# Wetlands and Aquatic Processes

## Dissolved Phosphorus Retention and Release from a Coastal Plain In-Stream Wetland

J. M. Novak,* K. C. Stone, A. A. Szogi, D. W. Watts, and M. H. Johnson

### ABSTRACT

**Dissolved phosphorus (DP) can be released from wetlands as a result of flooding or shifts in water column concentrations. Our objectives were to determine the long-term (1460 d) DP retention and release characteristics of an in-stream wetland, and to evaluate how these characteristics respond to flooding, draining, and changes in DP concentrations. The studied in-stream wetland drains an agriculturally intensive subwatershed in the North Carolina Coastal Plain region. The wetland's DP retention and release characteristics were evaluated by measuring inflow and outflow DP concentrations, DP mass balance, and DP movement across the sediment–water column interface. Phosphorus sorption isotherms were measured to determine the sediment's equilibria P concentration (EPCo), and passive samplers were used to measure sediment pore water DP concentrations. Initially, the in-stream wetland was undersized (0.31 ha) and released 1.5 kg of DP. Increasing the in-stream wetland area to 0.67 ha by flooding resulted in more DP retention (28 kg) and low outflow DP concentrations. Draining the in-stream wetland from 0.67 to 0.33 ha caused the release of stored DP (12.1 kg). Shifts both in sediment pore water DP concentrations and sediment EPCo values corroborate the release of stored DP. Reflooding the wetland from 0.33 to 0.85 ha caused additional release of stored DP into the outflowing stream (10.9 kg). We conclude that for a time period, this in-stream wetland did provide DP retention. During other time periods, DP was released due to changes in wetland area, rainfall, and DP concentrations.**

There is a high density of confined livestock production in the North Carolina Coastal Plain region (Barker and Zublena, 1995). Because manure transportation costs are high and land available for manure application is limited, manure is spread onto fields near the animal operation. Over time, repeated manure applications to fields have caused some Coastal Plain soils to contain soil P concentrations in excess of plant nutritional needs (Barker and Zublena, 1995; Kellogg et al., 2000; Novak et al., 2000). As a result of runoff and erosion from P-enriched soils, DP concentrations and loads have increased in the Cape Fear and Nuese River systems (Cahoon et al., 1999; Kellogg et al., 2000; Mallin, 2000). High DP mass transport by these two North Carolina river systems into nutrient sensitive lakes, estuaries, and bays can increase the likelihood of eutrophication (Mallin, 2000). Excessive P in coastal water bodies has been linked to causing toxic algae blooms, which are harmful to both humans and aquatic life (Burkholder et al., 1997). Kellogg (2000) ranked the Cape Fear and Nuese River systems 1 and 15, respectively, of U.S. priority watersheds for water quality problems related to manure nutrient contamination.

Wetlands can reduce P loads transported by surface water systems (Reddy et al., 1999; Dosskey, 2001). In wetlands, P is assimilated through sorption to sediments and through P uptake by plants, periphyton, and microbial communities (Reddy et al., 1999); and by retention of P-enriched sediments (Dosskey, 2001). Among these P assimilation processes, sorption and precipitation can be the dominant retention mechanisms in some wetlands (Richardson, 1999). Phosphorus sorption and precipitation reactions in wetland sediments are influenced by pH and levels of Ca, Fe, and Al. In alkaline wetland sediments, inorganic P can be retained by formation of insoluble Ca–P or Mg–P compounds (Moore and Reddy, 1994; Reddy et al., 1999; Richardson, 1999). Formation of insoluble Fe- and Al-phosphate compounds is the dominant removal mechanism in acidic wetland systems (Khalid et al., 1977). Although wetland systems can retain P through a variety of mechanisms, if P influx amount exceeds the assimilation capacity, then they can release P (Omernik et al., 1981; Richardson, 1985; Qian and Richardson, 1997; Pant and Reddy, 2001).

The tendency of wetlands to bind or release P can be predicted by examining relationships between sediment P sorption and water column P concentrations. From the sediment P sorption isotherms, the sediment's equilibrium P concentration (EPCo) value can be measured (Logan, 1982; Reddy et al., 1999). The EPCo value represents the aqueous P concentration at which no net sorption or desorption occurs when a sediment is suspended in a water sample. When the water column DP concentration is below the sediments EPCo value, sediments can potentially release DP (Reddy et al., 1999).

Phosphorus loads transported by the Cape Fear and Nuese River systems can coincide with high precipitation and flooding from tropical storms and hurricanes (Bales et al., 2000). Wetlands can be also be flooded in response to recreation or irrigation requirements. Flooding coastal wetlands can potentially shift P equilibria reactions by altering sediment redox status and water column DP concentrations. Dissolved phosphorus can be released from sediment-bound P pools, thereby increasing the incidence of P chemical imbalances in downstream ecosystems. Although flooding of wetlands is a frequent occurrence in the North Carolina Coastal Plain region, there is sparse information on relationships between flooding and a wetland's P retention and release characteristics. To fully recommend or endorse

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**Abbreviations:** DP, dissolved phosphorus; EPCo, equilibrium phosphorus concentration; P, phosphorus.

wetlands to provide reliable P mitigation for southeastern U.S. Coastal Plain surface water systems, it is important to determine their retention and release characteristics due to shifts in DP concentrations, flooding, and draining. Our objectives were to determine the long-term DP retention and release characteristics of an in-stream wetland and to evaluate how these characteristics respond to flooding, draining, and shifts in DP concentrations.

## MATERIALS AND METHODS

### In-Stream Wetland Description

The in-stream wetland is located in the Herrings Marsh Run watershed of Duplin County, North Carolina. Duplin County is positioned in the agriculturally intensive Coastal Plain region of southeastern North Carolina (Barker and Zublena, 1995; Novak et al., 2000). Soils in this region are comprised of sands and clays that formed from marine and fluvial sediments (Daniels et al., 1999). Surface topography is mostly level to gently sloping and includes shallow depressional areas (Daniels et al., 1999). Forested wetlands can form in these depressional areas, especially when the depression intersects the water table or contacts a stream. This particular in-stream wetland is supplied with water from a shallow, first-order stream. The in-stream wetland outlet was dammed in the 1950s to increase the flooded area available for crop irrigation purposes (Star Maready, personal communication, 2001). A survey across the in-stream wetland was conducted in November 1995 to identify soil series and existing vegetation (Dr. Steve Broome, personal communication, 2002). Auger holes along transects across the in-stream wetland revealed that about half of the wetland contained the Bibb series (coarse-loamy, siliceous, acid thermic Typic Fluvaquent) and the other half contained the Pamlico series (sandy, siliceous, dysic, thermic Terric Haplosaprist). The vegetative survey showed that the dominant wetland plant species was cutgrass [*Leersia oryzoidesi* (L.) Sw.], with smaller amounts of rush (*Juncus effusus* L.) and cattail (*Typha latifolia* L.). These aquatic plants covered approximately 15 to 25% of the flooded wetland area. Trees growing around the perimeter of the in-stream wetland in drier areas include gums (*Nyssa aquatica* L.) and longleaf pine (*Pinus palustris* Mill.), while cypress [*Taxodium distichum* (L.) L.C. Rich. and *T. ascendens* Brongn.] grow within the wetland.

The stream that flows into the in-stream wetland drains a 200-ha subwatershed of the Herrings Marsh Run watershed. A swine (*Sus scrofa*) production facility is located approximately 750 m upstream from the in-stream wetland. Before this study, swine manure from this production facility was applied to a nearby grass field. Monitoring stream water adjacent to this grass field revealed that the stream contained elevated $NO_3$–N concentrations (between 4 and 9 mg $L^{-1}$, unpublished data, 2002). To mitigate the stream $NO_3$–N concentrations, the USDA–Natural Resource Conservation Service contracted with the owner to increase the flooded area by improving an earthen closure dam and installing a water depth control device (Fig. 1). Increasing the flooded area of the in-stream wetland was expected to decrease N concentrations by reducing nutrient-laden sediment movement and enhance N assimilation processes.

### In-Stream Wetland Water Elevations and Management

The in-stream wetland was surveyed in November 1995 to determine elevations around the perimeter and water depths (Fig. 1). Elevation data were indexed to a local USGS reference point, and the contours were reported relative to mean sea level. Elevations were recorded electronically to determine daily changes in the flood water depths from 1 Apr. 1996 (Day 91), until 31 Dec. 1999 (Day 1460). From the in-stream wetland's elevations, a grid file was generated using the Kriging Interpolation method contained in Surfer Graphic version 8.0 software (Scientific Software Corp., Sandy, UT). This software was then used to estimate the in-stream wetland surface area and storage volume for given flood water elevations. Changes in flood water elevations caused the in-stream wetland to range in area and storage volume from 0.31 to 0.85 ha and from 840 to 7037 $m^3$, respectively. The flood water residence times were then determined by dividing the storage volumes by an average outflow volume (ranging between 749 and 2528 $m^3$ $d^{-1}$). Consequently, the flood water residence time varied between 1 and 3 d.

Modifications to nutrient management practices and owner preferences of in-stream wetland usage caused the water depth to vary substantially from 1996 to 1999 (Fig. 2, Days 91–1460). Consequently, the area of the in-stream wetland varied between 0.31 and 0.85 ha (Table 1). Because the initial stream inflow–outflow equilibration was irregular, the water depth varied during the first 200 d of the study (Fig. 2). Between Days 205 and 280, water depth was stabilized, resulting in a wetland area of approximately 0.31 ha. After stabilization, $NO_3$–N removal efficiency was low, so the in-stream wetland was flooded between Days 281 and 877 to 0.67-ha to potentially increase $NO_3$–N removal through denitrification. After 878 d, wetland vegetation growth declined due to excessive flooding. Consequently, to improve plant growth conditions, the in-stream wetland was drained between Days 878 and 910. Draining the in-stream wetland caused an areal reduction to 0.33 ha between Days 911 and 1320. After Day 1320, the in-stream wetland was flooded again by the owner for irrigation and fishing purposes. After the second flooding, the in-stream wetland area increased to approximately 0.85 ha. A large range of water depths occurs in the in-stream wetland (Fig. 1, from 0.2 to 2.5 m deep) due to flooding and draining.

Total annual precipitation recorded 6 km away from the Herrings Marsh Run watershed in Warsaw, NC, for 1996, 1997, 1998, and 1999 were 1438, 1208, 1410, and 1854 mm, respectively (State Climate Office of North Carolina, 2002). High precipitation (almost 400 mm delivered in 3 d) from Hurricane Floyd contributed to the elevated 1999 amount.

### Stream Flows Estimation, Water Sample Collection, and Dissolved Phosphorus Measurement

H-flumes (Free Flow, Omaha, NE) equipped with pressure transducers were installed at the in-stream wetland inlet and outlet (Fig. 1). Flume water heights were measured using the pressure transducers. Stream inflow and outflow rates were estimated using relationships between flume water heights and flume area. Flow rates were determined at 15-min intervals and were pooled for a daily estimate of mean inflow and outflow rates. America Sigma automatic water samplers (Danaher Corp., Loveland, CO) were also installed at the inlet and outlet and were programmed to collect 3.5-d composite samples from Days 91 to 1460 (Fig. 1). Each composite sample contained 42 subsamples collected at 120-min intervals. The inlet and outlet sampling locations were called Site 1 and Site 4, respectively (Fig. 1).

Reflooding the in-stream wetland after Day 1342 resulted in water covering the inlet H-flume and disrupting inflow measurements and stream sample collection. Because of the severity of flooding, there was insufficient land area available to reinstall the H-flume and secure the stream sampling device.

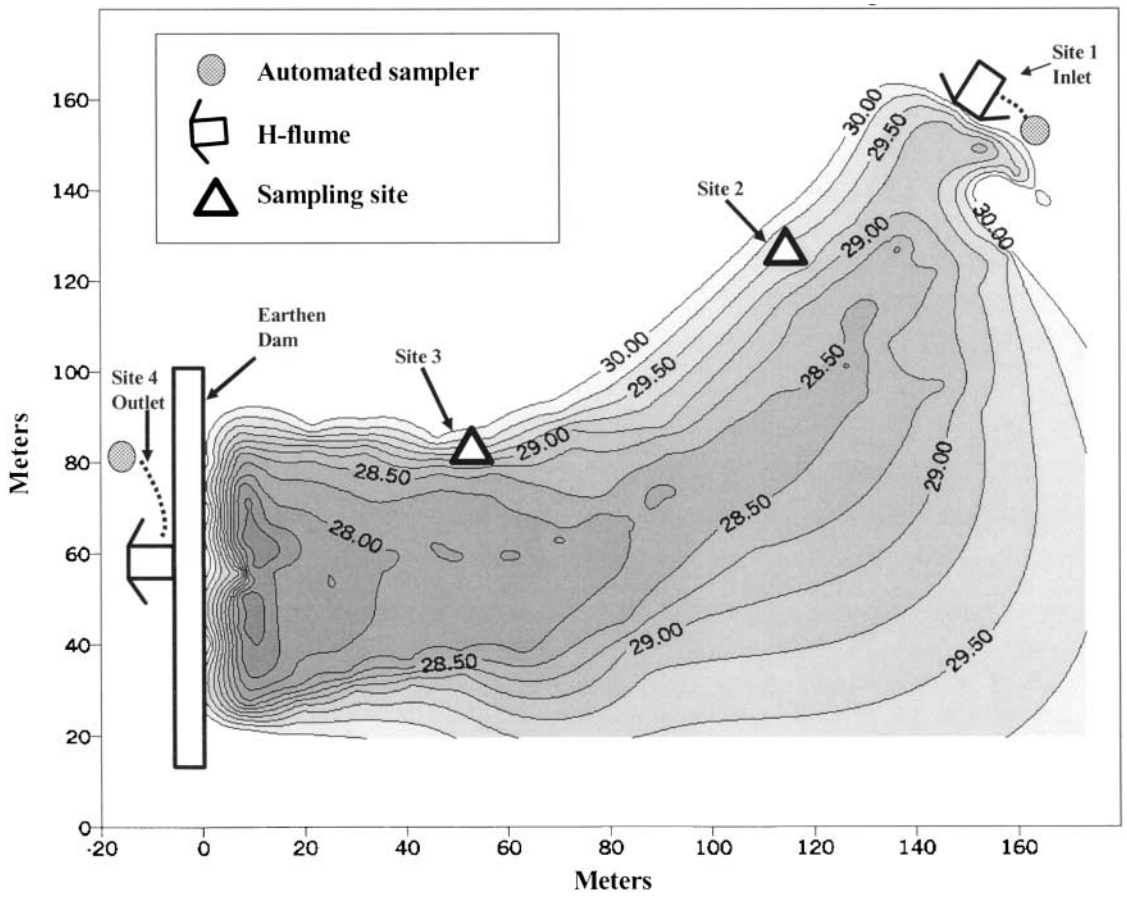


**Fig. 1. Location of in-stream wetland sampling sites, flumes, and automated samplers.**

Consequently, there were no stream inflow measurements and inlet DP samples between Days 1342 and 1460.

Dilute $H_2SO_4$ was placed in the automatic water sample bottles before sample collection to preserve the sample and avoid nutrient loss. The acidified sample bottles were collected weekly. The stream samples were filtered in the laboratory (0.45 μm) and were analyzed for DP on a TRAACS Auto analyzer (Bran Lubbe, Elmsford, NY) using USEPA Method 365.1 (USEPA, 1983). The minimum DP detection limit was 7.5 μg $L^{-1}$. A 0 μg $L^{-1}$ value was assigned when a sample had a predicted DP concentration below the detection limit.

## Dissolved Phosphorus Mass Loads

Daily inflow and outflow DP mass load estimates were calculated by multiplying the daily mean flows and DP concentrations. Because DP concentrations were measured in composite samples collected every 3.5 d, DP concentrations were linearly interpolated during a 3- to 4-d interval to provide continuous estimates of daily DP inflow and outflow concentrations. Changes in water elevation (Fig. 2) were used to establish time intervals (as days of study) corresponding to the in-stream wetland area fluctuations (Table 1). Total flows, DP mass loads, and mean DP concentrations measured at the in-stream inflow and outflow locations between these days were then determined (Table 1). Dissolved P mass flux differences (Δ) between the cumulative inlet and outlet mass values were determined by subtraction for each time interval. A DP loading rate was estimated by dividing the cumulative DP mass at the inlet by the in-stream wetland area and by the number of days in the specific time interval (units expressed as mg DP $m^{-2}$ $d^{-1}$). The rate of DP released or retained by the in-stream wetland was calculated in a similar manner, except the cumulative mass at the outlet was used. A positive (+◆) and negative (−◆) DP rate value implies that DP was retained or released, respectively, by the in-stream wetland. The mean inflow and outflow DP concentrations for each time interval were tested for significant differences using a Mann-Whitney Rank Sum test by SigmaStat version 2.03 software (SPSS Corp., Chicago, IL).

## Sediment Collection and Equilibrium Phosphorus Concentration Measurements

In addition to sampling the in-stream wetland inlet (Site 1) and outlet (Site 4), two sites within the wetland were selected that correspond to approximately one-third and two-thirds the distance along the flow continuum. The one-third and two-thirds locations were called Sites 2 and 3, respectively (Fig. 1). Both of these sites were located in a shallow part of the wetland (Fig. 1, water depths between 0.2 and 0.8 m) approximately 3 to 5 m from the flooded area fringe. Sediment cores (5-cm diam.) were collected near each site on Days 603, 968, and 1333 when the passive samplers were installed (see explanation in next subsection). A soil probe equipped with a plastic tube insert was used to collect a 25-cm deep core sample. After collection, the sediment tubes were capped and placed on ice. The sediment cores were air-dried and ground to pass a 2-mm sieve. The sediments were characterized for their pH values (1:2 sediment/water ratio) and organic C contents using a LECO C and N analyzer (LECO Corp., St. Joseph, MI). The sediments had pH values and organic C contents that ranged from 5.1 to 6.0 and 9.9 to 90.9 mg $kg^{-1}$, respectively.

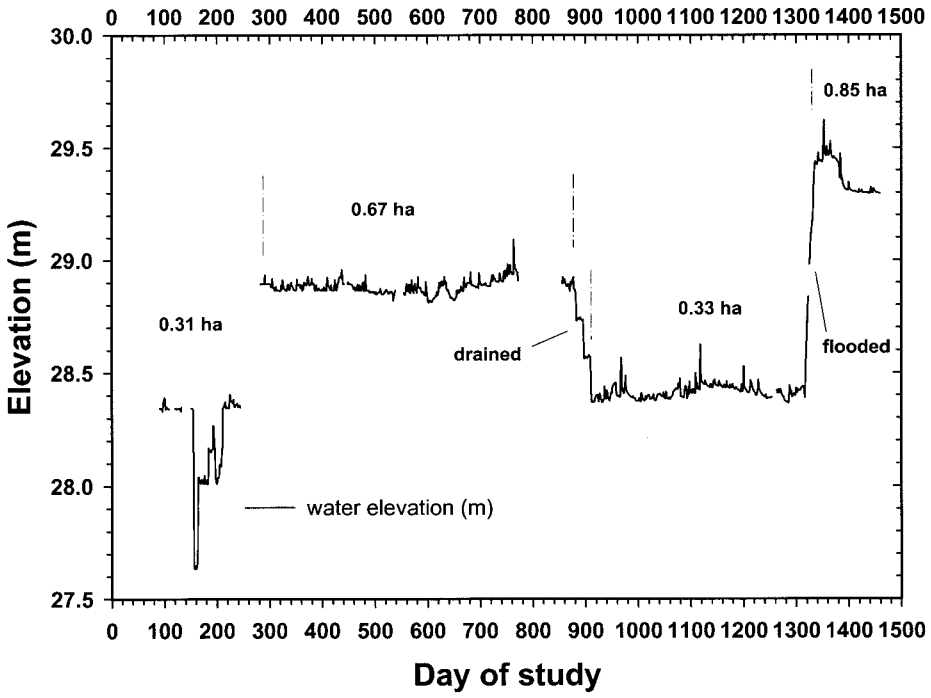


**Fig. 2. Daily water elevations and areal size of the in-stream wetland.**

Before each sediment core was collected, a 250-mL grab sample of the water column was acquired using an amber-colored bottle. The bottle and cap were prerinsed three times with water before final collection. The grab samples were placed on ice and DP measured using analytical procedures mentioned above.

The P sorption isotherm for each sediment sample ($n$ = 12) was conducted using a modified method of Mozaffari and Sims (1994). The modifications included shaking (18 h) triplicate tubes containing 1 g of sediment with 10 mL of inorganic P (made from $KH_2PO_4$ dissolved in 0.01 $M$ $CaCl_2$) solutions containing 0, 12, 25, 50, 75, 100, 125, and 150 μg $L^{-1}$. After centrifugation and filtration (0.45 μm), the inorganic P concentration remaining in the supernatant (equilibrium P concentration) was quantified using the colorimetric method of Murphy and Riley (1962). Phosphorus sorption was calculated as the difference between the amount of P initially added and that in the solution at equilibrium.

The P sorption isotherm was constructed by plotting the mean quantity of P sorbed (mg $kg^{-1}$) against the mean P equilibrium concentration (mg $L^{-1}$) using the linear version of the Langmuir equation:

$$c/(x/m) = (1/S_{max})\ c + 1/(k)(S_{max})$$

where $x/m$ (mg $kg^{-1}$) is the quantity of P sorbed by the sediment, $S_{max}$ (mg $kg^{-1}$) is the P sorption maxima, $k$ (L $mg^{-1}$) is a sorption constant relative to P binding energy, and $c$ (mg $L^{-1}$) is the P equilibrium concentration (Olsen and Watanabe, 1957). The sediment sorption data fit the Langmuir equation well with all $r^2$ values $> 0.9$ (data not shown). The EPCo concentration at zero sorption was calculated for each isotherm when the quantity of P sorbed equaled 0 mg $kg^{-1}$. Previously sorbed P was accounted for using the correction method of Sallade and Sims (1997). This was accomplished by extracting sediments using Mehlich 3 reagent (Mehlich, 1984), quantifying the extracted Mehlich 3 P concentrations, and subtracting these values from all P isotherm values before plotting. The sediment's P sorption or desorption tendency was determined by plotting grab sample DP concentrations against the sediment's EPCo values.

## Water Column-Sediment Sampling

At all four sites, Plexiglas passive samplers (peepers) were used once a year (in 1997, 1998, and 1999) to sample sediment

**Table 1. In-stream wetland (ISW) areas, water residence time, flows, dissolved phosphorus (DP) concentrations, and mass values measured at the inlet and outlet (standard deviations are shown in parentheses and na = not available).**

| Days | ISW area | Water residence | Total volume | | Mean DP conc.† | | Mass DP | | Δ‡ | ◆§ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet | | |
| | ha | days | $m^3 \times 10^3$ | | μg $L^{-1}$ | | kg | | | mg $m^{-2}$ $d^{-1}$ |
| 91–280 | 0.31 | 1.0 | 153.9 | 141.5 | 60 (58)a | 72 (129)a | 6.4 | 7.9 | −1.5 | −2.6 |
| 281–877 | 0.67 | 2.5 | 621.5 | 827.4 | 67 (159)a | 25 (46)b | 58.2 | 30.1 | +28.1 | +7.0 |
| 878–910 | drained | na | 5.3 | 29.1 | 27 (19)a | 236 (448)b | 0.1 | 6.9 | −6.8 | na |
| 911–1320 | 0.33 | 1.0 | 185.3 | 403.9 | 19 (29)a | 29 (45)a | 6.4 | 11.7 | −5.2 | −3.9 |
| 1321–1341 | flooded | na | 5.7 | 6.5 | 33 (11)a | 127 (135)b | 0.1 | 1.0 | −0.9 | na |
| | | | | | | total¶ | 71.2 | 57.6 | +13.6 | |
| 1342–1460 | 0.85 | 3.0 | na | 300.6 | na | 33 (11) | na | 10 | na | na |

† Means followed by different letters are significantly different at $P = 0.05$.
‡ Difference between DP mass measured at the inlet and outlet, where a + and − value indicates DP retention and release, respectively.
§ Dissolved P retention (+) and release (−) rates calculated by dividing the outlet DP mass by ISW area and days of study.
¶ Totals were calculated not using DP masses between Days 1342 and 1460 due to lack of inlet DP mass estimate.

pore water and the overlying water column. Two parallel sets of 3-mL open-ended compartments spaced at 1-cm intervals were routed into each peeper for a total of 23 compartments (Simon et al., 1985). A 0.2-μm Nucleopore porous polycarbonate membrane was placed on one side of the peeper, and a Plexiglas cover was used to seal this membrane. From the open side of the peeper, Milli-Q water was added to each compartment, and it was sealed in a similar manner. The peepers were stored in a bucket of Milli-Q water and the head-space was purged with $N_2$ gas for 24 h. After purging, the bucket was sealed to maintain the peepers under anoxic conditions during transportation to the in-stream wetland.

Duplicate sets of peepers were installed about midstream near Sites 1 and 4, while peepers at Sites 2 and 3 were located between 3 and 5 m into the in-stream wetland. The peepers at each site were placed into the sediment so that approximately one-half of the compartments extended above the sediments. At Sites 1 and 4, the peepers were oriented so that the compartments were parallel to stream flow to promote passive diffusion of dissolved nutrients into the compartments. The peepers were installed during August and September of 1997, 1998, and 1999, and they remained at their locations under continuous flooding conditions for 14 d. The 2-wk equilibration period for 1997, 1998, and 1999 corresponds to Days 603 to 617, 968 to 982, and 1333 to 1347, respectively. At the time of installation and removal, water column and peeper depths were measured. Immediately after the peepers were removed from the sediment, a plastic syringe was used to evacuate the compartment liquid. The liquid sample from each compartment (representing the water column and sediment pore water) was transferred to a 4-mL plastic vial, previously acidified (1 μL of 50% $H_2SO_4$) to lower the pH of the sample to about two. They were then sealed with a cap and immediately transported on ice back to the laboratory. The DP concentration for each sample was measured using analytical methods as described above.

## RESULTS AND DISCUSSION

### Relationships between In-Stream Wetland Area and Dissolved Phosphorus Fluxes

During the initial time interval (Days 91–200), the in-stream wetland water elevations varied because of inflow and outflow dissimilarities (Fig. 2). Between Days 205 and 280, stream outflow and inflow relationships were stabilized. After flow stabilization, the in-stream wetland area was approximately 0.31 ha.

During Days 91 to 280, both stream inflow and outflow had high mean DP concentrations (Table 1). There was no significant difference between the mean DP inflow and outflow concentrations (Table 1, $P = 0.31$). The large standard deviation in the outflow mean DP concentration is probably a result of the severe changes in water elevations. The in-stream wetland between Days 91 and 280 released 1.5 kg of DP, which corresponds to a daily DP release rate of $-2.6$ mg DP $m^{-2}$ $d^{-1}$ (Table 1). There was insufficient P assimilation capacity, probably due to the small ISW area, to provide effective DP retention at the DP loading rate delivered during this interval (10.9 mg DP $m^{-2}$ $d^{-1}$).

Between Days 281 and 877, the in-stream wetland was flooded in anticipation of more $NO_3$–N removal through denitrification. Consequently, the in-stream wetland increased in area from 0.31 to 0.67 ha. During this interval, we noted that total outflow volume from the in-stream wetland was almost 1.3-fold higher than total inflow volume (Table 1). We attributed this to a high number of storm events ($n = 30$) during early 1997 (Days 366–520) that collectively deposited almost 400 mm of precipitation near the Herrings Marsh Run watershed (State Climate Office of North Carolina, 2002). Consequently, storm runoff caused several intense daily inflow water volumes that ranged from 100 to 6700 $m^3$ $d^{-1}$. These intense stream inflows were also DP enriched because the highest 1997 daily DP concentration (1600 μg $L^{-1}$) was measured at the inlet on Day 485. The large standard deviation associated with the inflow DP mean concentration confirms the wide range of measured DP concentrations.

While flooded, 58.2 kg of DP entered the in-stream wetland during Days 281 to 877 (Table 1). This corresponds to a daily DP loading rate of 14.6 mg DP $m^{-2}$ $d^{-1}$. In spite of this high daily DP loading rate, flooding the in-stream wetland resulted in 28.1 kg of DP retention and a significant reduction in the mean outflow DP concentration ($P < 0.05$). Retaining 28.1 kg of DP by the flooded in-stream wetland corresponds to a daily DP retention rate of +7.0 mg DP $m^{-2}$ $d^{-1}$ (Table 1). Dissolved P retained by the ISW was probably stored in the sediment, vegetation, plankton, periphyton, and microbial P pools (Reddy et al., 1999).

The use of passive samplers allowed for a snap-shot of P stored in the sediments and potential exchanges between sediment-bound P and the water column. Passive samplers were installed between Days 603 to 617 when the in-stream wetland was flooded (Days 281–877). Sediment pore water at Site 3 had fairly high DP concentrations relative to the other sites (Fig. 3). We interpret the higher sediment DP concentrations at Site 3 to indicate more DP retention by sediments as a result of flooding. Flooding the in-stream wetland increased by 3600 $m^2$ the sediment area available for sorption and pore water storage. Additionally, flooding the in-stream wetland increased the water residence time from 1 to 2.5 d, thereby providing more time for sediment P equilibration to occur (Table 1). These findings imply that flooding a wetland can increase P retention. This assumes, however, that the wetland sediments are not P-laden; otherwise, flooding will shift sediment redox conditions and cause P release.

Not all of the 58.2 kg of DP that entered the in-stream wetland between Days 281 to 877 was retained. The in-stream wetland released 30.1 kg of DP during this time period (Table 1). A portion of this large mass of DP was probably released during time periods when the water column DP concentration was less than the sediment EPC value. This explanation is plausible because at Day 603, the tendency of the sediments was to release DP through desorption to the water column (Fig. 4). Dissolved P release from other P pools (i.e., organic matter, plant residue, periphyton decomposition, etc.) probably also contributed to the high DP outflow loads (Reddy et al., 1999; Richardson, 1999).

Flooding between Days 281 and 877 resulted in a deeper water habitat (28.9-m elevations) that precluded normal wetland vegetative growth and development. A

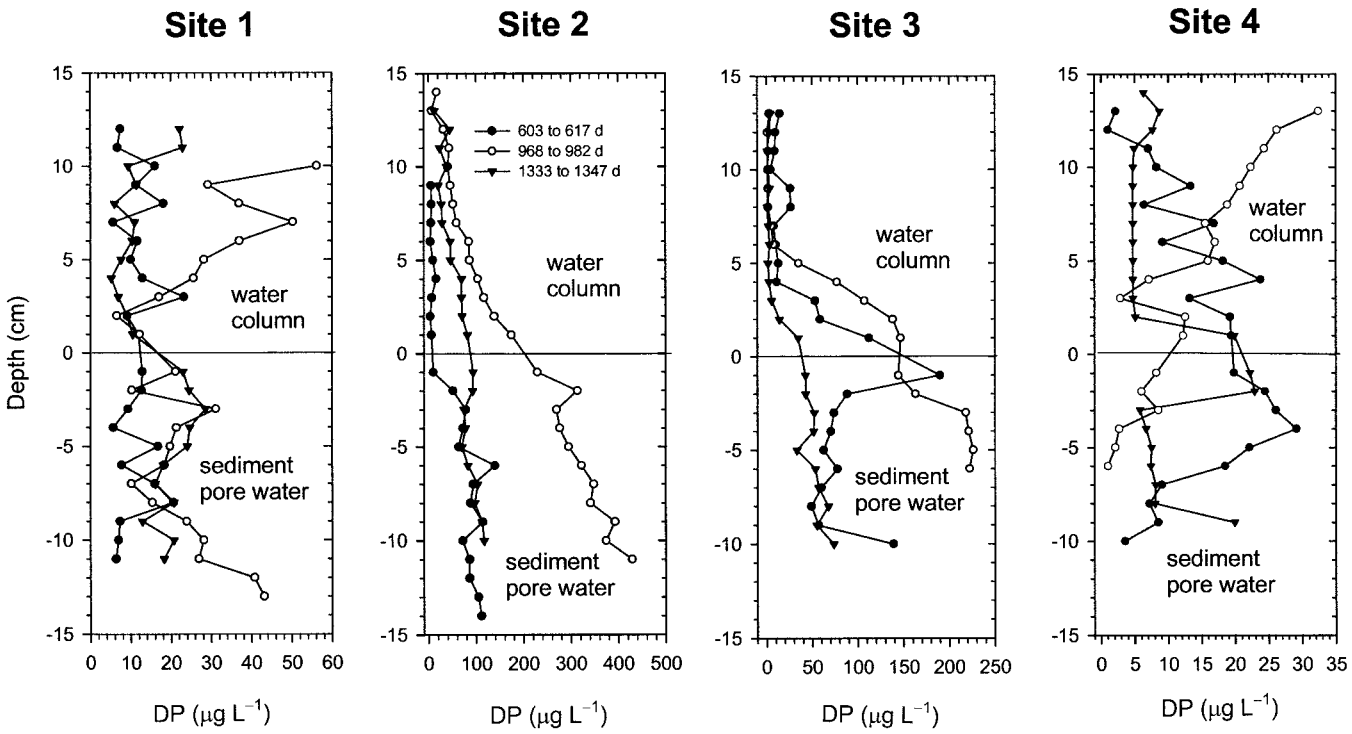


**Fig. 3. Dissolved phosphorus (DP) concentration profiles of the water column and sediment pore water.**

concern arose that a decrease in wetland vegetation growth would reduce N mitigation. To improve conditions for wetland plant growth, the in-stream wetland flood water elevation was decreased to approximately 28.4 m through draining. This corresponds to an area decline from 0.67 to 0.33 ha between Days 878 and 910 (Fig. 2). The large volume of water discharged (Table 1, $29.1 \times 10^3$ m) in a short time interval (32 d) resulted in outflowing water with a high mean DP concentration (236 μg $L^{-1}$) that was also highly variable (SD = 448 μg $L^{-1}$). During this time interval, 6.8 kg of DP was exported into the outflowing stream (Table 1). Bostrom et al. (1988) reported that DP desorption will occur when P-enriched bottom sediment is resuspended by water circulation into surface water zones that have low DP concentrations. We speculate that turbulence created by draining the pond promoted DP released from resuspended P-enriched sediments. Outflowing stream water could then transport DP out of the in-stream wetland. After draining, the flood water elevation was maintained between 28.4 and 28.7 m from Days 911 to 1320 (Fig. 2). Water elevations varied by 0.3 m during this time interval due to a series of storms that delivered high rainfall amounts from Days 970 to 1000 (254 mm) and Days 1100 to 1160 (314 mm). Water was released from the in-stream wetland to maintain water elevations during this interval of high rainfall. Consequently, there was a twofold increase in outflow volume compared with inflow (Table 1). In spite of the high rainfall, only 6.4 kg of DP entered into the in-stream wetland during Days 911 to 1320. This inlet DP mass value is considerably lower (ninefold decrease) when compared with the inlet DP mass measured during the previous time interval (58.3 kg, Days 281–910). This corresponds with a reduction in the daily DP loading rate from 14.6 to 4.7 mg DP $m^{-2}$ $d^{-1}$. In spite of the large reduction in the daily DP loading rate, the in-stream wetland still released DP (Table 1, −3.9 mg $m^{-2}$ $d^{-1}$). Because there was no significant difference between the mean outflow and inflow DP concentrations ($P = 0.20$), DP releases were explained by the high outflow volume, change in wetland area, and low inflow DP concentrations. During Days 878 to 1320, there was a decline in sediment area available to store P (a 3600-$m^2$ decrease) and an equilibria shift across the water–sediment interface as a result of the low inflow

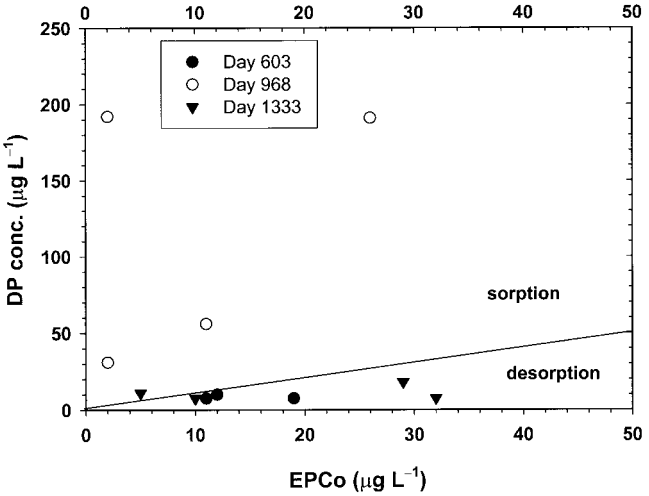


**Fig. 4. Relationship between the sediment's equilibrium P concentration (EPCo) and the water column dissolved phosphorus (DP) concentration (1:1 plotted line separates fields representing DP sorption and desorption).**

DP concentrations. This latter explanation is supported by the large decline in sediment pore DP concentrations at both Sites 2 and 3 between Days 1333 and 1347 with concentrations measured earlier (Fig. 3, between Days 968 and 982). The concentration decline was especially large at Site 2, where sediment pore water DP concentrations dropped from 300 to 425 to between 80 and 120 $\mu g\ L^{-1}$.

Upward P mass transfer will occur across the sediment–water interface when the water column DP concentrations are less than DP concentrations in sediment pore water (Reddy et al., 1999). Because sediment pore water DP concentrations at Sites 2 and 3 are collectively higher (ranging from 150 to 420 $\mu g\ L^{-1}$ between Days 969 and 982) than mean inflow DP concentrations after Day 878 ($<33\ \mu g\ L^{-1}$), upward DP migration occurred. We believe that the low inflow DP concentrations were related to an interruption of manure application to the field located upstream. This animal production facility enlarged their manure storage lagoon in January 1998 (about Day 731), enabling the operation to hold manure throughout 1998 and for the first-half of 1999 (to about Day 1275, Star Maready, personal communication, 1999). The lull in manure application from Days 731 to about 1275, coupled with stream P assimilation processes (e.g., sorption to channel sediments, reductions caused by nutrient spiraling, uptake by plants, periphyton, and microorganisms), conceivably contributed to the 50% decline (67 vs. 33 $\mu g\ L^{-1}$) in the mean stream inflow DP concentrations.

The in-stream wetland was reflooded during a 20-d period (Fig. 2, between Days 1321 and 1341) by the owner to increase water storage for recreational and irrigation use. Reflooding caused the water elevation to increase from 28.4 m to between 29.3 and 29.6 m, which resulted in an areal increase to 0.85 ha (Fig. 2). During the reflooding time period (20 d), 0.1 kg of DP entered the in-stream wetland, while 0.9 kg of DP was released. Releasing almost 1 kg of DP during a short time period caused the mean outflow DP concentration to be almost fourfold higher than mean inflow (Table 1, 127 vs. 33 $\mu g\ L^{-1}$).

After reflooding was complete, the in-stream wetland was maintained at 0.85 ha between Days 1342 and 1460 (Fig. 2). Unfortunately, reflooding the pond submerged the inlet H-flume; consequently, no inlet flow volumes or DP concentrations were available. The lack of quantifying P inflow amounts prevented a prediction of P assimilation by the in-stream wetland during this time period. However, stream outflow and DP concentrations were measured and showed that the in-stream wetland released 10 kg of DP. The release of DP was supported by a decline in sediment pore water DP concentrations at Sites 2 and 3 (Fig. 3, Days 1333–1347) and the tendency of the sediment to desorb DP (Fig. 4, Day 1333). Continued DP release from the in-stream wetland during reflooding was explained by a combination of re-exposing P-laden sediment to anoxic conditions and to high outflow volumes. Reflooding the in-stream wetland during Days 1321 to 1460 increased the sediment area in contact with water by 6400 $m^2$. Sediments within this 6400-$m^2$ area already contained sorbed P from the previous period (Days 281–877) of high P loading (14.6 mg DP $m^{-2}\ d^{-1}$). Re-exposing P-laden sediments to anoxic conditions by reflooding would cause a redox shift resulting in sediment-bound P releases. This explanation is conceivable, considering that under anoxic conditions amorphous and poorly crystalline Fe-oxides in these sediments could release P after reduction of $Fe^{3+}$ to $Fe^{2+}$ through chemical and biological processes (Moore and Reddy, 1994; Pant and Reddy, 2001). Dissolved P export from the in-stream wetland was expedited by the high total outflow volume ($300 \times 10^3\ m^3$), which was attributed to high rainfall associated with Hurricane Floyd. This hurricane deposited almost 400 mm of rainfall between 13 and 15 Sept. 1999 (Days 1347–1349) near the Herrings Marsh Run watershed.

## CONCLUSIONS

Wetlands provide an important water quality function by sequestering P from urban and agricultural sources. Exceeding a wetland's P assimilation capacity can result in the release of DP into stream and river systems thereafter, calling into question the long-term P mitigation effectiveness of wetlands. Our objectives were to determine the long-term DP retention and release characteristics of a North Carolina Coastal Plain in-stream wetland and to evaluate how these characteristics respond to management effects like flooding, draining, and shifts in DP concentrations. This study showed that an in-stream wetland was capable of both retaining and releasing DP. At the initial DP loading rate, this in-stream wetland did not have sufficient P assimilation capacity to effectively retain DP. The in-stream wetland was flooded, thereby increasing both sediment surface area and water residence time. While flooded, high DP loads were transported into the in-stream wetland as a result of high rainfall that remobilized P stored in upstream locations. The in-stream wetland, under these conditions, did retain approximately 52% of the inflowing DP mass (30.1 kg/58.2 kg). We speculate that more DP retention was due to higher sediment surface area and residence time that allowed more sorption and exchange reactions to occur. The DP retention was only temporary because redraining the in-stream wetland resulted in high DP mass releases (almost 13 kg) into the outflowing stream. Contributing to the high DP mass releases were stream inflow with low DP concentrations, high wetland outflow, and a decrease in sediment area available to store P. Enlarging the wetland area through reflooding contributed to DP releases from the sediments.

During a few time intervals, this in-stream wetland was able to store DP and discharged water with lower DP concentrations than stream inflow. Both of these facts suggest that periodically the in-stream wetland was able to mitigate DP. The release of almost 80% of the cumulative inflow DP mass (57.2 kg/71.2 kg), however, indicates that this in-stream wetland did not provide effective long-term DP retention. Long-term DP retention by P-laden wetlands may be difficult to achieve, especially if the wetland is subject to draining and flood-

ing and to shifts in stream inflow DP concentrations. This implies that if P loads into stream and river systems are reduced by implementation of total maximum daily load requirements, the resulting low water column DP concentrations may promote stored DP releases from P-laden wetlands. This suggests that, although management efforts have reduced P inputs into these river and stream systems, their DP concentrations may not correspondingly decrease immediately. Dissolved P concentrations may remain high in the water column until P stored in the wetland sediments are at equilibrium.

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