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

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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).

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

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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; Hangen 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 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 (0.1 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 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. 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.