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COMPARATIVE RECHARGE RATES OF ISOLATED AND RIVERINE WETLANDS

by

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And thank you to my family—Mama, Daddy, Cameron—for always believing in me, pushing me, always giving me support and advice, and never letting me give up.

ABSTRACT

Isolated wetlands have a slightly depressed topography surrounded by an upland area. There is no direct surface water connection, as with riverine wetlands; however, there is a groundwater connection that allows isolated wetlands to have similar hydrologic functions to riverine wetlands. This study sought to compare surficial aquifer groundwater recharge rates of several isolated and riverine wetlands in the Coastal Plain of the Carolinas by evaluating soil characteristics, water table fluctuations, and precipitation from January 2012 – September 2012. Data analysis indicated no significant difference in mean recharge rates between the isolated and riverine wetlands at each study site. Whereas soil texture was expected to be an important influence on groundwater recharge, factors that caused a significant difference in mean recharge rate between sites were precipitation frequency and precipitation intensity. As a second component to this study, it was shown how the calculated recharge rates can be used to aid in the calibration of the hydrologic modeling program Hydrological Simulation Program-Fortran (HSPF). Using field data as the standard, parameters in the model's PERC function can be manipulated until PERC matches the observed recharge values. Land management implications from this study include the comparative efficacy of the recharge capability of isolated wetlands, the relevance of soil texture below the unsaturated zone when addressing seasonal effects on hydrologic behavior, and the applicability of field data in watershed modeling.

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R	Rate of groundwater recharge.
S_y	Specific yield.
h_a	Projected maximum water table depth in the absence of precipitation.
h_m	Minimum observed water table depth after a precipitation event.
Δt	Duration of the recharge event.
h_i	Minimum water depth observed the start of the recession period.
h_0	Maximum water depth observed the end of the recession period.
e	Base of the natural logarithm.
α	Recession coefficient.
t	Time.
P	Precipitation.

LIST OF ABBREVIATIONS

CW	Connected wetland
DTW	Depth to water
DWQ	Dept. of Water Quality
EPA	US Environmental Protection Agency
HSPF	Hydrological Simulation Program-Fortran
IW	Isolated wetland
IWC	Isolated wetland connectivity
NC	North Carolina
NCDENR	North Carolina Dept. of Environment and Natural Resources
NCWAM	North Carolina Wetland Assessment Method
NRC	National Research Council
NRCS	Natural Resources Conservation Service
PVC	polyvinyl chloride
RW	Riverine wetland
SEIWA	Southeastern Isolated Wetland Assessment
SC	South Carolina
USACE	United States Army Corps of Engineers
USC	University of South Carolina
USGS	U.S. Geological Survey
WMA	Wildlife Management Area
WTF	Water table fluctuation

CHAPTER 1

INTRODUCTION

Isolated wetlands are located throughout the United States and have variations in characteristics that are dependent upon each wetland's geographic location, climate, and geomorphology. These microhabitats are called depressional wetlands, as they have a slightly depressed topography surrounded by an upland area. Most notably, isolated wetlands have no surface water connection; however, their depressed topography allows a hydric regime to develop. Hydrologic inputs to isolated wetland systems are primarily precipitation, surface runoff, and groundwater inflow. Outputs are evapotranspiration, and groundwater outflow (Brinson 1990; Lugo et. al. 1990). As with several other types of wetlands, isolated wetlands can serve as areas for stormwater retention and groundwater recharge (Van de Kamp and Hayashi 1998; Leibowitz 2003; Leibowitz and Nadeau 2003).

In contrast, riverine or floodplain wetlands generally have a downward slope from upland to lowland. This area serves as the riparian buffer zone between the upland and a surface water body, such as a stream or river. As overland water travels to a drainage point, a valley is created at the lowest elevation where the vegetation and soils along the bank to adapt to the hydric regime. Because riverine wetlands are located along rivers, the primary inputs are overland flow and precipitation. Groundwater can also be an input. Like isolated wetlands, recharge can occur in floodplain wetlands—usually after surface water recedes. Outputs to these systems are evapotranspiration, discharge, and gaining streams. Research has demonstrated that riverine or floodplain wetlands have important hydrologic functions including stream buffering, water storage, and groundwater recharge (Richardson 1994).

Both of these wetland types have inputs and outputs that are a part of the system's water budget. One of the many components to the water budget is groundwater recharge—the addition of water to a subsurface aquifer. This type of input to the water budget is valuable because it functions as a water source during low river flows and low precipitation, and its abundance affects human, animal, and plant populations (Richardson 1994; Achayra and Barbier 2000).

Studies have shown that wetlands are a focal point for groundwater recharge (Richardson 1994; van de Kamp and Hayashi 1998). With the suggestion that geographically isolated wetlands may have similar hydrologic capabilities as riverine wetlands—based on their physical characteristics—there is a need to study the recharge capabilities of isolated wetlands. To the extent this issue has been studied, most of the focus has been on prairie potholes found in dry climates. Research in the Southeastern United States is in its beginning phases.

The purpose of this study was to perform a comparative analysis of groundwater recharge rates in the surficial aquifer of several isolated wetlands to recharge rates measured in the surficial aquifer of several riverine wetlands—both in response to storm events. In this study, recharge is defined as water that percolates through the vadose zone to the zone of saturation and reaches the water table (Lerner et. al. 1990; Devries and Simmers 2002).

CHAPTER 2

BACKGROUND

2.1 Wetlands

Wetlands are ecosystems with a dominant presence of water that generally remain inundated seasonally or constantly by surface water, groundwater, or both. As a result of this hydrologic regime, the soils and plants have been influenced by and adapted to constant or partial flooding for extended periods of time.

Water is a soil-forming factor that plays a large role in dictating the eventual physical, chemical, and biological nature of the soil. Wetland soils are formed under saturated conditions that determine chemical processes in the soil environment. Soil textures can vary depending upon geography, the amount of water present, and the amount of organic matter. Wetland soils typically have high water storage capacity, which favors creation of an anaerobic environment as water fills pore spaces instead of air (Federal Register 1994; NRC 1995). For survival, wetland plants have to adapt to these soil conditions in order to obtain the necessary nutrients for propagation, growth, and development.

Wetland plant species are often flood-tolerant and have minimal flooding constraints, but their abundance and distribution are variable because not all wetlands are subjected to constant ponding—as is the case with ephemeral and floodplain wetlands. The largest factor for wetland plants to overcome is the chemical environment of the soil. The lack of oxygen in the soil creates a major challenge, but physical adaptations allow wetland plants to obtain atmospheric oxygen and transport it to subsurface roots and create oxidized zones in which the plant can carry out its functions (Mendelssohn and Batzer 2006).

The combined characteristics of hydric regime, hydric soils and hydric plants are used to determine if an area is considered a wetland. Wetland delineation guidelines created by the Federal Manual for Delineating Wetlands (1989) list a series of field indicators that assess hydric regime, soil texture, and ecosystem flora to determine wetland boundaries.

2.2 Groundwater recharge

As mentioned earlier, groundwater recharge is one of the components of the water budget of an ecosystem. A definition of recharge provided by DeVries and Simmers (2002) the "the downward flow of water reaching the water table, forming an addition to the groundwater reservoir." When surface water percolates through the soil to the water table (the top of the surficial aquifer), it displaces air in soil pores. The subsequent addition of water to the water table causes an increase in volume of that aquifer. Pore size varies with soil texture and determines the speed at which the pore pressure equilibrates. When air is able to quickly escape the pressure caused by infiltrating water, the speed at which water is able to move throughout the soil profile increases (Williams 1978). As a result, soil textures with a greater amount of large pores (e.g. soils with a high percentage of gravel and sand) allow water to move more readily than soil textures with small pores (e.g. high percentage of silt and clay). The increased friction between soil water and soil particles also increases with smaller pore sizes and slows drainage.

As water percolates through the soil, it is added to the aquifer—a subsurface reservoir that is used by the surrounding vegetation as well as humans. During evaporation, water from the surficial aquifer moves upward and becomes available to plants. Some groundwater systems discharge to a waterway and assist in maintaining flows. And in perched systems where the water table intersects the land surface, groundwater becomes surface water. In terms of human benefits, individuals living in rural areas often use groundwater as a drinking water source and many agriculture regimes use groundwater for irrigation.

2.3 Geomorphology of riverine and isolated wetlands

While there is an overall variation in the topography of isolated wetlands and riverine wetlands, the underlying theme is that both ecosystems have some degree of depressed topography. While isolated wetlands have a singular depression surrounded by upland on all sides, riverine wetlands typically have a linear depression that bisects two segments of land and a slope from the upland to the depressed area. The National Research Council (NRC 1995) defines an isolated wetland as a "wetland not adjacent to another body of water", meaning the wetland is not at the fringe of a surface water body. Because most waters flow in the direction of downward sloping land (surficially or subsurficially), the downward slope caused by the depressed topography of both ecosystems makes them discharge areas for surface water. The presence of that water can create inundated areas and increase the likelihood of that area developing a hydric regime. That hydric regime would then lead to the development of hydric soils and the occurrence of hydric plants—meeting the established qualifications of being classified as a wetland.

Moving forward with the NRC’s definition of isolated wetlands, these ecosystems have no direct surface water connection, but surface water sources may include precipitation, surface runoff, or spillover from other wetlands or water bodies (Tiner 2003). In some cases, if the water table intersects the land surface, groundwater serves as surface water. As mentioned earlier, riverine wetlands have a continuous source of surface water, as they are the riparian areas for waterways. Although high water levels may not exist continuously, the hydropattern maintains the hydric regime.

Where the surface hydrology of isolated and riverine wetlands has been frequently compared (possibly due to the easily observed differences between the two systems), there has been minimal comparison of the soils profiles found in each of these systems. The hydropatterns of both wetland systems create the opportunity for the development of hydric soils. Soil profiles vary regionally and the presence of a hydric soil has to be made based on the evaluation of the soil in each specific location. Little research has been conducted to directly assess the similarity between the soil types of isolated wetlands and riverine wetlands within close proximity of one another.

Although riverine wetlands and isolated wetlands are different in topography and surface water hydrology, they generally have similar groundwater hydrogeology (Tiner 2003), primarily within the surficial aquifer. Despite the lack of a constant surface water connection, it is generally understood that all or most isolated wetlands maintain a groundwater connection to their surrounding areas, including nearby wetlands or surface water bodies (Tiner 2003). Stream channels are often in contact with the surficial aquifer and have the capability of supplying water to (influent stream) or receiving water from (effluent stream) the aquifer (Todd 1959). During the Hydrologic Connectivity, Water

Quality Function, and Biocriteria of Coastal Plain Geographically Isolated Wetlands study (IWC 2013), it was found that several isolated wetlands were connected to a nearby wetland and/or surface water body via the surficial aquifer.

2.4 Wetlands and humans

One of the ecologic functions of wetlands that are of benefit to humans is their water storage capability, which reduces the amount of flooding by capturing and storing stormwater runoff. Wetlands' ability to serve as sites for biogeochemical cycling and sediment reservoirs also makes them useful for erosion control, sediment control, water quality improvement, and waste water treatment (Richardson 1994). Humans also benefit from estuaries as they provide a habitat for many organisms harvested by the aquatic agriculture industry. In a recreational sense, wetlands are prime habitats for a variety of wildlife, which many people enjoy in a variety of ways—the foundation of ecotourism.

Although the functions, values, and benefits of wetlands are currently well-known, this has not always been the case. In 1850 the U.S. Congress passed the Swamp Land Act that encouraged citizens to convert swamps into land suitable for agriculture (Lewis 2001). The practice of converting wetlands continued over the next century. Prior to 1970 the U.S. federal government had no interest in protecting wetlands, directly, and by the mid-1980s the total acreage of wetlands in the U.S. had been decreased by 50% (Dahl 1990; Lewis 2001).

The initial pieces of legislature that resulted in the protection of wetlands, such as the Migratory Bird Treaty Act of 1918, were written with the intention of protecting and preserving migratory waterfowl habitat for the benefit of hunters (Mackenthum 1998), not to protect wetlands because they are hydrologically vital ecosystems. The Clean

Water Act, which called for the preservation of the chemical, physical, and biological integrity of the nation’s waters, resulted in new laws supporting the improved quality of surface water bodies, but was unclear in terms of federal protection of wetlands. Once decision-makers realized that water from a wetland often feeds larger water bodies, it became clear that the integrity of a wetland can impact surface water quality. Consequently, Congress included jurisdiction to encompass wetlands in Section 404 of the Clean Water Act (Lewis 2001), which required that entity wishing to dredge or fill a wetland to submit a permit to the U.S. Army Corps of Engineers (EPA 1994; Mackenthum 1998).

However, the unclear interpretation of the law later extended to wetlands that are not adjacent to flowing waters. The debate over isolated wetland protection jurisdiction has existed for over a decade, beginning with the 2001 Supreme Court case Solid Waste Agency of Northern Cook County v. United States Army Corps of Engineers, when United States Army Corps of Engineers’ (USACE) jurisdiction was re-defined and isolated wetlands were removed from jurisdiction under the grounds that they are not considered navigable waterways, nor are they connected to a navigable waterway (SWANCC vs. USACE et. al. 2001). That ruling was clarified in Supreme Court cases Rapanos v. United States and Carabell v. United States, in which USACE agencies were given jurisdiction over wetlands adjacent to traditional navigable waterways and tributaries, tributaries that are seasonal or “relatively permanent”, and wetlands directly adjacent to seasonal tributaries (Rapanos and Carabell vs. USACE 2006). Jurisdiction, on a case-by-case basis, also extends to seasonal tributaries and wetlands that may affect the physical, chemical, or biological integrity of traditional navigable waterways (SWANCC vs. USACE et. al. 2001).

Isolated wetlands are particularly vulnerable to destruction and loss from urbanization and development due to their size and difficulty to detect. The cumulative loss of isolated wetlands will decrease the number of sites that provide stormwater retention, groundwater recharge, nutrient retention, and water quality improvement (Plocher et. al. 2003)—all of which have ecologic as well as economic impacts. Moreover, the destruction of isolated wetlands in exchange for urban development increases the amount of impervious surfaces, which decreases water quality and increases the likelihood of flooding. Further understanding isolated wetlands on a scientific basis will aid in defining ecological and economic importance. This study aims to strengthen that scientific basis by adding to the current body of knowledge and exploring the capabilities of these two ecosystems.

CHAPTER 3

RESEARCH OBJECTIVE

Due to isolated wetlands' comparatively small size, it has been questioned whether or not they are capable of the same hydrologic functions as other wetland types. The objective of this study was to address that line of questioning by comparing groundwater recharge rates of isolated wetlands to that of riverine wetlands. Soil characteristics, changes in water table elevation, and precipitation for several riverine and isolated wetland systems was used to make the rate comparison, and that comparison provides insight on how a direct surface water connection may—or may not—impact a wetland's recharge capabilities. This data and the research findings could further strengthen the argument of their ecological importance.

As a second component to this study, the calculated recharge rates were used to aid in the calibration of the hydrologic modeling program Hydrological Simulation Program-Fortran (HSPF) which is used to simulate the occurrences of natural systems. Many components of the hydrologic cycle are simulated in HSPF, and by using observed measurements (as opposed to the recommended default values), we aimed to refine the recommended calibration inputs to ensure the model creates a stream flow output that more closely represents what is seen in a natural system.

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Study Sites

Four isolated wetland sites—located in Marion County, SC (2 sites); Horry County, SC (1 site); and Brunswick County, NC (1 site)—were used in this study (Figure 4.1). These sites were designated isolated wetland sites by either the Southeastern Isolated Wetland Assessment (SEIWA) conducted by RTI International, North Carolina Department of Environment and Natural Resources Division of Water Quality (NCDENR DWQ), South Carolina Department of Health and Environmental Control (SCDHEC), and University of South Carolina (USC) (SEIWA 2010) or by the Hydrologic Connectivity, Water Quality Function, and Biocriteria of Coastal Plain Geographically Isolated Wetlands (IWC) study conducted by NCDENR DWQ and USC. All sites are within Wildlife Management Areas or nature preserves in the Coastal Plain of the Carolinas.

Each study site contained an isolated wetland, an adjacent upland, and a riverine wetland with a surface water connection. There were no immediately observable surface water connections between the isolated wetlands and the riverine wetlands, but assessments have shown a subsurface hydrologic connection (IWC 2013). Within each site, sub-sites were named to identify each specific area (Table 4.1).

Figure 4.1. Geographic site locations

Four monitoring wells were installed at each at each site. The four wells at each site were identified as <IW, Upland, CW, RW>. *Isolated wetland* (IW) indicated the edge of isolated wetland. *Upland* identified the upland area between the isolated wetland and wetland with a surface water connection. *Connected wetland* (CW) identified a location at the edge of the riverine wetland. And *riverine wetland* (RW) referred to a location in the riverine wetland that is closer to the surface water. Due to the location of the accompanying monitoring well and its proximity to the surface water body, the MF site did not have an RW sub-site.

Table 4.1. Well identifiers for each site and sub-site. Marion County sites are located in USGS HUC 03040204. Horry and Brunswick County sites are located in HUC 03040207.

Well ID	Site ID	Sub-sites	County
MA-01	MA	Isolated wetland	Marion, SC
MA-02	MA	Upland	Marion
MA-03	MA	Connected wetland	Marion
MAFL	MA	Riverine wetland	Marion
MF-01	MF	Isolated wetland	Marion
MF-02	MF	Upland	Marion
MF-03	MF	Upland	Marion
MF-04	MF	Connected wetland	Marion
LB-01	LB	Isolated wetland	Horry, SC
LB-02	LB	Upland	Horry
LB-03	LB	Upland	Horry
LB-04	LB	Connected wetland	Horry
LBFL	LB	Riverine wetland	Horry
BR-1a	BR	Isolated wetland	Brunswick, NC
BR-1b	BR	Upland	Brunswick
BR -1c	BR	Connected wetland	Brunswick
BR-12	BR	Upland	Brunswick
BR-2a	BR	Isolated wetland	Brunswick
BR-2b	BR	Upland	Brunswick
BR-2c	BR	Connected wetland	Brunswick
BRFL	BR	Riverine wetland	Brunswick

4.1.1 Marion County Sites: MA and MF

The MA site and the MF site were located within the Marsh Wildlife Management Area that covers 3,464 ha of land in the southwestern part of Marion County near Gresham, SC. The MA site was located approximately 2 km southwest of the MF site (Figure 4.1). The two sites areas have similar vegetation, with the exception of the MA upland area which is filled with planted herbaceous vegetation.

The isolated wetlands in both sites were classified as basin wetlands based on the guidelines established by the North Carolina Wetland Assessment Method (NC WAM 2010). Table 4.2 lists the wetland types associated with each isolated and connected/riverine wetland. According to the NC WAM guidelines, basin wetlands are described as “depressions surrounded by uplands” that may be “seasonally to semi-permanently inundated but may lose surface hydrology during later portions of the growing season” (NC WAM 2010). The primary difference between basin wetlands and pocosins are often dominated by the presence of waxy vegetation.

The connected/riverine sites at both Marion County sites were classified as riverine swamp forest with following characteristics:

- Headwaters of streams in depressions subject to surface flow and/or groundwater expression
- Wettest portions of large river floodplains and other permanent water bodies, including linear depressions that lead to stream systems

  Linear depressions (both with and without surface water channels [natural or manmade] draining to rivers and sounds in the Middle Atlantic Coastal Plain (2010).

Table 4.2. Study site locations and wetland types

Site Name	Coordinates (DMS)	IW size (ha)	NC WAM Type – IW	NC WAM Type – CW/RW
MA	79° 27' 27.289" W, 33° 56' 57.948" N	0.46	Basin wetland	Riverine swamp forest
MF	79° 26' 45.962" W, 33° 57' 53.427" N	0.50	Basin wetland	Riverine swamp forest
LB	78° 52' 4.212" W, 33° 48' 57.021" N	1.70	Pocosin	Riverine swamp forest
BR1	78° 16' 36.894" W, 34° 3' 14.580" N	0.09	Basin wetland	Riverine swamp forest
BR2	78° 16' 35.242" W, 34° 3' 13.536" N	0.11	Basin wetland	Riverine swamp forest

A point to be noted, the connected wetland sub-site at MA is transected by a road, unnaturally disconnecting it from the remainder of the wetland with a surface water connection.

4.1.2 Horry County Site: LB

The LB site is located within the Lewis Ocean Bay Heritage Preserve/Wildlife Management Area. As a heritage preserve, this 9,690-acre tract of land is protected from destruction with the intent to conserve resources deemed naturally and culturally significant to South Carolina. It has also been designated an Important Bird Area by the South Carolina Audubon Society (SCDNR 2013).

The isolated wetland, with a size of 1.70 ha (Table 4.2) was classified as a pocosin by NC WAM guidelines. According to the NC WAM descriptions, pocosins are primarily fed by “a high or perched water table resulting from precipitation and slow drainage” (NC WAM 2010). The isolated wetland at this site was also dominated by waxy vegetation. This site had undergone a prescribed burn within one year prior to the start of this study. The effect of the burn was still apparent in the appearance of the isolated wetland. The riverine wetland at the LB site was classified as a riverine swamp forest with the same characteristics as the riverine swamp forest in the Marion County sites.

4.1.3 Brunswick County Site: BR

Located in the central portion of Brunswick County—near Supply, NC—the BR site was located in Green Swamp Preserve (7,051 ha) (TNC 2013). The Green Swamp Preserve is also a protected area with prescribed burning. The study area at this site was burned one year prior to the start of this study. This site contained two adjacent isolated wetlands and both isolated wetlands were classified as basin wetlands. The riverine wetland was classified as a riverine swamp forest; however, describing it as a sinkhole with a surface hydrologic connection to downstream water would be more accurate.

The presence of two isolated wetlands sets this site apart from the remaining study sites. Also, the connected wetland was indirectly connected to the nearby surface waterway and it almost appeared to be a larger isolated wetland itself. The riverine wetland sub-site was located 1.23km from the remainder of the site as it was the most accessible location to collect the proper data for this study.

4.2 Data Collection

Data collected in the IWC study that was used in the present study includes water level measurements, physical and topographic measurements, and soil characterizations. The primary investigator of the present study was also responsible for collecting the data for the IWC study with the exception of soil profiles taken at the MF and BR sites. Water level data at the BR site was collected as an extension of the SEIWA study. Water level and soil data at all riverine sub-sites were collected solely for the purpose of the present study.

4.2.1 Groundwater Monitoring

At each site, groundwater monitoring wells were installed in the surficial aquifer to create a transect that extended from the edge of the isolated wetland to the connected wetland (Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5, Figure 4.6). With the exception of the LB site, due to geographic constraints and surface water levels, it was not possible to extend the transect for the RW wells, so they were installed in the most accessible location. Wells located in the isolated wetland, upland, and connected wetland of the MA and LB sites were constructed of polyvinyl chloride (PVC) casing and bored using a Geoprobe operated by ARM Environmental Services, Inc. technicians, while wells at the MF and BR sites were constructed of PVC casing and bored by hand. All wells in the riverine wetland sub-site were constructed of PVC and bored by hand. The location of the screens for each well is shown in the figures in Section 5.1. Each well had a diameter of 5 cm and depths between approximately 2m– 7m. Wells were constructed following the guidelines from Sprecher 1993, 2000. Commercial well sand (#4) was used to fill the space between the well casing and bore hole. The top 15 cm was filled with Bentonite pellets to eliminate the opportunity for surface water to affect water level measurements in the well. Wells at the MA and LB site were installed in July 2011, wells at the MF site were installed in May 2011, and wells at the BR site were installed in June 2010 and January 2011 (for BR12). All wells in the RW sub-site were installed in January 2012.

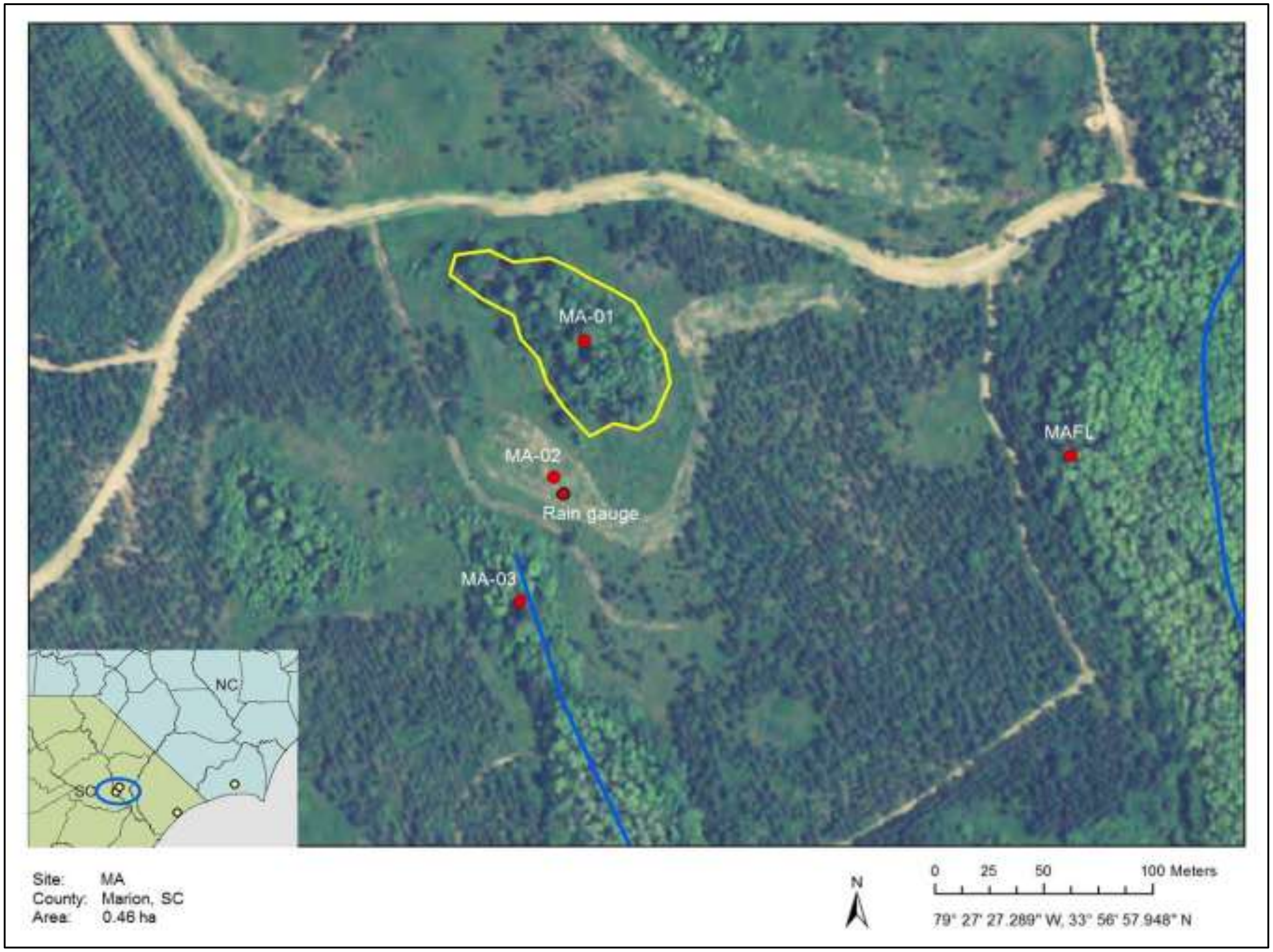

Figure 4.2. Transect of groundwater monitoring wells at MA site. The isolated wetland is outlined in yellow and nearby surface water body in blue. Well associations with sub-sites are as follows: MA-01, isolated wetland; MA-02, upland; MA-03, connected wetland; MAFL, riverine wetland. Projection: NAD 83 UTM

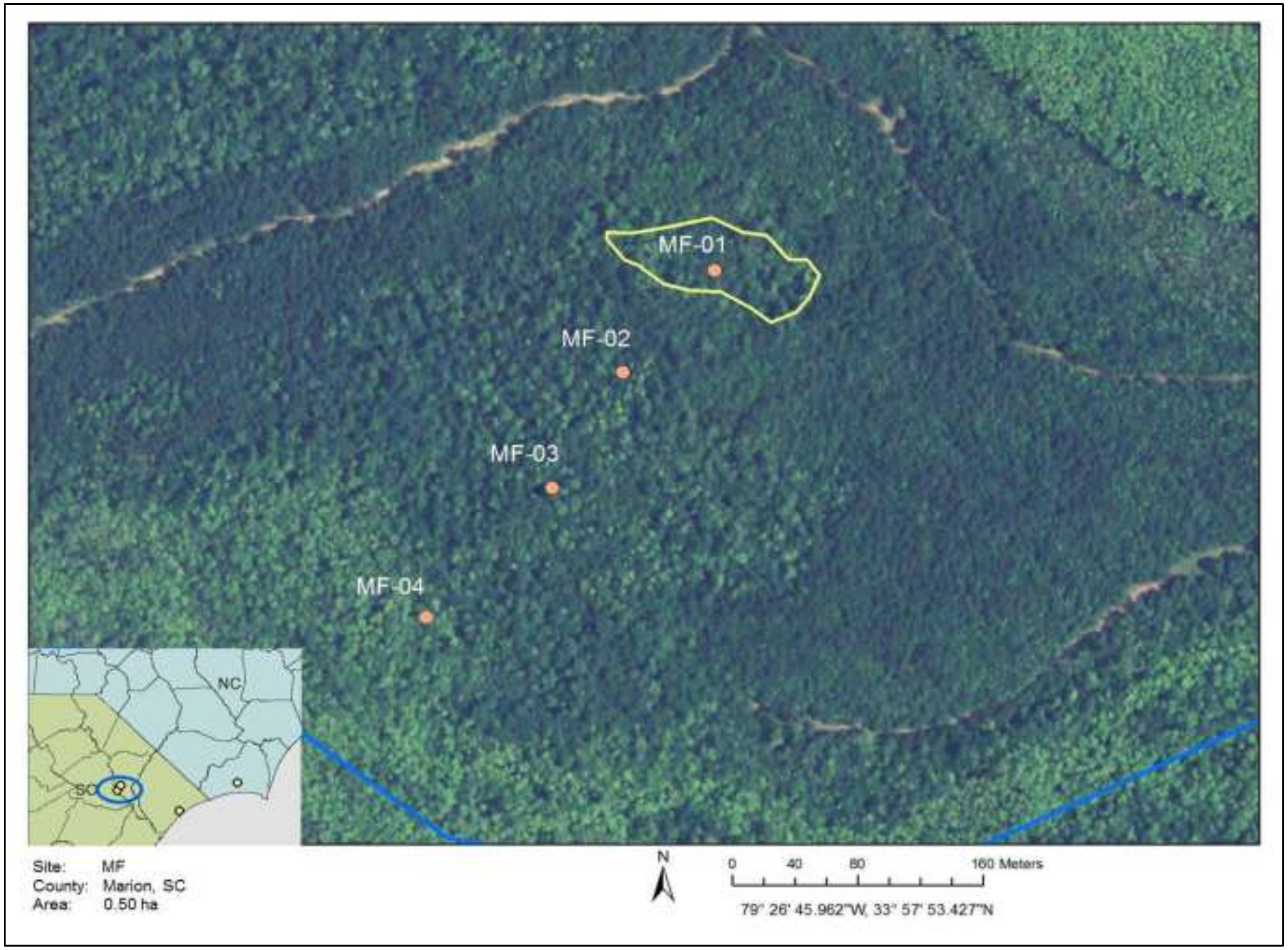

Figure 4.3. Transect of groundwater monitoring wells at MF site. The isolated wetland is outlined in yellow and nearby surface water body in blue. Well associations with sub-sites are as follows: MF-01, isolated wetland; MF-02, upland; MF-03, upland; MF-04, connected wetland. Projection: NAD 83 UTM 17N

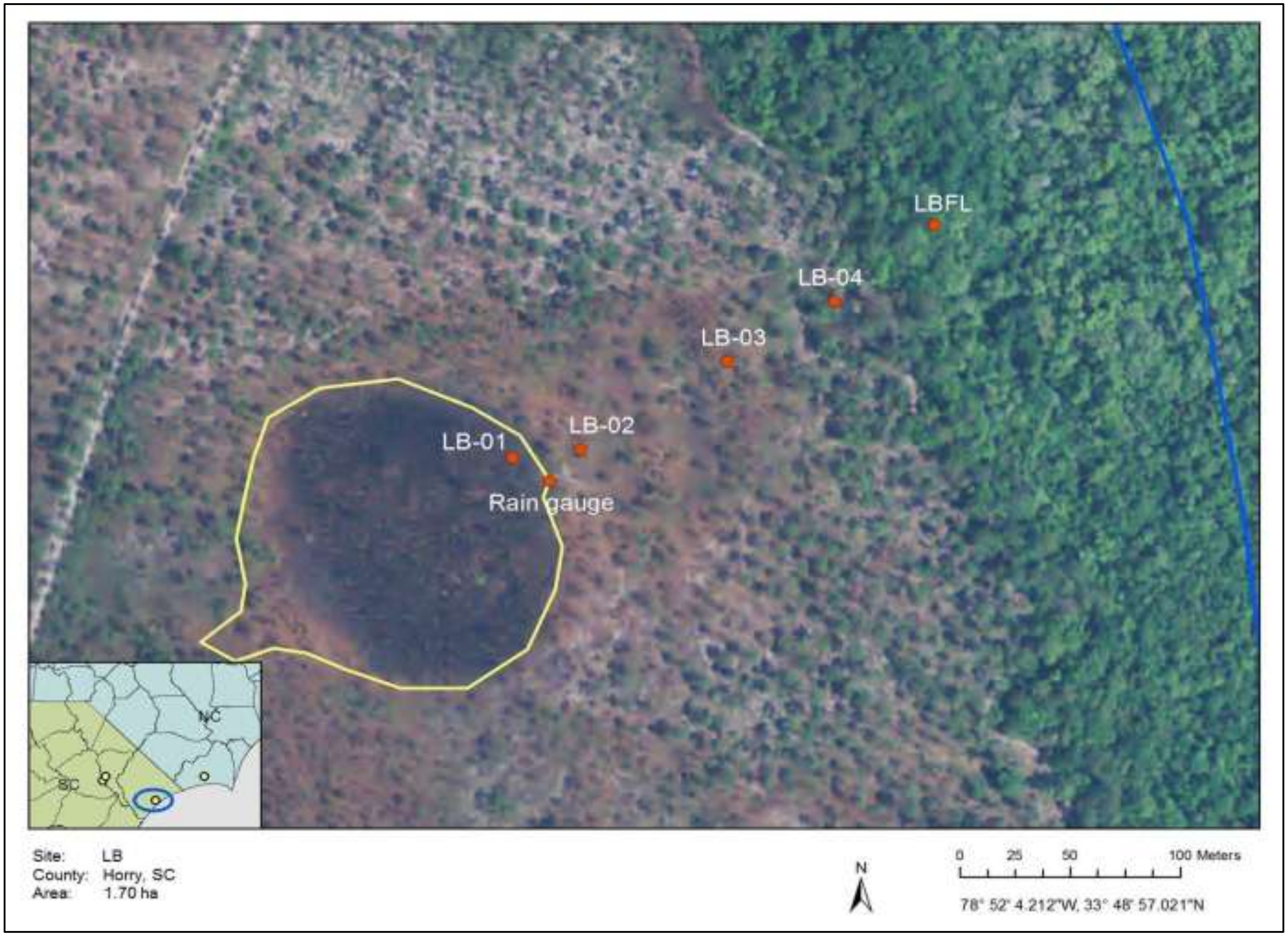

Figure 4.4. Transect of groundwater monitoring wells at LB site. The isolated wetland is outlined in yellow and nearby surface water body in blue. Well associations with sub-sites are as follows: LB-01, isolated wetland; LB-02, upland; LB-03, upland; LB-04, connected wetland; LBFL, riverine wetland. Projection: NAD 83 UTM 17N

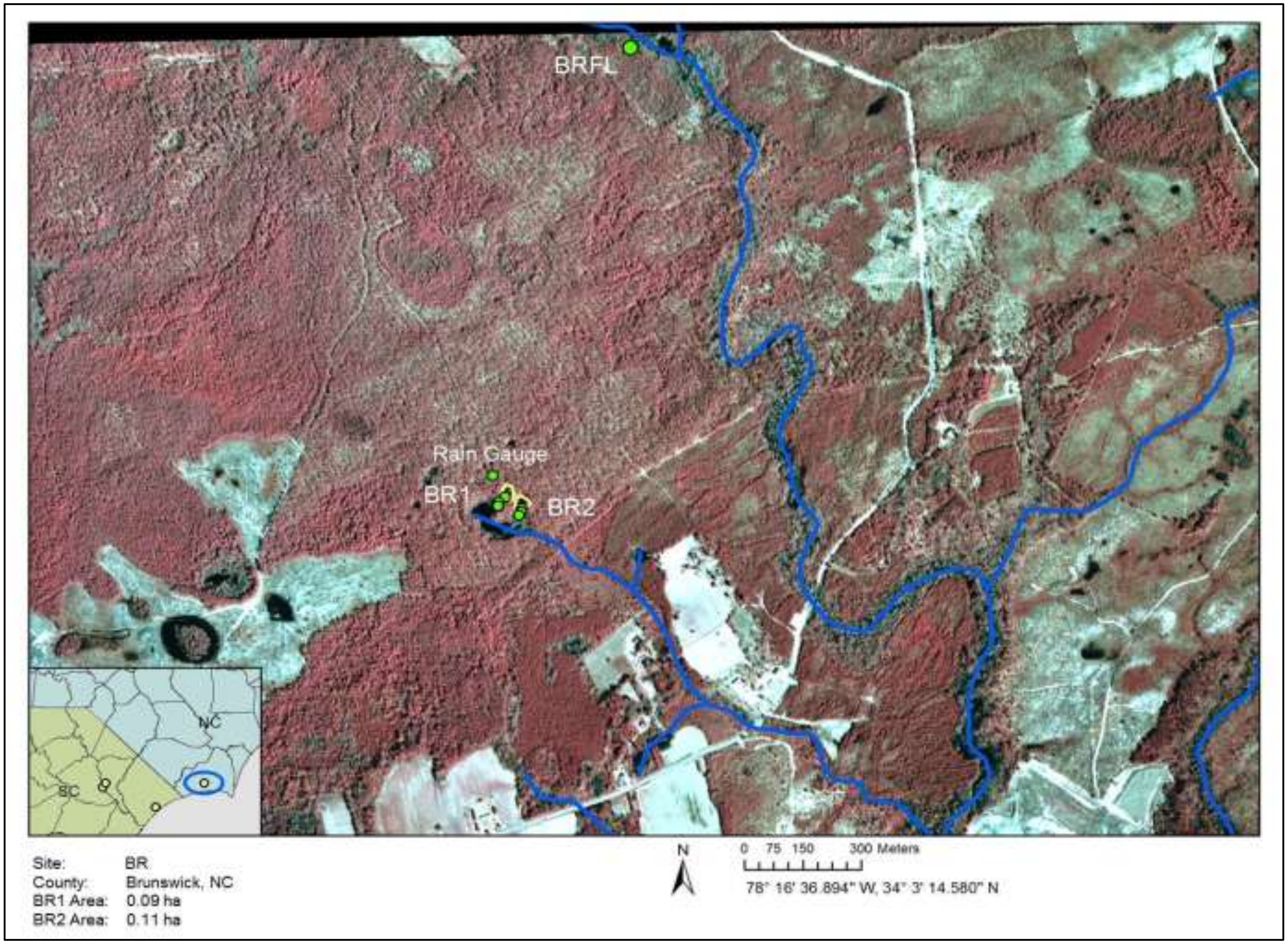

Figure 4.5. Aerial view of groundwater monitoring wells at BR site, showing all wells at the site. Well BRFL is associated with the riverine wetland sub-site. Well transects of BR1 and BR2 isolated wetlands are shown in Figure 4.6. NAD 83 UTM 17N

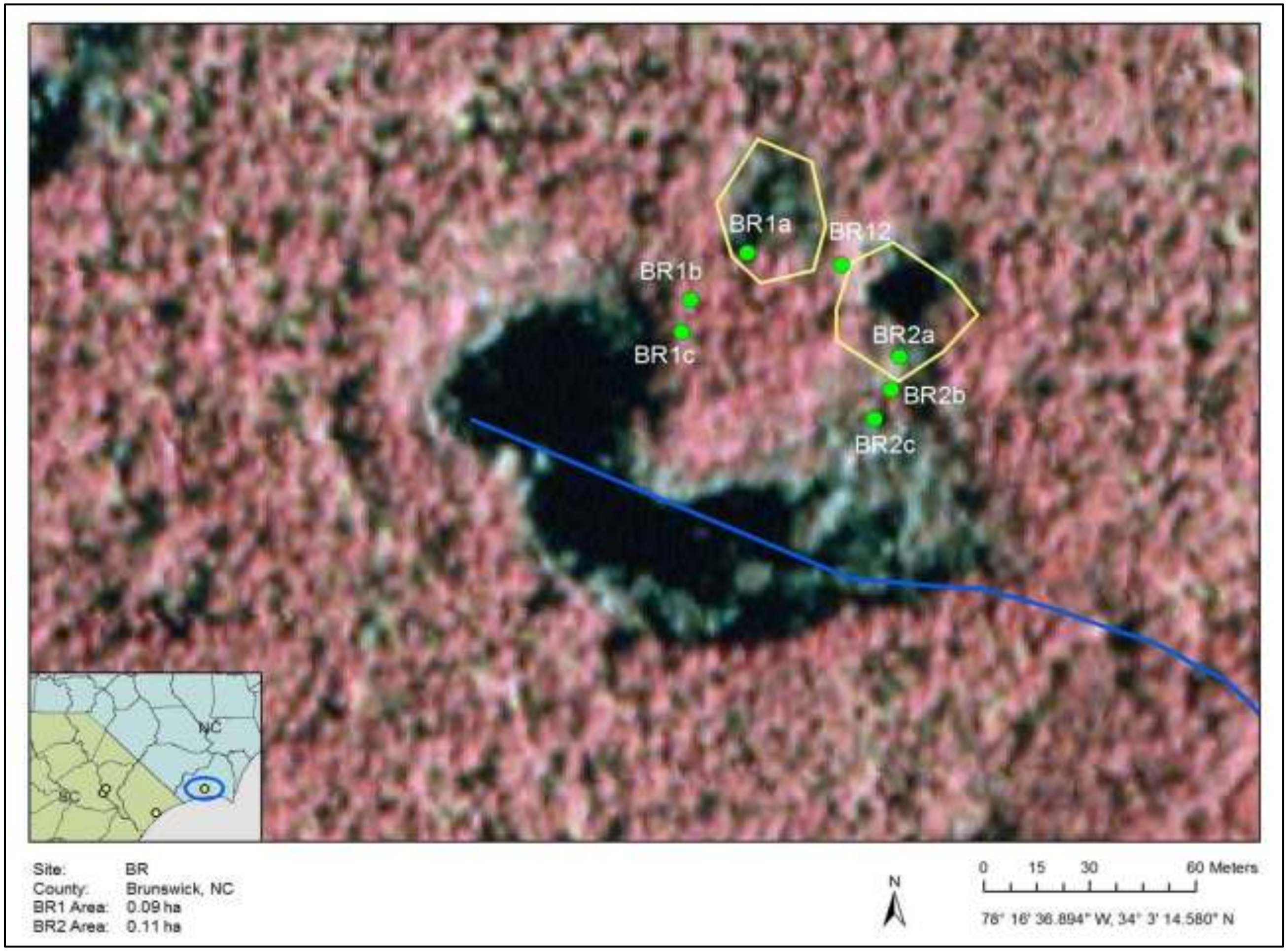

Figure 4.6. Transect of groundwater monitoring wells at the BR site with an outline of the isolated wetland (in yellow) and nearby surface water body (in blue). Well associations with sub-sites are as follows: BR1a and BR2a, isolated wetland; BR1b and BR2b, upland; BR1c and BR2c, connected wetland; BR12, upland (between isolated wetlands). No data loggers were placed in wells 1c and 2c. Projection: NAD 83 UTM 17N

All monitoring wells were outfitted with pressure transducers whose accompanying software translated the pressure measurements to changes in water table depth. Wells in the IW, upland, and CW sub-sites were outfitted with LevelTROLL®500 and 700 transducers and wells in the RW sub-sites were outfitted with either a WL16S GlobalWater or a U20-001-01 HOBO® water level logger. The pressure/level sensors on the TROLL and GlobalWater loggers have ±0.1% accuracy. The HOBO loggers have a water level accuracy of ±0.05% and a raw pressure accuracy of ±0.3%.

Water level loggers recorded hourly temperature and water level. Logger data was downloaded every two months for the duration of the data collection period. At each data download instance, discrete water table measurements were also made using a Geotech Water Level Meter (also referred to as an e-tape) with a 3m/30m accuracy level. The water level meter was used to establish an initial depth to water (DTW) measurement from a designated measuring point at the top of the well casing. Each time logger data was downloaded, the e-tape reading was compared to the logger reading. All readings were recorded on field sheets (Appendix A) and if there was 0.06cm difference between the logger reading and the e-tape reading, then the logger DTW was set to match the e-tape reading. This was done to correct for electronic drift of the water level loggers.

Once the logger data was downloaded, it was compiled into a Microsoft Excel spreadsheet and converted into a measurement for the depth to water from ground level and water table elevations (as determined by level surveying, which is discussed in Section 4.2.2). A spreadsheet containing this data was created for each well used during the study that was outfitted with a water level logger. Field sheets were completed during each download event. Datasets for wells located in IW, upland, and CW sub-sites were collected from July 2011 – September 2012 (data collection at the BR site ceased June 2012); but only data from January 2012 – September 2012 was used during analysis. Data for wells located in the RW sub-sites was collected from January 2012 – September 2012 (data collection at the BR site ceased June 2012).

4.2.2 Differential Level Surveying

After well construction was complete, differential level surveys were conducted to determine the elevation above sea level at the top of each well casing (at the specified measuring point used throughout the study). At the South Carolina sites, the South Carolina Geodetic Survey set elevation benchmarks from which differential surveys were performed (Table 4.3). At the Brunswick County site, a pre-existing monitoring well (installed during the SEIWA study) with a known elevation was used as the temporary benchmark, and from there the elevation of the remaining wells were determined (Table 4.3). Water table elevations were calculated by subtracting the recorded DTW from the measured survey elevation.

4.2.3 Soil Classification

During the time of well construction, soil profiles were created either from soil cores (when mechanical boring was used) or by recorded changes in soil texture as depth increased (when wells were hand bored). In both instances, a Munsell Soil Color Chart (Munsell Color Company 2000) was used to determine chroma, value, and hue; and the “Soil Texture by Feel Flow Chart” (Brookings Institution 2000) was used to determine soil texture. Stratigraphy maps detailing observed soil profiles can be found in Section 5.1.

Table 4.3. Elevation at well locations

Well ID	Ground Elevation (m msl)
MA-01	8.081
MA-02	8.476
MA-03	7.933
LB-01	12.110
LB-02	12.216
LB-03	10.799
LB-04	8.391
LBFL	6.787
MF-01	9.065
MF-02	9.783
MF-03	8.833
MF-04	8.577
BR1a	15.845
BR1b	16.878
BR1c	16.867
BR12	16.587
BR2a	14.641
BR2b	15.909
BR1c	15.198

The observed profiles were also compared to soil type data at each site and sub-site retrieved from the Natural Resources Conservation Service (NRCS) for continuity (Table 4.4.).

4.2.4 Precipitation

To collect precipitation data, Onset™ RG2 and RG3 tipping bucket rain gauges were installed at each site in an open area to minimize interception. The rain gauges had a calibration accuracy of ±0.1% and a time accuracy of ± 1 minute per month. Because of the sparsely interrupted no overhead vegetation at the MF site, one rain gauge was used for both Marion County sites. The tipping bucket-style rain gauges were set to record hourly air temperature and amount of precipitation. Each tip had the capacity to hold a specific amount of precipitation, allowing the number of “tips” to be converted into a measurement of precipitation. For the Brunswick County and Horry County rain gauges, each tip represented 0.020 cm. Each tip of the Marion County rain gauge represented 0.025 cm.

Data from the rain gauges was downloaded every two months during the same site visit in which the water level logger data was downloaded. Those datasets were also compiled into Microsoft Excel spreadsheets for a continuous dataset from January 2012 – September 2012 for each site (data collection at the BR site ceased June 2012).

Table 4.4. Soil names, abbreviations, textures, and drainage classes for sub-sites

Soil Name	Name abbreviation	Location	Soil Texture (<1m)	Drainage class
Lakeland sand, 0-6% slope	LaB	Marion Co, SC	Sand	Excessively drained
Tawcaw-Chastain association	TC	Marion Co, SC	Clay, clay loam	Poorly drained
Cantey Loam	Cn	Marion Co, SC	Loam, clay	Poorly drained
Echaw sand	Ec	Horry Co, SC	Sand	Moderately well drained
Johnston loam	Jn	Horry Co, SC	Loam	Very poorly drained
Kureb fine sand, 1-8% slope	KrB	Brunswick Co, NC	Fine sand, sand	Excessively drained
Muckalee loam	Mk	Brunswick Co, NC	Loam, sandy loam	Poorly drained

4.2.5 Recharge Measurement

Based on the literature, regional climate of the sites, and underlying geomorphology of the sites, the water table fluctuation (WTF) method was chosen to estimate recharge rates. This method is best used for unconfined aquifers (Healy and

Cook 2002) with shallow water tables that have a rapid response to precipitation (Moon *et. al.* 2004). The WTF method uses a water table budget to assume that a rise in the water table, as measured by an increase in a surficial groundwater well, is caused by recharge (Healy and Cook 2002; Crosbie *et. al*. 2005). In an equation adapted by Callahan *et. al.* (2012), recharge is measured as

$$R = [S_y(h_a - h_{m)}] / \Delta t \qquad (1)$$

where R is the rate of recharge [cm/day] from the maximum water table depth (h_a) [cm] to the minimum water table depth (h_m) [cm], S_y [dimensionless] is the specific yield, and Δt is the duration of the recharge event [days] (Scanlon *et.al.* 2002; Healy and Cook 2002; Callahan *et. al.* 2012**)**. This method is commonly used for recharge calculation and is especially appropriate for measuring recharge over short periods of time (Healy and Cook 2002), such as during (and after) storm events where precipitation is high over a short period of time. The WTF method is also ideal for use in sandy soils, where the water table's response to precipitation occurs within 24 hours of the precipitation event (Williams 1978). Using Equation 1, recharge values were calculated using the water table rise associated with each type of storm event, as characterized by the amount of precipitation in a continuous period.

In order to account for natural groundwater recession rate in the absence of precipitation, Equation 2 was used to explain the exponential decay of the water table to be used when determining h_a. The equation, which was originally used by Zhang and Schilling (2006) and adapted by Callahan *et. al.* (2012), is written as

$$h_a = h_i + h_0[1 - e^{-\alpha t}] \qquad (2)$$

where h_a [m] is the projected water table depth at the end of the recession period, h_i [m] is the water table depth at the beginning of the recession period, h_0 [m] is the observed maximum water table depth at the end of the recession period, α [d^{-1}] is the recession coefficient, and t [d] is time. For a conceptual representation of the relationships between Equation 1. and Equation 2., refer to Figure 4.7.

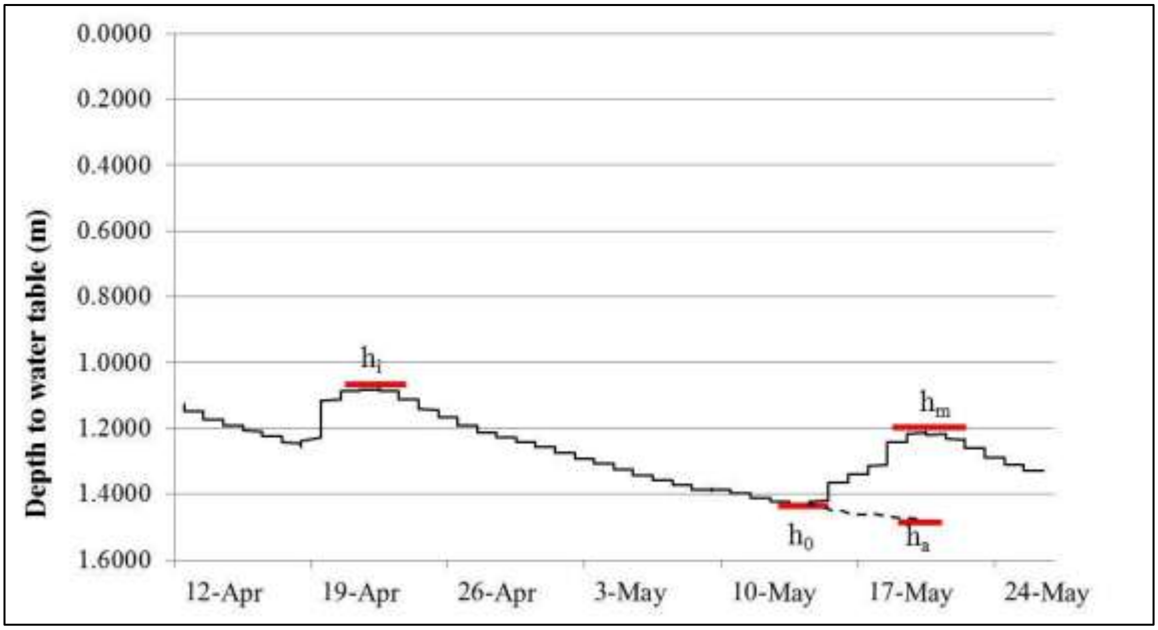

Figure 4.7. Relationship between the hydraulic head variables. In Equation 1. and Equation 2., h_i is the minimum water table depth at the beginning of the recession period, h_0 is the observed maximum water table depth at the end of the recession period, h_a is the projected water table depth at the end of the recession period, and h_m is the minimum depth to water at the beginning of the storm event.

Using a subset of the water level data, S_y values were calculated using a formula established by Williams (1978) and adapted by Callahan *et. al.* (2012). In the formula

$$S_y = P/\Delta h \tag{3}$$

S_y is specific yield [dimensionless], P [cm] is precipitation, and Δh [cm] is the change in hydraulic head prior to the water table rise. For each site, four storm events were chosen to measure the ratio of the volume of water drained throughout the soil profile to the total volume of water in the soil (specific yield, defined). The events used for S_y calculation were different from the events used for recharge rate calculation, and were chosen based on the duration of the event (between 1 – 8 consecutive hours), the amount of precipitation that occurred during the event (>1 cm for most sites), and the depth to water below the ground surface (0.02 m – 1.1 m).

These constraints were specified due to the amount of precipitation needed to induce a water table response that could be directly associated with a storm event. Precipitation frequency (identified by a specific period) was also used as a constraint, but due to equipment malfunctions and the aforementioned constraints not being met, choosing multiple storm events within a period was not always possible. The values for the four events were averaged and then used as input for Equation 1.

Within each site, a S_y value was calculated for each soil type. It would have been preferred that a S_y value be designated for each sub-site because designating S_y values for soil types does not account for drainage variability created by vegetation in the sub-site (e.g. an IW and an upland sub-site may have the same soil type, but the vegetation and organic matter within the topsoil can increase drainage, and thus, increase S_y values). However, given the stipulation established by Williams (1978) that water tables greater than 110 cm do not truly reflect the parabolic recharge and drainage capabilities of a soil, S_y values cannot be accurately calculated for water tables at that depth using this method. In this study some sub-sites consistently had water table depths greater than 110 cm and S_y values had to be established for each soil type. Table 4.5 shows the average calculated S_y values for each sub-site and soil type.

Table 4.5. Specific yield values± standard deviation calculated based on soil types at each site

Site Name	Sub-site	Soil Type (abbreviation)*	Sy
MA	Isolated wetland	LaB	0.32±0.08
MA	Upland	LaB	0.15±1.20
MA	Connected wetland	TC	0.21±0.17
MA	Riverine wetland	TC	0.18±0.10
MF	Isolated wetland	LaB/Cn	0.10±0.02
MF	Upland	Cn	0.12±0.06
MF	Connected wetland	TC	0.18±0.11
LB	Isolated wetland	Ec	0.13±0.08
LB	Upland	Ec	0.18±0.02
LB	Connected wetland	EcJo	0.17±0.02
LB	Riverine wetland	Jo	0.15±0.03
BR	Isolated wetland	KrB	0.28±0.21
BR	Upland	KrB	0.28±0.21
BR	Connected wetland	KrB	0.28±0.21
BR	Riverine wetland	Mk	0.18±0.06

**see Table 4.4. for explanation of abbreviations*

The calculated h_a and S_y, values were converted (if necessary) and inserted into Equation 1 to estimate recharge rates [cm/day] for each site for each precipitation event. Classification of storm events can be found in the results section of this report.

CHAPTER 5

STUDY RESULTS

5.1 Soil profiles

During the construction of the wells, soil profiles were taken that noted the texture and color (chroma, hue, and value), and the depths at which those characteristics changed. From the profile data, maps were created as a visual representation of the underlying stratigraphy. Each profile was segmented into units of the primary soil texture. Within the profile—and the units—small segments of a single soil texture were also represented. In addition to the soil profiles, the stratigraphy maps also show the location of the monitoring well, the placement of the screened portion of the well, and the water level under two different conditions.

5.1.1 Site BR

Due to the presence of two isolated wetlands and the location of the wells, multiple stratigraphy maps were created for this site, but as a result of BRFL being installed outside of the transect, its soil profile is detailed in Table 5.1., instead of within in the maps below.

At BR1 (Figure 5.1) a unit of medium grain-sized sand that was between 1 m – 3 m thick existed throughout the transect. At wells BR1c and BR1b, within the unit of sand were segments of loamy sand (0.5 m – 1 m thick) and clay (1 m thick). Weathered shale was observed as a third layer at BR1c and sandy clay was observed above and below the clay layer at well BR1b. Well BR1a simply had a surface layer of silty loam approximately 1 m thick atop the aforementioned unit of medium grain-sized sand.

Figure 5.2 shows that at the second isolated wetland, BR2, there was a 0.5 m thick unit of loam at the ground surface throughout the transect. A second unit of medium grain-sized sand, between 1 m – 2 m, existed beneath the loam, but was horizontally intersected by a layer of sandy clay. At the bottom the soil profiles throughout BR2 a unit of clay was observed. Sandy clay loam segments were also noted at BR2c at 1 m and 2 m below the ground surface.

Table 5.1. Detail of soil profile at BRFL

Depth below ground (m)	Texture	Munsell color
0 – 0.20	clay loam	7.5YR 2.5/1
0.20 – 0.36	silty clay	7.5YR 2.5/1
0.36 – 0.81	loamy sand	7.5YR 3/1
0.81 – 1.35	sand	7.5YR 4/1
1.35 – 1.84	loamy sand	7.5YR 3/1

5.1.2 Site LB

Stratigraphy at the LB site in Horry County (Figure 5.13) showed a first-level unit of medium grain-sized sand for 1.5 m – 2 m with a mixture of rounded and sub-rounded grains. Within this unit, a loamy sand segment at LB-02 was observed. The second-level unit observed was 1 m – 3 m thick and consisted of fine grain-sized sand, with the presence of a loamy sand segment at LB-01. Medium grain-sized sand was also observed at the third-level unit of this site. However, that sediment layer was not observed in cores from LB-03 and LBFL. At the surficial layer, a silty loam was observed at the connected wetland (LBFL) and the isolated wetland (LB-01). The silty loam at LBFL consisted of a high amount of organic matter with a light and fluffy texture.

5.1.3 Site MA

In the stratigraphy at the MA site (Figure 5.4) the sediment composition consisted of a first-level unit of medium grain-sized sand that was 1.2 m – 3 m thick, while the second-level unit consisted of coarse sand and was approximately 4.5 m thick. The third unit of medium grain-sized sand was observed nearly 5 m below ground surface, but only at well MA-01. Loam, loamy sand, and silty loam segments were observed at the surface (topsoil) at wells MA-01, MA-02, and MA-03, respectively. A surficial layer of clay loam underlain by a discontinuous layer of sandy clay loam was observed at both the isolated wetland and the connected wetland. The lowest unit of two of the cores (MA-02 and MA-03) contained dark-colored, hard clay.

Table 5.2. Details of soil profile at MAFL

Depth below ground (m)	Texture	Munsell color
0 – 0.43	silty clay	10YR 3/2
0.43 – 0.99	sand	7.5YR 5/1
0.99 – 1.07	sandy clay loam	10YR 5/2
1.07 – 1.32	sandy clay	10YR 4/1
1.32 – 1.63	sandy clay	10YR 4/2
1.63 – 1.73	loamy sand	10YR 4/1
1.73 – 1.91	loamy sand	10YR 4/2

5.1.4 Site MF

A 0.6 m – 1.2 m layer of medium grain-sized sand was observed as the first-level unit only at MF-02 (Figure 5.5). A second-level unit of loamy sand, 0.6 m – 1.2 m in thickness was observed at each of the wells throughout the transect, but serves as the first-level unit for MF-03 only. And a third-level unit of medium grain-sized sand was observed underlying the entire transect (approximately 1.2 m below land surface). Soil cores indicated the presence of loamy sandy clay 0.6 m below land surface at MF-03 and sandy clay 1 m below land surface at MF-04. A surficial layer of loam was observed within the isolated wetland (at MF-01) while a surficial layer of clay loam was observed within the connected wetland (at MF-04).

5.2 Precipitation

Due to the placement of the rain gauges (one in Marion County for MA and MF sites; one in Horry County for LB site; one in Brunswick County for BR site) each rain gauge is named for the county in which it is located. Although given the county's name, the measured precipitation was only at the study sites, and is not an indication of the precipitation throughout the entire county.

5.2.1 Trends throughout the study period

During the study period, the average daily precipitation ranged from 0.09 cm - 0.54 cm, 0.10 cm – 0.66 cm, and 0.12 cm – 0.41 cm measured at the Marion, Horry, and Brunswick County sites, respectively (Table 5.3.). Due to a malfunction of the Marion and Brunswick County rain gauges, precipitation data was not available after June for those sites. At the Brunswick County site, average monthly precipitation amounts increased from January to March (later winter to early spring), decreased in April, and increased again in May. At the Marion County sites, average precipitation amounts increased continuously from January to May. And at the Horry County site, a steady increase in precipitation was observed from January – March, with consistent month-to-month fluctuations occurring until September.

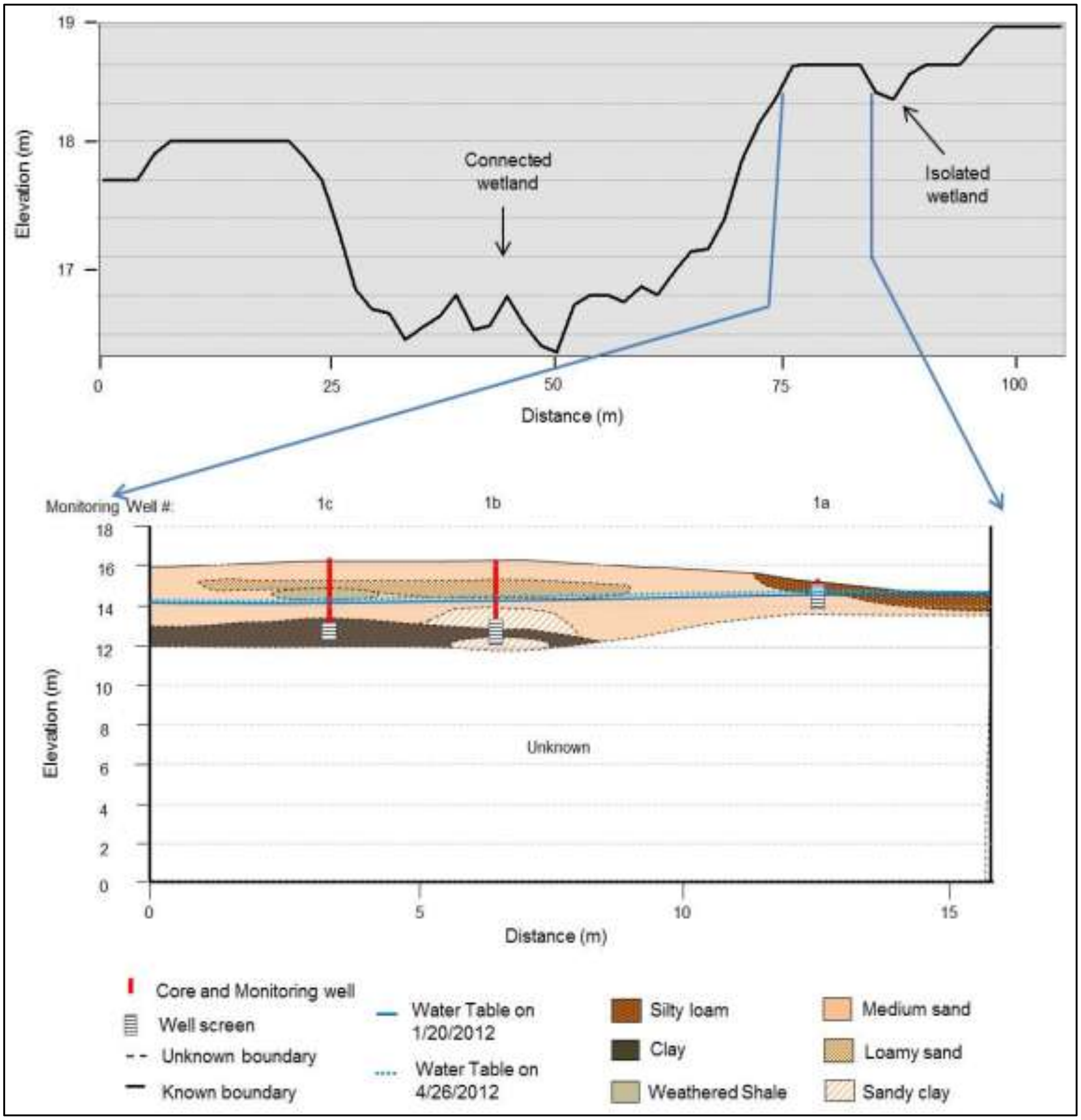

Figure 5.1. Stratigraphic map of the soil profile of isolated wetland BR1 at the BR site. Vertical exaggeration: 15.1x (upper image) and 0.4x (lower image)

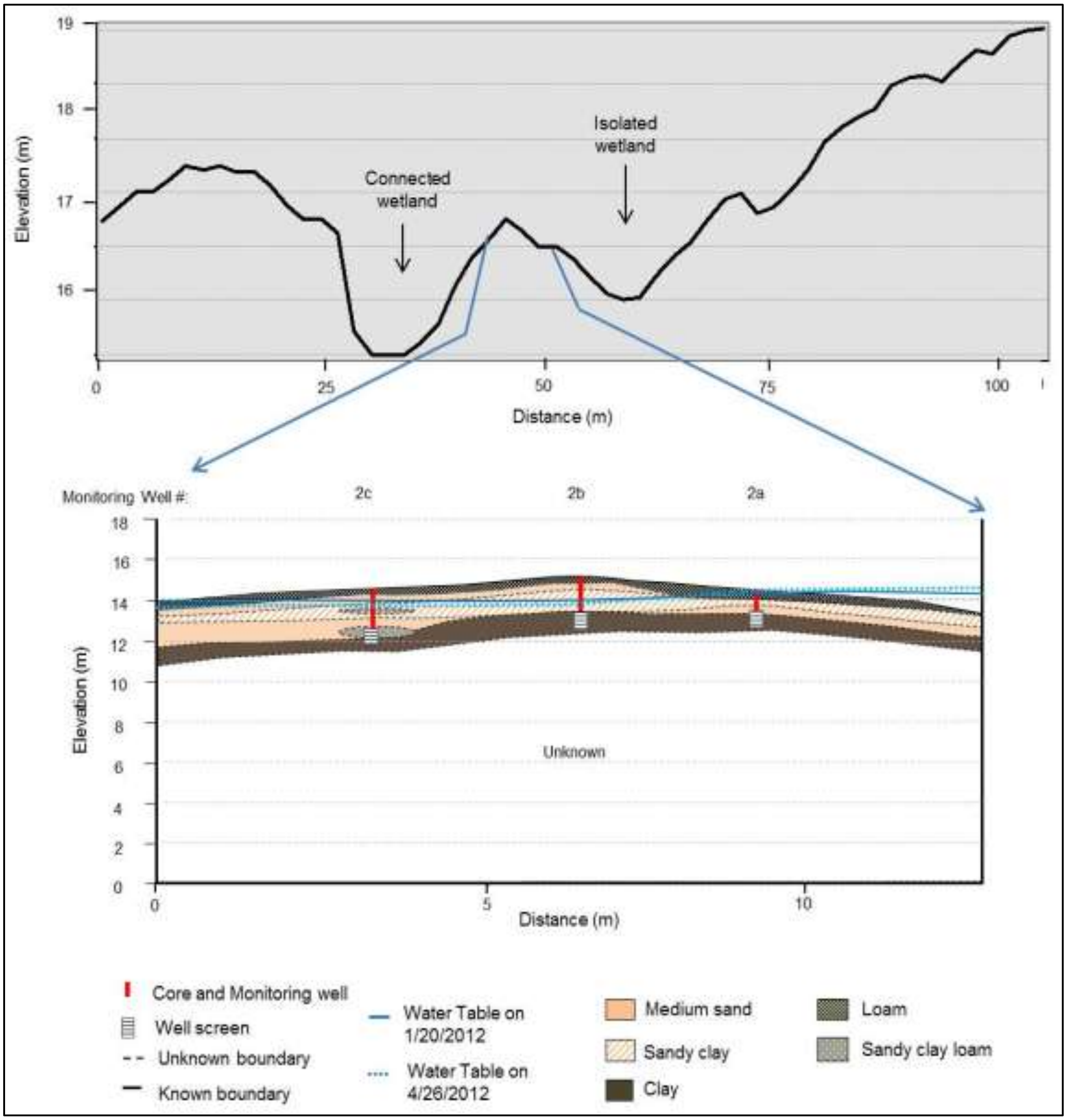

Figure 5.2. Stratigraphic map of the soil profile of isolated wetland BR2 at the BR site. Vertical exaggeration: 9.8x (upper image) and 0.3x (lower image)

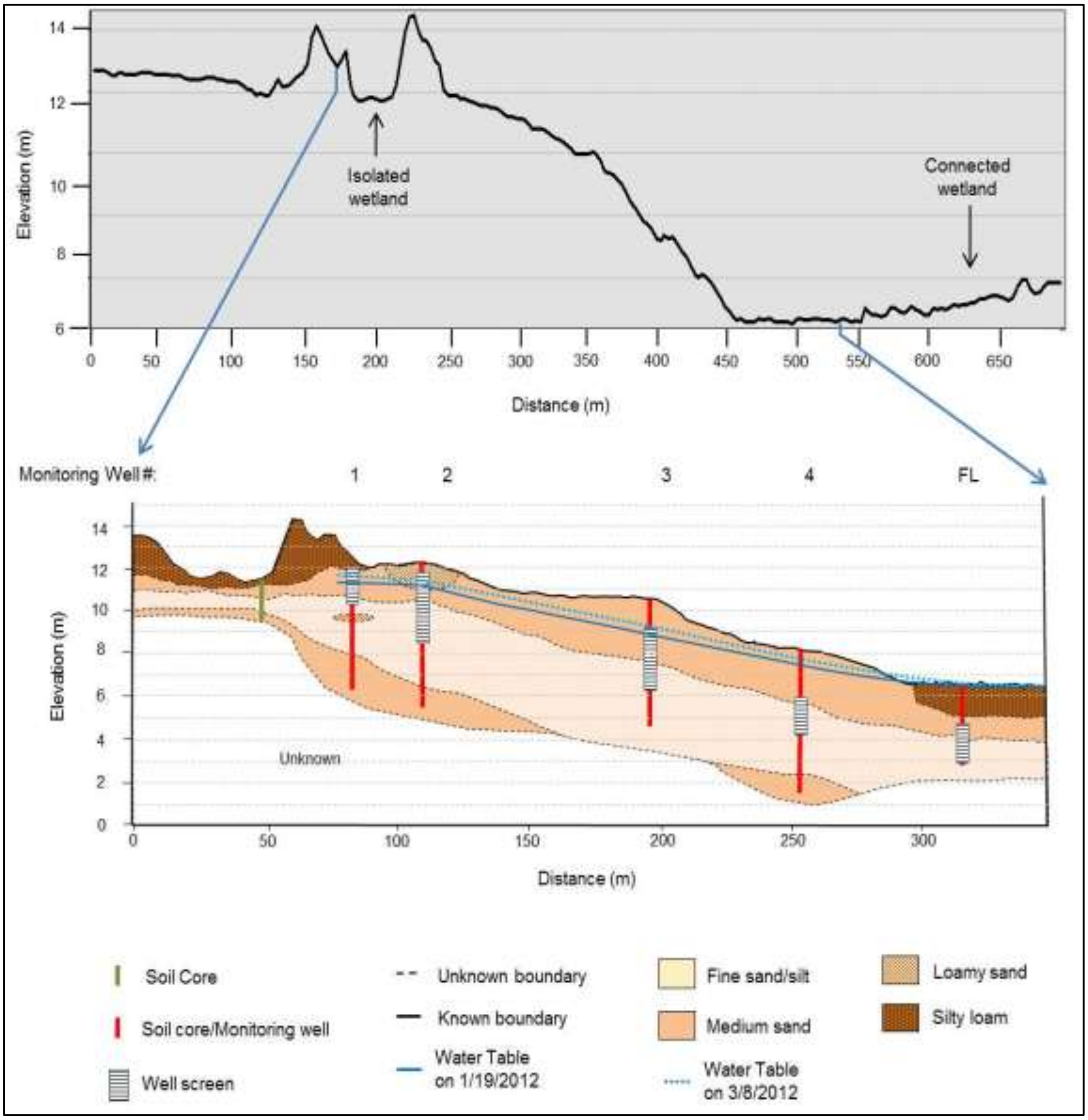

Figure 5.3. Stratigraphic map of the soil profile at the LB site. Vertical exaggeration: 24.4x (upper image) and 8.3x (lower image)

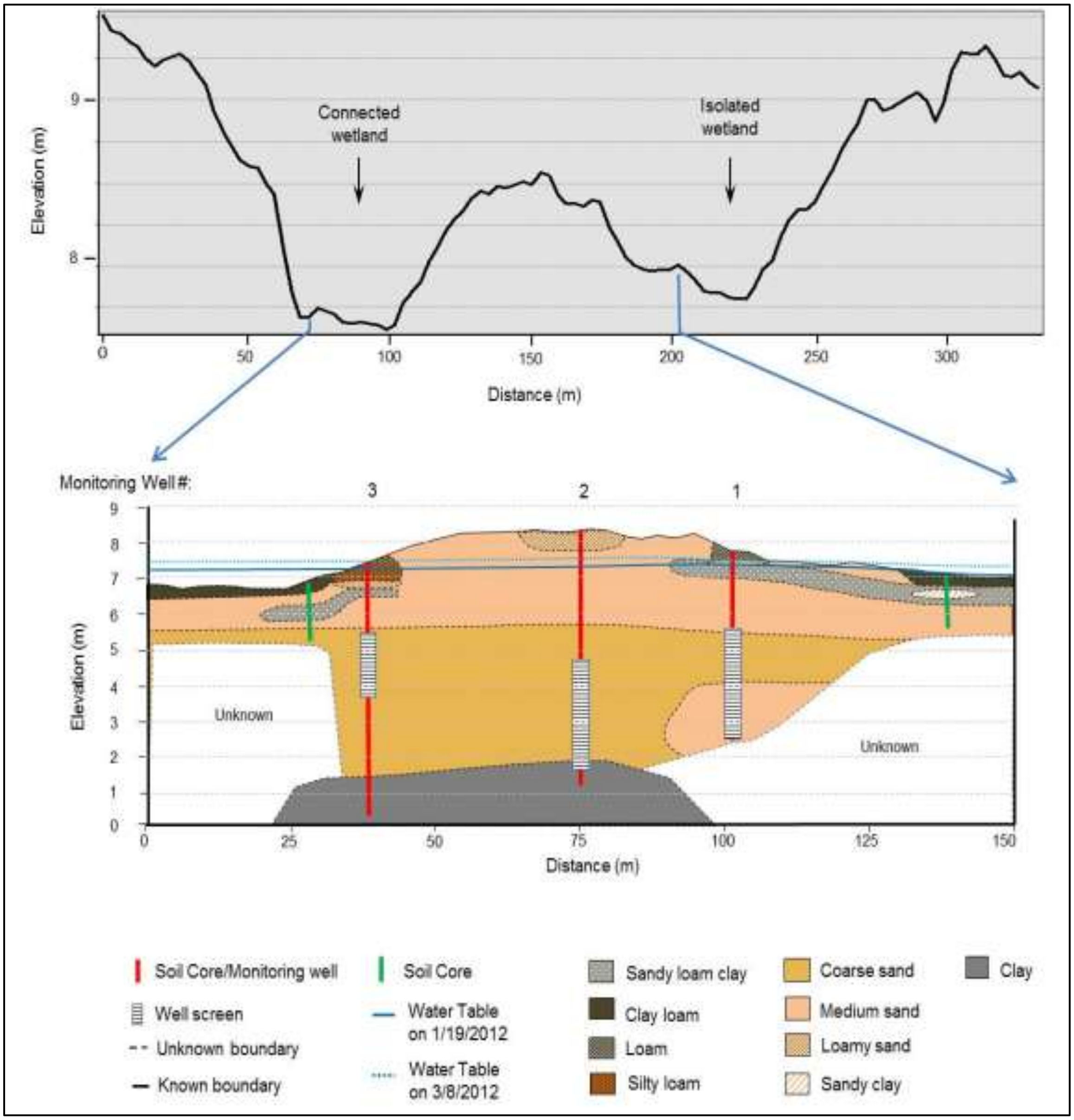

Figure 5.4. Stratigraphic map of the soil profile at the MA site. Vertical exaggeration: 49.6x (upper image) and 5.3x (lower image)

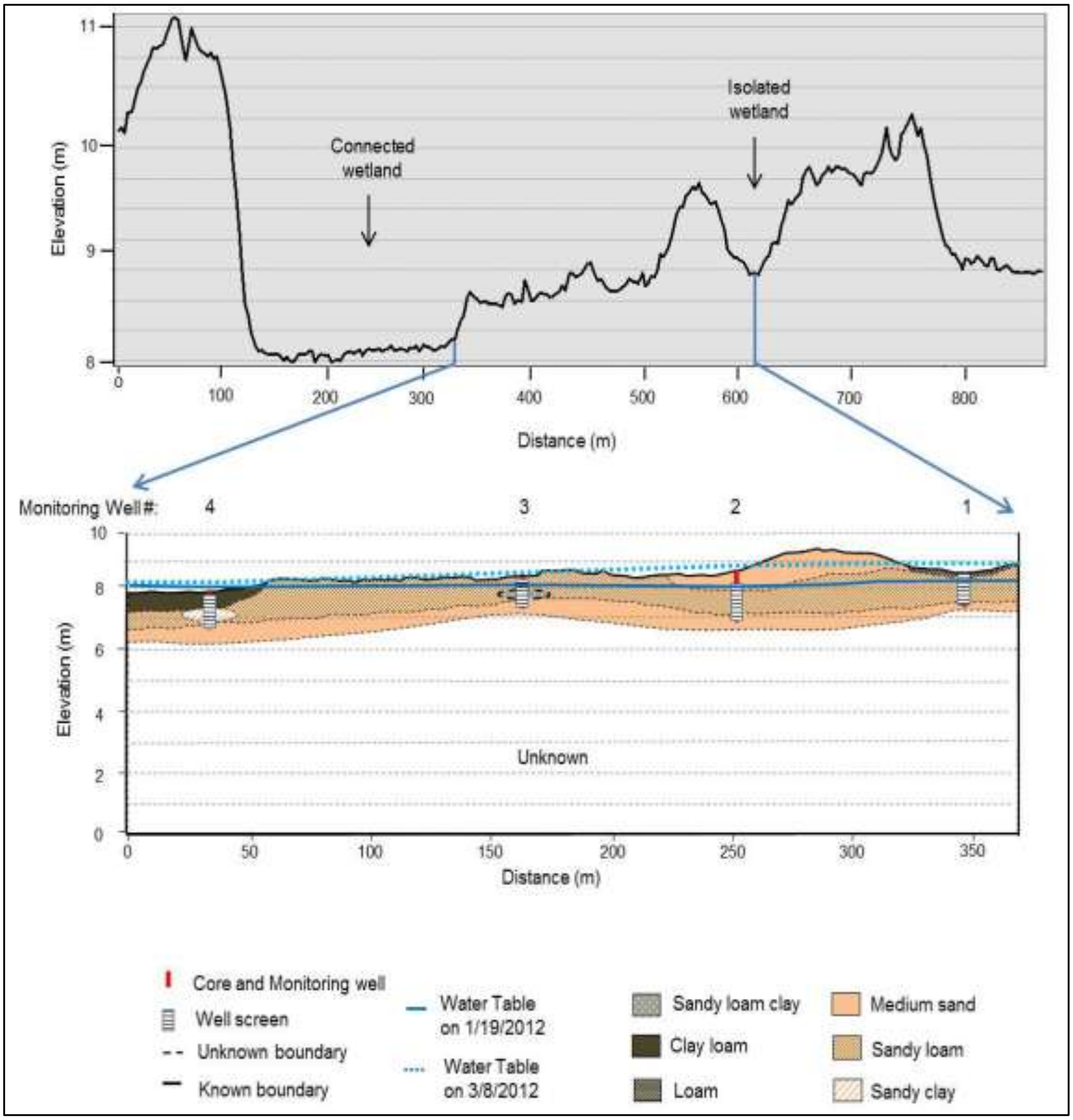

Figure 5.5. Stratigraphic map of the soil profile at the MF site. Vertical exaggeration: 89.3x (upper image) and 12.7x (lower image)

Table 5.3. Average daily observed precipitation

Site	County	*Average daily precipitation (cm)*								
		Jan	Feb	March	Apr	May	June	July	Aug	Sept
MA/MF	Marion	0.09	0.19	0.30	0.34	0.49	0.54	-	-	-
LB	Horry	0.10	0.16	0.31	0.14	0.66	0.14	0.39	0.64	0.15
BR	Brunswick	0.12	0.19	0.41	0.26	0.30	-	-	-	-

5.2.2 Classification of major and minor storm events

Classification of “major” and “minor” precipitation events was necessary in order to assess the water table’s response to various amounts of precipitation. For each rain gauge a threshold was used to identify minor and major storm events and that threshold was established based on the amount of precipitation observed throughout the study period. The events listed in Table 5.4, Table 5.5, and Table 5.6 were events used for recharge calculations. Other storm events occurred during the study period, but the listed events were used based on their ability to elicit a water table response appropriate for recharge rate measurement. For an event to qualify for use in the calculations, falling precipitation had to cause a measureable rise in water table level, and the event had to be isolated (no precipitation at least 24-hours before or after the event) so it was evident that a water table rise could be attributed to a specific storm event. All precipitation throughout the study period is shown in the hydrographs for each site in Section 5.3.

The precipitation observed during minor storm events at the Marion County sites ranged from 0.61 cm – 1.24 cm and the major events precipitation ranged from 2.79 cm – 5.72 cm (Table 5.4). For this rain gauge, the minor/major threshold was 2 cm (a major event had ≥2 cm of rain). The precipitation amount for minor storm events in Horry County ranged from 0.86 cm – 1.58 cm, while the range for major events was 2.56 cm –

9.80 cm (Table 5.5). This site had the same category threshold as the Marion County site. In Brunswick County, major storm events consisted of any event creating ≥1 cm of precipitation (Table 5.6). Minor event precipitation ranged from 0.56 cm – 0.96 cm and major event precipitation ranged from 1.04 cm – 5.88 cm.

Table 5.4. Marion County Storm Events

Storm Date	Precipitation (cm)	Event Type
1/27/2012	0.76	minor
2/16/2012	0.74	minor
2/18/2012	2.79	major
2/24/2012	0.91	minor
2/27/2012	1.19	minor
3/2/2012	0.61	minor
3/4/2012	5.72	major
3/17/2012	0.64	minor
3/30/2012	0.71	minor
4/5/2012	4.29	major
4/18/2012	4.32	major
5/14/2012	3.10	major
6/10/2012	1.24	minor

Table 5.5. Horry County Storm Events

Storm Date	Precipitation (cm)	Event Type
1/27/2012	0.86	minor
2/19/2012	3.18	major
3/18/2012	1.26	minor
4/22/2012	1.10	minor
5/13/2012	2.56	major
5/30/2012	5.60	major
7/10/2012	3.72	major
7/29/2012	1.58	minor
8/11/2012	0.92	minor
8/18/2012	1.52	minor
8/19/2012	9.80	major
8/21/2012	1.48	minor

Table 5.6. Brunswick County Storm Events

Storm Date	Precipitation (cm)	Event Type
1/18/12	0.56	minor
1/27/12	0.57	minor
2/10/12	1.10	major
2/16/12	0.96	minor
2/18/12	2.90	major
2/24/12	1.04	major
3/3/12	5.88	major
3/25/12	4.54	major
4/6/12	1.64	major
4/21/12	0.88	minor
4/27/12	2.76	major
5/9/12	0.88	minor
5/14/12	0.68	minor

5.3 Groundwater hydrology

The following sections detail the water table fluctuations observed during the study. Well identifiers are listed on each of the hydrographs and water table maps, and references are made to their associated sub-sites within the text. A clear association of well identifiers and their sub-sites can be found in Table 4.1. Their locations are also described in Section 4.1.

5.3.1 Site MF

At the beginning of the study period South Carolina was in a persistent drought status; that status is reflected in the low water table depths observed in the beginning of the study (Figure 5.6). While low water tables can be expected during summer months, when evapotranspiration is high, the water table at this site was at a consistently low level (comparatively) during winter months, when evapotranspiration is low and water tables are expected to be at annual high levels. Low water table levels were observed throughout the site, but the lowest water table levels were observed at well MF-02. At this well, the water table remained below the depth of the water level logger until multiple precipitation events in early March. After those events, a significant rise in water table levels occurred throughout the site.

The water level loggers in the monitoring wells detected a rapid response to precipitation (within in 24 hours). Once the water table rose above the logger in well MF-02, it too displayed a rapid response to precipitation. A rapid water table decline was also noted throughout the site. Water tables at wells the isolated wetland (MF-01), connected wetland (MF-04), and one upland (MF-03) sub-sites appeared to be much more sensitive to groundwater recharge and elicited more of a response than the water table at well MF-02.

A response to an increase in precipitation was also noticed at this site. Frequent precipitation from March – May resulted in sustained relatively high water tables through the remainder of the summer months.

5.3.2 Site MA

As with the water table at the MF site, the MA site also exhibited impact from the drought with low water table levels during the winter months. Minimal water table fluctuations occurred until multiple consecutive precipitation events in late February/early March (Figure 5.7). After those storm events, a significant rise in water table levels occurred throughout the site. Groundwater at this site also displayed a response to precipitation within 24 hours, but with a more gradual recession than observed at the MF site.

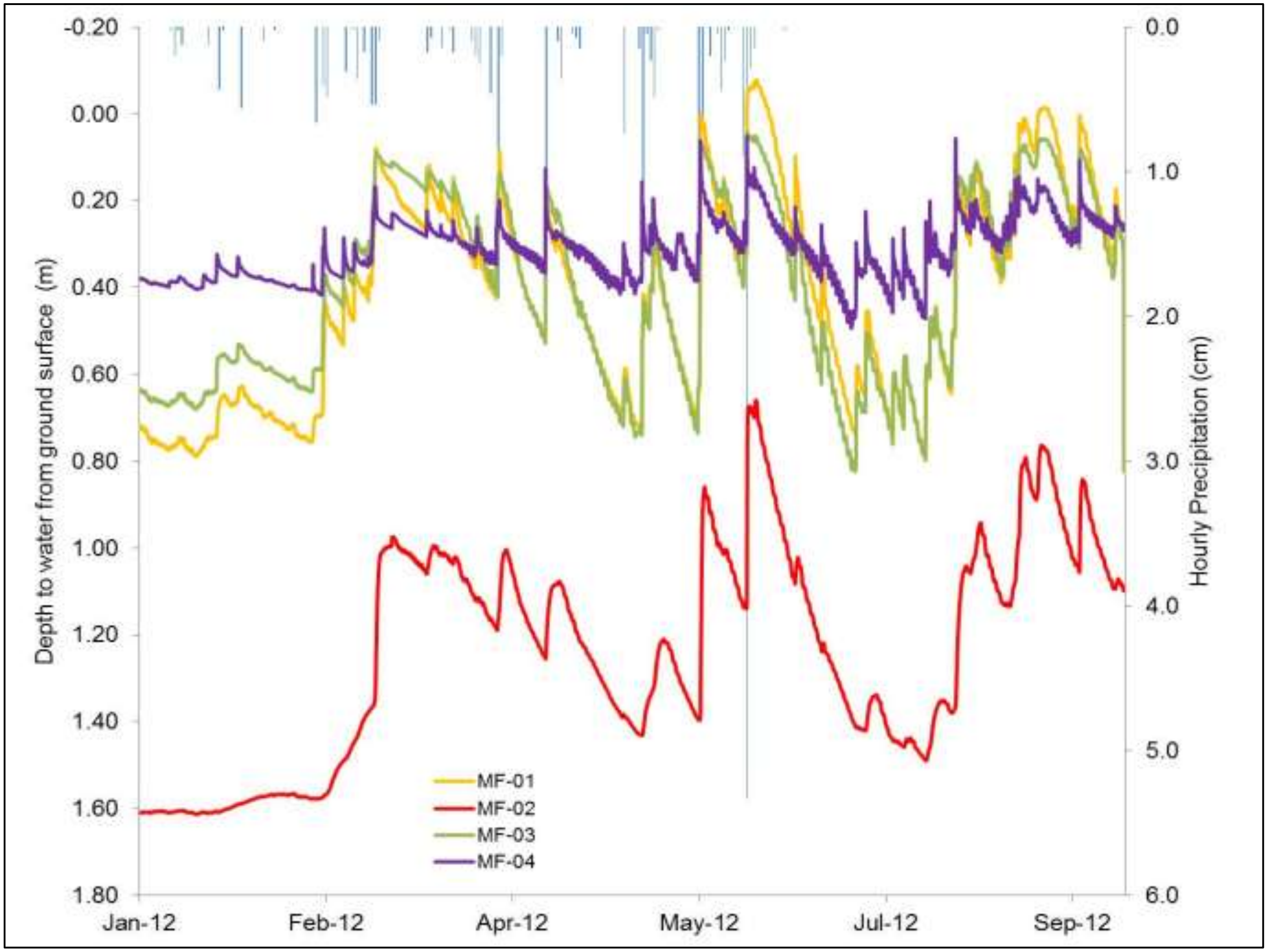

Figure 5.6. Hydrograph of water table fluctuations and hourly precipitation at the MF site (Marion Co., SC) from January 2012 to September 2012.

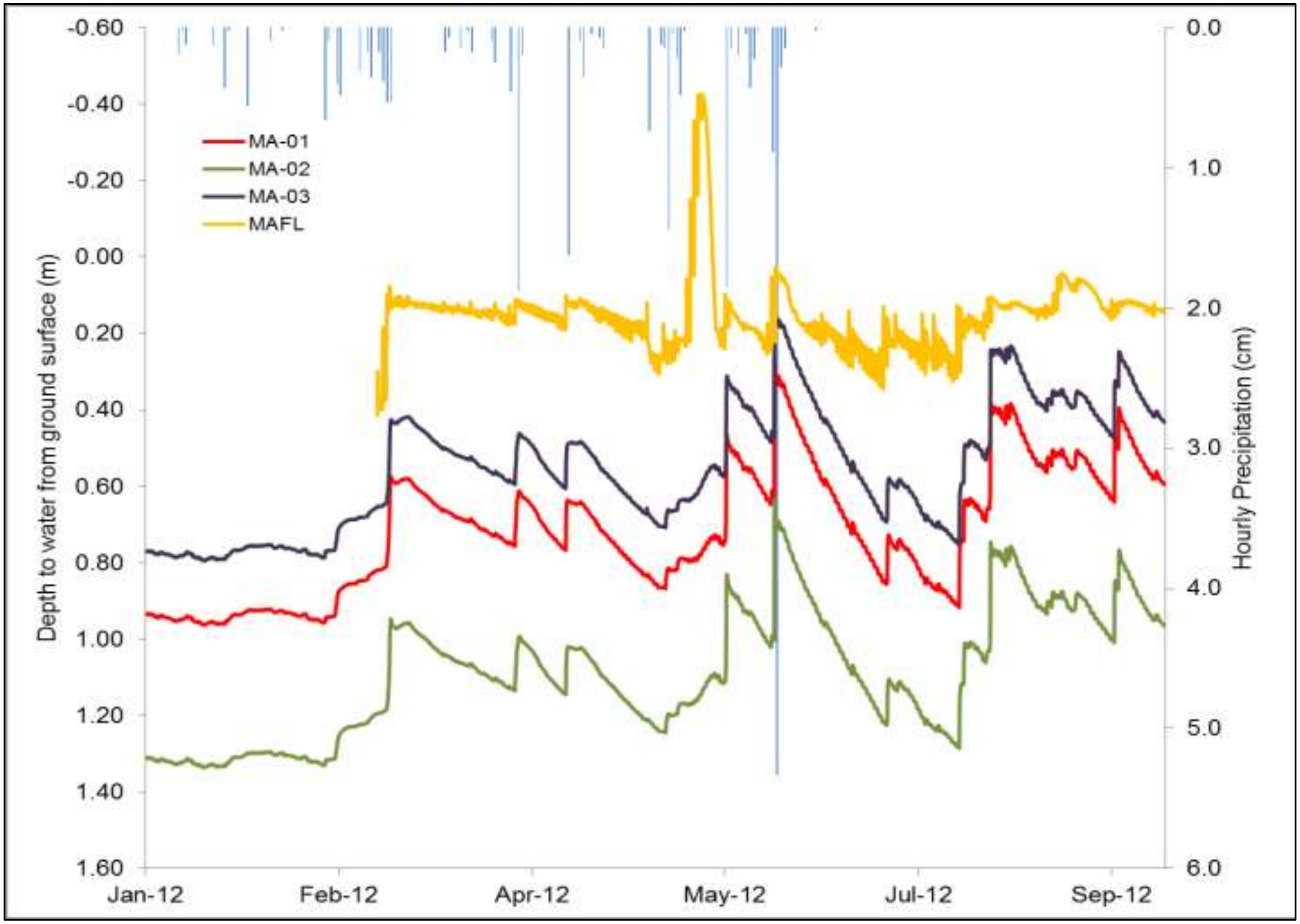

Figure 5.7. Hydrograph of water table fluctuations and hourly precipitation at the MA site (Marion Co., SC) from January 2012 to September 2012.

As for sensitivity, the water table at the riverine wetland sub-site (MAFL) appeared to be more sensitive to recharge than the water table at the remaining sub-sites. During one particularly large storm event, the water table within the riverine wetland rose above the ground surface (i.e. negative depth).

Larger storm events elicited a greater water table response and an increase in storm events was observed throughout the spring and summer months. This resulted in water table levels remaining relatively constant, despite the anticipated seasonal increase in evapotranspiration.

5.3.3 Site LB

During the study period, an incident occurred at the well located in the riverine wetland sub-site (LBFL), wherein the monitoring well was destroyed and the water level logger was damaged. The monitoring well was reconstructed and a new logger installed. However, as a result of the damage, data for April and May were not collected.

As Figure 5.8 displays, the water table throughout the site elicited a rapid response to precipitation events, with a gradual groundwater recession. Groundwater at the upland well farthest from either wetland type (LB-03) elicited responses, but they were relatively less pronounced than that of the water table at the other wells (for small precipitation events). A variation in sensitivity was also noted at the riverine wetland well (LBFL). On at least three occasions, the water table at the riverine wetland rose above ground level.

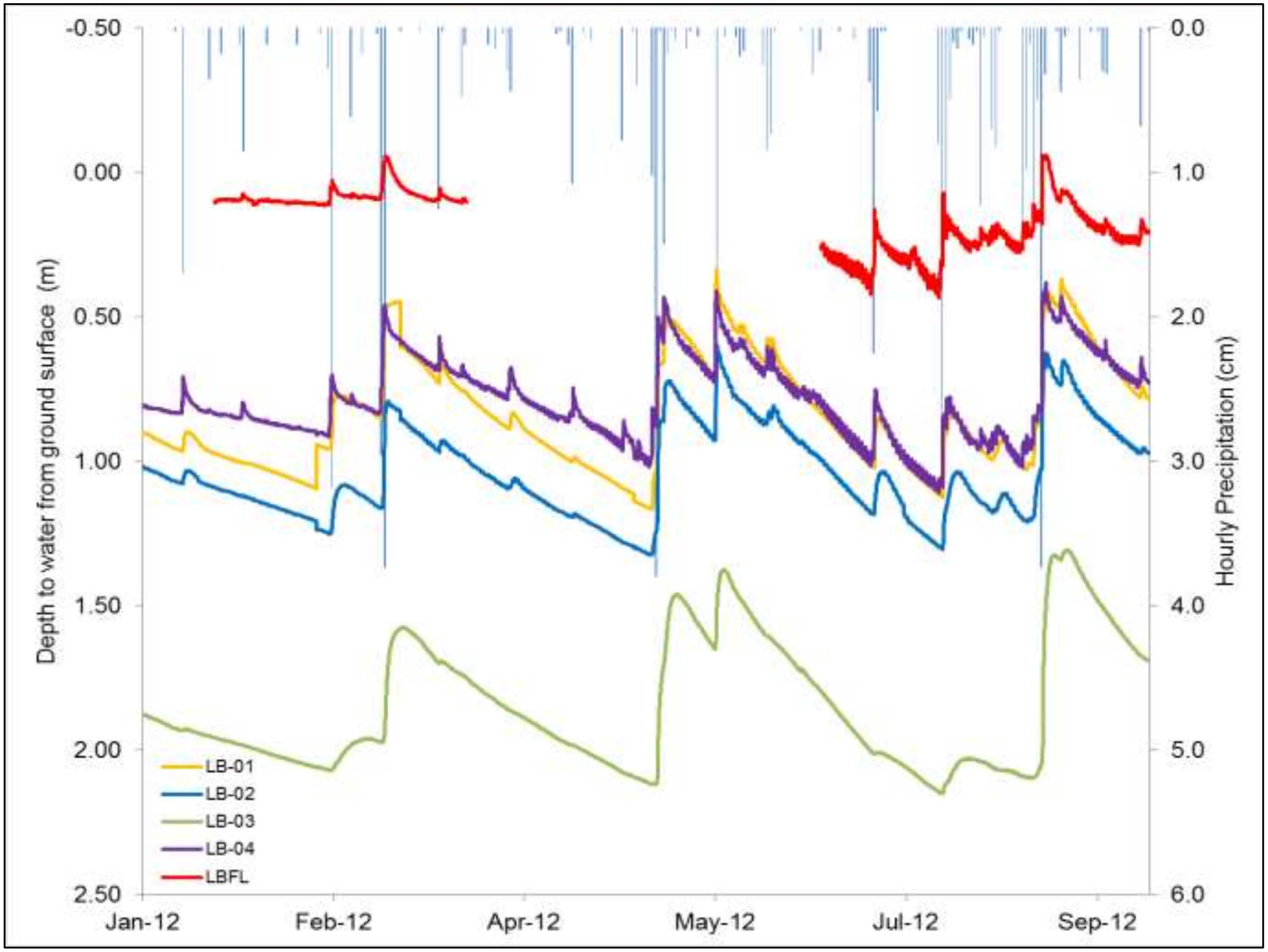

Figure 5.8. Hydrograph of water table fluctuations and hourly precipitation at the LB site (Horry Co., SC) from January 2012 to September 2012.

Water table elevations at the LB site indicated no seasonal fluctuations, as water levels remained in a fairly consistent range at each of the monitoring wells. However, as with the Marion County sites, a lack of fluctuation may be explained by the steady amount of precipitation that allowed the surficial aquifer to remain at a fairly stable level, despite an anticipated increase in evapotranspiration.

The water table at this site also displayed an impact from the drought with unexpected, relatively low water table levels preceding multiple precipitation events.

5.3.4 Site BR

The water table at the BR site displayed a slightly different drought response than the other sites (Figure 5.9). Here, there was a visible decline in water table depth, whereas the water table at the other sites appeared low, but stable. Again, multiple minor storm events in early March created the opportunity for a rise in water table levels.
The most exaggerated responses were seen at the riverine (BRFL) and isolated (BR1a, BR2a) wetlands, with the riverine wetland having the most active, or sensitive, precipitation response. The water table at all other sub-sites responded only minimally to precipitation. As with the South Carolina sites, no seasonal trends were observed, with the exception of a steady frequency of storm events.

5.4 Spatial patterns of groundwater flow

During the data analysis, observations were made regarding the direction of groundwater flow within each of the study sites. As mentioned in Section 5.3, the water table at all sites exhibited a drought response in the form of unseasonably low levels.

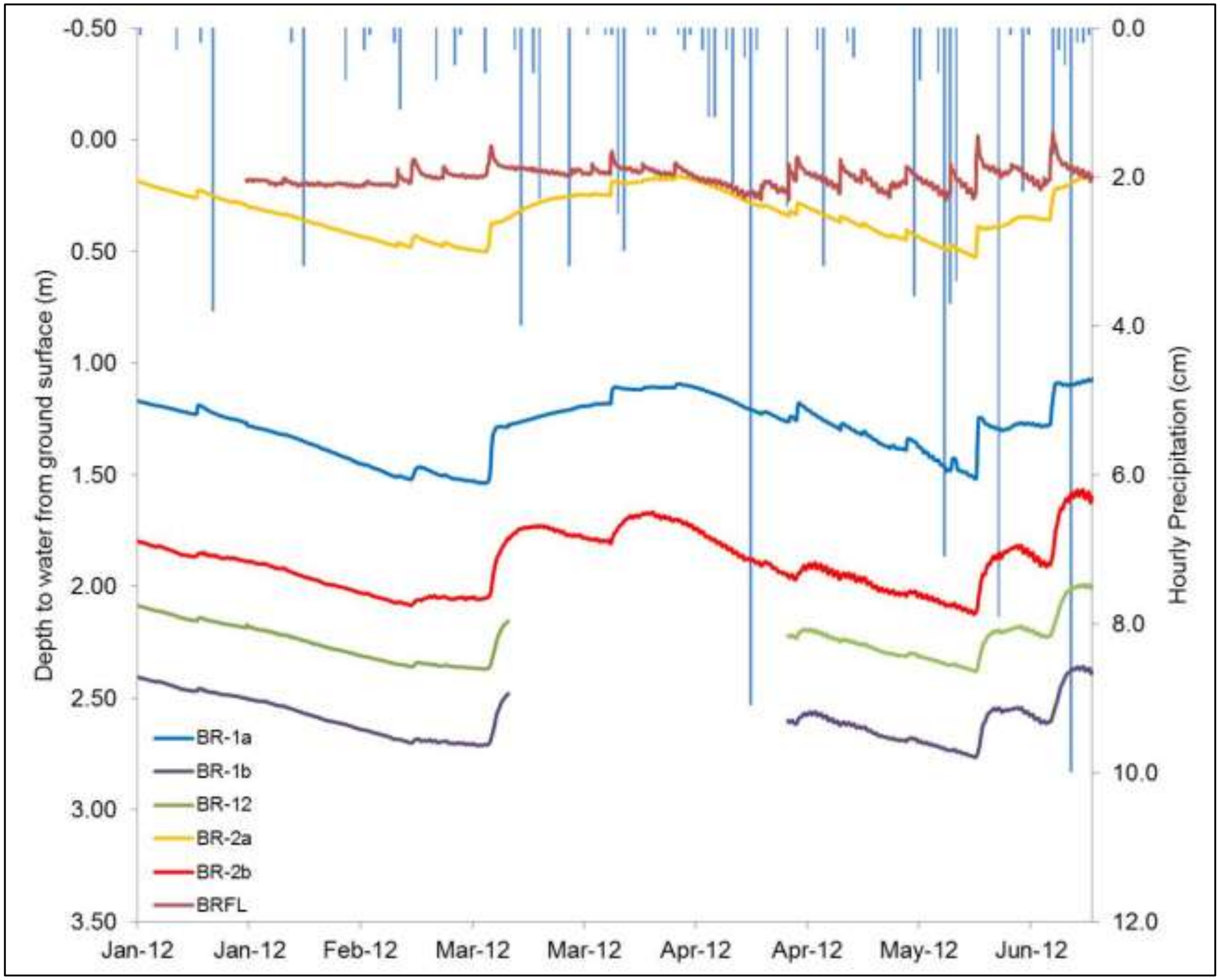

Figure 5.9. Hydrograph of water table fluctuations and hourly precipitation at the BR site (Brunswick Co., NC) from January 2012 to June 2012.

Water levels from that low period—designated as the dry period—(water level on Jan 19, 2012 and Jan 20, 2012) were compared to the levels observed after the water table rise—designated as the wet period—(water level on Mar 8, 2012 and Apr 26, 2012) to identify variation in flow direction. A juxtoposed comparision in water table depths during the two periods was included in the stratigraphic maps and is shown for each of the sites in the figures in Section 5.1.

ArcGIS was also used to create water table elevation maps, in which water table elevations were derived from the elevations in Table 4.3 and the depth to water measurements from the water level loggers. Using the IDW analysis feature, ArcMap interpolated the water table elevations within each site, based upon the known elevations at each of the monitoring wells. From this map, multi-directional flow from an aerial view can be observed and inferences about directional flow can be made.

5.4.1 Site LB

During low flows (Figure 5.10) as well as after several precipitation events (Figure 5.11), the highest water table elevation was observed at the isolated wetland (LB-01) and the lowest at the riverine wetland (LBFL), indicating that groundwater at that site flowed from the isolated wetland to the riverine wetland. On average, a 0.2 m increase in water level occurred between the dry and wet conditions.

5.4.2 Site BR

At the BR site, groundwater flowed from BR1 to BR2, as indicated by the highest water table elevation at BR1a and the lowest elevation at BR2b. This activity is shown during low flows in Figure 5.12. A similar directional pattern occurred during high flows, with the addition of the increased water table elevation at BR1b (Figure 5.13). That increase indicated multi-directional flow from BR1 to the connected wetland in addition to BR2. The BRFL well was installed outside of the transect so it was not included in the water table maps.

5.4.3 Site MF

Unlike the directional flow observed at the other sites, during the dry period the lowest water table elevation was seen at MF-02, an upland well (Figure 5.14). However, the depiction of this occurrence may be over-dramatized by ArcMap because the change in elevation is slight. Also, groundwater activity and flow surrounding the transect may provide a more comprehensive picture of the situation. After an approximate 0.4 m increase in water level, the lowest elevation was seen at the MF-04, the connected wetland, and groundwater flowed directly from the isolated wetland to the connected wetland (Figure 5.15).

5.4.4 Site MA

At the MA site, regardless of high or low groundwater levels, the lowest water table elevation remains at MAFL (riverine wetland), indicating that it is possible that groundwater eventually flows in that direction (it cannot be definitively said without additional data). For the remainder of the monitoring wells, groundwater flows from the isolated wetland (MA-01) to the connected wetland (MA-03) during low flows (Figure 5.16) and in the opposite direction—from the connected wetland to the isolated wetland—once the water table has increased approximately 0.08-m water table rise (Figure 5.17). Because the MAFL well was installed outside of the transect, it was excluded from the water table maps.

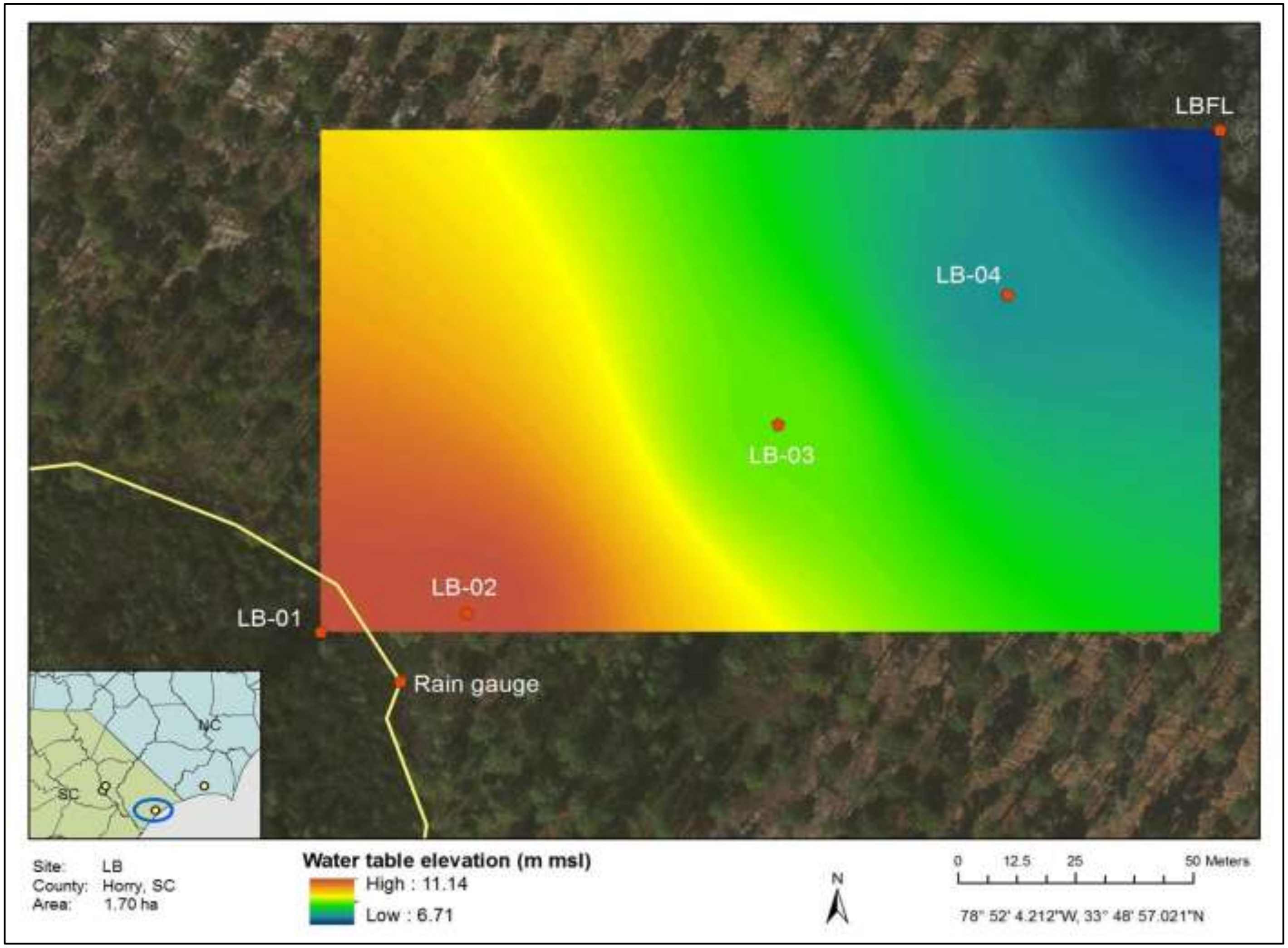

Figure 5.10. Water table map showing groundwater directional flow at the LB site during times of low water levels, on Jan 19, 2012

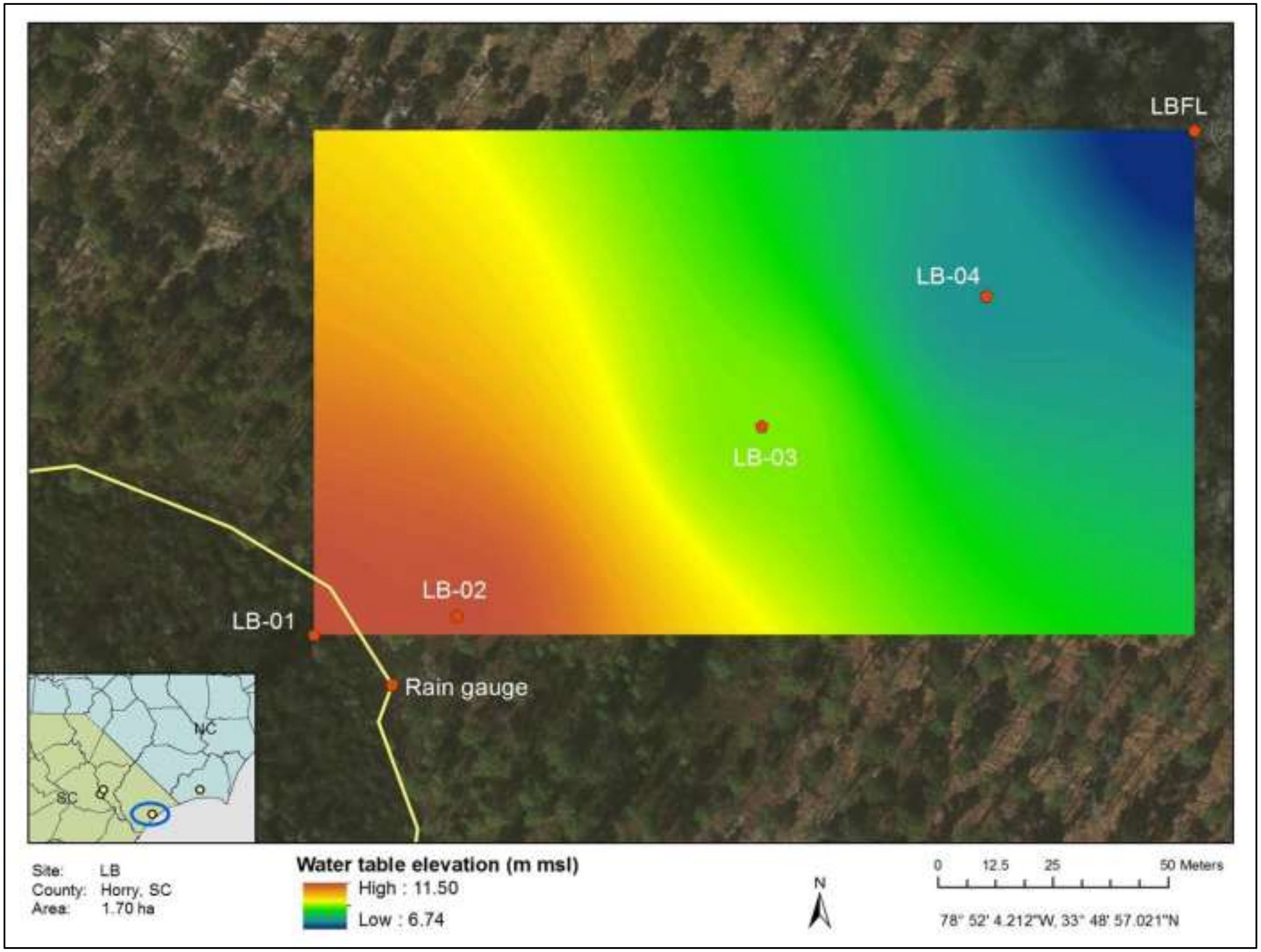

Figure 5.11. Water table map showing groundwater directional flow at LB site after multiple precipitation events, on Mar 8, 2012

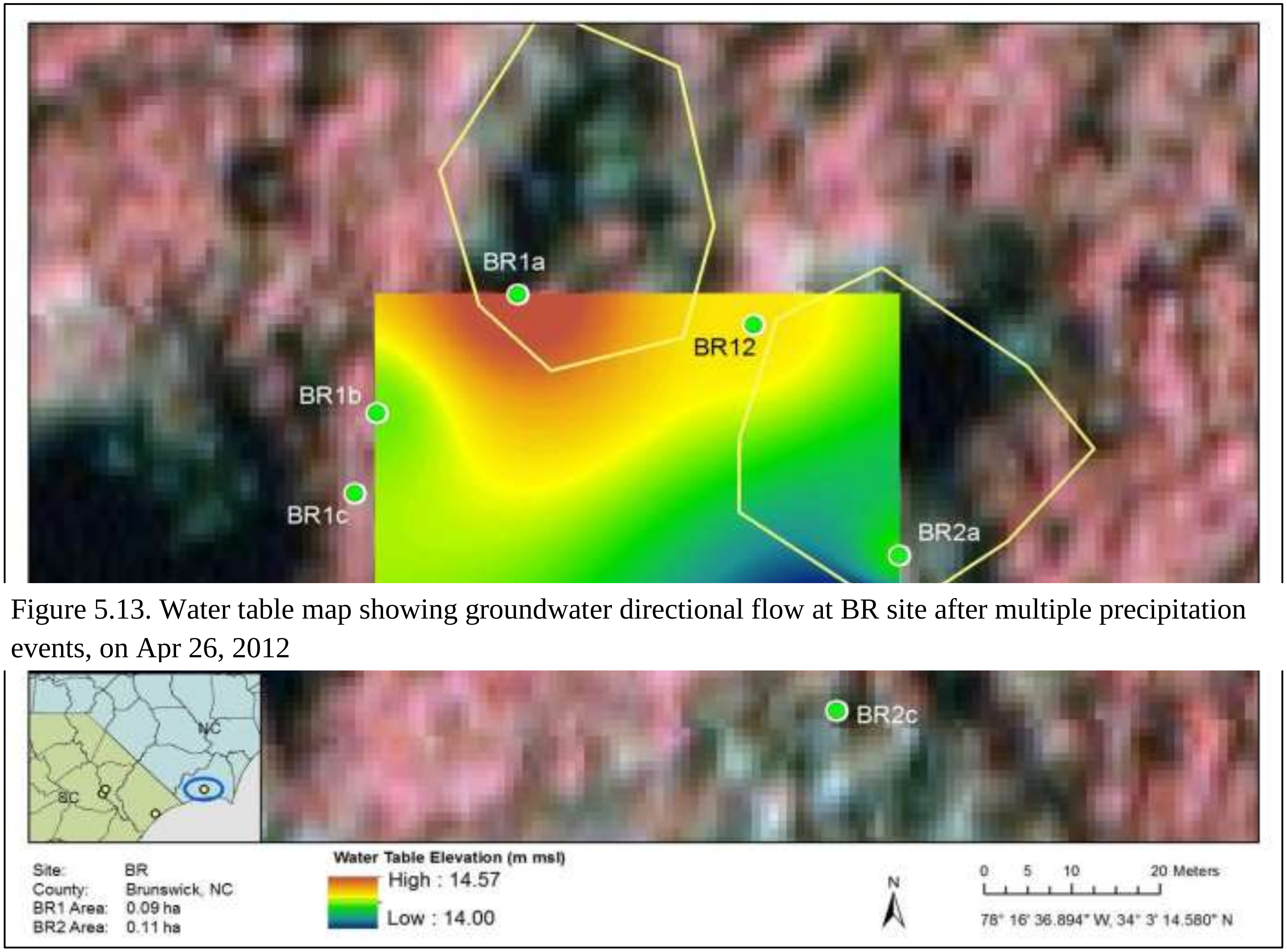

Figure 5.13. Water table map showing groundwater directional flow at BR site after multiple precipitation events, on Apr 26, 2012

Figure 5.12. Water table map showing groundwater directional flow at the BR site during times of low water levels, on Jan 20, 2012

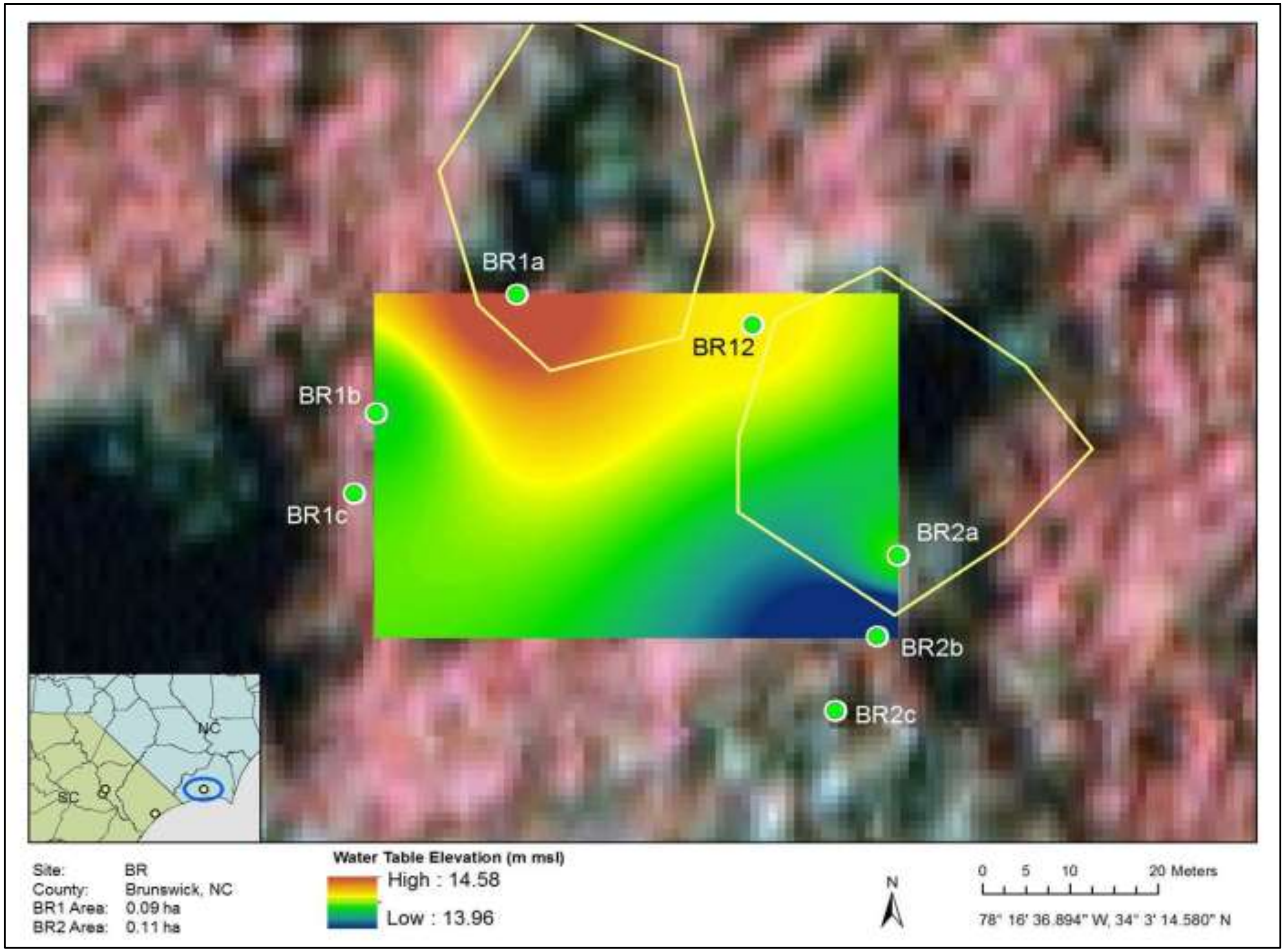

Figure 5.13. Water table map showing groundwater directional flow at BR site after multiple precipitation events, on Jan 20, 2012

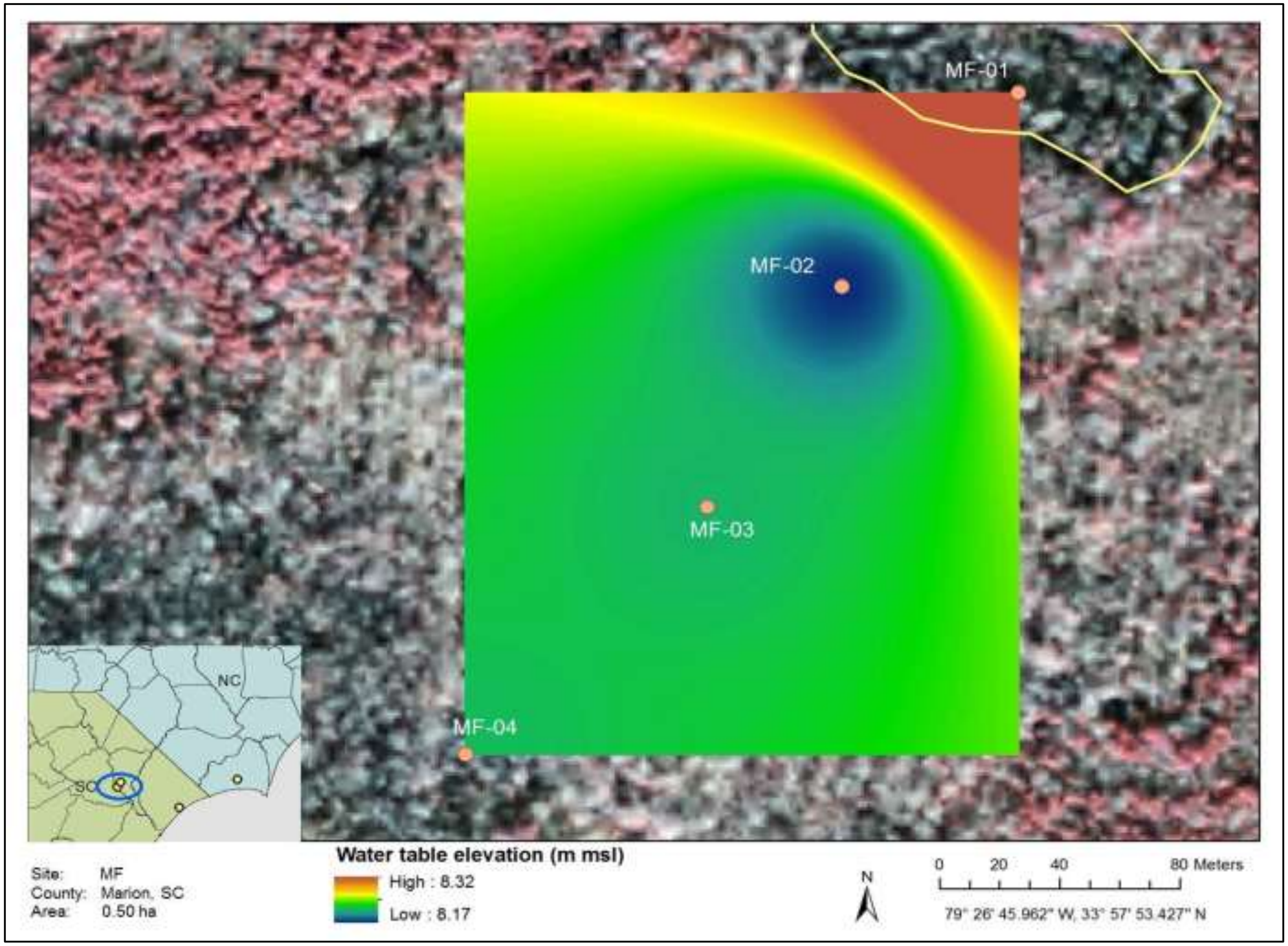

Figure 5.14. Water table map showing groundwater directional flow at the MF site during times of low water levels, on Jan 19, 2012

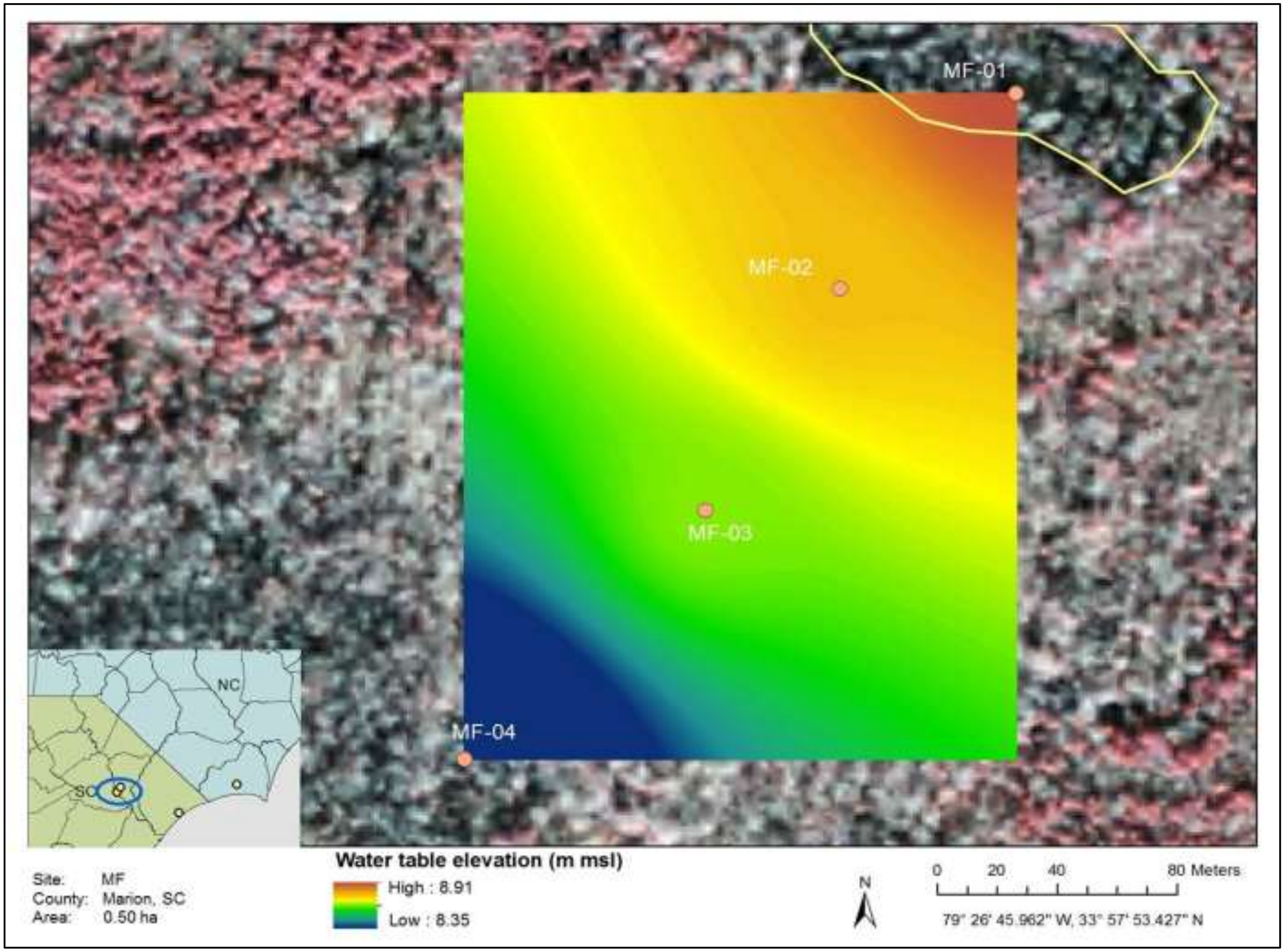

Figure 5.15. Water table map showing groundwater directional flow at the MF site after several precipitation events, on Mar 8, 2012

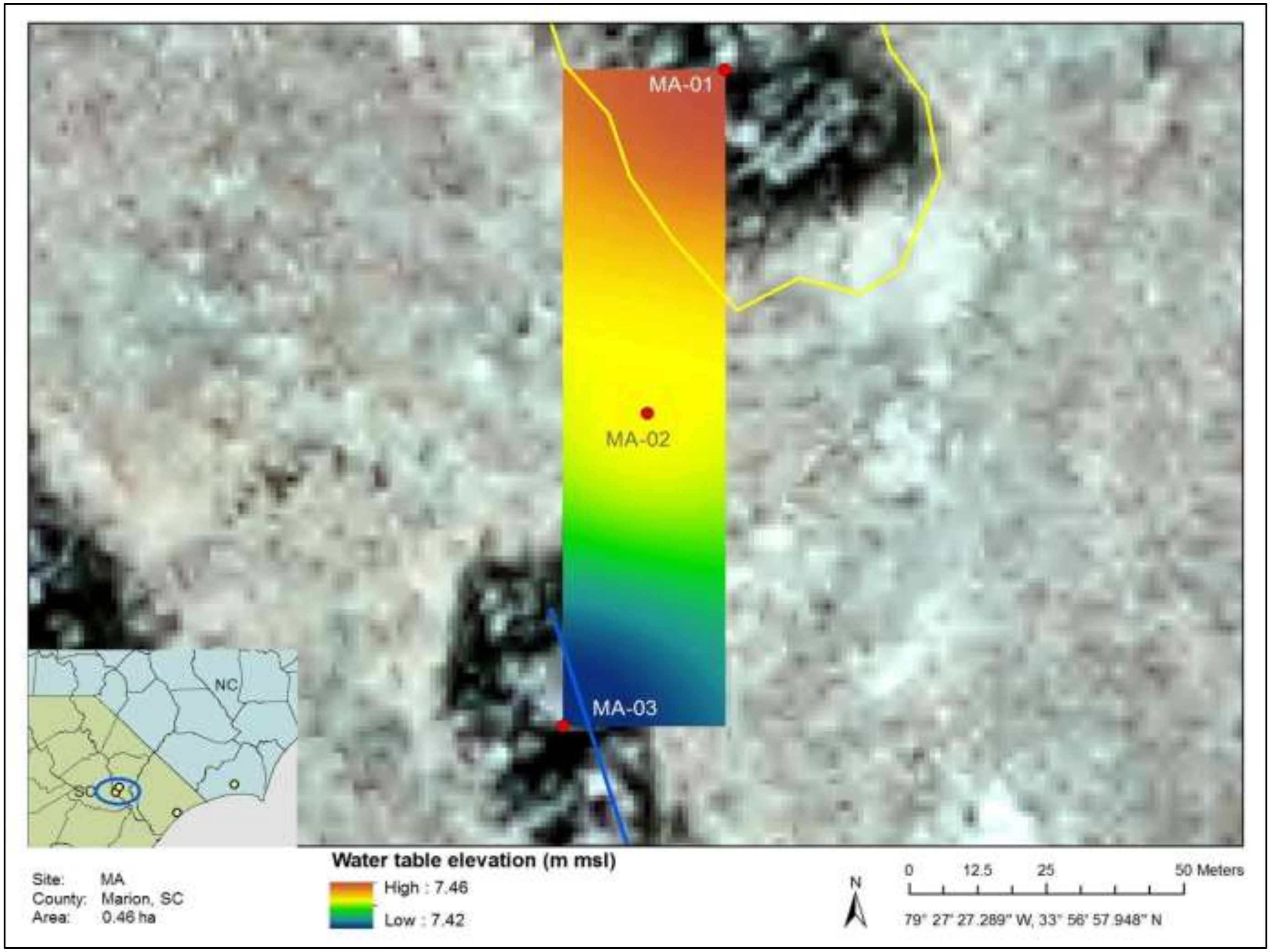

Figure 5.16. Water table map showing groundwater directional flow at the MA site during times of low water levels, on Jan 19, 2012

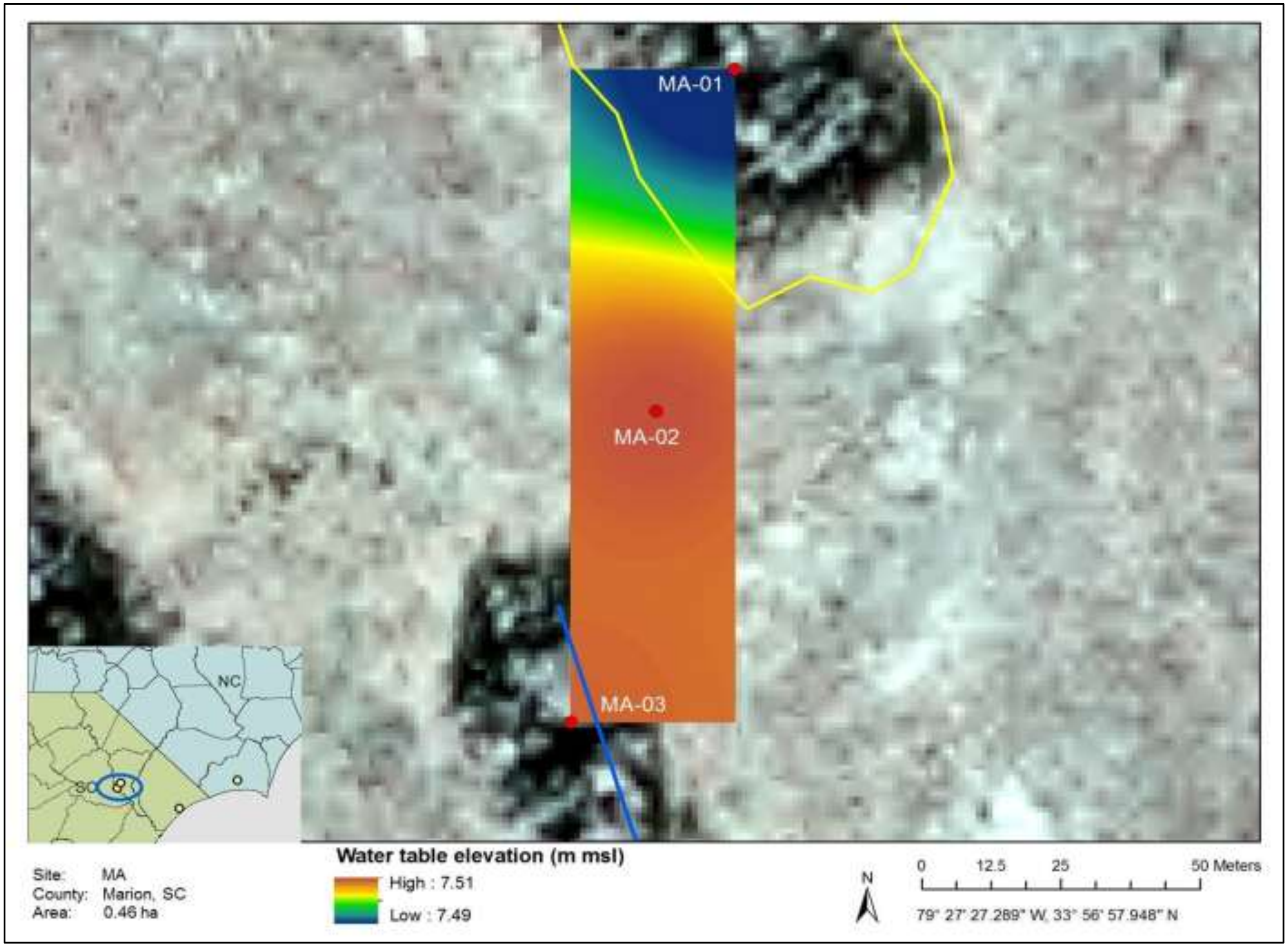

Figure 5.17. Water table map showing groundwater directional flow at the MA site after multiple precipitation events, on Mar 8, 2012

5.5 Recharge Rates

One of the qualitative observations made in the hydrograph analysis was a difference in water table recession when there was a more frequent occurrence of precipitation. As a result, separate recession coefficients for each soil type in Equation 2 were calculated for wet and dry months, as shown in Table 5.7.

Table 5.7. Recession coefficient values for each site

Site Name	Sub-site	Associated Soil Series	α	
			Dry period	*Wet period*
BR	Upland	BnB	0.004	0.003
BR	IW	Mk	0.013	0.033
BR	RW	Mu	0.185	0.131
LB	Upland	Ec	0.006	0.021
LB	IW/CW	EcJo	0.011	0.027
LB	RW	Jo	0.257	0.223
MA	Upland	LaB	0.013	0.026
MA	IW/CW	LaB/Cn	0.019	0.048
MA	RW	TC	0.022	0.089
MF	Upland	Cn	0.023	0.016
MF	IW	LaB/Cn	0.111	0.091
MF	RW	TC	0.072	0.092

The dry and wet periods were dictated by the frequency of precipitation during the study period. For sites MA and MF the dry period was from January – April and the wet period from May – June; for sites BR and LB the dry period was from January – March and the wet period was from April – September. The dry and wet periods were determined based on the variation in water table responses as observed from the hydrographs.

5.5.1 Overall comparison between sub-sites

The objective of this study was to compare recharge rates between isolated wetland and riverine wetlands. In comparing the overall recharge rates between sub-sites, there was no sub-site type that consistently displayed the largest or smallest recharge rate across all of the sites, with the exception of the two Marion County sites (MA and MF). There the RW sub-sites displayed faster average rates than the IW sub-sites (Table 5.8). At the BR site, the BR1 isolated wetland displayed the fastest rate while the BR2 isolated wetland displayed the slowest rate. And at the LB site, the IW sub-site displayed a faster average rate than the RW sub-site. When the rates displayed in Table 5.8 are averaged, the riverine wetlands have a faster rate at 4.38 cm/day than the isolated wetlands at 3.75 cm/day. A statistical analysis of the observed recharge rates is detailed in Section 5.5.3.

Table 5.8 Mean recharge rates± standard deviation (cm/day) per sub-site type

Site Name	IW	Upland	CW*	RW
BR1	6.66±3.85	4.74±4.99	-	3.32±1.69
BR2	2.23±1.37	4.74±4.99	-	3.32±1.69
LB	3.32±4.05	3.11±3.11	5.22±3.52	2.56±1.87
MA	2.73±3.23	1.55±1.43	1.64±2.09	5.73±4.70
MF	3.81±2.34	2.97±2.88	-	5.90±6.18
Overall	3.75±1.73	3.42±1.35	3.43±2.53	4.17±1.54

**not all sites have the connected wetland (CW) sub-site*

Section 5.5.2 Rate comparisons within each site

Average recharge rates in response to major and minor precipitation events were calculated for each study site. Tables in this section include the number of observations used for rate calculations at each site, the overall rates per event type, and the rates per event type during the dry and wet periods.

As shown in Table 5.9, at the BR site, the fastest overall rates were observed in IW-1 (BR1) for both major and minor storm events, and the slowest rates were observed at IW-2 (BR2). Recharges rates at the RW sub-site were faster than IW-2 rates, but slower than IW-1 rates. The same trend was observed after minor storm events during the dry period, from Jan – March, and the wet period, from April – June. However, the RW also displayed the highest rates after major events during the dry period and the lowest (comparatively) after major events during the wet period.

Table 5.9 Mean recharge rate± standard deviation per period and event type for BR site. (n) is the number of events

Sub-site	Event Type	Soil Type in Aquifer	R (cm/day)		
			Overall (n)	*Dry period (n)*	*Wet period (n)*
IW-1	Minor	Silty loam	9.83±2.50 (6)	9.27±2.99 (3)	10.40±2.39 (3)
IW-2	Minor	Loam	1.21±0.55 (3)	1.35 (1)	1.14±0.76 (2)
Upland	Minor	Loamy sand	8.33±5.19 (9)	6.50±4.56 (6)	12.00±5.04 (3)
RW	Minor	Clay loam	3.66±1.74 (5)	4.22±2.20 (3)	2.82±0.37 (2)
IW-1	Major	Silty loam	3.48±1.48 (6)	2.65±0.96 (4)	5.14±0.02 (2)
IW-2	Major	Loam	2.85±1.37 (5)	3.09±1.45 (3)	2.49±1.68 (2)
Upland	Major	Loamy sand	2.42±3.30 (14)	1.87±2.92 (10)	1.50±1.50 (4)
RW	Major	Clay loam	3.08±1.75 (7)	3.37±2.04 (5)	2.34±0.37 (2)

At the LB site, RW rates were overall higher than IW rates after minor events; and IW rates were higher than RW rates after major events (Table 5.10). IW rates were also comparatively higher after minor events during the dry period and major events during the wet period. The opposite trend was observed at the RW, where rates were higher after major events during the dry period and minor events during the wet period. Average recharge rates at the CW remained higher than IW and RW rates at all times except after major events during the wet period. In several instances throughout all the sites, a clear response to a storm event (a rise and subsequent fall of the water table attributed to a single, isolated storm event) could not be determined for some sub-sites, and a limited number of observations were used in the calculations.

As displayed by the values in Table 5.11, the highest recharge rate values for the MA site were observed at the RW sub-site at all times except after major events during the wet period—just as was observed at the CW at the LB site. After major events during the wet period, recharge rates at the IW were higher than those at the RW. The same trend occurred at the MF site (Table 5.12); however average values for the IW after minor events during the wet period could not be calculated because the water table was above the ground surface during the chosen rain events.

Table 5.10 Mean recharge rate± standard deviation per period and event type for LB site. (n) is the number of events

Sub-site	Event Type	Soil Type in Aquifer		R (cm/day)	
			Overall (n)	*Dry period (n)*	*Wet period (n)*
IW	Minor	Silty loam	1.79±1.41 (6)	1.31 (1)	1.88±1.55 (5)
Upland	Minor	Medium sand	3.19±3.68 (12)	0.95±0.92 (3)	3.94±3.98 (9)
CW	Minor	Medium sand	4.34±3.04 (8)	3.55±1.35 (2)	4.49±3.74 (6)
RW	Minor	Silty loam	2.04±2.12 (6)	0.44 (1)	2.36±2.20 (5)
IW	Major	Silty loam	5.62±5.85 (4)	0.10 (1)	7.17±6.09 (3)
Upland	Major	Medium sand	3.00±2.36 (9)	0.51±0.31 (2)	3.71±2.18 (7)
CW	Major	Medium sand	6.49±3.76 (6)	4.26 (1)	6.94±4.02 (5)
RW	Major	Silty loam	3.61±0.59 (3)	2.97 (1)	3.93±0.29 (2)

Table 5.11 Mean recharge rate± standard deviation per period and event type for MA site. (n) is the number of events

Sub-site	Event Type	Soil Type in Aquifer		R (cm/day)	
			Overall (n)	*Dry period (n)*	*Wet period (n)*
IW	Minor	Loam	2.34±3.85 (7)	0.91±0.89 (6)	10.87 (1)
Upland	Minor	Medium sand	1.35±1.65 (7)	0.82±0.94 (6)	4.55 (1)
CW	Minor	Silty loam	1.45±2.47 (7)	0.53±0.48 (6)	6.97 (1)
RW	Minor	Silty clay	7.80±5.82 (2)	3.69 (1)	11.92 (1)
IW	Major	Loam	3.42±3.85 (4)	2.99±2.27 (3)	4.71 (1)
Upland	Major	Medium sand	1.90±1.06 (4)	1.68±1.17 (3)	2.57 (1)
CW	Major	Silty loam	1.98±1.45 (4)	1.38±1.01 (3)	3.77 (1)
RW	Major	Silty clay	4.35±4.49 (3)	5.83±5.21 (2)	1.40 (1)

Table 5.12 Mean recharge rate± standard deviation per period and event type for MF site. (n) is the number of events

Sub-site	Event Type	Soil Type in Aquifer		R (cm/day)	
			Overall (n)	*Dry period (n)*	*Wet period (n)*
IW	Minor	Loam	3.52±2.12 (7)	3.52±2.12 (7)	(0)
Upland	Minor	Sandy loam	2.50±1.18 (10)	2.52±1.24 (9)	2.33 (1)
RW	Minor	Clay loam	5.17±2.91 (7)	5.17±2.91 (6)	2.38 (1)
IW	Major	Loam	4.23±2.83 (5)	4.50±3.19 (4)	3.15 (1)
Upland	Major	Sandy loam	3.64±4.38 (7)	4.06±4.64 (6)	1.16 (1)
RW	Major	Clay loam	7.63±9.70 (5)	8.99±10.64 (4)	2.18 (1)

5.5.3 Statistical Analysis

In order to determine a level of significance between the rate values, a repeated measures analysis of variance (ANOVA) was run using the calculated mean recharge rates for each of the sites (and sub-sites) for the following factors: precipitation frequency, sub-site type, and event type.

Based on the Wilks' lambda MANOVA test p-values shown in Table 5.13, there was no significant difference in mean recharge rates between the sub-sites within each study site (p>0.10), however there was a significant difference between recharge rates associated with frequency and event type. Frequency exhibited a significant impact on mean recharge rates at the LB site (p=0.048), MA site (p=0.042), MF site (p=0.103), and overall sites (p=0.02), while event type exhibited a significant impact on mean recharge rates at the LB site (p=0.103) and MA site (p=0.087). In other words, there was a significant difference in the mean recharge rates observed during the wet and dry periods at those sites; and there was a difference in recharge rates in response to the different event types.

Table 5.13 P-values for factors affecting mean recharge rate

Factor	P-value (α = 0.10)				
	Site: BR	*Site: LB*	*Site: MA*	*Site: MF*	*All Sites*
Frequency	0.463	0.042	0.048	0.103	0.024
Event Type	0.281	0.103	0.087	0.434	0.287
Sub-Site Type	0.823	0.162	0.157	0.349	0.809

Although it was observed that precipitation frequency caused a significant difference in mean rate for several of the tested sites, the primary objective of this study was to determine if there was a significant difference in mean recharge rate between sub-sites—riverine wetland and isolated wetlands—during different rain events. Sub-site type was the factor used in the repeated measures analysis, and despite the lack of significant findings (no significant difference in mean recharge rate between sub-site types) a multiple comparison analysis was still performed to see what results could have potentially occurred given more data. The multiple comparison analysis showed that at the MA site, under dry conditions, the mean recharge rate for the riverine wetland site was significantly different (p=0.019) from the remaining sub-sites.

In order to determine if various conditions had an impact on recharge rate, interactions between event type, frequency, and sub-site type were also analyzed (Table 5.14). Due to the small sample size, the interaction between sub-site type and event type (how individual sub-sites responded to major and minor storm events) could not be tested. A significant difference in mean recharge rates (p>0.10) was observed for the frequency-event type interaction at the MA site (p=0.052) and the average rate across all sites (p=0.060), indicating that the combination of one of the event types with one of the precipitation conditions (e.g. major event during the dry period) caused a significant difference in the mean recharge rate observed between sites.

Table 5.14 P-values for interactions affecting mean recharge rate

Interaction	P-value ($\alpha = 0.10$)				
	Site: BR	*Site: LB*	*Site: MA*	*Site: MF*	*All Sites*
Frequency*Event Type	0.520	0.334	0.052	0.123	0.060
Frequency*Sub-Site Type	0.350	0.741	0.626	0.149	0.221

CHAPTER 6

RECHARGE DISCUSSION

Groundwater recharge rates have major implications for shallow groundwater quality and those rates can be impacted by many factors including climate, topography, soil saturation, and soil texture. The objective of this study was to compare the groundwater recharge rates of several isolated and riverine wetland systems by evaluating soil characteristics, water table fluctuations, and precipitation. This combination of data was used to characterize the groundwater hydrology of these two systems and calculate—and compare—their mean recharge rates.

For the four sub-sites (upland, isolated wetland, connected wetland, and riverine wetland) at each study site, the water table responses to two factors were measured: major and minor rain events, and precipitation frequency. Despite the variation in topography and surface water hydrology, no significant difference in mean recharge rates between the two systems was found based on the data collected in this study and the statistical analysis conducted thereafter. Nor was there a significant difference in mean recharge rate observed between *any* of the sub-sites. Factors that caused a significant difference in rate were frequency and event type. In this study, precipitation frequency was divided into dry and wet periods that were determined based on the amount and frequency of precipitation that occurred at each site during the study period. Storm events were categorized as major or minor based on the amount and duration of precipitation. Due to the spatial and temporal variability of precipitation, event identification and categorization was site-specific. Data collection began in January 2012 and very little precipitation fell until, generally, early March 2012. Data collection ended in either June 2012 or September 2012—depending upon site. Thus, the dry period was January 2012-March 2012, and the wet period was April 2012-June 2012/September 2012. In this study, it would appear that weather patterns have a more significant impact on recharge capabilities than wetland type because weather patterns affect soil moisture and the hydraulic movements of water through soil.

All of the sites used in study are located in the Coastal Plain of the Carolinas. Despite their different locations, and varying topsoil textures, they are all underlain by a sandy soil and that sandy soil is where the water table is located. Nolan *et. al.* (2007) found that the hydrogeologic characteristics that dictated water movement in the saturated zone contribute to the recharge rates in the unsaturated zone. This point was further strengthened by Callahan *et. al.* (2012) with the statement “Considering only the hydraulic character of the upper few meters of the subsurface may lead to misconceptions of the role of groundwater recharge to distribute storm event water through (and beneath) the watershed…”. These two studies stress the relevance of considering deeper soil textures when analyzing and characterizing groundwater recharge rates. The findings of this study suggest that a lack of significant difference in recharge rates between the two wetland types—and the upland—at each site, is a result of their similar soil texture below the unsaturated zone. It is possible that surface soil texture has less of an impact due to macropores created by soil biota that allows was to rapidly percolate. Soil saturation and hydraulic capabilities may be influencing the water table's movement in response to the two types of rain events.

It is interesting that there was a significant difference in recharge response to event types at the MA site, but not the MF, despite their geographic proximity. It is possible that this is due to the larger soil particles/pore size at the MA site allows water to drain and for the water table to move more readily than at the MF site. The same can be said about the sandy soils that allow for easy drainage at the LB site. However, the MF site had its own enigma in that the water table behavior at the MF-02 well (an upland well) was different from that of the other wells. During the dry period, the water table at MF-02 displayed the lowest elevation in the transect. After several large storm events, the water table rose dramatically and the change in water table elevation changed the groundwater connectivity within the transect. This occurrence may be a result of MF-02 being a deeper well than the others, or other causes that cannot be determined without additional data.

While addressing the initial objective of recharge rate comparison of the sub-site types a curious and unanticipated observation occurred: the influence of precipitation frequency on recharge rates. One possible explanation for the significant difference in recharge rates between the dry and wet periods pertains to soil moisture content. As the amount of precipitation increased over the spring, the amount of available soil moisture also increased. In turn, the soils were more likely to be saturated throughout the soil profile, which would impact the water table's ability to receive water, let alone fluctuate. Less precipitation means less available water capacity, decreased soil moisture, and more freedom for the water table to fluctuate as a result of the empty pore spaces. The BR site was the only site that was significantly impacted by an increase in precipitation during the study period (different mean recharge rates during the dry and wet periods). The isolated wetlands at the BR site are located in a landscape matrix of several other isolated wetlands in addition to a riverine wetland. It is possible that the water table responses are dampened because the data for this specific site is a small piece of a larger system.

The impact of precipitation frequency on recharge rates was initially noticed during the calculation of the natural groundwater recession rates, but its significance was not realized until the conclusion of the statistical analysis. A qualitative analysis of the hydrographs indicated a difference between the water table recession early in the study period and later during the study period. That difference spawned the development of the two precipitation frequency categories, an occurrence that proved to be more significant than initially thought. Soil type, particle size, pore size, and soil moisture appear to dictate groundwater movement. Those four variables/characteristics are affected by the amount of precipitation in a given amount of time, and the climatic conditions.

CHAPTER 7

HSPF APPLICATION

As a practical application for the recharge rate calculation, the values can be used to determine the calibration input for the hydrologic modeling program Hydrological Simulation Program-Fortran (HSPF). The model was developed by AQUA TERRA Consultants in cooperation with USGS and EPA to simulate hydrologic processes and their water quality components, on pervious surfaces, impervious surfaces, streams and impoundments in a watershed (Bicknell et.al. 1996).

HSPF is often used for management purposes, including stream flow and recharge estimation (Ockerman 2005), land use-water quality relationships (Tong and Chen 2001), and solute transport (Laroche et. al. 1996). Using meteorological data as input, and a series of hierarchical modules, the model is able to create time-variable scenarios based on theory, lab experiments, and field data; and output is produced in the form of continuous hydrographs.

In order for the model to be useful to study a particular watershed, the model has to be calibrated to that specific watershed. The objective of the calibration process is to tailor the model settings so they more closely reflect the physical responses either observed or expected in a specific geographic area. The simulated output should resemble the observed output. Input calibration parameters include (but are not limited to) topography, land cover, land use, climate, and soil type. Because several model parameters are not available from field data, those parameter values are manually determined during the calibration process by comparing simulated and observed flow volumes (Skahill 2004). PEST is a model-independent software that allows the user tocalibrate various parameters within HSPF. It is a tool that mathematically considers the parameters of HSPF that need to be calibrated, and looks at different value permutations and combinations to determine which values result in a stream flow time series that most closely resembles the observed. For large watersheds, PEST is the primary means for calibrating many parameters. By providing actual field data from the watershed as input for calibration, instead of relying primarily on PEST, a more specific range of values can be used during the calibration process, and the likelihood of a more realistic output increases.

For this study, the objective was to focus on the model parameters that affect stream flow, such as surface runoff, infiltration, percolation, and interflow. As mentioned earlier, there are hierarchical algorithms that determine the model output and through testing a series of HSPF parameters and a review of the literature, the function that most resembles vadose zone estimations of recharge is known as PERC.

7.1 The PERC function

Pervious land processes in HSPF occur in a series of storage zones and hydrologic responses are dictated by land cover, soil type, and topography. The PERC function is used to calculate water percolating from the upper zone to the lower zone and is given as a rate of inches/time interval. As a physical frame of reference for the zones, interflow occurs in the upper zone and baseflow occurs in the lower zone. The present study assumes that the water table is located in the lower zone. HSPF calculates that percolation function using the following equation:

$$PERC = 0.1*INFILT*INFFAC*UZSN*(UZRAT - LZRAT)**3 \quad (4)$$

where INFILT is soil infiltration rate (in/hr), INFFAC is the amount of frozen ground, UZSN is the upper zone nominal storage (in), UZRAT is the ratio of the upper zone storage (UZS) to upper zone nominal storage (UZSN), and LZRAT is the ratio of the lower zone storage (LZS) to lower zone nominal storage (LZSN). Because there was never frozen ground at the study sites, INFFAC was automatically set to one.

In HSPF, soil infiltration rate (in/hr) is a function of soil characteristics and calibration ranges are typically determined based on hydrologic soil group (EPA 2000). High INFILT values result in increased baseflow as a result of more water moving into the lower zone; and low INFILT values result in increased interflow and overland flow values.

UZSN refers to the nominal amount of soil moisture storage (in) one would expect to observe in the upper zone. UZSN is listed as a percentage of LZSN that is dictated by topography and land cover. As UZSN increases, the amount of water available for evapotranspiration increases. Typically, UZS is set to equal UZSN unless it is known that the conditions were particularly wet or dry at the time (EPA 2000).

LZSN refers to the nominal amount of soil moisture storage (in) one could expect to observe and is determined by the soil characteristics in a given region listed in the ARM Model User Manual (Donigian and Davis, 1978). LZS is the fraction of soil moisture (in) that is actually observed and as with UZS and UZSN, LZS is typically set to equal LZSN unless conditions were particularly wet or dry at the time.

7.2 Manipulation of parameters

Although a PERC value cannot be directly manipulated by the user, within the equation for the PERC function, some parameters can be designated by the user to produce the desired PERC value. The value ranges of the INFILT, UZSN, and LZSN parameters shown in Table 7.1 are the ranges listed in the HSPF Technical Note 6 (2010) and the values currently used in the calibration of two of the watersheds used in the first part of this study.

Table 7.1. PERC parameters and values

Name	Unit	*Typical range*	*Possible range*	Values (inches)			
				Pee Dee Calibration		*Waccamaw Calibration*	
				Wetland	*Forest*	*Wetland*	*Forest*
INFILT	in/hr	0.01-0.25	0.001-0.50	0.45	0.39	0.26	0.15
LZSN	in	3.0-8.0	2.0-15.0	2	2	2.11	15
UZSN	in	0.10-1.0	0.05-2.0	2	1.98	1.06	0.75

INFILT is set based on the soil texture at the ground surface. With the assumption that LZSN is based on the maximum soil moisture that could be observed, the user can establish values based on field data and variably manipulate LZSN and USZN until a PERC value similar to the calculated recharge rate is observed. It is a process similar to what PEST does, but because it is user guided and based on observed data, the range of values that can be used for LZSN and UZSN is more specified and will increase the chance of producing a more realistic PERC value.

CHAPTER 8

CONCLUSION

The results of this study indicate that wetland type did not significantly affect the rate of groundwater recharge; however, event type and precipitation frequency did. Rates observed during periods of sporadic precipitation were different from rates observed during periods of frequent precipitation. The results of this study also showed that soil texture in the saturated zone can be a driving force in the unsaturated zone, when saturated soil textures are similarly drained.

Land management implications from the findings of this study include the relevance and impact of underlying soil texture when addressing hydrologic behavior. Recharged groundwater is often used as a drinking water source and it feeds many surface water bodies, so when natural resource managers are considering the water budget of an ecosystem and attempting to account for the amount of groundwater that will be replenished, surficial soil texture does not significantly impact the amount the recharge rate, and thus, how quickly underground aquifers can be replenished.

From a practical standpoint, there was not an observed statistically significant difference in the recharge rates of isolated and riverine wetlands in this study. That does not diminish isolated wetlands' ecologic relevance. Recharge *does* occur at isolated wetlands; and as locations of recharge, their presence increases the capability for an area to replenish groundwater resources. One could even argue that because infiltrating water collects in the depression and surrounding groundwater follows the downward slope of the depression and remains in the depression, isolated wetlands recharge more groundwater than uplands or riverine wetlands. Regulatory agencies should consider the implications of decreasing the aforementioned opportunities to replenish groundwater when making permit decisions. Practical application of this research could also be useful to land manager and hydrologic modelers. This study demonstrated not only how field data can be used to calibrate HSPF for a specific watershed, but how physical conditions—such as soil textures in the saturated zone and recent precipitation trends—should be taken into account when making adjustments for a specific stream reach.

Conclusions from this work would be strengthened by a longer monitoring period and additional study sites. Increasing both of these factors not only provides more robust data, but also provides an opportunity for conclusive statistical results. However, the overall implications and conclusions of this research still demonstrate the influence of isolated wetlands on the groundwater of an ecosystem. It would also be interesting to see future research that compared similar data from the Coastal Plain to that of the Piedmont region.

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APPENDIX A

FIELD DATA COLLECTION SHEET

Table A.1 Field data collection sheet

	Date	Checked by:	Well ID	Time	Well Depth below land (feet)	Total Depth (feet)	Riser Length (feet)	E-Tape DTW (feet)	Logger DTW (feet)	DL Status	DL Serial #	Desiccant Status
1			MA-01		17	21.27	4.25				157042	
2			MA-02		18	22.50	3.21				156662	
3			MA-03		10	14.62	3.74				156943	
4			LB-01		7	11.45	4.10				156502	
5			LB-02		12	16.55	4.20				156646	
6			LB-03		15	19.29	4.10				156670	
7			LB-04		12	15.96	3.87				156718	
8			MF-01		4.04	7.85	3.88				157348	
9			MF-02		6.41	9.15	3.29				157366	
10			MF-03		3.46	6.92	4.03				157361	
11			MF-04		5.17	9.56	4.21				157355	
12			BR1a		7.10	9.95	2.85				157044	
13			BR1b		13.84	15.00	1.16				157299	
14			BR2a		4.34	9.78	5.44				157280	
15			BR2b		8.75	9.91	1.16				156902	
16			BR12		10.79	15.31	4.52				157045	

APPENDIX B

WATER TABLE ELEVATION HYDROGRAPHS

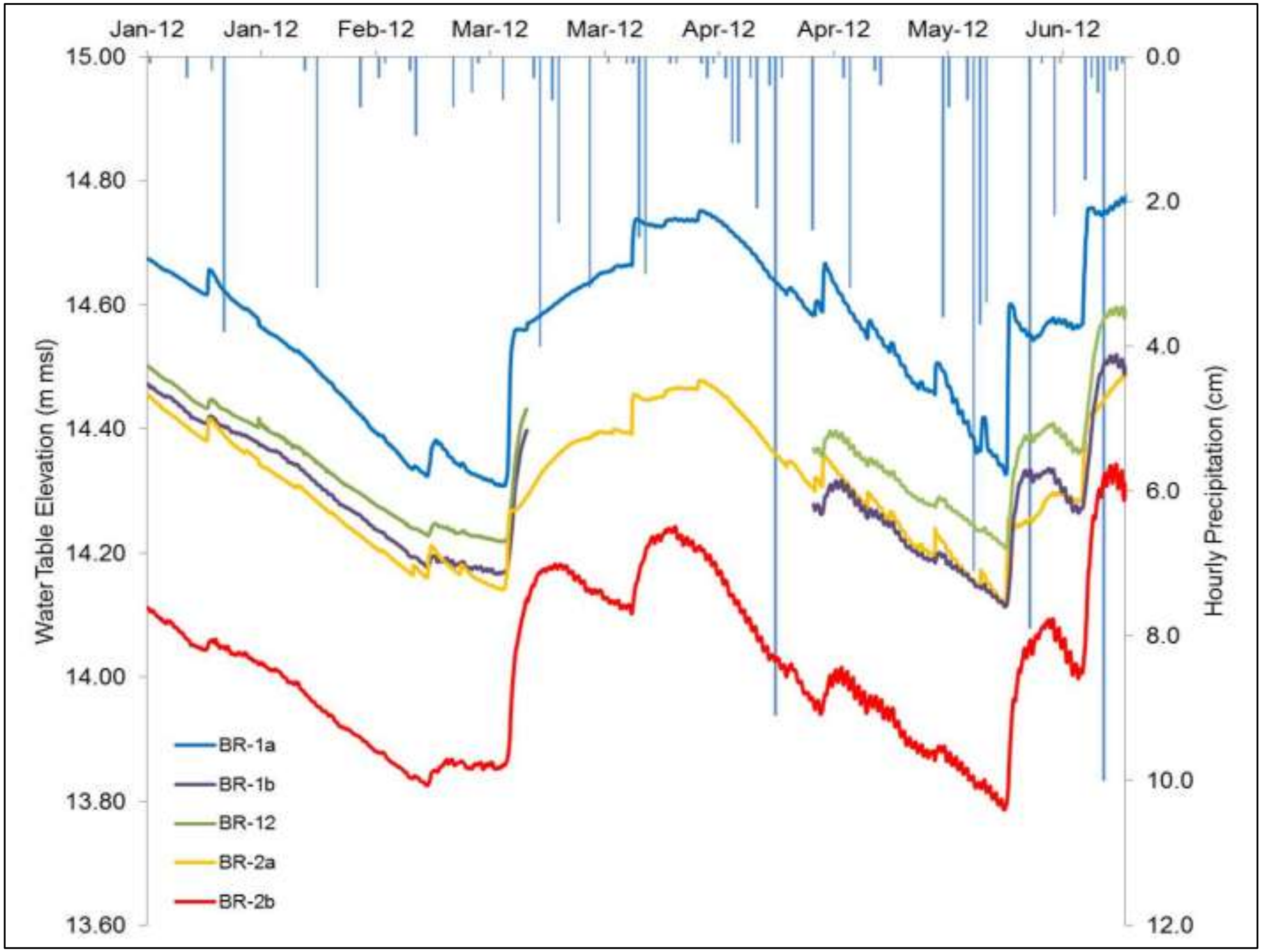

Figure B.1 Water table elevation hydrograph for the BR site. Due to its location outside of the transect, the riverine wetland well (BRFL) is excluded.

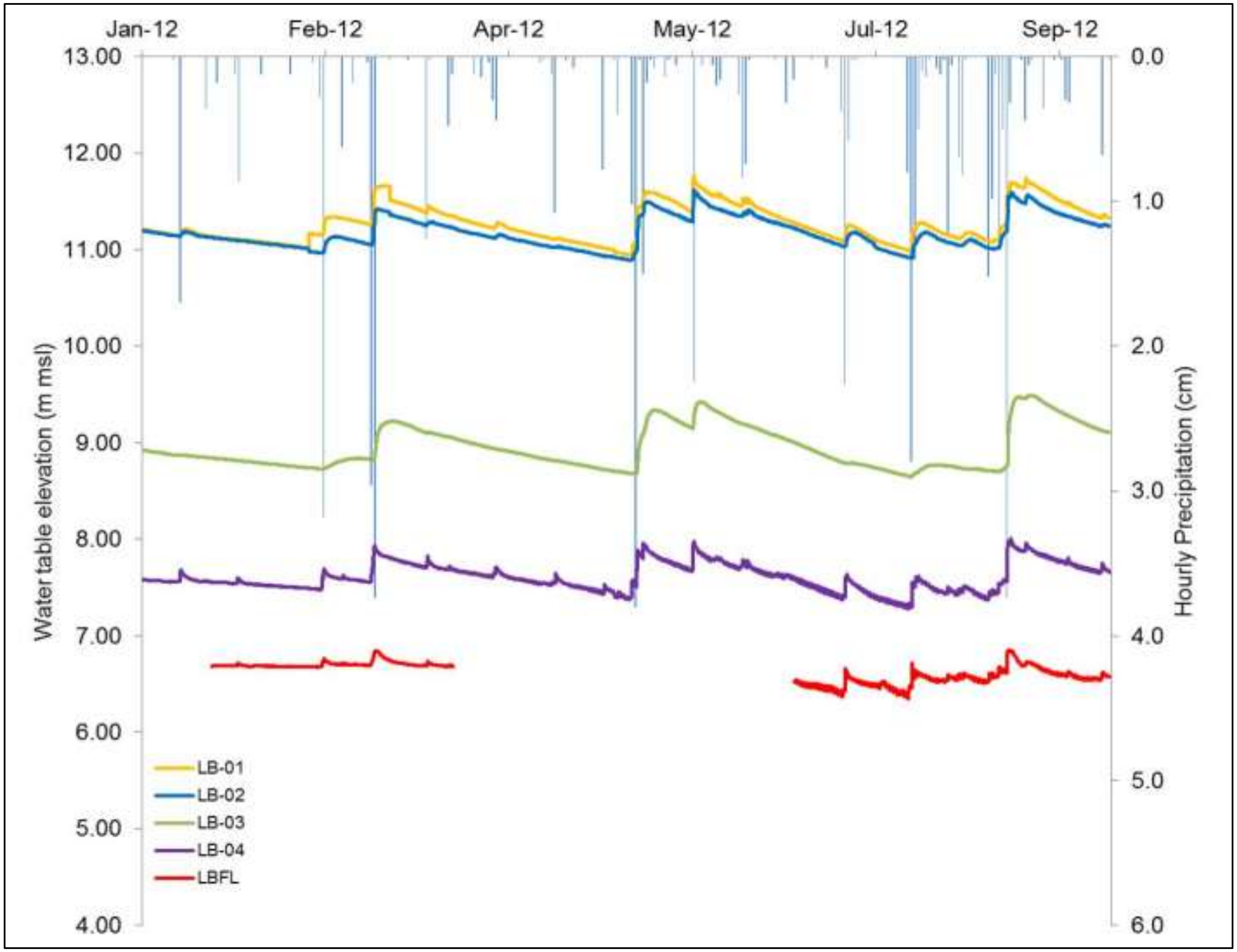

Figure B.2 Water table elevation hydrograph for the LB site.

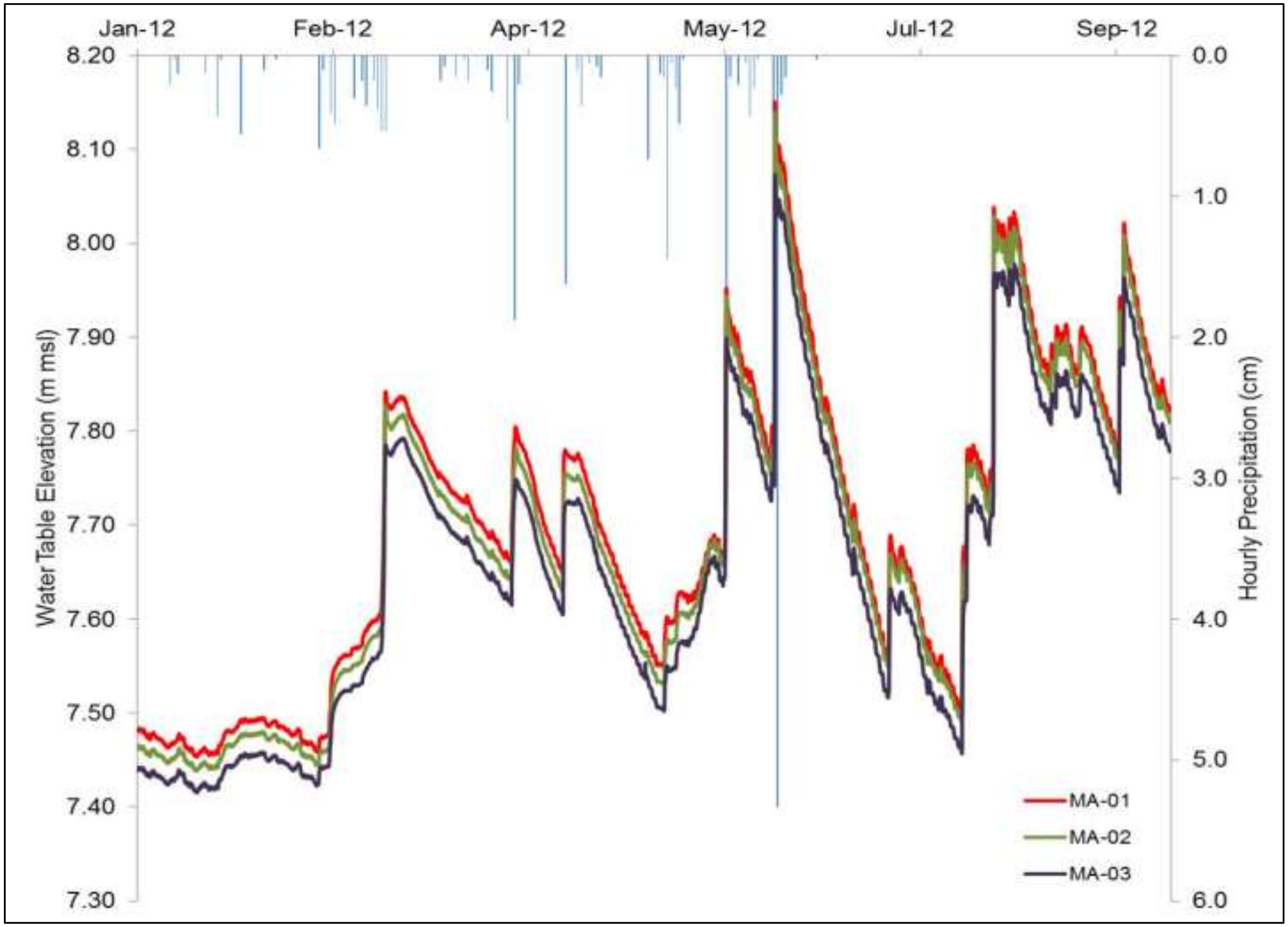

Figure B.3 Water table elevation hydrograph for the MF site. Due to its location outside of the transect, the riverine wetland well (MAFL) is excluded.

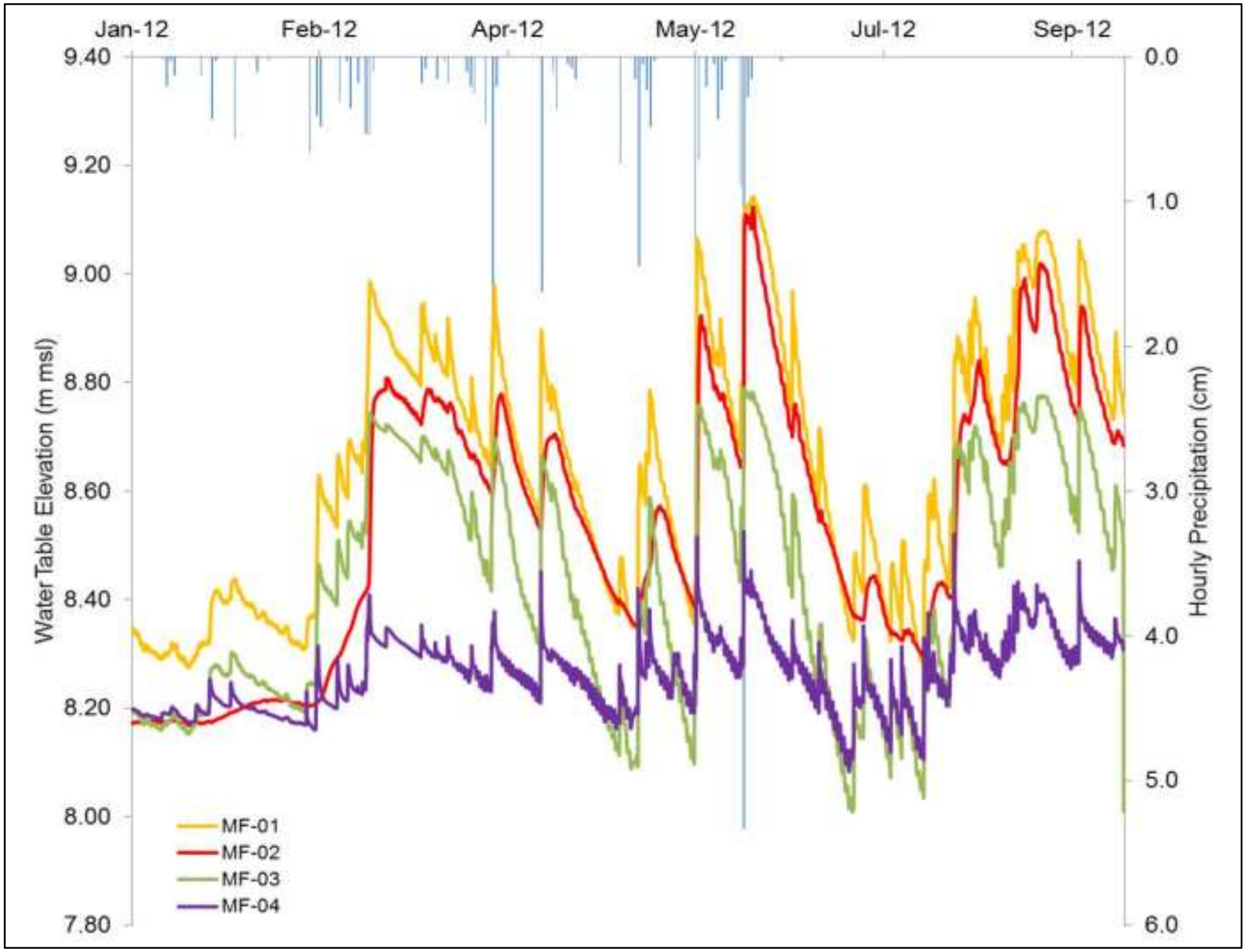

Figure B.4 Water table elevation hydrograph for the MF site.