

Assessment of water budgets and the hydrologic performance of a created mitigation wetland—A modeling approach



Bradley J. Petru^a, George M. Chescheir^b, Changwoo Ahn^{a,*}

^a Department of Environmental Science and Policy, George Mason University, 4400 University Drive, Fairfax, VA 22030, USA

^b Department of Biological and Agricultural Engineering, North Carolina State University, Box 7625, Raleigh, NC 27695, USA

ARTICLE INFO

Article history:

Received 26 September 2013

Received in revised form 16 July 2014

Accepted 8 August 2014

Keywords:

Wetland hydrology
Soil disturbance
Water budget model
Wetland mitigation
Created wetlands
DRAINMOD

ABSTRACT

The study used a water balance model (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 along with precipitation, temperature, soil physical properties (soil water characteristic curve and saturated hydraulic conductivity) and estimated site characteristics (surface roughness and surface storage). The model was tested for two areas, one nondisturbed and the other disturbed, by construction practices commonly adopted for a mitigation wetland created in the region. A third model was created to represent the disturbed boundary conditions (wetland design), but substituted soil data observed at the nondisturbed study area. DRAINMOD successfully predicted the hydrologic regimes of both nondisturbed and disturbed areas. The model of the nondisturbed area could not accurately predict hydrology of the disturbed area. More importantly, the model of the disturbed area with the soils data from the nondisturbed area could not accurately predict the hydrology of the disturbed area. The models were used to evaluate a set of performance criteria across a 60-year (1952 to 2011) simulation period. Ponding for longer than 60 consecutive days during the growing season occurred at the disturbed study area in 39 out of 60 years and these conditions lasted the entire growing season (219 days) in multiple years. Prolonged inundation of the surface for longer than 100 consecutive days took place in at least 15 of the years simulated compared to two years in the nondisturbed model. The modified disturbed model (using nondisturbed soil data) satisfied jurisdictional hydrology more frequently compared to the disturbed model (33 years versus 22 years, respectively) and prolonged inundation was limited to 8 years during the simulation period with the longest single event lasting 168 consecutive days. The differences were attributed to the reduced drainable porosity and vertical saturated hydraulic conductivity in the disturbed wetland area which translated to a demand for surface storage in order to achieve accurate model calibration and jurisdictional wetland hydrology. The study shows that disturbance to key soil properties will require surface storage to achieve jurisdictional hydrology, and that construction practices can result in longer durations of ponding during the growing season, thus potentially altering the habitat type for the wetland from what was originally designed (e.g., from a forested wetland to open water or emergent habitats).

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1. Introduction

One of the many uses of a water budget model is to predict the post-construction hydrologic regime of a constructed or restored wetland (Pierce, 1993; Daniels et al., 2000), and this is performed during the feasibility stage. Precision in the water budget model is important for regulatory success (US Army Corps of Engineers

Norfolk District and VA DEQ, 2004), and because wetland habitat composition and function are dependent on the relationship of the water table relative to the soil surface (Richter et al., 1996; Mitsch and Gosselink, 2007). The water budget uses soil hydraulic properties and long term climate data to predict the average long term hydrology that will occur as a result of a proposed grading plan. The soil properties in the model typically reflect the undisturbed (pre-construction) landscape where the wetland will be built or restored. The precision of a water budget model may become compromised by ignoring groundwater storage, assuming soil hydraulic properties from literature to represent field

* Corresponding author. Tel.: +1 703 993 3978; fax: +1 703 993 1066.
E-mail address: cahn@gmu.edu (C. Ahn).

conditions, and/or using nondisturbed soil properties to predict disturbed soil conditions. It is important to understand the influence that disturbed soil properties (collapsed pore space, reduced vertical saturated hydraulic conductivity, or other) have on the water budget model in order to achieve both ecological and regulatory success criteria.

It is difficult to engineer forested wetland mitigation hydrology without overcompensating water storage (inducing long durations of inundation) because one needs to consider variation in climate from year to year while achieving wetland hydrology in most years. Surface berms are often used to achieve mitigated wetland hydrologic success because a wetland is replacing another impacted wetland, it is an expensive process, and vegetative growth is directly dependent on the hydrologic regime (Pierce, 1993). Teskey and Hinckley (1977a) identified flood frequency, flood duration, time of year of the flooding occurrence, water depth, and siltation as critical factors that affect vegetation communities within wetland systems and this holds true to forested mitigation wetlands. 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 during the late fall, winter, and early spring seasons when tree growth is dormant, followed by a natural draw down of the water table below the surface during the peak of the growing season when vegetative productivity is at the maximum (Tiner, 1999; Sun et al., 2002). Forested wetland hydrology is inherently dependent on soil structure in the near surface root zone and the ability for the water table to migrate through it.

A problem with the modeling process is that the model (or user) often presumes that optimum soil hydraulic properties for a given soil unit will persist immediately after construction close out. Heavy earth-moving machinery has a negative effect on soil structure, porosity, water retention capacity, specific yield, infiltration and soil aeration (Ballard, 2000; Lenhard, 1986; Sun et al., 2002; Xu et al., 2002). A similar negative effect has been found to result from bedding and harvesting during silvicultural activities, and from tillage practices associated with agricultural production (Bosch et al., 2008; Buczko et al., 2006; Glab and Kulig, 2008; Hagen et al., 2002; Lopez et al., 1996; Lyon et al., 1998; Prevost, 2004; McFero Grace et al., 2006; Richard et al., 2001; Sillon et al., 2003; Tarawally et al., 2004; Tomer et al., 2006). Studies on constructed wetlands have shown that soil disturbance resulting from the construction activities has a negative effect on the desired wetland hydrology (Bruland and Richardson, 2004, 2005; Campbell et al., 2002; Cole and Brooks, 2000; Gilbert, 1994; Stolt et al., 2000). These hydraulic properties are important for soil water storage and movement which directly effects the performance of a water budget model and influences wetland habitat development. The loss of soil water storage in created forested wetland soils will result in reduced infiltration, increased surface runoff or prolonged durations of ponding; and thus an inappropriate hydrologic regime for the desired habitat (permanently ponded, ponded to drought-like, or inappropriate hydrology at the wrong point in the growing season) (Tiner, 1999).

DRAINMOD (Skaggs, 1978; Skaggs et al., 2012) is a powerful field scale, water budget model that has been used extensively in agricultural production and wetland management. The model has been used to correlate the frequency and duration of water table inundation to 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 wetlands.

This study used DRAINMOD to investigate the changes to soil hydraulic properties that resulted from the construction of a wetland, and examined how disturbed soil properties influenced the accuracy of a water budget model. DRAINMOD was used to calibrate field observed well and soil hydraulic property data taken from a landscape that represents before (nondisturbed) and after (disturbed) the construction of a forested mitigation wetland. The DRAINMOD model of the disturbed study area was used in conjunction with soils collected from the nondisturbed study area to evaluate how the nondisturbed soils would predict the hydrology in the proposed wetland landscape boundary conditions (wetland design). Long term simulations (January 1952 to December 2011) were conducted to test how the Disturbed (D), Nondisturbed (ND); and the Disturbed Alt (D_{alt}) models, or the disturbed model containing soils hydraulic properties observed at the nondisturbed study area, would meet a suite of performance criterion. The implication of the results was discussed in terms of regulatory and ecological considerations in wetland mitigation.

2. Methods

2.1. Site description

Peters Farm (PF) wetland mitigation bank (38°23'44.38"N, 77°55'58.36"W) was constructed on alluvial deposits originating from the red silt-stone and diabase bedrock material of the Culpeper Basin rift formation located within the Piedmont physiographic province. The wetland is situated within the floodplain of Elk Run, approximately 5.3 km southeast of Calverton, Virginia. 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 Fluvaquent Dystrudepts), a soil listed to contain hydric inclusions of the Bowman series (mesic Typic Endoaquolls) at 5% and Albano series (mesic Typic Edoaqualls) 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 (0.1 to 1.0 m high by 3 m wide) that are held constant at 66.8 m above mean sea level (msl). There was a single primary earthen spillway 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 spillway over an approximate 900 m distance (0.1% slope). A sub-surface 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. A single polyvinyl chloride (PVC) drainage pipe (approximately 0.2 m in diameter) was installed within the spillway section of the berm at approximately 65.9 m above msl. A free-rotating, 90-degree elbow with a straight riser pipe (both PVC) were attached to the main PVC drainage pipe. The inverted elevation of the PVC riser pipe was rotated to approximately 66.3 m above msl during this study.

This configuration allows for manual adjustment of the outflow elevation in order to determine the permanent spillway elevation. A majority of the surface outflow is conveyed through the drainage pipe unless the adjacent river is at flood stage. 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 (approximately 100 m apart) as a majority of the field was left ungraded. 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.

2.2. DRAINMOD model

DRAINMOD is a field tested computer model developed to predict drainage conditions in poorly drained soils (Skaggs, 1978; Skaggs et al., 2012). The model assumes there are parallel drainage sinks (ditches, tiles, or pipes) at a defined spacing and depth above a restrictive layer. The precision of a model is greatly amplified with specific information on soil and climate conditions. DRAINMOD uses soil properties for each soil horizon above the restrictive layer, weather data, plant variables and site characteristics to calculate hourly water budgets of a system. Drainage parameters and site characteristic inputs include surface storage, surface roughness (minor surface undulations), depth of drain from surface, effective radius of drains, drain spacing, actual distance from surface to impermeable layer, rooting depth, and soil properties (Skaggs, 1978). 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.

The model uses the Hooghoudt equation (Hooghoudt, 1940) to predict the relationship between water table depth and the drainage rate. Water table depths are predicted hourly at the midpoint between the two drainage sinks. 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).

2.3. Soil hydraulic and physicochemical analyses

All soil hydraulic and physicochemical data used in these DRAINMOD models were collected, analyzed and reported by Petru et al. (2013). Soil property inputs to the model include the mean soil water characteristic curve (SWCC), mean lateral and vertical saturated hydraulic conductivity (K_{sat_L} and K_{sat_V} , respectively), mean soil horizon boundary thickness, and mean root depth for both elevations of the solum (upper horizon: <25 cm and lower horizon: >40 cm) for the ND and D study areas. The soil texture observed in both horizons of the ND study area (74 cm thick) soil profile was a silt loam and the D study area (122 cm thick) soil profile was a silty clay loam (Petru et al., 2013). A thick layer of coarse alluvium (170 to 220 cm thick) was found below the solum; above the bedrock (approximately 300 cm below the soil surface). Depth of restrictive layer (approximately 300 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 observations of soil profiles during the excavation of the soil cores. A soil utility program within DRAINMOD calculates the relationships

between the water table depth and the drained volume, upward flux, and Green and Ampt Infiltration Parameters (Green and Ampt, 1911) from the SWCC, K_{sat_V} , soil layer thicknesses, and root depths.

2.4. 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. DRAINMOD can be calibrated accurately with relatively short durations of daily well readings and climate data (approximately 6 months) (He et al., 2002; Skaggs et al., 2012). The absolute deviations between observed and predicted daily water table depths and the associated coefficient of determination (R^2) values were used as calibration metrics. The average absolute deviation is defined as follows:

$$AAD = \frac{\sum |Y_m - Y_p|}{n} \quad (1)$$

where, AAD is the average absolute deviation (cm), Y_m is the measured water table at the end of each day (cm), Y_p is the predicted water table depth at the end of each day (cm), and n is the number of days for which data was collected. Caldwell et al. (2011) gave the measurement of AAD more credence in the calibration process compared to the R^2 values because the intent of the model is to mimic water table fluctuations. However, in recent years more criticism has been put on the calibration methods (Moriasi et al., 2007), and therefore the Nash–Sutcliffe measure of efficiency (E) was also used to critique the calibration performance as defined in Legates and McCabe (1999).

The period of November 2009 to June 2011 was used in our study to calibrate the ND model and the period from September 2010 to August 2011 was used to calibrate the D study areas. Daily precipitation, and the maximum and minimum temperature were collected for PF from the National Weather Service (NWS) Warrenton, Virginia (Station no.: 448888; $-77^\circ 77'W$, $38^\circ 68'N$); 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 the Thornthwaite Equation (Thornthwaite, 1948). The Thornthwaite Equation produces daily PET values which are distributed within the model over a 12 h period (7 am to 7 pm) when daylight is assumed to have an influence on PET. Daily rainfall data recorded at the weather station was disaggregated into hourly values within the model and distributed during the hours of 5 pm and 9 pm (4 h duration). The distribution time frame was chosen to coincide with the period when thunderstorms are most common and to provide the rainfall volume equal exposure to the influence of PET and nightfall.

The Thornthwaite Equation 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 the weather station to input into the PF DRAINMOD models. In order to create PET correction factors, monthly 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 in DRAINMOD 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). Mean open water evapotranspiration (ET) estimates calculated from the Penman–Monteith method were garnered from the North Carolina Climate Retrieval and Observations Network of the Southeast Database (NC CRONOS) for both the Dulles International Airport in Loudoun County, Virginia (National Weather Service–Automated Surface Observation System (NWS–ASOS) for May 2002 to December 2009), and the Culpeper, Virginia regional airport (Federal Aviation Administration–Automated Weather Observation System (FAA–AWOS) for September 2002 to December 2009) and averaged together to produce mean monthly ET values for the region. The mean monthly ET values garnered from CRONOS were then divided by the PET rates predicted by DRAINMOD to produce the monthly PET correction factors for the PF DRAINMOD study sites.

The objectives were to create two DRAINMOD models which accurately predict hydrology at the ND and D study areas. Then soils data (SWCC, K_{sat_v} , and the K_{sat_l} value for the solum) collected at the nondisturbed study area were input into the calibrated D model to determine if it could accurately predict the hydrology observed at the D study area. These models (ND, D, and Dalt) were used to predict the long term water budget (1952 to 2011) and to evaluate a suite of performance criteria.

2.5. Water budget assumptions

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

- a system of parallel and equally spaced sinks (ditches or drains) estimates subsurface drainage,
- 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 to the surface. This zone was assumed to be drained to equilibrium in the soil profile,
- 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 (upward movement) of water from the water table to the soil surface meets the demand of PET (Skaggs, 1978; Skaggs et al., 2012). Upward flux is calculated in a soil preparation program when setting up DRAINMOD and it uses the Darcy–Buckingham equation for unsaturated flow. When upward flux does not meet the PET demand, water is removed from the dry zone to satisfy PET. Once the dry zone reaches the rooting depth 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 water balance is calculated hourly for a section of the soil surface area which extends from the surface down to an impermeable layer and is located midway between two parallel drains or sinks (Skaggs et al., 2012). In this study, the wetland surface is represented by the midpoint between the two drains as done by He et al. (2002) and the outfall pipe represents the drain or sink. The water budget equation on the soil surface follows:

$$\Delta S = P - SO - I \quad (2)$$

where the ΔS is the change in surface storage (cm), P is the precipitation (cm), the primary hydrologic input coming into the wetland. SO is the surface outflow leaving the wetland over the weir (cm) and I is volume of precipitation that infiltrated the soil profile (cm).

The water budget within the soil profile is:

$$\Delta V_a = ET + D - I \quad (3)$$

where ΔV_a is the change in soil air volume or water free pore space (cm), ET is the volume of water evaporated and transpired from the soil profile back to the atmosphere (cm), and D is the volume of ground water within the soil profile that drained from the site (cm).

Surface contributions to the wetland were not included in this water budget because of the limited size of the uphill watershed (<4 ac) and the existence of another created wetland (approximately 2.5 ac in size) situated directly uphill. While this wetland does convey to the study area, the smaller wetland captures a majority of the uphill runoff and has not been observed to contribute much hydrology to the study area as a result of the large surface storage in the smaller wetland cell.

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 (Eqs. (2) and (3)) for both study areas (Table 2) needs to be carefully interpreted, particularly the infiltration and drainage components. DRAINMOD calculates two equations (Eqs. (2) and (3)) 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 (Fig. 2a). 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 (Hooghoudt, 1940) which 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 (Fig. 2b). 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 (Fig. 2c). The water loss predicted by DRAINMOD as subsurface drainage should probably be considered surface outflow in this particular situation due to the geotextile liner limiting subsurface outflow. 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.

2.6. Wetland hydrologic performance criteria

The calibrated models were used to test six performance criteria (Table 1). 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. However, water budgets designed for mitigation purposes tend to be conservative and generally do not consider excess water as a problem. Rarely has there been a maximum threshold applied to the duration of soil saturation or ponding in forested

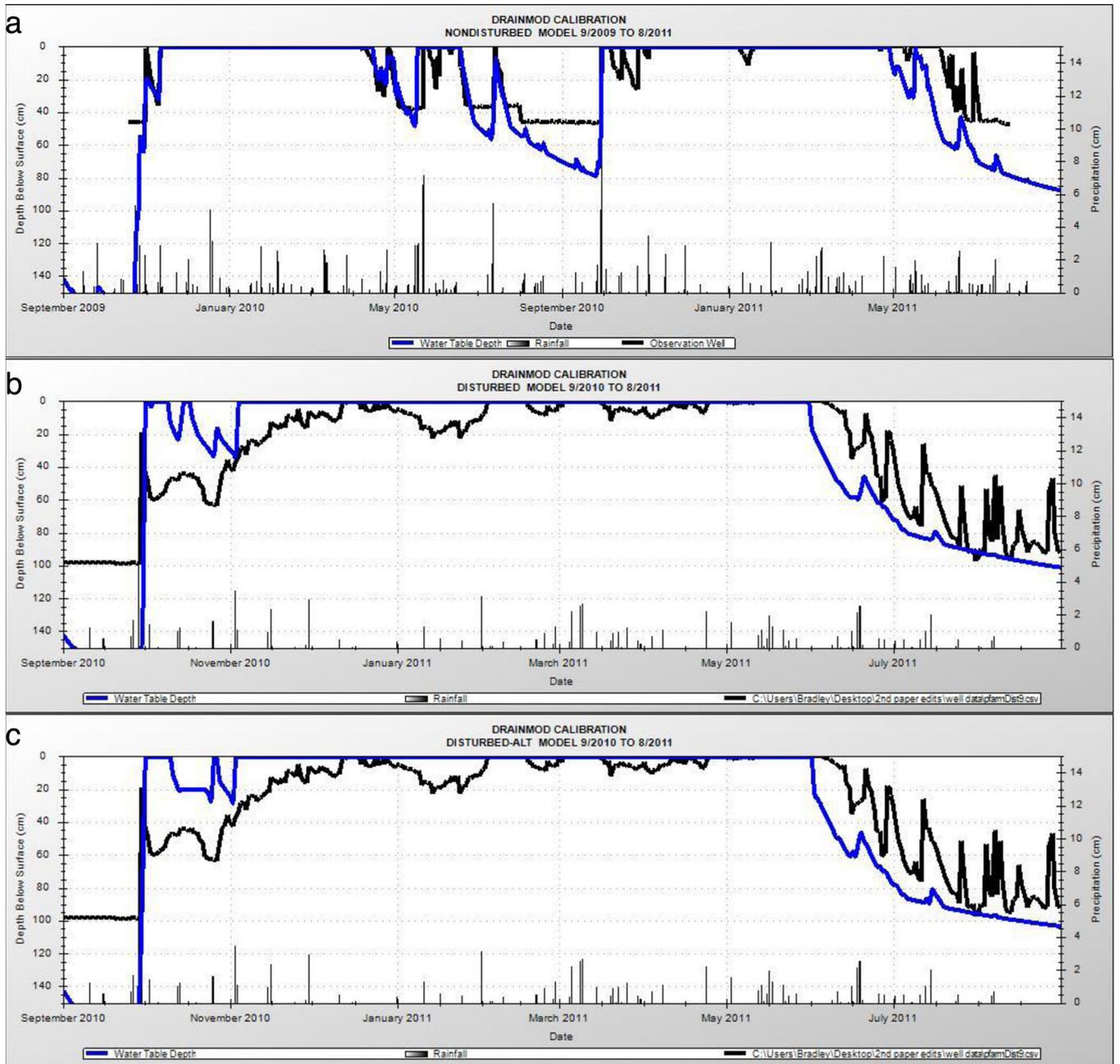


Fig. 1. (a) Calibration of the PF nondisturbed DRAINMOD model to observed well data. (b) Calibration of the PF disturbed DRAINMOD model to observed well data. (c) Simulation of the PF disturbed-alt DRAINMOD model in comparison to observed well data collected at the disturbed study site.

Table 1
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—27 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. ((US Army Corps of Engineers, 2008, 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 2
DRAINMOD model parameters used in the calibrated ND and D models.

Parameter	ND	D
Drain pipe depth (cm)	120	120
Drain pipe spacing (cm)	9000	6000
Drain pipe radius (cm)	5	5
Surface storage max (cm)	10	30
Surface roughness (cm)	5	15
Lateral saturated hydraulic conductivity		
Top horizon (cm/h)	0.2	0.02
Bottom horizon (cm/h)	1.0	1.0

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 is 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 and Hinckley, 1977a,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.

3. Results

3.1. Calibration of the models

The calibration of the models started with assumed values controlling drainage intensity (i.e. drain spacing, drain depth, and K_{satL} of soil horizons). Changes were then made to the parameters until drainage conditions mimicked the automated well data (Fig. 1a and b). The soil data from the nondisturbed study area was input into the disturbed model (D_{alt}) and was also compared to the automated well data (Fig. 1c). Parameters such as drain spacing were interpreted from aerial imagery and then simulations were made after repeated incremental increases and decreases in value were made to fine tune their influence on the ND and D models. After each parameter adjustment the model was run again and the hydrograph data and validation metrics were interpreted. Drain spacing was calibrated first, then this strategy was repeated for drain depth, surface storage, and surface roughness. Drain depth was initially estimated as the elevation difference from the study area to the landscape elevation outside the wetland outfall. The initial depth of maximum surface storage was estimated from the distance from the study area to the spillway elevation of the wetland. Incremental changes were then made to both of these parameters and the results were reviewed. Surface roughness was set at one half the maximum surface storage in both models (Table 2). The objective of the calibration process was to get as low of a daily AAD, and as high of an R^2 and E value as possible by mimicking the observed water table fluctuations with the predicted model. Different calibration values were needed for the drain pipe spacing (9000 cm and 6000 cm), surface storage (10 cm and 30 cm), and surface roughness (5 cm and 10 cm) for the ND and D models, respectively (Table 2).

The ND model was found to be in good agreement with an AAD of 8.9 cm, an R^2 value of 0.71 and an E value of 0.12 (Table 3). The D model was found to be in good agreement with an AAD of 17.9 cm, an R^2 value of 0.78 and an E value of 0.45. The D_{alt} model was found

Table 3
Measure of model calibration in terms of absolute average difference (AAD), coefficient of determination R^2 , and efficiency (E).

Model ID	AAD (cm)	R^2	E
ND	8.9	0.71	0.12
D	17.9	0.79	0.45
D_{alt}	18.1	0.77	0.40

to be in good agreement with an AAD of 18.1 cm, R^2 value of 0.77 and an E value of 0.45 (Table 3).

3.2. 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, D and D_{alt} are given in Table 4. The water budget shows that on average 98.3 cm of precipitation comes into all three models. Approximately 9.0% (8.8 cm) of the precipitation leaves the ND site as surface runoff (Table 4) because of the low surface storage (10 cm) (Table 2). The water budgets show that 91.0% (89.4 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 (65.6 cm) and 23.7 cm was released 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% (0.2 cm) of the 98.3 cm of precipitation leaves the D site as surface runoff across the weir because of the increased surface storage (30 cm). Additionally there was a predicted water loss from the D study area of 68.1 cm due to ET (Table 4). A large volume of water (29.9 cm) was released as subsurface drainage (SSD) (Table 4).

The water budget of the D_{alt} simulation showed that approximately 96.5% (94.9 cm) of the precipitation infiltrates the soil profile (Table 4). Only 3.5% (3.4 cm) of the 98.3 cm of precipitation leaves the D_{alt} site. Additionally there was a predicted water loss from the D_{alt} study area of 69.2 cm due to ET (Table 4). A large volume of water (25.5 cm) was released as subsurface drainage (SSD) (Table 4).

3.3. Long-term simulation results

3.3.1. Jurisdictional wetland hydrology

The calibrated ND model satisfied Criterion 1 (30WT27D) in 57 out of 60 years and Criterion 2 (30WT14D) in 58 out of 60 years (Table 5). There were 13 years out of the 60 year simulation where the water table was within 30 cm of the surface for longer than 100 consecutive days in the ND model. The calibrated D model satisfied Criterion 1 (30WT27D) in 56 out of 60 years and Criterion 2 (30WT14D) in 57 out of 60 years (Table 5). There were 22 years out of the 60 year simulation where the water table was within 30 cm of the surface for longer than 100 consecutive days in the D model. The D_{alt} model satisfied Criterion 1 (30WT27D) in 56 out of 60 years and Criterion 2 (30WT14D) in 57 out of 60 years (Table 5). There were 33 years out of the 60 year simulation where the water table was within 30 cm of the surface for longer than 100 consecutive days in the D_{alt} model.

3.4. Ponding conditions

The calibrated ND model satisfied Criterion 3 (0WT7D) a water table ponded for at least 7 consecutive days in 49 of 60 years (Table 5). The calibrated ND model satisfied Criterion 4 (0WT30D) a water table ponded for at least 30 consecutive days in 39 out of 60

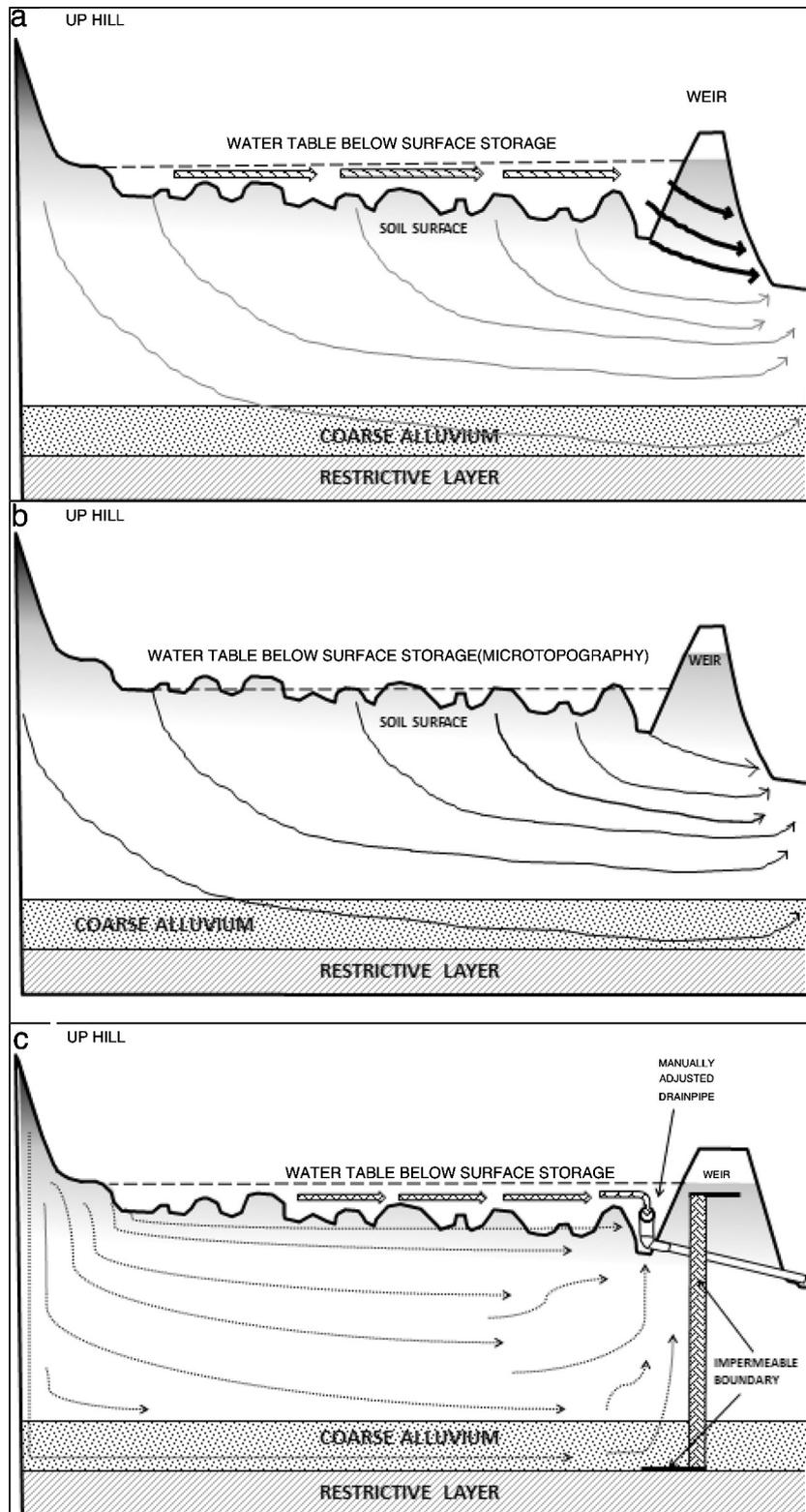


Fig. 2. (a) DRAINMOD model conditions when water table is below weir but above surface roughness (Kirkham's flow). (b) DRAINMOD model conditions when water table is below surface roughness but above soil surface (Hoogoudt flow). (c) Drainage conditions that are really occurring with DRAINMOD for the PF constructed wetland.

years (Table 5). The longest duration of ponding in the calibrated ND model during the 60-year simulation was 219 consecutive which represents 100% of the growing season, but this occurred once during the 60 year simulation period. Two separate years across the 60 year simulation period had ponding for longer than 100 days. The

calibrated D model satisfied Criterion 3 in all 60 years and Criterion 4 in 57 out of 60 years. The longest duration of ponding in the calibrated D model during the 60 year simulation was 219 consecutive days which represents 100% of the growing season. There were 15 separate years where ponding exceeded 100 continuous days

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.

Location	Inputs	Outputs			
	Precipitation	Runoff (RO)	Infiltration (I)	Evapotranspiration (ET)	Drainage (D)
ND	98.3 (100%)	8.9 (9.0%)	89.4 (91.0%)	65.6	23.7
D	98.3 (100%)	0.04 (0.0004%)	98.1(99.8%)	68.1	29.9
D _{alt}	98.3 (100%)	3.9 (4.0%)	94.4(96.0%)	69.2	25.5

during the 60 year simulation. The D_{alt} model satisfied Criterion 3 in all 38 out of 60 years and Criterion 4 in 30 out of 60 years (Table 5). The longest duration of ponding in the D_{alt} model during the 60 year simulation was 168 consecutive days which represents 77% of the growing season. Only eight years out of 60 experienced ponding conditions for longer than 100 consecutive days.

3.5. Ecological thresholds

The calibrated ND model satisfied Criterion 5 (30WT100D) 13 years out of the 60 year simulation and satisfied Criterion 6 (0WT60D) in 17 out of 60 years (Table 5). The calibrated D model satisfied Criterion 5 in 22 out of 60 years and Criterion 6 in 39 out of 60 years. The D_{alt} model satisfied Criterion 5 in 33 out of 60 years and Criterion 6 in 21 out of 60 years (Table 5).

4. Discussion

The wetland construction process commonly involves soil disturbance including substantial excavation, stripping, stockpiling and redistribution of the upper soil horizons (Stolt et al., 2000; Bruland and Richardson, 2004). In this study, the loss of macropore structure within the soil matrix at the D study area (Petru et al., 2013) required more surface storage and surface roughness in order to retain water onsite long enough to calibrate the D model and for that model to satisfy wetland hydrology. Conservative approaches to wetland designs anticipate some degree of error in water budget estimates (to account for variance in climate and disturbance to soil), and therefore permanent grade controls (berms with weirs or spillways) are typically used to create surface storage. 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 or via ET. Often times pipes, flashboards and other adjustable measures are used to respond to annual or seasonal variations in hydrology such as in this study area. It should be noted that frequent manipulation of these control structures in an effort to address immediate hydrologic concerns may further compromise the predictive power of the long term model (which is based on an outfall elevation).

Many forested wetlands that are built for mitigation purposes must adhere to hydrologic standards (minimum depth of water table in soil profile for a duration of time) in order to declare successful wetland hydrology has been achieved (US Army Corps of Engineers Norfolk District and VA DEQ, 2004). From the regulatory success perspective, a surplus of water is not expected to have adverse effect on wetland habitat (e.g. emergent, herbaceous,

scrub-shrub, or forested wetlands, etc.). However, water budgets developed for the purpose of wetland mitigation must consider two targets, regulatory and ecological. These targets translate to the minimum and maximum durations of near surface saturation, respectively. Mitigation wetlands within Virginia and other areas of the mid-Atlantic must target a minimum duration of 12.5% of the frost-free growing season, as a single saturation event in most years regardless of habitat (forested wetland versus emergent meadow) (Environmental Laboratory, 1987; US Army Corps of Engineers Norfolk District and VA DEQ, 2004). All three of the models (ND, D, and D_{alt}) met this target (Criterion 1) (Table 5). 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 free water table is within the upper 30 cm of the soil profile for at least 14 consecutive days during the growing season (US Army Corps of Engineers, 2010). All three models (ND, D, and D_{alt}) met this target (Criterion 2) (Table 1). The berm and drainage pipe set design can steer the water budget focus on achieving minimum regulatory standards. Limiting the scope of the water budget to the regulatory requirement puts less emphasis on the upper limits of a hydrologic regime of specific habitat types (e.g. emergent, herbaceous, scrub-shrub, or forested wetlands, etc.).

The secondary, ecological target in forested wetland construction or restoration should focus on the upper end of the duration of inundation during the growing season, because there are limits to the duration of inundation that trees find ecologically suitable (Teskey and Hinckley, 1977a). Teskey and Hinckley (1977b) found that mature buttonbush (*Cephalanthus occidentalis*) died after flooding for more than 53% of the growing season; a majority of mature silver maple (*Acer saccharinum*) died after two years of continuous inundation and that flooding prevented seed germination; mature sweetgum (*Liquidambar styraciflua*) died if inundated more than 44% of the growing season and seedlings died if submerged for more than 32 days during the growing season; mature blackgum (*Nyssa sylvatica*) died if flooded more than 31% of the growing season; 95% of sycamore (*Platanus occidentalis*) seedlings die after 32 days of soil saturation during the growing season; mature eastern cottonwood (*Populus deltoides*) died after two years of continuous inundation and 47% of seedlings died after 30 days of inundation during the growing season; mature swamp chestnut oak (*Quercus michauxii*) dies if flooded more than 34% of the growing season; and mature willow oak (*Quercus phellos*) become impaired or die when flooded more than 31% of the growing season.

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 and Hinckley,

Table 5
Performance analysis of the three models, ND, D and D_{alt}. Data provided in years of occurrence out of the 60 year simulation period (1952 to 2012).

Model ID	Criterion 1 (30WT27D)	Criterion 2 (30WT14D)	Criterion 3 (0WT7D)	Criterion 4 (0WT30D)	Criterion 5 (30WT100D)	Criterion 6 (0WT60D)
ND	57	58	49	39	13	17
D	56	57	56	53	22	29
D _{alt}	56	57	38	30	33	21

1977a,b; Melichar et al., 1983; Hook, 1984; Vreugdenhil et al., 2006). Rarely is the ND model expected to have ponding for longer than 60 days (17 out of 60 years or 28% of the time). Generally an increase in surface storage will promote longer durations of inundation that become recharged after average rainfall events, frequently before the water table has an opportunity to draw down to the surface. The D model was exceeding ponding for at least 60 consecutive days in 65% of the time (39 out of 60 years). The ponding in the D model lasted the full 219 days of the growing season in multiple years simulated and there are at least 15 years in the simulation period where ponding has exceeded 100 consecutive days. The reduction in the volume of drainable water in the soil profile at the disturbed study site (Petru et al., 2013) had an underlying influence in the D model. Less water was needed to raise and lower the water table as a result of precipitation and ET. The result is a landscape that is either ponded or extremely dry with very little saturation in between. The reduction in macropore structure translated to a shorter period of time when the water table is capable of being within the near surface zone (<30 cm) as shown in the results for Criterion 5 (Table 5). The disturbed study area required larger volumes of surface storage in order to be calibrated, and in order to meet jurisdictional hydrology because there was reduced soil water storage.

The substitution of the nondisturbed soil data into the D model (D_{alt}) promoted more residence time of water in the near surface, root-zone (33 years for D_{alt} compared to 22 years for D in Criterion 5). The D_{alt} model resulted in ponding that exceeded 100 consecutive days (Criterion 6) only 35% of the time versus 65% of the time in the D model (21 years versus 39 years, respectively). The ponding never exceeded 168 consecutive days in the D_{alt} model and 100 consecutive days of ponding was achieved only 8 years during the 60 year simulation period. The D_{alt} model shows the use of nondisturbed soil hydraulic properties with boundary conditions (wetland design) from the proposed landscape may result in inaccurate predictions of hydrology. The Calibrated D model exhibited longer durations of ponding and an increased frequency of prolonged inundation compared to the other two models. This arises from the need for surface storage in the D model to compensate for the loss of soil water storage which was previously observed in the disturbed soil data (Petru et al., 2013).

5. Conclusion

This study presented an application of DRAINMOD to model created mitigation wetlands without drainage networks that are located in fine to medium grained alluvial soils. While the water budget predictions were considered acceptable, further improvements to DRAINMOD are needed to more accurately predict surface outputs from a management pipe located above the wetland bench within a surface berm.

There is an ecological upper limit that a water budget must consider when modeling forested wetland construction or restoration in terms of the frequency and duration that high water tables are present during the peak months of vegetative growth. The predictive power of the water budget model for the nondisturbed area in this study was compromised by soil disturbance during construction which translated into a new soil with new hydraulic properties that could not have been forecasted. Additionally, the D_{alt} model would not have predicted the prolonged inundation and near surface saturation during the growing season as observed in the disturbed model. Most water budget models assume that nondisturbed soil properties can be used in a proposed wetland design (boundary condition) to predict the post construction hydrology. These results show that key soil hydraulic properties collected

from the preconstruction landscape could not accurately predict the hydrologic regime of the post-disturbance landscape setting.

More research is needed to better understand how soil hydraulic properties such as saturated hydraulic conductivity and the soil water characteristic curve (which are important for subsurface water storage and movement) respond to disturbance across a range of soil textures and under differing forms of disturbance (soil compaction versus soil excavation and mixing, etc.). It also is unclear how these newly formed soil properties will change over time with soil and vegetation development. Water budgets that model created or restored wetlands in which there is significant soil disturbance across a large area should consider using soil hydraulic properties that reflect their disturbed state as these soil conditions will remain for some time post construction.

Acknowledgments

The study was sponsored by Piedmont Wetland Research Fund by WSSI (Wetland Studies and Solution Inc.) and the Peterson Family Foundation. Thanks go to Angler Environmental as well for providing support and research sites for this work.

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