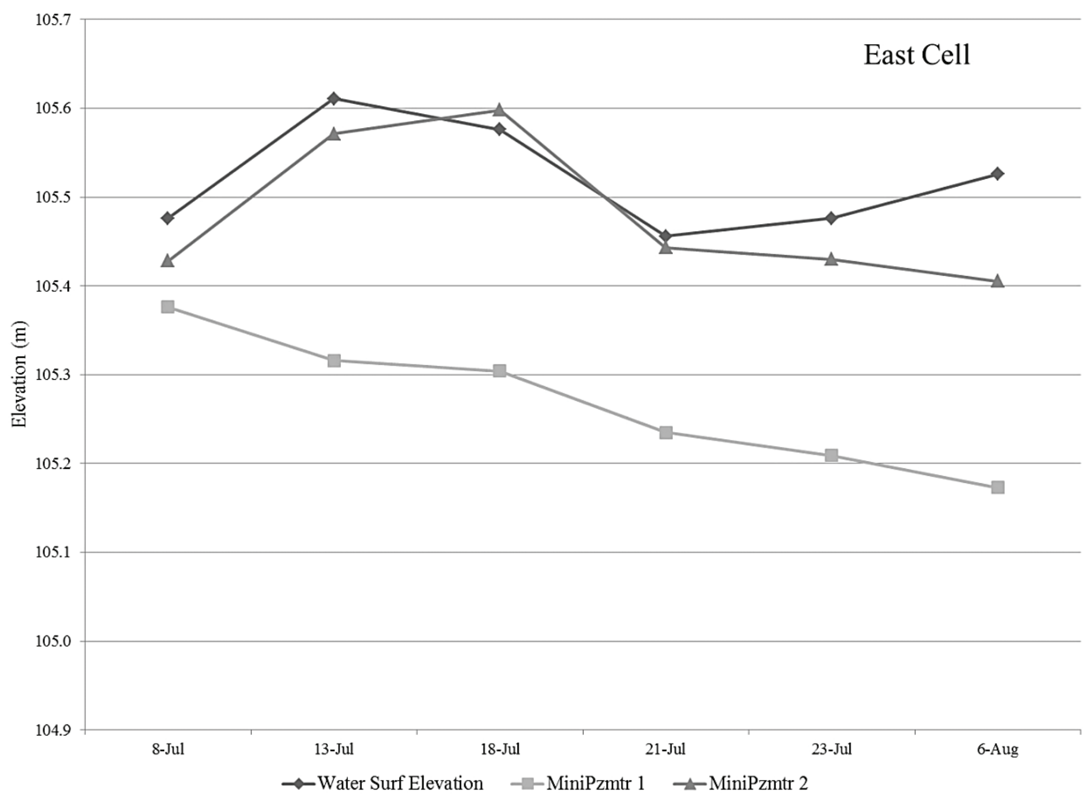


Figure 6. Small differences in hydraulic head as measured by minipiezometers.

Measurements taken from seepage meters and minipiezometers were used to calculate values for hydraulic conductivity. Hydraulic conductivity for the clay soils underlying the wetlands were assessed using Darcy's Law

$$Q = KIA \tag{9}$$

where Q is in milliliters acquired by seepage meter collection bag; K is the hydraulic conductivity measured in ml per day; I is the gradient of the local system, as determined by $\Delta h/\Delta l$ (from minipiezometer measurements) initially in units of meters but which become unitless; A is the cross-sectional area of the seepage meter barrel and also in meters. Rearranging to solve for K the formula becomes

$$Q/IA = K \tag{10}$$

Hydraulic conductivity calculated from values measured in the field was 0.0054 μm/s. This compared to published values by the USDA for the original Trinity Clay soil of 0.21 μm/s (USDA, 2012). The larger values reported by the USDA may be due in part to the testing procedures on undisturbed soils that may have included macropores, root networks and insect/animal burrows; the smaller values as derived by the seepage trials at the wetland may be due to the compaction of the clay by heavy machinery during wetland construction. Clay materials typically have low hydraulic conductivity and using the value derived above (0.0054 μm/s) saturation below wetland cells would occur at a rate of 0.17 m/yr.

To continue the study of the groundwater in the wetland area, a total of 8 piezometers were installed across the wetland in a north-south transect along the east and west sides, two at the north end near the settling basins, two at the midpoint of the midcells, two between the midcells and the south cells and two near the far south end of the south cells. This study was designed to establish gradient and flow direction of groundwater; by establishing piezometer locations for groundwater monitoring it was expected that illustration of north-south/east-west lines would be fully realized.

Piezometer BU01 was drilled at the southwest corner of the vegetated portion of the settling basins. This is furthest north and was located at the edge of a field that is typically mown for hay. There are two large, pecan trees in proximity (one about 20 feet north of the piezometer). Piezometer BU02 was drilled near the diversion pump station approximately 200 m from the East Fork and 100 m from the settling basins; it is drilled north of the access road in a flat depression. Piezometer BU03 was drilled at the edge of the dirt road/levee, west of the southwest corner of the cell; BU04 was also drilled at the edge of the road/levee, on the east. Both of these piezometers are within 25 meters of the wetland cell. Piezometers BU03 and BU04 were purposely drilled near the evaporation and seepage study sites in the midcells. This plan assured observation of groundwater in coordination with the water budget terms measured in this study and provided the opportunity to view potential groundwater to surface water interaction. Piezometer BU05 was drilled in a field north of the south section of cells at the northwest corner; the field is alternately mowed for hay or given to cattle grazing. Piezometer BU06 was drilled near an old levee that now serves as flow-through from midcells to the south cell section. BU07 and BU08 were located at positions similar to BU03 and BU04 (at the edge of the perimeter road in close proximity to the cell), but are in the south section of cells (see Figure 7, below). The 8 piezometers were noted and marked with GPS points for wetland management personnel; completion was designed for long-term residence.

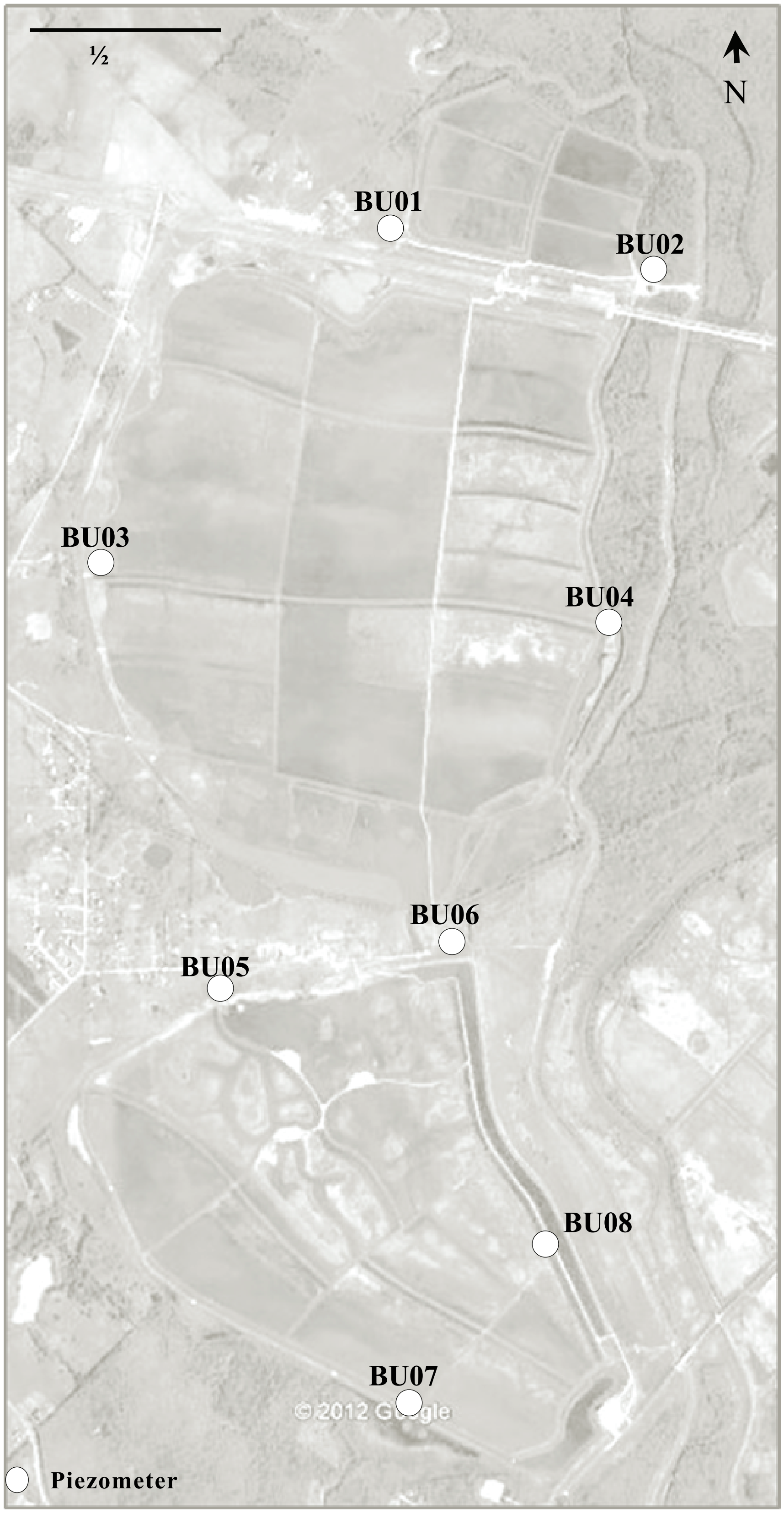


Figure 7. Piezometer locations and reference identification.

At each drill site the materials were noted and depths described until groundwater was encountered. All 8 of the wells encountered groundwater but each had somewhat different depths to the water bearing materials (see Figures 8 and 9, below).

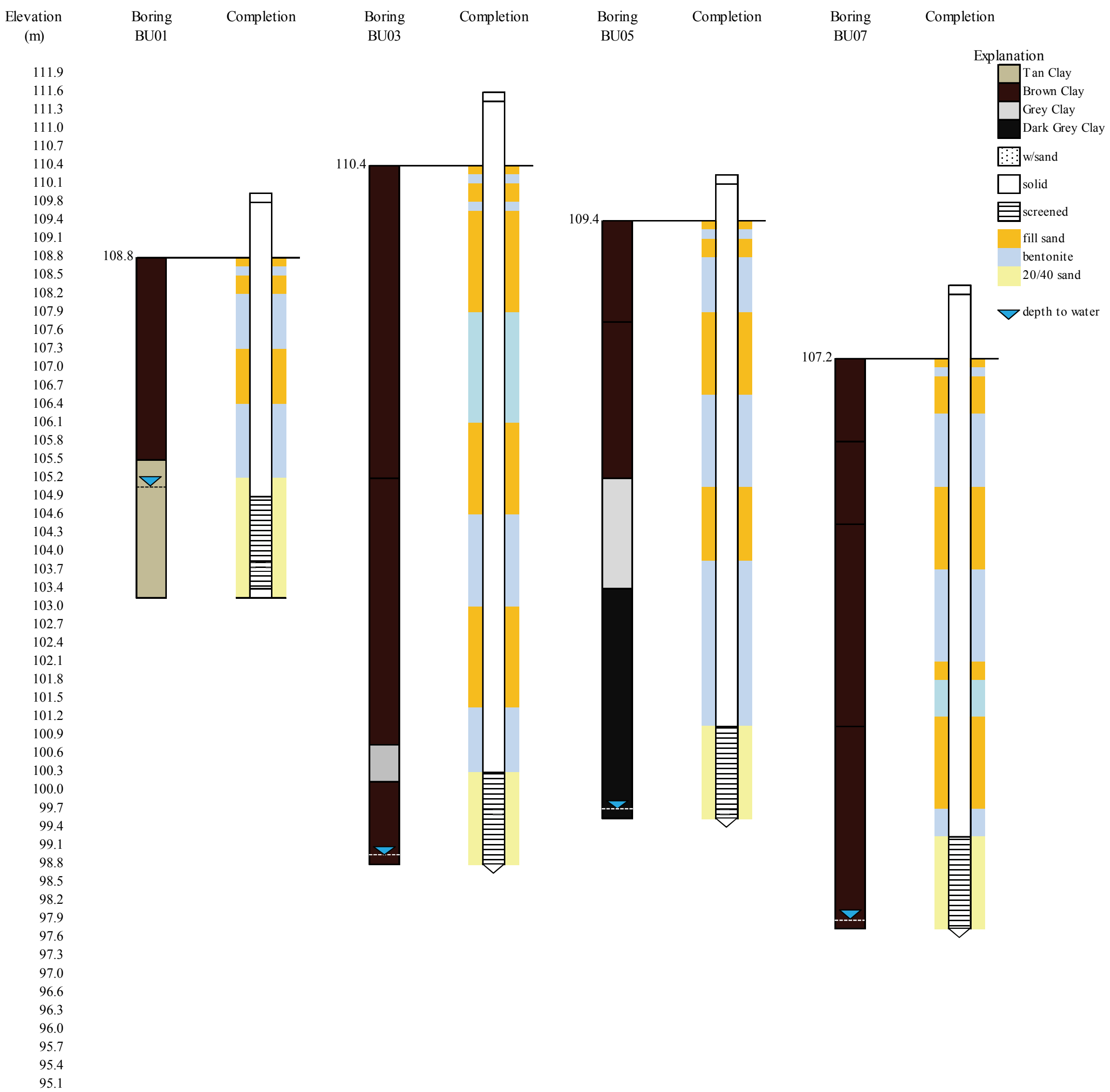


Figure 8. Piezometers BU01, BU03, BU05, BU07; drill log and completion with initial groundwater elevations marked. Not to scale, horizontal.

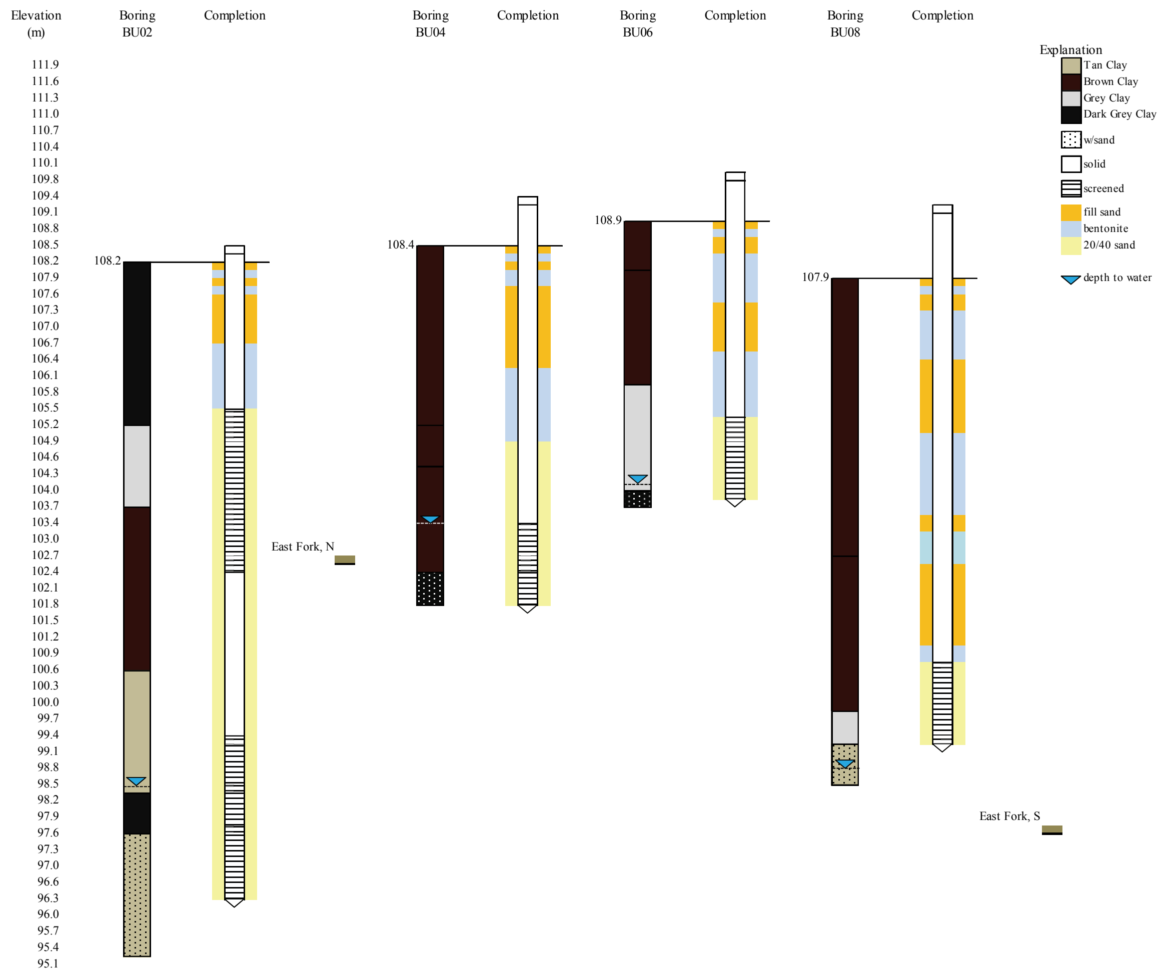


Figure 9. Piezometers BU02, BU04, BU06, BU08; drill log and completion with initial groundwater elevations marked. Note elevations as surveyed for the East Fork Trinity River, north and south end of wetland. Not to scale, horizontal.

Each of the wells in the north-south line along the west side of the wetland were clays throughout (cuttings were light to dark brown, light grey to dark grey) varying from 9.4 to 11.6 meters deep with BU01 being much more shallow at 5.6 meters. The wells in a north-south line on the east side of the wetland were clays throughout with fine sands encountered below the point at which groundwater was noted.

The clear difference in materials encountered while drilling for piezometers on the west side of the wetland as compared to the east side of the wetland (see Figure 10, below) suggests two possible depositional patterns typical of floodplains. One possibility is that there was soil erosion from higher elevations to lower as the area grades more steeply into the floodplain. This possibility would provide finer materials that were transported from the upland area to the floodplain below as anthropogenic alterations (such as clearing for agriculture) and/or seasonal rains produced accumulation of washed clays. This would answer for the clays found on the west side of the wetland encountered during drilling. Another possibility is that lighter, fine materials would be suspended by the flooding stream and carried further from the source of flooding than heavier, coarse materials. This possibility would also provide fines on the western edge of the wetland, as seen in the materials during drilling, and provide understanding of the lenses of sand encountered nearer the river to the east of the wetland. Either of these possibilities would provide thicker clays to the west side of the floodplain. Although the wetland resides entirely on Quaternary Alluvium, there are Quaternary fluviatile terrace deposits to the west of the midcells (BU03 and BU04) at an elevation increase of 50 meters, and also at the center area (BU05 and BU06). Historic stream flow in the meandering channel may have created point bar deposition, sands, that were encountered on drilling in closer proximity to the existing river. If the alluvium thins to the west and the fines increase with distance from river, the correlation of cuttings illustrate this subsurface system and suggests that depositional patterns created lenses of course grained material, sands, that may not be continuous or connected and yet contain shallow groundwater as seen in the lateral pattern underlying the wetland.

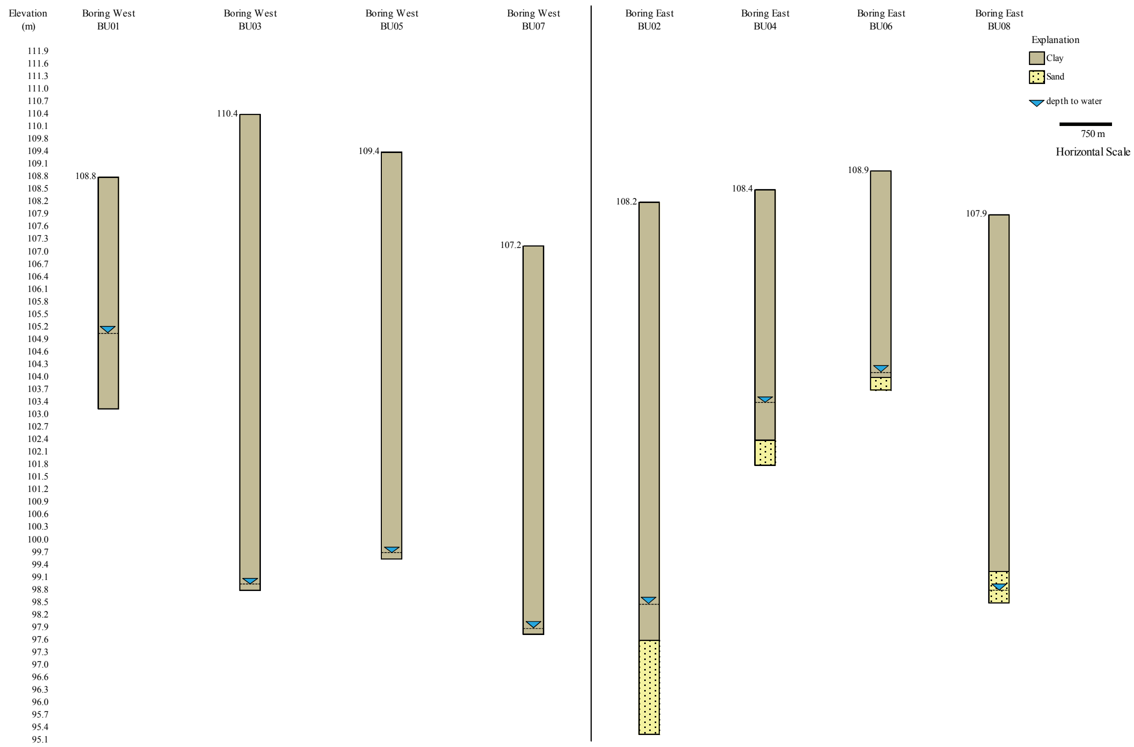


Figure 10. Drilled materials for eight piezometers; illustrated west north-south transect on the left, east north-south transect on the right. Horizontal scale noted.

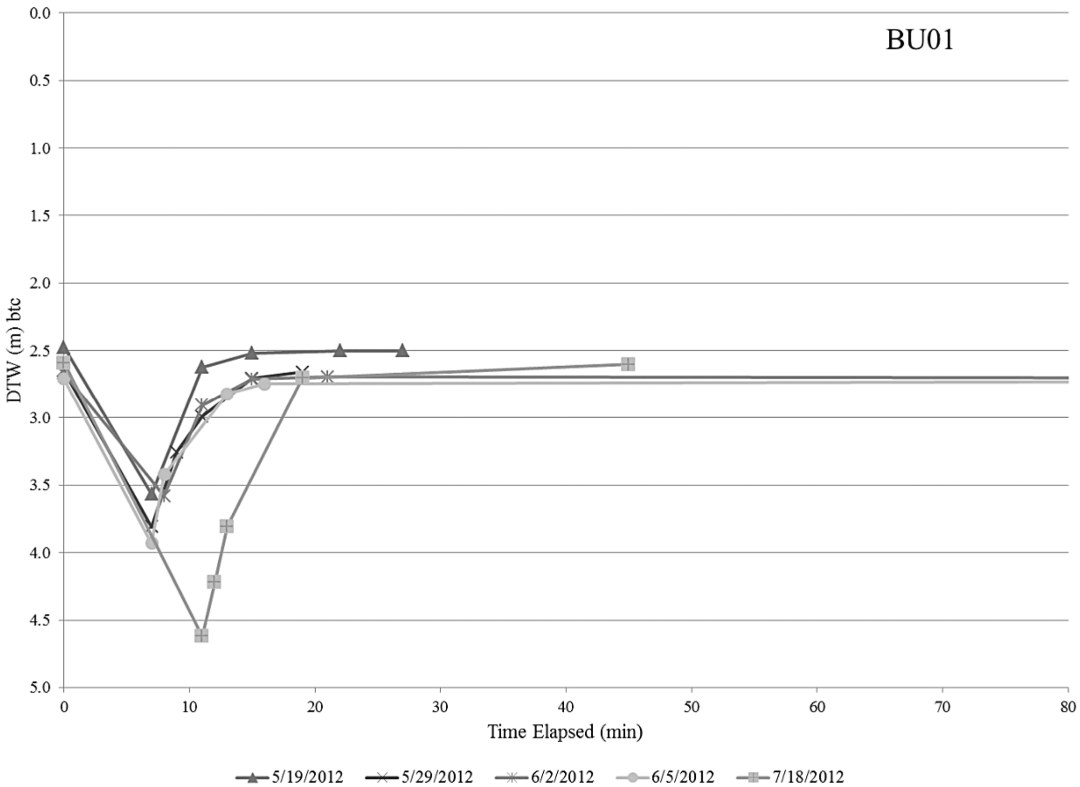
Initial groundwater levels were measured with a water level indicator and recorded over several weeks as the piezometers were developed. Levels were consistent and remained tight within each location. Minimum and maximum were determined and mean values were calculated for each (Table 7); with the exception of BU05 the groundwater recovery levels varied only within a few centimeters over the bailing period.

Table 7. Elevations for groundwater as recorded April 7 – August 6, 2012

	Groundwater Elevations, HAE (m)							
	BU01	BU02	BU03	BU04	BU05	BU06	BU07	BU08
MIN	106.8	104.0	107.1	106.5	99.6	105.3	104.9	105.6
MAX	108.0	104.2	107.3	106.7	106.1	106.1	105.4	106.0
MEAN	107.4	104.1	107.2	106.6	101.6	105.8	105.1	105.8

The wells were developed over a period of weeks, bailing a consistent volume of water and/or pore volume, until the groundwater in the pipe bailed clear of residual sediments. Each piezometer was bailed consistently, by hand, with the same equipment, removing the same amount of water each time (with the exception of those done on 7/18 at which time the quantity bailed was increased to further investigate recovery rates). Although these piezometers were not meant to be production wells, the development of the wells suggests a stable groundwater source and recovery is consistent over time, through multiple bailing sessions (Figures 11 and 12).

Recovery responses to bailing of BU01 has a similar pattern over time to measured depth to water level; each event required approximately 10 minutes to return to original depth. The one exception (on 7/18) was where almost twice the volume was bailed compared to previous times but the shape of recovery curve and the recovery time was similar to other attempts. Piezometer BU02, which is located by the diversion pump east of the settling basins, was a deeper well and screened in two zones. Response to bailing of this well demonstrated good recovery time to near initial depth, but oftentimes did not fully recover (to the centimeter) until the next day or at least within 12 hours; this piezometer decreased in initial depths as the summer months progressed This may be showing the results from the two zones. Piezometer BU04 had the most consistent recovery over time, although it is clear that the volume response also decreased over the summer months. BU07 recovery to bailing was similar each time in that although it had a rapid response initially, it took a 24 hour period (not noted on this chart due to space limitations) to completely recover to original depth to water.



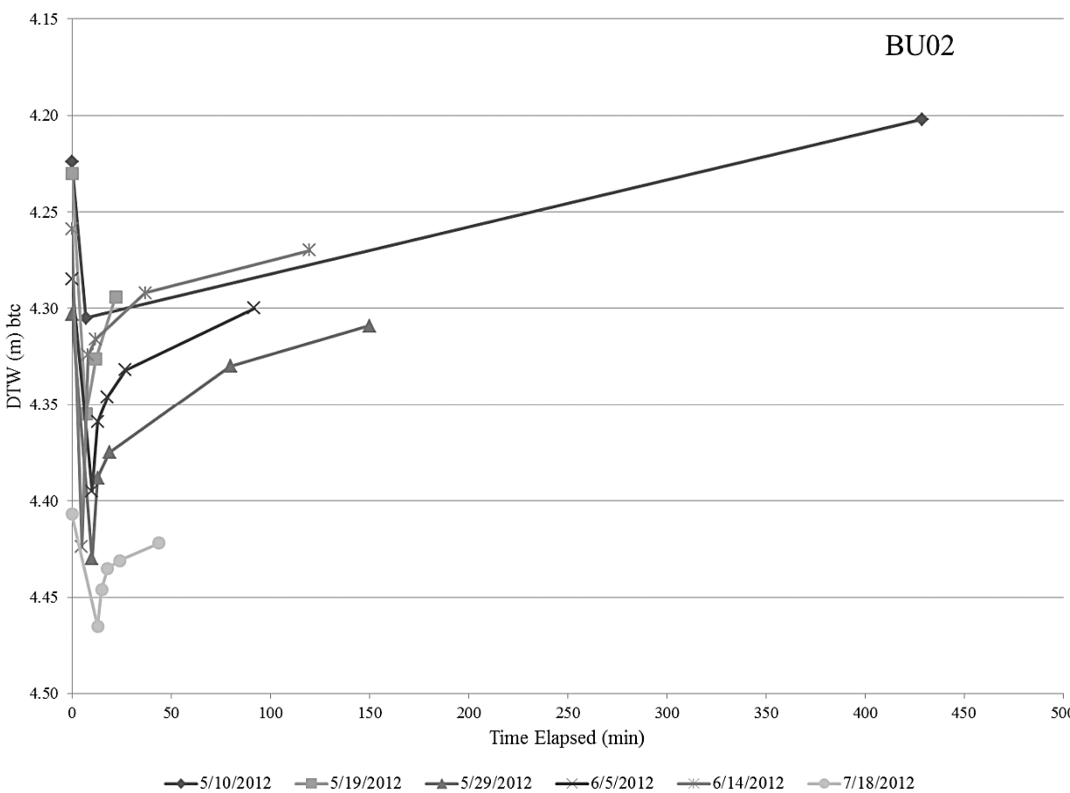
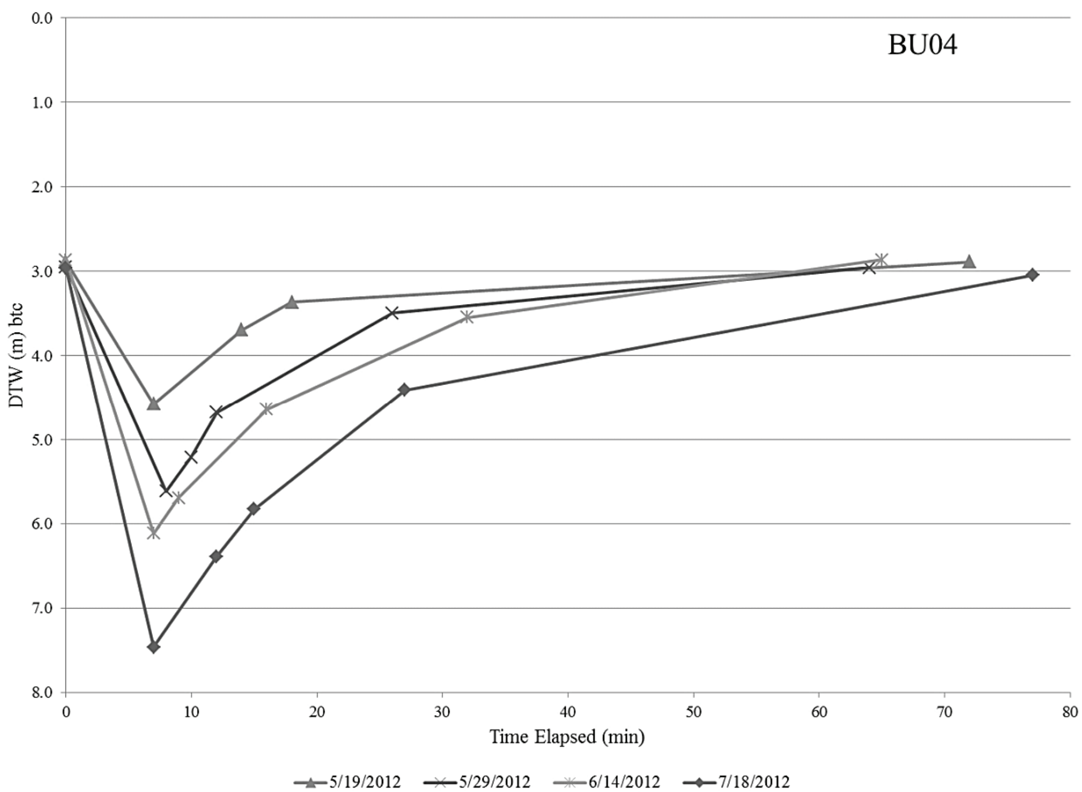


Figure 11. BU01 and BU02 response and recovery.



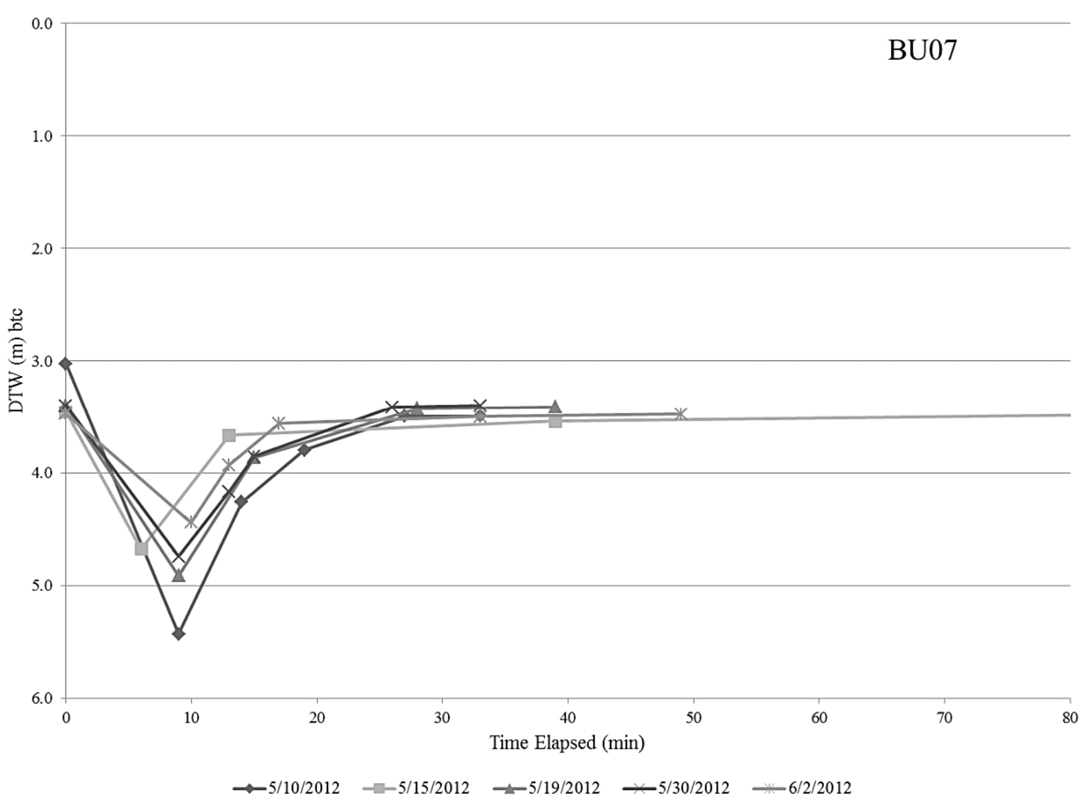


Figure 12. BU04 and BU07 response and recovery

Groundwater levels demonstrate a clear west to east with a slight north to south gradient. Piezometers on the west north-south transect have average groundwater levels descending with the north-south gradient of the wetland (as illustrated Figure 13 below, left) – as do the piezometers on the east north-south transect (as illustrated Figure 13 below, right). There is also the drop in groundwater elevations on the right as compared to those illustrated on the left, from upslope toward the river, especially with BU01 to BU02 and BU03 to BU04. The subsurface gradient is further illustrated in Figure 14 which shows groundwater contours drawn from water levels on July 13. Groundwater in piezometer BU01 may not be connected to that near BU03 in that it is considerably shallower and there is no control on that continuity.

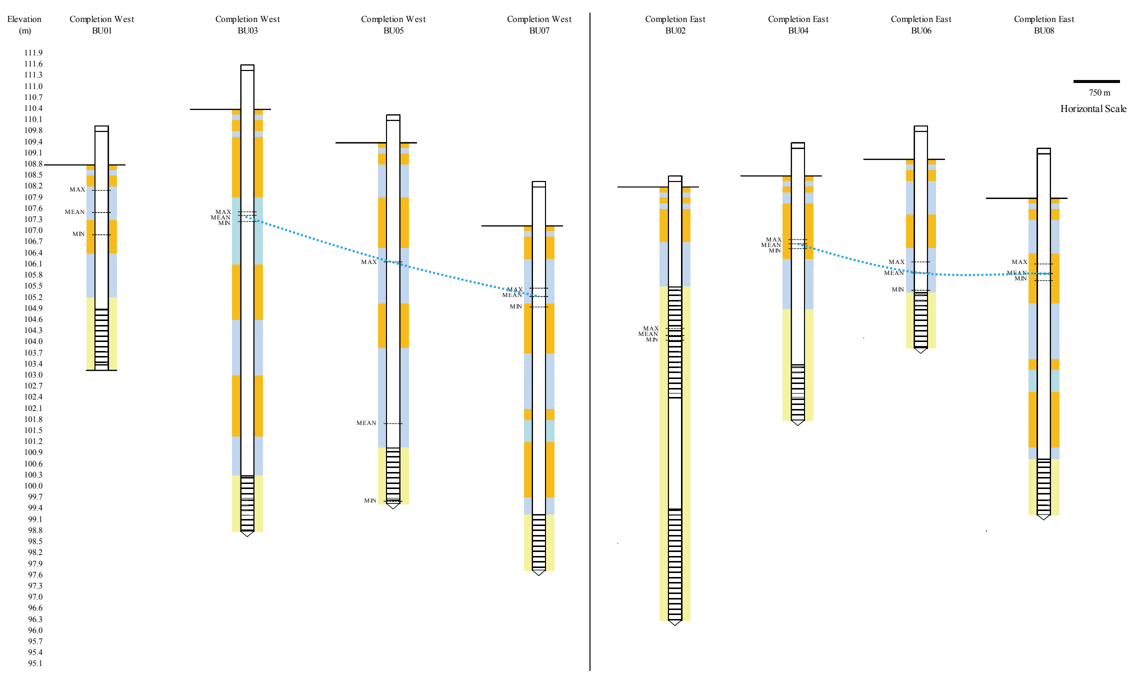


Figure 13. Average groundwater levels as measured over April 7 – August 6, 2012; illustrated west north-south transect on the left, east north-south transect on the right. Horizontal scale noted.

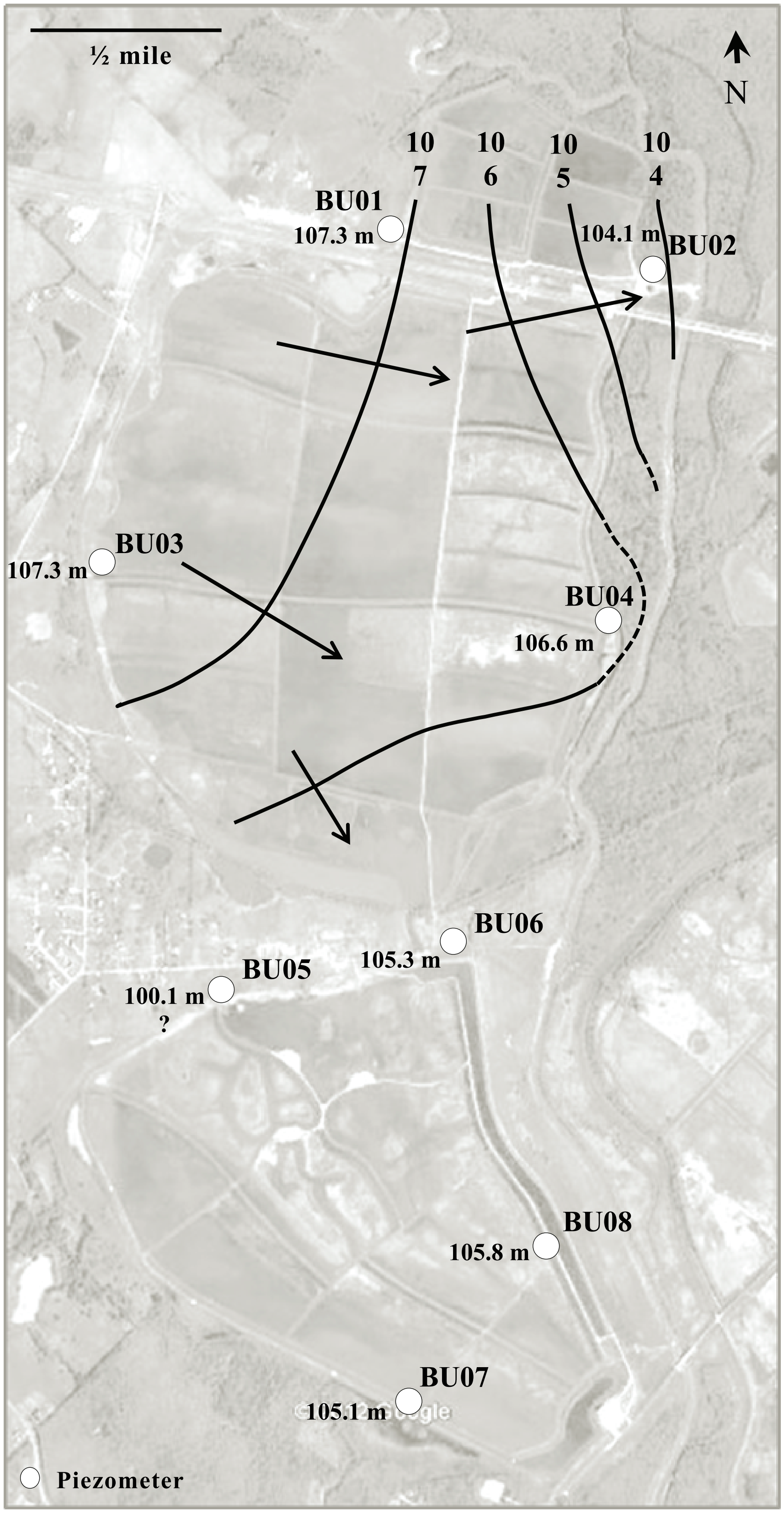


Figure 14. Groundwater contouring for given control points on July13, 2012.

Groundwater levels are further illustrated by the placement of initial groundwater elevations on completion logs for direct measurements taken on May 10, June 20, July 13, August 6, and September 15 (see Figures 15 and 16, below).

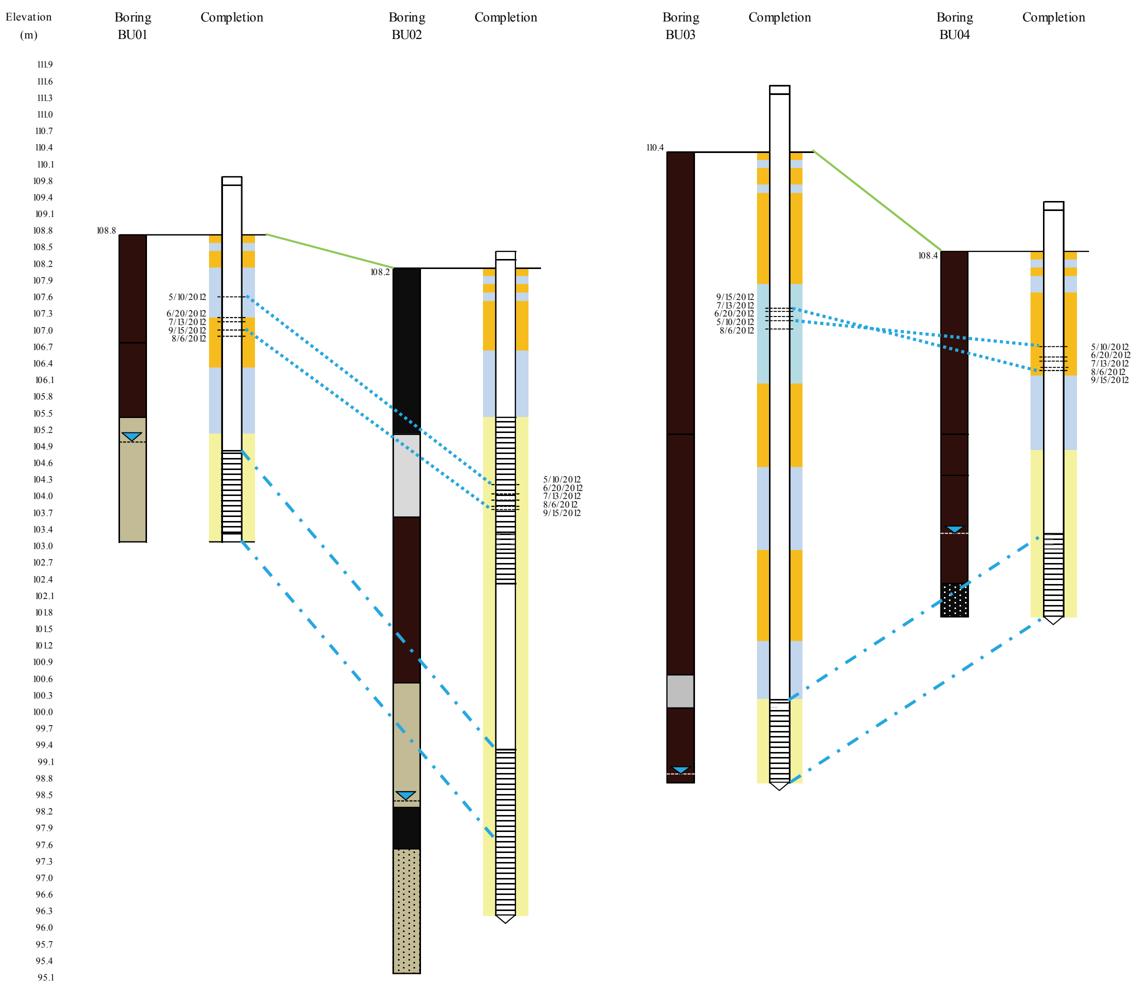


Figure 15. Piezometers BU01, BU02, BU03, BU04 paired west to east illustrating groundwater elevations per five weeks measurement.

Water levels in May were highest, possibly due to consistent spring rains throughout April and up through the first week of May. Water levels in July and August were lowest. Levels at earliest date and latest date correlate well for the piezometer set on the

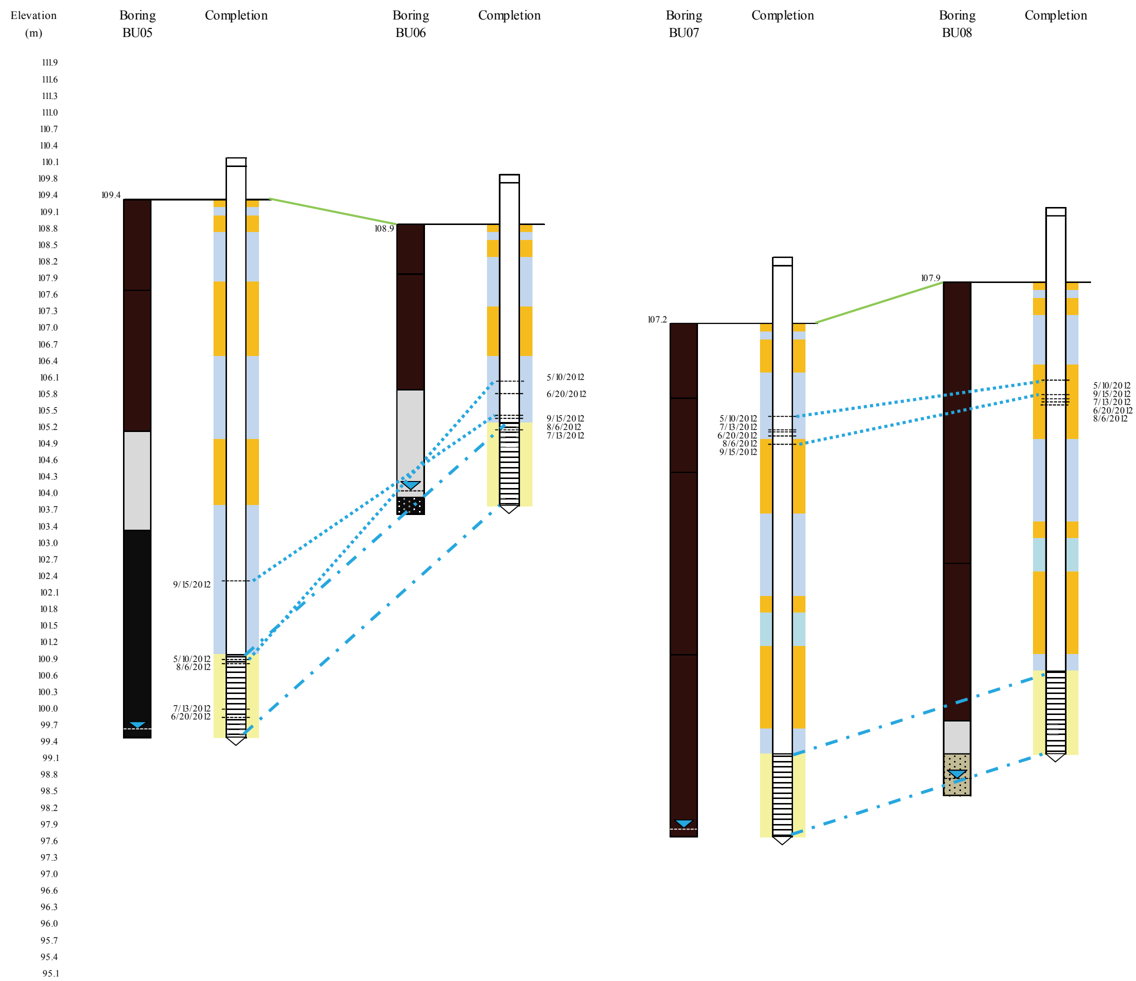


Figure 16. Piezometers BU05, BU06, BU07, BU08 paired west to east illustrating groundwater elevations per five weeks measurement.

north end (BU01 and BU02) and for the set on the south end (BU07 and BU08). However, levels for earliest and latest date cross in the mid and center sets (BU03 and BU04, BU05 and BU06) such that highest levels were on the latest date and lower depths to water were measured earlier in the series in the west piezometer as compared to that of the east piezometer. This suggests a discontinuity in the subsurface materials that support the argument that although there are lenses of groundwater bearing materials, they may not be continuous or connected.

Figures 15 and 16 also illustrate surface elevation relative to depth of piezometer, with depth to water in correspondence to screened section of pipe. With the exception of the south set (BU07 and BU08) all of the piezometers illustrate a down gradient from west to east, from higher elevation toward the river. The south set has an east to west down gradient due to wetland construction where the wetland cell trains were designed to move water east to west toward the canal that feeds the holding pond prior to being pumped for conveyance to the reservoir. Note BU05 as anomalous in comparison to the other seven piezometers: while each of the piezometers have tight, close measurements in depth to water over time, BU05 not only varies widely in depths to water over time but also demonstrates a steady increase over time. From May to June the level drops, but then rises in July and August and then in September the level rises to surpass that measured in May. Possible reasons for this rise in groundwater may be due to the depth of this piezometer. Water may not have been encountered during drilling until well into the bedrock material; the cuttings were dark grey, very stiff as a marl.

Following successful well development pressure sensors were placed within six of the piezometers and a data logger staked nearby to record groundwater fluctuations. Piezometers BU01, BU02, BU03, BU04, BU07, and BU08 were logged hourly for groundwater activity (see Figures 17 and 18, below). Piezometers BU05 and BU06 were somewhat unproductive during the bailing process, often bailed dry rapidly, and/or did not clear of residual sediments satisfactorily enough to allow clear readings from the pressure transducer and therefore were not logged. The hydrograph response line for the same timeframe (July 1 through August 5) does illustrate individual changes per piezometer location, with rises and falls spaced differently according to each localized environment. However, each hydrograph also appears to respond generally to recharge from the same rain storms. Specifically the high rainfall events of the 8th and 9th result in a hydrograph peak in all three piezometers. The rainfall events of the 15th and 16th were small enough that precipitation had little or no effect on the water table, possibly due to vegetation needs or surface evaporation. The recharge response is supported by the drop in groundwater elevations as the end of July passes with no rain.

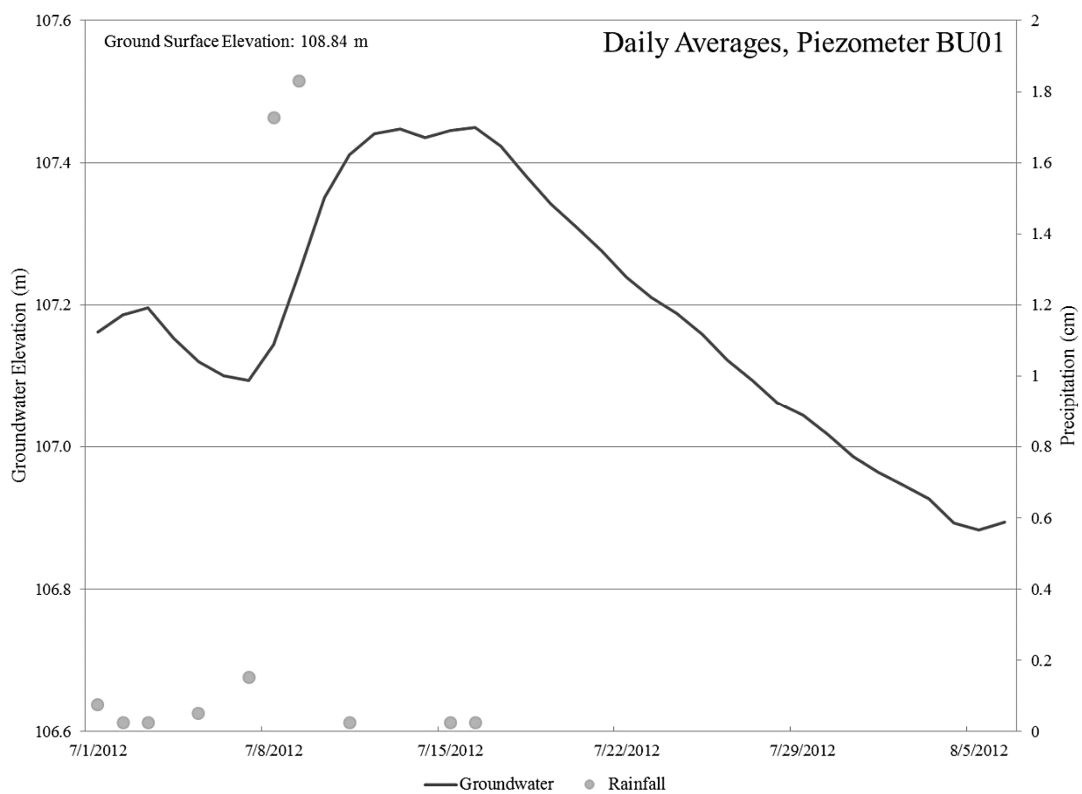


Figure 17. Groundwater elevations in BU01 and response to precipitation.

Some of the recorded fluctuations in groundwater illustrate events not anticipated for this study, but which add value to the information gathered in that they contribute to understanding of the water budget. For example, the clearly diel variations in

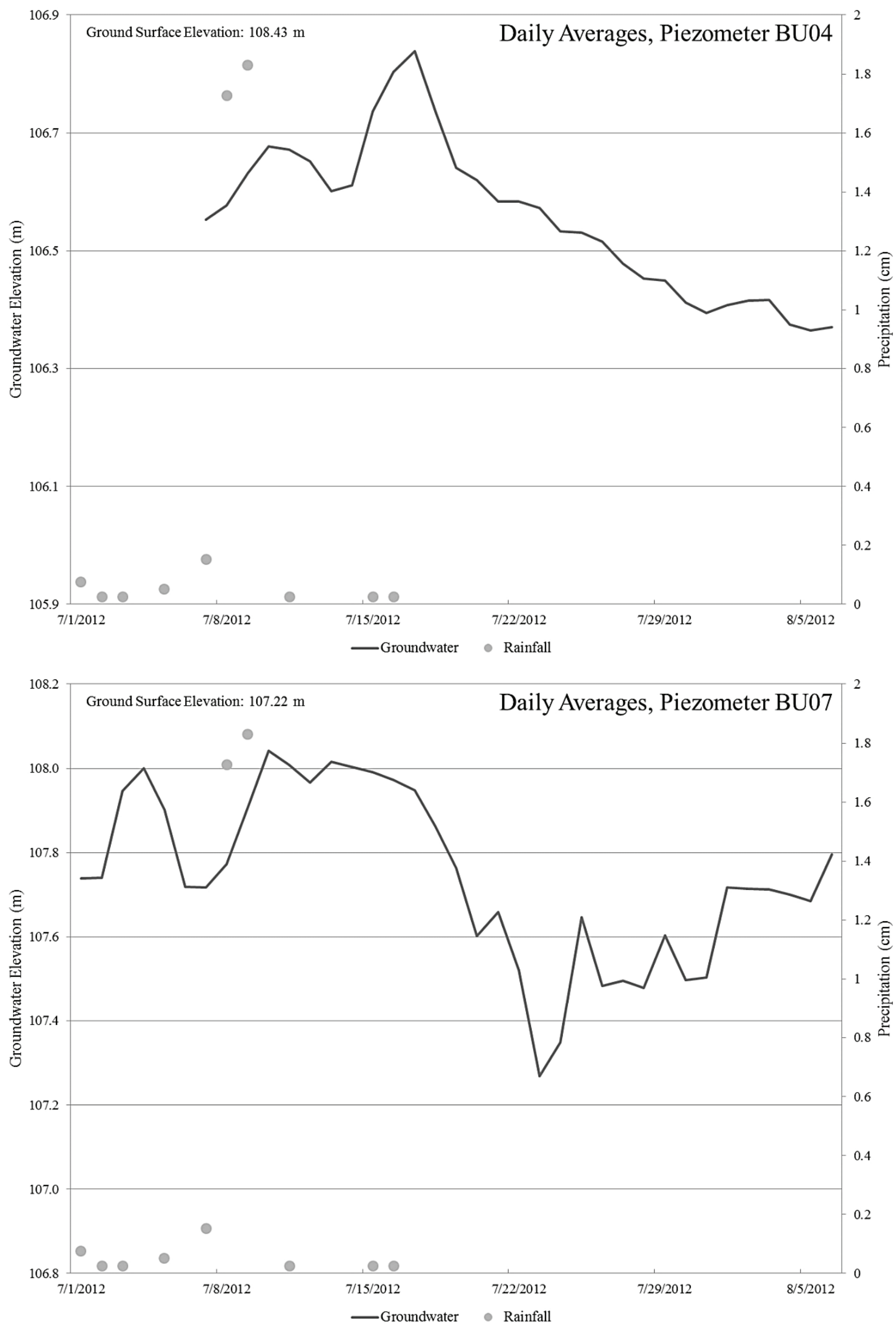


Figure 18. Groundwater elevations (BU04, BU07) and response to precipitation.

groundwater elevations as seen in Figure 19 below, suggest that the water levels are impacted by vegetation. This figure demonstrates groundwater levels over two days for BU01.

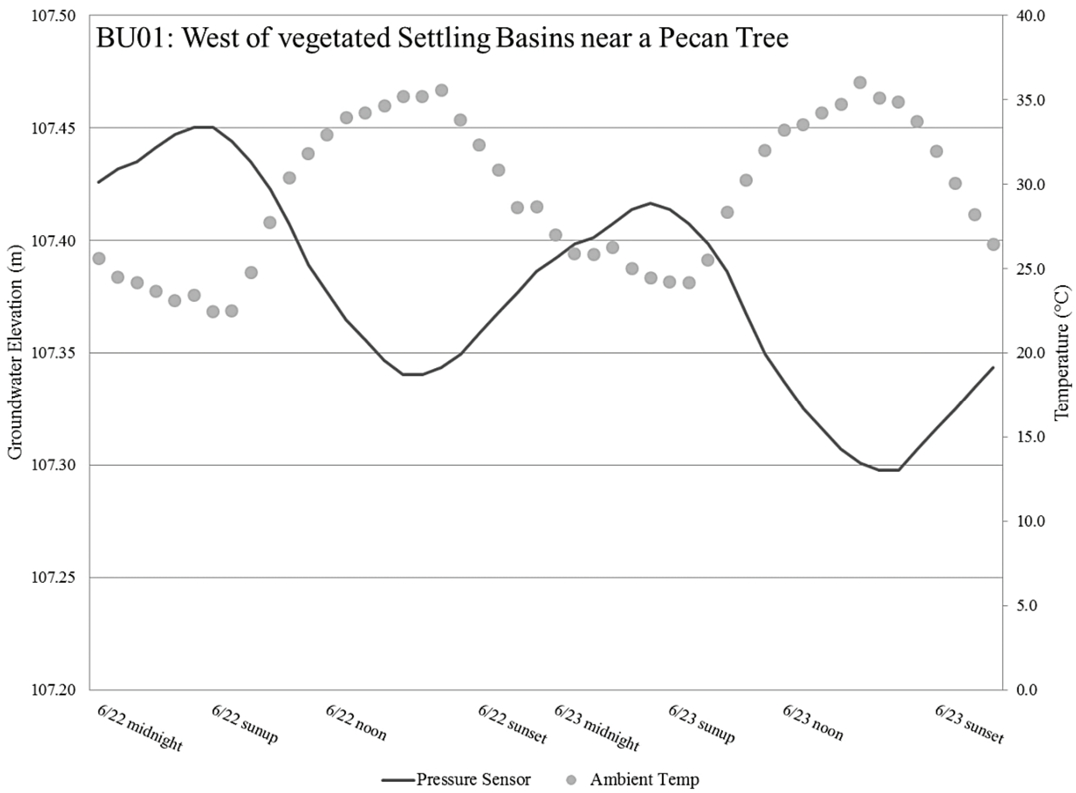


Figure 19. Two days' fluctuation in groundwater, BU01.

BU01 is a shallow piezometer and falls within the drip-lines for the pecan tree (see Figure 20, below); perhaps deeper piezometers would not be as dramatically affected. The weeks before and after the illustrated time in Figure 19 were both low rainfall (0.13 meters for each week) and the decline in groundwater reflects the tree’s need for water and its effect on the local water budget.

Figure 20. Pecan tree near BU01; note piezometer (1.1 meter) within circled area.

The water budget was assessed with precipitation measurements, evaluation of infiltration, and values for evaporation and transpiration as determined by direct measurement. These terms were calculated from actual events for a single day in cool season (January 28) and one in warm season (June 12); they were also compiled for a 30 day interval for both seasons (see Table 8, below). Daily inflow from the river and outflow quantities from conveyance were provided by NTMWD.

Measurements recorded by NTMWD for January 28 indicate inflow of 79.3 million gallons diverted from the river. That same day there were 67.3 million gallons pumped from the holding pond at the end of the wetland to the reservoir at Lavon. It did

Table 8. Water budget inputs and outputs

Date	Diversion	Precip	Seepage	Conveyance	Evap	Transp	Total IN	Total OUT	Storage
28-Jan	79	0	0.8	67	18	0	80	86	-5.5
12-Jun	50	0	0.8	39	20	18	51	77	-26.3
Jan 15-Feb 15	2335	15	25	2105	165	0	2374	2270	103.9
Jun 13-Jul 13	1368	71	25	1064	513	338	1463	1915	-451.5

All figures reported in million gallons

not rain that day and there was no transpiration measured because vegetation was either dead or cold-weather dormant. Exfiltration was included as a calculation based on seepage values (see Results, above) and contribute a slight gain of 0.8 million gallons. Evaporation was measured that day at a rate of 0.00076 m/hr scaled up to an open water area of the wetland, or 15.2 million gallons. Evaporation for vegetated areas was calculated with a rate of 0.00014 m/hr for a total of 3.0 million gallons; total evaporation was 18.2 million gallons. Total inflow for that day minus total outflow was a difference of 5.5 million gallons. For measurements made in the summer, June 12, NTMWD reports diversion at 50.3 million gallons, and conveyance was 39.4 million gallons. Precipitation was zero and exfiltration did not vary from winter, remaining at 0.8 million gallons. Evaporation was calculated to a lower quantity as compared to that of winter, at 12.2 million gallons due to increased vegetation coverage that limits the evaporative surface, although the actual open water rate for that day was higher at 0.00097 m/hr compared to the vegetation evaporation rate of 0.00027 m/hr; total evaporation for this day was 20 million gallons. Transpiration was calculated from direct measurements to 17.8 million gallons per day in summer. Total inflow for that day minus total outflow was a difference of 26.3 million gallons. Water budgets are difficult to assess due to the variable qualities of actual sunlight, humidity, wind etc. that affect each of the budget terms over time, but by narrowing the timeframe to a single days' actual events the water budget balances closely and differences may be insignificant. Given the timeframe of one month, the imbalance increases as the possible error compounds. This may be due to error in measurement; perhaps due to some term that was not considered in this study, such as bank loss; perhaps due to the nature of wetland management maintenance.

Solving for the differences in the water budget indicates that there is more water leaving the wetland – through conveyance, evaporation, infiltration, and transpiration – than there is being input through diversion water and precipitation. When considered from larger timeframes (one month or more) discrepancies may be attributed in part to daily differences between diversion of river water into the settling basins and conveyance quantities to the Lavon treatment plant during each month; averaging these monthly quantities smoothed fluctuations, but also indicated there is uniformity from month to month. This seeming uniformity is not the case as diversion and conveyance are not one-to-one, and disparity between the diversion and conveyance is also increased because of residence times in the cells. Residence time varies from 8-11 days with flow through the 4-4.5 mile path of the wetland. Flow-through may be slowed or stopped completely because of maintenance of equipment and management of vegetation and wildlife (Mokry, 2011). Residence times also vary in response to conveyance requirements and intra-cell gates may be opened completely to facilitate flow-through and increase conveyance rates. Residence time may be thought of as storage for the water budget equation, and storage could range 70-90%; entire cells may be drained dry or shut off from all inflow/outflow. For those months with a significant difference there is some explanation in residence, or storage of water held or released from cell to cell over the month (Mokry, 2011).

In a final step to the groundwater to surface water investigation, water sampling was completed in late September. The samples were tested in the field for electrical conductance, although time constraints did not allow for alkalinity titrations in the field. Measured pH in the field was 6.9 on average; temperature averaged 25.6 °C for groundwater and 27 °C for surface water (see Table 9, below).

Electrical conductance (EC) measurements in the field were high in water removed from piezometers, with BU03 (midcells, west) being highest at 8540 microsiemens (μS) and lowest in BU06 (levee, east) at 691 μS. EC was measured in surface water ranging from 790 μS (south cell) to 685 μS (midcells, east). Surface water levels average at 759 μS; the setting basin (SURFB3) where river water is initially diverted to the wetland was measured at 773 μS. Water tested from the minipiezometers was similar to that of the surface water on the east, with average of the two minipiezometers at 812 μS and that of the surface water 786 μS (piezometer BU04 at 906 μS). However, water tested from the minipiezometer on the west were greater than twice that of the surface water (1711 μS compared to 685 μS); groundwater from the nearby BU03 at 8540 μS. A pattern was noted from the field in that EC was higher in groundwater and sediment water taken from the west side of the wetland compared to that taken from the east side of the wetland. Values were substantially different in this observation with the only exception being EC taken from BU01 compared to BU02, which are both on the northernmost end of the north-south transect on either side of the setting basins (1156 μS compared to 1182 μS).

Table 9. Initial conditions for water samples, measured in the field

Measure	BU01	BU02	BU03	BU04	BU05	BU06	BU07	BU08	SURFB3	SURF4B	SURF6B	SURF8A	MPW4B	MPE6B	MPW6B
Ec (µS)	1156	1182	8540	906	3635	691	5574	951	773	685	786	790	1711	687	937
pH	6.6	6.5	6.8	7.1	6.8	7.1	7.0	7.0	7.0	6.7	6.9	6.9	na	na	na
Temperature (°C)	25.7	28.2	27.0	24.9	23.2	24.1	27.0	24.8	27.2	27.8	27.2	27.0	na	na	na

Table 10. Water sampling results

Species	BU01	BU02	BU03	BU04	BU05	BU06	BU07	BU08	SURFB3	SURF4B	SURF6B	SURF8A	MPW4B	MPE6B	MPW6B
Cl^-	91	68	164	64	485	23	909	62	111	100	94	64	189	65	124
SO_4^{2-}	99	79	707	60	100	29	372	77	104	93	100	75	20	33	5
NO_3^-	22	nd	nd	16	nd	nd	nd	26	31	25	12	nd	nd	11	1
F^-	1	0	nd	1	nd	1	nd	0	1	1	1	1	0	1	0
PO_4^{3-}	nd	nd	nd	nd	nd	nd	nd	nd	1	2	2	1	3	4	8
HCO_3^-	467	507	3968	412	2393	1520	1804	990	124	378	194	276	999	622	738
K^+	nd	nd	nd	14	nd	50	nd	nd	nd	nd	nd	nd	nd	33	59
Ca^{2+}	197	142	286	114	495	307	475	284	43	95	58	66	119	100	132
Na^+	48	84	1552	87	543	178	816	114	120	144	112	100	361	152	161
Mg^{2+}	9	14	32	4	81	23	46	10	6	6	5	4	7	8	11

Results in ppm

Water samples from the 15 wetland locations analyzed described common anion and cations concentrations (see Table 10, below). Chloride ranged widely in groundwater, from 23.4 parts per million (ppm) in BU06 to 485.3 ppm in BU05. Chloride is accepted as a naturally occurring substance in drinking water; the EPA considers chloride in terms of a secondary maximum contaminant level (SMCL) set at 250 ppm (USEPA, 2012). Surface water in the midcells averaged 97.0 ppm chloride and were quite similar individually (100.4 and 93.5 west to east, respectively). Water sampled from the settling basin was 110.6 ppm and in the south was 63.5 ppm chloride, suggesting a decrease in concentration as the water passes through the wetland polishing process. Sulfate also ranged widely, from 28.5 in BU06 to 371.7 in BU07. Sulfate decreased from settling basin to south cell by 29.4 ppm. Sulfate is also a naturally occurring constituent in drinking water, with SMCL limits set at 250 ppm. Nitrates were measured in groundwater in very high levels in BU01, BU04, and BU08. The highest nitrate level was measured in the settling basin, 31.1 ppm and reduced by passage through the wetland to an undetectable level in the south cell. Nitrates were found in the sediment water of minipiezometers in the midcell, east – but not in that measured from the west midcell; nitrate in the groundwater sampled from piezometer BU04 (midcell, east) was 16.4 ppm and undetectable in midcell, west. Nitrate is considered by the EPA to be a dangerous contaminant if found in drinking water; maximum contaminant level goals are set at 1 ppm for nitrate (USEPA, 2012). Fluoride was found in the groundwater sampled from BU01, BU02, BU04, BU06, and BU08, in all surface water and in all sediment water; results ranged from 0.4 to 0.9 ppm. No phosphates were found in any of the groundwater sampled from the piezometers however, it was found in all surface water and in all sediment water; results ranged from 1.3 ppm in the settling basin, 2.0 ppm in the midcells, 1.0 ppm in the south cell; sediment waters measured highest at 3.0 in the west and 3.8, 7.9 ppm in the east. Phosphates are present in natural water and are preferred in concentrations of range 0.05 – 0.1 ppm. Waters throughout the wetland are highly alkaline, with highest levels in those locations that had very high EC, for example in BU03, BU05, and BU07. The lowest alkalinity was found in the settling basin surface water at 93.0 ppm.

Cations found in the wetland waters were as wide ranging as anions. For example, calcium was high in the groundwater sample from the piezometers, at 113.8 ppm in BU04 to 494.9 in BU05. Compared to the groundwater, surface water was somewhat limited in calcium, averaging only 65.5 ppm. Sodium levels in groundwater ranged from a low of 48.2 ppm in BU01 at the northeast corner of the wetland footprint to a high of 1552.0 ppm found in BU03 (which also had an EC of 8540 μS); sodium levels in the sediment water near BU03 had a correspondingly high level of 361.1 ppm compared to the minipiezometers on the east that had 151.9 and 160.7 where the groundwater (piezometer BU04) was 87.1 ppm. Magnesium averaged 27.4 ppm in the groundwater; 5.3 ppm in the surface water; and 8.6 ppm in the sediment water. Potassium was found in samples from the east side of the wetland with 13.5 and 49.9 ppm (BU04 and BU06); 32.7 and 58.8 ppm in the two sediment water samples from midcell, east (near BU04). These were the only four measurements of potassium detected in the sampling set. All waters sampled from the wetland may be considered rich in cations; typical drinking water (mineral water) contains calcium, sodium and magnesium in wide-ranging values but not exceeding limits of 60-70 ppm calcium, 8-10 ppm sodium, and 10-20 ppm magnesium.

CHAPTER FIVE

Conclusions

This study suggests that although evaporation during summer is expected, evaporation in winter is also substantial due to seasonal variations in humidity levels and greater open water conditions. Vegetation cover contributed to shade and wind break during summer months and evaporation in vegetated spaces was much more limited than in winter.

Transpiration may be the second greatest loss to the wetland budget, during summer. These rates suggest that cattail is the species that transpires the greatest loss of all species observed in this study and lotus transpires the least. Low transpiration rates and limited evaporation created by the large surficial coverage of the lotus leaf makes it an effective wetland plant: it anchors in sediments at a wide range of water depths and protects against water loss.

The results of seepage meter deployment and monitoring were interesting in that the collection bags filled with water rather than emptied of water: there was exfiltration rather than infiltration. This exchange, or seepage, also suggests the possibility of exchange in the other direction, as infiltration, and as such there is a potential interaction between surface water and groundwater in the wetland footprint. Minipiezometer data support this measurement in that head was higher in groundwater as compared to surface water when water levels remain fairly constant.

The water budget balanced reasonably well, given a day's timeframe, but differences compound as the timeframe is extended. Transpiration and evaporation are notoriously difficult to measure due to issues with logistics and equipment. Oftentimes estimates made for water budgets rely on off-site fixtures. However, direct measurements of actual on-site conditions may prove useful as a comparison factor for estimations derived from historic data and equations.

Precipitation was measured throughout the study at the site and contributes one term in the water budget but also has an impact on groundwater. Observations from groundwater monitoring indicate that there is local recharge from precipitation events. Even though the calculations for permeability indicate a slow rate of penetration into the clays (0.0054 μm/s), it may be that surface cracks in the clay soils of 2-3 inches wide and up to 20 inches deep (USDA, 2012) allow access to fractures in the subsurface bedding planes and precipitation moves to the groundwater more rapidly than K values would suggest. Recharge may also be moving laterally from the upslope areas to the west of the wetland, which are not Trinity Clay soils, and this recharge may be driving the change in water chemistry seen from the groundwater samples on the west compared to those on the east (see Figure 21).

The calculations for hydraulic conductivity (K) values derived for the clays underlying the wetland cells are not indicative of the recovery rates as seen in the bailing of groundwater during development of the eight piezometers installed for this study. Presence of shallow alluvial materials such as sands and gravels would be more likely, given the consistent water supply during well development. Response to bailing and groundwater level recovery indicates that the groundwater in this area must be flowing more efficiently than the permeability of the clay soil should allow. Alluvial sediments as deposited by the East Fork may comprise a substantial shallow groundwater system.

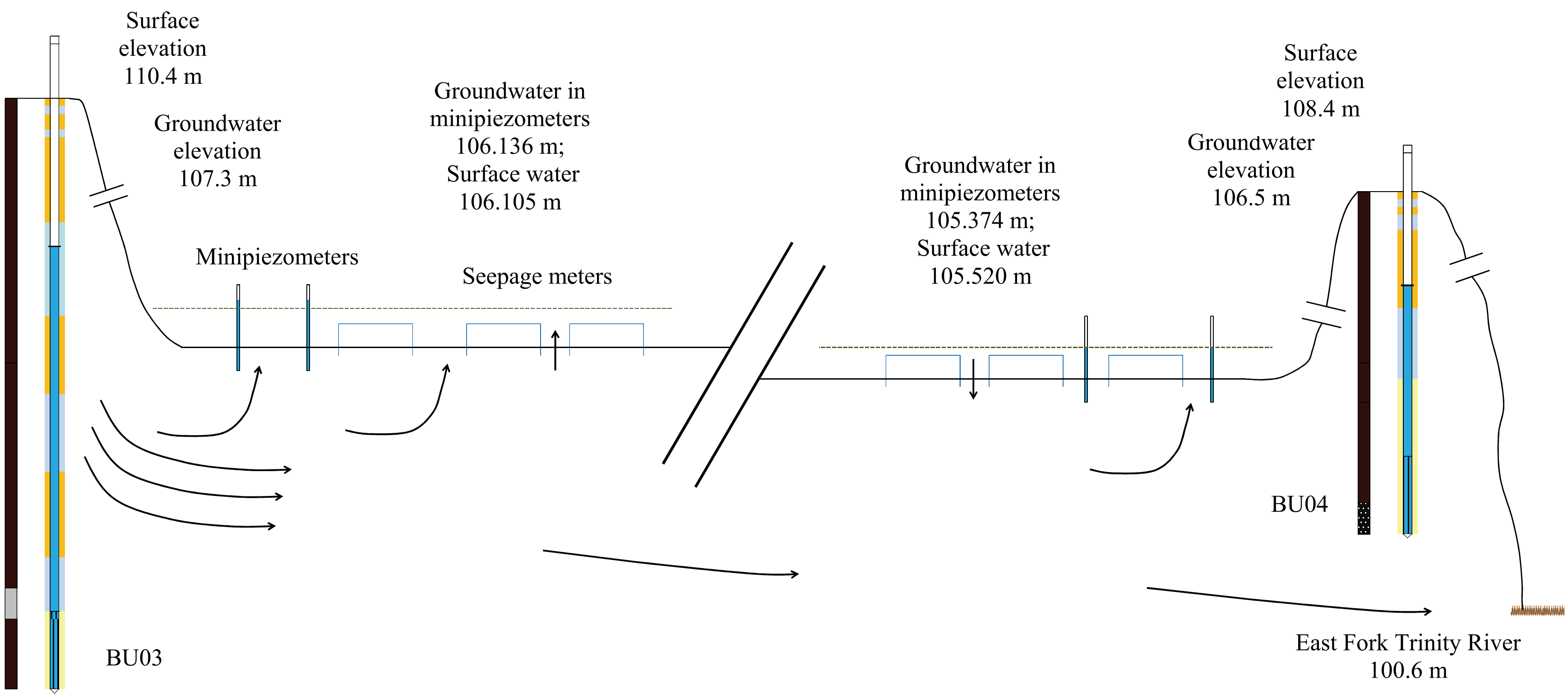


Figure 21. Illustration of potential groundwater flow paths from west, at BU03 east toward the river at BU04.

The more permeable, sandier materials may be discontinuous but evidence supports their interaction.

The investigation of the groundwater conditions at the EFWP resulted in the illustration of a west to east gradient in groundwater elevations (see Figure 21). This was supported by measurements from piezometers, minipiezometers and water chemistry. Groundwater trends toward the river through the floodplain. According to calculations made on hydraulic conductivity values, seepage into the sediments immediately underlying the wetland cells will progress at 0.17 m/yr; this means that in the three years of current productivity (2009-2012) the sediments have experienced approximately 0.5 meters saturation from the surface water. Given the sands encountered in the subsurface on the east side of the wetland footprint, groundwater movement on this path may be more rapid than rates calculated for clay. This evidence suggests that there is currently interaction between the groundwater and the surface water at the EFWP.

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