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Effectiveness of Restored Wetlands for the Treatment of Agricultural Runoff

Office of Research and Development
National Risk Management Research Laboratory, Ada, Oklahoma 74820

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Notice

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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

The goal of this report is to provide information on the effectiveness of restoring small wetlands in agricultural areas to intercept surface water runoff and attenuate nutrients and suspended sediments in these surface waters. This report describes the history of drainage practices in the State of Delaware, the relatively recent practices of wetland and stream corridor restorations in Delaware, and the projected benefits of these restorations practices on the waters of Delaware. Due to the ability of wetlands to sequester and process nutrients and sediments, they are being implemented more frequently as a means of restoring lost ecosystem services such as water quality and water quantity. Although this report provides some valuable information regarding performance of these small wetland systems, climatic conditions limited the amount of data that could be collected and prevented a full assessment of how effective these systems might attenuate nutrients and sediments. Identifying specific cause-effect relationships was not possible with the limited data collected, but general trends in some of these relations is presented. This report does provide a solid foundation and a jumping off point for additional work to evaluate the effectiveness of these small wetland systems across a broader array of agricultural landscapes, with the goal of filling in the data gaps that still exist which limit the use of these systems in a comprehensive watershed management program.

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Executive Summary

Synopsis

1. Current water management and drainage activities in Delaware afford opportunities to implement site-specific, ecologically beneficial projects which can be incorporated into comprehensive watershed management plans.
2. These projects apply construction techniques intended to improve degraded water quality in watersheds throughout Delaware.
3. Current research indicates that multiple management practices including vegetated riparian buffers, wetland restoration, and stream channel restoration can retain and assimilate nutrients (nitrogen and phosphorus) and retain suspended solids from agricultural runoff.

Executive Summary

Throughout the Delmarva Peninsula drainage activities that commenced during colonial times and intensified during the 20th century have resulted in the creation of extensive ditch systems through the generally flat, alluvial soils for the purpose of rapidly removing water in order to support agriculture and human habitation. Ditching frequently involved extending surface water systems (ditches) into areas that were naturally perennial or seasonal wetlands, resulting in the drainage of these forested wetlands and the lowering of the local water table. The straight configuration of the ditches and the straightening, widening, and deepening of some perennial nontidal stream channels expedited flow downstream and accommodated the larger volumes of storm flow coming from the watershed which were no longer being retained by wetlands. The large decrease in storm water residence time on the land and the larger volumes resulted in greatly elevated loadings of sediments and nutrients to downstream lower energy waters (i.e., lakes/ponds, tidal rivers, estuaries). The ensuing shallowing and occurrences of algal blooms triggered by nutrient enrichment in these low energy “receiving” waters have impacted both human economic activities and ecological health to varying extent which in some cases has been catastrophic.

In Delaware since the 1990’s there has been substantial and increasing effort to reestablish some of the wetland acreage that has been lost over the past 300 years. Such restoration is part of a broader strategy to develop comprehensive watershed management plans as part of TMDL driven Pollution Control Strategies. The objective of this work has been to enhance the sediment/nutrient retention capability within watersheds, with an ultimate goal of achieving improvement in economic and ecological condition in areas that have been impacted by the reduction or elimination of the buffering functions afforded by wetlands. This exploratory project represents the first concerted effort by the State of Delaware to obtain some water quality data from a restored wetland and adjacent riparian corridor in order to examine the interception and retention of sediments and nutrients transported in overland runoff from agricultural fields.

The main element of this project involved water sampling during five rain events large enough to generate overland runoff from corn and soybean fields on a farm in west-central Kent County, Delaware. Samples were collected from the inflows and outflows of three restored wetland cells and a perennially flowing ditch (Iron Mine Prong) above and below the area into which the wetlands discharge. Concentrations of sediments (measured as total suspended solids - TSS), total nitrogen (TN), total phosphorus (TP), and dissolved inorganic fractions thereof including nitrate + nitrite (NO_3 + NO_2), ammonia (NH_3), and soluble reactive phosphorus (SRP) were determined. The conclusions of the current study are limited due to insufficient resources to quantify fluxes and, due to the small dataset. We recommend that the results be interpreted cautiously despite some statistically significant differences between sampling events and sites.
It was understood entering the study that TSS and nutrient concentrations can vary substantially over the course of a storm hydrograph and that the results from samples grabbed at some unknown point in the hydrograph curve are of limited usefulness. However, it also seemed reasonable that the sampling of multiple storm events might improve the understanding regarding the range of nutrient levels that occur in storm water runoff from a typical Delaware farm field under known agricultural activity. This may allow some patterns to be developed that would be beneficial to the planning of more comprehensive studies that do involve flux determination.

Among all four wetland inflows (one of the wetlands had two inflows) and across all five storm sampling events, ranges for constituents in mg l^{-1} were as follows: TSS (7 – 58), TN (1.06 – 4.77), NO_3 + NO_2 (0.018 – 2.33), NH_3 (0.011 – 1.01), TP (0.65 - 5.36), SRP (0.55 – 4.14). Among all three wetland outflows and across all five storm sampling events, ranges for constituents in mg l^{-1} were as follows: TSS (5 – 78), TN (0.90 – 3.76), NO_3 + NO_2 (0.017 – 1.92), NH_3 (0.017

– 0.70), TP (0.55 – 3.13), SRP (0.38 – 3.18). In Iron Mine Prong, concentrations did not differ between the two sites for any constituents and were generally lower than wetland inflows and outflows, particularly on the high end of the range. The highest levels measured at the Iron Mine Prong site below the wetland discharge were as follows for TSS (59), TN (1.89), $NO_3 + NO_2$ (0.86), NH_3 (0.37), TP (0.53), SRP (0.35). This difference on the higher end of the ranges between Iron Mine Prong and the wetlands shows that at this level of sampling the volume of runoff entering the stream from the wetlands was relatively small with a sediment/nutrient load insufficient to have measurable impact on the much higher volume of water flowing in from higher in the watershed. This difference in volume between the wetland outflows and Iron Mine Prong was apparent visually at the time samples were collected. For Iron Mine Prong, TSS, TP and SRP levels were about an order of magnitude more during storm events than during baseflow. Differences between baseflow and stormflow were not apparent for any nitrogen constituents.

The findings of this study indicate a need to conduct future work which is particularly focused on P dynamics associated with wetland cells, shapes and sizes of wetlands cells, retention time, flow volumes and concentration variability over storm hydrographs.

Keywords: agriculture, Clean Water Act, nitrogen, nutrients, phosphorous, retention, riparian, runoff, watershed, water quality, wetlands.

1.0

Background Information

Historical Summary of Delaware Drainage Practices

Delaware is located on the Delmarva Peninsula between Chesapeake Bay and Delaware Bay with 91% of the geomorphic classification being coastal plain (Maxted 1995). This alluvial, generally flat land is characterized as well to poorly drained with loamy or sandy soils and loamy to clayey subsoil (Tiner 1985). Approximately 37% of Delaware is overlain by poorly drained soils, with a high water table during most of the year (DNREC 2004). Average rainfall in Delaware usually exceeds plant needs and evaporation rates (DNREC 2004). This combination of topography, soil and climate conditions has posed a drainage problem since colonial settlement to farmers who have cleared most of the native forest for agricultural use.

In Delaware, there are community and private drainage systems dating back to the 1700's. These drainage ditch systems are inland extensions of natural perennial stream channels. These ditches were constructed to manage soil and water resources for agricultural purposes, and to provide flood protection. Without an effective drainage system, poorly-drained soils become saturated or flooded, thereby diminishing or eliminating agricultural productivity and creating problems for residential landuse. Several decades ago, the Delaware General Assembly enacted the 1951 Drainage Law to establish, finance and maintain drainage organizations (i.e. tax ditch organizations - referred to hereafter as "organization/s). Formation of an organization can only be initiated by landowners who petition Superior Court to resolve drainage or flooding concerns. This petition results in the Conservation District requesting an investigation by the Delaware Department of Natural Resources (DNREC) Division of Soil and Water Conservation (DSWC) to "…determine whether the formation of an organization and construction of a tax ditch system is practicable and feasible, and is in the interest of the public health, safety and welfare." If so determined, the Conservation District files the petition in Superior Court, and the Board of Ditch Commissioners (as directed by the resident judge) prepares a report on the proposed tax ditch.

Thus, these community drainage systems (tax ditches) are governmental subdivisions of the State and are watershed-based landowner organizations formed by a prescribed legal process in Superior Court. An organization is comprised of all landowners (also referred to as Taxables) in a particular watershed (drainage area) or sub-watershed. The operations of an organization are overseen by ditch managers and a secretary/treasurer who are landowners within the watershed. These "officers" are elected at an annual meeting by the Taxables. To date, 228 organizations exist statewide which manage more than 2000 miles of ditches (channels) that serve more than 100,000 residents and over half of the state-maintained roads. The 2000 miles of ditches, with the help of approximately another 2000 miles of private (on farm) drainage systems, provide water management service for more than 350,000 acres (~ 1/3) of land in Delaware. System drainage areas range in size from 2 acres to 56,000 acres, while ditches range in size from 6 to 80 feet wide and 2 to 14 feet deep. Ditch dimension is dependent upon the acreage being drained and topography.

The DSWC assists by planning, implementing, and administering the Water Management Program, which includes tax ditches. Once a tax ditch plan is approved the system is ready to be constructed. Construction is usually done by the Conservation District, utilizing equipment and operators in the respective County. Historically, these operators utilized construction methods that achieved the singular goal of rapidly removing excess water from the land without ecological consideration. Around 1990 efforts began to educate and train these planners and operators to develop and construct drainage projects in ecologically sensitive ways. Since then the DNREC has focused on constructing ecologically sensitive drainage/water management projects. This shift in focus has resulted in the development of numerous practices that have been demonstrated to reduce ecological impacts resulting from the initial construction and subsequent maintenance of tax ditches. In addition to performing on-site management practices to reduce direct impact, the water management program has instituted measures to mitigate for these impacts and go further by implementing practices that enhance, create and restore habitats along these ditch corridors. These practices are supported by a requirement from former Governor Castle's Executive Order No. 56 (1988) that mandates state agencies to achieve no-net wetland loss with their projects (Gov. Castle EO-56 1988).

The following list of practices has evolved into the Delaware Tax Ditch Best Management Practices manual. Some of the more prominent best management practices (BMP/s) include:

- minimizing clearing widths through forested areas;
- relocating channels around sensitive habitat or wetland areas;
- installing structures to control water levels in the channels;
- performing one-sided construction;
- saving trees within the construction zone;
- minimizing construction of downstream outlets;
- installing a berm along the channel with an inlet pipe to maintain the historical water level in adjacent wetlands
- blocking off old channels that drain only wetland areas.

Recent Water Management Program efforts have also included the construction of wetland restoration "cells" adjacent to active agricultural fields. The "cells" intercept agricultural runoff before it enters an adjacent ditch or natural stream channel. In other instances wetland cells are established in-line and upstream of restored channels, with surface water flow generated from field run-off. While these projects are primarily designed to function as wildlife habitat, they can also provide water quality benefit by sequestering suspended sediments and nutrients. Additionally, a few of these projects have instituted stream corridor restoration of highly degraded streams and adjacent floodplains to natural stream morphology.

To ensure BMPs implementation, the DNREC routinely provides wetland/ environmental training sessions for both technical and administrative staff members. The DNREC has constructed several projects incorporating BMPs to test their effectiveness. These projects have resulted in the establishment of sites which demonstrate that economically necessary drainage and ecological quality can be mutually beneficial.

Wetland Restoration in Marginal Agricultural Fields

Throughout Delaware, agricultural operations are performed on a variety of fields with varying soil types, shapes, and sizes. Opportunities for ecologically-focused wetland restoration or creation are particularly strong where an area of marginally productive, poorly drained soil overlaps with an area that has a configuration that complicates tillage such as a point or corner. Historically, most poorly-drained portions of fields were forested wetlands. The reestablishment of wetlands in these areas results in ecological benefits which include creation/enhancement of wildlife habitat, increased biodiversity, and reduction in the rate at which stormwater runoff is discharged to contiguous streams. The reductions in water volume and nutrients represent measurable indicators which may be used to demonstrate improvements in water quality and overall stream character. Examples of potential benefits to farming operations from such wetland restoration efforts include (1) the removal from production of portions of marginal and non-productive fields and (2) the opportunity to re-contour the remainder of the field in a manner that further enhances crop production while the equipment is onsite.

Until recently wetland restoration technique was limited largely to the construction of open-water ponds, which exhibit relatively low plant and animal diversity. Recent efforts have focused on a variety of techniques that encourage a high diversity of plant and animal species. These techniques include the construction of micro-topography (humps and bumps), addition of organic matter, placing coarse woody debris, relocation of trees and shrubs, and creation of irregular shapes. These detailed techniques have proven to "jump-start" initial macroinvertebrate and amphibian establishment in restoration projects (Alsfeld et al. 2005) and result in projects that closely replicate natural wetlands (DNREC 2004).

Much of the construction is performed using relatively small equipment. A D-6 dozer, used in conjunction with medium sized backhoes and excavators, is all that is needed to accomplish the water management and restoration goals for each project. Using this small equipment and the operators from the local Conservation Districts has kept overall project costs down. For example, the cost of constructing a one-acre wetland typically ranges between 2,500 and $4,500, including excavation, spreading of soils, lining with clay soil layers, replacement of top spoil , planting of trees/shrubs/ emergent vegetation, relocation of large trees, addition of course woody debris, addition of organic material, seeding, and any needed pipe/s or outlet structure/s.

Stream Corridor Restoration

Activities such as agriculture, road-building, residential and commercial development and drainage have resulted in the degradation of much of Delaware's nontidal stream and riparian (the area interfacing and fringing a stream) habitat. These activities have altered the state's aquatic habitats, water-dependent species and surrounding upland environments. The DNREC has estimated that 90 percent of Delaware's streams and rivers have been modified.

To address these concerns the DNREC has initiated an effort to restore stream corridor habitats. The overarching goal of stream corridor restoration projects is to restore highly disturbed and/or degraded streams and their surrounding riparian areas to natural, stable stream channels with high ecological functionality. Specific objectives include: 1) restoration of degraded stream channels to a more natural morphology; 2) re-establishment of biological diversity; 3) reduction in surface water pollutants; 4) increase in wildlife habitat; and 5) protection and improvement in water quality.

Presently, stream corridor restoration efforts are implemented when private landowners request restoration projects or when DNREC personnel have located potential sites on state-owned lands. The restoration projects completed have been successful in restoring wetland and upland habitat, and providing natural stream channel stability.

Recent projects have focused on using geomorphic approaches to convert ditches that are straight, exhibit rapid water discharge, and are steep-sided with minimum riparian vegetation to channels that are sinuous, exhibit reduced flow rates, and have wider, naturally vegetated flood plains. Other efforts have focused on restoring degraded natural streams to provide long-term physical stability and improve ecological value.

Benefits of Ecological Restoration

- Increase and enhance aquatic habitat and wildlife habitat
- Retention and uptake of nutrients and sediments to improve water quality
- Promote the establishment of native plant species and control invasive species
- Protect rare and endangered species
- Increase recreational opportunities - bird watching and hunting
- Stream bank stabilization
- Aesthetics and education
- Ground-water recharge, water storage and flood control

It appears that greater success may be achieved by creating wetlands in many smaller cells in strategic places rather than constructing fewer large systems. Landowners are more agreeable to selectively constructing small cells in areas that are problematic for farming. Additionally, the cost effectiveness of strategically placing many smaller cells better allows for concentration on specific areas which contribute disproportionately to stream degradation, in essence potentially having a more positive effect on adjacent and downstream water quality than by creating a very large wetland in one area.

The creation and positioning of small wetland cells between agricultural fields and surface water streams to intercept some proportion of the nutrient load being discharged from the fields during storm events would seem to have potential for widespread application as an alternative for water quality protection, remediation, or enhancement. The objective of this exploratory project was to obtain some baseline data to examine differences in concentrations of suspended sediments (total suspended solids) and nutrients (nitrogen and phosphorus) between stormwater runoff flowing into and out of three small, constructed wetland cells. Due to nutrients and habitat degradation being primary issues Delaware is currently implementing Total Maximum Daily Loads (TMDL's) in many watersheds (DNREC 2006). This baseline data is considered important to the future development of a larger, more comprehensive study to quantify loadings of such variables and thereby better understand the extent to which man-made wetlands function as buffers against eutrophication and sedimentation in downstream waters.

2.0
Methods

Sampling Sites

The restored wetlands evaluated during this exploratory project were constructed to replicate natural wetland systems. They are not simply “pond/open water” systems. Rather, the “cells” contain the following natural features which enhance ecological functioning. A primary feature is “microtopography” which promotes diversity in plant and animal communities. Additionally, organic matter (e.g., straw) and coarse woody-debris are added to facilitate biological activity and provide habitat. Relocated live trees further enhance nutrient assimilation. The ages of the cells are approximately 4 to 5 years. In addition to the initial plantings they are vegetating naturally through succession.

For this project, the DNREC reviewed over 200 potential sites and along with the USEPA visited approximately 30 of the more promising sites. A total of 12 sites were then preliminarily selected: nine sites were wetlands that were restored within the past 2 to 8 years; three sites were constructed specifically for this project. Based on limited resources, three farms, Haines, Pratt, and Kolakowski were selected for sampling. However, because of prolonged drought conditions and insufficient amounts of runoff at Pratt and Kolakowski, only the Haines site was sampled (see note).

(Note: The Kolakowski site has two wetland cells which both outlet into the same hedgerow ditch with a watershed drainage area of approximately 8 acres total with cell sizes of .5 acre and .7 acre. The Pratt site has two cells in-line which empty into a restored stream similar to Haines. Watershed drainage area at Pratt is 10.5 acres with cell sizes of 1.6 acres and 1.3 acres.)

Figure 1a-c shows the Haines site (a) prior to construction, (b) following addition of meanders to the channel of Iron Mine Prong, a perennially flowing ditch, and (c) following completion of the wetland cells. Runoff of stormwater from the fields is routed into three independent wetland cells which discharge to Iron Mine Prong (Figure 1c). Approximately 12 acres of fields drain into Wetland Cell 2, while Wetland Cells 1 and 3 have approximately 4 acres each of field drainage. Wetland Cells 1 and 3 have a single inflow whereas Cell 2 has two inflows. Each wetland cell has a single outflow. Individual cell sizes were: Cell 1 = .25 acre; Cell 2 = .45 acre; and Cell 3 = .5 acre. Drainage area upstream of the project site is approximately 1260 acres.

The crop fields at the Haines site are in typical continuous corn/wheat/soybean rotation. Fertilizer rates for these crop fields are unknown although they are assumed to be current Delaware Department of Agriculture application recommendations from year to year. Precipitation events and their magnitude which coincided with sampling dates can be found in Appendix 2.

Sampling Approach

Field sampling and laboratory analysis were conducted by the DNREC Environmental Laboratory Section, which is an EPA certified lab, according to EPA approved methods and the State of Delaware (2004). Monitoring began in early-April 2005. Seven sampling events occurred, two under baseflow conditions and five under stormflow conditions. Events 1, 2, and 5 occurred during October and November, Event 3 occurred during late-June, and Event 4 occurred during early September. During the baseflow events, sampling was limited to the Iron Mine Prong along which two sites were sampled (Figure 1c). These sites, S-1 and S-2, were upstream (inflow) and downstream (outflow) of the wetland discharge area, respectively. Sampling during the stormflow events included Iron Mine Prong plus the inflow and outflow sites for each of the three wetland cells (Figure 1c). Outflow samples were collected from the discharge pipe of each wetland cell whereas inflow samples were collected from swales or shallow ditches cut into the field to direct runoff.

During each sampling event a single grab sample was taken from each site and subsequently tested for nutrients (phosphorus and nitrogen), total suspended solids and pH (Table 1). Samples were placed on ice in the field and processed in the laboratory according to procedures provided in Table 1. There was no determination of water flow, thus variability in concentration over the respective storm hydrographs and fluxes is unknown. Analysis was done for total phosphorus (TP) and total nitrogen (TN) because those variables are primary eutrophication targets for Delaware TMDLs, and for dissolved fractions thereof including soluble reactive phosphorus (SRP), nitrate + nitrite nitrogen (NO3 + NO2) and ammonia (NH3) due to the direct response potential of these constituents for fueling aquatic plant growth. Total suspended solid (TSS) was sampled as a surrogate for suspended sediments in the water. The data for all variables tested is provided in Appendix 1.

Figure 1a. Aerial photo of the Haines Farm site prior to construction of wetland cells and stream restoration of Iron Mine Prong. 1997. (North is top of photo).

Figure 1b. Aerial photo of Haines Farm site during construction of the stream restoration of Iron Mine Prong and prior to wetland cell construction. 2002 (North is top of photo).

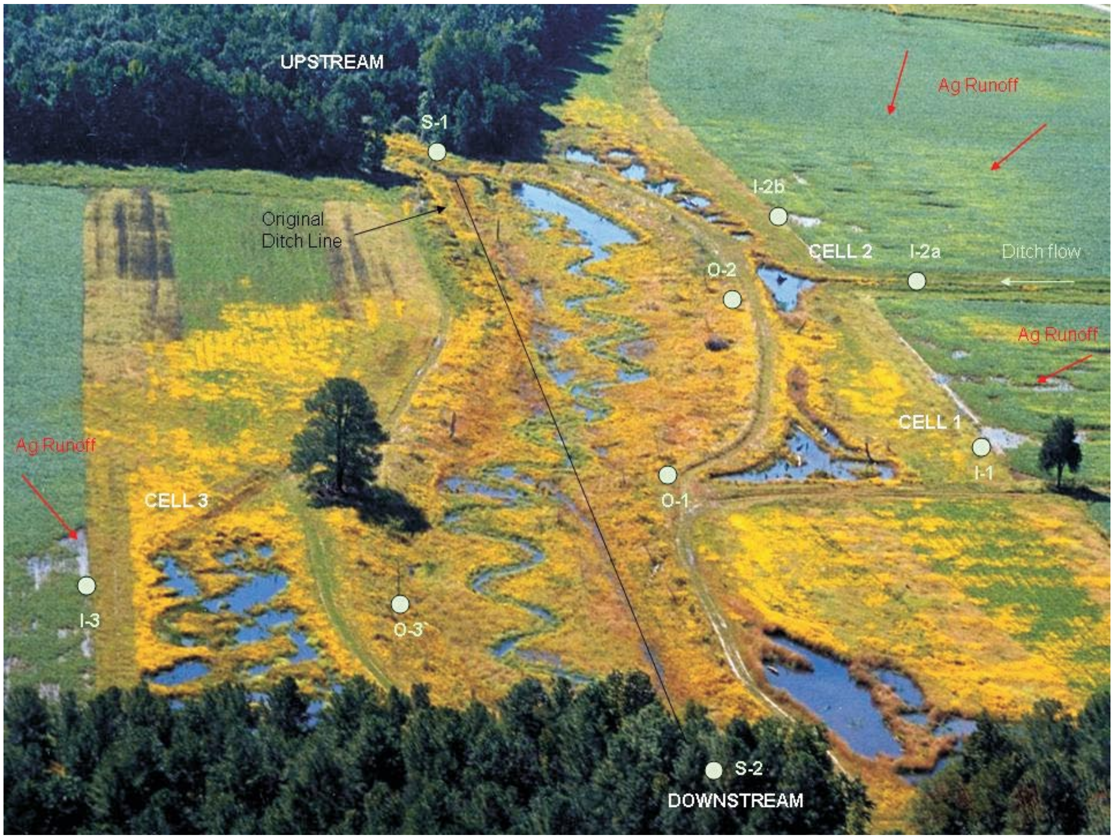

Figure 1c. Aerial photo of Haines Farm site (Kent Co., Delaware) with labeled sample locations 2004. (North is bottom of photo).

Statistical Analysis

All statistical testing was done using STATGRAPHICS PLUS Version 5.0. The significance level selected for rejection of the null hypothesis is $\alpha = 0.05$.

Two major factors expected to affect variable concentrations included sampling event and sampling site. Their effects were tested using a mixed model Two-Way ANOVA without replication, with sampling event as the random factor and sampling site as the fixed factor (Zar 1999).

Differences between inflow and outflow concentrations for the individual wetland cells ($n = 5$ per site) and Iron Mine Prong ($n = 7$ per site) were tested using the nonparametric Wilcoxon paired-sample test (Zar 1999). For Cell 2, the inflows were not averaged because the influence of each upon the outflow was unknown due to the lack of flow data. Tests were one-tailed because it was expected that outflows would be lower than inflows due to the retention function of the wetlands.

Differences in concentrations between the outflows and differences between the inflows were tested using the nonparametric Friedman's test (Zar 1999) for block designs. The nonparametric tests were used primarily because the small data sets frequently violated the equal variance requirement for using parametric tests.

The testing processes for differences between (1) sampling events, (2) inflow and outflow for the wetland cells and Iron Mine Prong, and (3) the differences between inflows and between outflows each involved the running of several consecutive tests. Such repetition increases the chance for making a Type 1 error. To protect against committing a Type 1 error a conservative approach to the analysis is to divide α by n (Holm 1979). Thus, for (1), six tests were run ($n = 6$ variables). The adjusted significance level is $P = 0.008$ (0.05 / 6). For (2), for each variable there were five comparisons (n tests) run; C-1 I vs. O, C-2 I2a vs. O, C-2 I2b vs. O, Cell 3 I vs. O, and Stream I vs. O. The adjusted significance level is $P = 0.01$ (0.05 / 5). For (3), for each variable there were two tests run thus the adjusted significance level is 0.025. P values < 0.05 are recognized in the analysis but are regarded as suggestive rather than significant.

3.0
Results

Overall Concentration Observations

Among all four wetland inflows and across all five storm sampling events, ranges for constituents in mg l^{-1} were as follows; TSS (7 – 58), TN (1.06 – 4.77), $NO_3 + NO_2$ (0.018 – 2.33), NH_3 (0.011 – 1.01), TP (0.65 - 5.36), SRP (0.55 – 4.14). Among all three wetland outflows and across all five storm sampling events, ranges for constituents in mg l^{-1} were as follows; TSS (5 – 78), TN (0.90 – 3.76), $NO_3 + NO_2$ (0.017 – 1.92), NH_3 (0.017 – 0.70), TP (0.55 – 3.13), SRP (0.38 – 3.18). In Iron Mine Prong, concentrations did not differ between the two sites for any constituents and were generally lower than wetland inflows and outflows, particularly on the high end of the range. The constituents likely were broken down through natural processes, plant uptake, or had traveled downstream in suspension (i.e. phosphorous). The highest levels measured at the Iron Mine Prong site below the wetland discharge were as follows for TSS (59), TN (1.89), $NO_3 + NO_2$ (0.86), NH_3 (0.37), TP (0.53), SRP (0.35).

Sampling Event and Sampling Site Effects

When all nine sites were included in the Two-Way ANOVA, the random factor, Event, had a highly significant effect on TN, $NO_3 + NO_2$, NH_3 and TSS ($P < 0.01$). An approaching significant effect was obtained for TP ($P = 0.046$) while SRP was insignificant ($P = 0.286$). Concentration means for each of the variables were generally highest after Event 3 (Figure 2). This was the only sampling event that occurred during the peak growing season. No other Event patterns were evident. When the model was run separately for the combined wetland cell inflows (four sites) and combined outflows (three sites), Event was no longer significant for TP.

The fixed factor, Site, had a highly significant effect on TP, SRP, and TN ($P < 0.01$) but no significant effect on $NO_3 + NO_2$, NH_3, and TSS ($P = 0.05$). When the model was run separately for the combined inflows and combined outflows, TN was only significant for the outflows ($P = 0.015$). Site differences are identified below.

Individual Wetland Cells and Iron Mine Prong

Comparison of Inflow vs. Outflow concentrations show that TP and SRP concentration were significantly greater in the inflows of Cells 1 and 3 than in the outflows (Table 2, Figure 3), and that TN concentrations were significantly higher in Iron Mine Prong above the wetland cells than below the cells (Table 2). For TN, Figure 4 shows that while the paired above vs. below differences were small, they were consistent. For concentrations of all other variables, inflow vs. outflow comparisons were not significant at $P = 0.05$ (Table 2).

Collective Wetland Inflows and Outflows

Differences between wetland cell inflows and between outflows were significant for TP and SRP at $P = 0.05$ (Table 3, Figure 3). Differences between $NO_3 + NO_2$ among the outflows were also significant at $P = 0.05$ (Table 3, Figure 3). For all other variables inflow and outflow comparisons were not significant at $P = 0.05$ (Table 3, Figure 3). Once again, the data analysis process involved running several consecutive similar tests therefore the significant results for SRP inflow and $NO_3 + NO_2$ outflow should be considered cautiously.

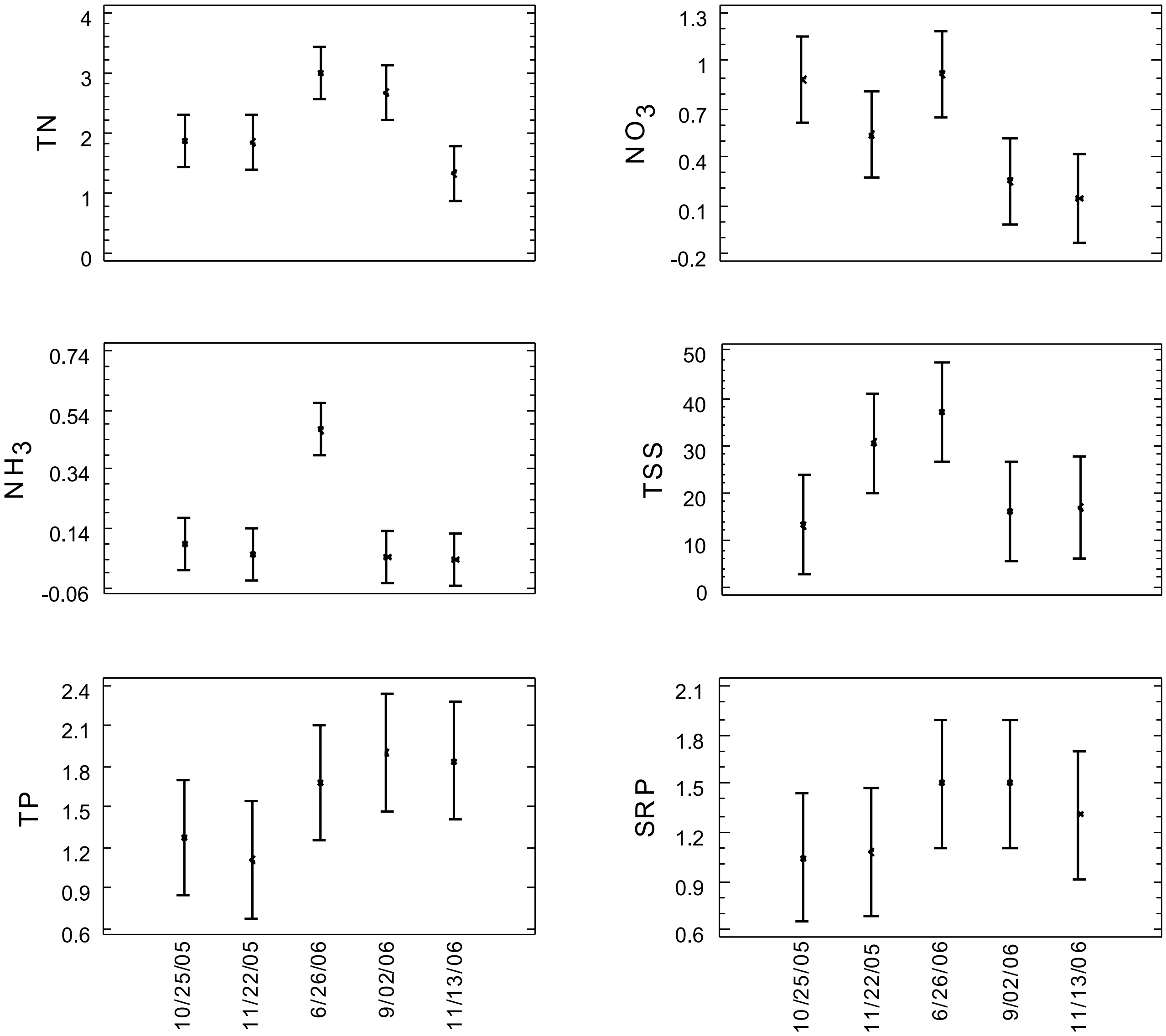

Figure 2: Means plots with Tukey HSD 95 % intervals for Total Nitrogen (TN), Nitrate + Nitrite Nitrogen (NO_3 + NO_2), Dissolved Ammonia (NH_3), Total Suspended Solids (TSS), Total Phosphorus (TP) and Soluble Reactive Phosphorus (SRP) inclusive of all storm sampling events for nine sites (wetland inflows, outflows and perennial receiving stream) located on the Haines Farm, Kent County, Delaware. All units are milligrams per liter. See Figure 1 for site locations.

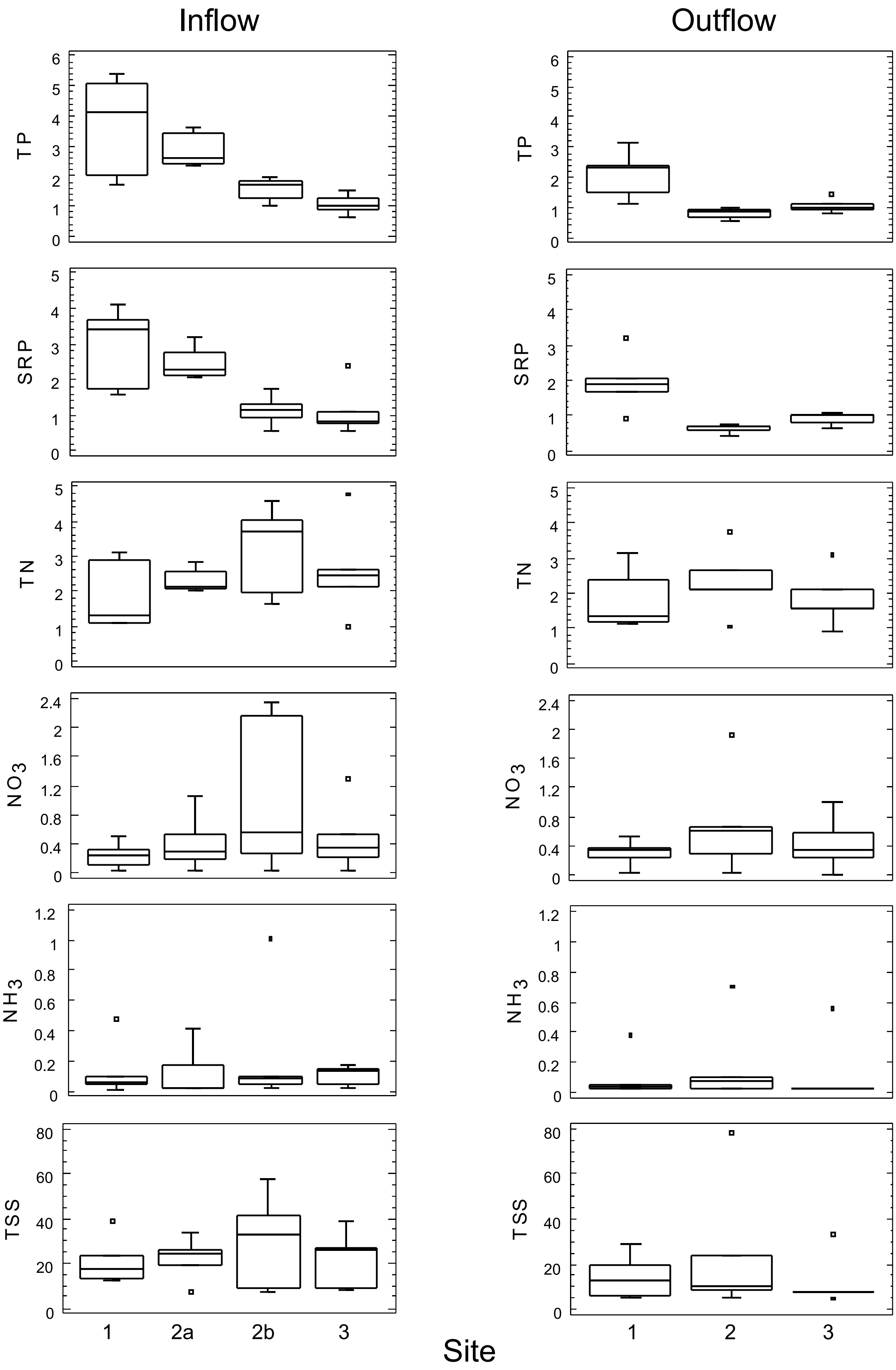

Figure 3: Box plots for Total Phosphorus (TP), Soluble Reactive Phosphorus (SRP) Total Nitrogen (TN), Nitrate + Nitrite Nitrogen (NO_3 + NO_2), Dissolved Ammonia (NH_3), and Total Suspended Solids (TSS), inclusive of five storm sampling events for wetland cell inflows and outflows on the Haines Farm, Kent County, Delaware. All units are milligrams per liter. See Figure 1 for site locations.

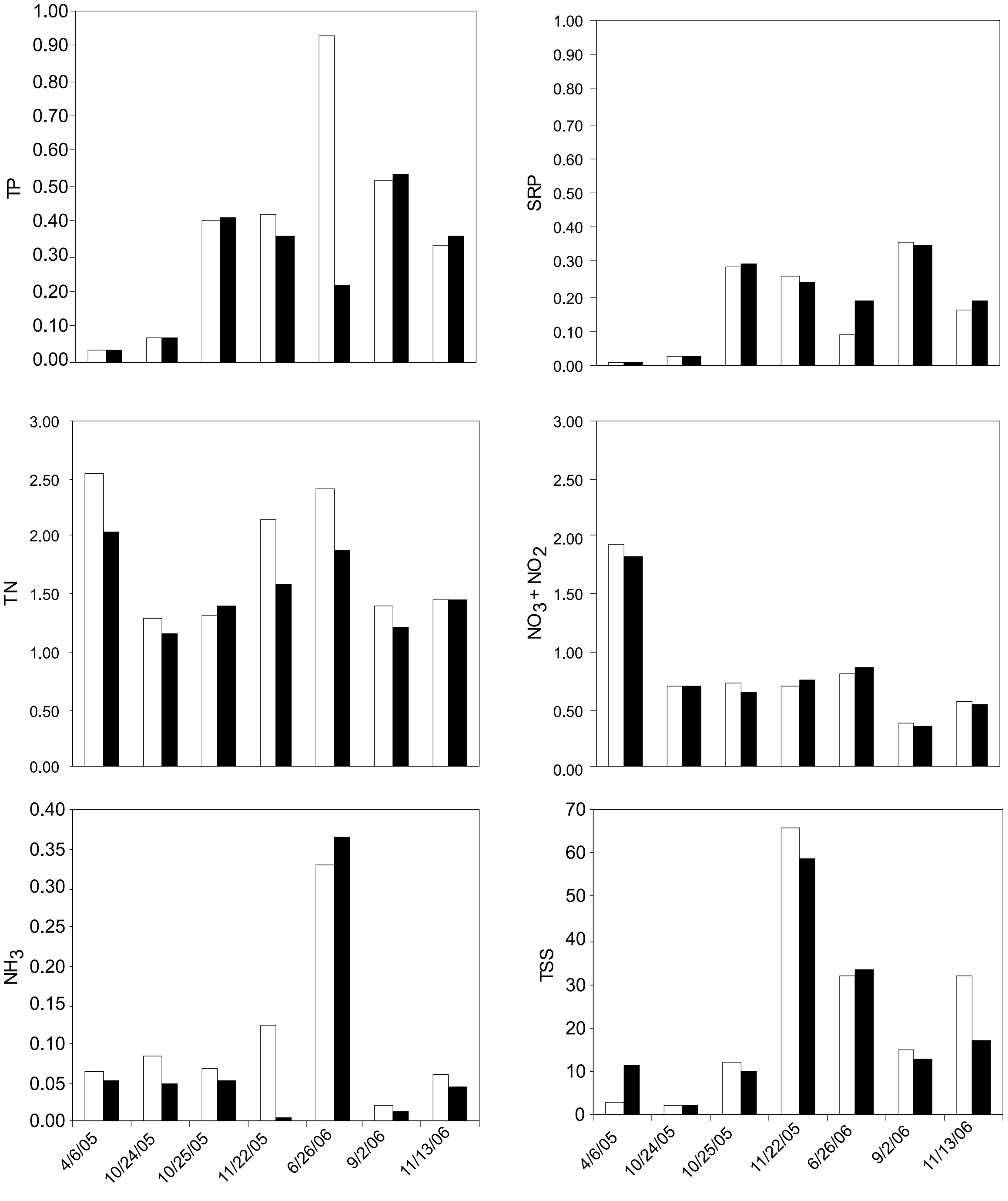

Figure 4: Concentrations of Total Phosphorus (TP), Soluble Reactive Phosphorus (SRP) Total Nitrogen (TN), Nitrate + Nitrite Nitrogen ($NO_3 + NO_2$), Dissolved Ammonia (NH_3), and Total Suspended Solids (TSS), inclusive of 2 base flow (4/06/05 and 10/24/05) and five storm sampling events for a perennial coastal plain stream which flows through the Haines Farm, Kent County, Delaware. White bars represent farm inflow (above wetland cells). Black bars represent farm outflow (below wetland cells). All sampling was done in the perennial stream. All units are milligrams per liter. See Figure 1 for site locations.

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Discussion and Conclusions

New techniques in water management in Delaware are resulting in opportunities for environmentally sensitive construction which includes wetlands restoration/creation and stream restoration. Developing beneficial watershed management plans which include BMPs and pollution control strategies (from TMDLs) may prove to be important in achieving improvement in overall water quality. As part of a watershed management plan, it is anticipated that the creation and restoration of many small wetlands and the restoration of stream channels in combination with the restoration of riparian buffers may have a cumulative and measurable effect on water quality. Each of these actions can be done quickly, efficiently and at low-cost.

Buffers are widely recognized as helpful in sequestering nutrients before they enter downstream waters. Generally, and vegetation type dependent, narrow buffering (<15m) removes some nitrogen while wider buffers of greater than 50 m perform more consistently and remove larger amounts of nitrogen (Mayer et al. 2006). By positioning many small wetland cells within buffered areas which receive agricultural runoff, perhaps a higher level of nitrogen and phosphorus uptake and removal may be achieved. Restoring a straightened ditch configuration to a natural and, to varying extent, sinuous stream channel slows water flow and increases the interaction with vegetation in the adjacent restored floodplain, thus facilitating further nutrient uptake and sediment trapping. Wildlife benefits from both wetland and stream restoration actions include enhancement of habitats for feeding, nesting, reproduction, loafing/resting and protection from predators.

An objective of creating wetlands on the Haines Farm and similar sites elsewhere is that they may function as buffers by filtering nutrients and other particulate matter that would otherwise be mobilized from the land directly into waterways during storm events. The intent is that such filtration will ultimately contribute to water quality improvement within receiving waters. Although the results from the exploratory sampling of the present study do not definitively show how the Haines wetland cells function with respect to filtering stormwater runoff, there existed a number of occasions where inflow-outflow comparisons showed a decrease in nutrients and suspended solids. While many of these relations are not statistically significant and therefore may be just part of the random variability of the system, it is indicative of these wetlands potentially providing a nutrient and sediment reduction effect. This apparent lack of discriminatory ability based on these data is probably an artifact of the study design, which does not account for the high variability that is known to occur in nutrient concentrations over the course of a storm hydrograph. For example, it is difficult to know if the higher nutrient concentrations associated with Event 3 are due to seasonal variation in crop management or simply the timing of sample collection within that particular storm hydrograph. Furthermore, it also could be that the overall lack of spatial and temporal patterns in N concentrations is due to the retention capacity of the wetlands being simply overwhelmed by the volume of runoff generated by large storm events. A better understanding of nutrient and sediment retention in these wetlands is not possible without implementing a study which carefully quantifies the flux over multiple storm events. Although the importance of quantifying constituent loads was known entering the present study, there were insufficient resources available to support that level of effort.

The findings of this exploratory study indicate that planning for future work may best be focused on P dynamics. It seems worthwhile to examine why the outflows of Cells 1 and 3 had TP and SRP that were consistently and considerably lower than their respective inflows. Also, it would be useful to identify any differences in watershed dynamics or wetland cell configuration that caused Cell 2 to have the appearance of having no P retention. Although it would be desirable to better understand N dynamics in the wetland cells, the N data from this study provide no obvious directional guidance for future work. It does appear that large storms may create sufficient runoff and volume to result in a flow-through condition for at least N and TSS. However, runoff generated by normal and more frequent smaller storms which do not overwhelm the retention capacity of these thin, small-volume lenses of water may indeed be filtered significantly. This would result in a reduced impact on water quality in receiving streams, such as the perennial ditch flowing through the Haines Farm. It is notable that the Pratt and Kolakowski sites were not observed to deliver any runoff from the wetland cells into downstream surface waters even though they received similar rain events. It was determined during the study that the watershed area of these two sites was also much smaller than Haines, thus inadvertently underscoring the importance of sizing created wetlands to the size of their respective watershed.

Future research should be a much more focused study which utilizes automated, flow-triggered sampling devices, and weirs which would allow the calculation of flow and loadings. It would need to understand the filtering dynamics within man-made wetlands associated with small and large storms alike. This next step should also include a closer attention to wetland cell/watershed size, and shallow groundwater input.

Table 1: Water quality variables analyzed for the RARE exploratory man-made wetland monitoring project during 2005 and 2006 at nine sites on the Haines Farm, west of Dover, Delaware. EPA method reference can be found online at www.epa.gov.

Variable	***Method Reference (EPA)***	***Reporting Level***	***Container***	***Preservation***	***Holding Time***
Water Column Nutrients					
Total Phosphorus (TP)	EPA365.1 M	0.005 mg/l P	HPDE 2L	Cool to ≤6°C, dark, digest within 7 days	28 days
Soluble Ortho-phosphorus (SRP)	EPA365.1	0.005 mg/l P	HPDE 2L	Filter, Cool to ≤6°C, dark	48 hours
Total Nitrogen (TN)	SM 4500 NC	0.08 mg/l N	HPDE 2L	Cool to ≤6°C, dark, digest within 7 days	28 days
Nitrate+Nitrite N ($NO_3 + NO_2$)	EPA353.2	0.005 mg/l N	HPDE 2L	Cool to ≤6°C, dark, H_2SO_4 to pH < 2	28 days
Ammonia Nitrogen (NH_3)	EPA350.1	0.005 mg/l N	HPDE 2L	Cool to ≤6°C, dark, H_2SO_4 to pH < 2	28 days
Total Suspended Solids (TSS)	EPA160.2	2 mg/l	HPDE 2L	Cool to ≤6°C, dark	7 days
pH – Field	EPA150.1	0.2 pH units	NA	NA	NA

Table 2: Comparisons of Inflow vs. Outflow concentrations (mg l-1) for selected nutrient species and total suspended solids for the RARE exploratory man-made wetland monitoring project on the Haines Farm, west of Dover, Delaware during 2005 and 2006. Wetland cell 3 had two inflows. Iron Mine Prong (Ditch) results based on n = 7 per site, wetland cells based on n = 5 per site. Statistically significant results at α = 0.05 are bolded. Wilcoxon paired-sample test of the median.

	Ditch S-1 vs. S-2	Wetland Cell 1 I vs. O	Wetland Cell 2 Ia vs. O	Wetland Cell 2 Ib vs. O	Wetland Cell 3 I vs. O
TP	0.500	**0.030**	**0.030**	**0.030**	0.500
SRP	0.664	**0.030**	**0.030**	0.053	0.394
TN	**0.038**	0.500	0.658	0.053	0.130
$NO_3 + NO_2$	0.277	0.860	0.791	0.295	0.705
NH3	0.075	0.209	0.606	0.140	0.394
TSS	0.223	0.208	1.00	0.295	0.209

Table 3: Concentration (mg l-1) comparisons between Inflows and between Outflows for selected nutrient species and total suspended solids for the RARE exploratory man-made wetland monitoring project on the Haines Farm, west of Dover, Delaware during 2005 and 2006. Statistically significant results at $\alpha = 0.05$ are bolded. Friedman's test of the median for block designs.

	Inflows		Outflows	
	P	Differences	P	Differences
TP	**0.003**	1, 2a > 2b, 3	**0.007**	1 > 2, 3
SRP	**0.048**	1, 2a > 2b, 3	**0.007**	1 > 2, 3
TN	0.373		0.613	
$NO_3 + NO_2$	0.137		**0.040**	1 < 2, 3
NH_3	0.696		0.247	
TSS	0.455		0.143	

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Appendices

Appendix 1 All nutrients and TSS (mg/L), pH in Standard Units. (TP=Total Phosphorous; SRP=Soluble Reactive Phosphorous; TN=Total Nitrogen; NO_3+NO_2=Nitrate+Nitrite; NH_3=Dissolved Ammonia; TSS=Total Suspended Solids; ND=No Data; C=Wetland Cell; In=Inflow; Out=Outflow). No samples collected at any wetland cells on April 6, 2005, and October 24, 2005.

	Date	S-1 In	S-2 Out	C-1 In	C-1 Out	C-2a In	C-2b In	C-2 Out	C-3 In	C-3 Out
TP	4/6/05	0.030	0.033							
	10/24/05	0.069	0.066							
	10/25/05	0.400	0.411	2.013	1.144	2.409	1.962	0.903	1.280	0.957
	11/22/05	0.424	0.360	1.700	1.513	2.337	1.259	0.704	0.645	1.016
	6/26/06	0.930	0.216	4.151	3.130	3.401	1.033	0.553	0.898	0.793
	9/2/06	0.516	0.531	5.363	2.414	2.564	1.849	0.918	1.518	1.422
	11/13/06	0.328	0.354	5.090	2.320	3.630	1.720	0.972	1.010	1.110
SRP	4/6/05	0.012	0.011							
	10/24/05	0.029	0.027							
	10/25/05	0.290	0.297	1.560	0.914	2.080	1.740	0.670	1.080	0.771
	11/22/05	0.256	0.244	1.720	1.680	2.290	1.310	0.580	0.549	1.090
	6/26/06	0.087	0.187	4.140	3.180	3.200	0.956	0.384	0.741	0.649
	9/2/06	0.357	0.348	3.420	2.030	2.130	1.120	0.728	2.390	1.000
	11/13/06	0.156	0.185	3.680	1.910	2.780	0.558	0.716	0.787	0.987
TN	4/6/05	2.55	2.05							
	10/24/05	1.29	1.15							
	10/25/05	1.32	1.40	1.06	1.14	2.05	3.71	2.08	2.43	1.55
	11/22/05	2.14	1.58	1.09	1.33	2.14	1.97	2.11	2.63	1.53
	6/26/06	2.42	1.89	3.10	3.12	2.83	4.58	3.76	2.13	3.09
	9/2/06	1.40	1.20	2.90	2.35	2.58	4.04	2.64	4.77	2.07
	11/13/06	1.45	1.46	1.32	1.19	2.01	1.64	1.03	0.96	0.90
NO_3+NO_2	4/6/05	1.930	1.840							
	10/24/05	0.695	0.702							
	10/25/05	0.722	0.645	0.499	0.383	1.050	2.330	0.668	1.290	0.357
	11/22/05	0.711	0.753	0.252	0.361	0.533	0.546	0.599	0.517	0.583
	6/26/06	0.824	0.862	0.318	0.534	0.288	2.160	1.920	0.360	0.992
	9/2/06	0.389	0.364	0.101	0.237	0.184	0.267	0.302	0.206	0.241
	11/13/06	0.567	0.555	0.034	0.025	0.030	0.027	0.025	0.018	0.017
NH_3	4/6/05	0.063	0.055							

	Date	S-1 In	S-2 Out	C-1 In	C-1 Out	C-2a In	C-2b In	C-2 Out	C-3 In	C-3 Out
	10/24/05	0.083	0.047							
	10/25/05	0.070	0.055	0.051	0.051	0.174	0.098	0.075	0.171	0.030
	11/22/05	0.125	0.005	0.011	0.026	0.017	0.046	0.098	0.130	0.025
	6/26/06	0.332	0.367	0.468	0.377	0.406	1.010	0.701	0.048	0.555
	9/2/06	0.021	0.015	0.093	0.023	0.021	0.022	0.020	0.146	0.019
	11/13/06	0.062	0.046	0.045	0.033	0.019	0.077	0.017	0.014	0.020
TSS	4/6/05	3	11							
	10/24/05	2	2							
	10/25/05	12	10	23	13	34	7	5	9	5
	11/22/05	66	59	39	20	24	9	24	26	8
	6/26/06	32	33	17	29	26	58	78	27	33
	9/2/06	15	13	13	6	7	33	10	39	8
	11/13/06	32	17	12	5	19	41	9	8	8
pH	4/6/05	6.03	6.09							
	10/24/05	7.49	8.07							
	10/25/05	7.77	7.02	7.28	7.23	7.07	6.93	8.05	7.61	6.94
	11/22/05	6.68	6.71	6.64	6.70	6.60	6.85	6.94	6.90	6.84
	6/26/06	6.88	6.94	6.91	6.95	6.75	7.03	7.08	6.89	7.35
	9/2/06	6.70	6.64	6.89	6.67	6.77	6.75	6.70	6.69	
	11/13/06	ND	ND	ND	ND	ND	ND	ND	ND	ND

PRECIPITATION EVENTS AT HAINES FARM SITE DURING SAMPLING EVENTS (Sandtown, Delaware -- CSWMC. Station ID - DSND.)

Appendix 2 Weather data from and around the dates of sampling at the Haines site. The Sandtown weather station is approximately 1.2 miles from the Haines site. Data is from the Delaware Environmental Observation System webpage (www.deos.udel.edu).

Sample Date	Date	Max Temp (°F)	Min Temp (°F)	Avg. Wind (mph)	Avg. Wind Dir. (°)	Peak Gust (mph)	Precipitation (in)
	4/5/2005	68.1	34.8	2.1	61	34	0
4/6/2005	4/6/2005	81.7	48.5	3.5	59.3	34	0
	4/7/2005	74.1	59	5	57.8	62.6	0.69
	4/8/2005	61.3	42.9	2.9	296.7	32.2	1.95
	10/22/2005	63.1	52.1	4.4	201.2	39.4	0.96
	10/23/2005	60.6	41.9	3.5	95.3	48.3	0
10/24/2005	10/24/2005	56.3	40.2	4.7	259.2	48.3	0.74
10/25/2005	10/25/2005	53	41.5	3.1	56.5	34	0.75
	10/26/2005	56.5	40.8	3.9	95.3	50.1	0.04
	11/20/2005	59.3	31.3	1.3	54.7	23.3	0
	11/21/2005	52.7	40.1	2.1	333.2	50.1	1.12
11/22/2005	11/22/2005	48.8	36.8	5.1	58.6	55.5	0.84
	11/23/2005	38.3	30.9	4.4	74.3	44.7	0
	6/23/2006	85.6	68.9	2	45.1	16.1	0.15
	6/24/2006	83.8	68.5	2.3	39.7	14.9	1.13
	6/25/2006	78.7	68.4	1.5	342.2	14.3	1.54
6/26/2006	6/26/2006	78.4	71.8	2.5	10	15.5	1.1
	6/27/2006	82.3	73.7	3.8	9.7	27.4	0.12
	8/31/2006	72.6	65.1	6	251.5	23.2	0
	9/1/2006	67	62.2	9.7	254.8	45.2	1.39
9/2/2006	9/2/2006	70.3	60.3	2.8	36	47.6	0.07
	9/3/2006	73.8	57.9	0.4	25.9	7.6	0.01
	11/11/2006	77.3	51.3	3	36.6	17.6	0
	11/12/2006	61.5	51.9	3.7	277.4	27.7	0.48
11/13/2006	11/13/2006	61	53.5	3.3	290	25.3	0.22
	11/14/2006	61.8	53.9	8.4	95.2	12.8	0.01

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