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Groundwater influence on water budget of a small constructed floodplain wetland in the Ridge and Valley of Virginia, USA☆

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ABSTRACT

Study region: A floodplain in the headwaters of a tributary to the Chesapeake Bay, Ridge and Valley of the Eastern United States.
Study focus: This study investigated the influence of groundwater exchange in the annual wetland hydrologic budget and identified spatial and temporal variability in groundwater hydraulic gradients using an array of nested piezometers.
New hydrological insights for the region: Data showed that the created wetland met hydrologic success criteria, and that the wetland storage was fully connected with the groundwater table. Water-surface storage fluctuation was not fully explained by precipitation and evapotranspiration, suggesting that storage was highly influenced by groundwater inputs. The potentiometric surface showed that hillslope seep recharge was the dominant groundwater vector. However, during the summer and fall months, the adjacent stream channel was a losing system, and storm-driven rise in stream stage affected wetland storage. The complex hydrology of this relatively small wetland indicates that predicting the fluctuations of storage for design of unconfined floodplain wetlands is challenging, and that if the influence of groundwater seepage is negated, then fluctuations may be underestimated to the point of harming vegetation.

1. Introduction

Constructed wetlands (CWs) provide ecological services that improve water quality and are often used as engineered best management practices (BMPs) for controlling and treating stormwater runoff from land disturbance (Guardo et al., 1995; Kadlec, 2009; Mitsch et al., 2005). CWs have the potential to act as nutrient sinks, which are essential tools for nutrient management in ecologically sensitive areas, such as the Chesapeake Bay Watershed (Boesch et al., 2001) and in the face of changing climates (Seavy et al., 2009). The capacity of a CW to remove pollutants from stormwater is a function of site-specific physical and chemical characteristics of wetland substrates and vegetation (Carleton et al., 2000; Kincanon and McAnally, 2004; Reddy et al., 1999), as well as the pollutant delivery pathways and hydrology of the area (Braskerud, 2002; Kadlec,

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2009). The characteristics that affect wetland nutrient-removal capacity must be considered during design, construction, and management of these built systems (Fisher and Acreman, 2004; Kadlec and Hey, 1994).

Floodplains offer a suite of characteristics that facilitate hydraulic and nutrient retention, such as wetland vegetation, low slope gradients, and proximity to streams (Bradley, 2002). These characteristics make floodplains desirable locations for CWs by enhancing connectivity to the stream and, subsequently, the physicochemical processes performed by wetland vegetation, microbes, and soils found in riparian zones (Tockner et al., 2010). Nutrient removal by constructed floodplain wetlands has been reported often in literature (Carleton et al., 2001; Moustafa et al., 1996; Noe and Hupp, 2007), making them practical options for stormwater managers in the appropriate hydrogeomorphic setting. Hydrology is the driver for many of retentive processes that occur through the establishment and proliferation of wetlands. Groundwater and surface waters intersect at seep or slope wetlands that are commonly found in the floodplain of a stream (Mitsch, 2000). These hydrologic intersections act as hotspots along the stream network for biogeochemical processing, fueled by continual carbon and nutrient loading from contributing flows and with meso- and micro-scale energy gradients in redox potentials (Burt and Pinay, 2005; Tockner et al., 1999). The dynamic pattern of saturation and drying caused by a fluctuating water table facilitates nutrient retentive processing preformed by both anaerobic and aerobic microbes (Reddy and DeLaune 2008). Understanding this hydrologic pattern may better inform wetland creation or restoration where the goal is to re-establish the hydrology that creates optimal environments for microbial immobilization of nonpoint source (NPS) pollutants in stormwater runoff (Rucker and Schrautzer, 2010). To this end, it is beneficial for the wetland designer to quantify hydrologic inputs and losses, and evaluate water-table fluctuations to estimate the effective wetland water-quality volume for both anaerobically and aerobically facilitated nutrient transformations.

Groundwater exchange in natural and constructed wetlands has been shown to be a driving factor in biogeochemical processes (Hunt et al., 1999). However, knowledge gaps exist in the literature related to unique complexity of groundwater exchange in riparian wetland-stream systems in the Ridge and Valley and the implications of seasonal variability on floodplain wetland establishment. Recent studies on floodplain groundwater and surface-water exchange highlight a need to expand from the traditional scale of surface-water nutrient fate and transport to a focus on in-channel processes that encompasses the active floodplain (Woessner, 2000). Hydrologic interaction and flux is also important relative to dynamic water chemistry, such as pH, which field studies have shown to influence vegetation densities, particularly in sensitive bog wetlands (Mouser et al., 2005). Due to the complex nature of groundwater flux and the period of time needed to fully characterize water-table fluctuations, few wetland water budgets completely characterize the hydrologic budget to include groundwater exchange, despite the complex interactions of adjacent topography and how they influence riparian hydrology (Claxton et al., 2003; Winter, 1999) and potential role in nutrient fate and transport (Bradley and Gilvear, 2000; Raisin et al., 1999). A study of wetland water budgets found that the groundwater component had the highest level of uncertainty and had the largest amount of error (Favero et al., 2007).

As part of a larger study to implement and monitor innovative stormwater BMPs, a constructed floodplain wetland was built in 2007 near Winchester, VA, along Opequon Creek. The objectives of this study were to: (1) determine if the constructed system met hydrologic success criteria; (2) investigate the influence of the groundwater component in the annual wetland hydrologic budget during the time period of this study; and (3) identify spatial and temporal variability in groundwater hydraulic gradients. The data collected describe local hydrology of a built environment that may be applied in other efforts to restore retention capacity of floodplains of tributaries in sensitive watersheds. These results will inform better design of CW in floodplains in terms of hydrology and hydraulic storage in the floodplain, as well as address the knowledge gap that exists between scientific research of connectivity of floodplain groundwater and estimating wetland water budgets.

2. Materials and methods

2.1. Study area

Hedgebrook Farm CW lies along Opequon Creek, just south of the City of Winchester, VA, in the larger Potomac Watershed (Fig. 1). The CW encompasses 0.2 ha of floodplain pasture provided by the private landowner at Hedgebrook Farm. The contributing catchment basin to Opequon Creek at this location is approximately 30 km^2; predominately cattle pasture with increasing residential and commercial development. At stream baseflow, the wetland is disconnected from the stream, receiving hydrologic inputs of precipitation and groundwater only. The study period included the first establishment year after construction and the majority of the subsequent year, from February 2008 to September 2009. January 2008 was used to establish a baseline water table elevation.

Soils within the study location are mapped as predominantly Massanetta loam, alluvium derived from limestone with less than 2% slopes and clay subsoil. The geology of the area is characterized by karst features such as sinkholes, springs, poorly developed surface drainage over carbonate bedrock (Orndorff and Harlow 2002). The average annual precipitation for the area is 88 cm, but during the two years of this study, the area received 106 and 85 cm (January 2008–October 2009), respectively (NOAA, 2010). A 9-year period of record for discharge of Opequon Creek was available at gage station 1.683.450, located 2.4 km downstream from the CW. Peak discharge was 1.78 cm and mean annual daily discharge was 0.14 cm during the period of study (USGS, 2009). Stream gage records show seasonal responses of the creek to precipitation and a discernable

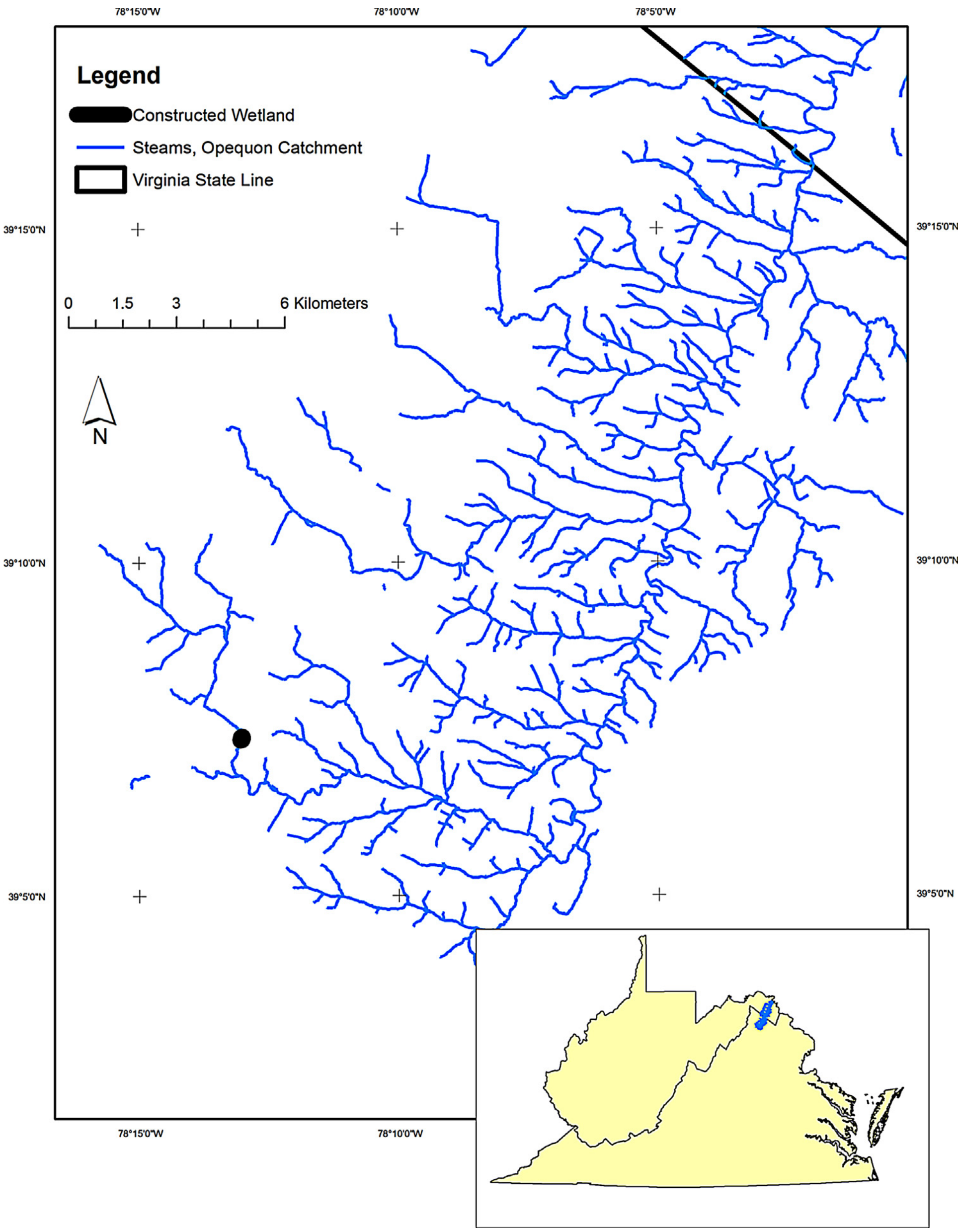

Fig. 1. Study location (black diamond) at Hedgebrook farm along Opequon Creek in Northern Virginia, USA.

dry period surrounding the installation of the constructed wetland in May 2007. Persisting low water-table elevations may still be a result of this 3-year drought (Moorhead, 2003).

2.2. Constructed wetland design

The CW was built in fall of 2007 as a demonstration project with funding from the Chesapeake Bay Foundation, administered by the National Fish and Wildlife Foundation, for studies dealing with the removal of nutrient from stormwater. The CW was designed using recommendations from the Virginia Department of Conservation and Recreation (VADCR) Stormwater Manual (VADCR, 2010) and included a variety of macrotopographic features with specified depths and surface areas within the floodplain area, including deep pools (1–1.3 m), a low marsh (0.3 m), and high-marsh areas (0–0.1 m) of intermittent inundation (Fig. 2) (VADCR, 1999, 2010). The high-marsh elevation was set to match the elevation of previously established wetland vegetation. This elevation corresponded with the bankfull elevation in the stream channel as identified by field observations, channel cross-sectional geometry, and an area-weighted flood frequency analysis of stream flow data (USDA

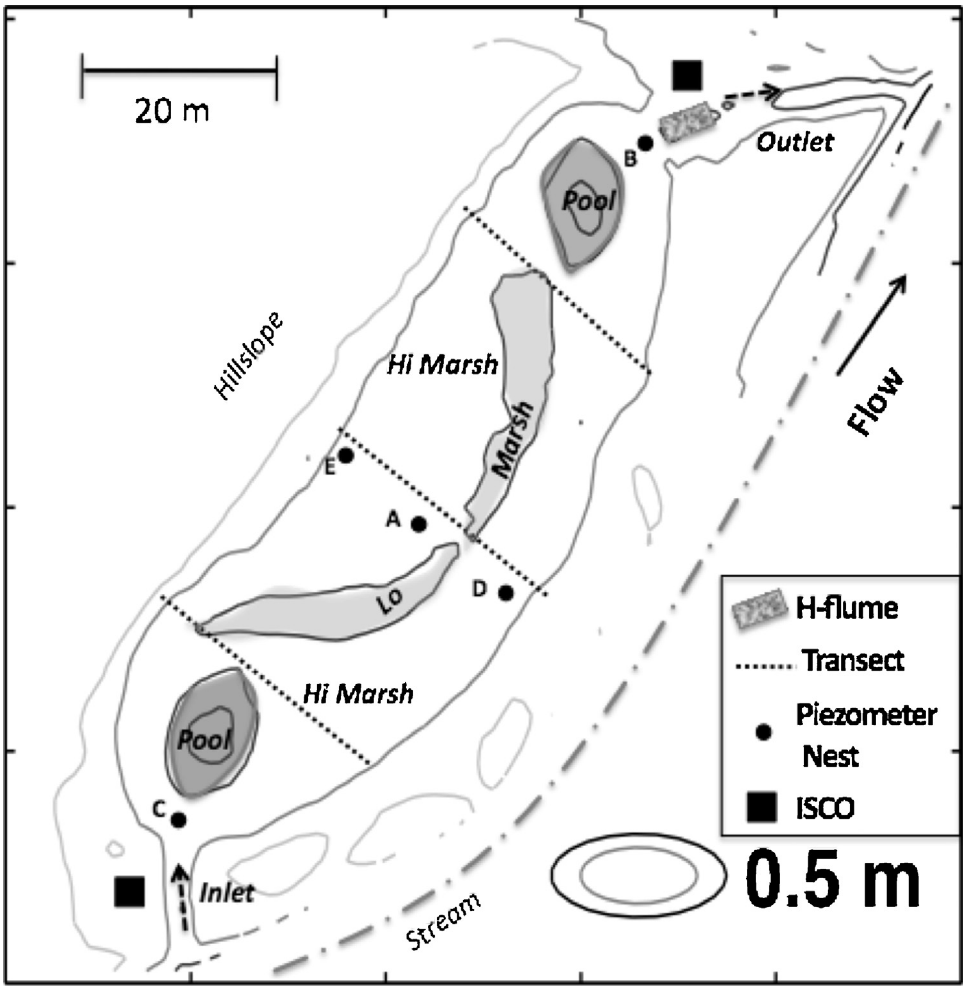

Fig. 2. Constructed wetland topography with piezometer locations and flow direction orientation.

NRCS, 2008). A berm was formed around the CW to enclose the area and route overland flows from the adjacent hillslope and upland areas around the wetland to maintain a single inlet an outlet for water quality monitoring during overbank events.

Construction practices called for as little disturbance as possible during excavation, particularly in the high-marsh area. After excavation, a final till was performed to decrease the effects of soil compaction. A mix of native wetland grasses and annual rye was immediately spread. Five months later, native wetland plugs were planted in delineated areas based on design water depth and anticipated inundation patterns, and included *Scirpus validus* (bulrush), *Pontederia cordata* (pickerelweed), *Sagittaria latifolia* (arrowhead,) and *Acorus calamus* (sweetflag). These emergent species have rooting depths between 15 and 42 cm. The established wetland has a total surface area of approximately 1300 m^2, a wet-season baseflow volume of 100 m^3, and a volume of 250 m^3 when outflow through the outlet structure (H-flume) is at capacity (0.3 m deep).

2.3. Field measurements

Five nests of three variable-depth piezometers were installed within the CW in January 2008 (beginning of baseline data period) and monitored until 2010. Data are missing for the two time periods, the first half of November 2008 and the month of January 2009. Piezometers were constructed of 3.81-cm diameter solid PVC of various lengths (length required to reach datum plus a significant riser to extend through tall grasses), a 10-cm long slotted PVC section (0.025-cm slot thickness) that was coupled to the riser, and a flush-joint PVC drive point. Water-level measurements were recorded at each piezometer datum, which was set as the elevation of the center of the 10-cm long slotted pipe portion below the riser. Piezometers were installed in the wetland by coring to the desired depth with an 8.9-cm hand auger, inserting the piezometer, backfilling with coarse sand to a depth above the slot, backfilling with cored soil to within 15 cm from the surface, and capping with bentonite to provide a water-tight seal around the PVC riser to eliminate preferential flow to the subsurface. Piezometers were then developed by adding of a slug of water to flush out small particulates.

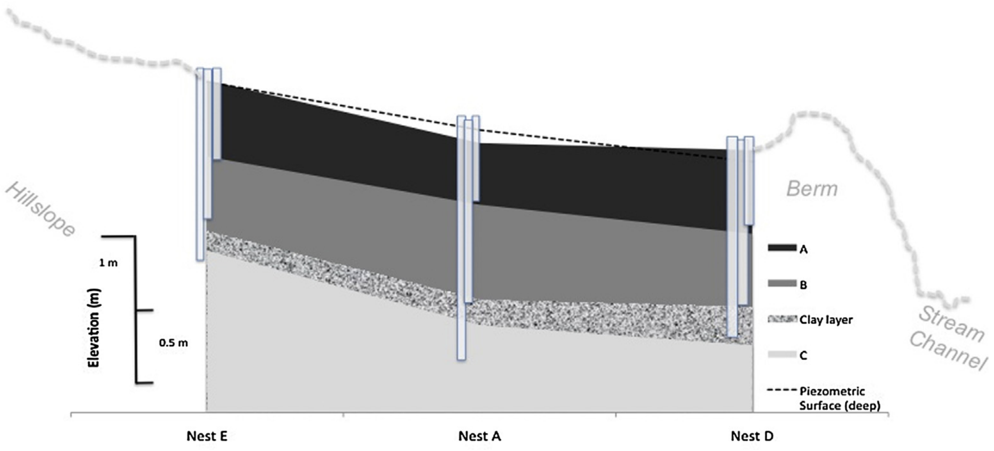

Fig. 3. Perpendicular transect of nested piezometers with associated soil profiles and water levels from May 2008.

Table 1
Nested piezometer datum and soil layer information.

Nest	Piezometer	Depth (m)	Datum[a] (m)	Soil layer description
A	1—deep	1.47	−1.47	Clay, dispersed sand and gravel
	2—middle	1.04	−1.11	Heavy clay
	3—shallow	0.44	−0.43	Silty clay loam
B	4—deep	1.31	−1.55	Sandy clay
	5—middle	0.89	−1.16	Heavy clay, dispersed sand
	6—shallow	0.53	−0.78	Sandy clay loam
C	7—deep	0.95	−1.01	Clay, some small gravel
	8—middle	0.63	−0.66	Heavy clay
	9—shallow	0.37	−0.47	Clay loam
D	10—deep	1.28	−1.33	Clay, dispersed sand and gravel
	11—middle	1.00	−1.10	Heavy clay
	12—shallow	0.50	−0.59	Clayey sand loam
E	13—deep	1.22	−0.80	Clay
	14—middle	0.95	−0.53	Clay
	15—shallow	0.54	−0.14	Clay loam

[a] Datum is the relative elevation of the point in the subsoil profile where water levels were read in each piezometer; the central Nest A—peizometer 1 ground is elevation zero.

Each piezometer nest contained three piezometers; a deep piezometer that extends below a clay lense, a middle piezometer that is located in the clay layer, and a shallow piezometer that is above the clay layer (Fig. 3). Absolute pressure and temperature were continuously monitored in each piezometer with water-level loggers (Onset Corp., Bourne, MA; accurate to 0.5 cm hydraulic head). An additional well was incorporated in October 2008 to record atmospheric pressure in a mock piezometer casing in the wetland berm. Previous to this, atmospheric pressure was measured in dry piezometers as well as at a proximate weather station (6.4 km away), and a relationship between the atmospheric pressure at the wetland site and that of the weather station was used during periods when there were no dry piezometers.

Locations of piezometer nests were determined by selecting a central location in the high marsh and using triangulation over the wetland surface area, capturing perpendicular and parallel flows from hillslope across floodplain to stream, and along the hydraulic gradient down the floodplain. Specific depths of individual piezometer datum were selected using field observations of change in color and field texture in soil profile layer (Table 1). The objective was to capture the influence of this change in texture on groundwater movement.

2.4. Mapping

Wetland topography was described with approximately 420 survey points using a Total Station (Topcon Corp., Tokyo, Japan). Piezometers were surveyed at the soil surface, and the elevation data were georeferenced to correspond to the topographic survey. This placed all piezometers in the same plane of reference. The error associated with surveying and determination of piezometer datum elevations was within 2 cm.

2.5. Hydraulic conductivity

The Hvorslev method (Hvorslev, 1951) was used to determine the hydraulic conductivity of the soil layer at a depth of 1 m. Slug tests were performed by adding a 1-L slug of water into the piezometers that had datums closest to1 m deep in Nests A, B, and D. Pressure measurements were logged every 20 s after slugs were introduced into the piezometer casings. Absolute pressures in piezometers that did not receive the slugs were also measured and recorded every minute. The slug response was established between the time of peak of the introduced slug and the time the water level equilibrated. There was no measured rainfall during the slug testing.

2.6. Water table and hydroperiod

Pressure data collected in piezometers was processed using MATLAB (Mathworks, Natick, MA). Data were filtered to remove measurements of pressure when probes were removed from the risers for downloading and when measurements reflected less than 2 cm of head to account for dead space at the bottom imposed by the threading of the drive point. Hydraulic head in each piezometer was computed by subtracting the recorded atmospheric pressure from the measured absolute pressure, resulting in a head (h_p) for the piezometeric surface in each piezometer. Water-level elevations were then determined by adding h_p to respective datum elevations. Daily-averaged pressure measurements were used in analysis of annual hydroperiod trends, while hourly data were used in analysis of event-specific responses.

Water-table data from the middle Nest A (Fig. 2) were used in the determination of hydrologic success. The success criteria for jurisdictional delineation for wetland hydrology was the observation of the water table in the upper foot of soil for duration of the growing season (USACE, 1987). Hydroperiod seasons were delineated using statistical zonation, which compared the generalized distance within an analysis window through the time series using the following equation:

$$D^2 = \frac{(\bar{a_1} - \bar{a_2})^2}{{s_1}^2 - {s_2}^2} \tag{1}$$

where D^2 is the generalized distance that indicates shifts in trend, a is the middle of the data range within the analysis window, a_1 is data within the data window $[(a-h){:}a]$, a_2 is data within the data window $[a{:}(a+h)]$, h is half of the selected analysis window, and s is the variance within the data (Davis, 2002). The Euclidean distance zonation was also employed as a second method to delineate hydrologic temporal zones using the following equation:

$$E = (\bar{a_1} - \bar{a_2})^2 \tag{2}$$

where E is the Euclidean distance.

2.7. Hydrologic budget

A deductive approach was utilized to quantify the magnitude of the groundwater component in the hydrologic budget. During the study period, there were no overbank flows. The water-balance equation was simplified by assuming no groundwater exchange, and change in storage (ΔS) was calculated using the following equation:

$$\Delta S = P - \mathrm{ET} \tag{3}$$

where S is wetland storage (mm), P is precipitation (mm), and ET is evapotranspiration (mm). It has become common practice to negate the effects of groundwater exchange in estimating wetland water budgets (Pierce, 1993), so this simplified budget was used as a null hypothesis of which to disprove the accurate application at the study site location. ΔS was calculated on a daily time step and cumulative storage was the resultant summation over the study period. This time series was then compared to observed water table records. The difference between the two time series provided an estimation of groundwater exchange (discharge and recharge) component of the hydrologic budget.

Weather data were accessed from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC, http://lwf.ncdc.noaa.gov/oa/ncdc.html). Precipitation and air temperature were obtained from the Winchester, VA station (COOP ID 449.181), located approximately 6.4 km from the study site. Solar radiation data were obtained from the most proximate NOAA weather station, which was in Charlottesville, VA (COOP ID 441.593), located approximately 128 km from the study site. Daily ET (mm/d) was calculated with the Priestley and Taylor (Priestley and Taylor, 1972) method using the following equation:

$$\mathrm{E}T_0 = \frac{\alpha}{\lambda}\left(\frac{s(R_n - G)}{s + \gamma}\right) \tag{4}$$

where α is the Priestley and Taylor coefficient, λ is the latent heat of vaporization (MJ/kg), R_n is net radiation (MJ/m^2-d), G is soil heat flux (MJ/m^2-d), s is the slope of the saturation vapor pressure based on average-daily temperatures calculated as the mean of the maximum and minimum measured temperatures (kPa/°C), and γ is the psychrometric constant (kPa/°C). The Priestley and Taylor method was selected over other ET estimation methods due to the ease of its use with the meteorological data available for the region and accepted use in well-watered short grass systems in humid regions (McAneney and Itier,

Table 2
Saturated hydraulic conductivity estimates from the data collected using a falling head slug test in piezometers.

Nest	K_{sat} (cm/s)	Depth (m)	Datum (m)	Location
A	3.91×10^{-6}	1.04	−1.11	Center
B	1.39×10^{-4}	0.89	−1.16	Outlet
D	5.57×10^{-5}	1.00	−1.10	Streamside

1996). A Priestley and Taylor coefficient of 1.26 was selected for well-watered short grasses in humid regions (Lhomme, 1997). Predicted R_n values were determined from an empirical relationship developed by Irmak et al. (2003) that used inputs of daily maximum and minimum temperatures, measured total solar radiation, and the inverse distance from the sun. G was determined using a linear relationship with net radiation (R_n), which was developed in a Sweden study on rolling agricultural fields (DeHeer-Amissah et al., 1981).

$$G = -0.021 + 0.356R_n \tag{5}$$

2.8. Hydraulic gradients

Lateral two-dimensional gradients were calculated between piezometer nests, comprising four adjacent triangular piezometric planes. These four planes were identified using a counter-clockwise convention between nests and denoted as EAB, ECA, DBA, and DAC (Fig. 1). Groundwater gradients with flow components i and j in the planar x and y directions were spatially differentiated with the following relationship (Freeze and Cherry, 1979):

$$\nu = \frac{\partial z}{\partial x}i + \frac{\partial z}{\partial y}j \tag{6}$$

where ν is the hydraulic gradient, $\partial z/\partial x$ (m/m) and $\partial z/\partial y$ (m/m) are flow components in the x and y directions, respectively, corresponding with the field survey orientation and calculated with the following relationships (Abriola and Pinder, 1982):

$$\frac{\partial z}{\partial x} = \frac{(z_1 - z_2)(y_2 - y_3) - (z_2 - z_3)(y_1 - y_2)}{(x_1 - x_2)(y_2 - y_3) - (x_2 - x_3)(y_1 - y_2)} \tag{7}$$

$$\frac{\partial z}{\partial y} = \frac{(z_1 - z_2)(x_2 - x_3) - (z_2 - z_3)(x_1 - x_2)}{(x_2 - x_3)(y_1 - y_2) - (x_1 - x_2)(y_2 - y_3)} \tag{8}$$

where x (m) is the surveyed easting, y (m) is the surveyed northing, and z (m) is the observed water level elevation, each in the respective piezometer. Deep piezometers had the most complete record and, because of this, were used in all gradient calculations.

Flow magnitude and direction were calculated using the following equations respectively (Mouser et al., 2005):

$$\nu_{\mathrm{mag}} = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \tag{9}$$

$$\nu_{\mathrm{dir}} = \tan^{-1}\left(\frac{\frac{\partial z}{\partial x}}{\frac{\partial z}{\partial y}}\right) \tag{10}$$

3. Results and discussion

3.1. Hydraulic conductivity

Saturated hydraulic conductivity varied within two orders of magnitude between nests. All values were within the range for clay loam soils (Brady and Weil, 2002; Table 2). The nest at the wetland center (Nest A) exhibited slower K_{sat} than the streamside and outlet nests (Nests D and B). This supported field observations of sandier soils in the outlet area. The slower K_{sat} at streamside relative to the middle next may be due to increased coarse materials that are typically found in fluvial deposits in the natural berm of the creek, roughly 2 m from this nest.

3.2. Hydroperiod

Shallow piezometer data were used to delineate periods of connectivity between storage volume and groundwater. With the absence of a confining layer within the top portion of the wetland soil column, the piezometric water level in these shallow piezometers reflected the general water-table level. The middle and deep piezometer datum were located at or below a change in soil texture (thick clay) and were used to evaluate vertical movement of groundwater. Nest A in the center of the wetland was used to characterize the general hydroperiod of the system.

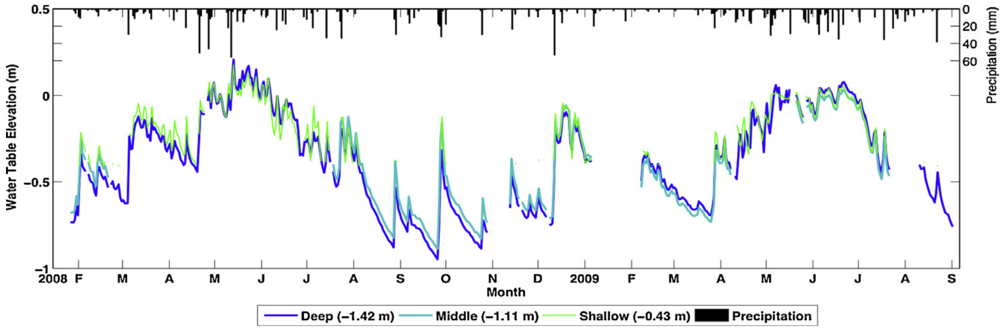

Fig. 4. Daily average water level elevation in central wetland piezometer Nest A. The ground elevation of the deep piezometer is the zero datum.

Trends in rise and fall in response to inputs from precipitation and surface flows occurred at the same time in all three piezometers at all five nests, indicating that the connected water table moved freely through the soil profile and across the floodplain without confinement (Fig. 4). Piezometric water levels indicated a connected free-water surface and groundwater table and were consistently highest in the central Nest A (excluding Nest E, which lays at a higher elevation than the other four nests that are in the high marsh). This may be attributed to the confluence of the flowpath from the hillslope to the stream and the flowpath down the floodplain gradient that occurs in the wetland center at Nest A.

The constructed wetland met hydrological success criteria, which were defined as the jurisdictional hydrologic criteria defined by the United State Army Corps of Engineers. The criteria states that wetland hydrology may be established with observation of the water table within the top 0.3 m of the wetland surface for a duration of the growing season (USACE, 1987). Water-table elevations central nest were measured as being within 0.3 m of the surface for a significant duration of the growing season (Fig. 4). The growing season begins in late April in the Ridge and Valley of Northeastern Virginia.

The CW water-table response to temporal variations over an annual hydroperiod was described by delineating seasons using statistical zonation. Results showed a delineation between two main seasons: (1) the wet season from March through July, when groundwater levels were highest, and (2) the dry season from mid-July through December, when groundwater levels were lowest and event-driven patterns were prevalent (Fig. 5). These 'wet' and 'dry' seasons are referenced throughout the remainder of the paper.

3.3. Wetland water budget

The period of record available for precipitation data from NCDC was May 1982–March 2010. The 27-year average annual precipitation was 976 mm of rainfall, where the annual precipitation was 1085 mm and 1060 mm for 2008 and 2009, respectively. However, during the winter months of January–March, the average rainfall was 207 mm, where that of the study years was only 158 mm and 110 mm. Furthermore, during the spring/summer months of May–August, the average long-term rainfall was 360 mm, where that of the study years was 413 mm and 512 mm. This comparison of the historical annual trends to those of the study years suggests that the precipitation trends were not typical for the region, resulting in seasonal variations that affected the annual hydroperiod during the study. Maximum ET was estimated during the summer and reached

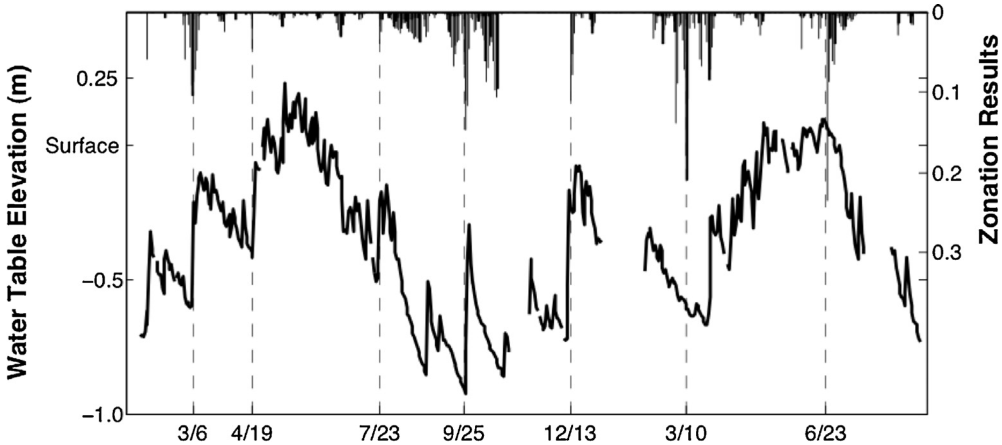

Fig. 5. Delineation of hydroperiod seasons resulting from statistical zonation analysis on piezometer A1 time series water table data. Generalized distance (D^2) reported as zonation results on secondary axis.

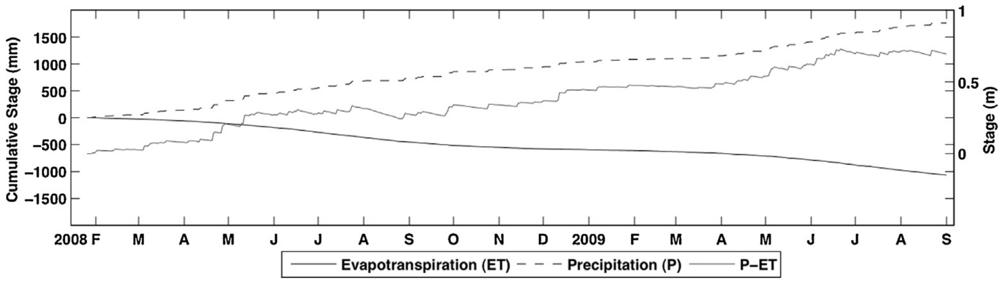

Fig. 6. Water budget components of precipitation and evapotranspiration and changes over time. P-ET Storage (ΔS) calculated as cumulative precipitation less evapotranspiration on a daily timestep.

5 mm/day (average daily air temperature 22 °C). ET was at a minimum during the winter and fell to below 1 mm/day (average daily air temperature 0 °C). These estimations and trends are typical for the region.

The annual hydrologic budget was calculated using the ΔS simplified model, considering only components of P and ET. Cumulative fluxes exhibited seasonal trends that resulted in temporary net surplus or net loss in storage. Throughout the study time period, precipitation influx was greater in magnitude during an annual cycle than the loss to evapotranspiration, resulting in a net positive storage, or cumulative stage (Fig. 6). Field measurements indicated that the water table fluctuated highly and storage was largely dependent on precipitation. Storage was highest from May through June and low water-table levels persisted in the months of August through December.

The ΔS model and water table fluctuations indicated similar general seasonal trends with gains in the late winter and spring and declines from summer into fall (Fig. 6). However, the magnitude of change in the ΔS model was considerably smaller than that of the water table fluctuations in both years of study. Since there were no recorded overbank flows, groundwater exchange was the only remaining water budget component left unaccounted for in the model. In the evaluation of the water budget as represented by the observed water table elevation, ground water was considered a net flux and soil storage was neglected since, well levels were similar in early February 2008 and February 2009. A raise in water table was considered a gaining flux and a decrease in water table was considered a losing flux. In 2008, water table elevation was around −0.4 m in February and declined through the month. Gains were observed from March through June 1, when a losing trend began and persisted through September. From September through December, water table elevations fluctuated greatly in response to precipitation, with fluxes up to 0.5 m before stabilizing around −0.6 m in December. Then, gains occurred and persisted through the end of the year and presumably through January, returning the water table to approximately −0.4 m in February 2009. The trend in 2009 was similar, however the losing flux persisted through March in 2009 and the gaining trend persisted through much of June 2009. In both years, water tables fell to 0.7 m in September. Annually, total groundwater flux was approximately 0.8 m (Fig. 7)

The magnitude of the groundwater component (GW) in the annual water budget was estimated by examining the difference between ΔS and the observed storage in Nest A, where both time series began at the water table depth measured in early February 2008 (approximately −0.75 m). From the first rainfall after this time through mid July, the water table was higher than the predicted storage model, reaching a maximum difference of 0.55 m in May 2008. Beginning in August and persisting through mid December 2008, the water table was lower than the predicted storage model with the exception of a brief period of time after three consecutive days of rain in late September. The greatest difference in the water table and predicted model during this time was 0.50 m, occurring in September and October. By February 2009, the predicted model and water table were within 0.1 m from each other around the −0.30 m elevation. Based on these findings, it is reasonable to conclude that the ΔS model predicted the total annual water budget within 10% of observations; however, during any point in time within the annual hydroperiod, the model may have been up to 0.55 m off in terms of water table elevation.

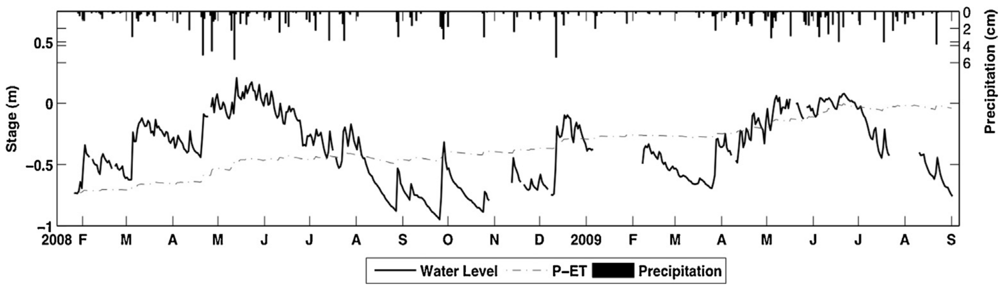

Fig. 7. Water budget (P-ET) as compared to observed water table fluctuations in the deep piezometer in Nest A. P-ET is assumed to start at a relative zero at the beginning of the study period.

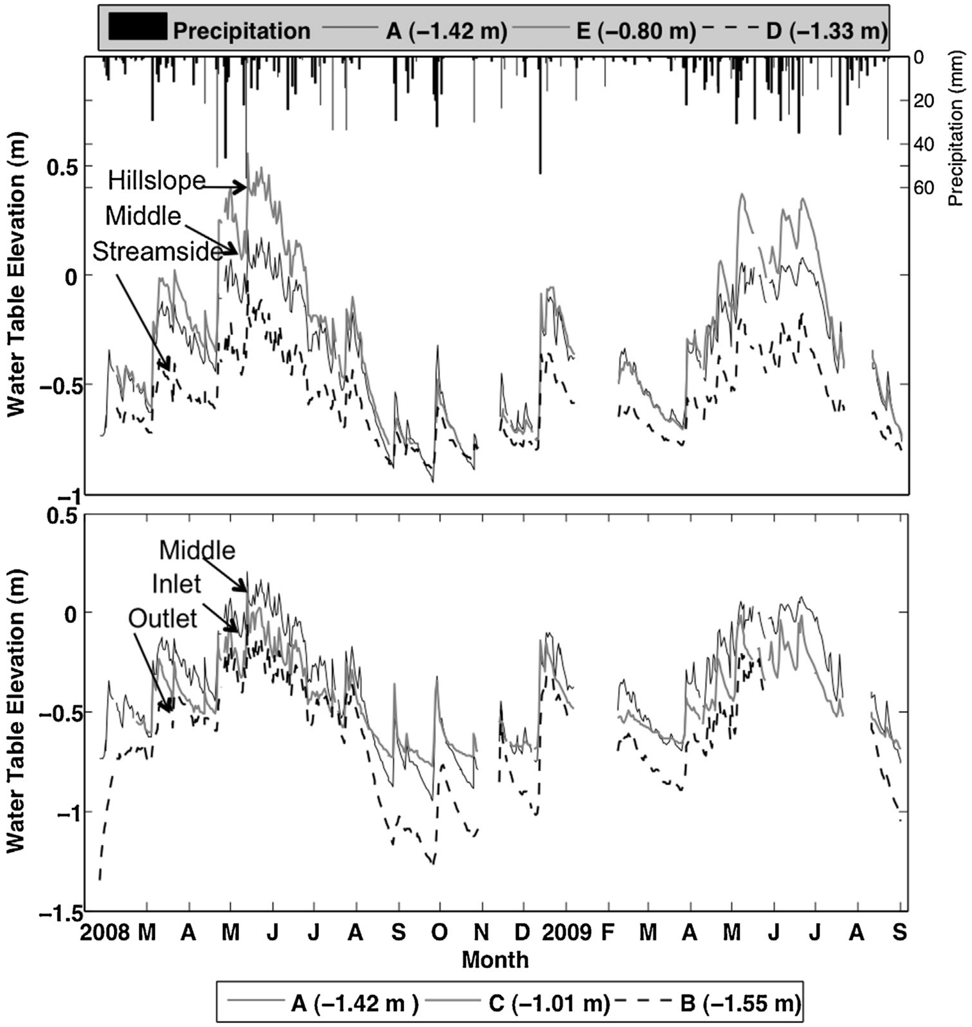

Fig. 8. Water levels in deep piezometers within five nests and compared within the perpendicular transect (top) and parallel transect (bottom) to the stream channel.

Relying on a ΔS model to accurately predict water table fluctuation may cause considerable failures in design because large fluctuation may produce conditions that are either too dry or too wet for many species of wetland vegetation. Furthermore, the water treatment potential of the CW would potential decrease when the water table is not within the root zone of the vegetation, as this is a critical factor for optimal biological nutrient uptake and sequestration in plant biomass in wetlands (Tanner, 1996; Yang et al., 2001). The rooting depth of the planted native wetland vegetation in the Hedgebrook CW is between 15 and 23 cm. During this study, the water table was observed within the rooting depth continuously during the months of March–July. This is a period of frequent precipitation and subsequent vegetation growth and a time of active conversion and sequestration of nutrients from stormwater runoff and groundwater by wetland vegetation and microbes.

Potential errors in the model may have been introduced du to assumptions made. The application of the Priestley and Taylor method for estimating ET may have introduced error into the model. The selection of a static alpha that was not empirically defined may lead to over-prediction of ET losses (Soucha et al., 1996). However, Priestley and Taylor estimates of ET have shown to adequately represent losses in saturated, short-canopy, humid systems (Drexler et al., 2004; Sumner and Jacobs, 2005).

3.4. Hydraulic gradients

Hydrological and topographical characteristics of the site indicate that this wetland functions as a seep or riparian wetland; it is located at the base of a sloped area where the groundwater surface intersects the land surface and it discharges water downstream as surface flow or groundwater. The CW was generally recharging groundwater in the dry season, when losing vertical gradients were observed in all piezometer nests. Conversely, the CW was generally discharging groundwater in the wet season, when gaining vertical gradients were observed most notably in the central Nest A. Following precipitation

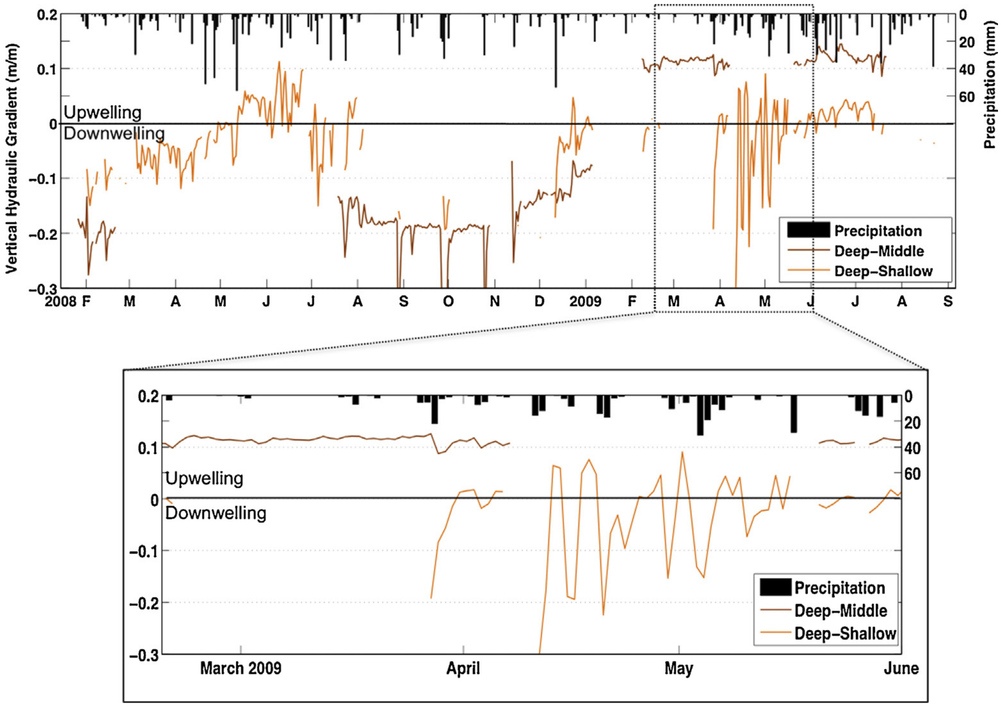

Fig. 9. Vertical hydraulic gradients measured in Nest A between deep, middle, and shallow piezometers. Portion of hydroperiod blown up to highlight fast response time in hydraulic gradient to precipitation (average daily gradients, total daily precipitation).

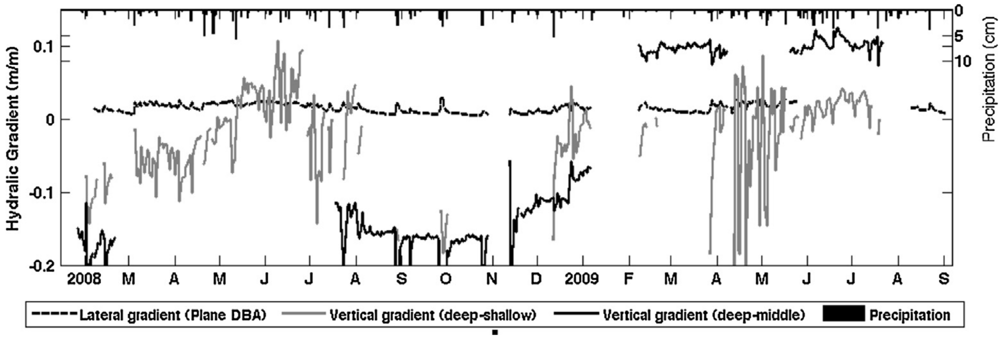

Fig. 10. Vertical hydraulic gradient between the deep and shallow piezometer in Nest A compared to the lateral hydraulic gradient from the wetland toward the stream channel (Plane DBA).

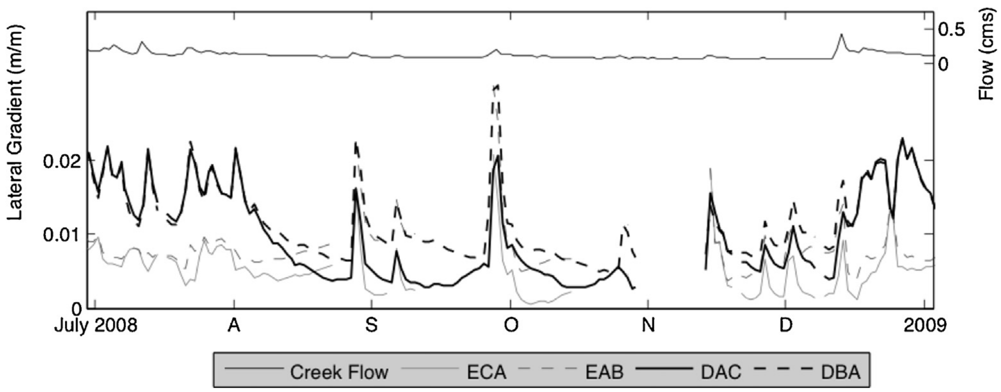

Fig. 11. Lateral hydraulic gradient calculated from water-level records in deep piezometers during the dry season and Opequon Creek flow record (USGS 01614830).

events, relatively extreme downward gradients were documented at the streamside Nests D and C. High piezometric potentials in the middle horizon piezometer suggest a convergence of shallow groundwater flow. This was observed particularly during the summer months in central Nest A.

Water table level was consistently highest in the hillslope Nest E and showed the greatest lateral hydraulic gradient to be along the transect perpendicular to the stream, from hillslope to the channel (Fig. 8). In the lateral transect, piezometric water levels showed a very modest gradient from the wetland inlet to the outlet: however, these two transects intersect in the wetland center at Nest A, where groundwater potentials were greatest amongst the nests in the high marsh area. Generally, flow was moving from the hillslope to stream and laterally along the floodplain from the inlet area of the wetland toward the outlet (Fig. 10). Water levels at the outlet Nest B were lower than the other nests in the high marsh, suggesting a change in soil texture between the middle transect and the outlet.

In the central Nest A, hydraulic gradients indicated recharge from the beginning of the study period (Jan 2008) until May 2008 when a discharge gradient began to build through the end of June (Fig. 9). Recharge occurred again from July through the following February. While winter months are typically periods of discharge, as there are minimal ET losses during low temperatures and vegetation dormancy, an uncharacteristically dry winter of 2009 created recharge gradients that persisted later into the winter months than expected. Discharging conditions again occurred in February and persisted through the early spring.

Water table level generally responded quickly to rainfall events. A response in water-table elevation and hydraulic gradient was observed typically within the same day as the measured rainfall. The response was also quick to tailoff, producing the spikey hydraulic gradients shown in Fig. 9. Particularly in spring 2009, the vertical hydraulic gradient showed downwelling right after measured precipitation followed by a quick shift to upwelling within 2–3 days. This fast response to precipitation may be attributed to a fractured hydrogeologic framework of the area.

The magnitude of vertical hydraulic gradients (ranging from −0.3 to 0.1 m/m) was significantly greater than that of lateral hydraulic gradients (ranging from 0.0 to 0.02 m/m), and most often, by an order of magnitude. The dominant flowpath of water was vertically through the wetland substrate (Fig. 10), with the greatest vertical gradients measured closest to the stream. Combining the effects of highly fluctuating vertical gradients with shifts in lateral gradients indicates that the hydrology of this small CW is very complex and highly variable on both spatial and temporal scales, regardless of the relatively flat surface topography.

Piezometric planes between nests were created through triangulation, resulting in four triangles that each shared two faces and mid-point of Nest A (refer to Fig. 2). Response to precipitation in planes EAB and ECA were longer and more gradual to peak than those near the stream channel in planes DAC and DBA, where response was more immediate (Fig. 11). The hillslope planes also fall off sharply after reaching peak, while the planes near the channel taper off gradually. These trends were as expected as water drained from the hillslope and toward a swollen stream channel. Rise in stream stage appears to affect the planes close to the channel and occurs quickly to the peak of the event and then slowly recedes after the peak as storage drains back into the creek. As expected, the planes closest to the hillslope seemed to be influenced more by the hillslope–floodplain water-table fluctuations, while the planes closest to the stream were impacted by the changes in stream stage.

Overall, lateral gradients from hillslope to stream dictate the lateral water movement through the floodplain. However, in the dry season, flow directions varied and oscillated frequently between flowing to and away from the stream. Groundwater gradients may have been influenced by the rise in stage of surface water in the stream to create a ridge along the stream that forced water into the floodplain. This stream-stage, wetland storage interaction has been documented through model application stream-floodplain wetland settings (Bradley, 2002).

4. Conclusions

Within a year after construction, the CW met hydrologic criteria. The wetland water surface was fully connected to the water table and responded to precipitation with little evidence of major confining layers in the soil profile. The overall hydrology, storage, and movement of water in the wetland were driven by precipitation. The dominant influence of rainfall events was evident in the hydroperiod as well as hydraulic gradients throughout the wetland.

The hydrologic budget was computed using a simplified model as commonly used in design that excluded influence of groundwater exchange. When compared to observed water levels, it was apparent that the simplified ΔS model resulted in the underestimation of wetland storage and water table fluctuation (up to 0.6 m of stage), which are critical factors for wetland vegetation establishment and water treatment. Hydroperiod fluctuation of 1 m would produce conditions that are either too dry or too wet for many kinds of native vegetation if they were selected based on a simplified model. These findings highlight the importance of correctly characterizing local groundwater hydrology to better predict hydrology, which will drive the establishment and proliferation of a created wetland.

Patterns in hydraulic gradients indicated a significant impact of the adjacent hillslope that dominated the lateral flow of water during the wet season (March–July) and of the fluctuating adjacent stream stage that dominated in the dry season (August–December). Water levels also indicated great temporal variability in vertical hydraulic gradient, which closely followed precipitation trends. These findings on vertical gradient variability and complex seasonality were consistent with other water-table dynamics studies in Appalachian floodplains (Cole and Brooks, 2000; Moorhead, 2001) as well as findings of modeled variably-saturated resorted wetlands (Boswell and Olyphant, 2007).

Increasingly clayey soils with depth appeared to have an influence on drainage of water from the adjacent hillslope. These findings were also consistent with those of Moorhead (2001) in a Southern Appalachian floodplain. With a median depth to water measurement of −37 cm (maximum = 21 cm, minimum = −98 cm), this site would fall into the severely disturbed main-stem floodplain class as described by Cole and Brooks (2000). Given the atypical nature of the annual precipitation trends during the years of study, the depth to water measurements may have been effected by uncharacteristic periods of little precipitation during the winter months, when discharge is generally expected. With this consideration, more years of water table data are needed to clearly classify this site within a disturbance classification.

This work addressed a gap in the scientific knowledge on the magnitude of groundwater exchange on the annual water balance of constructed wetland systems in floodplain environments. These findings highlight the importance of water table data collection during the design process to accurately characterize the total water table fluctuation to ensure success of these systems in establishing and maintaining their indented ecological functions. More research is needed to characterize the variability in floodplain hydrology so that design success criteria may be accurately applied within the context of specific local conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.10.003.

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