# ASSESSMENT OF WATER BUDGETS AND HYDROLOGIC PERFORMANCE OF A CREATED MITIGATION WETLAND – A MODELING APPROACH

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## Abstract:

This study used a water balance model (i.e. DRAINMOD) to compute water budgets of a mitigation wetland created in the Piedmont region of Virginia. The calibration of the model was conducted with automated well data collected during the 17 month monitoring period. Other input data included precipitation, temperature, soil physical properties (soil water characteristic curve and saturated hydraulic conductivity) and site characteristics (surface roughness and surface storage). A modeling approach was taken to evaluate the responses of the study areas to changes in surface and soil hydraulic conditions caused by construction activities. Six hydrologic performance criteria were used to evaluate the response of the areas to these changes. The models successfully predicted the hydrologic regimes of nondisturbed and disturbed areas. The models were used to evaluate a set of performance criteria across a 60-year (1952 to 2011) simulation period. The nondisturbed model could not predict the hydrologic regime at the disturbed study area showing how soil disturbance can influence the hydrologic modeling of restored landscapes. The DRAINMOD application showed that the both models would have achieved wetland hydrology in a majority of the years without the need for surface storage. Soil disturbance and increase in surface storage due to construction activities lead to 155 more consecutive days of ponding. Results show that too much surface storage can increase in near surface saturation and ponding during the growing season, thus potentially shifting the hydrologic regime from a forested wetland to open water or emergent wetland habitats.

*Keywords:*

Wetland hydrology, soil disturbance, water budget model, wetland mitigation, created wetlands, DRAINMOD

## *Introduction*

Water budget models are used to predict the post-construction hydrologic regime of constructed wetlands (Pierce, 1993; Daniels et al., 2000). Conservative approaches to wetland design anticipate some degree of error in water budget estimates (to account for variance in climate and soil data) and therefore typically employ permanent grade controls (berms with weirs or spillways) to create surface storage in order to ensure that wetland hydrology is achieved in all but the driest years. This simple design element can in turn put less emphasis on the precision of data needed for a reliable wetland water budget. Water budgets developed for mitigation wetlands tend to only target regulatory hydrology requirements that define the lower (dryer) threshold of the proposed hydrologic regime. However, there needs to be more emphasis on the accurate prediction of the duration of near surface saturation and inundation during the growing season when a wetland is constructed to mitigate the loss of natural forested wetlands because there are limits to the duration of saturation that trees find ecologically suitable. In order to accomplish this goal, this study begins to translate the disturbance of key soil hydrologic properties disturbed by construction activities (Petru et al., 2013) into long term hydrologic regimes of a created wetland.

Wetlands delineated for regulatory purposes within the eastern mountains and piedmont regions of the United States are considered to have jurisdictional wetland hydrology when the water table is within the upper 30 cm of the soil profile for at least 14 consecutive days during the growing season (USACE, 2010). However, water budgets developed for the purpose of wetland mitigation within Virginia and other areas of the mid-Atlantic must target the regulatory hydrology requirement of a free water table within the upper 30 cm of the soil profile for at least 12.5% of the frost-free growing season, as a single saturation event in most years (Environmental Laboratory, 1987; USACE and VADEQ, 2004). For example, the Natural Resource Conservation Service (NRCS) Precipitation and Growing Season - WETS table for Warrenton, Virginia, identifies the average growing season based on a surface air temperature of 28º F to be 217 days in rural northern Virginia. 12.5% of this duration translates to approximately 27 continuous days of near-surface saturation that must occur between April 3rd and November 7th (NRCS, 2002). This duration (i.e., 12.5% of the growing season) then becomes a minimum lower threshold when creating water budgets for mitigation wetlands in Virginia regardless of habitat types (e.g., emergent, herbaceous, scrub-shrub, or forested wetlands, etc.) (USACE and VADEQ, 2004).

A surplus of water is not expected to have adverse impacts on wetland habitat from the regulatory success perspective and therefore excess water in the form of surface storage is typically ignored. Teskey (1977a) identified flood frequency, flood duration, time of year of the flooding, water depth, and siltation as critical factors that affect vegetation communities. The survivability of many bottomland seedling and mature tree species becomes extremely low after one to three months of continuous inundation during the growing season (Teskey, R., 1977 a and b, Melichar et al., 1983; Hook, 1984; Vreugdenhil et al., 2006). In fact wetland habitat composition and function are dependent on the hydrologic regime (Richter et al, 1996; Mitsch and Gosselink, 2007). Johnson et al. (2011) identified that 1-day, 3-day, 7 day and 30 day maximum water table levels were strongly associated with vegetative community composition in North Carolina wetlands. Bottomland forested wetlands commonly found in the mid-Atlantic and southeast United States have a hydrologic regime characterized by high water tables or inundation of water above the surface during the late fall, winter, and early spring seasons, followed by a natural draw down of the water table below the surface during the peak of the growing season (Tiner, 1999; Sun et al., 2002). There is an ecological upper limit that a water budget must consider when modeling forested wetland mitigation in terms of the frequency and duration that high water tables are present during the peak months of vegetative growth.

Model precision is greatly amplified with specific information on soil and climate conditions. DRAINMOD is a field tested computer model developed to predict drainage conditions in poorly drained soils (Skaggs, 1978; Skags et al. 2012). The model uses soil properties for each horizon above the restrictive layer, weather data, plant variables and site parameters to calculate hourly water budgets of a system. The performance of a given system may be simulated with long term climate data (e.g., >20 years) to evaluate the effects of annual and seasonal variability. DRAINMOD can provide calculations of water budget inputs and outputs across these simulation periods. Particularly useful in wetland modeling, it can predict the long term frequency of flooding (e.g. greater than 6 out of 10 years or >50%) and the annual longest duration (e.g. 12.5% of the growing season) that the free water table will exist above specified elevations (e.g. within 30 cm of the surface or above the surface). DRAINMOD has been used to correlate the frequency and duration of water table inundation and soil color and morphology (He et al., 2003; Vepraskas et al., 2004) and to describe the hydrology of wet landscapes with and without perimeter drains (He et al, 2002). It has been used to characterize the hydrology of naturally occurring forested wetlands (Chescheir et al. 2008), pocosins (Skaggs et al., 1991), and Carolina bay wetlands (Caldwell et al., 2007). DRAINMOD has also been used to determine the effect of land management practices on coastal wetlands (Richardson and McCarthy, 1994), to evaluate a panel of regulatory hydrologic criteria across several hydric soils (Skaggs et al., 1994), and to determine if jurisdictional wetland hydrology is satisfied in partially drained landscapes (Skaggs et al., 2005). DRAINMOD has been successfully applied to dewatering poorly drained soils (i.e. wet landscapes) and to characterize the hydrology of natural wetlands; however no documentation to date have used the model to characterize the hydrology of created mitigation wetlands.

This study shows how changes to key soil hydrologic properties resulting from construction activities impact the predictive power of water budgets. DRAINMOD is used to translate changes to surface storage and surface roughness properties and their influence on performance criteria governed by wetland hydrology, soil hydrologic descriptions, and ecological tolerances. The precision of a water budget prediction may become compromised by ignoring groundwater storage, assuming soil hydraulic properties from literature to represent field conditions, and/or using nondisturbed soil properties to predict disturbed soil conditions. This study focused on the latter. The primary objective of this study was to accurately calibrate DRAINMOD to predict the hydrology of soil profiles both disturbed and nondisturbed by common construction practices at a wetland mitigation bank created in the piedmont region of Virginia. The calibrated models were then used with long term climate data to determine the impacts that altered soil hydraulic properties would have in terms of hydrologic performance criteria for mitigation wetlands.

## *Methods*

### *Site Description*

Peters Farm (PF) wetland mitigation bank (38°23’44.38”N, 77°55’58.36”W) was constructed on alluvial deposits within the red silt-stone material of the Culpeper Basin rift formation located within the Piedmont physiographic province. The wetland was situated within the floodplain of Elk Run, approximately 5.3 km southeast of the locale known as Calverton, Virginia (Figure 1A). The study area was bush-mowed in 2006 and the wetlands were constructed during the summer of 2009. Soils mapped across the PF study site are primarily associated with the Rowland series (fine-loam, mixed, mesic Fluvaquentic Dystrudepts), a soil listed to contain hydric inclusions of the Bowman series (mesic Typic Endoaquolls) at 5% and Albano series (mesic Typic Edoaqualfs) at 2% (USDA-SCS, 1956). The growing season was defined by the average frost-free period between April 3rd (Julian day 93) and November 7th (Julian day 311), which is a total of 219 consecutive days (NRCS, 2002).

The design of PF utilizes surface berms (0.6 m high by 3 m wide) that are held constant at 66.8 m above mean sea level (msl) (Figure 1). There was a single primary earthen spillway (weir) that was temporarily set at approximately 66.4 m above msl. The wetland floor transitions from 66.7 m in the western corner down to 65.8 m below the weir over an approximate 900 m distance (0.1% slope) (Figure 1). A single PVC pipe (approximately 0.2 m in diameter) was installed within the spillway approximately 65.9 m above msl and was used to determine the final weir elevation. A 90-degree elbow and straight riser pipe (PVC) are attached to the main PVC drainage pipe and allow for manual adjustment in order to determine the permanent spillway elevation. The inverted elevation of the PVC riser pipe was set at approximately 66.3 m above msl during this study. A subsurface impermeable membrane was installed vertically along the perimeter of the wetland cell. This membrane extends from the berm to bedrock which forces uphill groundwater contributions to surface within the wetland in order to leave the local landscape. The non-disturbed (ND) (+/- 66.3 m above msl) and disturbed (D) (+/- 66.1 m above msl) study areas are situated within the same wetland cell less than (100 m apart) as a majority of the field was left ungraded (Figure 1B). A single automated well made by Remote Data Systems, Inc. (Navassa, NC) was installed at each study area in order to collect daily water table measurements within the upper one half meter (0.5 m) of the solum.

### *DRAINMOD Model Set Up*

The DRAINMOD model assumes there are parallel drainage sinks (ditches, tiles, or pipes) at a defined spacing and depth above a restrictive layer. Water table depths are predicted at the midpoint between the two drainage sinks. The model uses the Hooghoudt equation (Hooghoudt, 1940) to predict the relationship between water table depth and the drainage rate. Drainage parameters and site characteristic inputs include surface storage, surface roughness, depth of drain from surface, effective radius of drains, drain spacing, actual distance from surface to impermeable layer, and soil properties (Skaggs, 1978). Two DRAINMOD models were created to represent field conditions at the PF ND and D study area. Recognizable differences between the root zone and lower solum at both study areas were not evident during the pre-study site investigation. Long term simulations (January 1952 to December 2011) were conducted to test how sensitive the hydrologic criteria are to adjustments in surface storage, surface roughness and drainable porosity.

### *Soil Hydraulic and Physicochemical Analyses*

Soil samples were collected at each study area from two uniform depths, within 25 cm of the soil surface (upper horizon) and below 40 cm (lower horizon). Soil property inputs include soil water characteristic curve (SWCC), lateral and vertical saturated hydraulic conductivity ($Ksat_L$ and $Ksat_V$, respectively), soil horizon boundary thickness, and root depth for both elevations of the solum for the ND and D study areas. The SWCC and $Ksat_V$ were determined from undisturbed soil cores (7.6 cm diameter x 7.6 cm radius) collected from within a 10 m radius of the automated well at each study area. The SWCC (from 0 cm to -15,000 cm) was determined from these soil cores using a low pressure (0 cm to -400 cm) cell apparatus (Klute, 1986) and from disturbed samples using a high pressure chamber (Cassel and Nielsen, 1986). The $Ksat_V$ was determined in the laboratory on these soil cores using the constant head method (Klute and Dirksen, 1986). $Ksat_L$ was determined in the field using the auger-hole method (Van Beers, 1958). All soil hydraulic and physicochemical analyses conducted are reported in Petru et al. (2013). The soil texture observed in both horizons of the ND (74 cm thick) soil profile was a silt loam and the D (122 cm thick) soil profile was a silty clay loam (Petru et al., 2013). A thick layer of coarse alluvium (80 to 130 cm) was found below the solum; above the bedrock (approximately 200 cm below the soil surface). Depth of restrictive layer (approximately 200 cm below surface) was estimated from a series of soil pits excavated during the preconstruction site analysis in conjunction with trench work conducted to install the impermeable barrier. The thickness of the coarse alluvium was estimated as the difference between the observed solum thickness and the estimated bedrock depth. Root zones were estimated from soil profiles during the excavation of the soil cores. A soil utility program within DRAINMOD calculates additional soil input values from the SWCC, $Ksat_V$, soil layer thicknesses, and root depths. The calculated inputs include relationships between the water table depth and the drained volume, upward flux, and *Green and Ampt Infiltration Parameters* (Green and Ampt, 1911).

### *Calibration of Models*

Caldwell et al (2011) showed that natural wetland hydrology of Carolina bays can be reliably predicted in DRAINMOD by adjusting the drainage parameters even though a ditch or drain network did not exist. This was done by adjusting the depth of drains, drain pipe spacing, drain pipe radius, maximum surface storage and surface roughness (micro-topography) to recreate surface and subsurface drainage intensities appropriate for the wetland. The average absolute difference (AAD) of daily water table elevations (predicted vs. observed) and the associated $R^2$ values were used as performance metrics to evaluate the predicted water table from each DRAINMOD calibration simulation against the observed well data. In this study the measurement of AAD was given more credence in the calibration process compared to the $R^2$ values because the intent of the model was to mimic water table fluctuations. The calibrations for the models were conducted against daily automated well data.

DRAINMOD can be calibrated accurately with relatively short durations of daily well readings and climate data (approximately 6 months) (He et al., 2002). The period of November 2009 to June 2011 was used in this study for the ND and D study areas at PF. Daily precipitation, and the maximum and minimum temperature were collected for PF from the 3 SE weather station Warrenton, Virginia (Station #: 448888; -77º 77’W, 38º 68’N); located approximately 16.5 km to the northwest of the study site. This maximum and minimum temperature was used to predict the daily potential evapotranspiration (PET) within DRAINMOD using a weather utility program (Robbins, 1988). Daily rainfall data recorded at the weather station was applied within the model during the hours of 5 pm and 9 pm (4 hour duration) in order to avoid conflict with the maximum hourly PET estimates.

The Thornthwaite Equation (Thornthwaite, 1948) was the default method for determining potential evapotranspiration (PET) in the DRAINMOD model. However, the Thornthwaite method can underestimate PET in the winter and overestimate PET in the summer at southern coastal plain locations (Amatya et al., 1995). Therefore, PET correction factors were developed for weather station to input into DRAINMOD. Monthly PET factors were garnered for the Warrenton, Virginia Station: 440860 (Fauquier County). A generic DRAINMOD model was created where subsurface irrigation was set to be artificially high in order to provide adequate water near the surface for removal during all months. The PET correction factors were set to 1.0 for all 12 months of the calendar year and the model was simulated to produce average monthly PET rates (1952 to 2011). The values garnered for the weather station were divided by the potential PET rates predicted by DRAINMOD to produce the monthly PET correction factors for the PF study sites (Table 1).

### *Water Budget Assumptions*

There were several assumptions made for DRAINMOD simulations of water budget and they are as follows:

- a system of parallel and equally spaced sinks (ditches or drains)
- homogeneous soil properties within each layer,
- a constant depth to impermeable restrictive layer,
- a constant rainfall rate across study area,
- water balance in the soil conducted as the sum of two zones,
    - a wet zone extending from the water table up to the root zone and perhaps to the surface. This zone was assumed to be drained to equilibrium in the soil profile,
    - and a dry zone. Water removed from the saturated root zone by PET was assumed to occur directly from the water table as long as the upward flux of water from the water table to the soil surface meets PET demand. Once the soil in the root zone reaches the wilting point no more water can be removed from the dry zone and ET was set equal to upward flux.

DRAINMOD calculated the average hydrologic inputs and outputs into the water budget across the 60 year simulation period (1952 to 2011). The daily water budget equation on the soil surface follows:

$$\Delta S = P - RO - I \qquad (1a)$$

Where the $\Delta S$ is the change in surface storage, P was the precipitation, the primary hydrologic input coming into the wetland. RO is the runoff leaving the wetland over the weir and I is volume of precipitation that infiltrated the soil profile.

The water budget within the soil profile is:

$$\Delta V_a = ET + D - I \qquad (1b)$$

Where $\Delta V_a$ is the change in soil air volume, ET is the volume of water evaporated and transpired from the soil profile back to the atmosphere, and D is the volume of water within the soil profile that drained from the site.

Surface contributions to the wetland were not included in this water budget because of the limited size of the watershed (< 4 acres) and the existence of another created wetland directly uphill which captures a majority of the uphill runoff.

### *Wetland Hydrologic Performance Criteria*

The calibrated models were used to test six performance criteria (Table 2):

- Criterion 1: a water table within 30 cm of the soil surface for at least 12.5% of the growing season (27 consecutive days in this application). This criterion corresponds to jurisdictional wetland hydrology definition as per the *Corps of Engineers Wetlands Delineation Manual (Environmental Laboratory, 1987)* and it is still the minimum threshold for acceptable hydrology when evaluating the hydrologic performance of many existing mitigation wetlands in northern Virginia (USACE and VADEQ, 2004).
- Criterion 2: water table within 30 cm of the soil surface for at least 14 consecutive days during the growing season. This is jurisdictional hydrology when conducting wetland delineations in the Atlantic and gulf coastal plain region and the eastern mountains and piedmont region of the U.S. in accordance to the updated regional supplemental guidance (USACE, 2008 and 2010, respectively).
- Criterion 3: a water table that is ponded above the surface for 7 consecutive days. This corresponds to the Natural Resource Conservation Service (NRCS) definition of a soil that is frequently ponded for a *long duration* and thus subject to hydric soils criteria (Federal Register 2012).
- Criterion 4: a water table that is ponded above the surface for 30 consecutive days. This corresponds to the NRCS definition of a soil that is frequently ponded for a *very long duration* and thus subject to hydric soils criteria (Federal Register, 2012).
- Criterion 5: a water table within the upper 30 cm of the soil profile for at least 100 consecutive days during the growing season (46.1% of growing season).
- Criterion 6: a water table ponded for at least 60 consecutive days during the growing season (27.7% of growing season).

Richter et al. (1996) developed a suite of ecologically relevant hydrologic parameters that focus primarily on frequency, duration and rate of change in hydrologic conditions in landscapes associated with rivers and dams. This method has been adapted to translate groundwater relationships in terms of vegetation community composition in efforts to support successful restoration projects (Johnson et al., 2011). However, rarely has there been a maximum threshold applied to the duration of soil saturation or ponding in forested wetland mitigation water budgets.

This limit is ecological in nature and should be defined by the physiological effects that high water tables exert on tree growth. The "ecological" upper limit to the duration that the water table was near or above the surface is different across wetland habitats (i.e. emergent vs. shrub vs. forested). Criterion 5 and 6 were selected by the authors as potential ecological upper limits for tree growth based on references regarding seedling and mature tree growth in wet conditions (Teskey, 1977 a and b; Melichar et al., 1983; Hook, 1984; Richter et al., 1996; Vreugdenhil et al., 2006). The long term simulations were conducted to predict the frequency of occurrence that each of these criteria would occur across a 60 year period (January 1952 to December 2011). Additionally the calibrated models were used to determine the longest duration that the water table would be near the surface (<30 cm) and ponded (above 0 cm) during the 60 year simulation.

The DRAINMOD models were used to assess sensitivity of the wetland performance criteria to changes in maximum surface storage, surface roughness and drainable porosity. Simulations were conducted to determine how a +/-20%, +/-40%, +/-60%, +/-80%, +/-100% change to these model parameters would influence the frequency of long-term criteria success in terms of the six performance criteria. Additional +300%, +400% and +900% change were added to the evaluation of the storage parameters. Changes to the drainable porosity were made throughout the SWCC and are presented in terms of the volume of water required to lower the water table to 30 cm below the surface (i.e., regulatory water depth) (Environmental Laboratory 1987).

## *Results*

### *Calibration of the models*

The calibration of the models started with assumed values controlling drainage intensity (i.e., drain spacing, drain depth, and $Ksat_L$ of soil horizons). Changes were then made to the parameters until drainage conditions mimicked the automated well data (Table 3, Figure 2A and B). As an example, drain spacing was originally set low at 10 meters and simulations were made after repeated incremental increases in value were made. After each parameter adjustment the model was run again and the hydrograph data was interpreted. The objective of the calibration process was to get as low of a daily AAD as possible which was accomplished by mimicking the observed water table fluctuations with the predicted model.

The models were found acceptable when the AAD was 6.59 cm and 15.8 cm for the ND and D study areas, respectively (Table 3). Approximately 74% of the variance can be explained by the ND model and 83% by the D model (Table 3). Different values were needed for the drain pipe spacing, effective radius of drain pipe, surface storage, surface roughness, and the $Ksat_L$ of the solum and buried alluvium in order to calibrate the two DRAINMOD models (Table 3). Additionally the ND model could not be calibrated to the observed well data collected at the D study area. This emphasizes the fact that the soil hydrologic data (SWCC and $Ksat_V$) used in each model were fundamentally different between the two study sites (Petru et al, 2013).

### *Water Budget Models of Nondisturbed and Disturbed Study Areas.*

The average water balance as computed in DRAINMOD for the 60 year simulations (1952 to 2011) for ND and D are given in Table 4. The water budget shows that on average 98.3

cm of precipitation comes into both study areas. Approximately 41% (40.3 cm) of the precipitation leaves the ND site as surface runoff (Table 4) because of the low surface storage (2 cm) (Table 1). The water budgets show that 59% (58.0 cm) of the precipitation infiltrates the soil profile at the ND study area (Table 4). A majority of this volume of water was discharged back to the atmosphere as ET (53.9 cm) and 4.1 cm was retained as subsurface drainage (SSD).

The water budget of the D study area showed that approximately 99.8% (98.1 cm) of the precipitation infiltrates the soil profile (Table 4). Only 0.2% (0.1 cm) of the 98.3 cm of precipitation leaves the D site as surface runoff across the weir because the increased surface storage (30 cm). Additionally there was a predicted water loss from the D study area due to ET of 52.4 cm (Table 4). The reduced runoff at the D study area translates into more water stored within and above the soil profile for some duration at the D study area, and then released slowly through the manually adjusted pipe situated above the wetland floor. A large volume of water (45.7 cm) was predicted as subsurface drainage (SSD) at the D study area compared to the ND study area (4.1 cm) because of the difference in surface storage (Table 4).

## *Long-Term Simulation Results*

### *Jurisdictional Wetland Hydrology*

The calibrated ND model satisfied Criterion 1 (30WT27D) a water table within 30 cm of the soil surface for at least 27 continuous days in 53 out of 60 years (Figure 4). The calibrated ND model satisfied Criterion 2 (30WT14D) a water table within 30 cm of the soil surface for at least 14 consecutive days in 60 out of 60 years (Figure 4). The longest duration that the water table was within 30 cm of the soil surface at the ND area during the calibrated model 60 year simulation was 90 consecutive days during the 217 day growing season (Figure 5). The ND model showed that Criterion 1 would be satisfied in at least 39 out of 60 years without surface storage (Figure 4). Furthermore, the duration of near surface saturation (<30cm) would exist for approximately 52 days during the growing season without surface storage (Figure 6). Adjustments to surface roughness had little effect on Criteria 1 or 2 (Table 6). Additionally the duration of extended flooding did not increase as surface roughness increased until surface storage had to be modified within DRAINMOD (surface roughness increases beyond 300% as shown in Figure 7).

The calibrated D model satisfied Criterion 1 (30WT27D) in 57 out of 60 years and Criterion 2 (30WT14D) in all 60 years (Figure 6). The longest duration the water table was within 30 cm of the soil surface during the calibrated D model 60 year simulation was 217 consecutive days (Figure 7). The D model showed that Criterion 1 would be satisfied in 1 out of 60 years without surface storage (Figure 6). Furthermore, without surface storage the longest duration that near surface saturation (<30cm) would be approximately 27 consecutive day during the growing season (Figure 6). The D model showed that Criteria 1 and 2 would be achieved with even small amounts of surface roughness (Table 6).

### *Ponding Conditions*

The calibrated ND model satisfied Criterion 3 (0WT7D) a water table ponded for at least 7 consecutive days in 55 of 60 years. The calibrated ND model satisfied Criterion 4 (0WT30D) a water table ponded for at least 30 consecutive days in 7 out of 60 years (Table 6). The longest duration of ponding in the calibrated ND model during the 60-year simulation was 40 consecutive days (Table 5) which represents 18% of the growing season. The calibrated D model satisfied Criterion 3 in all 60 years and Criterion 4 in 55 out of 60 years (Table 6). The longest duration of ponding in the calibrated D model during the 60 year simulation was 217 consecutive days (Table 5) which represents 100% of the growing season. Criteria 3 and 4 were positively influenced by adjustments to surface roughness in both models (Table 6).

### *Ecological Thresholds*

The calibrated ND model did not satisfy Criterion 5 (30WT100D) or Criterion 6 (0WT60D) in the 60 year simulation (Table 6). The calibrated D model satisfied Criterion 5 in 13 out of 60 years and Criterion 6 in 38 out of 60 years (Table 6). An increase in surface storage to 20 cm at the ND model satisfies Criterion 5 in 41 out of 60 years and Criteria 6 in 59 out of 60 years (Figure 6). Both models show that there is the potential for near surface saturation or ponding upwards of 217 days with just 8 cm of surface storage (Figure 5). This duration translates into the entire growing season (April 17th to October 23rd). Increases to surface roughness beyond the calibrated values had a positive influence on Criteria 5 and 6 in both models (Table 6).

## *Discussion*

The wetland construction process commonly involves soil disturbance including substantial excavation, stripping, stockpiling and redistribution of the upper soil horizons (Clewell and Lea, 1990; Stolt et al., 2000, Bruland and Richardson 2003). The loss of macro-structure 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 predictive power of a water budget of a constructed wetland (Pierce, 1993). Petru et al. (2013) showed that new soil textures can unexpectedly arise at these study sites by vertical and lateral mixing of soil horizons. There was a difference observed in the SWCC and $Ksat_V$ between the ND and D study areas that translated to the parent DRAINMOD model developed for this study. The calibration parameters (Table 3) are clearly different between the two models. The ND model could not be calibrated to the well data from the D study area regardless of parameter value modification. This shows the use of field-scale, nondisturbed soil hydraulic properties to model water tables in severely altered landscapes (cut-fill, stockpile, high traffic, etc.) may result in inaccurate predictions of hydrology.

Generally an increase in surface storage will promote longer durations of inundation that become perpetually recharged after average rainfall events, frequently before the water table has an opportunity to draw down to the surface. In these circumstances the hydrologic regime tends to maintain permanent inundation from the early fall months into the late spring or summer, followed by extreme dry conditions during the peak summer months. The comparison of water budgets shows that more water would be stored above the surface at the D study area. This resulted because the drainable porosity was reduced in the D soil profile (Petru et al. 2013) thereby promoting more water to pond at the surface. The lower subsurface storage capacity creates a demand for surface storage in order to achieve duration tolerances set forward for wetland hydrology. However, many constructed wetlands are excessively engineered to retain surface storage of 30 cm or more to conservatively guarantee jurisdictional hydrologic success criteria are achieved. Spillways and weirs elevated above the wetland capture average precipitation events and retain the water in order to offset potential drought conditions that may occur in the future. While wetland hydrology (Criteria 1 and 2) may be achieved in every year at Peters Farm, surface storage increases beyond 300% (up to 8 cm) in the ND model and as little as -60% (up to 12 cm) in the D model translate into ponding durations that exist throughout most if not all of the growing season and (Figure 5 and Figure 7, respectively). Most bottomland hardwood species that are commonly planted in created wetlands, such as oaks (*Quercus spp*.), ashes (*Fraxinus spp*.), maples (*Acer spp*.) and elms (*Ulmus spp*.), tend to die as a result of repeated ponding for extended durations when plant productivity and air temperature are at the highest (Teskey, R., 1977 a and b, Melichar et al., 1983; Hook, 1984; Vreugdenhil et al., 2006). The application of an ecological upper limit to the duration of inundation is often ignored when creating mitigation wetland water budgets (regardless of habitat type) because the focus is centralized around achieving minimum duration standards for wetland hydrology. Perhaps more emphasis should be placed on the use of surface roughness perpendicular to the direction of hydrologic discharge from the wetland in order to attenuate near surface saturation between rainfall. An unintended consequence in over-engineering surface storage may be prolonged durations of inundation between average precipitation events as shown in this example. This may result in a shift from the target hydrology for forested wetland habitat towards that of open water or submerged aquatic vegetation.

Limitations are shown in this study regarding DRAINMOD in application to wetland designs where a drain pipe may be at or elevated above the surface. The prediction of the water budget (Equations 1a and 1b) for both study areas (Table 4) needs to be carefully interpreted, particularly the infiltration and drainage components. DRAINMOD calculates two equations (Equations 1a and 1b) to predict subsurface drainage from a wetland. Determination of which equation was applied depended on the elevation of the water table in relation to the soil surface. If the elevation of the ponded water was above the surface roughness ($S_r$) the model used the Kirkham equation (Kirkham 1957) for subsurface drainage under ponded conditions. The Kirkham equation assumes that the ponded water can move across the surface toward the drain before entering the soil and becoming subsurface flow. The flow described in the Kirkham equation results in higher drainage rates since most of the flow path was unrestricted and the preferred subsurface flow paths are short (Figure 3A). Once the ponded water table was below $S_r$, the water cannot flow freely across the surface and infiltrates into the soil, then DRAINMOD used the Hooghoudt equation (1940) that predicts subsurface drainage under these conditions. The result was lower subsurface drainage rates since all the flow paths through the soil are much longer and through a restrictive media (Figure 3B). Therefore, the use of the Kirkham equation in our simulations served as a surrogate for the process of surface water moving across the soil surface and through the management pipe (Figure 3C). The water loss predicted by DRAINMOD as subsurface drainage should probably be considered surface runoff in this particular situation. The output from the wetland system would likely occur as short term ponding maintained by a slow draw down of the water table which would be controlled by elevation of the PVC pipe. The model currently uses the Kirkham equation to describe surface flow to the sink and a routine should be added to DRAINMOD that better describes surface drainage below maximum storage in these systems where a pipe was used to control draw down.

This study originally included a second study site that was dominated by smectitic (shrink-swell) clay soils. The hysteresis effect that occurs as a result of the shrinking and swelling process presents difficulties in the DRAINMOD model in regards to predicting the effect that ET has on water table draw down and upward flux. DRAINMOD models similar to this study could not be calibrated to observed well data from landscapes containing these soil types. This was because the drainable porosity was different between wetting and drying conditions. Improvements to DRAINMOD are needed in terms of the method the model uses to predict the soil water content during the wetting and drying processes once the water table has disappeared.

## *Conclusion*

This study presented an application of DRAINMOD to model created mitigation wetlands without drainage networks that are located in fine to coarse grained alluvial soils and evaluate the model responses to changes in drainage parameters. The results show how some key soil hydraulic properties collected from the preconstruction landscape could not be used to predict hydrologic regime of the post-disturbance landscape setting because they were changed by construction activities. The difference in key soil hydraulic properties that influence subsurface water storage and movement resulted in a nondisturbed water table model that could not be calibrated to accurately predict hydrologic conditions at the disturbed study area. The calibration of the disturbed model also showed that drainage parameter values other than those of the nondisturbed model are needed for the disturbed model to accurately predict water table fluctuation. More research is needed to investigate how key soil hydraulic properties important for subsurface water storage and movement respond to disturbance across different soil textures. There is also a need for a better understanding of how soil hydraulic properties affecting subsurface water storage and movement change over time with soil development and how this applies to wetland restoration. This may require the consideration of soil properties in their disturbed state if appropriate. Water budgets that model created or restored wetlands in which there is significant soil disturbance should use soil hydraulic properties that reflect their disturbed state as these soil conditions will remain for some time post construction.

Further improvements to DRAINMOD are needed to more accurately predict surface outputs from a management pipe located within a surface berm and above the surface of the wetland bench. The simulations showed that increases in surface roughness and surface storage can extend ponded or near surface saturated conditions throughout most or all of the growing season. The reduced drainable porosity at the disturbed study area translated into less subsurface water storage. Therefore surface storage improvements were needed to calibrate the model and achieve success criteria. Although these jurisdictional hydrology performance criteria may be achieved, large storage volumes may have an adverse impact on the intended hydrologic regime and result in perpetual ponding throughout most or all of the growing season. This may translate into a shift from forested wetland habitat towards that of open water or submerged aquatic vegetation, and a net loss in mitigated wetland value.

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Table 1. DRAINMOD monthly ET correction factors created for Warrenton, Virginia, Station: 440860.

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.03 | 0.38 | 0.80 | 0.90 | 0.84 | 0.85 | 0.84 | 0.95 | 1.11 | 1.13 | 1.13 | 0.56 |

Table 2. Performance criteria applied for DRAINMOD simulations in this study.

| ID | Definition |
|---|---|
| Criterion 1 (30WT27D) | Jurisdictional wetland hydrology defined as the water table within 30 cm of the soil surface for 12.5% of the 219 day growing season – 311 consecutive days (Environmental Laboratory, 1987) |
| Criterion 2 (30WT14D) | Jurisdictional hydrology defined as the water table within 30 cm of the soil surface for 14 consecutive days. ((USACE, 2008; USACE, 2010). |
| Criterion 3 (0WT7D) | Ponding on the soil surface for 7 consecutive days (NRCS ponded for long duration definition). |
| Criterion 4 (0WT30D) | Soil ponded on the soil surface for 30 consecutive days (NRCS ponded for a very long duration definition). |
| Criterion 5 (30WT100D) | Water table within 30 cm of the soil surface 100 consecutive days. Ecological upper limit |
| Criterion 6 (0WT60D) | Ponding on the soil surface for 60 consecutive days. Ecological upper limit |

Table 3. Calibration values of the nondisturbed (ND) and disturbed (D) areas of Peters Farm wetland DRAINMOD models.

| Variable | ND | D |
|---|---|---|
| Drain Depth from Surface (cm) | 40 | 110 |
| Drain Pipe Spacing (m) | 900 | 33 |
| Effective Radius of Pipe (cm) | 5 | 20 |
| Maximum Surface Storage (cm) | 2 | 30 |
| Sufrace Roughness (cm) | 1 | 10 |
| Depth to Bedrock (cm) | 200 | 250 |
| $Ksat_L$ of Solum (cm/hr) | 2.7 | 0.6 |
| Deep $Ksat_L$ (cm/hr) | 1.0 | 0.1 |
| AAD (cm) | 6.59 | 15.8 |
| $R^2$ | 0.74 | 0.83 |

Table 4. Average water balance for the modeled well locations in the study sites during the modeled 60 year simulation (January 1952 to January 2012. The percent of the total hydrologic input is given in parentheses.

| | Inputs | Outputs | | | |
|---|---|---|---|---|---|
| Location | Precipitation | Runoff (RO) | Infiltration (I) | Evapotranpiration (ET) | Drainage (D)_ |
| ND | 98.3 (100%) | 40.3 (41.0%) | 58.0 (59.0%) | 53.9 | 4.1 |
| D | 98.3 (100%) | 0.1 (0.2%) | 98.1(99.8%) | 52.4 | 45.7 |

Table 5. The effect that changes in surface roughness has on the single longest duration (days) of hydrologic occurrence that the water table is near the surface (<30 cm) and ponded (>0 cm) across a 60-year simulation (1952-2012) for the Nondisturbed (ND) and Disturbed (D) study areas.

| | Nondisturbed (ND) area | | | | | | | | | | | | | | Disturbed (D) area | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % Change | -100 | -80 | -60 | -40 | -20 | 0 | 20 | 40 | 60 | 80 | 100 | 300 | 400 | 900 | -100 | -80 | -60 | -40 | -20 | 0 | 20 | 40 | 60 | 80 | 100 | 300 | 400 | 900 |
| Surface Roughness (cm) | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2[#] | 4[#] | 5[#] | 10[#] | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 40[#] | 50[#] | 100[#] |
| < 30 cm | 86 | 86 | 89 | 89 | 90 | 90 | 95 | 95 | 95 | 95 | 100 | 217 | 217 | 217 | 51 | 93 | 97 | 160 | 161 | 181 | 217 | 217 | 217 | 217 | 217 | 217 | 217 | 217 |
| Ponded | 39 | 39 | 40 | 40 | 40 | 40 | 43 | 41 | 46 | 46 | 85 | 101 | 217 | 217 | 28 | 45 | 92 | 96 | 217 | 217 | 217 | 217 | 217 | 217 | 217 | 217 | 217 | 217 |

[#] Surface storage set to twice the surface roughness value.

Table 6. The effect that changes in surface roughness has on the hydrologic performance criteria across a 60-year simulation (1952-2012) for the Nondisturbed (ND) and Disturbed (D) study areas.

| | Nondisturbed area (ND) | | | | | | | | | | | | | | Disturbed area (D) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % Change | -100 | -80 | -60 | -40 | -20 | 0 | 20 | 40 | 60 | 80 | 100 | 300 | 400 | 900 | -100 | -80 | -60 | -40 | -20 | 0 | 20 | 40 | 60 | 80 | 100 | 300 | 400 | 900 |
| Surface Roughness (cm) | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | $2^{\#}$ | $4^{\#}$ | $5^{\#}$ | $10^{\#}$ | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | $20^{\#}$ | $40^{\#}$ | $50^{\#}$ | $100^{\#}$ |
| Criterion 1 (30WT24D) | 52 | 52 | 53 | 53 | 53 | 53 | 53 | 53 | 54 | 55 | 59 | 60 | 60 | 60 | 15 | 36 | 50 | 55 | 57 | 57 | 57 | 57 | 57 | 57 | 57 | 58 | 58 | 58 |
| Criterion 2 (30WT14D) | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 44 | 53 | 58 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| Criterion 3 (0WT7D) | 55 | 55 | 55 | 56 | 56 | 55 | 56 | 56 | 57 | 57 | 60 | 60 | 60 | 60 | 21 | 52 | 56 | 62 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| Criterion 4 (0WT30D) | 4 | 4 | 5 | 6 | 6 | 7 | 8 | 14 | 14 | 14 | 43 | 57 | 59 | 59 | 0 | 7 | 31 | 42 | 50 | 55 | 56 | 56 | 56 | 57 | 57 | 57 | 57 | 57 |
| Criterion 5 (30WT100D) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 13 | 18 | 45 | 0 | 0 | 0 | 4 | 7 | 13 | 19 | 22 | 28 | 30 | 31 | 39 | 40 | 42 |
| Criterion 6 (0WT60D) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 38 | 48 | 59 | 0 | 0 | 3 | 11 | 28 | 38 | 45 | 46 | 47 | 47 | 47 | 50 | 50 | 52 |