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Hydrologic Variations Within Created and Natural Wetlands in Southeastern Virginia

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HYDROLOGIC VARIATIONS WITHIN CREATED AND NATURAL WETLANDS IN SOUTHEASTERN VIRGINIA

by

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ABSTRACT

HYDROLOGIC VARIATIONS WITHIN CREATED AND NATURAL WETLANDS IN SOUTHEASTERN VIRGINIA

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The hydrology of wetlands, particularly how wetland soils collect, store, and redistribute water strongly affects how wetland systems function. In created wetlands, construction processes and materials influence the hydrology and consequently, the potential for successful reestablishment of target vegetation communities. During 2002-2004, the Virginia Department of Transportation constructed large mitigation wetlands on two different Quaternary aged surfaces with very similar hydrogeomorphic conditions. The Sandy Bottom Nature Park site (SBNP) located in Hampton, VA and rests on the sandy loam Tabb Formation while the Charles City Wetland site (CCW) lies on the older and clay-rich Shirley Formation. This study documents and synthesizes stratigraphic and soil permeability data with biweekly and hourly hydrologic data collected from piezometer nests located in the constructed and surrounding natural wetlands at both locations in order to understand the influences of different construction practices on the hydrology of these mitigation wetlands. The clay-rich soils at the CCW natural and constructed sites displayed both endoaquic and epiaquic conditions that varied spatially and temporally as a result of the removal of the A-horizon and the exposure of the expansive clay-containing Btg-horizon. The newly constructed CCW wetland had a much faster response to precipitation than the natural wetland because the combination of moderately expansive clay soils and unusually dry weather resulted in extensive soil

cracking on the newly graded surface at all but the wettest areas. The SBNP wetland site, constructed by filling in an existing lake with a variety of sediment types, contained extensive finer-grained layers that were tightly compacted during construction. These compacted layers impeded vertical flow and resulted in epiaquic conditions that were never observed in the surrounding natural wetland formed on loamy sediments.

The data collected during this study show that several factors can affect the hydrology of both natural and constructed pocosin wetland sites. Significant climatic influences include evapotranspiration, seasonal precipitation variations, and diurnal barometric pressure fluctuations. Geologic factors include landscape position, regional aquifer characteristics, stratigraphic variations in shallow sediments and soils, and both primary and secondary porosity. Construction practices affect hydrology via scraping surface soils, layering and compaction of sediments, deep ripping, and the addition and mixing of organic material into the final wetland surface.

This thesis is dedicated to my late father, Jack Despres.

ACKNOWLEDGMENTS

I would like to thank my committee members, Drs. Lee Daniels, Joe Rule, and Don Swift for their help and guidance. I would especially like to thank my advisor Dr. Rich Whittecar for his invaluable insight and persistence to push me towards completion. I am also extremely thankful for the assistance of Rob Gucwa, Mike Howell, Kevin Murphy, Daniel Raines, Eric Seavey, and Jeff Vandever in the field, especially on those days when it was 20 degrees and snowing or a balmy 98 degrees in the shade. A special thanks goes to Cara Bergschneider and Gabby Fajardo at Virginia Tech for sharing their hydrologic and soil bulk density data with me. I would also like to thank Dr. Ron Butler from the University of Maine at Farmington for his assistance with the statistical methods I used. I owe a debt of gratitude to R.C. Kidd for his help in fabricating and fixing equipment as I broke it, all with a minimal amount of complaining. Lastly, I would like to thank my family for their love and support they gave me through this experience.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

LIST OF FIGURES (continued)

Figure Page

CHAPTER I

INTRODUCTION

An understanding of the hydrology of wetlands is critical to knowing how wetland systems function. In particular, knowledge of how wetland soils collect, store, and redistribute water is necessary when designing constructed wetland sites, such as those used to mitigate for the disturbance or destruction of existing natural wetlands. It is also necessary to understand how wetland construction processes and the materials used influence the hydrology and consequently, the functions of a created wetland.

During 2002-2004, the Virginia Department of Transportation (VDOT) constructed large mitigation wetlands across two landscapes where the natural hydrologic patterns are very similar, even though they both have distinct geologic settings (Figure 1). The construction practices and materials used at the two sites were quite different. If the new wetlands function successfully over the next several decades, all of the natural and constructed wetland sites in and around these two large projects should have the same general vegetation (palustrine forest) and range of wetness conditions.

Ongoing research at these sites requires geologic assessments and periodic hydrologic monitoring. The research completed for this thesis project expanded the amount of data previously collected at these two sites. The primary goal of this research was to increase the knowledge of the effects that wetland construction practices have on the hydrology of created mitigation wetland sites in different geologic settings in southeastern Virginia.

The model journal of this thesis is the Journal of Hydrology.

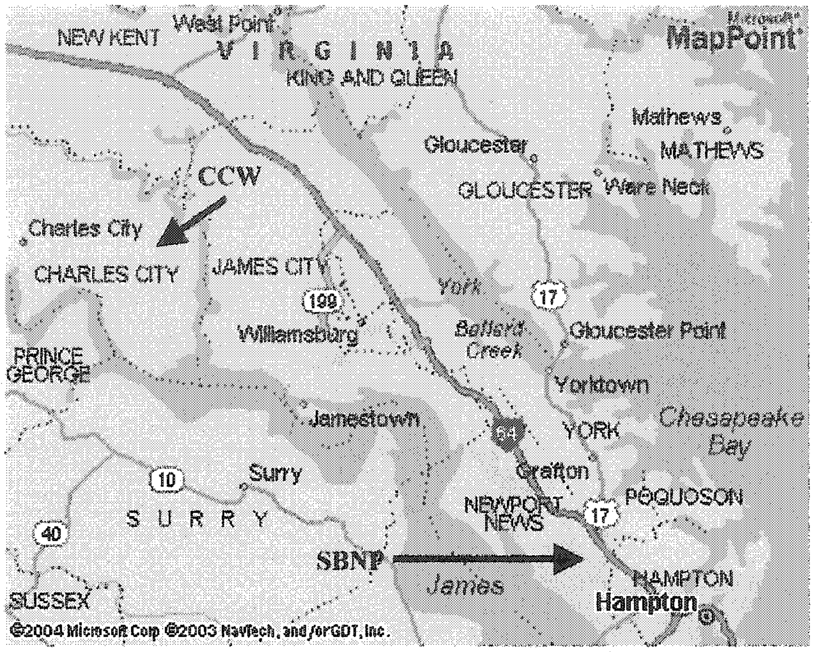

Fig. 1. Locations of Charles City and Sandy Bottom Nature Park study sites.

Wetland Functions and Preservation

Wetlands have many chemical, biological and physical functions important to the health of ecosystems. Once seen as nuisances that needed to be drained to make useful, wetlands are now recognized as indicators of Earth's ecological health (Mitsch and Gosselink 1986; Shilts 2000). Wetlands benefit whole ecosystems including human populations. They trap sediments and sequester or break down nutrients and toxic chemicals carried by inflowing water. Wetlands can also act as groundwater recharge zones or as points of discharge. Coastal and floodplain wetlands may diminish the effects of flooding and erosion resulting from tides, storms, and runoff by reducing flow velocities and by temporarily storing water and releasing it slowly. Wetlands also provide habitat for many organisms such as aquatic and terrestrial animals and may host a large diversity of plant life (Hayes 1993). Wetlands are also carbon, nitrogen, and sulfur

sinks, which may be an important consideration as concerns about potential global climate change grow (Mitsch and Gosselink 1986; Sun et al. 2002).

In the 1780s, wetlands covered approximately 748,300 hectares, or more than 7% of Virginia. By the mid-1980's, 435,000 hectares of wetland remained, a loss of about 42% in 200 years (Dahl 1990 *in* Hayes 1993). Historically, most wetland losses that have occurred in the U.S. resulted either directly or indirectly from programs supported by the government. Agricultural and industrial practices, as well as urban development and recreation have led to the destruction of Virginia's wetlands by ditching, draining, dredging, filling, diking, and damming. These practices, combined with human-induced and natural occurrences of erosion, saltwater intrusion, and plant succession, have led to widespread wetland loss and degradation. Only in recent times have the development and implementation of new policies and administrative programs resulted in significant decreases in wetland loss (Hayes 1993; Whigham 1999).

Most streams and wetlands are currently protected from destruction under the Clean Water Act of 1977. The Army Corps of Engineers (COE) manages the permitting process that may allow for the destruction of wetland areas (Kruczynski 1989). Road construction, mining, and other activities that affect large areas of land may require the disturbance of wetlands that is determined to be unavoidable. The COE may permit the disturbance of a wetland if a larger area of self-sustaining wetland is constructed at another location. These compensatory mitigation projects often involve the creation of new wetlands by grading non-wetland areas down to the level of neighboring wetlands, ultimately creating new landscape features (Whittecar and Daniels 1999).

Wetland Hydrology

Hydrology plays a critical role in wetland functions through interactions with vegetation and soils. Basic hydrological data such as groundwater dynamics and seasonal water balance are essential in understanding wetland ecosystem functions and to determine if a natural or constructed site is a wetland that falls under the jurisdiction of specific regulations (Sun et al. 2002).

The Hydrogeomorphic Classification (Brinson 1993) was developed to identify broad groups of wetlands that function similarly based on three criteria that influence wetland function. These criteria are geomorphic setting, water source, and hydrodynamics. The geomorphic setting refers to the landform in which the wetland occurs, as well as its geologic evolution and topographic position in the landscape. Water source refers to the origin of water prior to entering the wetland system and may include groundwater discharge, precipitation and overbank flow (riverine systems). Hydrodynamics refers to the level of energy and direction that water moves in the wetland system (Rheinhardt et al. 2002).

The position of the wetland in the landscape affects many aspects of the hydrogeomorphic functions of the wetland, especially the pattern of groundwater recharge and discharge. For example, Mineral Soil Flats (Brinson 1993), known locally as "pocosins," develop on broad, nearly flat interfluves that are unable to quickly absorb and drain precipitation down through their substrata and over their surfaces. Hydric conditions develop on interfluvial flats due to abundant precipitation and the presence of low relief. They form in areas of groundwater recharge and typically have a seasonal range of water levels that may exceed 2 meters during many years. Pocosins (Algonquin

for "swamps-on-a-hill") cover large expanses of southeastern Virginia, particularly where the surficial geological unit has relatively low permeability, coupled with low slope and poor dissection (Whittecar and Daniels 1999; Rheinhardt et al. 2002). Pocosins are precipitation driven systems where water flows outward from their centers and may eventually form headwater streams near their outer boundaries (Brinson 1991). A groundwater dome commonly forms in pocosin systems, where the top of the dome (highest groundwater levels) forms in the middle of the wetland. The top of the dome is often characterized by pronounced downward movement of groundwater while the edges of the dome exhibit dominantly lateral groundwater movement. Water movement at the edge of the groundwater dome is toward regional drains, such as valley bottoms including rivers and streams.

Many areas around these wetlands would meet official hydric soil criteria if the water table rose closer to the surface during the winter months. These marginally wet areas are presumably ideal locations for creating new wetlands, particularly if grading down the surface of the land closer to the seasonal high water table can generate wetland hydrology. Obviously, the structure and permeability of the soil on this newly constructed surface will reflect the methods used to grade the surface down, amend the remaining soil, and prepare the surface for planting.

Rheinhardt and Brinson (2000, 2002) evaluated the ecological performance of 49 mitigation wetland sites built for the North Carolina Department of Transportation. They reported that wetland sites that had the A-horizon removed and no soil amendments added were often ecologically unsuccessful and the planted vegetation usually failed to flourish. Trees planted at these sites may have survived the COE required 3-5 year

sampling period, but were often stunted. The study concluded that at seven sites, poor soil quality was due to the removal of the A-horizon and resulted in high vegetation mortality. Soil alteration at these sites was due to excavation either during wetland construction or from prior land use, such as agriculture. The study also reported that at several of these sites, soil compaction was prominent, often marked by the presence of deep ruts as well as a lack of organic matter (on the recently lowered surface).

The process of how and when different parts of the soil become saturated may influence the eventual success of these constructed wetlands for several reasons. Epiaquic conditions, as defined by the Soil Science Society of America (2004), occur when soil that is saturated in one or more layers within 2 m of the surface also has one or more lower layers of soil that are unsaturated within 2 m of the surface. This condition most likely exists due to the perching effect of one or more layers present, preventing water infiltration downward into the soil profile. Griffin et al. (1998) stated that in the Texas Coast Prairie Major Land Resource Area, soil scientists recognize conditions where soils have ponded water at or near the surface for extended periods of time while the subsoil remains unsaturated. Epiaquic conditions may indicate hydrologically stressful circumstances for vegetation because roots may not readily penetrate into the perching layer if it is extremely hard or compacted (W.L. Daniels 2003 personal communication). Root systems in epiaquic settings may therefore be more prone to drying out than would a deeper, unrestricted root system. Shallower root systems may also be vulnerable to extreme weather events such as high winds that could result in toppling that would otherwise not occur in a forest community with a deeper root system.

Endoaquic conditions are more favorable for vegetation than epiaquic environments. Endoaquic conditions occur when all layers are saturated to a depth of two meters from the surface, in effect indicating that a hard or compacted perching layer is not present and water may move freely downward through the soil profile from the surface. Roots are therefore able to establish themselves deeper into the soil profile, increasing stability of vegetation and its ability to take up soil water.

Soil Cracking

Some wetland soils are prone to periodic drying either seasonally or during drought periods. Desiccation may lead to shrinkage causing cracks to form in the soil. These cracks form due to the contraction of shrink-swell minerals such as smectites and vermiculites present in the soil (Krauskopf and Bird 1995). Cracks can change the hydraulic properties of the soils. Germann (1990) and Jones (1981) describe the effects of cracking on infiltration and redistribution of water in non-wetland soils. Little information exists, however, on cracking influences in wetland soils. The presence of cracks can be expected to increase the hydraulic conductivity of the wetland soils. If shrinkage is temporary, due to the ability of the soil to become rewetted, cracking may result in temporal changes of the hydraulic response of soils, leading to non-Darcian behavior. During dryer times of the year, cracks may be present, creating one set of hydrologic conditions. During wetter times of the year, cracks may not exist, creating different hydrologic conditions (Baird 1995).

Site Descriptions

The two study locations, each including a natural and constructed wetland site are both located in the middle of broad flat Coastal Plain terraces (Figure 1) and thus, are

classified as Mineral Soil Flat wetlands (Brinson 1993). Therefore, on a landscape scale, the sites are expected to have pocosin-like hydrology. Natural wetland sites along the edges of both of VDOT's constructed sites display similar hydroperiods. However, differences in the patterns of near-surface permeability in these wetlands may prove to be critical to VDOT's ability to establish the target wetland vegetation community at the mitigation sites. These differences may stem from variations in the geologic strata, the degree of soil development, and the construction practices used.

Charles City Wetland Mitigation Site

The Charles City Wetland Mitigation Site (CCW) is a VDOT-constructed wetland located west of Route 623 in Charles City County, Virginia. This site was created to mitigate for wetland disturbance caused by the construction of Route 199 in Williamsburg, VA (Figure 2). Researchers from Virginia Polytechnic Institute and State University, Old Dominion University, and Virginia Institute of Marine Science have constructed two large plots at the CCW constructed site to conduct nutrient loading experiments.

The CCW site sits on the Shirley Formation, which underlies many of the mid-level terraces that flank the James River estuary (Mixon et al. 1989). Radiometric dates on Shirley material suggest an age of 200-400 Ka for the formation (Mixon et al. 1982). The Shirley ranges in thickness from a featheredge against the Kingsmill scarp to the west to more than 24 m in paleochannels. The Shirley Formation disconformably overlies late Tertiary and older Pleistocene formations in the Lower Coastal Plain. Along the James River, the ancient estuary sediments that make up the Shirley generally fine upwards. At two gravel mines in located in Charles City County, the Shirley Formation

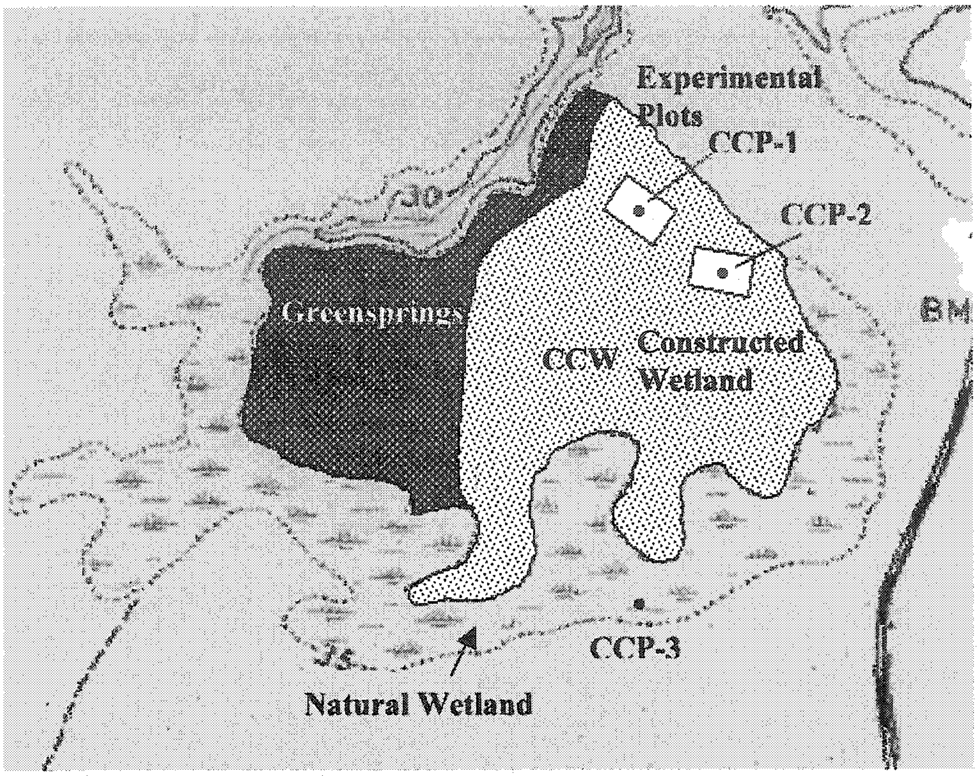

Fig. 2. Topographic map of Charles City and Greensprings mitigation wetland sites. Monitoring wells are located at each of the four corners of the plots and piezometers are positioned in the middle of each plot. Scale is 1:24000.

is well exposed and displays pebbly-to-bouldery gravel beds that lie beneath a sequence of coarse-to-fine sands which are capped by clayey sandy silt (Johnson et al. 1987). The upper-most beds can exceed 3 m in thickness and may display weak cementation (G.R. Whittecar 2004 personal communication).

Both the CCW before construction and the surrounding natural wetlands contain mostly Chickahominy loam soils. The soil consists of a dark gray loam at the surface that may be approximately 0.2 m in thickness, followed by a massive clay loam Btg-horizon that may exceed 1.5 m in thickness. Below the B-horizon is a loamy sand C-

horizon. Chickahominy soil may contain large amounts of expansive clays such as montmorillonite (Hodges et al. 1990).

The total area of the CCW site is 20.77 hectares, including 18.31 hectares designated to be forested wetland. Wetland designers wanted to lower the land surface to an elevation reflected by the surface of the natural wetlands to the south, an elevation they took to represent the water table. Thus, the wetland area was constructed by excavation of the upper soil profile to a depth of 0.4 to 0.6 m.

Compaction of soil can lead to perching (epiaquic) conditions, particularly if the soil is fine-grained. Generally, compaction effects are more pronounced and penetrate more deeply into the soil profile with wetter soils and heavier loads (Brady and Weil 1999). Thus, fine-grained soils commonly become compacted when heavy equipment is used in the wetland construction process. During construction activities that took place in 2003, it was observed that equipment used weighed in excess of 36000 kg (Caterpillar 2004).

The broad expanses of compacted argillic (Btg) horizon at the CCW site cracked significantly during the study period when they were exposed after regrading. The desiccation cracks were most numerous where the soil surface was most often free of standing water. Because 2002 was drier than average, most of the CCW surface was dry for long periods of time. During subsequent wetter periods, the initial cracking persisted for months after the surface was inundated. The presence of megapores, such as soil cracks may be an important factor in understanding the hydrology of the CCW site.

The site was constructed in 1998 by grading the surface down via scraping with a bulldozer blade. The site however, was not corrected for possible compaction that

resulted from the construction process. During the summer and fall of 2003, much of the site was regraded to a lower elevation, as some areas did not demonstrate the proper hydrologic conditions. During this operation, the areas that were regraded were also 'ripped' and organically amended to decrease the effects of compaction and create more favorable conditions for vegetation. To rip, operators used a rake-like implement attached to a bulldozer blade to loosen the soil to an approximate depth of 0.25-0.5 m.

The natural wetland site is located to the southeast of the CCW constructed site. The forested wetland there contains the same soils as the constructed wetland with a few exceptions. The A-horizon is up to 0.1 m deep at the natural site, while at the constructed site most of the A and E-horizon were removed during construction to reduce the elevation of the surface to achieve the proper hydrologic conditions. The Btg horizon present in the natural wetland is not considered compacted, although it is very dense at depth. The natural site supports a typical wetland vegetation community, while the constructed wetland was planted in the spring of 2004.

Sandy Bottom Wetland Mitigation Site

Chisman Lakes in Hampton, Virginia were acidified gravel pits abandoned for several decades. The property was deeded to the City of Hampton with a restriction stating that the Virginia Department of Transportation (VDOT) had the right to use portions of the site for wetland mitigation purposes should the need arise (Daniels et al. 1995). In the late 1990s, the land was altered considerably and turned into the Sandy Bottom Nature Park (SBNP) (Figure 3).

The park sits on the Tabb Formation, a late Pleistocene unit deposited in the ancestral Chesapeake Bay that has been dated at 120-70 Ka (Peebles et al. 1984).

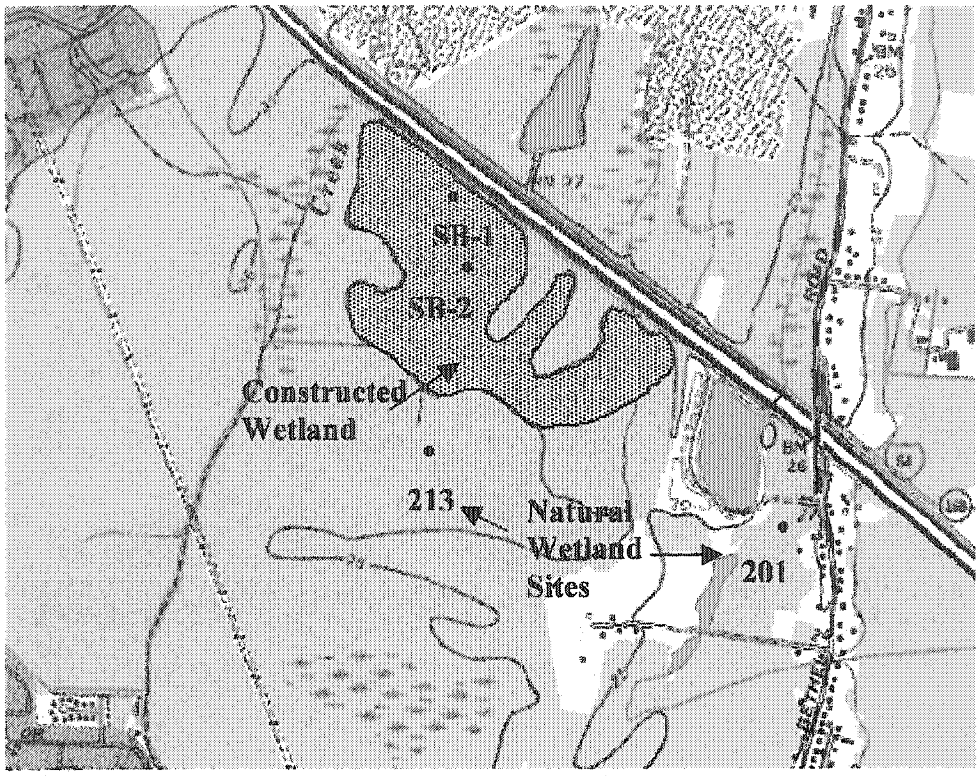

Fig. 3. Topographic map of Sandy Bottom Nature Park mitigation wetland site. Constructed wetland is shaded. Piezometer locations are also shown. Scale is 1:50000.

On the York-James Peninsula, the gravelly sand at the base of the formation grades upwards into a gray to yellowish-brown, burrowed, quartzose, fine to medium sand. The medium to fine sands grade vertically into a fine sandy clayey silt (Johnson et al. 1987). Based on three 30 m deep boreholes, Daniels et al. (1995) reported that the Tabb Formation at the study site is approximately 7.6 m thick, capped by a sandy silt at the surface.

The natural soils at SBNP are dominantly comprised of the Tomotley soil series. A sandy loam A-horizon is present at the surface and is approximately 0.5 m thick. Below this layer is a 0.25 m thick sandy loam E-horizon. A Btg-horizon follows the E-

horizon and is approximately 1m thick and grades from a sandy loam to a loamy sand with depth. Below the B-horizon, a massive sand C-horizon is located (Daniels et al. 1995).

For the past two decades the SBNP site contained two borrow pit lakes excavated into the Tabb Formation, separated by a narrow finger of spoil material. The larger lake was known as the 'bad lake' because of its acidic chemistry, while the smaller lake, known as the 'good lake' exhibited only slightly acidic conditions. In the fall of 2002, the larger lake was filled in to create 21.04 hectares of wetland to mitigate for destruction caused during the construction of the Hampton Roads Center Parkway. As of 8/2004, the final grading certain portions was still pending and the site is to be planted in Fall 2004.

The constructed wetland was created by filling in the existing lakes with non-native coarse to fine-grained sediments. The finer-grained sediments contain higher amounts of clay than the surrounding native soils and are more prone to compaction than the original native sediment. Therefore, compaction that occurred during construction may alter hydrologic conditions of the constructed wetland that would not normally be observed in a natural setting. Significant cracking was not observed at this site.

Large, relatively undisturbed forested wetland sites are located at SBNP (Daniels et al. 1995). Study sites 201 and 213 (Figure 3) established by Daniels et al. (1995) were locations in a grid of monitoring wells used by Whittecar and Daniels (1999). The wetter site (201) is located approximately 50 m to the west-northwest of Big Bethel Road, near the entrance to the park. The other site (213) is located in a wetland approximately 100 m to the northeast of the Hampton Roads Center Parkway. There is no evidence of compaction at either natural site.

To recap, VDOT constructed two mitigation wetlands on distinct Coastal Plain formations with different soil textures and degrees of soil development by using very different construction techniques and materials. Comparisons of the pattern of permeability in these soils and sediments may help explain the different hydrologic responses of these materials to seasonal changes and precipitation events.

Purpose and Objectives of Research

The purpose of this research was to understand the hydrologic impacts of wetland construction techniques used in different geologic and pedologic settings.

The objectives of this study were:

1. To determine the causes of variations in patterns of hydrologic response to recharge events.
2. To determine the effects that construction practices used in mitigation wetlands have on the permeability and hydrologic response in fine-grained soils.
3. To determine the effects that construction practices used in constructing wetlands have on the permeability and hydrologic response in stratified multi-textured soils.
4. To determine if soil cracking influences the hydrology of a constructed wetland.

CHAPTER II

METHODS

In order to meet the objectives of this research, one must evaluate the stratigraphic setting and collect hydrologic and permeability data from critical levels in the shallow subsurface. These data will permit quantification of differences in rates of hydrologic responses to recharge events at the natural and constructed wetland sites. Statistical analyses were used with some of the data to determine if differences observed at the sites were significant.

Stratigraphic Data

Based upon the quality and close proximity of sites used in previous stratigraphic studies (Johnson et al. 1987; Daniels et al. 1995; Whittecar and Daniels 1999), stratigraphic data collection for this research focused on the shallow subsurface. Stratigraphic data were gained during borehole excavation for well and piezometer installation (discussed below) at both CCW and SBNP locations. A hand auger was used and augered soil material was sampled at approximately every 0.15 m and described for composition and texture. Maximum borehole depths were approximately 3 m. Several other shallow boreholes were made throughout the constructed wetland sites to further explore the stratigraphy that was controlling the hydrology at these locations.

Soil Permeability Data

Soil permeability was determined in the laboratory for soils of both natural and constructed wetland sites at both SBNP and CCW locations. At each sampling location, soil samples were retrieved using a coring instrument that acquired a 0.05 m diameter soil

sample approximately 0.15 m long inside a clear polycarbonate tube (Figure 4). Three soil samples were obtained from three different depths within one meter of the surface, for a total of nine samples collected at each sampling location (Table 1).

One suite was taken from both the natural and constructed sites at CCW and SBNP (Table 1). With the exception of CCW-1, all samples were located at a piezometer nest. Sample CCW-1 was obtained between the two experimental plots where the surface had been graded down, but never ripped to loosen the soil at the surface and reduce compaction due to the construction process.

Table 1
Permeability sampling depths for CCW and SBNP sites.

Site	Surface Condition	Shallow (m)	Intermediate (m)	Deep (m)
CCW-3	Natural	0.15	0.46	0.71
CCW-1	Scraped only	0.10	0.36	0.61
213	Natural	0.15	0.51	0.76
SB-2	Compacted fill	0.10	0.36	0.61

Once the sample was obtained, the tube/sample was trimmed to 0.06 m with an electric chop saw and loaded into a permeameter. Permeameters permit the measurement of the hydraulic conductivity of materials (Fetter 2001). In most cases, a falling-head permeameter was employed due to the low conductivity nature of the sediments sampled (Figure 5). However, in one case, the sample was noncohesive and had a relatively high permeability. A constant-head permeameter was used in this case (Figure 6).

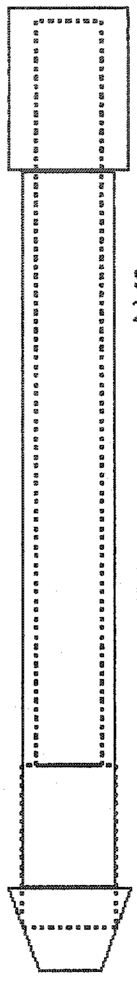

Fig. 4. Diagram of soil core sampling device. Coring device was designed to be driven into the ground with a sledgehammer. Total length of instrument is 80 cm.

Fetter (2001) defines the equation for measuring the hydraulic conductivity using a falling head permeameter as

$$K = (d_t^2 L / d_c^2 t) \ln(h_o/h)$$

where

K is hydraulic conductivity (cm s^{-1})

L is sample length (cm)

h_o is initial head in the falling tube (cm)

h is final head in the falling tube (cm)

t is the time that it takes for the head to go from h_o to h (s)

d_t is the inside diameter of the falling head tube (cm)

d_c is the inside diameter of the sample chamber (cm)

The equation used to find the hydraulic conductivity of a sample where a constant head permeameter is used is defined by Fetter (2001) as

$$K = VL/Ath$$

where

K is the hydraulic conductivity (cm/s)

V is the volume of water discharging in time t (cm^3 s^{-1})

L is the length of the sample (cm)

A is the cross-sectional area of the sample (cm)

t is the amount of time in which V water is passed through the sample (s)

h is the hydraulic head (cm)

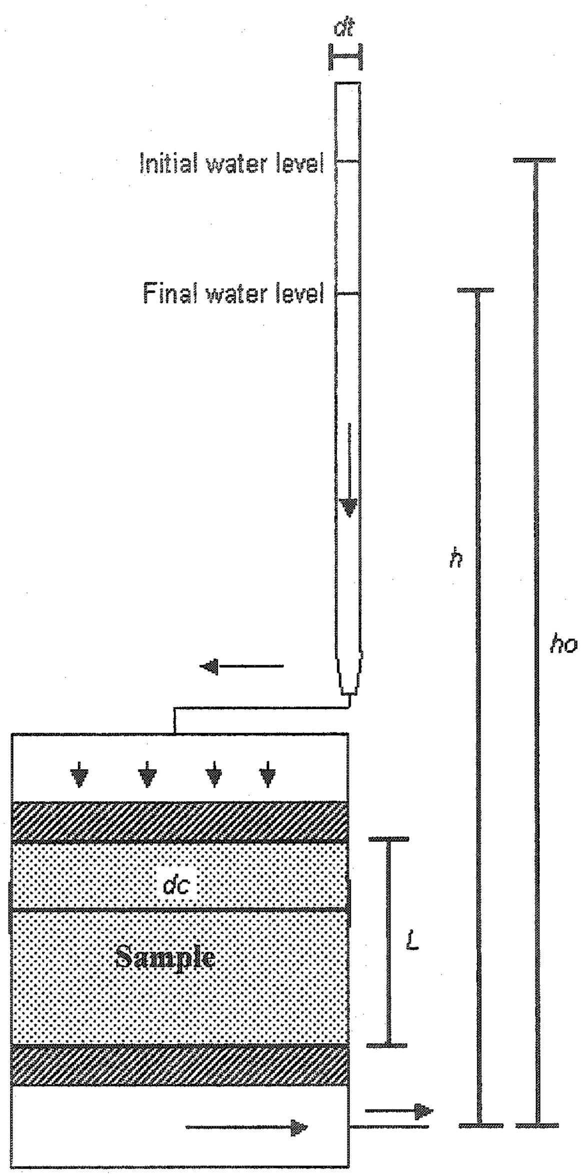

Fig. 5. Diagram of the falling-head permeameter. Device was used to determine the hydraulic conductivity of the soil samples.

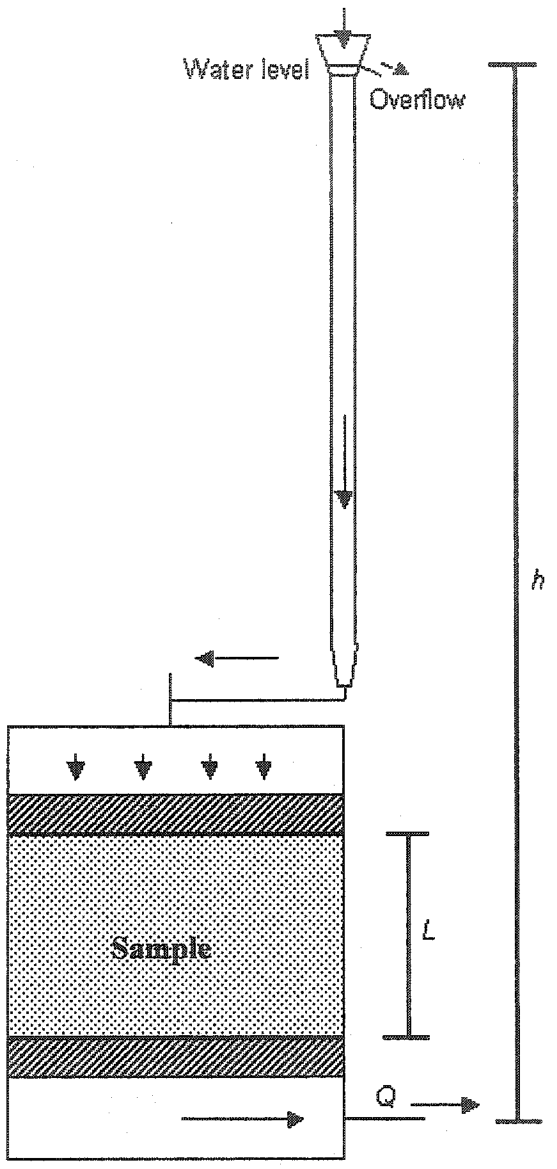

Fig. 6. Diagram of the constant-head permeameter. Device was used to determine the hydraulic conductivity of the soil samples.

Three replicate soil samples were collected from each depth to statistically compare the variation between them (nine total samples at each site). The three replicated samples were taken within a 1 m^2 plot laid on top of the ground. Samples were then statistically compared to determine if significant differences in permeability existed

among the three depths (e.g. constructed shallow v. constructed deep) or between natural and constructed sites for the same depth (e.g. CCW constructed shallow v. natural shallow).

Each sample was run through the permeameter three times. Because there were three replicate samples in most cases, a total of up to nine values were used to calculate a mean hydraulic conductivity for each of the three depths at each of the four sample sites. The Kruskal-Wallis test was used to test for statistical differences among the data groups of each site. Analysis of variance (ANOVA) would have been employed, however many of the sample populations failed the normality test and therefore the Kruskal-Wallis test, the non-parametric equivalent of ANOVA, was used (Woolson and Clarke 2002). If a group demonstrated that there was a significant difference in permeability among the three sampling depths, a pairwise comparison was then employed to determine where the difference was or differences were, such as between the surface and intermediate depths at the CCW natural site.

To make comparisons between to the natural and constructed sites for the same depth, the Mann-Whitney U-test was employed since the population of each group (*n*) was less than ten and the data were not normally distributed (Woolson and Clarke 2002). The Mann-Whitney test allowed comparisons to be made such as between the shallow depth permeability values for CCW natural and constructed sites.

Hydrologic Conditions

Hydrologic conditions of both CCW and SBNP were investigated by installing and monitoring wells and piezometers screened at various elevations of interest at each

site. Water level data were collected at each site for approximately 0.5-1.5 years, depending on the site.

Piezometer and Well Construction

At the CCW constructed site, monitoring wells and piezometers were placed in and around the two experimental plots (Figure 2) rather than throughout the mitigation site so hydrologic data could be utilized for the organic amendment experiments. Well placement within or around the plots also reduced the likelihood of disturbance to the wells and piezometers during final grading and planting of the site. A three-piezometer nest was constructed in the center of each plot. Plot 1 was topographically higher and therefore drier than plot 2, which was slightly lower (by approximately 0.06 m) and therefore remained wetter. Upper piezometers were installed to a depth of about 0.26-0.30 m below grade while middle piezometers were installed to a depth of about 1.70-1.89 m below grade, depending on the shallow stratigraphy. The lower piezometers were installed to a depth of 2.73-2.82 m. The bottom of each piezometer was capped and screened for 0.15 m. Each well casing was positioned in the augured hole and sand placed in the annular space surrounding the casing to cover over the screened portion of the casing. Excavated material was used to fill in the remaining annular space. Bentonite was then be used to seal around the top of the casing. All piezometers were constructed using 0.04 m diameter schedule 40 polyvinyl chloride (PVC) pipe and screen.

Four monitoring wells were installed at the corners of each plot. Each one was constructed using 0.06 m diameter schedule 40 PVC pipe and screen and installed to a depth ranging from 1.22-1.83 m. The wells were screened from the bottom of the well to the ground surface. Sand was placed around the screen and capped with bentonite.

A third piezometer nest was installed at CCW, in the natural wetland surrounding the newly constructed site. It was constructed in much the same way as the other two CCW constructed wetland nests. One piezometer was installed to a depth of 0.46 m below grade, the second one to a depth of 1.72 m, and the third one was installed to a depth of 2.52 m below the ground surface. All three piezometers were constructed using 0.04 m PVC schedule 40 pipe and screen. Sand was placed around the screen and capped with a bentonite seal.

Table 2
CCW piezometer information. The point is the 15 cm long screened portion of the piezometer.

Piezometer ID	Setting	Depth of Point (m)	Material at Point
CCP-1A	Constructed	0.26 (upper)	Silty clay
CCP-1B	Constructed	1.89 (middle)	Sand
CCP-1C	Constructed	2.73 (lower)	Sandy clay
CCP-2A	Constructed	0.32 (upper)	Silty clay
CCP-2B	Constructed	1.70 (middle)	Sand
CCP-2C	Constructed	2.82 (lower)	Clay
CCP-3A	Natural	0.46 (upper)	Silty clay
CCP-3B	Natural	1.72 (middle)	Fine sand w/ clay lenses
CCP-3C	Natural	2.52 (lower)	Silty clay w/ sand lenses

At the SBNP natural site, piezometer nests were installed at two locations (Figure 3). The sites varied in their topographic position. Site 201 was lower in elevation and

wetter at the surface than site 213. Two piezometers were installed per nest. All piezometers were screened at the bottom 0.15 m and constructed using 0.04 m diameter PVC pipe and screen. Short piezometers were installed to a depth of 0.60-0.61 m below the surface while lower piezometers were installed to a depth of 1.88-2.70 m below grade. Sand was placed around the screened portions of each piezometer, augered material placed on top of this, and finally capped and sealed with bentonite to prevent seepage down the sides of the casing.

The SBNP constructed site also had two piezometer nests installed within it (Figure 3). Both nests were comprised of three 0.04 m diameter PVC piezometers with the bottom 0.15 m screened. Upper piezometers were located at a depth of 0.44-0.49 m below the surface while the middle piezometers were installed to a depth of 1.80-1.89 m below grade. The lower piezometers were installed to a depth of 2.32-2.68 m. Sand was placed around the screened portions of each piezometer, augered material placed on top of this, and finally capped and sealed with bentonite to prevent seepage down the sides of the casing.

Riser heights were measured and recorded for all wells and piezometers as the length from the surface of the ground to the highest point of the casing. Top of casing (TOC) elevations were also determined at each site as well. At the CCW site, an arbitrary datum was established at 10.668 m (35.00 ft) above mean sea level (MSL). All well and piezometer TOC elevations for both the natural and constructed sites were established from this datum using a CST/berger surveying level (SAL Series 28X). The TOC elevations of the piezometers at the SBNP reference sites were determined using the elevation of two existing wells from a previous study and surveyed in from these known

elevations. At the SBNP constructed site, the TOC elevation of piezometer SB-1A was established at 7.62 m (25.00 ft) above MSL. All five remaining piezometers were referenced from this elevation.

Table 3
SBNP piezometer information. The point is the six inch long screened portion of the piezometer.

Piezometer ID	Setting	Depth of Point (m)	Material at Point
201-SP	Natural	0.60 (upper)	Sandy loam
201-DP	Natural	1.88 (lower)	Sandy loam

213-SP	Natural	0.61 (upper)	Sandy loam
213-DP	Natural	2.70 (lower)	Sandy loam

SB-1A	Constructed	0.44 (upper)	Clay loam
SB-1B	Constructed	1.89 (middle)	Sand
SB-1C	Constructed	2.32 (lower)	Sandy clay

SB-2A	Constructed	0.49 (upper)	Clay loam
SB-2B	Constructed	1.80 (middle)	Sand
SB-2C	Constructed	2.68 (lower)	Sandy clay

Water Level Monitoring

Biweekly water level sampling of all wells and piezometers occurred using a 30.48 m (100 ft) Slope Indicator water level indicator (Model Number 51453). If water

levels were too high to use the instrument (i.e. within 0.30 m of the TOC), a ruler was used instead.

Hourly water level sampling occurred in selected piezometers (Table 4) from 2/22/2004 to 5/29/2004. Continuous sampling was accomplished by installing Solinst Levelloger Model 3001 pressure transducers in the piezometers. Pressure transducers were installed in the piezometers by suspending them on a wire line at approximately 0.30 m above the bottom of the piezometer to keep them out of mud and silt accumulations. The elevation of each transducer was determined using the TOC elevation and subtracting the distance from the top of casing to the instrument (machined line on case).

Table 4
CCW and SBNP piezometers that were sampled hourly.

Nest ID	Upper	Middle	Lower
CCP-3	X	X	
CCP-1	X	X	
213	X		X
SB-2	X	X	X

The instruments use pressure to determine water level. Therefore, the instruments measured the force exerted on them by both the water column present in the piezometer and the atmospheric barometric pressure. Thus, it was necessary to filter the data of atmospheric barometric pressure to acquire accurate water level data. At each location a Solinst Barologger was installed to measure and record atmospheric barometric pressure to be able to correct the water level data. The Levelloggers and Barologgers were

programmed to record water levels/barometric pressure once every hour throughout the sampling period. Initially, transducer data were recorded to the tenths place (0.0 ft). The instruments were reprogrammed and redeployed on 3/11/2004 to read and record to the hundredths place (0.00 ft). All data were converted to metric units.

Soil Saturation Conditions

Epiaquic and endoaquic soil conditions were determined by direct and indirect methods. Boreholes were excavated near areas that had ponding, which allowed for direct observation of the water table level. If the water table was at the surface and therefore connected to the ponded areas, the site displayed endoaquic conditions. If the water table was significantly deeper than the surface and therefore not connected the ponding, the site was found to be epiaquic. Direct observation was only possible if the perching layer was at or just below the surface during wet conditions.

Indirect methods were used to determine soil saturation conditions using stratigraphic and biweekly hydrologic data. If, stratigraphic data indicated that perching layers could be present, then it was assumed that epiaquic conditions could exist at these sites and further investigation followed. However, if no perching layers were present, then it was assumed that epiaquic conditions could not exist even if the hydrologic data supported such conditions at these sites. With no perching layer present, water was free to move downward and not have been impeded which would have been necessary for epiaquic conditions to form.

If perching layers such as tight clay beds were found to exist over strata that may transmit water with relative ease such as a thick sand bed, this ‘aquifer’ may or may not be fully saturated. If the sand bed is fully saturated, then endoaquic conditions would

exist. However, if the confined aquifer is not fully saturated, then epiaquic conditions would be demonstrated.

In this study, piezometer screen depths and strata types and thicknesses were determined, as well as hydrologic data gathered. If the upper well contained water but the middle well's water level was below that of the upper well's screen elevation, then epiaquic conditions were demonstrated (Figure 7). If the water level of the lower piezometer was at or above the screened portion of the upper well, then it was probable that this confined aquifer was fully saturated, indicating endoaquic conditions (Figure 8).

The extent of the capillary fringe for the sediment type in which the middle well was screened was also utilized. Since the fringe is water-bearing sediment, it was also used to determine soil saturation conditions, instead of the true water level elevation of the middle well. Capillary fringe extents were based on data published by Tiner (1999).

Precipitation Response

Precipitation data were gathered from 2/22/2004 to 5/29/2004 using two Onset tipping-bucket rain gages (Model RG2), one installed at both the SBNP and CCW locations. The rain gages were interfaced with a Hobo event datalogger to record each tip as an event. These event data were then manipulated to represent hourly rainfall totals throughout the sampling period for each site. Graphs of precipitation data plotted with the hourly hydrologic data allowed determination of the response (lag) times between specific precipitation events and groundwater fluctuations.

Based upon techniques developed for surface water hydrographs (McNamara 1998), numerous response times were determined from these data and are described in detail in the Results section.

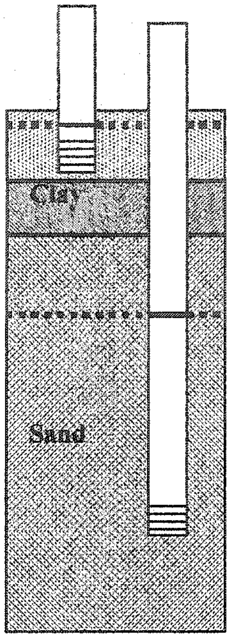

Fig. 7. Diagram showing epiaquic conditions with a perching layer present.

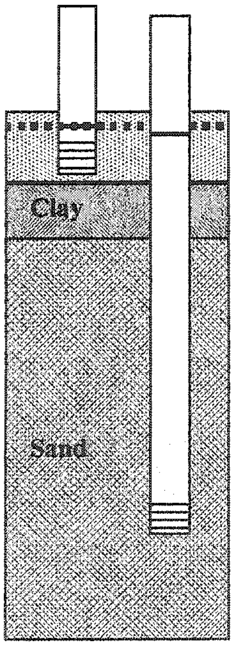

Fig. 8. Diagram showing endoaquic conditions with a perching layer present.

CHAPTER III

RESULTS

The results of the stratigraphic and the permeability analysis reveal notable differences between the study sites. Some of these differences may explain the variations in hydrologic response exhibited by the piezometers.

Stratigraphic Data

At the CCW location, the natural and constructed sites are both dominated by a thick Bt horizon formed in Chickahominy silt clay loam profiles (Figures 9 and 10). However, the natural site has a 0.08 m thick organic-rich A-horizon while this horizon is absent in many areas of the constructed site. Regrading at the constructed site removed 0.4 to 0.6 m of natural soil including the A-horizon and as much as 0.5 m of the B-horizon. Over the entire CCW constructed site, much of the surface was amended with organic matter during regrading activities in late 2003. However, many other areas were not amended, leaving the compacted argillic B-horizon as the surface.

At the SBNP location, there were several major differences between the soils of the constructed and natural sites. As seen in Figure 11, the natural site consisted of a relatively uniform sandy loam, overlain by an argillic Bt-horizon. At the constructed site, material that was used to fill in the lakes varied in grain size and texture (Figure 12). The result was the creation of an artificial stratigraphic profile that consisted of a very compacted sandy loam at the surface, underlain by several sand looser layers interbedded with thin clay lenses throughout. Below the alternating clay/sand layers, at a depth of approximately 2.6 m, was a much more massive clay bed of at least 0.5 m in thickness

(limit of hand auger). To determine the extent of the relatively clean sands present between the compacted surface and tight clay at depth, several boreholes were made around the piezometer nest SB-2. These borings indicated that the buried sand strata extend in at least 5 m in all directions from SB-2. Of particular note is that the sand layers extended from SB-2 to the surface water canal 20 m to the west. The sand beds outcropped along the side and bottom of the canal.

Soil Permeability Data

Soil permeability data (Tables 5 and 6, Appendix A) reflect the variations in hydraulic conductivity of strata within the upper meter of each site. The CCW natural site had hydraulic conductivity values that ranged from approximately 10^{-8} to 10^{-7} cm s^{-1} while the constructed site had values around 10^{-7} cm s^{-1} (Table 5). At the SBNP natural site, hydraulic conductivity values ranged from approximately 10^{-07} to 10^{-04} cm s^{-1}. The constructed site had permeability values that ranged from about 10^{-05} to 10^{-03} cm s^{-1} (Table 6).

Sample Site Depth Comparisons

As seen in Figure 13, the permeability for the CCW natural site was greatest at the intermediate sampling depth and the least at the deep sampling depth. The CCW constructed site showed the same pattern in that the intermediate depth had the highest permeability while the deepest sampling depth had the lowest permeability.

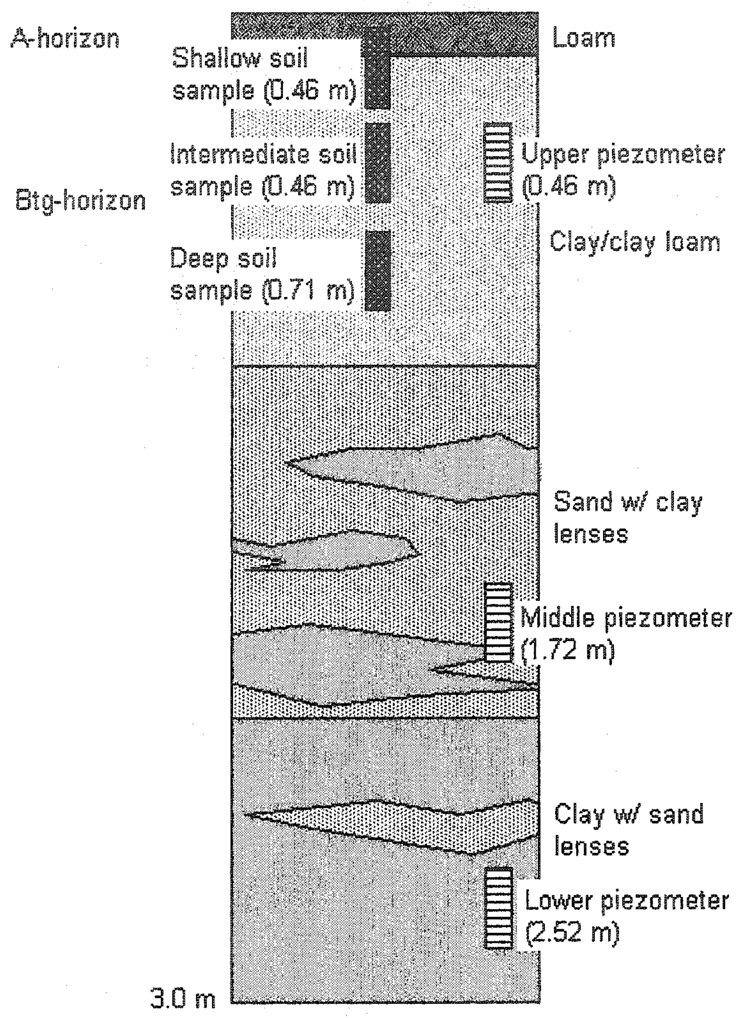

Fig. 9. Diagram representing soil and stratigraphic data of the CCW natural site. Depths of CCP-3 piezometer screens and soil

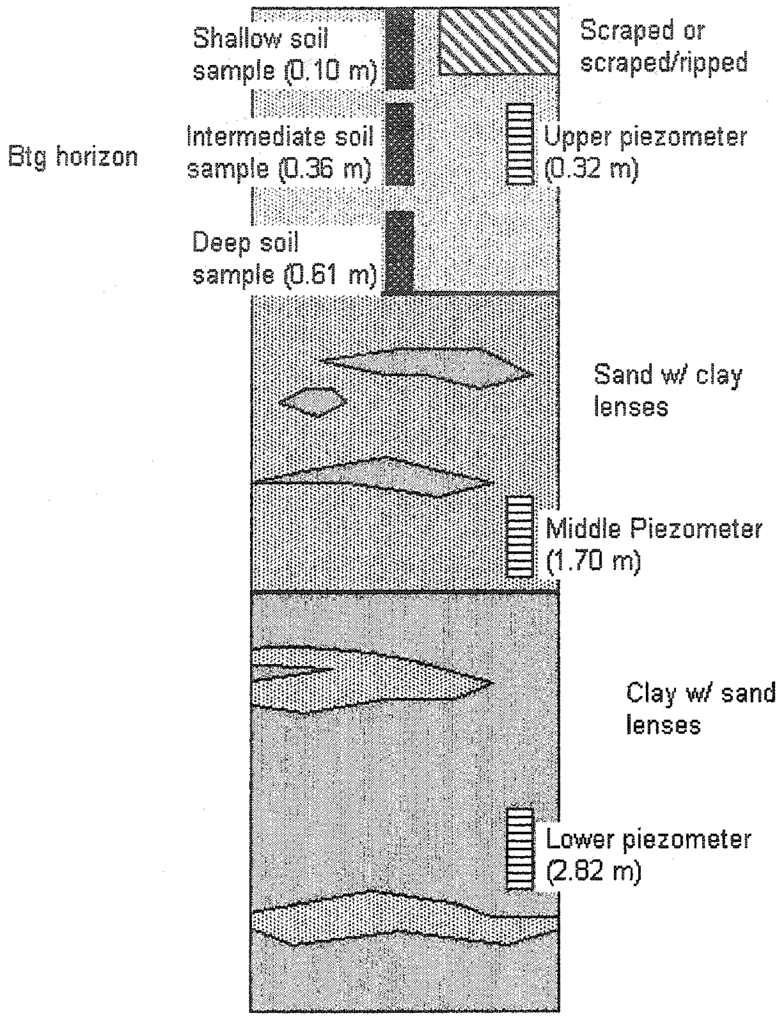

Fig. 10. Diagram representing soil and stratigraphic data of the CCW constructed site. Depths of CCP-1 piezometer screens and soil permeability samples are shown. Note that the surface may be ripped to approximately 0.5 m or not depending on the location within the constructed site.

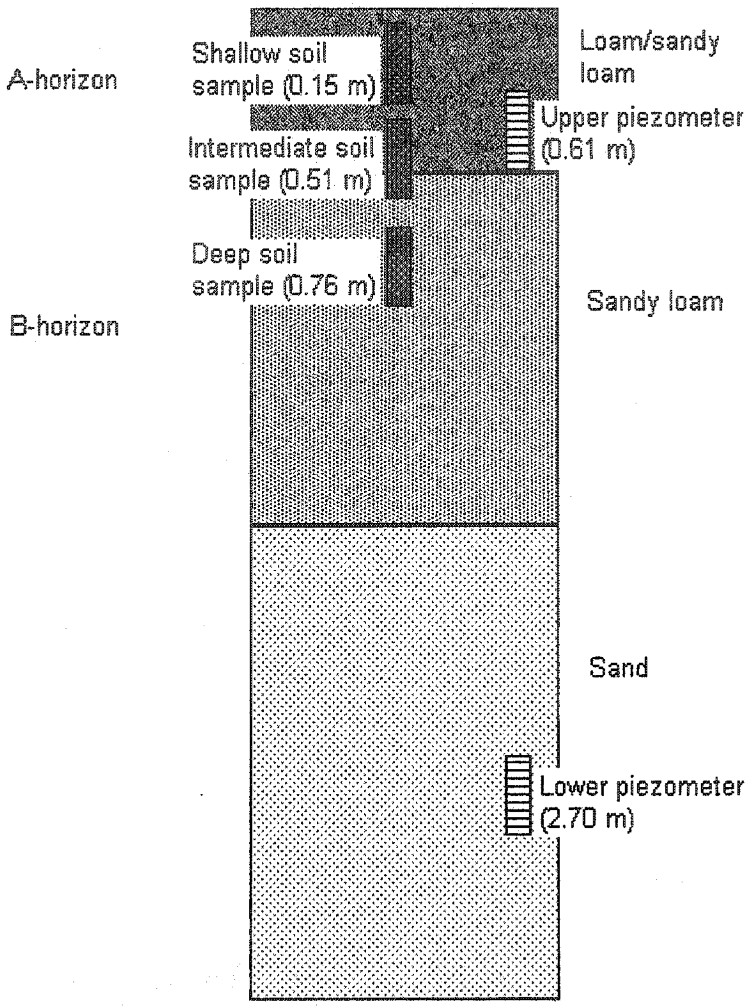

Fig. 11. Diagram representing soil and stratigraphic data of the SBNP natural site. Depths of site 201 and site 213 piezometer screens and soil permeability samples (213) are also shown.

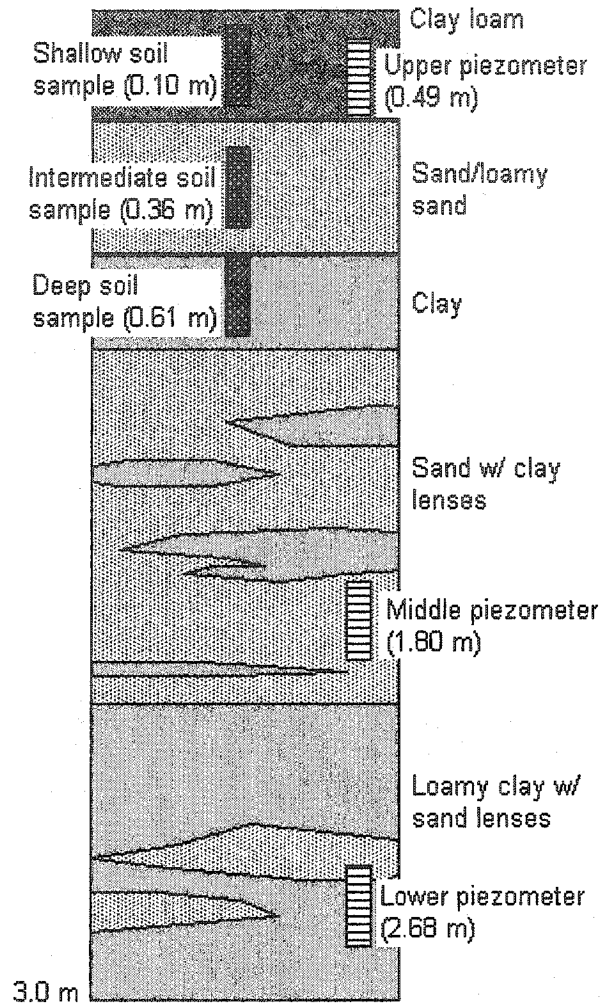

Fig. 12. Diagram representing soil and stratigraphic data from the SBNP constructed site. Depths of SB-2 piezometer screens and soil permeability samples are also shown.

Table 5

Summary of permeability data for CCW natural and constructed sites.

CCW Permeability Data	Depth (m)	*n*	Mean Hydraulic Conductivity cm s^{-1}	Standard Deviation cm s^{-1}
Natural (CCW-3)	Shallow (0.15)	9	9.0E-08	4.2E-08
	Intermediate (0.46)	9	1.3E-07	4.0E-08
	Deep (0.71)	9	7.0E-08	3.6E-08
Constructed (CCW-1)	Shallow (0.10)	9	3.0E-07	3.8E-07
	Intermediate (0.36)	9	3.1E-07	3.0E-07
	Deep (0.61)	9	1.2E-07	4.0E-08

Table 6

Summary of permeability data for SBNP natural and constructed sites.

SBNP Permeability Data	Depth (m)	*n*	Mean Hydraulic Conductivity cm s^{-1}	Standard Deviation cm s^{-1}
Natural (213)	Shallow (0.15)	9	1.9E-04	1.3E-04
	Intermediate (0.51)	6	3.4E-06	1.6E-06
	Deep (0.76)	9	3.5E-07	1.5E-07
Constructed (SB-2)	Shallow (0.10)	9	3.4E-05	3.0E-05
	Intermediate (0.36)	9	6.3E-03	2.3E-03
	Deep (0.61)	6	2.1E-05	2.3E-05

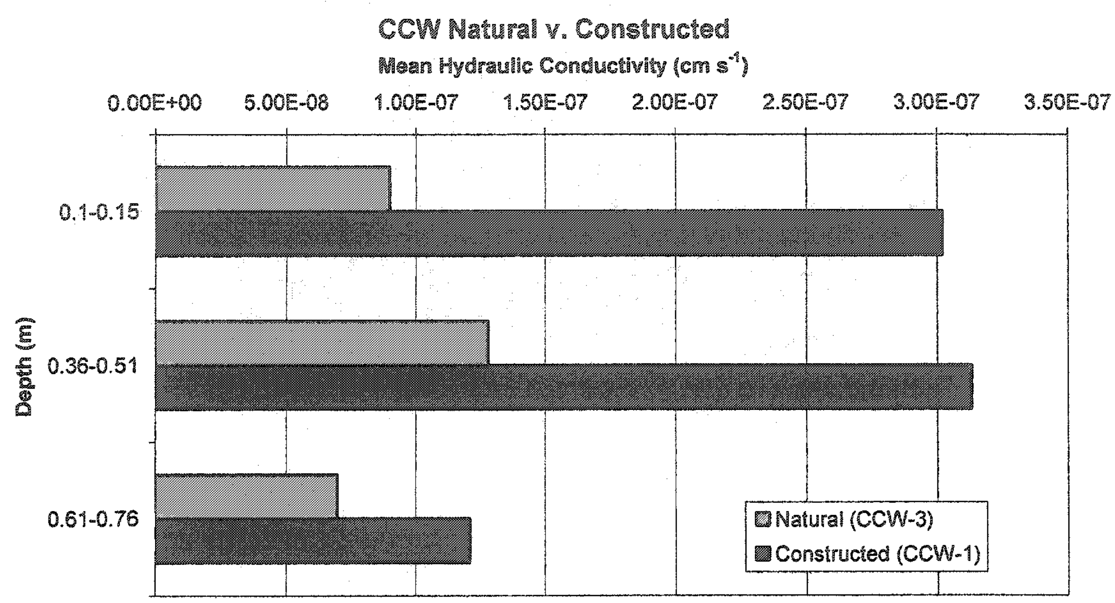

Fig. 13. Permeability data of CCW natural and constructed sites versus depth.

Group comparisons were performed using the Kruskal-Wallis test to determine if statistical differences in permeability existed among the three sampling depths for both the natural and constructed sampling sites at CCW and SBNP (Appendix B). At the CCW natural site, a significant difference in hydraulic conductivity was found between the intermediate and deep sample depths ($p \leq 0.05$). At the constructed site, the hydraulic conductivity of all three soil depths were found to be statistically the same.

At the SBNP natural site, the shallow sampling depth had the highest permeability and decreased with depth (Figures 14 and 15). The SBNP constructed site demonstrated a different pattern where the highest permeability was determined to be at the intermediate sampling depth while both the shallow and deep sampling depths had almost the same permeability, and were both much lower than the value of the intermediate depth.

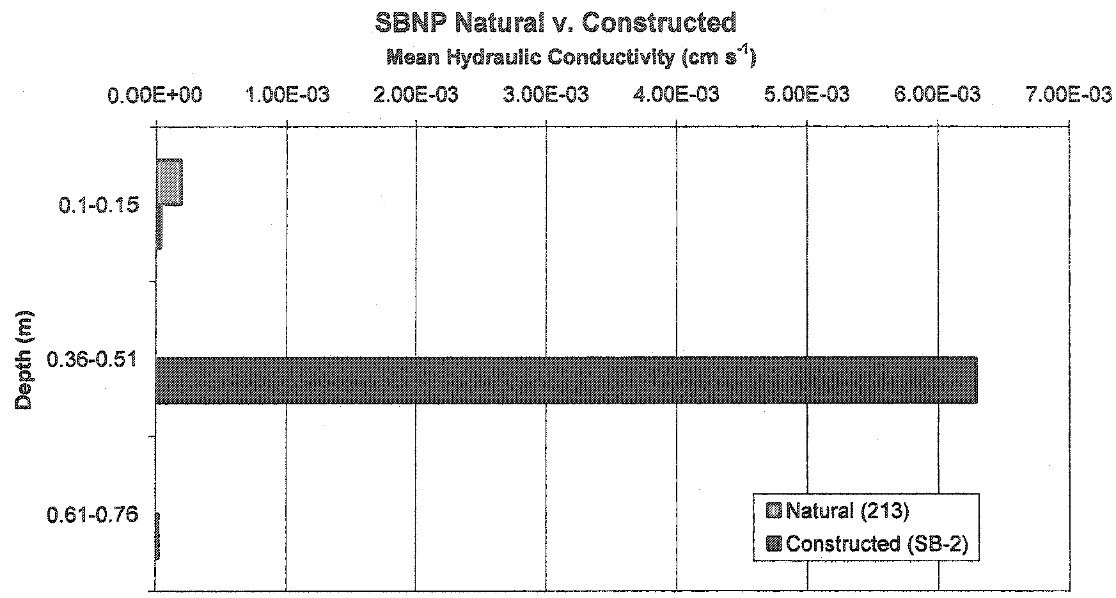

Fig. 14. Permeability data of SBNP natural and constructed sites versus depth.

Much like the two CCW sites, group comparisons were performed for both the SBNP natural and constructed sites to determine if significant permeability differences existed among the three sampling depths. At the SBNP natural site, the hydraulic conductivity was found to be significantly different between the shallow and deep sample depths ($p \leq 0.05$). At the SBNP constructed site, significant differences were found between the intermediate and deep and the intermediate and shallow sampling depths ($p \leq 0.05$). However, the shallow and deep sampling depths were not statistically different.

Site to Site Comparisons

Same-depth comparisons were made between the natural and constructed sites for both CCW and SBNP. At CCW, natural to constructed site comparisons for all

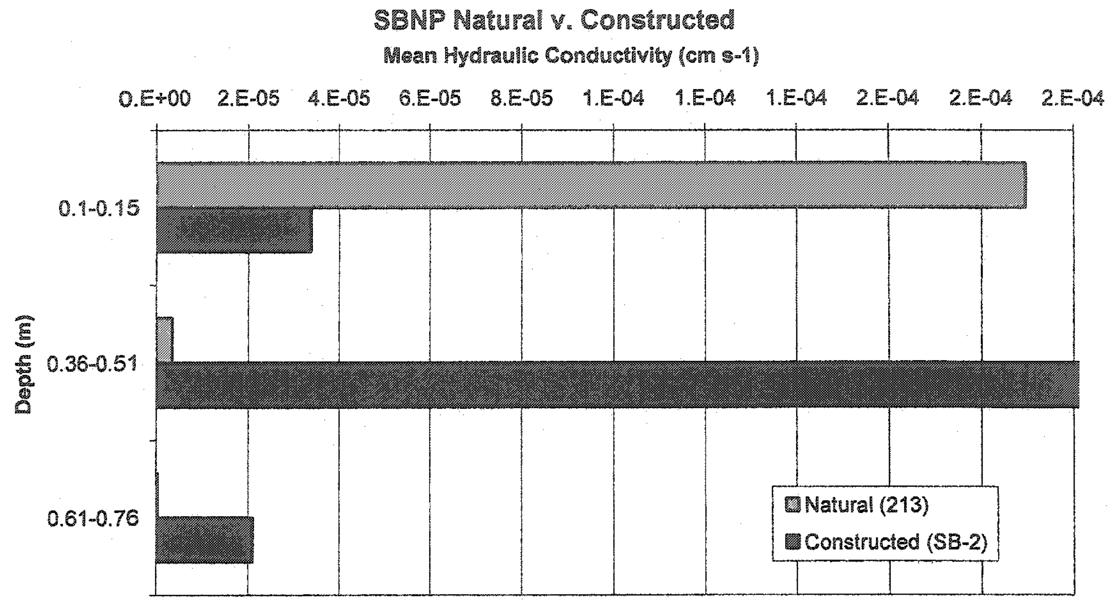

Fig. 15. Permeability data of SBNP natural and constructed sites versus depth. The scale has been changed to demonstrate finer scale differences.

three depths (shallow to shallow, intermediate to intermediate, and deep to deep) demonstrated they were all statistically different ($p \leq 0.05$). At SBNP, natural to constructed comparisons showed that the permeability of the shallow and intermediate sampling depths were significantly different. The natural deep to constructed deep permeability comparisons exhibited that the two were statistically the same (Appendix B).

Hydrologic Conditions

Biweekly data

The hydrologic conditions at the CCW natural site (CCP-3) showed that it was an area of recharge. As seen in Figure 16, differences in water levels can be observed throughout the sampling period of CCP-3 where the upper piezometer water level was

consistently higher than that of the middle and lower piezometers. This vertically 'stacked' pattern of the hydrograph (upper piezometer- high water level; lower piezometer- low water level) implies downward movement of water, which is indicative of an area of recharge. The three piezometers of CCP-3 had the same hydrologic patterns in that they all tended to respond at or about the same time and in the same direction throughout the sampling period.

The stacked pattern observed in the CCP-3 data was found in the piezometric data of the constructed site piezometer nests (CCP-1 and CCP-2) indicating that these parts of the constructed wetland act as areas of recharge (Figures 17 and 18). The natural site (CCP-3) and the wet plot (CCP-2) piezometer nests showed generally the same characteristics in that the two lower piezometers tended to have the same water level elevations. A noteworthy difference existed between the wet plot (CCP-1) and the natural site (CCP-3) piezometer nests in that instead of upper and lower piezometers having the same water levels, CCP-1 exhibited the same water levels in the upper and middle, with the lower piezometer generally having a lower water level throughout the sampling period. The middle and lower piezometers of CCP-2 (CCP-2B and CCP-2C) tended to follow the same elevation. However, there was a departure on 1/10/2004 where the water level of the lower piezometer was higher than that of the middle piezometer. This situation indicated groundwater movement upward at this location, as well as downward from the surface indicated by the data of CCP-2A and CCP-2B.

During the summer months of 2003, the water levels of CCP-1 and CCP-2 were extremely variable. Although data were not obtained for the whole summer of 2003, the natural site (CCP-3) did not show this variability in the data obtained. The two upper

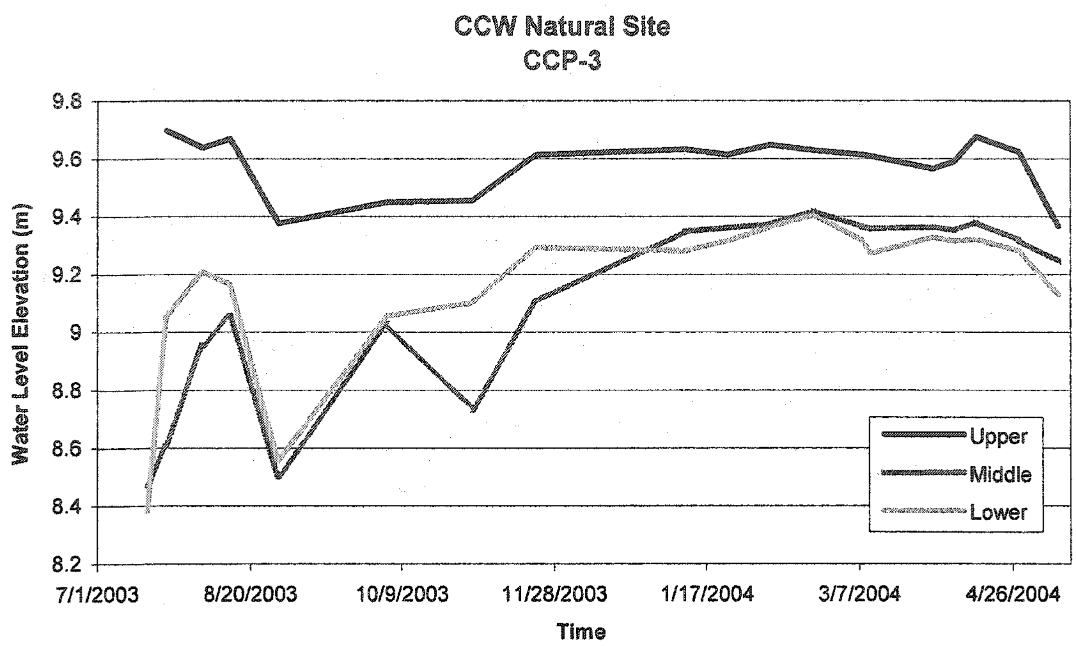

Fig. 16. Hydrograph for CCP-3, located in the natural wetland at CCW.

constructed site piezometers (CCP-1A and CCP-2A) tended to 'dry up' (water level dropped below the piezometer point) where the upper piezometer at the natural site (CCP-3A) never went dry during the sampling period.

The SBNP natural site piezometer data showed two distinct hydrologic patterns. In Figure 19, piezometer nest 201 showed that both the upper and the lower piezometer generally followed the same pattern where both piezometers had similar water levels throughout the sampling period. The pattern is indicative of an area of through-flow where groundwater was moving laterally rather than vertically. However, the piezometer nest 213 demonstrated a stacked pattern as seen in the CCW hydrologic data (Figure 20). The stacked pattern at 213 indicates that this area is an area of recharge.

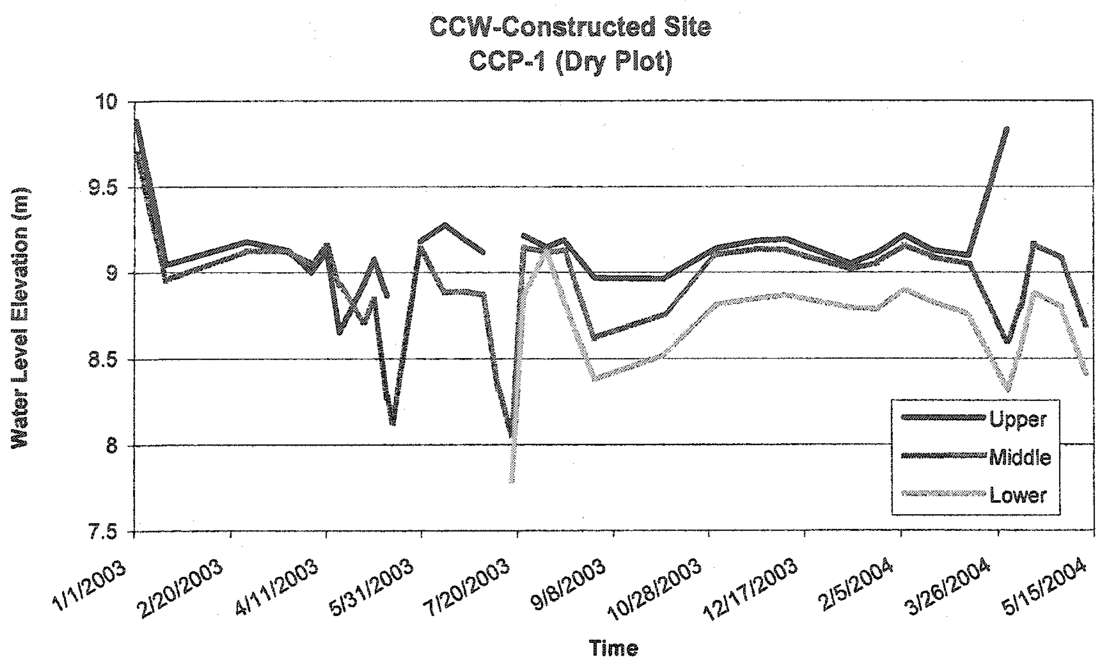

Fig. 17. Hydrograph for CCP-1, located in the constructed wetland at CCW.

At the SBNP constructed site, hydrologic data for the piezometer nests (SB-1 and SB-2) were extremely variable (Figures 21 and 22). Both nests demonstrated periods when the area acted as a recharge zone and then other times when water was moving upward through the soil profile. The lower piezometer at SB-1 tended to have higher water levels that the middle and upper piezometers throughout the study period indicating upward water movement. The hydrograph for the lower piezometer also showed a different hydrologic trend than either the shallow or intermediate piezometers. The other nest located at the SBNP constructed site (SB-2) also showed the same general characteristic of hydrologically different piezometer data as SB-1.

Constructed wetlands were also analyzed to determine if they demonstrated wetland hydrology as defined by the COE (1987) where the water table elevation must be

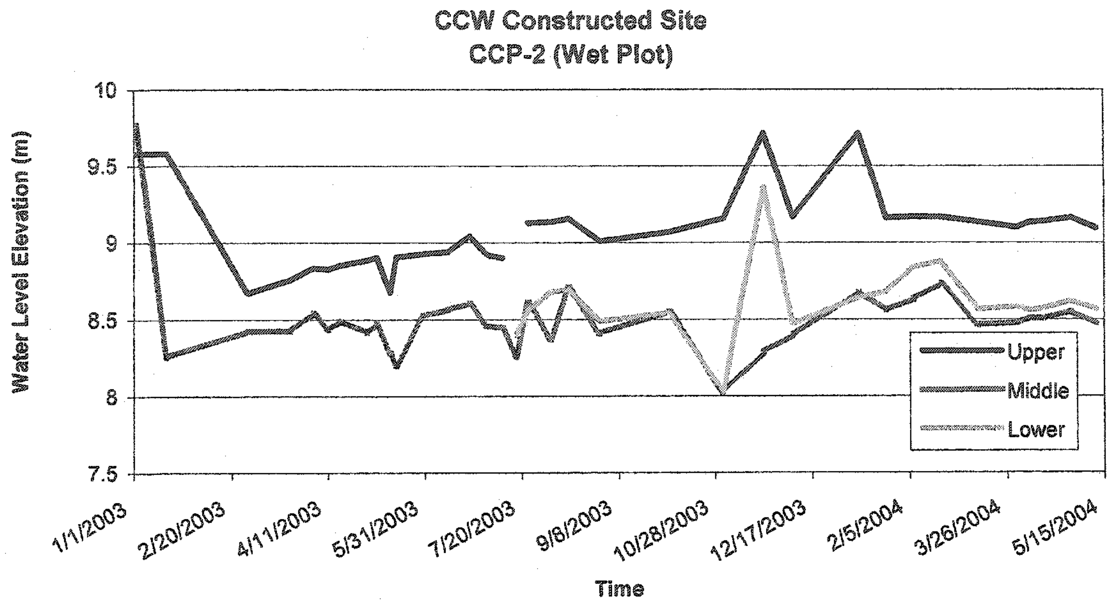

Fig. 18. Hydrograph for CCP-2, located in the constructed wetland at CCW.

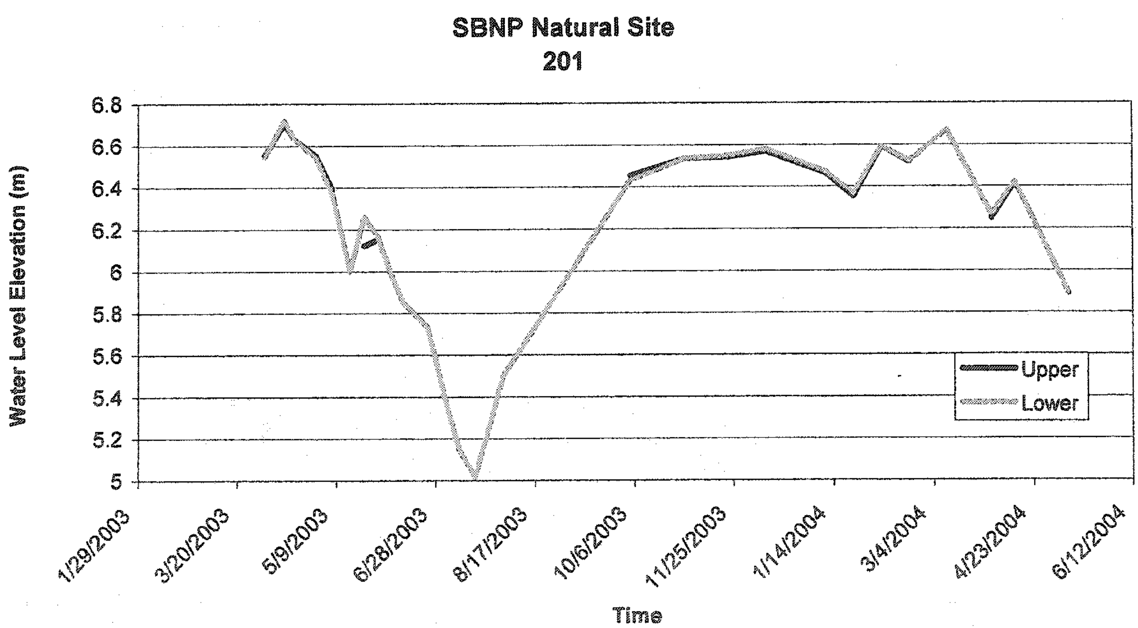

Fig. 19. Hydrograph for 201, located in the natural wetland at SBNP.

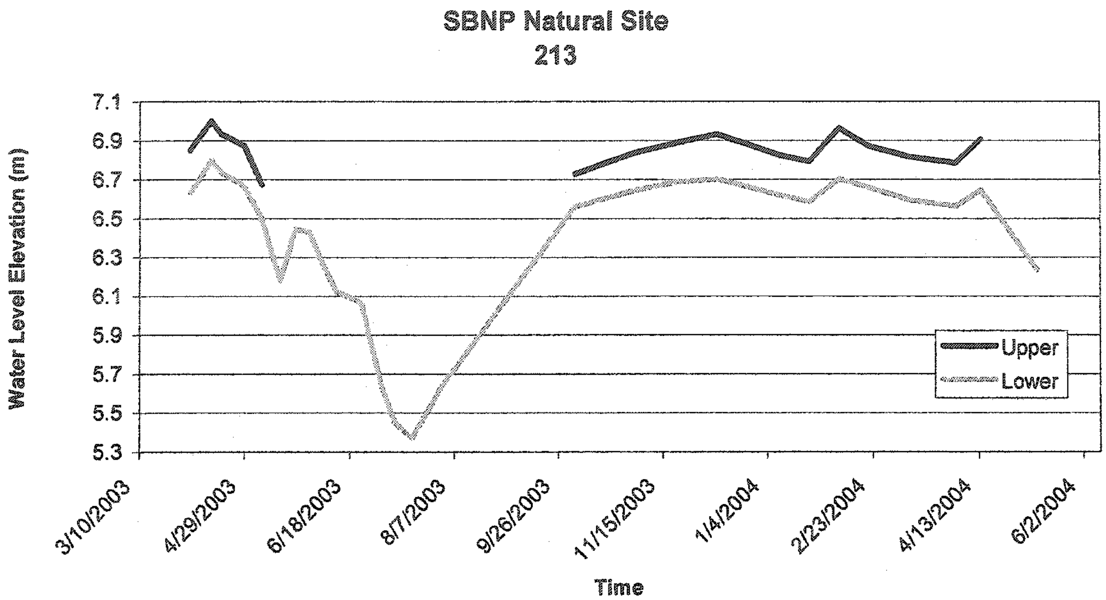

Fig. 20. Hydrograph for 213, located in the natural wetland at SBNP.

within 0.3048 m (12 in) of the surface for a continuous 12.5% of the growing season. At the CCW constructed site, biweekly groundwater data acquired from onsite monitoring wells were used to determine if wetland hydrology existed for at least 35 days (12.5% of a 273-day growing season). Based on these data, the CCW constructed site met the COE requirements for wetland hydrology for 2003 and 2004, marked by up to 53 days of continuous wetland hydrologic conditions where the water table was within 0.3048 m of the surface. Most well readings indicated that the water table was within 0.1524 m or less of the surface.

At the SBNP constructed site, upper piezometers were used to determine hydrologic conditions since monitoring wells were not installed at the site during the study period. At SBNP, the growing season was 325 and therefore wetland hydrology had to be demonstrated for 41 continuous days. The site met the COE requirements for

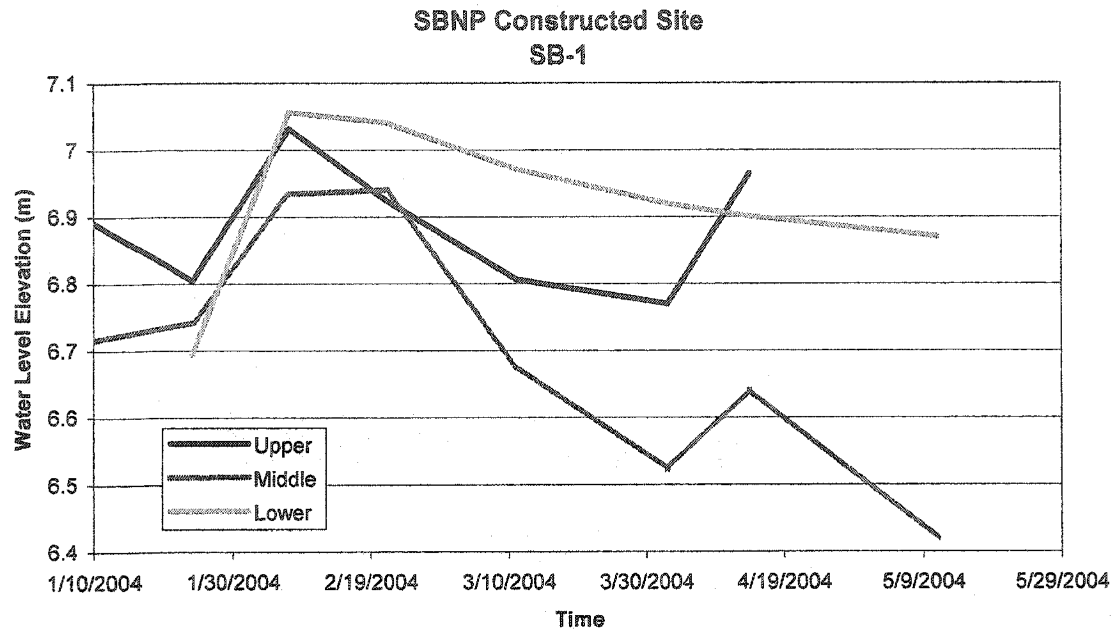

Fig. 21. Hydrograph for SB-1, located in the constructed wetland at SBNP.

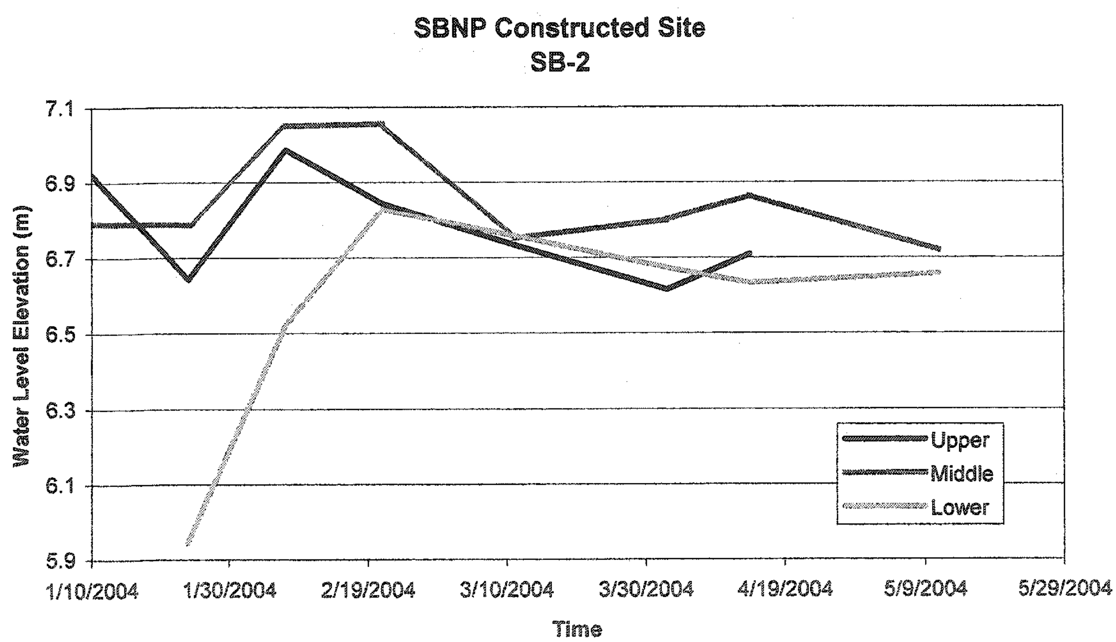

Fig. 22. Hydrograph for SB-2, located in the constructed wetland at SBNP.

wetland hydrology at one location (SB-1A) for 2004 with 73 days of continuous wetland hydrologic conditions (8 readings). Water table elevations were much more variable at SBNP than at CCW where the water table tended to stay within approximately 0.1524 m of the surface. At the SBNP sites, the water table elevation was quite variable and fluctuated significantly within the surface and 0.3048 m zone. The other location used at SBNP (SB-2A) did not display wetland hydrology for 2004 (as of 7/3/2004). If hydrologic data had been collected more frequently, such as once per week, and if monitoring wells had been employed instead of upper piezometers, more definitive results might have been obtained.

Hourly Data

Hourly sampling of water levels in selected piezometers occurred at CCW from 4/8/04 to 5/29/04 and at SBNP from 4/4/04 to 5/29/04. These data were collected to evaluate the speed of response (lag time) of the groundwater system to rainstorms. These data also supplement the interpretations of the biweekly hydrologic data.

Similar conditions were seen in the hourly data hydrographs and the hydrographs of the biweekly data. At the CCW site, data from the CCP-3 piezometer nest in the natural wetland demonstrated a recharge pattern between the upper and middle piezometers (Figure 23) that was also seen in the biweekly hydrograph. Both piezometers had generally the same pattern except during precipitation events where the upper piezometer had a greater and faster response than the middle piezometer (discussed below). Hourly data of the upper and middle piezometers of CCP-1 (constructed wetland) tended to show nearly the same water levels throughout the sampling period (Figure 24). The upper piezometers at the natural and constructed sites tended to go dry

during periods of low precipitation as well as toward the end of the sampling period when a seasonal drawdown was occurring. Water levels below the instrument were recorded as no data and appear as a discontinuous hydrograph line. The lower piezometers at both the natural and constructed sites were not continuously monitored due to budget constraints.

At the SBNP site, piezometer nest 213, which located in the natural wetland demonstrated nearly the same hydrologic pattern between the upper and lower piezometers including during precipitation events where both piezometers responded (Figure 25). Much like the piezometers at CCW natural and constructed sites, the upper piezometer, 213-SP tended to go dry during periods of little or no precipitation and near the end of the sampling period during a time of seasonal drawdown. This piezometer also responded faster and with a greater response than the lower piezometer at that site.

The three piezometers of SB-2, located at the SBNP constructed site, demonstrated the same variable patterns among the piezometers that were seen in the biweekly hydrograph data (Figure 26). The upper piezometer, SB-2A, tended to remain dry throughout much of the sampling period except during wetter periods. The middle piezometer, SB-2B, tended to exhibit a 'flashy' pattern while SB-2C, the lower piezometer had relatively constant water levels, showing slight response to wetter periods, especially when the water level in SB-2B was high.

Towards the end of the sampling period, at about 5/7/04, diurnal water level fluctuations occurred in the upper piezometers at the SBNP and CCW natural sites. The pattern occurred during a period of seasonal drawdown that can be observed in both the constructed and natural settings of CCW and SBNP. However, a strong diurnal

fluctuation only occurred at the CCW natural sites. Slight diurnal fluctuations were observed in the middle (SB-2B) piezometer at the CCW constructed site. These fluctuations were smaller in amplitude than those seen in the data of the natural sites, but occurred throughout the sampling period.

Soil Saturation Conditions

Two hydrologic methods were employed in this study to determine if endoaquic or epiaquic soil conditions existed at each site. Borehole excavations near observed ponding allowed direct observation of the water table and to see if it was vertically connected to the ponded areas (endoaquic) or not connected and therefore lower in the soil profile (epiaquic). Indirect soil saturation conditions were determined by comparing and evaluating biweekly hydrologic data and borehole data. These data were useful in determining saturation conditions deeper in the soil profile.

Ponding at the surface was observed regularly throughout the study period at the natural and constructed CCW sites. However, ponding may not have always indicted that the water table was at the surface at the constructed site. During permeameter sample collection at the constructed site (1/24/2004), holes were bored to approximately 1 m and the water table was never intercepted. Within 3 m of the borehole, ponding was present at the surface. However, the ponding was not connected to the water table. While excavating boreholes at the natural site (2/20/2004), ponding was present in depressions and swales and water levels in the boreholes tended to be at or just below the ground surface, indicating that the water table was at or just below the surface. Thus, at this time and place, ponding at the surface at the natural site was connected to the water table.

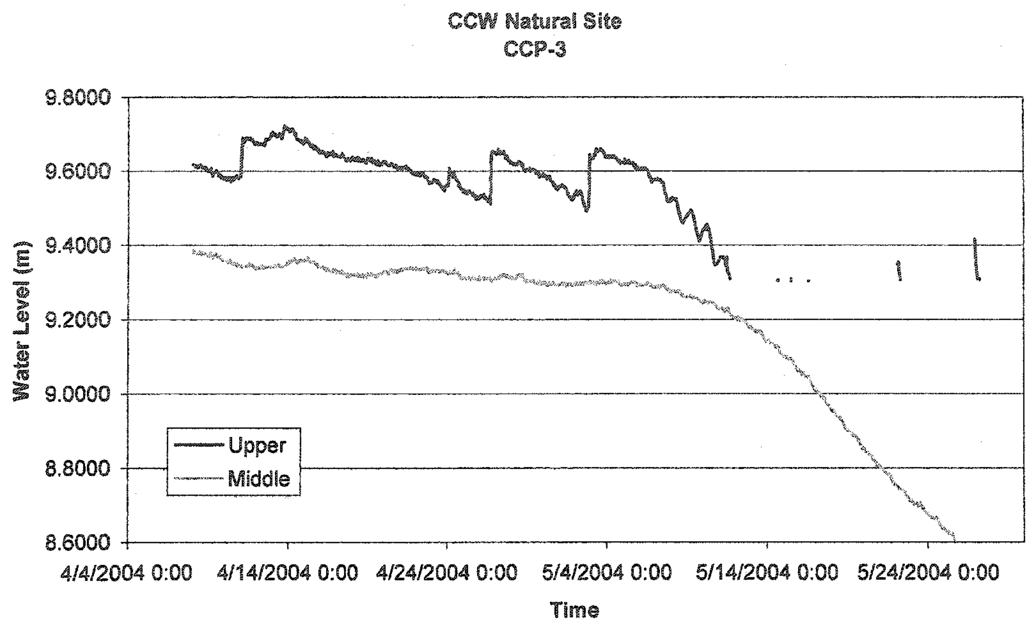

Fig. 23. Hourly hydrograph for CCP-3, located in the natural wetland at CCW.

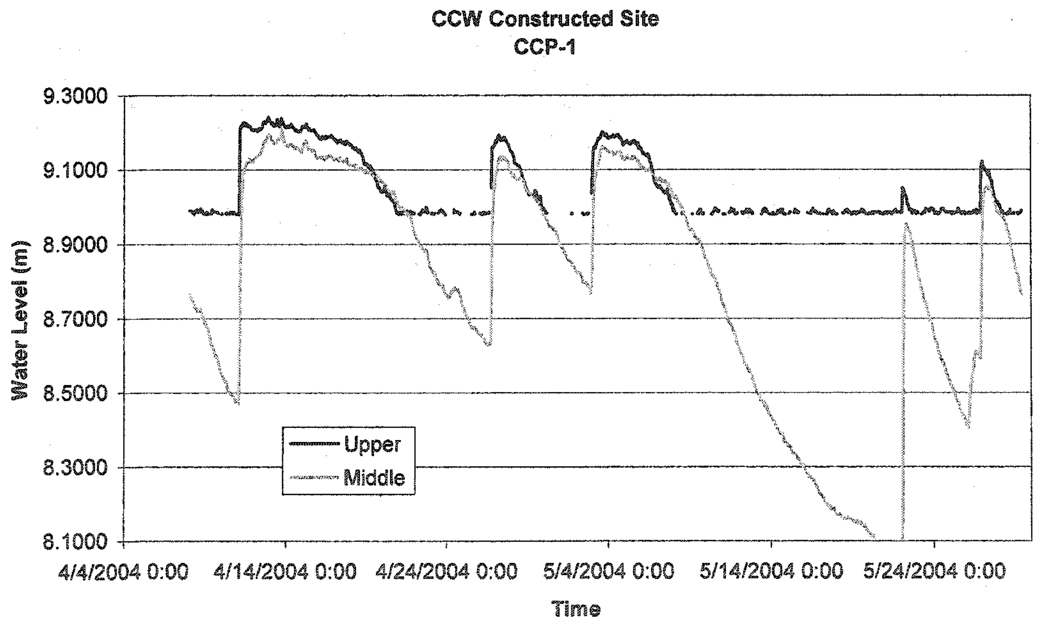

Fig. 24. Hourly hydrograph for CCP-1, located in the constructed wetland at CCW.

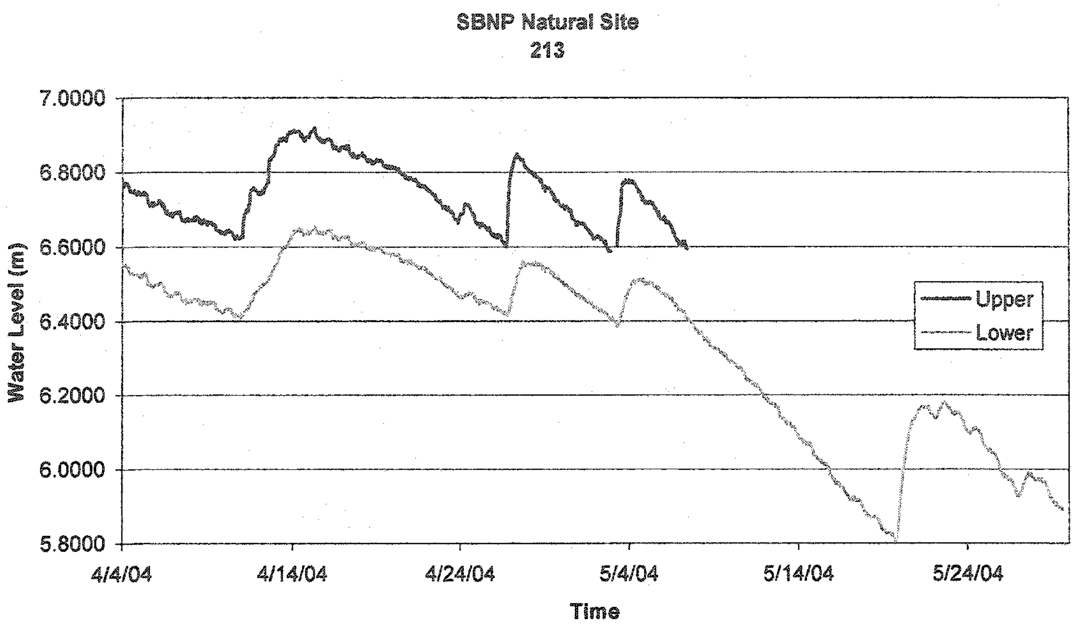

Fig. 25. Hourly hydrograph for 213, located in the natural wetland at SBNP.

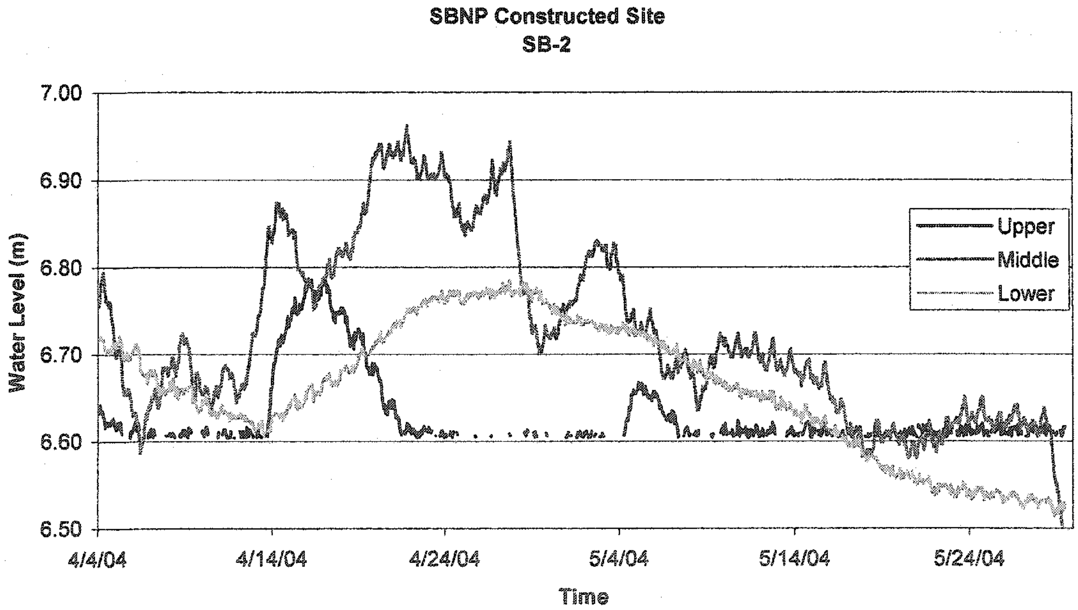

Fig. 26. Hourly hydrograph for SB-2, located in the constructed wetland at SBNP.

At SBNP, ponding at the surface was observed at both the natural and constructed sites during different times of the study. Ponding regularly occurred at piezometer nest 201 and also in a ditch located adjacent to piezometer nest 213. During borehole excavation at site 213 for permeameter samples (3/3/2004), water levels in each of the holes corresponded to the water level in the ditch, indicating that ponding at the surface was connected to the water table. Ponding at the constructed site was observed on the broad flats, generally the areas of highest elevation. Ponding was also seen at the breaks in slope between two different grades. On 4/8/2004, a 2 m borehole was excavated approximately 3 m away from an area of ponding, located on one such broad flat. The water table was never intercepted, indicating that surface ponding in the constructed site may not be connected to the water table.

Hydrograph and stratigraphic data were also used to determine soil saturation conditions. At the CCW natural site, both endoaquic and epiaquic conditions were displayed throughout the sampling period (Figure 27). During the periods of 8/13/2003-11/22/2003 and 6/17/2004-7/3/2004, the water level in the middle piezometer and resulting capillary fringe fell below the upper piezometer screen elevation. Since the upper well contained water during these periods, these hydrologic data are taken to infer epiaquic conditions. Endoaquic conditions prevailed at this location from approximately 11/22/2003-5/11/2004.

At the CCW constructed site, the middle piezometer water level and capillary fringe in the dry plot piezometer (CCP-1) rarely dipped below the upper piezometer screen elevation (Figure 28). Therefore, endoaquic conditions prevailed throughout most

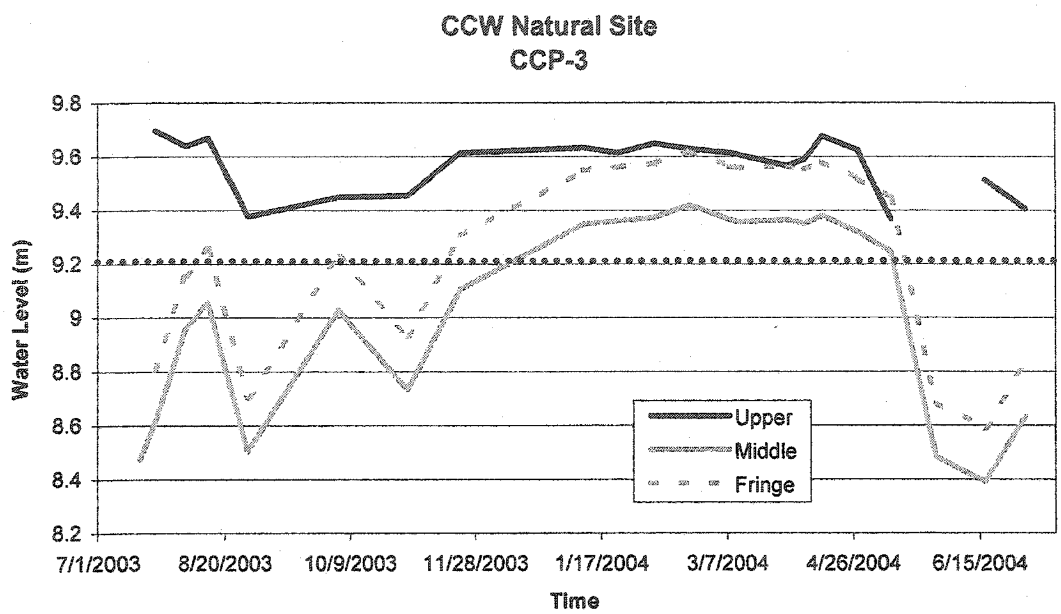

Fig. 27. Soil saturation determination hydrograph for site CCP-3. Capillary fringe is demonstrated by the dashed line and is 20 cm above the water level. The dotted horizontal line denotes upper piezometer screen elevation.

of the sampling period at the dry plot. The data suggest that epiaquic conditions only occurred from 8/29/2003-10/4/2003.

At the wet plot of the CCW constructed site, epiaquic conditions prevailed throughout much of the study period (Figure 29). The data suggest that during the periods of 8/4/2003-11/1/2003 and 1/24/2003-5/28/2004, epiaquic conditions existed at this location. Endoaquic conditions occurred infrequently at the wet plot.

At both SBNP natural sites (201 and 213), lower piezometer levels dropped well below the upper piezometer screen elevation. However, since there was no perching layer present, epiaquic conditions did not occur. Therefore, based on these data, the natural wetland sites at SBNP demonstrated that only endoaquic conditions occurred (Figures 30 and 31).

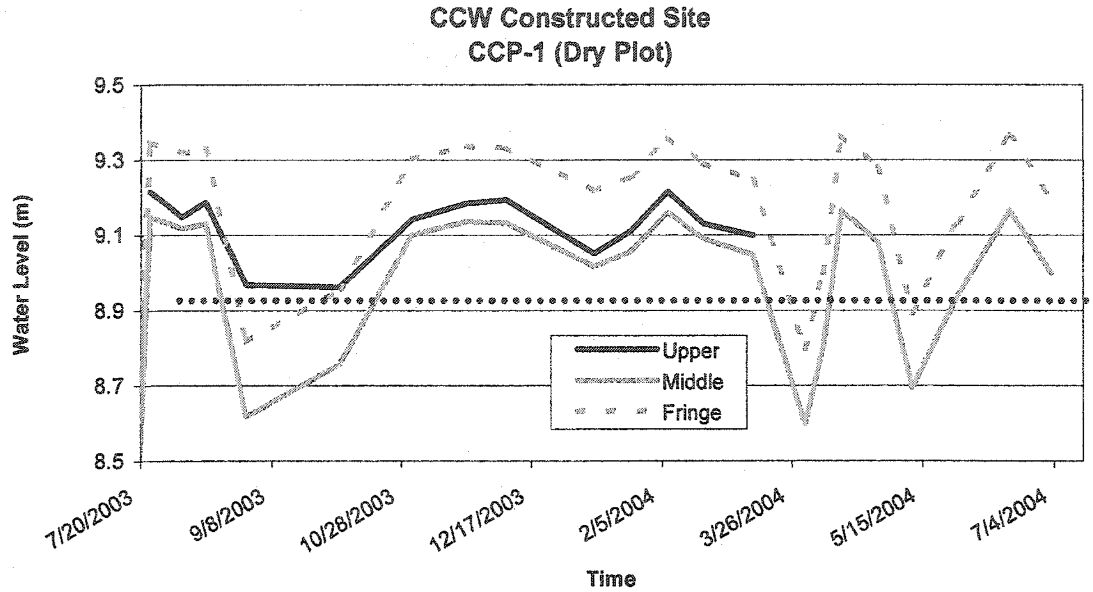

Fig. 28. Soil saturation determination hydrograph for site CCP-1. Capillary fringe is demonstrated by the dashed line and is 20 cm above the water level. The dotted horizontal line denotes upper piezometer screen elevation.

During the period of 1/10/2004-4/14/2004, the water level in the middle well at the SBNP constructed site SB-1 never dropped below the upper well screen elevation (Figure 32). On 5/11/2004, the water level in the middle piezometer dropped below the upper piezometer screen, however, the upper well was dry. Therefore, endoaquic conditions were demonstrated by the data.

At the SB-2 site, the water level in middle piezometer was higher than the upper well screen elevation throughout much of the study period (Figure 33). According to these hydrologic data, endoaquic conditions prevailed at the SBNP constructed site throughout the study period. Epiaquic conditions may have occurred at the site, after mid-April 2004, particularly for brief periods after heavy rains. However, epiaquic conditions could not be documented with these biweekly hydrologic data.

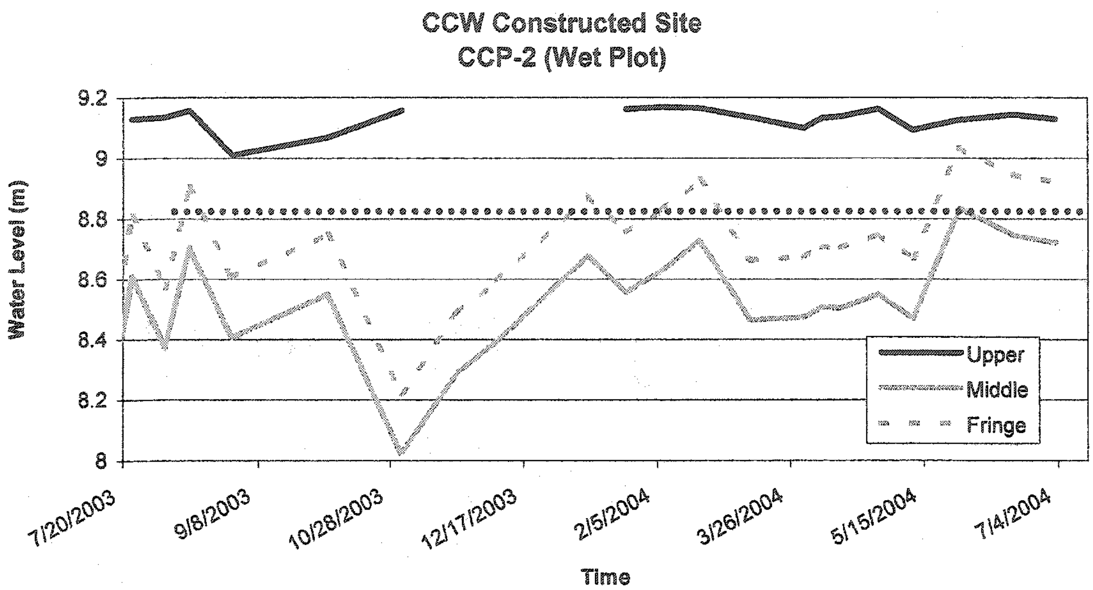

Fig. 29. Soil saturation determination hydrograph for site CCP-2. Capillary fringe is demonstrated by the dashed line and is 20 cm above the water level. The dotted horizontal line denotes upper piezometer screen elevation.

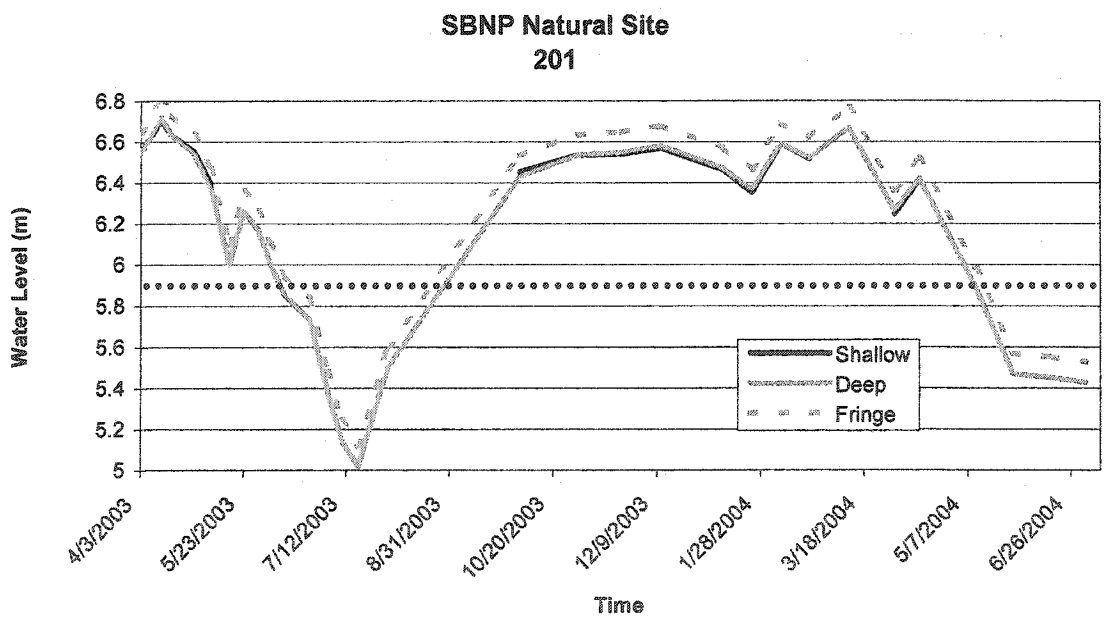

Fig. 30. Soil saturation determination hydrograph for site 201. Capillary fringe is demonstrated by the dashed line and is 15 cm above the water level. The dotted horizontal line denotes upper piezometer screen elevation.

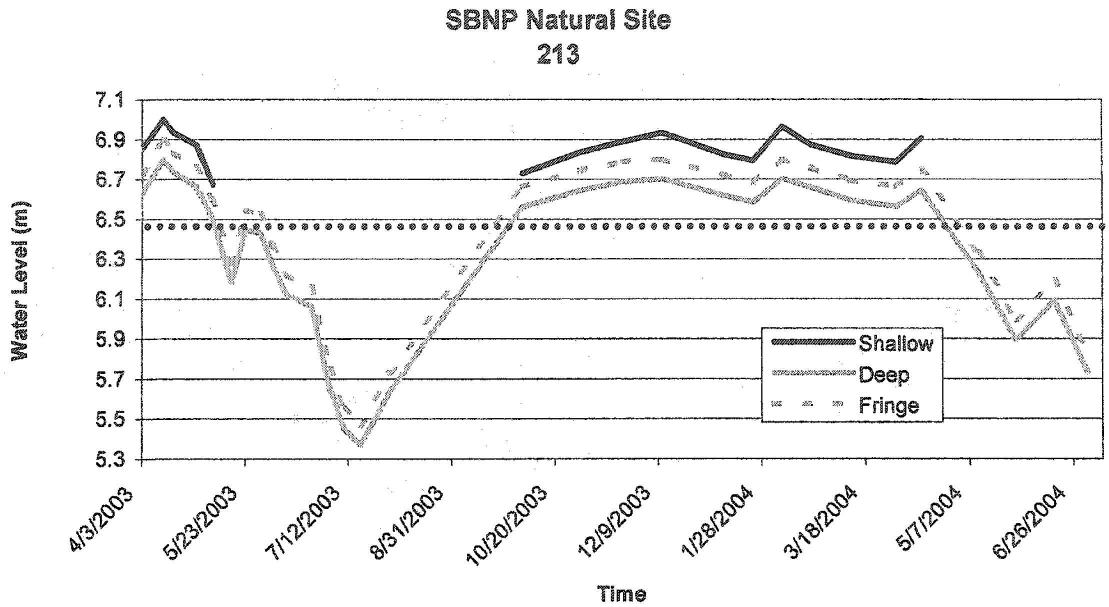

Fig. 31. Soil saturation determination hydrograph for site 213. Capillary fringe is demonstrated by the dashed line and is 15 cm above the water level. The dotted horizontal line denotes upper piezometer screen elevation.

Precipitation response was determined using several different measurements taken from the hyetograph (rainfall data) and hydrograph (hourly piezometer data) (Figure 35 as an example). Measurements were based on the work of McNamara et al. (1998) who evaluated stream discharge response to precipitation. The measurements were modified

Precipitation Response

in this study for use with groundwater. The variable T_{r1} was defined as the difference in time from the start of the precipitation event to the initial hydrograph response. The amount of time between the end of the precipitation event and the hydrograph peak was defined as T_{r2}. The variable T_{r3} was termed to be the amount of time between the start of

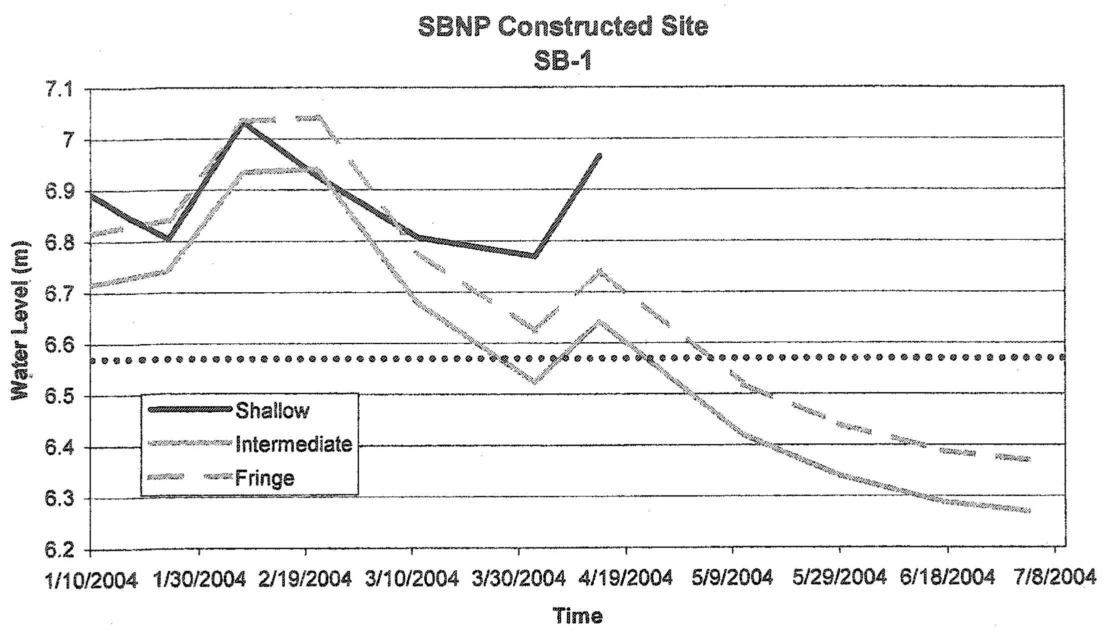

Fig. 32. Soil saturation determination hydrograph for site SB-1. Capillary fringe is demonstrated by the dashed line and is 10 cm above the water level. The dotted horizontal line denotes upper piezometer screen elevation.

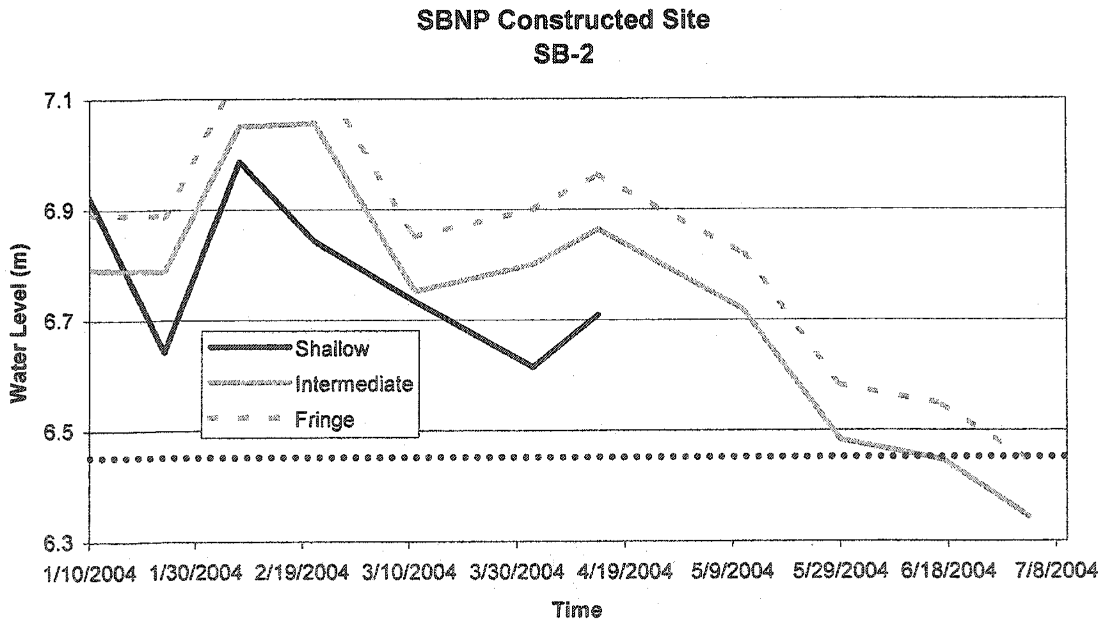

Fig. 33. Soil saturation determination hydrograph for site SB-2. Capillary fringe is demonstrated by the dashed line and is 10 cm above the water level. The dotted horizontal line denotes upper piezometer screen elevation.

the precipitation event and the hydrograph peak. The time between the centroid of the precipitation event and the hydrograph peak was defined as T_{lp}. The precipitation centroid (C_{50}) was defined by Dunne and Leopold (1978) as the time at which 50 percent of the total precipitation for the event has fallen. All responses were measured in hours. The degree of groundwater response, R_h was measured by determining the difference between the highest and lowest points of each storm hydrograph.

At the CCW natural site, piezometer data showed a relatively rapid response in the upper piezometer to precipitation events when observing the T_{r1} measurement (Table 7 and Figure 35). Of the two piezometers that were monitored, CCP-3A showed a quicker response time and greater R_h than CCP-3B. The measurements T_{r3} and T_{lp} showed the same general trend where CCP-3B responded slower than CCP-3A, except the response times were much greater than the T_{r1} measurement. Response peaks of CCP-3B were very small when a response could be determined. However, most of the time, a response could not be detected.

The upper piezometer monitored at the CCW constructed site (CCP-1A), showed a somewhat slower response to precipitation events than the upper piezometer at the CCW natural site (Table 7 and Figure 36). However, the middle piezometer at the constructed site (CCP-1B), demonstrated a faster response and a much greater R_h than CCP-3B, the middle piezometer at the natural site. Unlike the CCW natural data where T_{r3} and T_{lp} response times followed the same trend as T_{r1}, with a faster response in the upper piezometer and slower response in the middle piezometer, measurements for CCW constructed data showed a rapid response in both piezometers when using $Tr1$. However,

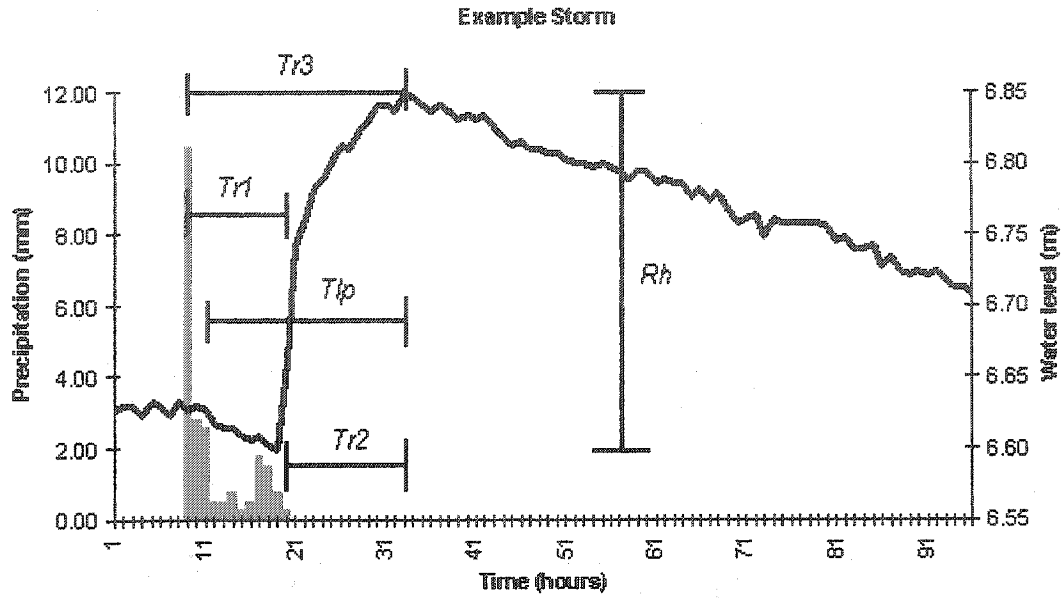

Fig. 34. Example storm hyetograph/hydrograph. Response measurements used in this study are demonstrated.

the T_{r3} and T_{lp} measurements for the middle piezometer (CCP-1B) demonstrated a longer response time than the upper piezometer.

At the SBNP natural site, groundwater response to precipitation was quite rapid in the upper piezometer (Figure 37) while in the lower piezometer, 213-DP, the response time was longer based on T_{r3} and T_{lp} measurements (Table 7). Much like the CCW constructed site response times, the *Tr1* measurement response times of the upper and lower piezometers were approximately the same while the T_{r3} and T_{lp} measurements showed a delayed response in the lower piezometer. The response factor R_h was slightly greater in the lower piezometer though it was determined that this fact did not reflect any trends and was simply due to the use of more rain events for the determination of the mean for the lower piezometer.

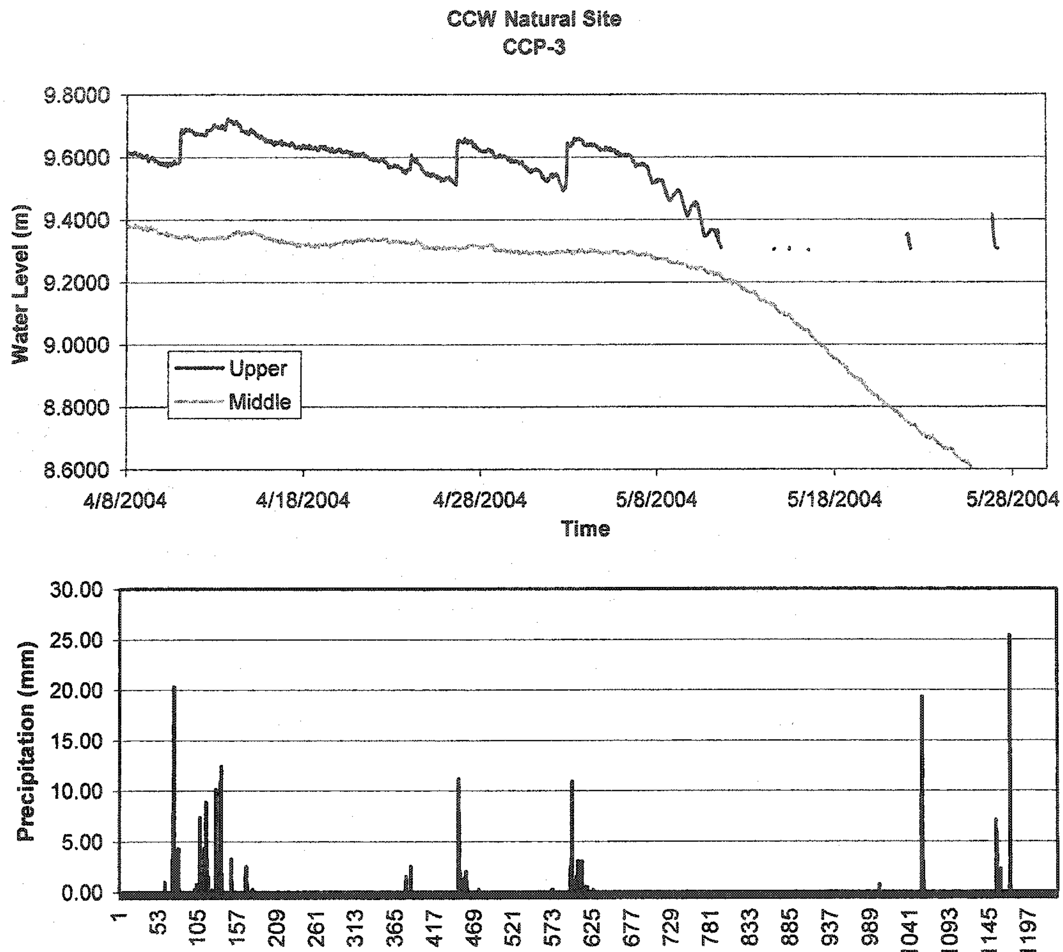

Fig. 35. Hourly hydrograph and precipitation data for CCP-3.

At the SBNP constructed site, SB-2A, SB-2B, and SB-2C were all monitored hourly. Precipitation response data for SB-2B and SB-2C were not determined. It was found that response times for SB-2B were not accurate as the water level data were overprinted with the effects of pumping done to dewater the canals. Response times for SB-2C were not determined either, as response to individual precipitation events could

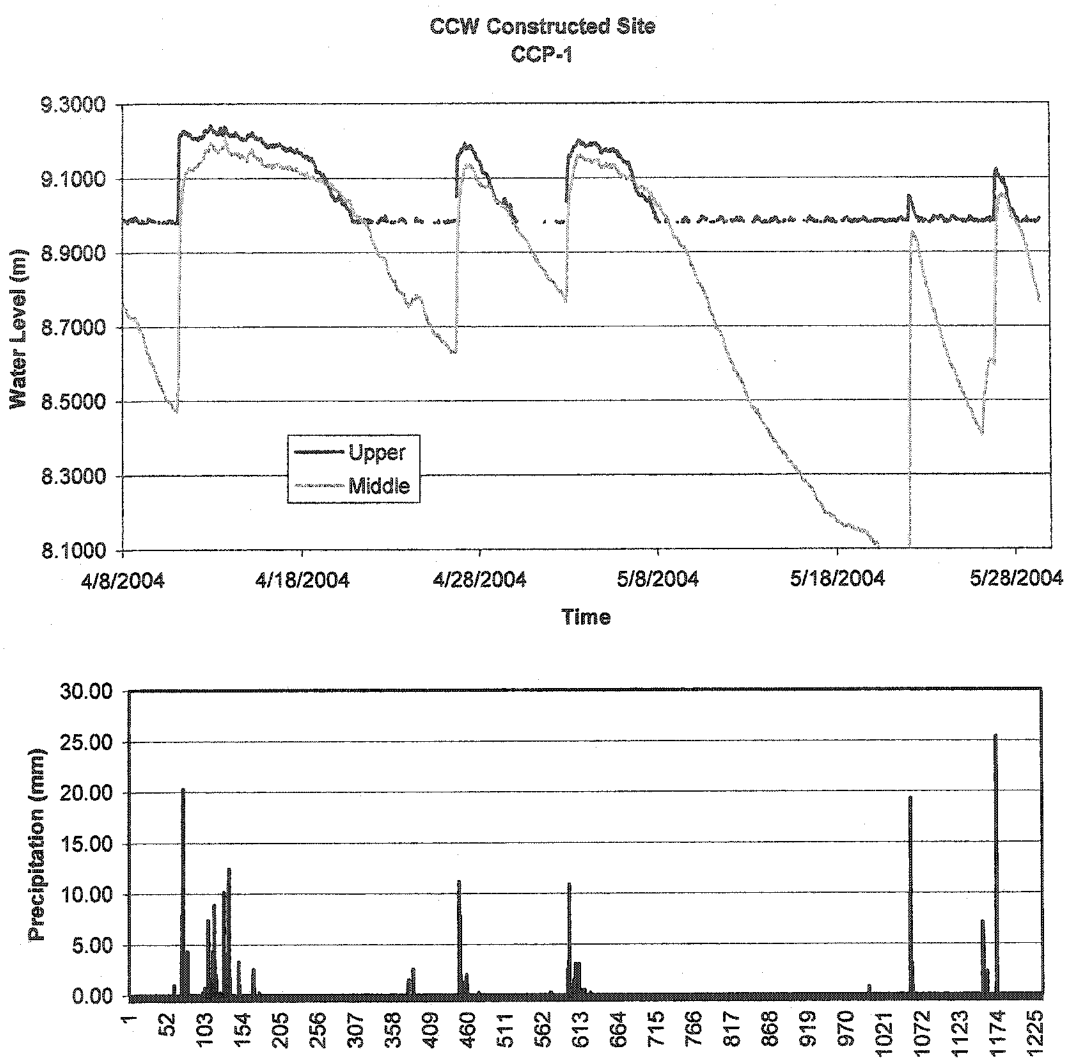

Fig. 36. Hourly hydrograph and precipitation data for CCP-1.

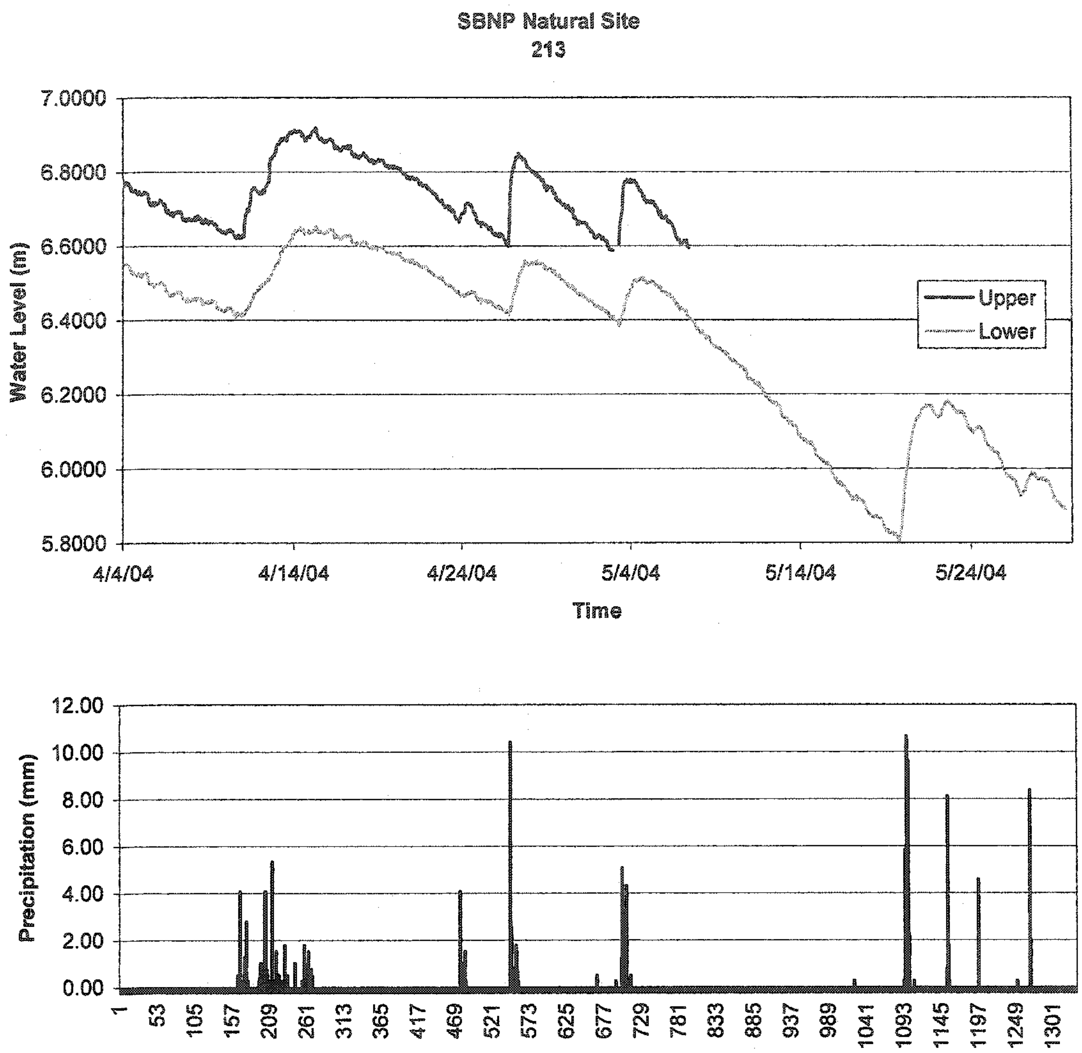

Fig. 37. Hourly hydrograph and precipitation data for 213.

not be determined. SB-2A responded to very few rain events throughout the sampling period (see Appendix D). From the two precipitation events where response times were calculated, it was determined that during dry periods, the piezometer responded very slowly to precipitation (Table 7). The measurement *Tr2* was not determined to be a significant measurement of precipitation response and therefore was not used in this study.

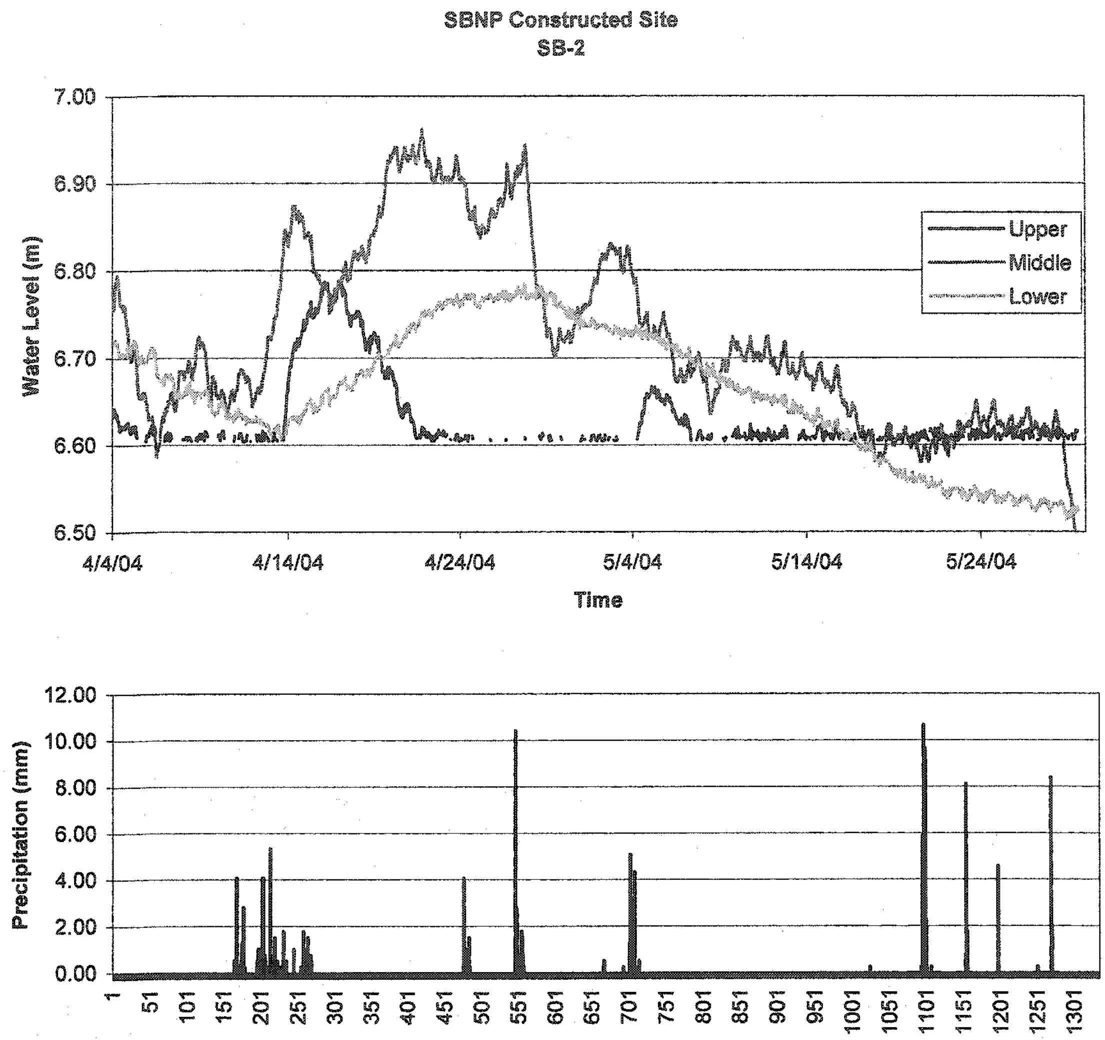

Fig. 38. Hourly hydrograph and precipitation data for SB-2.

Table 7
Precipitation response data for CCW and SBNP sites. Response factors are mean values based on the number of storm events used for each piezometer (*n*).

Piezometer	T_{r1} (*n*) (h)	T_{r2} (*n*) (h)	T_{r3} (*n*) (h)	T_{lp} (*n*) (h)	R_h (*n*) (m)
CCP-3A	0.67 (3)	-2.40 (5)	8.40 (5)	5.60 (5)	0.1361 (3)
CCP-3B	3.00 (2)	14.50 (2)	18.00 (2)	15.50 (2)	0.1053 (2)
CCP-1A	1.25 (4)	-1.00 (5)	9.80 (5)	7.00 (5)	0.1667 (4)
CCP-1B	1.20 (5)	5.20 (5)	14.40 (5)	11.60 (5)	0.5834 (5)
213-SP	2.25 (4)	13.50 (5)	22.00 (5)	15.60 (5)	0.1235 (4)
213-DP	2.17 (6)	24.50 (6)	31.83 (6)	27.33 (6)	0.1506 (5)
SB-2A	20.00 (2)	37.33 (3)	43.67 (3)	37.00 (3)	0.1091 (2)

CHAPTER IV

DISCUSSION

The data acquired in this study show striking similarities and differences between both the natural and constructed sites and the CCW and SBNP locations. These data and their implications are discussed below.

Stratigraphic Data

At the CCW location, the natural and constructed sites had the same general stratigraphic sequence with the exception of the surface. At the natural site, the soil profile consists of a loamy A-horizon and a very deep, argillic Btg-horizon that are typical of the Chickahominy soil series (Hodges et al. 1990). The same profile was observed at the constructed site with the exception that the A-horizon and some of the B-horizon had been removed during construction, resulting in little or no organic matter at the surface, and associated poor aggregation.

The amount of organic matter added and the technique utilized to incorporate it into the surface may have great implications on the success of the CCW constructed site. At the natural site, there was a well-aggregated, organic-rich A-horizon and compaction was minimal at the surface. At the constructed site, approximately two thirds of the site was amended with organic matter after the A-horizon was removed. The areas that were amended in 2003 when much of the site was regraded, tended to stay relatively moist and less compacted than areas with no organic amendments added. In the areas where no organic matter had been incorporated into the soil, the ground surface was more prone to drying out and seemed to be much more compacted.

The addition of organic matter to the CCW surface and the method by which it was applied seemed to decrease the degree of compaction. The surfaces of areas that were not amended with organic matter were graded by scraping with a bulldozer blade. No construction techniques were used in these areas to alleviate for compaction that occurred during the construction practice. However, areas that were amended were scraped and ripped using a ripper blade attached to the front of a bulldozer that ripped the surface to a depth of approximately 0.50 m. This process not only effectively loosened the soil to this depth, but also thoroughly mixed in organic amendments. Vegetation may prefer organically amended areas and the resulting decreased compaction since it may decrease effort for root growth and stress caused by the lack of available moisture (Whittecar and Daniels 1999).

At SBNP, the constructed and natural sites demonstrated very different stratigraphic packages. The natural site was comprised of a non-compacted loamy A-horizon and a B-horizon composed of a sandy loam (Daniels et al. 1995), common of the Tomotley soil series. At the constructed site, the sediment had a complex profile. At the surface, there was a very-fine grained 'cap' that previously had organic matter incorporated into it. The surface appeared to have been severely compacted, most likely the result of construction processes. The surface may act as a perching layer, impeding vertical downward movement or water and causing it to runoff rather than infiltrate. Although the surface has not been planted yet with the target species of the project, the very compacted conditions at the surface may not be favorable to vegetation, much like the non-amended areas of the CCW constructed site. However, 0.25 m below this tight layer are several alternating sand and clay layers that extend to approximately 3 m deep.

The sand layers may allow plant root growth with less effort and greater access to water. The sand layers may laterally transmit water laterally but the clay layers may act to impede vertical flow as well as root growth.

Soil Permeability Data

It was thought that permeability measurements made at CCW and SBNP locations would reflect the degree of compaction at the constructed sites. The hydraulic conductivity at the surfaces of the constructed sites were expected to be significantly less than that of the intermediate sample and possibly even the deep sample due to compaction resulting from the construction process. However, the data do not show this scenario at the CCW constructed site. Instead, the data showed no significant difference among the three depths. To further refute the idea of reduced permeability at the surface, between the natural and constructed sites there were significant differences among the depths and the constructed site had higher hydraulic conductivity values for all three depths compared to the natural setting. These data did not show any effects of construction on the soil, at the surface.

At SBNP, the shallow surface (0.15 m) of the natural setting was significantly more permeable than the intermediate (0.51 m) and deep (0.76 m) samples. The decreasing permeability with depth stems from the slight increase in clay content in the sandy loam Bt-horizon. The drastic decrease in permeability with depth was unexpected as the site can vertically transmit water with ease as demonstrated by the precipitation response data. Therefore, it is possible that the uncharacteristically low permeability samples were collected in an area with abnormally high amounts of fine sediment in the subsurface. Another possibility exists that the permeability of the natural soils at SBNP

are controlled by structures (megapores) that make secondary porosity very important. Soil samples obtained may not have included any of these structures.

At the SBNP constructed site, the shallow (0.10 m) and deep (0.61 m) samples were much less permeable than the intermediate sample (0.36 m). The material seemed to be analogous to the massive sand beds below this layer. Therefore, the ability for water to move not only vertically but also laterally is an important consideration at the constructed site.

Soil bulk density and permeability may be greatly affected by construction practices. High bulk density values, particularly those higher than 1.55 g cm^{-1} for clay-rich and 1.7 for sandy soils may impede vegetation growth and therefore limit the establishment of a vegetation community in a constructed wetland (Daniels 2004). Daniels et al. (2004) measured bulk density at the CCW and SBNP constructed sites (Appendix E). They found that the constructed sites had relatively high values, especially the SBNP constructed site where the average value at the surface (5 cm below the surface) was 1.82 g cm^{-1} and at 30 cm below the surface the value was 1.89 g cm^{-1}. The CCW constructed site had an average value of 1.42 g cm^{-1} at the surface while at 30 cm below the surface the value was 1.58 g cm^{-1}. Permeability data do not suggest that compaction occurred at depth from wetland construction practices. However, bulk density data support that compaction has occurred at both sites, especially at the 30 cm sampling depth at CCW and both 5 cm and 30 cm sampling depths at SBNP. Bulk density data for the natural soil would be useful for comparison purposes to determine if high bulk density values at the constructed site were anthropogenically induced.

Hydrologic Conditions

Biweekly Sampling

The CCW natural site appears to be an area of groundwater recharge. The stacked pattern represented in Figure 13 of CCW-3 showed downward movement of groundwater from the surface, with the source being precipitation. Since all three piezometers show the same general hydrologic pattern over the sampling period, it can be concluded that there is a well-developed hydrologic connection between the surface and subsurface. Downward movement of water can also be inferred at the constructed site in the CCP-1 and CCP-2 piezometer nests (Figures 14 and 15). In CCP-1, water movement was much the same as that of CCP-3, the piezometer nest at the natural site. However, CCP-2 showed downward movement between the upper and middle piezometers, but upward movement of groundwater was apparent between the middle and lower piezometers. This situation indicates that while the natural site seems to be a precipitation driven system, the constructed site has both precipitation and seasonal groundwater inputs. While the groundwater input may be a regional influence, it is most likely that in the case of piezometer nest CCP-2, it is a more localized phenomenon. CCP-2 lies within close proximity to the soil bank that is approximately 2-3 m higher than the elevation of the plot in which CCP-2 is located. The area of the plot may act as a discharge point for precipitation that has infiltrated the soil bank and moved through the ground.

In order to understand the movement of groundwater at the CCW constructed site, one piezometer nest (CCP-4) and a deep piezometer (CCP-5) were installed to the north of the experimental plots, at the break in slope between the graded wetland surface and

the A-horizon soil bank (Figure 39 and Appendix B). The premise was that the soil bank might be acting as a local recharge site and the area where CCP-1 was located was acting as a point of discharge. Therefore it was expected that a nest containing two wells screened at different depths would have shown an upward movement of water at the break in slope.

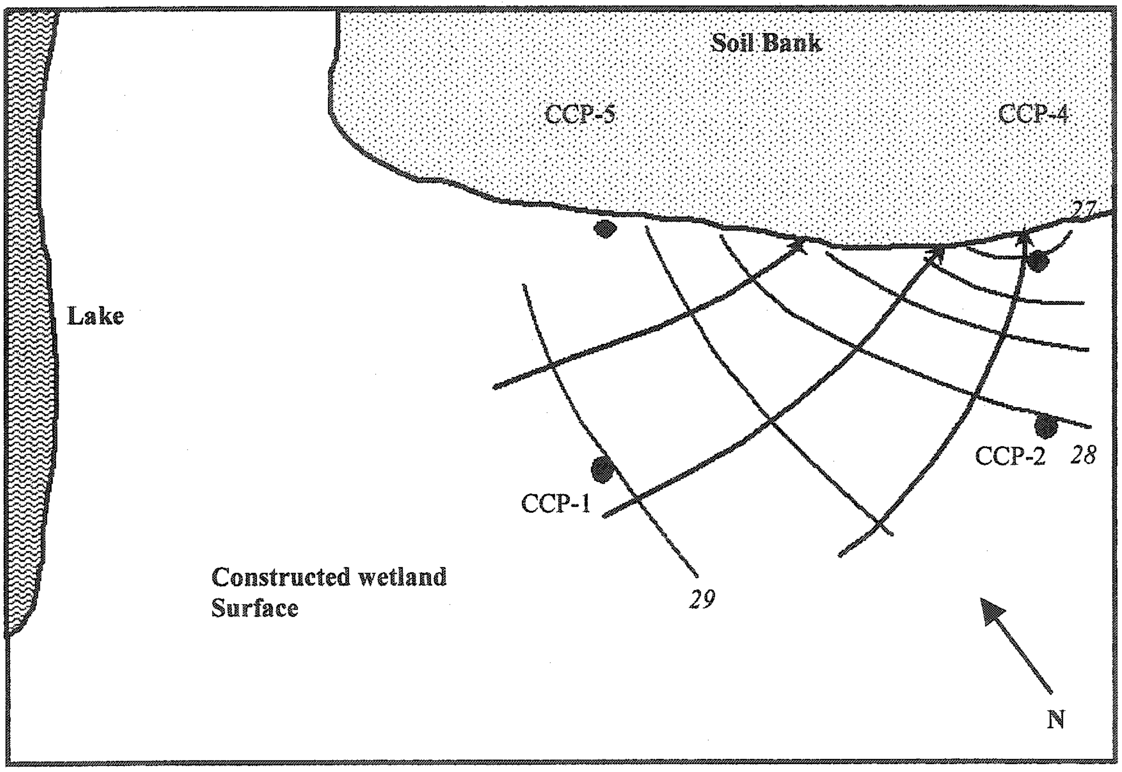

Fig. 39. Groundwater contour map of CCW constructed site. Map depicts groundwater flow toward soil bank on 7/3/2004. Water level data are from the deep piezometers. Contour lines are represented in feet above sea level.

The nests were sampled several times throughout 6/2004-7/2004 (Appendix B). The sampling event on 5/28/04 marked a change in the hydrology at CCP-2 in that the water level in the lower well was lower than that of the middle well. Therefore, CCP-2

now demonstrated downward movement of water and not upward movement it had previously displayed. Data gathered from the other piezometers allowed the water levels to be contoured as shown in Figure 39. This flow map for the area around the experimental plots showed that on 7/3/2004, water appeared to be flowing toward the soil bank, not away from it. The hydrograph for CCP-2 demonstrates that groundwater flow is different at different times of the year. Therefore, during wetter times, groundwater moves upwards from the lower piezometer to the middle piezometer, possibly the result of water movement from the soil bank. During dryer times of the year, it is preliminarily thought that the water table is ‘mounding’ up in the middle of the constructed site, driven by precipitation. The flow pattern depicted in Figure 39 probably reflects flow off the edge of this mound, where water is being lost from the wetland from downward and lateral groundwater movement off of the broad flat. Clearly, further studies are needed to fully understand this phenomenon.

In the sandy loam soils at the SBNP natural site, both upper and lower piezometers at sites 201 and 213 had hydrologic patterns that indicate an unimpeded connection between the surface and subsurface. The vertically stacked pattern observed in the site 213 hydrograph indicates that this area acts as a recharge site. Pocosin wetlands are characteristically sites of regional recharge as they are located at the top of the groundwater dome that forms under broad upland flats. The piezometer nest at site 201 showed a pattern where the lines were at the same elevation through time, thus indicating water is moving laterally as opposed to vertically. These data support the findings of Whittecar and Daniels (1999) who reported that seepage at this site moved east, away from the groundwater dome and towards a regional drain.

At the SBNP constructed site, the high degree of variability among the piezometers indicates very complex hydrology. At different times during the sampling period, piezometers demonstrated periods of recharge, discharge, and even lateral throughflow. The two upper piezometers were commonly dry except after rain events, indicating that the water table was not near the surface, but significantly deeper in the subsurface. Boreholes excavated throughout the site support the notion that during much of the sample period, the water table was not at or near the surface, but commonly 1-2 m down. In the natural setting for the same time period however, the water table was within 0.5 m of the surface. The stratigraphic data for the constructed site showed a complex package of sediments capped by a compacted fine-grained sandy loam. The tight layer seemed to impede flow as demonstrated by the borehole data, where ponding occurred at the surface while the water table was much lower in the subsurface. Water tended to pond at the surface, which may soak in over great lengths of time or evaporate. The water may also run off into the canal and surface water system present at the site. The surface ponding indicates that epiaquic conditions exist, at least for part of the time at the SBNP site. The COE recommends to those involved in the design and construction of mitigation wetlands to cap the graded surface with fine-grained sediments to keep the water in the system, to decrease the likelihood of losing it to the surface where it may be lost as through evaporation. At SBNP, the use of a fine-grained cap may be counterproductive by actually impeding downward movement of precipitation that drives these pocosin wetlands and forcing it to run off into the ditches, thus not effectively recharging the wetland system.

The middle piezometers, SB-1B and SB-2B, had very 'flashy' hydrographs in which they seemed to be responding rapidly to factors such as precipitation and possibly pumping-induced water level changes occurring in the surface water ditches. These data show no clear vertical connection between the surface and subsurface, as each piezometer had a different hydrologic trend.

The lower piezometers demonstrated two distinct patterns indicating an area of upward movement of water near the edge of the constructed site (SB-1C) and an area of downward movement in the middle of the site (SB-2C). The northeast edge of the constructed site where SB-1C is located is surrounded by land that is 1 to 1.5 m higher in elevation than the constructed wetland surface. This higher area includes an access road, I-64, and the land between the two roads (Figure 40). Therefore, for some time periods, the higher surface may act as an area of recharge while the edge of the constructed site may be where this water is discharged, much like the CCW constructed site situation discussed above.

For much of the sampling period, the area where SB-2C is located had the lowest head level of the three piezometers, indicative of downward movement of water. Even though several confining clay lenses separate the stratigraphic units that contain SB-2B and SB-2C, water seems to be able to migrate downward. The connection between these two stratigraphic layers is demonstrated when SB-2B had higher water levels, so too did the lower piezometer, SB-2C.

Piezometer nests were not constructed until late in the study due to construction practices occurring at the site. However, a longer data set may show broad seasonal patterns that cannot be seen in the current data set.

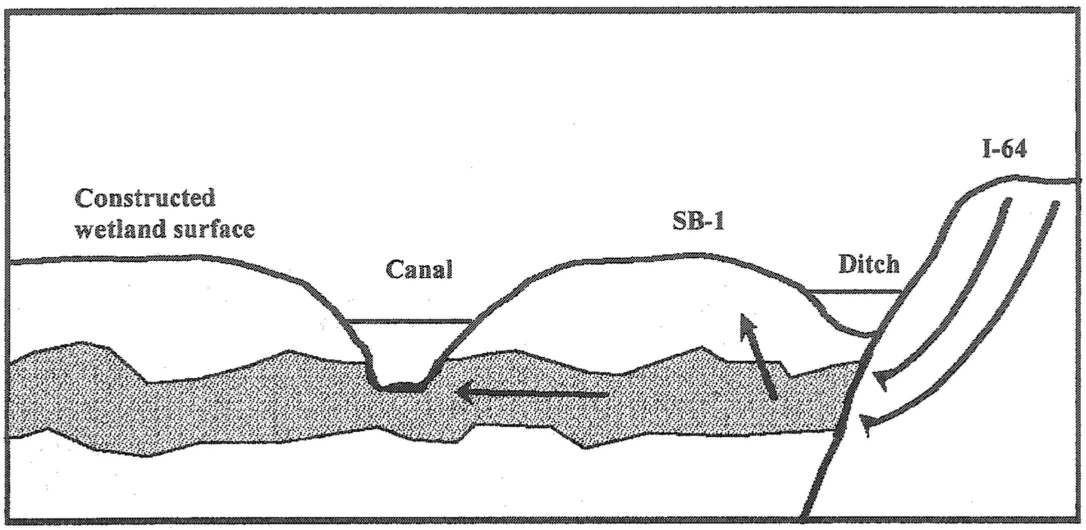

Fig. 40. Diagram demonstrating regional flow at SBNP. Flow patterns are influenced by the higher ground surface (~ 2 m) to the east of SBNP constructed site SB-1. Drawing is not to scale.

Hourly Sampling

The vertically stacked pattern observed in the CCW natural site hydrograph indicates that the area is a recharge site, much like the biweekly data demonstrate. The upper piezometer tended to respond strongly to precipitation events (discussed below) while the response in the middle piezometer was much less. Therefore, the two stratigraphic levels are hydrologically connected, but the connection is weak.

Hourly data obtained from the constructed site showed that the upper piezometer had slightly higher water levels than the middle piezometer, indicating downward vertical movement. These data also indicate that the two stratigraphic levels are clearly connected hydrologically. However, if the lower piezometer had been monitored hourly with the upper and middle piezometers, it would have most likely showed much lower water level than the upper and middle piezometers, much like that seen in the biweekly

data for CCP-1. Therefore, this site may act as a groundwater recharge zone driven by precipitation much like the natural site.

The natural site at SBNP, where piezometer nest site 213 was located, showed a stacked or recharge pattern described earlier like that observed in the biweekly data for this nest. Therefore, the area acts as a recharge zone, driven by precipitation. From the hourly data, it is apparent that there is an unimpeded connection between the surface and subsurface. Both piezometer water levels had the same general pattern and responded to precipitation event in much the same way. The response of both piezometers indicates a clear connection between the upper surface/subsurface and lower depths.

The hourly data obtained from SB-2 in the constructed wetland showed many of the same features as the biweekly data. SB-2A tended to remain dry much of the sampling period when during wetter periods, before construction resumed in early 2004, the surface was nearly inundated. The extremely dry surface conditions during late Spring 2004 were most likely due in part to pumping operations that occurred throughout the sampling period meant to lower water levels in the ditches for construction purposes. Therefore, groundwater was most likely lowered as a result of the ditch pumping as well. The middle piezometer, SB-2B demonstrated a flashy pattern as seen in the biweekly data. Flashiness may have been the result of two variables that acted on the stratigraphic layer in which the screen of SB-2B is located. The piezometer is located in a sand unit that is connected to the ditch. Water that entered the ditch and tended to raise its level, such as precipitation and runoff, would have also influenced the water present in the sand unit in which SB-2B is located. Therefore, if the addition of water to the canal system influenced the water level in SB-2B, so did the removal of water, such as by pumping

(discussed below). The lower piezometer, SB-2C had a very slow response. The water level in the lower piezometer tended to respond slowly to a water level increase in the middle piezometer, therefore indicating the two stratigraphic layers had some hydraulic connectivity as discussed above in the biweekly data section.

There was a general seasonal drawdown or lowering of the water table that can be observed in the CCW natural and constructed site data as well as the SBNP natural site data. The drawdown can be attributed to forest canopy leafout, where vegetation has a significant influence on groundwater and is a macroscale effect. After leafout, vegetation tends to deplete groundwater through evapotranspiration, where the vegetation effectively 'pumps' water from the ground, in through its roots, through conducting tissues, and ultimately expels the water into the atmosphere through leaf stomata (Fetter 2001; Mitch and Gosselink 1986; Whittecar and Daniels 1999). Diurnal fluctuations that occurred near the end of the sampling period in the upper piezometers at both CCW and SBNP natural sites clearly show the microscale effect that evapotranspiration has on groundwater levels. During the day, while the vegetation was transpiring, water levels in the upper piezometers dropped. At night, after the vegetation had stopped transpiring, water levels recovered.

Water levels in the middle piezometer (SB-2B), located in the SBNP constructed wetland showed complex, diurnal and semidiurnal water level fluctuations of 0.02 m (Figure 26). Because the site was treeless and the piezometer was relatively deep (1.70 m), evapotranspiration could not be the cause of the minor fluctuations. However, barometric pressure data plotted with the hydrologic data against time showed a strong inverse relationship between the barometric pressure and the water level of SB-2B. The

relationship appeared as a mirror image between the hydrograph and barometric pressure. Piezometer or well data that are clearly influenced by barometric pressure indicate that the aquifer in which the piezometer or well is screened is confined with high barometric efficiency (Freeze and Cherry 1979). If the sand bed is clearly connected to the ditch, it would only be confined if the water in the ditch is high enough to cover the sand unit. Ditch levels were that high before the sampling period and once pumping operations cease and ditch levels recover, the sand unit will be unquestionably confined.

Soil Saturation Conditions

The CCW natural site demonstrated both endoaquic and epiaquic conditions throughout the sampling period. Most of the time, endoaquic conditions prevailed. Epiaquic conditions occurred during times when the water level in the middle well was relatively low, yet water was present in the upper well. This situation may result after a period of rainfall where the water fills up the A-horizon and may result in ponding at the surface as well. The water is impeded by the tight Bt-horizon from percolating downward to the sandier strata below. Over time, the surface water slowly moves through the perching layer, adding water to the lower strata and is probably lost to the atmosphere through evaporation.

At the CCW constructed plot, it was determined using indirect soil saturation determination methods that endoaquic conditions prevailed throughout the sampling period. However, epiaquic conditions were observed directly on one occasion when the indirect (hydrologic) method demonstrated endoaquic conditions. Several factors may have resulted in these conflicting data. On 1/24/2004, when the borehole was excavated, ponding was occurring at the surface. This may indicate that the water was being

impeded at the surface rather than by the Bt-horizon several centimeters below the surface. The borehole was excavated between the two experimental plots where the surface had been scraped during the initial grading of the site, not scraped, organically amended, and ripped. Therefore, construction activities such as grading may have a profound impact on the wetland surface but not on the soil deeper in the profile.

Differences found in soil saturation conditions by the two methods at CCW may also indicate spatial variability throughout the constructed site and the importance of minor stratigraphic differences. The indirect method data show that the dry plot had mainly endoaquic conditions with a high water level in the middle piezometer while the wet plot seemed to favor more epiaquic conditions with a lower middle piezometer water level much of the time.

The CCW natural and constructed sites most likely have endoaquic and epiaquic conditions in different parts of the sites, at different times of the year. The indirect data demonstrated water levels for the screened elevations. They did not however, demonstrate water levels at any other elevations. The data showed when the sand beds below the Bt-horizon were saturated or unsaturated. However, no piezometer was installed in the Bt-horizon, allowing its saturation conditions to be monitored. Obviously, the different findings between the two methods reveal limitations and the importance of utilizing several techniques to discover the most useful and accurate.

At the SBNP natural site, both methods supported the notion that the area always had endoaquic conditions. This is further supported by the fact that no perching layers were found at either piezometer nest location.

At the SBNP constructed site, several perching layers were found, including the surface and the tight clay bed located at approximately one meter below the surface. However, the indirect data showed that the site was predominantly endoaquic at times when dry soils were encountered at depth when boring within close proximity to ponded surface water. Much like CCW, these contradictory findings suggest that other factors are confounding the results as well as demonstrating the limitations of the methods used in this study.

Precipitation Response

At the CCW natural site, the upper piezometer responded rapidly to rain events while the middle piezometer responded slower and with an overall smaller response. Clearly, a connection does exist between the upper and middle stratigraphic layers, however they are not as well connected as in the constructed wetland.

Precipitation response was faster overall at the CCW sites compared to the SBNP sites. Such a fast response in a much finer-grained soil seems counter-intuitive. The CCW natural and constructed sites are comprised of expansive clays thus leading to the supposition that precipitation response would be slower at CCW compared to the sandy loam soil at the SBNP natural site. Clay-rich soils would provide an extremely tortuous path for water to move through compared to the high permeability of the sandy loam at the SBNP natural site. Thus, a higher primary porosity would dictate that the sandy loam of SBNP would allow water to move much quicker and thus demonstrate faster precipitation response times compared to CCW. However, secondary porosity may be an important factor in this situation. It has been documented at CCW that cracks were present throughout the constructed site during the time of study, formed in the newly

exposed Bt horizon. The depths of these cracks may allow for efficient movement of water from the surface to the subsurface, resulting in rapid response times. The response time data for the CCW constructed site, where there was a fast initial response in both piezometers yet a slower peak response in the middle piezometer, might support the presence and influence of secondary porosity. Initially, the cracks in the soil will fill with water, leading to a rapid initial response (T_{r1}). Once the cracks are full of water, the movement of water is dependant on how fast the water may flow through the system, leading to slower peak response times as depicted by the T_{r3} and T_{lp} measurements. At the natural site, evidence of macropores (e.g. drainage into the borehole via soil piping or cracks) was apparent to approximately 0.5 m below the surface during piezometer construction at CCP-3. These conduits may allow percolation of water from the surface to the subsurface, much like the cracks that are present in the constructed wetland; however, evidence does not support that these structures appear deeper than 0.5 m below the surface.

Cracks seemed to only be present at the constructed site and varied in size and abundance. The largest and most abundant cracks were found in dryer areas or areas that had not been amended with organic matter. Wetter areas or more organically rich areas demonstrated smaller or less abundant cracks. Therefore, water availability and particularly the amount of organic matter present in the soil may influence crack development at the surface where increased organic matter may impede crack development. Surface cracking has been documented to extend up to 15 cm in depth and 4 cm in width. However, the presence and extent of these cracks at depth is unknown.

After a precipitation event, the hydrograph peaks displayed by the piezometers tended to have different rates of water level decline. These decay curves following precipitation events indicate how rapidly the system drained that water into the regional groundwater system. The steepness of the decay curve was used to indicate the rate of groundwater recharge. A relatively steep hydrograph decay curve reflects faster groundwater flow.

Water levels at the CCW natural site had a slower rate of decay than the SBNP natural site (Figure 41; Table 8). Therefore, the SBNP site lost its water more rapidly and demonstrates that it does not retain water as well as CCW. Instead, the natural site at SBNP allows water to pass down through its system faster due to its coarser, sandier texture. CCW had lower decay rates and therefore lost precipitation more slowly indicating that this site either stores the water more effectively, or is unable to pass the water through the system as efficiently. Due to its fine-grained nature, the CCW soil most likely cannot conduct water as efficiently as the SBNP natural soils.

The constructed site at CCW demonstrated that the argillic soil can support rapid movement of water at the surface and shallow subsurface particularly through megapores and cracking at depth (Figure 42; Table 8). Therefore, the primary porosity may control the decay factor of the CCW soil, which resulted in the slow rate of decay. The SBNP constructed site had a low rate of decay at the surface, which is characteristic of the fine-grained, extremely compacted nature of the sediment.

Decay rate observations fit with expected characteristics of stratigraphic formations, although the Tabb and Shirley Formations are both thick, fining-upward sequences of gravel to mud. The Shirley is more clay-rich at the surface and much older.

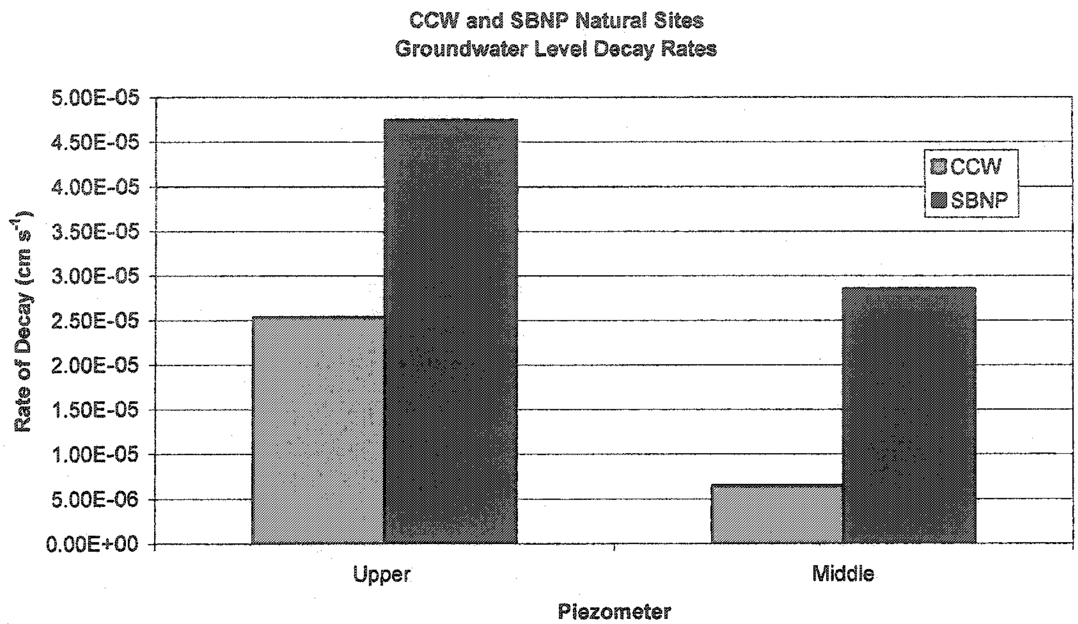

Fig. 41. Groundwater level decay rates for CCW and SBNP natural sites.

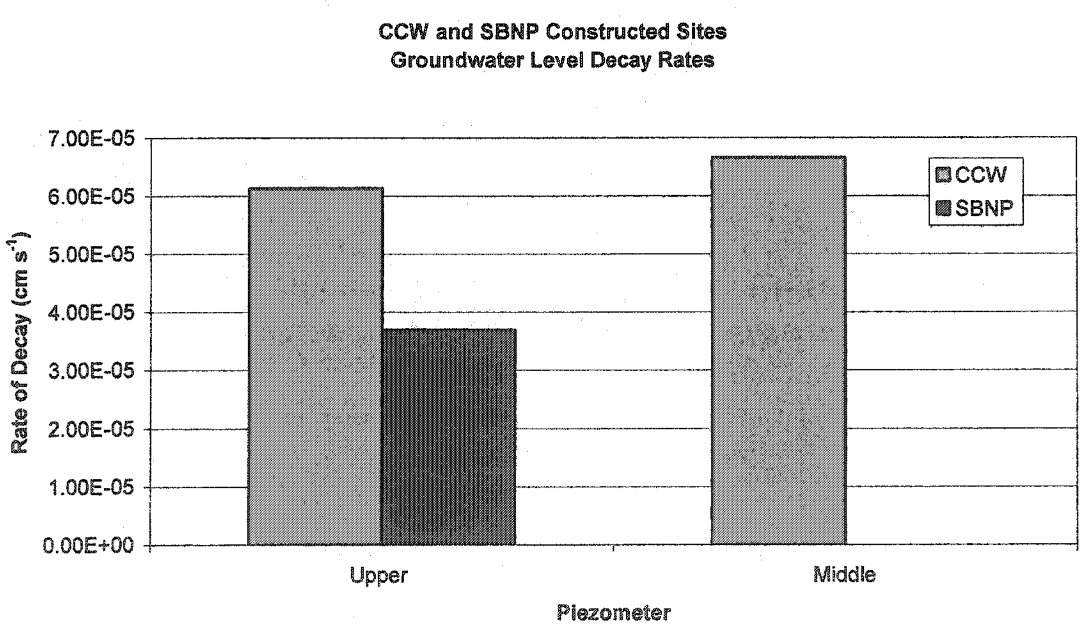

Fig. 42. Groundwater level decay rates for CCW and SBNP constructed sites. Note that data for the SBNP middle piezometer were not included due to surface water pumping overprint.

Table 8
Hydrograph precipitation decay rates for CCW and SBNP natural sites. Hourly upper and middle well data were used in rate determination.

Well ID	Mean Decay Rate ($cm\ s^{-1}$)	Well ID	Mean Decay Rate ($cm\ s^{-1}$)
CCP-3A	2.53E-05	213-SP	4.74E-05
CCP-3B	6.46E-06	213-DP	2.85E-05
CCP-1A	6.13E-05	SB-2A	3.69E-05
CCP-1B	6.66E-05		

This greater age is reflected in greater accumulations of clay in the subsurface soil horizons and greater amounts of iron cementation in sandy strata. Such widespread pedologic and diagenic effects will retard the downward seepage of groundwater present at recharge zones, such as pocosins. All other factors being equal, pocosin wetlands on the Tabb Formation should drain faster and have greater seasonal water table fluctuations than wetlands in the Shirley Formation.

CHAPTER V

CONCLUSIONS

The purpose of this research program was to investigate the hydrologic impacts of wetland construction techniques used in two different geologic and pedologic settings. The primary objectives of the study were to determine the causes of variations in patterns of hydrologic response to recharge events, to evaluate the effects that construction practices used in mitigation wetlands have on permeability and hydrologic response on both fine-grained and stratified multi-textured soils, and to determine if soil cracking influences the hydrology of a constructed wetland.

Variations in patterns of hydrologic response to recharge events were caused by several factors. Seasonal hydrologic fluctuations were common in all the hydrologic data for the natural and constructed sites at CCW and SBNP. These fluctuations were the direct result of the amount of precipitation and rate of evapotranspiration. During dry times of the year, from July through September where evapotranspiration often exceeds precipitation, piezometer levels were relatively low. During wetter times of the year, from January through March when evapotranspiration is very low, piezometer levels were generally high.

Diurnal hydrologic fluctuations were common at the natural wetland sites of CCW and SBNP. Fluctuations that were occurring at this scale were the result of evapotranspiration by trees where during daylight hours, trees pull water out of the ground and release it into the atmosphere. At night, after vegetation has stopped transpiring, groundwater levels recover. Diurnal fluctuations that occurred in the natural

setting were the result of evapotranspiration. Diurnal fluctuations only occurred in one case at the SBNP constructed site and were the result of high barometric efficiency between the atmosphere and the aquifer.

The rate of hydrologic response of various aquifers to individual rainfall events reflects the overall permeability of the aquifers and their hydrologic position within the wetland system. Aquifers with high permeability, from either primary porosity (e.g. sand) or secondary porosity (e.g. clay loam with cracks), transmitted water rapidly, and slowed in the most pronounced hydrologic fluctuations. The long-term decline of water levels after recharge events also reflected the permeability of the regional aquifer. The wetlands formed on higher permeability aquifer systems (e.g. SBNP) pass water more readily to underlying groundwater systems than those on lower permeability systems (e.g. CCW).

Construction practices used in mitigation wetlands produce significant effects on the permeability and hydrologic response of fine-grained soils. Hydrologic differences found between the CCW natural and constructed sites clearly illustrate several of these effects. The CCW natural site displayed both endoaquic and epiaquic conditions at different times of the year. During the drier times of the year, such as during the summer, the CCW constructed and natural sites displayed epiaquic conditions. During the wetter periods such as during the winter and early spring, these sites displayed endoaquic conditions. The sites displayed temporal variations in soil saturation characteristics as well, although different areas of the site displayed different conditions. The differences in saturation conditions and the differences of occurrence and duration of epiaquic status may be a result of the how the surface was constructed. Graded surfaces that were not

ripped or amended but simply scraped, usually had a perching layer at the surface and were predominantly epiaquic. Ripped and amended surfaces may ultimately loosen the surface to the ripping limit, allowing the surface to hold water better. However, these areas may still become epiaquic at different times of the year where a low permeability Btg-horizon still exists below the ripped zone.

At the CCW constructed site, the combination of moderately expansive clay soils and unusually dry weather resulted in extensive soil cracking on the newly graded surface at all but the wettest areas. These particular conditions altered the permeability of the surface layer by allowing direct access of water through the perching layer.

Practices used in constructing wetlands with stratified multi-textured soils, such as at SBNP, make patterns of permeability and hydrologic response that differ significantly from the surrounding loamy natural soils. The SBNP wetland site was constructed by filling in an existing lake with a variety of coarse to fine-grained sediment types. The finer-grained clay-rich layers became extremely compacted during construction. Strata in the upper 2 m of the constructed SBNP site displayed extreme groundwater fluctuations. Subsurface sandy beds connected to the surface water canal system responded rapidly to changes in the canal water levels. Rainfall response at the constructed site was variable, but was generally slower in the upper (compacted) portion of the soil profile than in the natural (loamy) wetland. The clay layers most likely impede vertical flow and therefore act as perching layers. Endoaquic and epiaquic conditions were observed at this site. Epiaquic conditions may occur both at the surface and within the subsurface. At the SBNP constructed site, the low permeability fine-grained cap that became compacted during grading may act as a perching layer and force

precipitation to run off rather than infiltrate. However, the highly permeable sand units that connect the canal system to the subsurface of the wetland influence available groundwater in the wetland.

Cracking at the CCW constructed site was determined to have significant effects on the hydrology of the site. Initially, it was assumed that the site would have a slow precipitation response much like the natural site, especially at depth. However, the subsurface of constructed site responded rapidly. Rapid response was most likely the result of the influence that secondary porosity had on the site. The severe cracking that was observed was likely transmitting water through the surface to the subsurface very rapidly and therefore much more influential than primary porosity. The removal of the A-horizon and the exposure of the expansive clay-containing Btg-horizon altered the hydrology of this site considerably from the hydrology displayed at the natural site. During times of the year when little precipitation fell, the surface was allowed to dry out and crack. Cracking created a conduit for water to travel from the surface to the subsurface with relative ease.

Several different methods were utilized to obtain and analyze the data for this thesis study. A procedure was developed to determine the permeability of undisturbed soil samples to conclude if compaction affected the permeability. The method worked quite well although if future work entails obtaining soil samples, a more reliable coring instrument should be fabricated. The instrument developed for this study failed repeatedly due to the stresses imparted on it by pounding it into the ground. Stronger pipe such as schedule 80 stainless steel pipe might increase the reliability of the instrument.

Precipitation response was calculated several ways. Three of these measurements proved useful in distinguishing response characteristics of the wetland sites, while the others did not demonstrate any significant characteristics or trends. The variable T_{r1} was useful in showing the initial response of the groundwater to rainfall. The variable T_{r3} was an important measurement that demonstrated the time from the start of the rain event to the peak groundwater level. The variable T_{lp} was also useful in showing the time between when half of the total precipitation had fallen and the peak groundwater level. These three measurements reflect different aspects of the storm and subsequent response by the groundwater. The variable T_{r2} did not prove especially useful, as it did not aid in explaining in any significant findings. Lastly, the magnitude of water table response, R_h seemed useful in demonstrating the degree of response to a precipitation event at a particular well screen elevation.

The direct method for determining soil saturation conditions (augering) was found to be very reliable yet time intensive. The indirect method (hydrograph analysis) shows promise in using hydrologic data for saturation determination. However, this method needs to be refined further to discriminate between epiaquic and endoaquic conditions. The most effective way to acquire more accurate results might be to employ more piezometers at varying depths of the soil profile. Piezometer installation at both CCW and SBNP sites were not initially installed for soil saturation determination. The piezometers were installed to aid in the understanding of the hydrology of the sites. Therefore, in most cases, piezometers were installed in water producing strata. Further studies should include the installation of piezometers in the lower permeability layers to determine their characteristics as well. If these layers are unsaturated, then epiaquic

conditions may be present, but not identified if the piezometers are installed in only water-transmitting strata.

This study would have benefited from acquiring more rainfall and hourly hydrologic data. Data gathered for several more storm events would have allowed statistical comparisons between the natural and constructed sites as well as the CCW and SBNP locations, thus making the conclusions more definitive. Also, if water levels were read more often, such as every 15 minutes, finer scale differences or similarities could be observed.

The data collected during this study show that several factors can affect the hydrology of both natural and constructed pocosin wetland sites. Significant climatic influences include evapotranspiration, seasonal precipitation variations, and diurnal barometric pressure fluctuations. Geologic factors include landscape position, regional aquifer characteristics, stratigraphic variations in shallow sediments and soils, and both primary and secondary porosity. Construction practices affect hydrology via scraping surface soils, layering and compaction of sediments, deep ripping, and the addition and mixing of organic material into the final wetland surface. The result of these influences is that both natural and constructed sites demonstrated endoaquic and epiaquic conditions, which varied both spatially and temporally.

Until recently, wetland soil quality has largely been ignored. In the Rheinhardt and Brinson (2002) studies where North Carolina Department of Transportation mitigation wetland sites were evaluated, they reported that in many cases, wetland success criteria were based on hydrologic and vegetation conditions. Usually, the presence of hydric soils at the wetland site is required by federal and state regulatory

agencies (e.g. COE and Department of Environment and Natural Resources) to consider a site successful, while soil quality however, may not be addressed. Criteria supported by the COE to achieve proper hydrologic conditions often support alteration of the soils by encouraging removal of the A-horizon to achieve wetland hydrology, like much of the CCW constructed site. Streever (1999) conducted a study where performance standards of mitigation wetlands were examined and determined that no performance standards existed for soils. Much of the CCW site was organically amended. However, many areas of the site were not amended and have poor soil conditions such as high bulk density and low amounts of organic matter.

Soil quality standards have only recently been suggested for mitigation wetland sites in Virginia (COE 2004). New recommendations by the Norfolk district office of the COE include amending soils that have had their A and/or B-horizon removed to increase the organic matter content to at least 5%. The COE also recommends ripping or chisel-plowing wetland surfaces to reduce soil bulk density to less than 1.35 g/cm^{-1} for loamy and finer-textured soils and less than 1.70 g/cm^{-1} for sandy soil prior to added organic material or topsoil.

Assessments in the future will need to determine if the hydrologic and compositional differences noted at CCW and SBNP significantly influence the establishment and rate of development of the desired forested wetland community at these sites.

REFERENCES

Baird, A.J., 1995. Hydrological Investigations of Soil Water and Groundwater Processes in Wetlands, *In:* J.M. Hughes and A.L. Heathwaite (eds.) Hydrology and Hydrochemistry of British Wetlands. John Wiley and Sons, Chichester, 111-129.

Brady, N.C., Weil, R.R., 1999. The Nature and Properties of Soils. Twelfth Edition. Prentice Hall, Upper Saddle River, 881 pp.

Brinson, M.M., 1993. A hydrogeomorphic classification for wetlands. Technical Report WRP-DE-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 79 pp.

Brinson, M.M., 1991. Landscape properties of pocosins and associated wetlands. Wetlands. 11:441-465.

Caterpillar Inc., 2004. Products. http://www.cat.com/cda/layout?m=37840&x=7.

Dahl, T.E., 1990. Wetlands- Losses in the United States, 1780's-1980's. US Fish and Wildlife Service Report to Congress, Washington, DC, 13 pp.

Daniels, W.L., Bergschneider, C., Fajardo, G., 2004. Soil bulk density data for Charles City Mitigation Wetland and Sandy Bottom Mitigation Wetland. Virginia Polytechnic Institute and State University. Unpublished data.

Daniels, W.L., Genther M., Whittecar G.R., Hodges B., Nagle S., 1995. Hydrogeology and Soils of Chisman Lakes Gravel Pit Wetlands Mitigation Site. Fieldtrip Guidebook, Virginia Association of Professional Soil Scientists Workshop, 31 pp.

Dunne, T., Leopold, L.B., 1978. Water in Environmental Planning. W.H. Freeman and Company, San Francisco, 818 pp.

Fetter, C.W., 2001. Applied Hydrogeology. Prentice Hall, Upper Saddle River, 598 pp.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice Hall, Englewood Cliffs, 233-234.

Germann, P.F., 1990. Macropores and hydrologic hillslope processes. *In:* M.G. Anderson and T.P. Burt (eds.) Process Studies in Hillslope Hydrology. John Wiley and Sons, Chichester, 327-363.

Griffin, R.W., Starowitz S.M., Wilding, L.P., 1998. Wetness Conditions and Redoximorphic Features in a Microtoposequence on the Texas Coast Prairie. *In:* M.C. Rabenhorst, J.C. Bell, and P.A. McDaniel (eds.) Quantifying Soil Hydromorphology. SSSA Special Publication Number 54. SSSA, Madison, WI, 151-172

Hayes, M.A., 1993. Virginia- Wetland Resources. *In:* USGS Water Supply Paper 2425, 387-392.

Hodges, R.L., Thomas, P.J., Edmonds, W.J., 1990. Supplemental Data for Soil Survey of Charles City County, Virginia. VAES Bulletin 90-3, 143 pp.

Johnson, G.H., Ward L.W., Peebles P.C., 1987. Stratigraphy and Paleontology of Pliocene and Pleistocene deposits of southeastern Virginia. *In:* G.R. Whittecar (ed.) Geological Excursions in Virginia and North Carolina. Southeastern section- GSA 36th annual meeting. Norfolk, VA.

Jones, J.A.A., 1981. The Nature of Soil Piping: a Review of Research. British Geomorphological Research Group Research Monograph Series 3. Geo Books, Norwich.

Krauskopf, K.B., Bird, D.K., 1995. Introduction to Geochemistry. McGraw-Hill, Boston, 647 pp.

Kruczynski, W.L., 1989. Mitigation and the section 404 program. *In:* J.A. Kusler, M.E. Kentula (eds.) Wetland Creation and Restoration: The Status of Science. Environmental Protection Agency, Corvallis, Oregon, 137-142.

McNamara, J.P., Kane, D.L., Hinzman, L.D., 1998. An analysis of streamflow hydrology in the Kuparuk River Basin, Artic Alaska: a nested watershed approach. J. of Hydrol. 206: 39-57.

Mitsch, W.J., Gosselink, J.G., 1986. Wetlands. Van Nostrand Reinhold Co, New York, 920 pp.

Mixon, R.B., Szabo B.J., Owens, J.P., 1982. Uranium-series dating of mollusks and corals, and age of Pleistocene deposits, Chesapeake Bay area, Virginia and Maryland. USGS paper 1067-E, 1-18.

Mixon, R.B., Berquist, C.R., Newell, W.L., Johnson, G.H., 1989. Geologic Map and Generalized Cross-Sections of the Coastal Plain and adjacent parts of the Piedmont, Virginia. USGS Map I-2033.

Peebles, P.C., Johnson G.H., Berquist C.R., 1984. The middle and late Pleistocene stratigraphy of the outer coastal plain, Southeastern Virginia. Virginia Minerals, 30:13-22.

Rheinhardt, R.D., Brinson, M.M., 2000. An Evaluation of the Effectiveness of Existing North Carolina Department of Transportation Wetland Mitigation Sites. North Carolina Department of Transportation and North Carolina State University Institute for Transportation Research and Education, Raleigh, NC.

Rheinhardt, R.D., Brinson, M.M., 2002. An Evaluation of North Carolina Department of Transportation Wetland Mitigation Sites: Selected Case Studies. North Carolina Department of Transportation and North Carolina State University Institute for Transportation Research and Education, Raleigh, NC.

Rheinhardt, R.D., Rheinhardt, M.C., Brinson, M.M., 2002. A Regional Guidebook for Applying the Hydrogeomorphic Approach to Assessing Wetland Functions of Wet Pine Flats on Minerals Soils in the Atlantic and Gulf Coastal Plains. ERDC/EL TR-02-9, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Shilts, E., 2000. Canada's Wetlands. Canadian Geographic poster.

Soil Science Society of America, 2004. www.soils.org.

Streever, B., 1999. Performance standards for wetland creation and restoration under Section 404. National Wetlands Newsletter. May/June 1999:10-13.

Sun, G., McNulty S.G., Amatya D.M., Skaggs R.W., Swift Jr. L.W., Shepard J.P., Reikerk H., 2002. A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US. J. of Hydrol. 263:92-104.

Tiner, R.W., 1999. Wetland Indicators. CRC, Boca Raton, 392 pp.

U.S. Army Corp of Engineers, 2004. Norfolk District Corps and Virginia Department of Environmental Quality Recommendations for Wetland Compensatory Mitigation:

Including Site Design, Permit Conditions, Performance and Monitoring Criteria. Norfolk, VA, 34 pp.

U.S. Army Corp of Engineers, 1987. Corps of Engineers Wetland Delineation Manual. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Whigham, D.F., 1999. Ecological issues related to wetland preservation, restoration, creation, and assessment. The Science of the Total Environment. 240:31-40.

Whittecar, G.R., Daniels W.L., 1999. Use of hydrogeomorphic concepts to design created wetlands in southeastern Virginia. Geomorphology. 31:355-371.

Woolson, R.F., Clarke, W.R., 2002. Statistical Methods for the Analysis of Biomedical Data. John Wiley and Sons, New York, 677 pp.

APPENDIX A

SOIL PERMEABILITY DATA

CCW Natural Site

Shallow Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
CCW3SR1	1	1.45	4.47	7.43	91.4	90.8	1246.65	6.88E-08		
	2	1.45	4.47	7.43	90.8	90.3	1379.2	5.22E-08		
	3	1.45	4.47	7.43	90.3	89.3	1255.6	1.16E-07	7.89E-08	3.29E-08
CCW3SR2	1	1.45	4.47	7.46	90.9	90.6	1310.35	3.30E-08		
	2	1.45	4.47	7.46	90.6	88.6	2861.73	1.02E-07		
	3	1.45	4.47	7.46	92.3	91.3	1251.5	1.14E-07	8.30E-08	4.37E-08
CCW3SR3	1	1.45	4.47	7.76	93	91.8	1044.85	1.69E-07		
	2	1.45	4.47	7.76	91.4	90.9	1418.33	5.26E-08		
	3	1.45	4.47	7.76	93.2	92.2	1444.96	1.02E-07	1.08E-07	5.85E-08

Intermediate Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
CCW3IR1	1	1.45	4.47	7.73	93	91.1	1549.9	1.81E-07		
	2	1.45	4.47	7.73	93.3	92.2	880.78	1.83E-07		
	3	1.45	4.47	7.73	93.2	92.2	1312.85	1.11E-07	1.58E-07	4.05E-08
CCW3IR2	1	1.45	4.47	7.79	95.1	94	1042.55	1.52E-07		
	2	1.45	4.47	7.79	95	93.9	1326	1.20E-07		
	3	1.45	4.47	7.79	95.5	94.6	1625.77	7.96E-08	1.17E-07	3.65E-08
CCW3IR3	1	1.45	4.47	7.53	95.3	94.3	1427.83	9.76E-08		
	2	1.45	4.47	7.53	94.9	94	1566.78	8.03E-08		
	3	1.45	4.47	7.53	95.3	93.7	1520.68	1.47E-07	1.08E-07	3.46E-08

Deep Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
CCW3DR1	1	1.45	4.47	5.02	94.9	94.2	1720.95	3.79E-08		
	2	1.45	4.47	5.02	95.6	95.1	1166.93	3.96E-08		
	3	1.45	4.47	5.02	95.1	94	1434.98	7.14E-08	4.96E-08	1.89E-08
CCW3DR2	1	1.45	4.47	7.7	95.5	95	1491.73	4.75E-08		
	2	1.45	4.47	7.7	95	94	1225.1	1.17E-07		
	3	1.45	4.47	7.7	94	93.6	1484.73	3.88E-08	6.76E-08	4.27E-08
CCW3DR3	1	1.45	4.47	7.69	94.6	93.3	1485.25	1.26E-07		
	2	1.45	4.47	7.69	93.3	92.1	1699.43	1.03E-07		
	3	1.45	4.47	7.69	92.1	91.2	2814.53	4.71E-08	9.18E-08	4.04E-08

SOIL PERMEABILITY DATA (continued)

CCW Constructed Site

Shallow Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
CCW1SR1	1	1.45	4.47	7.65	93.5	83.8	1.13E+03	1.30E-06		
	2	1.45	4.47	7.65	90.2	88.8	1.41E+03	1.49E-07		
	3	1.45	4.47	7.65	92.1	89.8	1.47E+03	2.31E-07	5.59E-07	6.40E-07
CCW1SR2	1	1.45	4.47	7.5	91.8	90	1.00E+03	2.60E-07		
	2	1.45	4.47	7.5	90	89.5	1.48E+03	4.96E-08		
	3	1.45	4.47	7.5	92.5	90.3	1.59E+03	1.99E-07	1.69E-07	1.08E-07
CCW1SR3	1	1.45	4.47	7.48	92.5	90.7	1.34E+03	1.92E-07		
	2	1.45	4.47	7.48	91.5	91.1	1.46E+03	3.94E-08		
	3	1.45	4.47	7.48	91.1	90	5.27E+02	3.03E-07	1.78E-07	1.32E-07

Intermediate Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
CCW1IR1	1	1.45	4.47	7.55	89.8	88.4	1.32E+03	1.57E-07		
	2	1.45	4.47	7.55	91.3	90.8	1.46E+03	4.97E-08		
	3	1.45	4.47	7.55	90.8	90.5	1.31E+03	3.35E-08	8.01E-08	6.72E-08
CCW1IR2	1	1.45	4.47	7.61	93.4	92.2	1.30E+03	1.33E-07		
	2	1.45	4.47	7.61	93.3	89.4	2.99E+03	1.90E-07		
	3	1.45	4.47	7.61	92.4	91	1.16E+03	1.75E-07	1.66E-07	2.97E-08
CCW1IR3	1	1.45	4.47	7.76	91	83.8	1.33E+03	8.43E-07		
	2	1.45	4.47	7.76	92.2	86.1	1.33E+03	6.99E-07		
	3	1.45	4.47	7.76	92	86.8	1.47E+03	5.38E-07	6.93E-07	1.52E-07

Deep Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
CCW1DR1	1	1.45	4.47	7.52	91.3	90.7	1.29E+03	6.73E-08		
	2	1.45	4.47	7.52	92.8	91.2	1.27E+03	1.80E-07		
	3	1.45	4.47	7.52	92.4	91.3	1.26E+03	1.25E-07	1.24E-07	5.64E-08
CCW1DR2	1	1.45	4.47	7.8	91.2	90.1	1.41E+03	1.18E-07		
	2	1.45	4.47	7.8	92.3	91.3	1.43E+03	1.04E-07		
	3	1.45	4.47	7.8	92.4	91.7	1.43E+03	7.27E-08	9.83E-08	2.33E-08
CCW1DR3	1	1.45	4.47	7.82	93	92.2	1.01E+03	1.18E-07		
	2	1.45	4.47	7.82	93	91.4	1.50E+03	1.58E-07		
	3	1.45	4.47	7.82	91.4	90.8	1.40E+03	6.44E-08	1.14E-07	4.71E-08

SOIL PERMEABILITY DATA (continued)

SBNP Natural Site

Shallow Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
SB213SR1	1	1.45	4.47	7.58	94.1	73.4	9.97E+00	3.31E-04		
	2	1.45	4.47	7.58	94.6	82.9	1.15E+01	1.52E-04		
	3	1.45	4.47	7.58	93.5	81.3	1.10E+01	1.69E-04	2.17E-04	9.89E-05
SB213SR2	1	1.45	4.47	7.52	93.7	73.9	1.03E+01	3.04E-04		
	2	1.45	4.47	7.52	93.6	66.3	1.45E+01	3.14E-04		
	3	1.45	4.47	7.52	95.3	67.3	1.43E+01	3.21E-04	3.13E-04	8.60E-06
SB213SR3	1	1.45	4.47	7.45	93.4	88	1.89E+01	4.11E-05		
	2	1.45	4.47	7.45	93	87.1	2.44E+01	3.52E-05		
	3	1.45	4.47	7.45	94.2	90	1.54E+01	3.88E-05	3.83E-05	2.98E-06

Intermediate Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
SB213IR1	1	1.45	4.47	5.2						
	2	1.45	4.47	5.2						
	3	1.45	4.47	5.2						
SB213IR2	1	1.45	4.47	7.67	92.5	35.2	1.25E+03	3.53E-06		
	2	1.45	4.47	7.67	90.1	78.9	1.11E+02	5.48E-06		
	3	1.45	4.47	7.67	91.8	85.1	7.34E+01	4.72E-06	4.57E-06	9.82E-07
SB213IR3	1	1.45	4.47	7.56	90.4	77.9	2.01E+02	3.44E-06		
	2	1.45	4.47	7.56	92.6	90.4	8.09E+01	1.38E-06		
	3	1.45	4.47	7.56	90.4	83.6	2.12E+02	1.71E-06	2.18E-06	1.11E-06

Deep Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
SB213DR1	1	1.45	4.47	7.66	92.2	85.9	1.21E+03	2.67E-07		
	2	1.45	4.47	7.66	93.4	92.2	1.68E+02	3.52E-07		
	3	1.45	4.47	7.66	93.6	88.2	1.12E+03	2.42E-07	2.87E-07	5.75E-08
SB213DR2	1	1.45	4.47	5.73	94.2	82.3	1.59E+03	5.20E-07		
	2	1.45	4.47	5.73	93.6	82.4	1.52E+03	5.14E-07		
	3	1.45	4.47	5.73	93.8	83.4	1.23E+03	5.84E-07	5.40E-07	3.87E-08
SB213DR3	1	1.45	4.47	7.5	87.5	83.2	1.06E+03	2.22E-07		
	2	1.45	4.47	7.5	91.7	86.4	1.23E+03	2.27E-07		
	3	1.45	4.47	7.5	86.4	85.1	4.01E+02	1.77E-07	2.08E-07	2.77E-08

SOIL PERMEABILITY DATA (continued)

SBNP Constructed Site

Shallow Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
SB2SR1	1	1.45	4.47	7.37	92.5	79.9	6.56E+01	2.89E-05		
	2	1.45	4.47	7.37	92.3	77.6	7.38E+01	3.04E-05		
	3	1.45	4.47	7.37	92.3	78.7	7.13E+01	2.89E-05	2.94E-05	8.83E-07
SB2SR2	1	1.45	4.47	7.28	92.3	69.5	5.68E+01	6.38E-05		
	2	1.45	4.47	7.28	92.3	65.8	5.16E+01	8.37E-05		
	3	1.45	4.47	7.28	92.8	71	5.60E+01	6.10E-05	6.95E-05	1.24E-05
SB2SR3	1	1.45	4.47	7.31	92.8	91.3	7.25E+01	2.88E-06		
	2	1.45	4.47	7.31	93.3	91.8	6.56E+01	3.17E-06		
	3	1.45	4.47	7.31	92.7	91.8	4.64E+01	2.69E-06	2.91E-06	2.39E-07

Intermediate Sample ID	Trial #	*A* (cm^2)	*L* (cm)	*h* (cm)	*V* (cm^3)	*t* (s)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
SB2IR1	1	15.69	7.31	28.8	92.5	301	4.97E-03		
	2	15.69	7.31	28.8	107.5	331.75	5.24E-03		
	3	15.69	7.31	28.8	93	278.75	5.40E-03	5.20E-03	2.15E-04
SB2IR2	1	15.69	7.35	28.8	76.2	120.78	1.03E-02		
	2	15.69	7.35	28.8	83.5	160.19	8.48E-03		
	3	15.69	7.35	28.8	66.5	143.46	7.54E-03	8.76E-03	1.38E-03
SB2IR3	1	15.69	7.28	28.8	63.1	143.03	7.11E-03		
	2	15.69	7.28	28.8	51	154.1	5.33E-03		
	3	15.69	7.28	28.8	42	299.9	2.26E-03	4.90E-03	2.45E-03

Deep Sample ID	Trial #	*dt* (cm)	*dc* (cm)	*L* (cm)	*ho* (cm)	*h* (cm)	*t* (min)	*K* (cm s^{-1})	AVG (cm s^{-1})	SD (cm s^{-1})
SB2SR1	1	1.45	4.47							
	2	1.45	4.47							
	3	1.45	4.47							
SB2SR2	1	1.45	4.47	7.7	94	71.9	7.53E+01	4.81E-05		
	2	1.45	4.47	7.7	93.4	78	6.03E+01	4.03E-05		
	3	1.45	4.47	7.7	90.9	66.9	1.10E+02	3.77E-05	4.20E-05	5.39E-06
SB2SR3	1	1.45	4.47	7.64	94.2	92.8	1.49E+03	1.35E-07		
	2	1.45	4.47	7.64	92.8	90.8	3.09E+03	9.45E-08		
	3	1.45	4.47	7.64	90.8	90.4	1.20E+03	4.91E-08	9.28E-08	4.28E-08

SOIL PERMEABILITY DATA (continued)

Average Permeability Values for CCW and SBNP natural and constructed sites

Sample ID	Mean ($cm\ s^{-1}$)	Standard Deviation ($cm\ s^{-1}$)
CCW-3 Shallow	8.99E-08	4.23E-08
CCW-3 Intermediate	1.28E-07	3.97E-08
CCW-3 Deep	6.97E-08	3.59E-08
CCW-1 Shallow	3.02E-07	3.83E-07
CCW-1 Intermediate	3.13E-07	3.00E-07
CCW-1 Deep	1.12E-07	4.02E-08
213 Shallow	1.90E-04	1.31E-04
213 Intermediate	3.38E-06	1.61E-06
213 Deep	3.45E-07	1.54E-07
SB-2 Shallow	3.39E-05	2.97E-05
SB-2 Intermediate	6.29E-03	2.33E-03
SB-2 Deep	2.11E-05	2.32E-05

APPENDIX B

SOIL PERMEABILITY STATISTICAL DATA

Mann Whitney Test Results for CCW

Sample 1 from CCW-3 Surface
Sample 2 from CCW-1 Surface

Two-sample Mann-Whitney rank sum test (2-sided)
Null hypothesis: The medians of the
two populations are equal.
Significance level: 0.05
Calculated statistic: U = 101
Corresponding P value for
sample sizes 11 and 11: P = 0.00663
***Inference*: The two medians are**
significantly different .
Reason: $P < 0.05$

Sample 1 from CCW-3 Intermediate
Sample 2 from CCW-1 Intermediate

Two-sample Mann-Whitney rank sum test (2-sided)
Null hypothesis: The medians of the
two populations are equal.
Significance level: 0.05
Calculated statistic: U = 92
Corresponding P value for
sample sizes 11 and 11: P = 0.04
***Inference*: The two medians are**
significantly different .
Reason: $P < 0.05$

Sample 1 from CCW-3 Deep
Sample 2 from CCW-1 Deep

Two-sample Mann-Whitney rank sum test (2-sided)
Null hypothesis: The medians of the
two populations are equal.
Significance level: 0.05
Calculated statistic: U = 94
Corresponding P value for
sample sizes 11 and 11: P = 0.0281
***Inference*: The two medians are**
significantly different .
Reason: $P < 0.05$

SOIL PERMEABILITY STATISTICAL DATA (continued)

Mann Whitney Test Results for SBNP

Sample 1 from 213 Surface
Sample 2 from SB-2 Surface

Two-sample Mann-Whitney rank sum test (2-sided)
Null hypothesis: The medians of the
two populations are equal.
Significance level: 0.05
Calculated statistic: U = 112
Corresponding P value for
sample sizes 11 and 11: P = 0.000275
***Inference*: The two medians are
significantly different .**
Reason: P < 0.05

Sample 1 from 213 Intermediate
Sample 2 from SB-2 Intermediate

Two-sample Mann-Whitney rank sum test (2-sided)
Null hypothesis: The medians of the
two populations are equal.
Significance level: 0.05
Calculated statistic: U = 88
Corresponding P value for
sample sizes 8 and 11: P = 2.65e-005
***Inference*: The two medians are
significantly different .**
Reason: P < 0.05

Sample 1 from 213 Deep
Sample 2 from SB-2 Deep

Two-sample Mann-Whitney rank sum test (2-sided)
Null hypothesis: The medians of the
two populations are equal.
Significance level: 0.05
Calculated statistic: U = 55
Corresponding P value for
sample sizes 11 and 8: P = 0.395
***Inference*: No significant evidence
for different median values.**
Reason: P > 0.05

SOIL PERMEABILITY STATISTICAL DATA (continued)

CCW-3

Kruskal-Wallis test
Null hypothesis: The groups all come from
the same population (there is no group effect).
Significance level: 0.05
Kruskal-Wallis statistic: 6.787
Corresponding P value for
chi-square with 2 degrees of freedom:
P = 0.0336
Inference: Reject null hypothesis.
Reason: P < 0.05

Comparison	Difference in Mean Ranks	First Group Mean Rank	Second Group Mean Rank	Q Observed	Q Critical	Inference
I vs D	9.555556	19.333333	9.777778	3.611661	3.31	Reject null hypothesis: P<=0.05
I vs S	6.444444	19.333333	12.888889	2.435771	2.77	Fail to reject null hypothesis: P>0.05
S vs D	3.111111	12.888889	9.777778	1.175889	2.77	Fail to reject null hypothesis: P>0.05

CCW-1

Kruskal-Wallis test
Null hypothesis: The groups all come from
the same population (there is no group effect).
Significance level: 0.05
Kruskal-Wallis statistic: 3.908
Corresponding P value for
chi-square with 2 degrees of freedom:
P = 0.1417
Inference: Fail to reject null hypothesis.
Reason: P > 0.05
No pairwise comparisons made.

SOIL PERMEABILITY STATISTICAL DATA (continued)

213

Kruskal-Wallis test
Null hypothesis: The groups all come from
the same population (there is no group effect).
Significance level: 0.05
Kruskal-Wallis statistic: 20.25
Corresponding P value for
chi-square with 2 degrees of freedom:
P = 0.0001
Inference: Reject null hypothesis.
Reason: P < 0.05

Comparison	Difference in Mean Ranks	First Group Mean Rank	Second Group Mean Rank	Q Observed	P Value	Inference
S vs D	15	20	5	4.5	0.0003	Reject null hypothesis: P<=0.01
S vs I	7.5	20	12.5	2.012461	0.1326	Fail to reject null hypothesis: P>0.05
I vs D	7.5	12.5	5	2.012461	0.1326	Fail to reject null hypothesis: P>0.05

SB-2

Kruskal-Wallis test
Null hypothesis: The groups all come from
the same population (there is no group effect).
Significance level: 0.05
Kruskal-Wallis statistic: 16.65
Corresponding P value for
chi-square with 2 degrees of freedom:
P = 0.0002
Inference: Reject null hypothesis.
Reason: P < 0.05

Comparison	Difference in Mean Ranks	First Group Mean Rank	Second Group Mean Rank	Q Observed	P Value	Inference
I vs D	13.5	20	6.5	3.62243	0.0009	Reject null hypothesis: P<=0.01
I vs S	11	20	9	3.3	0.003	Reject null hypothesis: P<=0.01
S vs D	2.5	9	6.5	0.67082	0.999	Fail to reject null hypothesis: P>0.05

APPENDIX C

BIWEEKLY CCW AND SBNP PIEZOMETER WATER LEVEL DATA

CCW Natural Data

Date	CCP-3A	CCP-3B	CCP-3C
7/17/2003		8.47	8.38
7/23/2003	9.70	8.61	9.05
8/4/2003	9.64	8.96	9.21
8/13/2003	9.67	9.06	9.17
8/29/2003	9.38	8.50	8.55
10/4/2003	9.45	9.03	9.06
11/1/2003	9.45	8.73	9.10
11/22/2003	9.61	9.10	9.29
1/10/2004	9.63	9.35	9.28
1/24/2004	9.61	9.36	9.31
2/7/2004	9.65	9.37	9.36
2/21/2004	9.63	9.42	9.40
3/8/2004	9.61	9.36	9.32
3/11/2004	9.61	9.36	9.27
3/31/2004	9.56	9.36	9.33
4/7/2004	9.59	9.35	9.31
4/14/2004	9.67	9.38	9.32
4/28/2004	9.62	9.32	9.28
5/11/2004	9.37	9.24	9.13
5/29/2004		8.48	8.22
6/17/2004	9.51	8.39	8.70
7/3/2004	9.41	8.63	9.10

BIWEEKLY CCW AND SBNP PIEZOMETER WATER LEVEL DATA (continued)

CCW Constructed Data

Date	CCP-1A	CCP-1B	CCP-1C	CCP-2A	CCP-2B	CCP-2C	CCP-4B	CCP-4C	CCP-5C
1/2/2003	9.88	9.70			9.77				
1/17/2003	9.04	8.95			8.26				
2/28/2003	9.18	9.13		8.67	8.42				
3/22/2003	9.13	9.12		8.76	8.42				
4/3/2003	9.00	9.05		8.83	8.54				
4/11/2003	9.12	9.16		8.83	8.44				
4/18/2003		8.92		8.85	8.49				
5/1/2003	8.93	8.71		8.88	8.41				
5/6/2003	9.08	8.84		8.90	8.47				
5/13/2003	8.86	8.28		8.67	8.28				
5/16/2003		8.13		8.91	8.20				
5/30/2003	9.18	9.14		8.93	8.52				
6/12/2003	9.28	8.88		8.94	8.56				
6/23/2003	9.18	8.88		9.04	8.60				
7/2/2003	9.12	8.87		8.92	8.46				
7/10/2003		8.33		8.90	8.45				
7/17/2003		8.05	7.79		8.26	8.39			
7/23/2003	9.21	9.15	8.86	9.13	8.61	8.55			
8/4/2003	9.15	9.12	9.13	9.13	8.37	8.68			
8/13/2003	9.19	9.13	8.84	9.16	8.71	8.69			
8/29/2003	8.97	8.62	8.38	9.01	8.41	8.49			
10/4/2003	8.96	8.76	8.52	9.07	8.55	8.54			
11/1/2003	9.14	9.10	8.81	9.16	8.02	8.03			
11/22/2003	9.18	9.13	8.85		8.29	9.36			
12/7/2003	9.19	9.13	8.87	9.17	8.39	8.47			
1/10/2004	9.05	9.02	8.79		8.68	8.64			
1/24/2004	9.11	9.06	8.78	9.16	8.56	8.68			
2/7/2004	9.21	9.16	8.90	9.17	8.63	8.84			
2/21/2004	9.13	9.09	8.83	9.17	8.73	8.88			
3/11/2004	9.10	9.05	8.75	9.13	8.46	8.56			
3/31/2004		8.60	8.31	9.10	8.47	8.58			
4/7/2004		8.80	8.56	9.13	8.51	8.56			
4/14/2004	9.21	9.17	8.88	9.14	8.50	8.57			
4/28/2004		9.08	8.80	9.16	8.55	8.62			
5/11/2004		8.69	8.41	9.09	8.47	8.56			
5/28/2004		8.93	8.63	9.13	8.83	8.34	8.38	7.43	7.70
6/17/2004	9.20	9.17	8.87	9.14	8.74	8.55	8.63	8.11	8.74
7/3/2004		9.00	8.73	9.13	8.72	8.61	8.67	8.24	8.82

BIWEEKLY CCW AND SBNP PIEZOMETER WATER LEVEL DATA (continued)

SBNP Natural Data

Date	201-SP	201-DP	213-SP	213-DP
4/3/2003	6.55	6.54	6.85	6.63
4/13/2003	6.71	6.72	7.00	6.80
4/18/2003	6.63	6.63	6.93	6.73
4/29/2003	6.55	6.54	6.87	6.66
5/7/2003	6.39	6.37	6.67	6.50
5/16/2003		6.00		6.18
5/23/2003		6.26	6.78	6.44
5/30/2003		6.17		6.43
6/5/2003		6.00		6.27
6/12/2003		5.85		6.12
6/24/2003		5.73		6.06
7/3/2003		5.38		5.65
7/10/2003		5.15		5.45
7/18/2003		5.02		5.37
8/1/2003		5.50		5.63
10/4/2003	6.45	6.43	6.73	6.56
11/1/2003	6.53	6.53	6.83	6.64
11/22/2003	6.54	6.55	6.89	6.69
12/11/2003	6.57	6.58	6.93	6.70
1/10/2004	6.46	6.47	6.82	6.62
1/24/2004	6.35	6.36	6.79	6.58
2/7/2004	6.59	6.59	6.96	6.70
2/21/2004	6.52	6.52	6.87	6.66
3/11/2004		6.67	6.82	6.59
4/2/2004	6.25	6.26	6.78	6.56
4/14/2004	6.42	6.42	6.90	6.64
5/11/2004		5.89		6.23
5/29/2004		5.47		5.89
6/17/2004		5.45		6.09
7/3/2004		5.43		5.73

BIWEEKLY CCW AND SBNP PIEZOMETER WATER LEVEL DATA
(continued)

SBNP Constructed Data

Date	SB-1A	SB-1B	SB-1C	SB-2A	SB-2B	SB-2C
1/10/2004	6.89	6.71		6.92	6.79	
1/24/2004	6.80	6.74	6.69	6.64	6.79	5.94
2/7/2004	7.03	6.93	7.06	6.99	7.05	6.52
2/21/2004	6.93	6.94	7.04	6.84	7.06	6.83
3/11/2004	6.81	6.68	6.97	6.73	6.75	6.76
4/2/2004	6.77	6.52	6.92	6.61	6.80	6.67
4/14/2004	6.96	6.64	6.90	6.71	6.86	6.63
5/11/2004		6.42	6.87		6.72	6.66
5/29/2004		6.34	6.83		6.48	6.52
6/17/2004		6.29	6.77		6.45	6.38
7/3/2004		6.27	6.73		6.34	6.26

APPENDIX D
PRECIPITATION RESPONSE DATA

CCW Natural Site

CCP-3A	T_{r1} (h)	T_{r2} (h)	T_{r3} (h)	T_{lp} (h)	R_h (m)
4/10/2004	1	-1	9	7	0.11
4/26/2004	0	0	14	11	0.15
5/2/2004	1	-10	13	6	0.15
5/22/2004	*	1	4	3	*
5/26/2004	*	-2	2	1	*
Mean	0.67	-2.40	8.40	5.60	0.14

CCP-3B	T_{r1} (h)	T_{r2} (h)	T_{r3} (h)	T_{lp} (h)	R_h (m)
4/10/2004	4	12	14	12	0.19
4/26/2004	2	17	22	19	0.02
Mean	3.00	14.50	18.00	15.50	0.11

CCW Constructed Site

CCP-1A	T_{r1} (h)	T_{r2} (h)	T_{r3} (h)	T_{lp} (h)	R_h (m)
4/10/2004	3	-1	9	7	0.25
4/26/2004	1	1	15	12	0.21
5/2/2004		-4	19	12	
5/22/2004	0	-1	2	1	0.07
5/26/2004	1	0	4	3	0.14
Mean	1.25	-1.00	9.80	7.00	0.17

CCP-1B	T_{r1} (h)	T_{r2} (h)	T_{r3} (h)	T_{lp} (h)	R_h (m)
4/10/2004	2	16	18	16	0.66
4/26/2004	1	3	17	14	0.51
5/2/2004	2	-4	19	12	0.40
5/22/2004	0	4	7	6	0.89
5/26/2004	1	7	11	10	0.46
Mean	1.20	5.20	14.40	11.60	0.58

PRECIPITATION RESPONSE DATA (continued)

SBNP Natural Site

213-SP	T_{r1} (h)	T_{r2} (h)	T_{r3} (h)	T_{lp} (h)	R_h (m)
4/10/2004	4	-3	18	9	0.04
4/12/2004	3	53	46	35	0.17
4/14/2004	2	2	18	9	0.04
4/26/2004	0	2	14	13	0.25
5/3/2004	*	0	14	12	*
Mean	2.25	13.50	22.00	15.60	0.12

213-DP	T_{r1} (h)	T_{r2} (h)	T_{r3} (h)	T_{lp} (h)	R_h (m)
4/10/2004	1	*	*	*	*
4/12/2004	*	60	54	43	0.15
4/14/2004	2	2	18	9	0.02
4/26/2004	1	11	23	22	0.15
5/3/2004	2	21	35	33	*
5/19/2004	5	38	44	40	0.37
5/25/2004	2	15	17	17	0.06
Mean	2.17	24.50	31.83	27.33	0.15

SBNP Constructed Site

SB-2A	T_{r1} (h)	T_{r2} (h)	T_{r3} (h)	T_{lp} (h)	R_h (m)
4/12/2004	39	55	96	85	0.18
4/14/2004	1	42	18	9	0.04
5/25/2004	*	15	17	17	*
Mean	20.00	37.33	43.67	37.00	0.11

* indicates no value was able to be calculated.

APPENDIX E

CCW AND SBNP CONSTRUCTED SITES BULK DENSITY DATA

Charles City Mitigation Wetland Bulk Density Averages				Sandy Bottom Mitigation Wetland Bulk Density Averages			
Surface	Average	Deep	Average	Surface	Average	Deep	Average
1	1.50	1	1.69	1	1.82	1	1.59
2	1.49	2	1.66	3	1.88	3	1.90
3	1.48	3	1.66	4	1.88	4	1.73
4	1.24	4	1.55	5	1.82	5	1.99
5	1.47	5	1.47	6	1.82	6	2.08
6	1.61	6	1.64	7	1.76	7	2.09
7	1.34	7	1.52	8	1.76	8	1.97
8	1.39	8	1.65	9	1.82	9	1.83
9	1.40	9	1.54	10	1.84	10	1.84
10	1.31	10	1.46	Overall	1.82	Overall	1.89
Overall	1.42	Overall	1.58				

Surface= 5 cm
Deep = 30 cm

APPENDIX F

UTM COORDINATES OF CCW AND SBNP PIEZOMETER NESTS

CCW	Latitude	Longitude
CCP-1	N 37° 20.633	W 76° 55.612
CCP-2	N 37° 20.616	W 76° 55.564
CCP-3	N 37° 20.416	W 76° 55.567
CCP-4	N 37° 20.608	W 76° 55.551
CCP-5	N 37° 20.648	W 76° 55.609

SBNP	Latitude	Longitude
201	N 37° 3.791	W 76° 25.703
213	N 37° 3.774	W 76° 26.313
SB-1	N 37° 4.620	W 76° 26.315
SB-2	N 37° 4.179	W 76° 26.307

VITAE

Aaron Dyer Despres received his B.A. from The University of Maine at Farmington in 2001 where he majored in Environmental Science and Geology/Chemistry. In August 2002, he began working on his M.S. in Geology at Old Dominion University, 4600 Elkhorn Avenue, Norfolk, VA, 23505. While at O.D.U., Aaron worked as a graduate teaching assistant during the academic year and as a graduate research assistant during the summer months. Aaron completed his M.S. in Geology in December 2004.