Simulated Flood of a Small Constructed Floodplain Wetland in Virginia: Event-Scale Pollutant Attenuation

A. Ludwig, W. C. Hession, D. Scott, D. Gallagher

Abstract. *A 0.2 ha constructed floodplain wetland in northern Virginia was artificially flooded using a controlled hydrograph to simulate an overbank event in the fall and spring. The objectives were to (1) evaluate the event-scale nutrient attenuation capacity of a constructed floodplain wetland, (2) identify spatial variability in nutrient concentrations throughout the wetland during simulated overbank flow conditions, and (3) identify temporal variability in nutrient removal between the fall and spring events and within a controlled flood hydrograph. TSS was the constituent with the greatest attenuation in terms of percent removed (73% spring, 69% fall) and total mass removed, while* NH_4^+ *had the greatest percent removal (54% spring, 58% fall) of the measured nutrient species. Greater removal of TP relative to* PO_4^- *suggests that particulate settling of sorbed P was the driving mechanism in P removal. Faster attenuation rates for* NH_4^+ *and TN in the spring resulted in larger mass removal than in the fall. Linear regression of mass flux was used to determine pollutant removal rates between the wetland inlet and outlet. Adjusting paired inlet-outlet data using an offset for residence time removed some variability in percent removal, indicating that sampling protocols must be selected carefully in order to provide the most accurate results. Spatial variability of dissolved fractions of N and P varied (relative standard deviation between 12% and 47%) in both seasons, while TSS variability was higher in the fall (above 130%) and relatively lower in the spring (58%). Overall, these results suggest that construction or restoration of floodplain wetlands may be an effective way to manage stormwater nutrient and sediment at concentrations commonly found in streams affected by land use change due to urbanization and agriculture.*

Keywords. *Constructed wetlands, Nutrients, Water quality.*

Riparian wetlands are important landscape features for the reduction of nutrients reaching receiving waterbodies, such as drinking water supply reservoirs and ecologically sensitive estuaries (Mitsch et al., 2001). Disruptions of the ecological connectivity of alluvial channels to their floodplains, due to anthropogenic influences, reduces the frequency and extent to which floodplain inundation can affect phenomena that maintain high levels of habitat diversity in floodplains (Ward and Stanford, 1995). Efforts have been made in the field of floodplain and wetland restoration to hydrologically reconnect riparian areas and impacted stream channels with the goal of recovering the ecological services provided by riparian wetlands (Acreman et al., 2003) and enhance landscape resiliency to disturbances in the face of changing climates (Seavy et al., 2009). Past studies have shown that nonpoint-source (NPS) pollutants, e.g., nitrogen (N), phosphorus (P), and sediment, may be attenuated from flows through natural and constructed floodplain wetlands in the time scale of storm events (Casey and Klaine, 2001; Schulz and Peall, 2001; Noe and Hupp, 2007). However, other experiments in a floodplain with historical agricultural use indicated that not all sites may be suitable for such restoration strategies due to legacy soil impacts if the ultimate goal is to capture all nutrient species (Jones et al., 2015). While recent modeling efforts have helped shed light on the complexity and extent of hyporheic exchange associated with channel-floodplain hydrology (Bates et al., 2000), a greater understanding of water quality improvements directly associated with channel-floodplain interactions is needed before these restorative projects can be properly credited in a mitigation scenario.

The driving pollutant removal mechanisms in treatment wetlands are physical settling of sediments, chemical sorption and soil mineralization (Noe et al., 2013), and uptake and transformation by microbes and wetland vegetation (Kadlec and Wallace, 2009; Kreiling et al., 2015). The time scale at which these mechanisms occur varies depending on seasonal factors such as temperature and solar energy inputs, as well as hydrologic and chemical inputs. Other factors also

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influence the treatment performance of wetlands, including watershed area (Carleton et al., 2001), plant processes (Reddy et al., 1999; Neubauer et al., 2005), and antecedent conditions (Kadlec, 2010). Identifying a monitoring method and correctly quantifying nutrient attenuation by treatment wetlands is essential for assessing their effectiveness in pollutant removal.

Phosphorus is of particular concern in most inland temperate regions because it is often the limiting nutrient for primary productivity and therefore controls the relative amount of standing biomass of aquatic autotrophs (Stevenson et al., 1996) and heterotrophs via respiration. Aquatic autotrophs control dissolved oxygen levels in surface waters, which is an important factor in the health of fish and macroinvertebrate assemblages (Wilhm and Dorris, 1968). Currently, there are no surface-water quality standards for P. The U.S. Environmental Protection Agency recommends total phosphorus (TP) levels below 0.50 mg L^{-1} (USEPA, 1986). However, TP levels in excess of 0.03 mg L^{-1} have been found to produce nuisance algal blooms in temperate lotic environments (Dodds et al., 2002).

Fisher and Acreman (2004) found that riparian wetlands reduced TP loadings; however, loadings of soluble P were likely to increase rather than decrease. Greater TP concentrations in groundwater associated with poorly drained riparian buffers suggested that wetland designs for nitrate removal might not be effective for P removal (Young and Briggs, 2008). Furthermore, historic land uses may pool P into sinks in sediments, causing a legacy effect, or residual effect, to occur when a system is converted to its previous hydrologic state (Smit and Steinman, 2015). However, the highly dynamic hydrology associated with riparian areas combined with native wetland vegetation may create favorable conditions for capture of particulate and dissolved P that may be traveling through preferential groundwater flowpaths or in overland stormflows (Braskerud, 2001; Fisher et al., 2009; Van de Moortel et al., 2009; Wetzel, 2001).

Recent research using field-scale testing indicates that constructed wetlands are capable of removing substantial amounts of targeted potential pollutants (Allred et al., 2014). These conclusions are based on varied methods for quantifying pollutant removal efficiencies because there is currently no consensus in the literature on how to analyze these data.

The objectives of this study were to: (1) evaluate the event-scale nutrient attenuation capacity of a constructed floodplain wetland, (2) identify the spatial variability in nutrient concentrations throughout the wetland during simulated overbank conditions, and (3) identify the temporal variability in nutrient removal between the fall and spring events and within a controlled flood hydrograph. The significance of this work is in its implications for floodplain restoration. The uniqueness lies in the fact that we were able to create controlled flood events through our constructed wetland, allowing us to control the flow into the wetland, inject nutrient amendments, establish spatial sampling locations, and simulate storm events in two different seasons. This work aims to shed light on the ecological services provided by riparian wetlands with regard to nutrient management.

METHODS

SITE DESCRIPTION

A 0.2 ha floodplain wetland was constructed adjacent to Opequon Creek to act as a demonstration site and experimental wetland for stormwater management as part of a larger project. Opequon Creek is a watershed targeted by state and federal efforts to reduce the amount of pollutants reaching Chesapeake Bay (Mostaghimi et al., 2003, 2004). The Opequon Creek drainage basin is characterized by forest and pasture agriculture as well as urbanization, mainly associated with the city of Winchester, Virginia. The project site is in the headwaters of Opequon Creek. The drainage area of the creek at this point is approximately 38 km^2 (fig. 1). Regional curve data for streams in the non-urban Ridge and Valley physiographic province of Virginia published by the U.S. Geological Survey (USGS) correlated a watershed of this size to a 1.5-year discharge of approximately 11.3 cms (regression data range of 2.8 to 22.6 cms) (Keaton et al., 2005). TP concentrations as high as 0.29 mg L^{-1} were measured by the USGS in samples collected at USGS gauge station 01614830, just downstream from the study site (USGS, 2009).

The wetland lies in converted pastureland, and it was designed using guidance provided by the Virginia Department of Conservation and Recreation (VADCR, 1999) for constructed stormwater wetlands. The inlet is a grass swale that was cut in the bank of the stream and conveys water via surface flow into the wetland. A forebay is located at the head of the wetland, and a low marsh lies within a high marsh. An exit pool is located just before the outlet structure (fig. 2), which is a 0.3 m H-flume. Outflow that passes the flume travels down a grass swale before discharging into the stream. The low marsh vegetation consisted of arrowhead (*Sagittaria latifolia*), bulrush (*Scirpus validus*), and pickerelweed (*Pontederia cordata*), while the high marsh vegetation consisted of sweetflag (*Acorus calamus*) and bulrush (*Scirpus validus*). The length-to-width ratio of the wetland is approximately 4.

The hydrologic budget for the wetland was characterized as part of a parallel study to test for signs of perched water tables or confining layers. The study found that surface and ground waters are connected, with no indications of confining layers or perching effects (Ludwig and Hession, 2015). Annual surface storage fluctuations are affected by groundwater exchange between the adjacent hillslope and stream channel. Initial groundwater table elevations were measured at the beginning of the fall and spring experimental flood events. Initial groundwater table levels in the center of the wetland were -0.8 m at the beginning of the fall event and -0.05 m (or at the soil surface) at the beginning of the spring event. The influence of groundwater exchange and evapotranspiration were assumed to be negligible during experiments because of the short event duration and imposed flood flows.

EXPERIMENTAL FLOOD EVENTS

The wetland was constructed in May 2007, and vegetative cover was established with native plant plugs and seed in November 2007. Overbank flow conditions were simulated

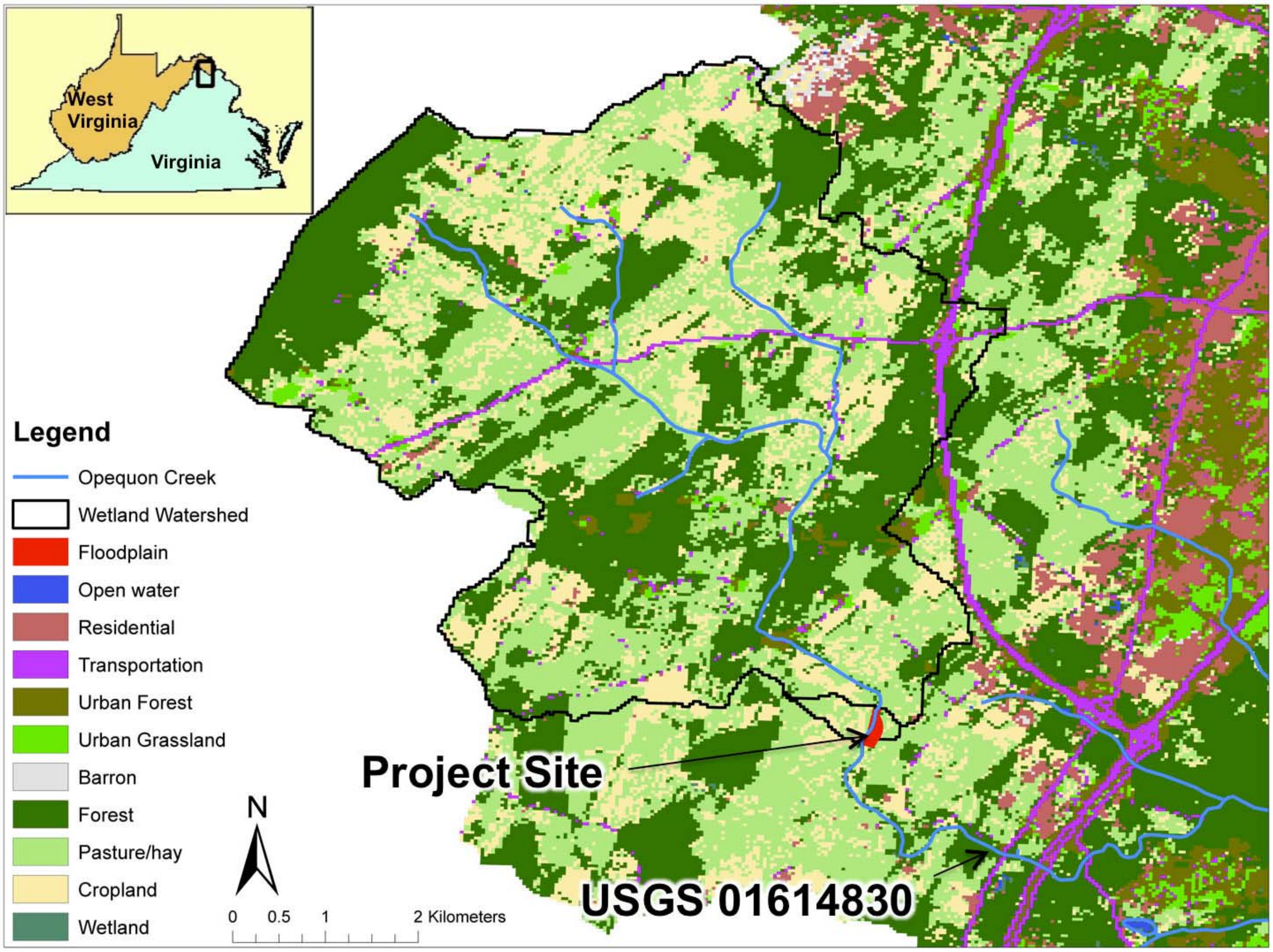

Figure 1. Drainage basin of Opequon Creek, location of project floodplain wetland site, and pertinent gauge station in northwest Virginia.

to provide a controlled, field-scale environment for capturing data to help describe the potential for water quality improvements due to enhanced channel-floodplain connectivity. Two experimental flood events were conducted in the floodplain wetland and were intensively monitored, both spatially and temporally, to characterize treatment performance. The first event was in November 2008, and the second was in May 2009. These time periods were selected to represent two separate seasons, fall and spring, to capture potential differences in performance due to vegetative cover conditions (dormant versus growing). Fall wetland conditions consisted of the presence of decaying and dormant emergent vegetation, an abundance of leaf litter from perimeter trees, a low water table, minimally inundated low marsh, and considerable amounts of exposed dry soil surfaces in the high marsh. Spring wetland conditions consisted of the presence of live and rigid emergent vegetation, a floating dense algal mat in the low marsh, a relatively high water table, complete inundation in the low marsh, and areas of inundation in the high marsh (fig. 3).

Experimental floods were created by pumping water out of the stream and into the wetland through the inlet swale using a John Deere 76 hp trash pump (John Deere, Moline, Ill.). Each event targeted a duration of 8 h and a flow rate of 4.25 m^3 min^{-1}, which was approximated as a commonly oc-curring flow rate for overbank events for the given channel dimensions and watershed area. These conditions were selected based on the goal of trying to produce an event that would mimic the duration and intensity of an overbank flow estimated from flow records at USGS gauge station 01614830 while suiting the practical needs of the data collection experiment, which included a need for the inflow rate to remain steady for a duration of time to allow for adequate sampling. A concentrated sodium nitrate and sodium phosphate slurry was incorporated into the pumped stream water using injection pumps (Fluid Metering, Inc., Syosset, N.Y.) at a rate of approximately 180 mL min^{-1} to attain concentrations that would mimic a natural seasonal storm event. The USGS reported that water quality sample data collected at gauge station 01614830 from May 2006 to May 2009 (n = 44) included PO_4-P concentrations ranging from 0.003 to 0.26 mg L^{-1} with an average of 0.02 mg L^{-1} and NO_3-N concentrations ranging from 3.19 to 1.77 mg L^{-1} with an average of 2.40 mg L^{-1}. The injection only occurred during steady-state flow conditions, as determined by observation of steady inflow and steady outflow and supported by water temperature data for the spring event. The average inflow concentrations of pertinent constituents are listed in table 1. The differences in concentrations were due to pump variability and limitations of the ion solution dissolving in the colder water temperatures of the fall event.

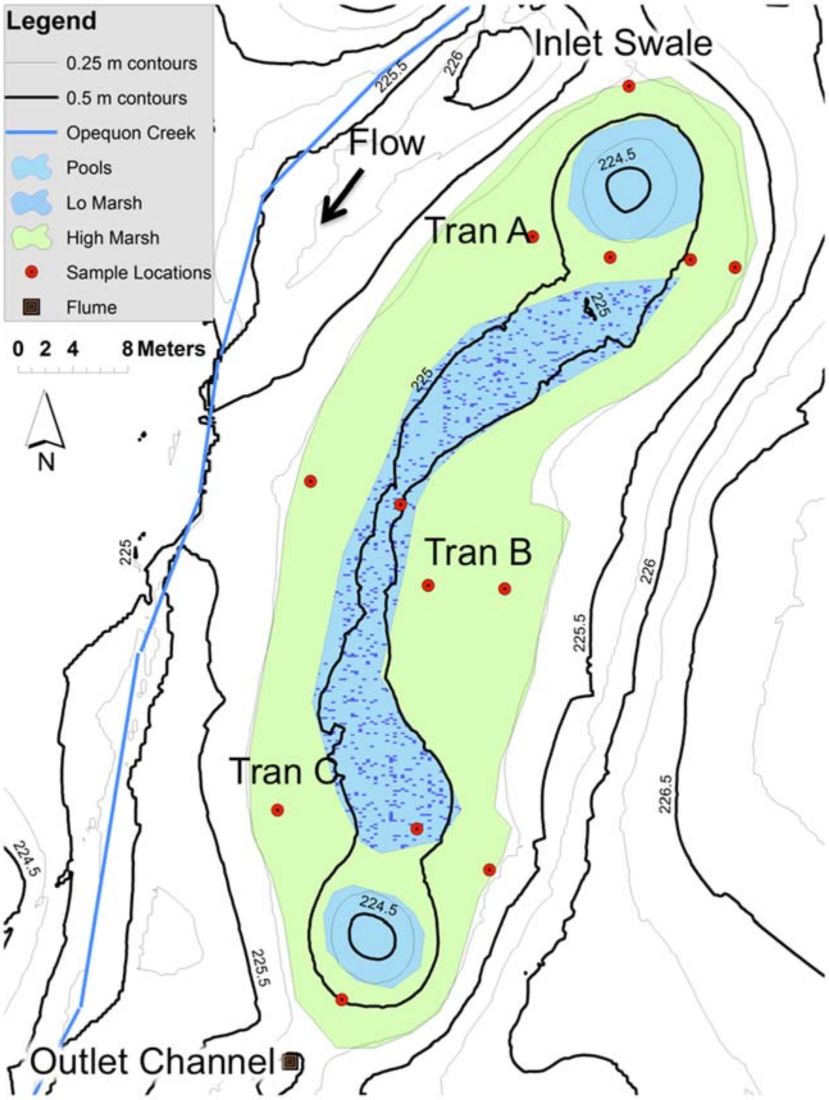

Figure 2. Constructed wetland topography and sample locations along three flow-normal transects (A, B, and C) near Winchester, Virginia. The flow of Opequon Creek at this point is generally north to south.

Figure 3. Photos of standing vegetation prior to experimental flood events in the fall of 2008 (left) and spring of 2009 (right).

Table 1. Average concentrations and standard deviations (SD) of water quality constituents in inflow water (comprised of stream baseflow and amendments) during two simulated storm events.

	Experiment Inflow Water Concentrations			
	Fall		Spring	
Constituent	Mean	SD	Mean	SD
PO_4-P (µg L^{-1})	4.87	2.23	15.7	4.38
TP (mg L^{-1})	0.06	0.04	0.07	0.01
NH_4-N (µg L^{-1})	25.3	9.70	38.5	6.90
NO_3-N (mg L^{-1})	2.83	0.08	2.16	0.28
TN (mg L^{-1})	3.22	0.21	3.09	0.04
DOC (mg L^{-1})	1.53	0.36	1.54	0.23
TSS (mg L^{-1})	54.5	32.9	66.9	30.0

EVENT SAMPLING

The wetland inlet and outlet were instrumented with automated sampling units (6712 Portable Samplers, Teledyne ISCO, Inc., Lincoln, Neb.). The inlet unit consisted of a 750 Area Velocity Flow Module and sampling unit, while the outlet unit consisted of a 730 Bubbler Flow Module and sampling unit to capture stage in the 0.3 m H-flume. Inflow was quantified using continuity of flow through a known cross-section (1 m base width, trapezoidal earthen channel) at a measured velocity, while a flume rating curve allowed quantifying of the outflow based on stage measurements. During the experiment, flow depth averaged 0.18 m in the inlet swale and approached 0.3 m in the outlet flume. Under these conditions, the potential error in reported flow rates was approximately 0.036 m^3 min^{-1}. Three sampling transects spanning the width of the wetland were installed perpendicular to the flow (A, B, and C in fig. 2), allowing sampling in the low and high marsh areas of the wetland. A total of 12 sampling locations were established along these three transects as directed by topography, and additional sampling sites were located at the inlet and outlet. Staff gauges were installed throughout the wetland and were used to monitor storage stage over the course of the events.

Two sampling techniques were used to quantify nutrient dynamics during the events. Inflow and outflow samples were collected continuously from the inlet channel and outlet flume using a time-dependent sampling program in the ISCO units over the course of the entire event. Flows were sampled and composited into 1 L acid-rinsed, polyethylene bottles. Sampling intervals varied between 10 and 20 min at the inlet and between 10 and 60 min at the outlet, where more frequent sampling occurred on the rising limb of the simulated hydrograph and longer intervals occurred during steady state and the falling limb. Snapshot or synoptic grab samples were collected at all 12 locations throughout the wetland within a 5 min window four separate times during the experiments, all occurring after steady state was determined by observation of the staff gauges.

Water quality parameters were measured from suspended sampling bridges to provide baseline characterization for general description. During the fall event, a calibrated YSI 556 handheld multiparameter instrument (YSI, Inc., Yellow Springs, Ohio) was used to record point measurements of dissolved oxygen (DO), temperature, and pH at each sampling location (fig. 2) during the mid-point of the flood event. During the spring event, a Hydrolab data sonde (Hach Co., Loveland, Colo.) was calibrated and deployed to continuously record measurements of DO, specific conductivity, temperature, and pH in the low marsh at transect B (fig. 2).

Water temperatures were used as an indicator of hydraulic mixing during the spring event based on the assumption that the injected stream water would have a different temperature than the relatively stagnant water stored in the wetland. This idea presented itself during the sampling in the fall season, so there is equivalent fall data. A monitoring chain was constructed of temperature probes strung along a steel-linked chain and suspended within a slotted PVC stilling well in the center of the exit pool located just before the outlet H-flume. Twelve thermistors were placed at 10 cm increments along the depth profile. The thermistors logged water temperature every minute during the spring event. Inspection of temperature time series data allowed for the breakdown of event hydrographs into three segments: (1) primary storage replacement, indicated by warming water temperatures as the high marsh storage water that existed in the wetland prior to inflow was being pushed out; (2) transient storage replacement, indicated by variability and falling water temperatures as the existing warm storage water and cooler inflow water were mixing; and (3) steady state, indicated by a constant warming trend that followed that of the air temperature throughout the day.

LABORATORY ANALYSES

Collected field samples were handled according to standard protocols for quality assurance (APHA, 2000). Nutrient analyses included (standard method in parentheses; APHA, 2000): total suspended solids (TSS, 2540 D), orthophosphorus (PO_4, 4500-P G), nitrate + nitrite (NO_3, 4500-NO3 I), ammonium as detected through acidification and measurement of ammonia (NH_3, 4500-NH_3 H), total phosphorus (TP, 4500-P H), and total nitrogen (TN, 4500-N C), and non-purgeable organic carbon (DOC, 5310-D/H). The NO_3 analysis used NO_3-to-NO_2 conversion. Throughout this article, reported NO_3 is the measured NO_3+NO_2 content of the sample. All N and P constituent data are reported as mass of N or P.

NUTRIENT ATTENUATION

The capacity of the wetland to attenuate nutrients at the event scale was analyzed using several methods. Percent mass removal (PMR) was determined for the entire event hydrograph using equation 1 (Kadlec and Wallace, 2009):

$$\text{PMR} = \sum\left(\frac{Q_i C_i - Q_o C_o}{Q_i C_i}\right) \quad (1)$$

where Q is flow (L^3/T), C is concentration (M/L^3), and i and o are inflow and outflow, respectively. The relationship between inlet and outlet flux was also used to determine percent removal during steady-state flow (SSPR), where the relationship was simplified under the assumption of equal inflow and outflow. The total mass removed during each event was ultimately determined as the difference in cumulative mass flux between the inlet and outlet.

Linear models were fit to the time series of cumulative mass flux of constituents at the inlet and outlet. These linear models were used to calculate nutrient attenuation rates. The slopes of the linear models represent the change in mass flux over time. Attenuation rate (M/T) was determined as the difference between the slope of the linear model of the inlet and that of the outlet. A comparison of the linear models with the variables of location (inlet or outlet), event time (minutes), and a combination of the two was performed in the open-source statistical package R (R Development Core Team, Vienna, Austria). Significant differences between the inlet and outlet models were determined with a significance level of $p < 0.01$. First-order rate constants (k_a) were determined using the following relationship between measured percent removal data and flow rate and assuming a negligible background concentration (Dortch, 1996):

$$1-\frac{RE}{100}=e^{\frac{-k_a}{q}} \qquad (2)$$

where RE is percent removal, q is flow rate (L^3/T), and k_a is the first-order volumetric removal rate constant (L/T).

SPATIAL AND TEMPORAL VARIABILITY OF NUTRIENTS

Spatial and temporal variability of nutrient concentrations and attenuation were quantified for the two events. Temperature data collected in the depth profile of the exit pool informed the delineation of segments of the hydrograph for a more detailed analysis of how nutrient dynamics changed over the course of the generated spring hydrograph. Specifically, these data were used to delineate the segments of time when the existing storage was being pushed from the wetland and when the full volume of this deepest point of the wetland was fully mixed. A steady-state analysis of removal was conducted when all the temperature sensors in the chain were trending the same and reflecting the warming of the ambient air temperature, providing information on SSPR.

Spatial variability of constituent concentrations was investigated using the data collected during the snapshot and synoptic sampling in each event (fig. 2). Variability in constituent concentrations was evaluated at a broad scale by lumping all grab samples together and determining the standard deviation. Additionally, samples collected along transects were compared to determine if design water depth (or location within macrotopographic features of the high marsh or low marsh) influenced concentrations. A two-sample t-test assuming unequal variances was performed between the group of grab samples from the high marsh and that from the low marsh using $\alpha = 0.05$.

RESIDENCE TIME

Cross-correlation analysis was used to determine the temporal discrepancy between the inlet and outlet PO_4 flux time series (Davis, 2002). The starting time for the cross-correlation analysis was the beginning of the nutrient injection. PO_4 was used for this analysis because we could anticipate a relatively stable inlet loading rate produced by the injection pump and a relatively stable baseline level in the inflow as compared with N species in the stream, which had a greater potential for fluctuation throughout the day. The temporal discrepancy between inlet and outlet PO_4 provides an estimate of hydraulic residence time. The outlet time series was shifted by lag intervals of 10 min until the two series' trends matched, as indicated by the highest correlation coefficient (R^2). Residence time was then determined to be the lag time associated with the highest R^2.

RESULTS

EVENT HYDROLOGY AND NUTRIENT LOADING

Average flow rates and nutrient loading rates were higher in the spring event than in the fall event (table 2). Inlet concentrations of PO_4, TP, NH_4^+, DOC, and TSS were higher in the spring event as well (table 3). Overall, the total volume passing through the constructed wetland in both events was similar; however, the starting water table elevation in the fall event was considerably lower than in the spring event, resulting in a larger available storage volume. Average DO levels were higher in the fall, as expected with the lower water temperature.

The chemical fractionation of N and P species in the inflow and outflow varied between the fall and spring events. Most of the N entering and leaving the wetland was in the form of NO_3-N; particulate N comprised a greater percentage of inflow N in the spring (29%) than in the fall (12%). Particulate P was the most abundant P form in the inflow and outflow; PO_4-P comprised more of the inflow P in the spring (21%) than in the fall (8%). Cross-correlation analysis of PO_4-P time series data collected at the inlet and outlet indicated that the residence time was approximately 110 min in the fall event and 130 min in the spring event. Correlation coefficients were plotted against total analysis lag time, and the curves were compared (fig. 4). The spring curve is arced and has a definitive maximum, while the fall curve is flatter with a less definitive maximum. This suggests that the wet-

Table 2. Pertinent characteristics of the fall and spring experimental flood events on the constructed wetland.

Characteristic	Fall	Spring
Volume treated (m^3)	1950	1900
Event time (hours:minutes)	8:12	7:18
Average Q ($m^3\ min^{-1}$)	4.21	4.94
Storage (m^3)	274	233
Starting head (m)	-0.8	-0.05
Average air temperature (°C)	5.1	10.6
Average water temperature (°C)	9.5	16
Average DO ($mg\ L^{-1}$)	10.9	9.5
Average pH	8	8

Table 3. Average constituent concentrations at the wetland inlet and outlet during the fall and spring controlled pumping experiments (ranges shown in parentheses). Sample size varied between 12 and 25.

Event and Location		PO_4-P ($\mu g\ L^{-1}$)	NH_4^+-N ($\mu g\ L^{-1}$)	NO_3-N ($mg\ L^{-1}$)	DOC ($mg\ L^{-1}$)	TP ($\mu g\ L^{-1}$)	TN ($mg\ L^{-1}$)	TSS ($mg\ L^{-1}$)
Fall	Inlet (n = 19)	4.9 (1-11)	25.3 (9-52)	2.8 (2.7-3.0)	1.5 (1.1-2.5)	60.8 (33-217)	3.2 (3.0-4.0)	54.5 (10-147)
	Outlet (n = 25)	4.7 (2-9)	14.6 (9-28)	2.6 (1.7-2.9)	2.3 (1.4-8.2)	62.6 (22-223)	3.1 (2.7-3.2)	33.6 (6-214)
Spring	Inlet (n = 14)	13.5 (4-25)	38.5 (24-49)	2.2 (1.7-2.4)	1.5 (1.2-2.1)	65.2 (36-93)	3.1 (1.9-3.6)	67.0 (36-135)
	Outlet (n = 12)	12.8 (7-19)	17.5 (11-30)	2.1 (0.2-2.3)	2.5 (1.4-9.4)	54.5 (34-90)	2.5 (0.7-3.1)	24.8 (6-67)

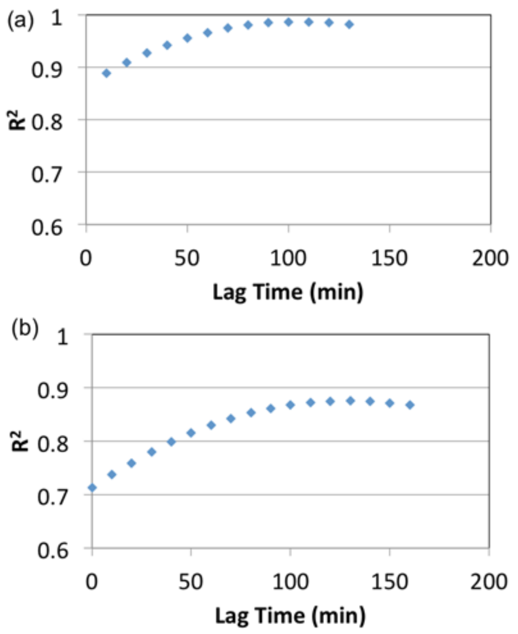

Figure 4. Distribution of correlation coefficients as a function of induced lag time during cross-correlation analysis for determination of residence time using PO_4-P concentration data for the (a) fall and (b) spring experimental flood events.

land storage water in the spring before the event had markedly different characteristics from the inflow. In the fall, the outflow was more similar to the inflow throughout the sample collection. A potassium bromide tracer experiment was performed during the spring event and produced a similar retention time of 100 min (Ludwig, 2010).

NUTRIENT ATTENUATION

Table 4 lists the percent mass removal determined from the inlet-outlet data in both seasons for targeted NPS pollutants. Greater removal in the fall was measured for TSS, NO_3-N PO_4-P, and TP. Conversely, greater removal of NH_4^+-N and TN was found in the spring. These removal values are a function of event inlet concentrations. Thus, for seasonal comparisons, the inlet concentrations must be considered. Average inlet concentrations were higher in the spring event for all constituents except TN and NO_3.

Table 4. Constituent percent mass removals, total mass removed, and removal rates in the fall and spring experimental flood events.

	Constituent	Fall	Spring
Percent removal	PO_4-P	23.1	8.18
	TP	37.0	24.5
	NH_4^+-N	54.1	57.6
	NO_3^--N	15.7	6.55
	TN	16.2	21.5
	DOC	-2.45	-3.58
	TSS	73.0	69.4
Mass removed	PO_4-P (g)	2.15	2.00
	TP (kg)	0.04	0.03
	NH_4^+-N (g)	26.0	41.4
	NO_3^--N (kg)	0.86	0.26
	TN (kg)	1.00	1.27
	DOC (kg)	-0.07	-0.10
	TSS (kg)	76.8	83.7
Removal rate	PO_4-P (mg min^{-1})	3.0 (1.8-4.1)	10 (3.9-16.3)
	TP (g min^{-1})	56	73
	NH_4^+-N (mg min^{-1})	43.0	109.0
	NO_3^--N (g min^{-1})	0.9	1.0
	TN (g min^{-1})	1.0	3.4
	DOC (g min^{-1})[a]	0.6	1.8
	TSS (g min^{-1})	190	200

[a] Rate of export.

Figure 5 illustrates how the mass removal rates were calculated. The slope differences of cumulative nutrient mass loadings were compared for the inlet and outlet locations. These slope differences are direct measurements of nutrient removal rates (M/T) within the wetland. Based on dummy variable regression, the slopes for fall PO_4-P differed by 3.0 mg min^{-1} (95% confidence interval 1.8-4.1, $p < 0.01$), and the slopes for spring PO_4-P differed by 10.1 mg min^{-1} (95% confidence interval 3.9-16.3, $p < 0.01$).

Rates of pollutant removal were higher in the spring event for all constituents (table 4). While the events treated approximately the same volumes, the spring event was shorter in duration and removed the same or greater constituent mass as compared to the fall event. There was a two-fold increase in removal rate in the spring for PO_4, NH_4^+, and TN.

Larger mass amounts of TP were removed relative to PO_4, suggesting that settling of particulate and particulate-bound P was the primary P removal mechanism. A larger percent of the NH_4^+ input was removed compared to the NO_3 input. Water chemistry conditions were optimal for nitrification, as DO was relatively high in both events and the pH was 8 (Kadlec and Wallace, 2009), likely resulting in higher removal of NH_4^+ relative to NO_3. The NH_4^+ from the transitional and anaerobic hyporheic zones may have gone through rapid nitrification to NO_3 with the transition from anaerobic conditions to aerobic conditions as DO increased in the water column due to the turbulent inflow (Cirmo and McDonnell, 1997). TSS and PO_4 removals were higher in the fall, when chemical sorption and physical settling would be the dominant removal mechanisms over the temporally sensitive biological removal mechanisms.

A dense algal mat was present in the low marsh between

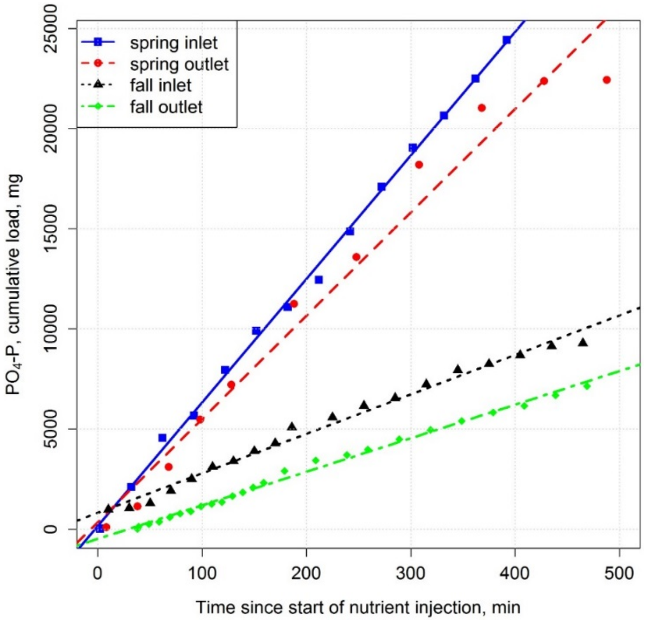

Figure 5. Cumulative mass loading curves for PO_4-P at the inlet and outlet during the fall and spring experimental flood events used for slope comparisons and to determine pollutant removal rate.

emergent vegetation in the spring. Dissolved nutrient dynamics were most likely affected by the presence of this mat; however, the interactions between the suspended biofilm community and the readily available dissolved nutrients are complex (Kadlec and Wallace, 2009). A boundary layer exists between the moving flow of the surface water and that of the pore water in wetland substrates. In spring, a high water table and a saturated high marsh may have limited the amount of PO_4 removal due to diffusion into pore water and exposure of sorption substrate surfaces to PO_4 carried by the overlying flow. The effects of this raised boundary layer may explain the lower percent removal of PO_4 in the spring event.

Overall higher removal rates in the spring may also be attributed to the presence of active vegetation (unlike the fall when vegetation was approaching a dormant state) or the increase in ambient temperatures (table 2), which affects the rates of microbial respiration and metabolism. Additionally, greater removal in the spring may be attributed to the increase in mixing throughout the wetland surface area. It is hypothesized that more of the nutrients that entered the wetland diffused into the transient storage zones and attenuated in storage instead of passing through the wetland in primary flow paths.

The first-order volumetric rate constants (k_a) for TP were 6.1 m year^{-1} in the fall and 4.1 m year^{-1} in the spring (table 5). These rates are lower than the rates suggested by a review of data from 282 wetlands in which Kadlec and Wallace (2009) found the median k_a to be 10 m year^{-1} (inlet TP concentrations ranged from 0.007 to 126 mg L^{-1} with a median of 4.66 mg L^{-1}). In a review of free-water surface stormwater treatment wetlands in the U.S., wide ranges of removal rate constants were reported for TP, NH_4^+, and NO_3 (Carleton et al., 2001). The rate constants for other constituents determined in this study were consistent with those reported in the review for wetlands of similar area and volume (Kadlec and Wallace, 2009).

Table 5. First-order volumetric removal rate constants for the fall and spring experimental flood events.

Constituent	Fall k_a (m year^{-1})	Spring k_a (m year^{-1})
PO_4-P	3.8	1.3
TP	6.1	4.0
NH_4^+-N	8.9	9.5
NO_3-N	2.6	1.1
TN	2.7	3.5
DOC	-0.4	-0.6
TSS	12.0	11.4

ATTENUATION VARIABILITY

Event segments as delineated by water temperature measurements in the profile of the exit pool assisted in indicating when steady state had been achieved during the spring sampling (fig. 6). This time was approximately 72 min into the event. Inlet and outlet samples were paired accordingly, and SSPR was calculated for each time step of sampling following 72 min.

SSPR was calculated in two ways to explore variability: first with data that were paired according to the same event time, and secondly with data pairs that accounted for residence time in an attempt to trace a volume of water through the wetland to best estimate the removal attributable to internal wetland storage processes. There was considerable variability in SSPR. The greatest variability was observed for PO_4-P, DOC, and TOC and generally in the fall event, where variability ranged from -90% to over 100%. When steady-state inlet and outlet data were paired with an offset to account for residence time, the results showed similar values for percent removal but with smaller amounts of variability relative to the paired data with no offset (fig. 7). The incorporation of a time offset equal to the estimated residence time may have removed some effects of the inlet concentration variability from the SSPR results. Microbial assimilation of nutrients during the spring likely acted as a consistent removal mechanism. Such variability in SSPR over the steady-state period suggests that treatment performance measurements are highly sensitive to when samples are collected during an event and that comprehensive performance assessment must characterize nutrient mass balances for the complete event.

The percent removal values determined with this paired analysis were slightly different from those determined with the mass loading calculations. The differences were not con-

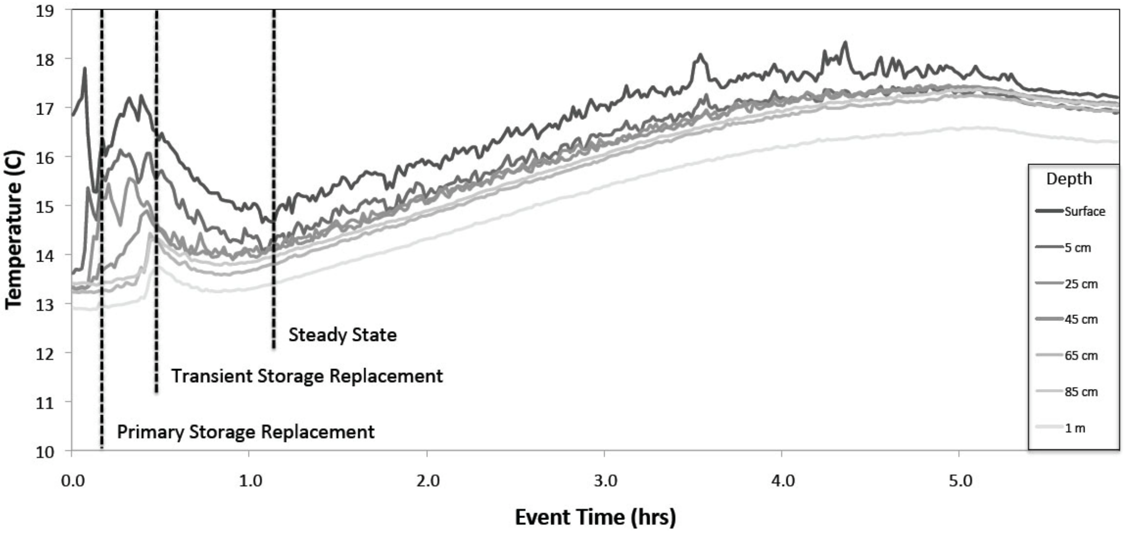

Figure 6. Temperature measurements throughout the spring experimental flood event as recorded from a depth profile chain in the exit pool and resultant delineation of event segments.

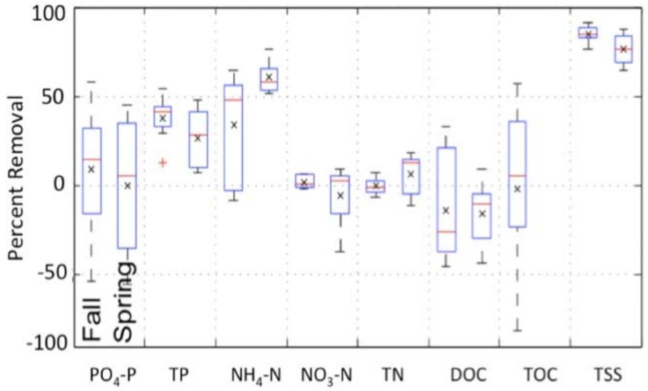

Figure 7. Distribution of percent removal across paired inlet-outlet data during steady-state flow in the fall and spring experimental flood events with a residence time lag between sample pairs. Total organic carbon (TOC) was not measured in spring. Bars represent 95% confidence intervals, red lines represent median values, × indicates the mean, and red + symbols indicate outliers.

sistently higher or lower and thus quantified a further source of variability: residence time. The difference between average percent removals calculated with the paired sample method and mass loading calculations ranged between 0% and 18%.

Spatial variability in dissolved nutrient concentrations and TSS were described by the relative standard deviation of the synoptic samples (table 6). Sample variability was as much as 47.2% of the average wetland storage concentrations for nutrient constituents, while TSS varied drastically (up to 134.3%) in the fall event. This fall TSS variation may be attributed to sediment entrainment from the bare ground exposed along the perimeter of the pools and low marsh areas, which was not present in the spring event, as the water level was higher. The NO$_3$ concentrations were higher and less variable than the PO$_4$ and NH$_4^+$ concentrations. Such relatively large spatial variability in nutrient concentrations throughout the wetland suggests that nutrient attenuation in the wetland is a result of many spatially variable processes occurring in a heterogeneous environment.

The influence of water depth on constituent concentrations was evaluated by comparing the means of grab samples in the high marsh to those of the low marsh (table 7). The greatest difference in constituent concentrations was measured in the fall samples, where four of the six constituents were found to have significantly different concentrations between the high marsh and low marsh. In the spring, only TSS was significantly different between the two locations. The detection of significantly different concentrations indicates that variable water depths influence the abundance of constituents in the water column. That the majority of constituents showed this difference in the fall, while only TSS showed this difference in the spring, indicates that there may also be a temporal component to this relationship.

Table 6. Spatial variability in snapshot grab samples during the fall and spring experimental flood events, reported as the relative standard deviation of average constituent concentration (n = 48).

	Relative Standard Deviation (%)	
Constituent	Fall	Spring
PO$_4$	47.2	27.8
NH$_4^+$	30.3	33.7
NO$_3$	11.9	13.7
TSS	134.3	57.5

Table 7. Average constituent concentrations in macrotopographic features from four snapshot grab samples, six sample sites in the high marsh, and three sample sites in the low marsh. Bold values indicate significant differences between high marsh and low marsh averages.

	Average Concentration			
	Fall		Spring	
Constituent	High Marsh	Low Marsh	High Marsh	Low Marsh
PO$_4$-P (µg L^{-1})	**7.10**	**4.26**	12.75	13.51
TP (mg L^{-1})	**0.08**	**0.03**	0.06	0.06
NH$_4^+$-N (µg L^{-1})	**23.0**	**28.2**	23.4	23.7
NO$_3$-N (mg L^{-1})	2.65	2.75	2.10	2.17
TN (mg L^{-1})	2.96	3.05	2.09	2.13
TSS (mg L^{-1})	**31.1**	**12.9**	**25.4**	**41.1**

CONCLUSION

Nutrient attenuation was measured during simulated flood conditions in a constructed floodplain wetland in fall and spring seasons. TSS was the constituent with the greatest attenuation in terms of percent removed and total mass removed, while NH$_4^+$ had the greatest percent removal of the measured nutrient fractions. Greater removal of TP relative to PO$_4$ suggests that particulate settling of sorbed P was the driving mechanism in P removal. Faster attenuation rates for ammonia and total N in the spring resulted in larger mass removal than in the fall. Warmer temperatures combined with live plants and sufficient storage DOC concentrations may have stimulated autotrophic and heterotrophic microbial communities, resulting in the greater attenuation of dissolved N and P from the injected water.

TSS and PO$_4$ had the most spatially variable concentrations within the wetland during simulated flood events, while PO$_4$ and carbon percent removal varied the most in the paired inlet-outlet data. Adjusting the paired inlet-outlet data using an offset for residence time removed some of the variability in percent removal. Further studies on constructed wetlands in riparian areas are needed to better describe the relationship between loading, residence time of stormwater, and expected attenuation rates of pollutants in the complex hydrology of these systems.

These findings suggest that constructed floodplain wetlands may be an effective way to manage stormwater nutrients and sediments at concentrations commonly found in streams affected by land use change due to urbanization and agriculture. This work complements other floodplain-scale research showing that these systems have the capacity to reduce nutrients and sediment in overbank flows (Kroes et al., 2015; Richardson et al., 2011; Roley et al., 2012). The spatial and temporal variability measured here, along with questions of application in areas with potentially high legacy soil nutrients due to historic agricultural land use (Jones et al., 2015), point to a gap in the understanding of how to best apply restoration efforts for maximum water quality benefits. A conclusion that can be drawn from these findings, as well as from long-term data collection experiments over annual cycles (Raisin et al., 1997), is that integrating this practice in the most appropriate locations in the landscape and as part of a larger watershed management plan would potentially decrease the amounts of nonpoint-source pollutants conveyed by streams into receiving waterbodies. Future research needs include practical protocols for assessing the presence of legacy soil impacts that may mobilize potential pollutants if floodplain hydrology were restored, as well as methods for remediating such impacts before restoration projects occur and for effectively crediting protocols for mitigation applications.

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