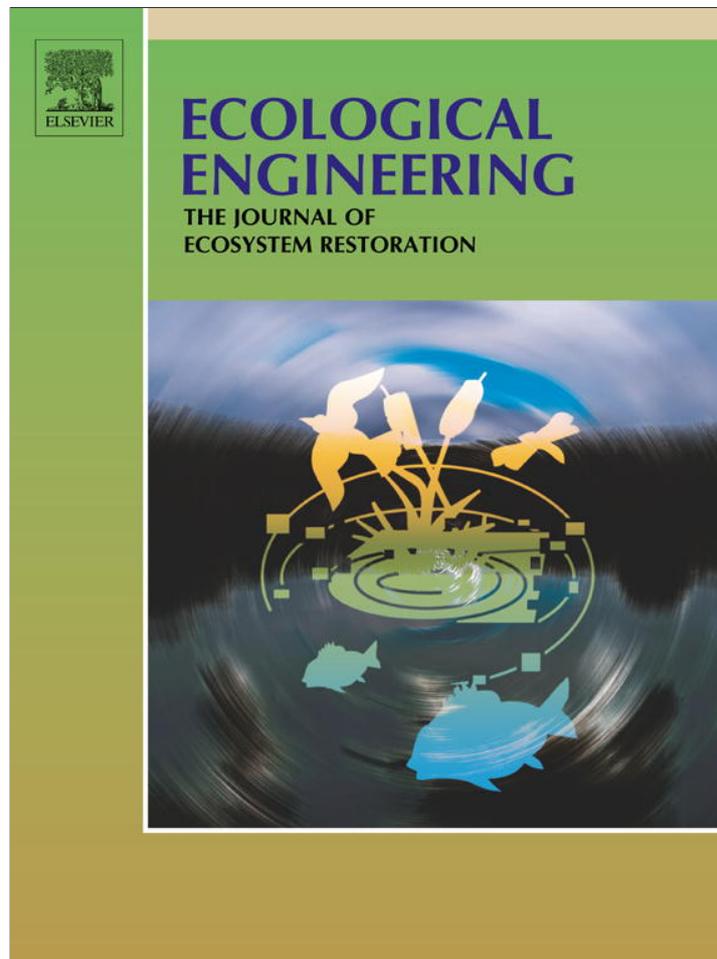


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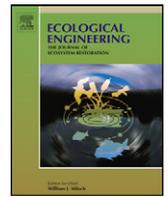
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Alteration of soil hydraulic properties during the construction of mitigation wetlands in the Virginia Piedmont

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ABSTRACT

Wetland hydrology is a critical component to the success of mitigation projects. The alteration of soil hydraulic properties during the construction may influence the hydrology of the wetland, thus affecting the mitigation success. We studied disturbed (i.e. by construction) and nondisturbed areas of two wetland mitigation banks (Blackjack, BJ and Peters Farm, PF), both located in the piedmont region of Virginia, for a variety of soil hydraulic and physicochemical properties. The surface soil horizon at BJ showed an increase in clay content from 18.6 to 40%, decrease in bulk density (D_b) from 1.56 to 1.45 g/cm³, decrease the drained volume (D_v) of water in the soil profile from 0.67 to 0.36 cm, decrease in available water content (AWC) from 22.7 to 15.8%, and a reduction in the ratio of AWC to TPS from 66 to 40%. Soil at PF showed an increase in clay content in the surface horizon from 20 to 30%, increase TPS from 37.2 to 40.0%, increase D_b from 1.52 to 1.67 g/cm³, increase the D_v in the soil profile from 3.5 to 6.6 cm, increase in AWC from 37.2 to 40.2%, and a decrease in the ratio of AWC to TPS from 58 to 44% in the surface horizon. The outcome showed that the impacts of common construction practices for mitigation wetlands affected drainable and plant available subsurface water storage, more so in fine grained soils. Key soil hydraulic properties should be considered in the disturbed or ameliorated state before water budgets are constructed to model wetland hydrology. Further studies are needed to investigate how the plant available and drainable water contents can be affected by construction practices in various soil textures, and how these properties might change in the long term.

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1. Introduction

According to the National Mitigation Banking Association (NMBA), as of January 2010, there are over 950 wetland mitigation banks within the United States of America (USA) approved by the U.S. Army Corps of Engineers (USACE) or the U.S. Environmental Protection Agency (USEPA), totaling more than 950,000 acres of wetlands (<http://www.mitigationbanking.org>, accessed November 27, 2011). The goal of the no-net-loss wetland mitigation policy has been reported generally unsuccessful in meeting the performance criteria legally mandated (National Research Council, 2001). Mitigation wetlands are often constructed with little attention to the relationship between soil structure, soil water storage, and the resulting water table which controls plant community development. Consequently, many wetland mitigation projects have been described as “too wet” or “too dry” for proper vegetation development (Whittecar and Daniels, 1999). These created and restored

mitigation wetlands have, in fact, been shown to differ from comparable natural wetlands in their hydrology (Confer and Niering, 1992; Shaffer et al., 1999; Cole and Brooks, 2000).

The wetland construction process commonly involves soil disturbance including the mass grading of the local landscape with substantial stockpiling and redistribution of the upper soil horizons (Clewel and Lea, 1990; Stolt et al., 2000; Bruland and Richardson, 2005). Soil disturbance can include compaction and the vertical integration of soil horizons and regolith which results in new soil textures and D_b values (Stolt et al., 2001). The loss of macrostructure and an increase in clay content can change the way water is held within the soil matrix (McIntyre, 1974), which in turn may alter the water budget of a constructed wetland (Pierce, 1993). Campbell et al. (2002) found that soils within created wetlands contained less organic matter, increased rock fragments and a greater D_b . Cole and Brooks (2000) found that the median depth to water table was much deeper in natural wetlands compared to created wetlands where the water table was more frequently in the root zone. Long term ponding is common in created wetlands where compaction removes all macro structure within the soil matrix.

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Changes to soil hydraulic properties as a result of the wetland construction process are similar to those documented during timber harvesting in the southeast United States (Sun et al., 2001) where they found that the water tables observed post-timber harvest were significantly elevated in both wetland and upland areas due to a reduction in macro-pore space. This resulted in a lower pore volume required to fill and drain; additionally there were no trees post-harvest to consume the water. Aust et al. (1995) found that compaction by rutting reduced 60% of the free gravitational water from the macro-pore space. The macro-pore space was reduced by 80% in traffic areas with a tenfold reduction in saturated hydraulic conductivity (K_{sat}) in the rutted areas (Aust et al., 1995). Xu et al. (2002) found an increase in D_b , reduced K_{sat} , and reduced macropore and TPS within the soil matrix after harvesting operations. Timber harvest operations turned out to affect the soil water characteristic curves (SWCC) of organic soils within the upper 60 cm (Grace et al., 2006), resulting in less drainable water and a reduction in the AWC. The SWCC is a series of water content measurements at different hydraulic head measurements ($-cm$ suction). The information contained within the SWCC can be used to partition the TPS volume of the soil matrix into a drainable water component which is important to maintain regulatory hydrologic success standards, and the plant available water component which is also critical for proper plant community establishment. The best way to understand water table drawdown processes as a result of evaporation or drainage within a constructed wetland soil profile is to create and understand the specific SWCC from the construction site. While many studies have investigated the SWCC in regards to timber harvesting and agricultural production, no studies have yet investigated the impacts that the construction process may have on the SWCC of created mitigation wetland soils.

Jurisdictional wetland hydrology success criteria have been defined as a free (drainable) water table within the upper 30 cm of the soil profile for at least 14 consecutive days during the growing season (USACE, 2010). Regional agreements between the Federal Government and individual states can increase this tolerance upwards to 12.5% of the growing season (Environmental Laboratory, 1987; USACE and VADEQ, 2004). This performance standard in conjunction with the local growing season duration forces wetland designers to take a conservative approach to water budgets resulting in a design that promotes long durations of inundation or soil saturation after average rainfall events. This behavior standardizes the hydrologic regime of the constructed wetland regardless of the intended plant community or habitat type so that jurisdictional requirements are ensured in a majority of years (>50%). A change in macro-pore space and soil texture can directly influence the SWCC and affects the water budget by changing the volume of drainable and plant available water in the soil matrix.

Bottomland forested wetlands commonly found in the mid-Atlantic and southeast United States have a hydrologic regime characterized by high water tables or prolonged inundation of water above the surface during the late fall, winter and early spring seasons, followed by a natural draw down below the surface during the growing seasons (Mitsch and Gosselink, 2007; Tiner, 1999). Most bottomland hardwood species that are commonly planted in created wetlands become stressed or die when long durations of inundation or near-surface saturation occur during the growing season (Hook, 1984; Melichar et al., 1983; Teskey and Hinckley, 1977; Vreugdenhil et al., 2006). Predicting the drainable and plant available water within a soil profile requires the detailed construction of the SWCC with water content measurements in the 0–100 cm range of pressure as well as the high end suctions experienced at the wilting point (WP) ($-15,000$ cm) (McIntyre, 1974).

This study investigated and compared soil properties, including D_b , TPS, soil organic matter (SOM), particle-size distribution

(PSD) or soil texture, lateral saturated hydraulic conductivity (K_{satL}) and vertical saturated hydraulic conductivity (K_{satV}), and the soil water characteristic curve (SWCC), from two areas, one disturbed by construction and the other not, at two different mitigation bank wetlands created in the Piedmont region of Virginia. The main question of this study is what extent do common construction practices impact soil properties at proposed restoration areas which in their undisturbed state were used to model the post-construction wetland hydrology. The study focused on soil properties that are critical in predicting the hydrologic characteristics of mitigation wetlands.

2. Materials and methods

2.1. Site descriptions

The study sites were chosen because both provide forested wetland mitigation credits within the Culpeper Basin rift formation of the Piedmont physiographic province. Each site contains areas that represent the preconstruction, nondisturbed soil conditions (the foundation for the wetland design and associated water budgets). Additionally the study sites provide an opportunity to investigate and compare the impact that construction practices have on soil water relationships in two dramatically different soil textures, one with high clay content and the other which is dominated by sands and silts.

The Blackjack Wetland Mitigation Bank (BJ) study site ($38^{\circ}35'23.86''N$, $77^{\circ}38'27.37''W$) was constructed in the headwater of the drainage catchment area of Summerduck Run, on the toe-slope of a weathering diabase intrusion known as Mount Pony (Fig. 1). The study site is located approximately 8.9 km southeast of the Town of Culpeper, Virginia. Soils are primarily associated with the Waxpool series (*fine, smectitic, mesic Aeric Epiaqualfs*), a shrink-swelling clay soil that is listed as hydric and occasionally ponded (USDA-SCS, 1952). Smectite clays are classified as a 2:1 clay mineral where an octahedral hydroxide sheet is sandwiched between two tetrahedral silica sheets (Gardiner and Miller, 2004). The hydrogen bonds between the silica and hydroxide sheets will accept water and hold the water between the sheets thereby swelling when saturated and shrinking when dry. Weathered saprolite and decomposing bedrock exists below the clay-rich subsoil horizon.

A majority of the study site was dominated by mature canopy to subcanopy-sized (>30–50 years old) hardwood and pine species before construction activities initiated. Evidence of historic silvicultural management (scattered trails, overgrown row-planted pine beds, staging areas, depressions, scrapes and rutting) was observable within the undeveloped components of the property. Land use within the region is either in silvicultural production, soybean/corn crops, or cattle grazing. Soil pits excavated throughout the property before construction identified two dominant horizons; a thin, coarse-textured upper layer and a thick, clay rich bottom horizon. These horizons were validated by supplemental soil auger tests bores of the nondisturbed study area which identified a uniform soil texture and horizon break approximately 25.4 cm below the surface which reflects a historic plow horizon from prior land use. BJ was constructed in three phases between 2004 and 2007; phase 3 is the disturbed wetland in this study and it was constructed in the fall of 2006–winter of 2007 (Fig. 1). The nondisturbed area for comparison is located near the entrance to the study site in a stand of Virginia pine (*Pinus virginia*), white oak (*Quercus alba*) and willow oak (*Q. phellos*) that are less than 26.5 cm in diameter at breast height.

The fundamental BJ wetland design created multiple basins in the high clay content sub-soils with surface berms used to catch

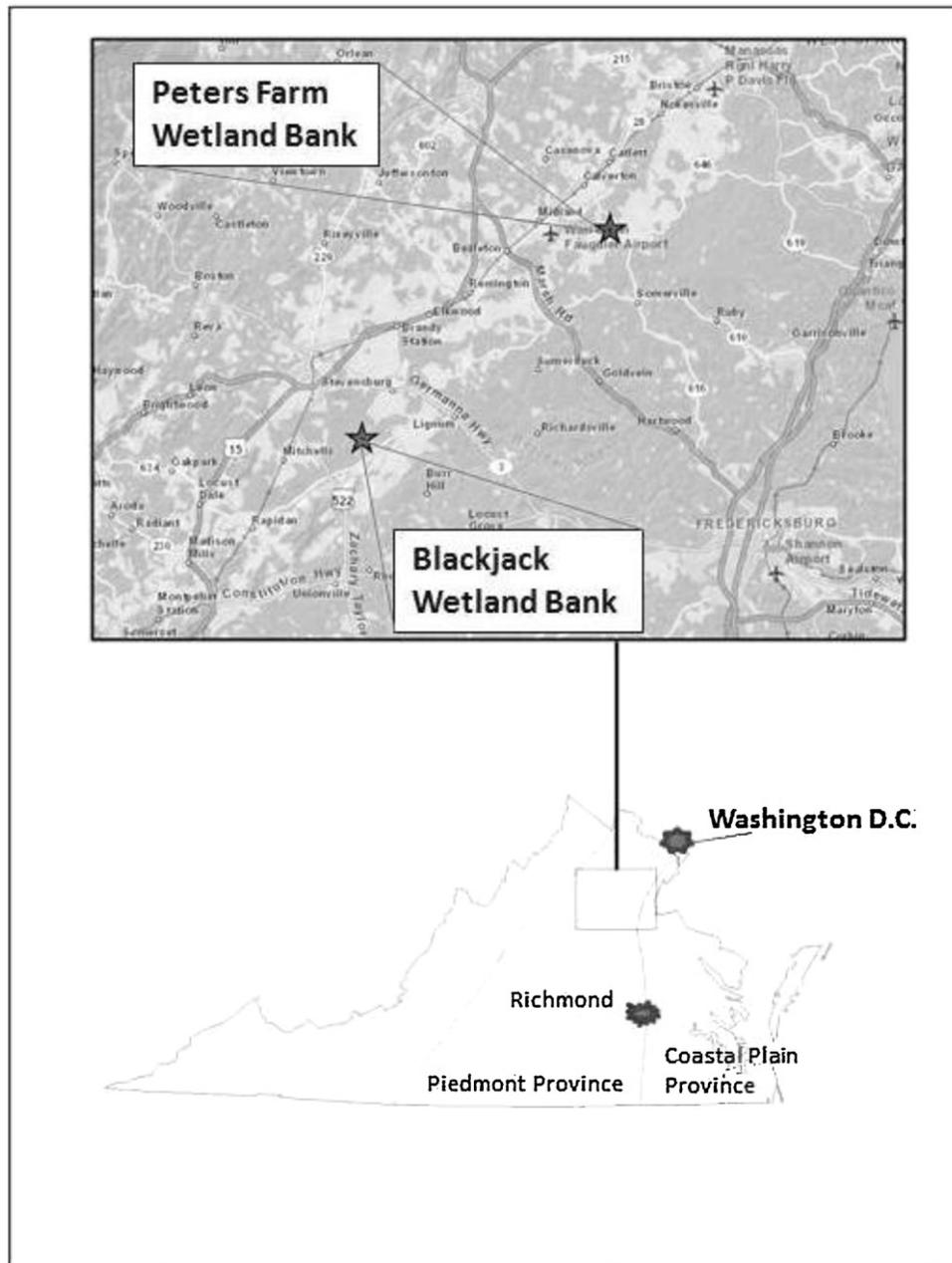


Fig. 1. The Blackjack (BJ) and Peters Farm (PF) wetland banks are located in the Piedmont physiographic province of Virginia.

precipitation and surface runoff from the watershed. Construction activities involved the mass grading of the entire wetland compound at least 1 m deep in order to achieve grade. Disturbance to the soil matrix involved cut-fill practices where the repeated stripping of subsoil with dozer cuts into the landscape in order to achieve subgrade. The topsoil horizon was so thin that the upper limits of the subsoil were integrated into the topsoil horizon during the initial stripping and temporary stockpiling process. The subsoil cut material was transported to temporary stockpiles or pushed to areas requiring fill. Heavy equipment was then used to repeatedly compress the cut and fill subgrade areas to specified D_b and elevation requirements before the re-spreading of topsoil. There was no importation of additional soil to achieve wetland grade.

The Peters Farm (PF) study site is a component of the Northern Virginia Regional Environmental Bank (NVREB) ($38^{\circ}23'44.38''N$, $77^{\circ}55'58.36''W$) and was constructed on alluvial deposits within

the large floodplain of Elk Run, approximately 5.3 km southeast of the locale known as Calverton, Virginia (Figure 1). The study area was bush-mowed in 2006 and the wetlands were constructed during the summer of 2009. Construction methods differed from BJ in that the existing soils are spatially variable and contain little clay. Soils mapped across the PF study site are primarily associated with the Rowland series (fine-loam, mixed, mesic Fluvaqueptic Dystrudepts) a soil listed to contain hydric inclusions of the Bowman (5%) and Albano (2%) series (USDA-SCS, 1956). Soil pits excavated throughout the area before construction identified a loamy surface horizon dominating the upper 30 cm, a clay rich zone between 50 and 120 cm, and a thick layer (20–100 cm) of coarse alluvium above the bedrock. PF has been maintained in agricultural production for over 100 years with recent land-use in the floodplain abandoned in the late 1990s due to poor trafficability and drainage.

The design of PF utilizes small surface berms with an impermeable membrane along the perimeter of the wetland cell. This membrane extends to bedrock which forces groundwater contributions to surface within the wetland in order to leave the landscape. Construction activities were limited to the approximate 10 m wide zone along the perimeter berm and a majority of the interior was left undisturbed. Soil disturbance on the site was limited. A trench was excavated along the berm footprint where soil within a 10–20 m wide zone was removed to bedrock and temporarily stockpiled in a linear fashion adjacent to the trench. Once the membrane was installed along the trench wall to bedrock the trench was backfilled and compacted. The excavation of a trench to bedrock and stockpiling that is associated with this design resulted in the mixing of different soil texture horizons and river stone throughout the backfill material. No additional soil was imported in order to achieve grade. Disturbed and nondisturbed study areas are actually situated within the same wetland cell, separated by less than 85 m, because a majority of the wetland footprint was not disturbed by excavation or compaction.

2.2. Study design

Disturbed and nondisturbed locations were established at the BJ and PF study sites. The experimental design for determining soil physical properties (SWCC, K_{sat} , PSD, D_b , OM) at both study sites were set up as a nested observation. Multiple sample points for each variable were collected from two depths representing the A and B soil horizons within an approximate 9.2 m radius of the automated well at all study locations. The exception to this protocol is the disturbed area at PF Wetland Bank; which is less than 10 m wide, and therefore sampling was staggered along a 14 m linear transect on either side of the well nest.

The nondisturbed soil profile at BJ was separated into a top (0–25.4 cm) and bottom (25.4–81.3 cm) soil horizon based on observed soil texture differences. No difference in soil texture was observed in the soil profile at the BJ disturbed area and the soil horizon extended to 129 cm below the surface. Therefore, soil sampling at the BJ disturbed area was conducted at equivalent depths to the nondisturbed study area. No soil texture break was observed at either of the PF soil profiles and the bedrock depth ranged from 200 to 250 cm below the surface. Since there was no texture difference at the PF study sites, the soil sampling depths mimicked the BJ protocol. Therefore, soil samples were collected in the top 25.4 cm of the soil profile and at depths deeper than 25.4 cm for all of the sites.

2.3. Soil sampling and analysis

SOM by percent was determined on 10 samples from each horizon at each study area using the dry combustion methods described in Nelson and Sommers (1982). The D_b (g/cm^3) was determined on soil cores taken for low pressure water content measurements using methods described in Blake and Hartage (1986). The soil texture characterizes the smaller-grained mineral composition of a soil matrix into percent gravel (>2.0 mm), sand (2.0–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm) content of each horizon (Gardiner and Miller, 2004). These samples, in conjunction with the high pressure water content soil samples, were collected from the soil remaining around the soil core which was excavated from each soil horizon for the low pressure water content measurements. Particle size analysis was conducted using the hydrometer technique (Gee and Bauder, 1986).

K_{satv} (cm/s) was determined using the constant and falling head laboratory methods outlined in Klute and Dirksen (1986). K_{satv} tests were conducted on completely saturated soil cores previously

extracted from each soil horizon for use in low pressure soil water content measurements. All of the soil cores at the PF were processed in a similar fashion as described above. Three (3) separate constant head test were conducted on all of the soil cores garnered at PF. Calculations of K_{satv} were determined using the constant head equation given:

$$K_{\text{satv}} = \frac{VL}{[At(H_2 - H_1)]}$$

where V is the volume of water that flows through the sample of cross-sectional area A in time t , and $(H_2 - H_1)$ is the hydraulic head difference across the sample length L . The extremely low K_{satv} observed in several of the disturbed top horizon soil cores suggested that the constant head test with 17 cm of head above the soil core may not be suitable to determine K_{satv} on all BJ subsoil cores. Therefore, the falling head method was conducted on BJ subsoil soil cores. Calculations of K_{satv} were conducted using the falling head equation given as:

$$K_{\text{satv}} = \left(\frac{L}{t}\right) \log_e \left(\frac{H_1}{H_2}\right)$$

where L is the distance (cm) across the sample and water column within the PVC pipe, t is the duration of time (s), and $(H_2 - H_1)$ is the hydraulic head difference across the sample length L . Two (2) separate falling head tests were conducted on all soil cores garnered at PF.

The Auger-hole Method (Van Beers, 1958) was used to determine the lateral saturated hydraulic conductivity (K_{satL}) (cm/h) in the field. Five measurements of K_{satL} were conducted on the top horizon and four were conducted on the bottom horizon of the nondisturbed area at BJ. The method suggests that the depth of the hole should be excavated at least 30 cm below the water table to offset a cone of depression that may result in fine textured soils from the artificial drawdown of the water table during the preparation process. However, the top horizon is approximately 25 cm in the nondisturbed area at BJ which technically violates this assumption. Data have been presented in this study for the BJ nondisturbed top horizon because there was a rapid and consistent rate of return to the hole and results would suggest that there was little if any cone of depression in the water table. Seven measurement of K_{satL} were conducted across the entire BJ disturbed soil profile because no discernible soil horizon break was observed. The K_{satL} was investigated across the entire soil profile at both PF study areas because no discernible difference was observed in clay content, SOM, D_b , TPS, and AWC between horizons. Eleven separate measurements of K_{satL} were conducted in the nondisturbed soil profile and nine measurements were conducted in the disturbed soil profile at PF.

2.4. SWCC: low and high pressure water content (θ) measurements

Soil water content was measured across a range of low (0 to –403 cm) and high (–1000 to –15,000 cm) pressures to construct SWCC's of the top and bottom soil horizons at areas that were disturbed and not disturbed by construction.

2.4.1. Low pressure water content (θ) measurements

Laboratory determination of the low pressure θ was conducted on undisturbed soil cores 7 cm deep and 7 cm in diameter. Analyses were performed at the NCSU-BAE Soil Laboratory on 5 cores for each depth in each soil at each site using methods described by Klute (1986). A series of pressures (–cm) were applied to each chamber and the corresponding volume of drained water was recorded in graduated cylinders after drainage to equilibrium was

met (typically 2–3 days). Soil cores were subject to 0 cm (saturation), –13.6 cm, –63.6 cm, –103.6 cm, and –403.6 cm pressures. Air leaks were detected in one nondisturbed top horizon and one disturbed bottom horizon soil core at the BJ study site and one disturbed top horizon soil core at the PF study site, and the samples were omitted.

2.4.2. High pressure water content (θ) measurements

Laboratory determination of the high pressure θ measurements were conducted on disturbed soil samples using methods described by Cassel and Nielsen (1986). These samples were collected in conjunction with soil samples for particle-size analysis from soil remaining around the soil core which was excavated from each soil horizon for the low pressure θ measurements. Five (5) disturbed soil samples from each soil horizon were subject to four (4) high pressure measurements equivalent to the: –1000 cm, –5000 cm, –10,000 cm, and –15,000 cm (WP) suctions. A series of pressures (–cm) were applied to the chamber and the volume of water removed after drainage ceased was collected and recorded (typically 2–3 days).

There were occasional occurrences of the water content measurements being higher at the –1000 cm pressures in the high pressure tests than in the –403.5 cm pressure in the low pressure test. These inconsistencies were due to the different methodologies used in the two tests, most notably the use of non-disturbed samples in the low pressure test as opposed to disturbed samples used in the high pressure test. Since the disturbed condition of the sample would have greater effect at lower pressures, the values for the 1000 cm on the disturbed sample were omitted from the SWCC analyses. Once corrected, the best visual match in water content values between low pressure measurements at –403.5 cm and high pressures at –5000 cm were paired together to create five separate SWCCs. The values were then averaged at each pressure measurement to create an average SWCC for each soil horizon in this study.

2.5. Relationship between volumes of water drained and water table depth, and drainable porosity

The volume of water drained (V_d) versus the water table depth relationship for the disturbed and nondisturbed soil profiles at both sites was determined from the SWCC as described by Skaggs et al. (1978). The volume of water (in depth units, cm^3 of water per cm^2 of surface area) required to raise the water table to the soil surface can be defined as the volume of water-free pore space above the water table, assuming drained to equilibrium conditions exist above the water table (Skaggs et al., 1978; Grace et al., 2006). V_d versus water table depth relationship was determined for the –21.3 cm, –41.3 cm, –61.3 cm and –81.28 cm (bottom of B horizon) depths at BJ site; and to the –18.4 cm, –36.8 cm, –55.3 cm and –73.7 cm (bottom of B horizon) depths at the PF study site. The drainable porosity (D_p) for each soil profile was determined from the slope of the V_d versus water table depth relationship, also modeled after procedures described in Skaggs et al. (1978).

2.6. Data analysis

All statistical analyses were conducted in SPSS ver. 19 (SPSS, Inc., 2010). Individual mean values for each soil horizon were tested for significance at the 0.05 probability level. BJ and PF turned out to be quite different in terms of the parent material, fine-grained weathering diabase versus a coarse-grained alluvium from silt/sand stone respectively, and this appears to have a tremendous influence on the soil properties. Thus we conducted a 2-way ANOVA on each

study site separately with soil depth and disturbance regime (i.e. prior- and post construction) as factors.

K_{satL} data were collected in the field from the top and bottom horizon at the BJ nondisturbed area and across the entire soil profile at the disturbed area. K_{satL} data from the nondisturbed BJ top and bottom soil horizons were compared using an independent sample t -test prior to comparison with the effective K_{satL} from the disturbed soil profile. The mean K_{satL} for the BJ nondisturbed bottom horizon and the effective K_{satL} of the disturbed soil profile were compared using 1-way ANOVA.

The different θ were used to create SWCCs for each soil horizon in the study. SWCCs were used to develop V_d versus water table depth relationships for the entire soil profile at each study location. The D_p was then estimated from the slope of this relationship. The water holding capacity (WHC) (Bruland and Richardson, 2004) or AWC as described in most studies (Veihmeyer and Hendrickson, 1931), does not correctly describe the plant available water storage in soils with high clay contents, or highly permeable soils within impermeable basins (Pierce, 1993). The concept of AWC would suggest that plant available water is defined by field capacity (FC) at the upper end and the WP at the lower end (Gardiner and Miller, 2004). The WP is typically assumed to be water held in the soil matrix at suctions greater than the root can exert on the soil (typically below –15,000 cm) (Richards and Weaver, 1943). The FC is defined as the water content held in the soil matrix after gravitational water has drained away (usually estimated at –330 cm), typically 2–3 days after irrigation or precipitation (Veihmeyer and Hendrickson, 1931). In instances where shallow clay liners, poorly drained soils or surface berms are used to promote wetland hydrology the process of gravitational drainage within 36 h is essentially removed (McIntyre, 1974). Limiting the soil water storage to that between FC and WP would underestimate the subsurface water storage. The plant available water in these circumstances and for the purposes of this study, are more accurately defined as that water held between TPS and WP.

3. Results and discussion

3.1. Clay content of soil texture

The effect that lateral and vertical mixing and compaction have on soil properties was most noticeable in the top horizon at the BJ disturbed area. The clay content at the BJ nondisturbed area was 18.5% in the top horizon and 61.7% in the bottom horizon. The clay content at the BJ disturbed area was 40.0% in the top horizon and 63.6% in the bottom horizon (Table 1). The mean clay content was greater in the bottom horizon compared to the top horizon at both of the BJ investigation areas. The clay content at the PF nondisturbed area was 20.1% in the top horizon and 18.4% in the bottom horizon. The clay content at the PF disturbed area was 31.5% in the top horizon and 30.7% in the bottom horizon (Table 3). There was no difference in the clay content between horizons at either study area ($p=0.722$), but the average clay content increased throughout the soil profile after disturbance (from approximately 20% to at least 31%).

It appears that the construction process increased the mean clay content in the BJ top horizon from 18.5 to 40%, resulting in a completely new soil texture with a different SWCC. The resultant modified soil texture is a phenomenon that is often encountered during disturbance activities that induce compaction, rutting, or mixing of soil layers. The substantial increase in clay in the near surface zone, particularly smectitic clay, would directly affect the water budget because the SWCC would be different, and by association the drainable and plant available water distribution within the

Table 1
Descriptive statistics for soil texture (sand, silt and clay content), soil organic matter (SOM), bulk density from tin ($T-D_b$), bulk density from core ($C-D_b$), total pore space (TP), available water content (AWC), vertical saturated hydraulic conductivity (K_{satv}), and lateral saturated hydraulic conductivity (K_{satl}) for top and bottom horizons nondisturbed (ND) and disturbed (D) areas at the Blackjack (BJ) and Peters Farm (PF) study sites.

	N	BJ				PF			
		ND Top	ND Bottom	D Top	D Bottom	ND Top	ND Bottom	D Top	D Bottom
Sand%	10	38.6 (6.3)	13.0 (2.0)	27.4 (10.0)	15.1 (3.5)	11.8 (2.6)	22.4 (8.0)	14.7 (6.0)	15.6 (6.1)
Silt%	10	42.8 (3.4)	25.3 (3.8)	32.6 (7.2)	21.3 (5.2)	68.1 (2.9)	59.3 (6.8)	53.8 (9.1)	53.7 (6.9)
Clay%	10	18.5 (7.8)	61.7 (5.6)	40.0 (16.8)	63.6 (5.3)	20.1 (1.1)	18.4 (1.5)	31.5 (5.9)	30.7 (4.0)
SOM%	10	5.0 (4.1)	4.6 (1.3)	5.4 (0.5)	4.6 (0.5)	3.3 (0.4)	3.1 (0.2)	3.3 (0.3)	3.7 (0.3)
D_b (g/cm^3)	4	1.56 (0.4)	1.28 (0.07) ^b	1.45 (0.18) ^b	1.22 (0.04)	1.52 (0.06) ^b	1.59 (0.20) ^b	1.67 (0.09) ^b	1.64 (0.07) ^b
TP (%)	4	36.7 (1.7)	53.6 (1.7) ^b	42.6 (8.3) ^b	54.9 (1.2)	37.2 (2.3) ^b	34.0 (2.5) ^b	40.2 (5.0) ^b	40.2 (5.0) ^b
AWC (%)	4	24.1 (1.6)	22.7 (0.8) ^b	15.8 (3.7) ^b	21.8 (0.2)	21.6 (2.4) ^b	20.7 (2.2) ^b	17.6 (9.4) ^b	16.3 (5.3) ^b
K_{satv} (cm/h)	4	4.169 (7.569)	0.006 (0.007) ^b	0.670 (1.307) ^b	0.001 (0.002) ^b	0.054 (0.099) ^b	6.325 (14.017) ^b	0.255 (0.530) ^b	0.386 (0.703) ^b
K_{satl} (cm/h)	4	12.5 (13.6) ^a	0.003 (.003)	0.0002 (.0004) ^a		2.71 (2.48) ^c		0.017 (0.026) ^d	
Pressure		ND Top	ND Bottom	D Top	D Bottom	ND Top	ND Bottom	D Top	D Bottom
Head (cm) N=	4	5	5	4	5	5	5	5	5
0 cm		0.367 (0.017)	0.536 (0.017)	0.471 (0.087)	0.549 (0.012)	0.372 (0.023)	0.351 (0.029)	0.401 (0.050)	0.399 (0.028)
-13.6		0.359 (0.020)	0.532 (0.018)	0.467 (0.090)	0.549 (0.012)	0.336 (0.027)	0.317 (0.034)	0.366 (0.050)	0.365 (0.033)
-63.6		0.347 (0.022)	0.531 (0.018)	0.462 (0.098)	0.549 (0.012)	0.309 (0.028)	0.289 (0.038)	0.338 (0.044)	0.340 (0.036)
-103.6		0.337 (0.024)	0.531 (0.018)	0.458 (0.100)	0.548 (0.011)	0.298 (0.029)	0.280 (0.038)	0.330 (0.042)	0.331 (0.036)
-203.6		0.322 (0.027)	0.527 (0.017)	0.402 (0.101)	0.547 (0.013)	0.283 (0.030)	0.266 (0.038)	0.317 (0.041)	0.317 (0.039)
-403.6		0.303 (0.027)	0.515 (0.015)	0.391 (0.104)	0.540 (0.011)	0.270 (0.031)	0.249 (0.039)	0.304 (0.038)	0.306 (0.040)
-5000		0.166 (0.013) ^b	0.375 (0.026)	0.328 (0.102)	0.410 (0.018) ^b	0.209 (0.012)	0.174 (0.008)	0.284 (0.025)	0.282 (0.023)
-10,000		0.144 (0.012) ^b	0.340 (0.013)	0.296 (0.094)	0.370 (0.017) ^b	0.174 (0.011)	0.146 (0.009)	0.248 (0.035)	0.240 (0.034)
-15,000		0.126 (0.011) ^b	0.309 (0.016)	0.266 (0.088)	0.334 (0.015) ^b	0.156 (0.010)	0.133 (0.009)	0.225 (0.036)	0.237 (0.034)

BJ, Blackjack study site; PF, Peters Farm study site; ND, nondisturbed area; D, disturbed area. Standard deviations are given in parenthesis.

- ^a N = 7.
- ^b N = 5.
- ^c N = 11.
- ^d N = 9.

Table 2
Results from the two-way ANOVA conducted on the Blackjack site soils.

Adjusted R ²	Sand %		Silt%		Clay%		SOM%		D _b		TP%		K _{satv} cm/h		K _{satL} cm/h		AWC%			
	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig		
	0.731		0.719		0.77		0.58		0.594		0.717		0.048		0.27		0.691			
Horizon	92.2	**	79.8	**	110.4	**	0.7	N/S	26.0	**	4.1	*	2.0	N/S	–	–	4.9	*		
Treatment	5.4	*	19.3	**	13.6	**	0.1	N/S	3.1	N/S	2.7	N/S	1.1	N/S	4.7	N/S ^a	20.3	**		
Treatment × Horizon	11.3	**	3.7	N/S	9.4	**	0.0	N/S	0.3	N/S	1.1	N/S	1.1	N/S	–	–	13.2	**		
cm of pressure	0		–13.5		–63.5		–103.5		–203.5		–403.5		–1000		–5000		–10,000		–15,000	
Adjusted R ²	0.717		0.714		0.706		0.710		0.711		0.718		0.736		0.767		0.772		0.755	
	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig		
Horizon	44.1	**	43.6	**	41.9	**	42.4	**	42.3	**	43.2	**	36.1	**	41.3	**	40.9	**	38.2	**
Treatment	2.7	N/S	3.0	N/S	2.9	N/S	3.0	N/S	3.5	N/S	4.2	N/S	16.5	**	19.1	**	20.0	**	17.3	**
Treatment × Horizon	1.1	N/S	1.0	N/S	1.0	N/S	1.1	N/S	1.2	N/S	1.4	N/S	5.7	**	8.06	*	9.3	*	8.7	*

^a One way ANOVA conducted between nondisturbed bottom horizon and effective K_{satL} of disturbed soil profile.

* p ≤ 0.05.

** p < 0.005.

soil profile would change from that which existed before construction. The PF study site was constructed in a floodplain setting and there may have been more clay content isolated at depth within the undisturbed soil profile at the location of the disturbed investigation area prior to construction compared to the nondisturbed investigation area. Stolt et al. (2000) investigated constructed and reference wetlands in southeastern Virginia and found higher variance in particle size distribution in alluvial settings which coincides with our findings. The unexpected increase in the clay content could affect the SWCC for the entire soil profile.

3.2. SOM

The SOM at the BJ nondisturbed area was 5.0% in top horizon and 4.6% in the bottom horizon (Table 1). The SOM at the BJ disturbed location was 5.4% in the top horizon and 4.6% in the bottom horizon. There was no difference in mean SOM content between soil horizons (p = 0.406) within each BJ investigation area, and the construction activities did not seem to effect the SOM between soil horizons across disturbed types (p = 0.836) (Table 2). The SOM at the PF nondisturbed area was 3.3% in top horizon and 3.1% in the bottom horizon (Table 3). The SOM at the PF disturbed location was 3.3% in the top horizon and 3.7% in the bottom horizon. There was no difference in the average SOM between soil horizons at each PF study area (p = 0.132).

The SOM observed at BJ was within recommended guidance of at least 5% for constructed wetlands (Daniels and Whittecar,

2004). The increase in SOM at the PF disturbed profile may be a result of higher SOM contents in the soil profile at this location before construction commenced and shows the spatial variability of floodplain soils.

3.3. D_b and TPS

The D_b at the BJ nondisturbed area was 1.56 g/cm³ in top horizon and 1.28 g/cm³ in the bottom horizon (Table 1). The D_b at the BJ disturbed location was 1.45 g/cm³ in top horizon and 1.22 g/cm³ in the bottom horizon. There was no difference in the mean D_b in the bottom horizon at either investigation area (p = 0.099) (Table 2). The construction activities affected the soil such that there was no difference in the average D_b of the top horizon of the disturbed area and either bottom soil horizon (p = 0.581). No difference exists in the average TPS between bottom soil horizons at either study area (p = 0.122) (Table 2), or between the top horizon at the disturbed area and either bottom soil horizon (p = 0.308).

The D_b at the PF nondisturbed area was 1.52 g/cm³ in top horizon and 1.59 g/cm³ in the bottom horizon (Table 1). The D_b at the PF disturbed location was 1.67 g/cm³ in top horizon and 1.64 g/cm³ in the bottom horizon. The D_b was greater in the PF top horizon compared to the bottom horizon at the disturbed soil profile (Table 3). There was no difference between the average D_b content in the bottom horizon at the PF nondisturbed and disturbed areas (p = 0.099). The TPS at the nondisturbed area was 37.2% in top horizon and 34.0% in the bottom horizon (Table 1). The TPS at the disturbed

Table 3
Results from the two-way ANOVA tests conducted on the Peters Farm Site soils.

Adjusted R ²	Sand %		Silt%		Clay%		SOM%		D _b		TP%		K _{satv} (cm/h)		K _{satL} (cm/h)		AWC%			
	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig		
	0.261		0.408		0.722		0.307		0.078		0.304		0.009		0.334		0.004			
Horizon	9.2	*	4.3	*	1.2	N/S	2.4	N/S	0.1	N/S	1.3	N/S	0.8	N/S	–	–	0.2	N/S		
Treatment	1.1	N/S	21.4	**	103.1	**	11.0	**	3.7	N/S	9.0	*	1.0	N/S	10.5	**	36.2	**		
Treatment × Horizon	6.5	*	4.2	*	0.1	N/S	6.9	*	50.8	N/S	1.0	N/S	1.0	N/S	–	–	0.0	**		
cm of pressure	0		–13.5		–63.5		–103.5		–203.5		–403.5		–1000		–5000		–10,000		–15,000	
Adjusted R ²	0.191		0.139		0.158		0.179		0.180		0.216		0.807		0.873		0.742		0.755	
	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig		
Horizon	0.6	N/S	0.3	N/S	0.3	N/S	0.3	N/S	0.3	N/S	0.3	N/S	16.4	**	5.3	*	2.3	N/S	0.2	N/S
Treatment	6.6	*	5.4	*	5.9	*	6.6	*	6.6	*	7.4	*	62.2	**	123.8	**	54.4	**	57.2	**
Treatment × Horizon	0.4	N/S	2.8	N/S	0.4	N/S	0.3	N/S	0.3	N/S	0.5	N/S	4.1	**	4.1	N/S	0.8	N/S	2.2	N/S

* p ≤ 0.05.

** p < 0.005.

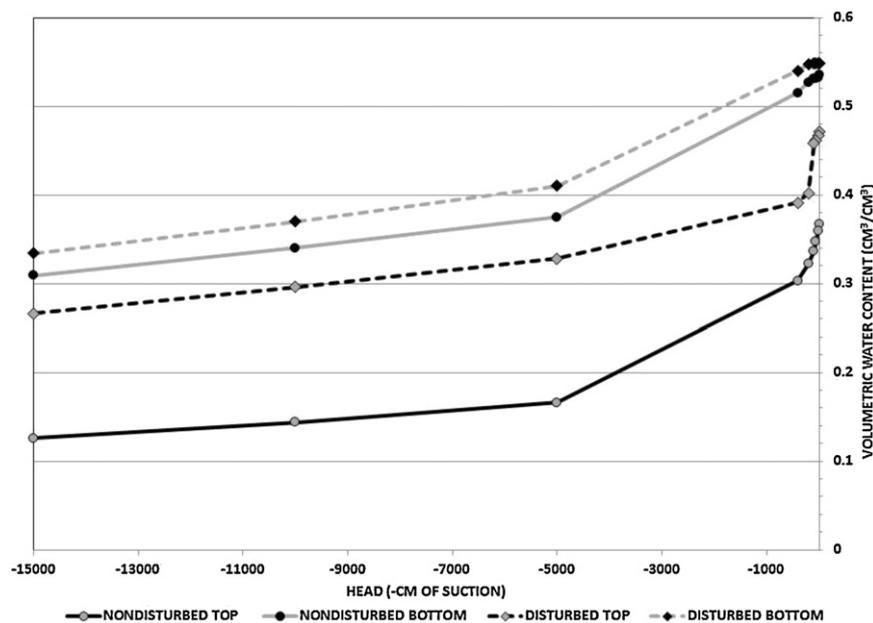


Fig. 2. SWCCs for the soil horizons at the control and treatment areas of Black Jack.

location was 40.2% in both horizons. There was no difference in the average TPS between bottom soil horizons at either study area ($p = 0.266$).

Campbell et al. (2002) found that D_b values of created wetlands in Pennsylvania were twice that of natural wetlands. The authors attributed the differences in D_b to high sand contents and compaction. In our study, the D_b of the BJ top horizon decreased after construction and the clay content increased. While no significant difference was observed in TPS between BJ study areas there was a trend toward an increase in TPS of the disturbed top horizon. This increase in TPS seemed to be a result of the homogenizing of the BJ disturbed top horizon with clay and compaction. While there was an increase in clay content at PF after construction the overall TPS is lower at PF compared to BJ because the dominance of coarser material comprising the soil matrix.

3.4. θ and SWCC

The effect that an increase in clay and soil compaction had on θ in the BJ top horizon can be observed when comparing the slopes of the SWCC in the lower pressure measurements (Fig. 2). The θ (Table 2) as measured throughout the SWCC's show that more water was held in the soil at the WP (-15,000 cm) in all other soil horizons when compared to the nondisturbed top horizon. The θ (Table 3) was the same between horizons at the individual PF study areas for every pressure measurement except at -1000 and -5000 cm. The SWCC's show that more water was held in the soil at all pressures in the PF disturbed soil profile compared to the nondisturbed top soil profile (Fig. 3). The top horizon at the BJ disturbed location reflects an intermediary SWCC between that of the nondisturbed top and both bottom horizon SWCC's. This was a result of the vertical integration of two different soil textures in conjunction with compaction. A portion of the soil water transfers from the drainable state to capillary and adsorptive.

3.5. AWC

The AWC at the BJ nondisturbed area was 24.1% in the top horizon and 22.7% in the bottom horizon (Table 1). The AWC at the BJ

disturbed area was 15.8% in the top horizon and 21.8% in the bottom horizon. The AWC at the PF nondisturbed area was 21.6% in the top horizon and 20.7% in the bottom horizon. There was no difference detected in average AWC between soil horizons within either PF study area ($p = 0.669$) (Table 3). The AWC at the PF disturbed area was 17.6% in the top horizon and 16.3% in the bottom horizon.

The shift in the ratio of plant available water versus total water storage (AWC/TPS) within the top soil horizons at the BJ study site was alarming. The mean TPS in the BJ top horizon increased from 37 to 43% after construction (Table 2). Approximately 66% of the TPS in the top soil horizon at the BJ nondisturbed area can hold plant available water compared to 40% at the disturbed area. There was a similar change in the water availability ratio between the PF study locations. There was approximately 34% TPS in the PF nondisturbed soil profile compared to 40% in the disturbed soil profile. Approximately 58% of this TPS in the PF nondisturbed soil profile was available to plants. The TPS increases at PF after construction but only 44% of the TPS was available for plant water storage.

The increase in clay content in conjunction with the collapse of macro-pore structure resulted in an increase in the TPS but an actual decrease the plant available water in the top horizon at the BJ disturbed area. The AWC was less in the PF disturbed soil profile compared to the nondisturbed soil profile and was likely associated with either an increase in clay content or soil structure.

3.6. Volume-drained relationship

A change to the SWCC in turn changed the volume of water required to lower the water table (a.k.a. V_d relationship) (Fig. 4). The drainable volume of water within the BJ soil profile changed from 0.67 cm over a soil matrix 81.3 cm thick (nondisturbed), to 0.36 cm of water over a soil matrix of 126 cm (disturbed). This represented a change in the D_p of the entire BJ soil profile from 0.8 to 0.3% respectively. The V_d relationship was reduced by almost 50% in a soil profile that was almost 50% thicker. The drainable volume of water within the PF soil profile changed from 3.5 cm over a soil matrix of 74 cm thick (nondisturbed), to 6.6 cm of water over a soil matrix of 122 cm (disturbed). This represented an increase in the

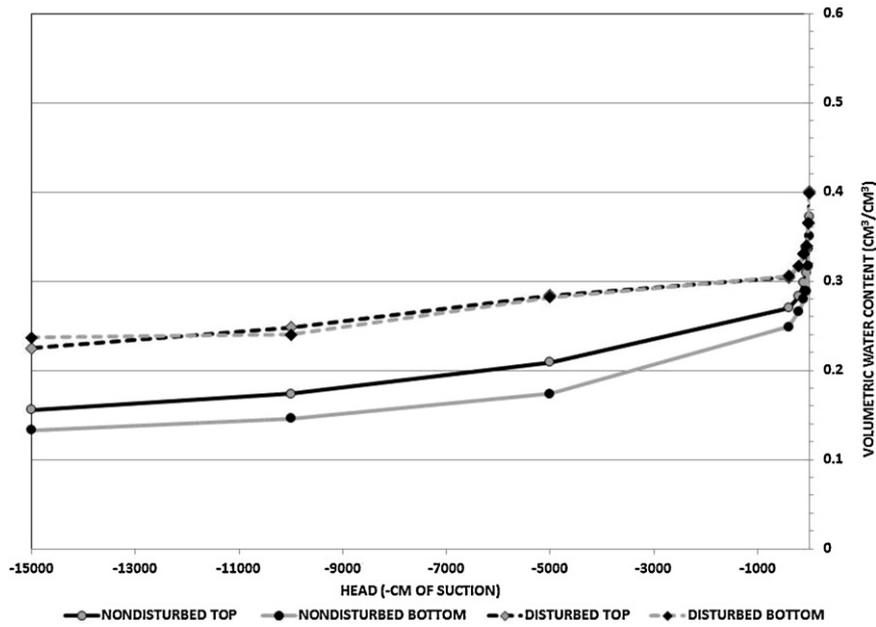


Fig. 3. SWCCs for the soil horizons at the control and treatment areas of Peters Farm.

D_p of the entire PF soil profile from 4.7 to 5.4% respectively. There was little effect on the V_d versus water table depth relationships and the associated D_p values because of the construction process.

Regardless of disturbance, the dominance of smectitic clay resulted in a majority of the water held within the soil matrix at suctions greater than that which would be considered drainable (-300 cm). The impact of such a low D_p is a water table that spends little time within the near surface zone (-30 to 0 cm). While the construction process increased the overall thickness of the BJ soil profile (increase in soil storage), the D_v of the soil profile was reduced at the BJ disturbed area by almost 50% because of the increase in clay. Notably the V_d relationship within the soil profile was similar at PF both study areas and it did not seem to be affected by construction (Fig. 4). The soil profile thickness increased from -76 cm below the surface at the PF nondisturbed area to -122 cm

at the disturbed area which actually provided for greater subsurface soil water storage. Regardless of the increase in clay and the lower overall TPS at PF, the dominance of coarser materials (sands and silts) provided the structure for drainable void space which facilitates readily available subsurface water storage.

3.7. Saturated hydraulic conductivity

The K_{satv} at the BJ nondisturbed area was 4.2 cm/h in top horizon and 6.0×10^{-3} cm/h in the bottom horizon (Table 1). The K_{satv} at the BJ disturbed location was 6.7×10^{-1} cm/h in top horizon and 1.0×10^{-3} cm/h in the bottom horizon. There was no difference in the average K_{satv} between soil horizons ($p = 0.176$), between nondisturbed and disturbed soil profiles ($p = 0.319$), or between soil horizons across BJ study areas ($p = 0.321$) (Table 2). The K_{satv}

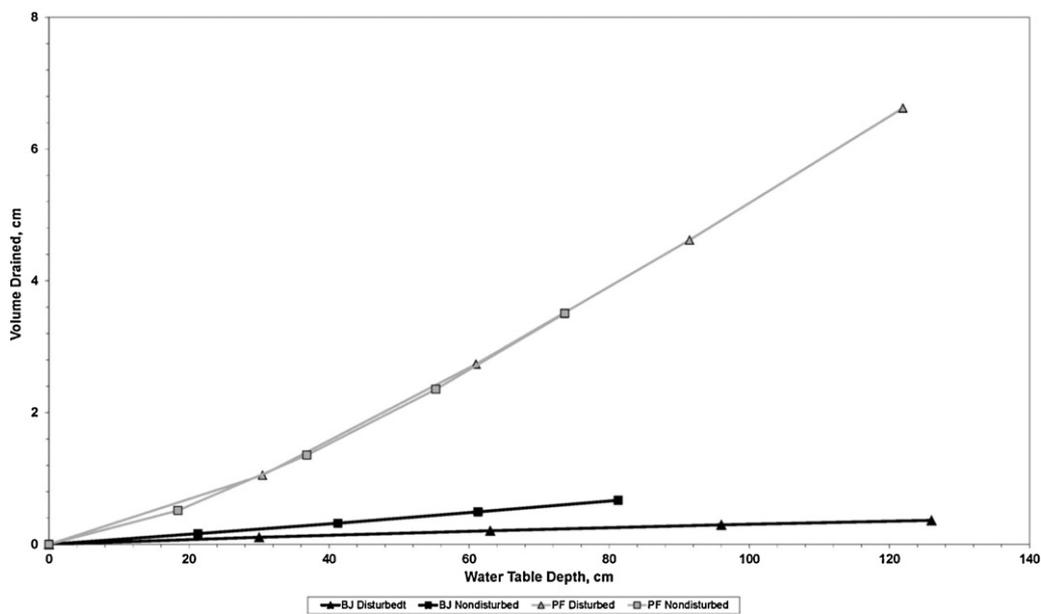


Fig. 4. Volume drained relationships developed for nondisturbed and disturbed areas at the BJ and PF study sites.

at the PF nondisturbed area was 5.4×10^{-2} cm/h in top horizon and 6.325 cm/h in the bottom horizon. The K_{satv} at the PF disturbed location was 2.55×10^{-1} cm/h in top horizon and 3.86×10^{-1} cm/h in the bottom horizon. There was no difference in the average K_{satv} between horizons ($p = 0.323$), between nondisturbed and disturbed soil profiles ($p = 0.375$), or between soil horizons across PF study areas ($p = 0.343$). These laboratory measurements of the BJ K_{satv} may have been affected by the soil core cutting off lateral macro-pore structure which has previously been observed by Ritchie et al. (1972). These conditions may accurately characterize field conditions as macro-pore connectivity was destroyed by the construction process.

The field observed K_{satL} (effective K_{sat}) was 12.5 cm/h in the top horizon and 3.0×10^{-3} cm/h in the bottom horizon of the BJ nondisturbed soil profile; the effective K_{satL} of the disturbed soil profile was 2.0×10^{-4} cm/h. There was no difference in the K_{satL} between the bottom horizon at the BJ nondisturbed area and the effective K_{satL} at the disturbed area ($p = 0.059$) (Table 2). The effective K_{satL} was 2.7 cm/h in the PF nondisturbed soil profile and 1.7×10^{-2} cm/h in the disturbed soil profile.

Little if any water was observed in the bore holes after initial bailing at the BJ disturbed area and in the bottom horizon of the BJ nondisturbed soil profile. The water observed in the hole was resulting from the drainage of the limited macro-pore structure that was exposed along the walls of the bore hole and likely some macro-conduits were closed by the auger process. Minimal drainable void structure would be expected after reviewing the BJ SWCC (Fig. 2) and the associated V_d relationship (Fig. 4). A majority of the water was held so tightly in the BJ soil matrix of the disturbed profile that water did not convey to an empty bore hole situated below the water table well beyond the 72 h test, thus yielding an extremely low K_{satL} value. This translates into conditions where there is the potential for adequate plant water storage but the rate of water movement through the soil matrix to the roots is reduced so greatly that a plant may not be able access adjacent soil water due to very little lateral movement.

3.8. Implication of the study

Generally a water budget must predict long durations of near surface saturation during the appropriate time of year. The disturbed BJ study area has extremely low D_p (0.3%) which can be translated best with an example of a mitigated wetland water budget that must achieve hydrologic performance standards. In this example there is an assumed evapotranspiration rate of 0.5 cm per day. This evapotranspiration rate would lower the water table from the surface to -167 cm in one day ($0.5/0.003 = 167$). It is therefore likely that most of the time when the water table is above 30 cm, ponded conditions exist on the wetland. Surface storage may be used to prolong surface saturation, but if the surface storage becomes too great then the resulting hydrologic regime may not be appropriate for the mitigated wetland habitat (forest, shrub, emergent, submerged aquatic vegetation).

The D_p was 5.4% at the PF disturbed area which would facilitate a slower rate of draw down. Given the same evapotranspiration rate the water table would lower from the surface to 30 cm below in 3.5 days ($0.5/0.054 = 9.3$ cm). This translates into less demand on surface storage to achieve the success standards for mitigation wetland hydrology. The larger void space between aggregates and lower mean clay content in the PF soil matrix provide more drainable water compared to BJ even though the TPS was greater at BJ. In order to achieve hydrologic success when constructing forested mitigation wetlands where the main drainage is controlled by surface berms and weirs as in Pierce (1993), the upper 30–45 cm of soil

should be coarse (with more macropores) to promote the storage of drainable water in the soil profile.

Guidance for creating wetland soil conditions by excavating or grading into upland areas recommend that amendments be made to the top soil to achieve a D_b less than 1.35 g/cm^3 and an organic matter content of at least 5% (Daniels and Whittecar, 2004). This D_b generally translates into a TPS of at least 50%. The coarse alluvium at PF contains a D_b above the recommendation which translates into a lower TPS. However, a large percentage of the TPS was plant available because of the larger void structure associated with more sand and silt, and less clay particles. Furthermore, the fine textured soil at BJ contains a D_b within acceptance of this recommendation but a large portion of the TPS was not available for plant consumption and a small fraction was drainable. A simple measurement of D_b or a standard target for TPS without consideration to soil texture may be misleading when calculating subsurface water storage in a water budget for mitigation wetlands constructed in soils with higher clay contents (+40%) or those that are smectitic in nature. Furthermore, water budgets should anticipate changes to the drainable and plant available water that may result from construction activities.

Typically, high clay and organic matter contents are associated with an increase in water retention within a soil profile. However, there appears to be a threshold at which point increased clay contents, particularly smectitic clay, may have a negative effect on the plant available and drainable water contents. Changes in these soil properties directly affect how a water budget would predict the hydrology of a created mitigation wetland that must meet jurisdictional requirements for wetland vegetation development.

The determination of soil texture, K_{satv} and the SWCC are extremely important components of a proper wetland creation/restoration feasibility investigation. Outside of academia, most wetland designers are limited to budgets which greatly restrict the ability to thoroughly investigate a landscape before construction. This brings up the issue of sampling strategies and balancing sampling intensity at specific points versus spatial coverage. These strategies should be developed based on the aerial footprint that the wetland encompasses in the landscape and the underlying soil types. In this study, repeated measurements of a soil property were made within a relatively close proximity (<10 m radius) in two horizons at the BJ and PF study sites. The average of these measurements strengthens the data set for a localized area and may account for error in a single point measurement. This approach may be appropriate for application to large scale homogeneous soil units such as those observed across the BJ compound. However, wetlands created in alluvial settings similar to those at PF may have high spatial variability within a short distance laterally and vertically (Stolt et al., 2000). Developing appropriate sampling strategies is important to the design of hydrologically connected wetlands and should be the topic of future research.

4. Summary and conclusions

The effect of the wetland construction process has on the AWC, D_p , D_b , TPS, SOM, the K_{satL} and K_{satv} , and the water content throughout the SWCC were studied in created mitigation wetlands located in two different landscapes within the Piedmont region of Virginia. Results of the study reveal that the construction process significantly reduced plant available water contents of soils at both sites, and both drainable and plant available water contents were reduced in soils at the site with high clay contents. While the SOM, D_b and TPS in the clay soil sites disturbed by construction were within recommended values, the plant available water and drainable water volumes were very low. This shows that the portion

of TPS that can store plant available and drainable water changes based on soil texture and disturbance.

The changes in soil hydraulic properties will likely influence the predictive power of a wetland water budget if pre-treatment soil properties are used in the analysis. The low volumes of drainable water associated with the reduced macro-pore structure in the upper soil horizons indicate that the free water table would spend very little time in the top 30 cm of the soil profile. This translates into a rapid rise and fall of the water table once it falls below the soil surface, and prolonged periods of inundation when the water table is above 30 cm. Findings from this research suggest that changes to key soil hydraulic properties be considered in the disturbed state or ameliorated before water budgets are constructed to model wetland hydrology. More information is needed about how the plant available and drainable water content can be affected by the construction of wetlands in various soil textures as well as in the long term.

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