Abstract

Bass, Kristopher Lucas. Evaluation of A Small In-Stream Constructed Wetland in North Carolina’s Coastal Plain. (Under the direction of Robert. O. Evans)

The use of in-stream wetlands is a growing practice being used to mitigate the impacts of non-point source (NPS) pollution. Wetlands promote physical, chemical, and biological processes that attenuate and convert nutrients which can lead to improved water quality. Wetland performance is sensitive to site conditions, making it difficult to precisely quantify their possible impact. Factors such as site specific soil, hydrologic, and vegetative characteristics influence wetland effectiveness. Typical design criteria include surface area/depth, retention time, plant coverage, and other hydrodynamic recommendations. One recommendation made by Scheuler (1992) for stormwater wetlands is that the design surface area be at least 1% of the contributing watershed size. Most urban areas are severely limited with regard to available land areas for wetland creation, thus, to be practical, smaller wetlands will be necessary in many locations.

This research involved a two year study to quantify impacts of an in-stream constructed wetland on water quality. The one hectare (2.4 ac) in-stream wetland was built to intercept drainage waters from approximately 240 hectares (600 ac) of agricultural and urban watershed, which resulted in a wetland:watershed area ratio of 0.004:1. The wetland was instrumented to monitor hydrology and water chemistry.

Water level recorders were used to measure stage at the wetland inlets and at the outlet. Weir equations and discharge curves combined with statistical modeling and calibration techniques were used to determine the flows through the wetland. A water balance was computed using inflow, outflow, precipitation, and potential
A watershed scale balance showed that the total volume of flow leaving the wetland was comparable to the estimated volume of drainage and runoff from various land uses.

Water quality samples were analyzed for total Kjeldahl nitrogen (TKN), ammonium-nitrogen (NH₄-N), nitrate-nitrogen (NO₃-N), total phosphorus (TP), and ortho-phosphorus (OP). Measurements of water temperature and dissolved oxygen levels were also made within the wetland. Background data acquisition began in early 1996. The evaluation period began in August of 1997 and continued through December of 1999.

Over the evaluation period, NO₃-N concentrations were reduced through the wetland by 60%, NH₄-N concentrations by 30%, and TKN levels by 9.5%. This resulted in a 20% drop in total nitrogen concentration. Phosphorus levels increased 55% between the wetland inlets and outlet. Actual reduction of NH₄-N and TKN concentrations may be slightly underestimated due to unaccounted for inputs. This may also contribute to the increases in phosphorus concentrations observed between the inlets and the outlet. In the first full year, NO₃-N, and NH₄-N levels were reduced 70% and 33%, respectively. A significant decrease in NO₃-N concentrations through the wetland was detected during the first winter, and in other nitrogen forms in the first full growing season. NO₃-N levels were 60% lower at the wetland outlet throughout the year. Ammonium nitrogen concentrations dropped 30% through the wetland during the growing season and 20% during the dormant season. TKN levels were reduced (15%) in winter months, but not during the growing season. Phosphorus concentrations were higher at the wetland outlet
than at the inlet throughout the year, but showed larger increases during the growing season.

Monthly nutrient reductions were generally associated with temperature changes. Higher temperatures resulted in greater reduction of NO$_3$-N and NH$_4$-N concentrations. Larger increases in TKN and phosphorus concentrations were also associated with higher temperatures.
Evaluation of a Small In-Stream Constructed Wetland in North Carolina’s Coastal Plain

By

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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Biological and Agricultural Engineering

Raleigh, North Carolina

2000

APPROVED BY:

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Chair of Advisory Committee
Biography

Kristopher Lucas Bass was born on January 27, 1975 in Charleston, South Carolina. He lived in Greenville and Raleigh, N.C. before moving to Fayetteville, N.C. when he was five years old. He graduated from Fayetteville’s Terry Sanford High School in 1993 and went to North Carolina State University in Raleigh. While working on his undergraduate degree in Biological and Agricultural Engineering, he worked for the department on flooding response and drainage experiments. A DrainMod modeling project resulted in a presentation at the 6th annual Undergraduate Research Symposium in the spring of 1997. During his undergraduate career, he also served as president of the soccer club, and was captain of the Ultimate Frisbee team.

His graduate work was also done at North Carolina State. His senior design project involving the design of a stormwater wetland prompted his further interest and study in this area. His research focused on the evaluation of an in-stream constructed wetland in eastern North Carolina. In the summer of 1998, he worked as a project consultant for the Cooperative Extension office in the Biological and Agricultural Engineering Dept., designing a constructed wetland for the Public Works Commission in Fayetteville, N.C. Also, in the spring of 1999, N.C. State’s Ultimate Frisbee team won the College Ultimate National Championships in Boulder, Colorado. He has recently accepted a consultant position and, upon graduation, will begin work with Blue: Land, Water, and Infrastructure in Raleigh.
Acknowledgements

The author would like to thank all of those involved with this project. First and foremost I thank God for strength and guidance, for I do all things through Him. Special thanks goes to Dr. Robert Evans for giving me the opportunity to work for him. Through his leadership and trust I learned not only academically, but also about life and work. Thanks to Dr. Wendell Gilliam and Dr. Greg Jennings for their participation and review of manuscripts. Also thanks goes for the support and efforts of those in our research group: Jonathan Smith, Kevin Tweedy, Daniel Taylor, Michael Dukes, and Michael Cook. It is an honor to work with them and call them my friends. I would also like to credit Dwayne Hinson and Rodney Johnson for their involvement and help. Special thanks goes to Mrs. Bertha Crabtree and her lab staff at the Soil Science department for undertaking the overwhelming sample analysis. Finally, thanks goes to my friends and family, who always believed in me and taught me the journey is so much more important than the destination.
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Chapter I

Evaluation of an In-Stream Constructed Wetland in North Carolina’s Coastal Plain

Introduction

Non-point Source Pollution

The importance and impacts of non-point source pollution have been well documented. Non-point source pollution is generated by water movement over land surfaces or through soil. This runoff and groundwater can carry excess nutrients, bacteria, sediment, metals, pesticides, and other harmful pollutants into surface waters. Non-point pollution can originate from agricultural, urban, municipal, industrial, marine, or mining sources. Presence of these pollutants in surface waters can lead to eutrophication, depleted oxygen, odors, and other quality problems. Recent events such as fish kills, shellfish contaminations, and bacteria discoveries have been attributed to non-point source pollution. North Carolina’s Department of Environment and Natural Resources (DENR) has designated non-point sources as the number one source of stream and estuary impairment.

Agriculture

Much of the land in eastern rural North Carolina is extensively in either agriculture or silviculture. Nearly 40% of cropland in N.C. is in poorly drained soils of the coastal plain and tidewater regions (North Carolina Cooperative Extension Service, NCCES). The flat topography allows for easier equipment operation and reduced erosion
potentials, and the shallow water table helps provide water to crops. However, flooding
during wet periods can be a danger to crops and can cause field accessibility problems.
Drainage systems (surface, subsurface, or a combination) are used in these areas to
maintain necessary water tables that will reduce crop stresses and allow equipment
operation. Most drainage systems have been designed and installed to minimize crop
stress during wet times of the year, but due to seasonal variations in rainfall and
evapotranspiration, these same drainage systems may overdrain soils during drier periods.
The sandy soils in the coastal plain are a source of additional problems. Sandy soils are
low in nutrients, and fertilizer must be used to ensure production. A combination of low
binding potential and high conductivity creates the potential for transport of nutrients
through the root zone and into shallow groundwater. Concern over nutrient movement is
especially great during winter months when rainfall is highest and crop uptake is at a
minimum. The problems with pollutant transport in these soils are complicated by the
drainage needed to farm. Surface and subsurface drainage can increase total outflow
compared to undrained forested land by 5% and 20% respectively. Peak outflow rates
are also dramatically increased especially in surface drainage systems (Evans et. al.,
1995). The U.S. Environmental Protection Agency (EPA) estimated that agriculture
contributes 53% of all non-point source pollution in the United States (USEPA, 1989;
Clark et. al., 1985).
**Urban**

Urbanization has also increased loads on nearby streams. The large amount of impervious surfaces such as roads and parking lots associated with urban areas reduce rainfall contact with soil and the possibility of infiltration, storage, or evapotranspiration. Extensive storm drainage networks have been developed to facilitate movement of water away from roads and homes to prevent flooding. These drainage schemes also convey runoff waters directly into stream flows. The combination of impervious surfaces and stormwater drainage systems greatly increases the amount of runoff from urban areas. The E.P.A. estimates that urban areas can have nine times as much runoff as natural areas of the same size. These factors also increase peak runoff discharges, putting a tremendous load on streams and streambanks. Large volumes of fast moving water can overload the capacity of many channelized streams designed to meet agricultural drainage requirements which can lead to flooding of surrounding urban areas.

**Pollutants**

Drainage and runoff from fields or urban areas can be exposed to a number of pollutants such as sediment, nutrients, pathogens, metals and toxic chemicals, sodium, and chloride. Sediment and other suspended solids can originate from fields, construction sites, stream banks, and other land with insufficient vegetative cover. Sediments can impair recreational use of waters by increasing turbidity, carry attached nutrients and metals into waters, and harm aquatic life (Kent, 1994). Nutrients from fertilizers applied to agricultural fields, lawns and other large areas, leaking or improperly operating sewage lines or septic systems, or landfills can also enter streams through
runoff or groundwater discharge. Excess nutrients are of particular concern in broad, slow flowing waters in coastal areas because they can support algal blooms, which can contribute to decreased recreational use, odor problems, and low oxygen levels (Paerl, 1987). Bacteria can enter streams through runoff in contact with waste sources such as septic systems. Bacteria can be dangerous to human health and accumulation can contaminate filter feeding aquatic life such as shellfish. Urban areas contain sources of metals such as trash cans, junk yards, and automobiles. Runoff and precipitation coming in contact with degrading metal products can carry amounts into nearby streams. Sources of dangerous chemicals include fuels storage facilities, industrial areas, hazardous waste sites, and concentrated commercial properties such as fertilizer distributing facilities.

The effects of non-point sources on water quality and stream health have made improved management a priority. Scientists and engineers have been working on methods to intercept drainage and urban runoff to improve water quality and hydrology. Drainage management schemes, sedimentation basins, ponds, buffers, and filters have been designed and incorporated to help alleviate some of these effects. Educational campaigns have been used to increase public awareness of what can be done to reduce potential pollutant transport. Regulations and legislation have also been incorporated to reduce discharges from many sources.
Wetlands

One management practice that has excellent potential for improving water quality is the use of constructed wetlands. Constructed wetlands use a combination of biological, chemical, and physical processes that can convert, remove, or immobilize certain pollutants, especially nutrients. Riparian wetlands can lower stream flows and decrease flooding potentials. Wetlands can also support plants and animals. Practical wetland construction locations in urban areas include directly in streams/drainage canals or in ponds with failed or breached dams. This ensures adequate water flow to support the wetland. Wetlands can provide stabilization of degrading streams and reduce flooding frequency in problem areas. Another advantage to wetland designs is that they are applicable in a variety of conditions. Constructed wetlands are currently being used in North Carolina’s lower coastal plain, upper coastal plain, piedmont, and mountain regions. The use of in stream and constructed wetlands is a suggested practice by the NCCES, but has not yet gained status as a best management practice under the N.C. Agricultural Cost Share Program.

In-stream wetlands are created by modifying existing streams, most often through excavation. Flow paths are maximized by forcing water around islands, land wedges, through thick vegetation, or similar obstacles. Small slopes also encourage velocity reductions. Wetland outlets can be designed to limit the exit flow, retaining storm waters for longer periods. Flow decreases may also be attained through increased evapotranspiration from wetland plants. Decreased velocities can help promote deposition of sediments and solids in the wetland and also lower potential erosion of
banks downstream. Wetland designs that include sedimentation basins or forebays can further increase suspended solid removals. Although constructed wetlands provide a number of hydrologic advantages downstream, the potential for negative impacts upstream exists. Flow retention increases the possibility for backups and floods upstream. Wetland designs must maximize downstream benefits while maintaining upstream conditions. Wetlands also support a wide variety of plants. Dense vegetation in wetlands can improve physical filtering of sediment, trash, and organic materials. Vegetation also shades shallow and slower moving waters to help reduce algae growth. Wetland plants also provide food and shelter for a diverse wildlife community.

The high water table in wetlands limits oxygen movement into soil creating anaerobic conditions. Aerobic conditions in upper soil layers and in microsites, created by oxygen transport through plant roots, can help convert soluble metals through the formation of oxide and hydroxide precipitates. The combination of aerobic and anaerobic conditions also encourages conversion and removal mechanisms such as nitrification/denitrification. These important processes that can convert soluble nitrogen forms into harmless nitrogen gas can only occur when aerobic and anaerobic conditions exist. Other chemical processes such as adsorption, volatilization, and microbial decomposition occur in wetlands (Kent, 1994). Further loss of pollutants and especially nutrients can be achieved by simple plant uptake, but plants must be harvested to truly remove the pollutants from the system. Chemical reactions and reduction in wetlands is primarily microbial driven. Wetland conditions support these microorganisms by buffering temperature changes, and neutralizing pH. Low oxygen conditions slow
decomposition and increase organic matter contents. Organic matter and plant roots provide substrate and carbon sources for microorganisms.

An advantage to constructed wetland designs is that they can be adjusted to work in a variety of conditions. This gives wetlands a particular advantage over some other management practices that may be applicable in limited situations. Although constructed wetlands can be used wherever water supplies are adequate, performance is affected by site soil, hydrologic, and vegetative characteristics. Research done by van der Volk and Jolly (1993) and Mitsch (1993) indicated that wetland location within a watershed is important. They concluded that wetlands in upper reaches of the watershed to protect lower order streams could provide increased benefits. The site specific nature of wetlands makes development of design guidelines difficult. Some general recommendations have been made regarding appropriate wetland components, sizes and dimensions, water depths and flows, and vegetative types and densities. Recommendations suggest wetland surface areas be 1-3% of the contributing watershed area to ensure significant water quality improvement (Scheuler, 1992). Most urban areas are severely limited with regard to available areas for wetland creation and costs required to build them. Urban stormwater management plans suggest management practices treat at least the first inch of rainfall with retention times of 24-72 hrs. Wetland designs may restrict retention times or volumes due to runoff flows, outlet conditions, or size limits. Wetland plants and planting schemes are also critical. Native plants may help promote survival and regeneration. Inappropriate species or planting techniques can lead to
wetland failure. The wildlife balance encouraged by diverse plant communities helps control mosquitoes.

Although wetlands have shown promise as a water management practice, the relationships between wetland benefits and variable site conditions and designs are not fully understood. Further evaluation of wetland performance in different conditions will more clearly identify the possibilities for wetlands in urban areas. Evaluations focused on wetlands with smaller wetland/watershed area ratios will help depict if significant benefits can be achieved with them. Investigation of the effects of wetland design variables such as outlet designs will help maximize design efficiencies. Planting techniques, selections, and densities must also be evaluated to determine optimal designs for wetland performance and survival. The potential for wetlands in a variety of conditions makes examination to determine their applicability and effectiveness imperative.

This project involved a constructed wetland built in Edenton, North Carolina. Edenton is located in the lower coastal plain and drainage waters from the town and surrounding watershed discharge into the nearby Albemarle Sound. The wetland was designed to intercept two ditches, which carry drainage waters from approximately 240 hectares (600 ac) of agricultural and urban watershed. The main goal of this research was to evaluate the ability of the wetland to improve water quality. Monitoring and analysis focused on hydrologic and chemical conditions during the first two years of wetland development. Results of this research provide insight on the potential for smaller wetlands in urban areas and in the coastal plain.
Descriptions of the research and results of this project are presented in the following chapters. Each chapter was written as in a paper format and are intended to stand alone. Site background and specifications follow this introduction. Chapter II describes the flow monitoring at the site. Details are given on the methods used and the applicability of the results. Chapter III explains the research on wetland water chemistry and quality. The overall changes of nitrogen and phosphorus forms are reported. Analysis of nutrient changes through the wetland over time is also presented. Further discussion includes the variation in nutrient concentrations that occur within the wetland. Chapter IV investigates the influence of other factors that can effect nutrient concentrations in a wetland. A complete description of water temperature and dissolved oxygen level monitoring is given. Analysis focuses on seasonal nutrient fluctuations and the general effect of water temperature on nutrient removals. The implications of dissolved oxygen levels are also discussed.

**Site Background**

The town of Edenton is located in eastern N.C. in the Chowan river basin. Edenton is primarily an agricultural community, but is also an expanding urban center with a population of about 7,000. Drainage from the entire watershed travels to the environmentally sensitive Albemarle Sound. Excavating and straightening streams has been used in the area for centuries to speed transport of drainage waters away from developed areas. This practice typically involves placing spoil onto the original floodplain. Raising the floodplain with spoil and/or deepening the channel reduces
contact of waters with this important filtering mechanism. One specific area of concern was an urban stream reach called Liza’s bottom. The stream carries drainage waters from agricultural lands and runoff from commercial and urban sources such as a solid waste processing site and a former farm supply facility. The channel had been altered so that the riparian floodplain was rarely functional. An in-stream constructed wetland was chosen for this site because of the relative landscape position within the watershed and the potential for water quality improvements and flow control capabilities.

A one ha (2.4 ac) wetland was constructed in April-May, 1997. The wetland was built by lowering the hydraulically dysfunctional floodplain area down to the channelized stream level and raising the stream bottom. The original channel bottom was approximately at sea level and the original floodplain elevation was 0.6m to 1m (2-3ft) above sea level. The soils found in the floodplain and used for the wetland substrate were variable, with some reduced and high in organic matter and others clayey in content. A low head, wooden bulkhead was installed at the outlet to maintain water depths of 0.1m to 0.5m (6-18”). The wetland bottom was graded for a mixture of shallow and deeper pool areas. Two islands were built in the interior to minimize transportation of cut/fill material and to provide sinuosity to the flowpath. The upstream island was about 60m (200 ft) long with a top elevation of 2m (7ft) above sea level. The downstream island was 30m (100 ft) long.

Native plants were used in the wetland and transplanted on a 3’ x 3’ spacing. The primary plants used were pickerelweed (*pontedaria cordata*), bur reed (*sparganium americanum*), cattails (*typha latifolia*), and lilies (*nuphar variegatum*). A few native
trees including black willow (*salix nigra*) and cypress (*taxodium distichum*) were planted around the perimeter and near the design pool level.

The wetland intercepts waters from approximately 240 hectares (600 ac) of surrounding watershed. One hundred and sixty hectares are attributed to agricultural and managed forest area, sixty ha to urban area, and twenty ha to intensive commercial areas. A schematic of the site is shown in Figure 1. Pictures of site construction, planting, and growth are shown in Appendix C.

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**Figure 1.** Edenton wetland schematic, including pre and post construction cross sections.
References


Chapter II

Flow Measurement in a Free Water Surface Constructed Wetland

K.L. Bass and R.O. Evans

Abstract

An in-stream wetland was built to intercept drainage from approximately 240 hectares (600 ac) of agricultural and urban watershed. One component of the research focused on quantifying hydrology in order to create a nutrient mass balance for the wetland. A flow monitoring plan was implemented that provided a continuous record of inlet and outlet flowrates. Continuous water level recorders were used to measure stage and combined with control structures and flowmeter derived stage-discharge curves to calculate flows at the main inlets and at the outlet. A monthly water balance was computed including inflow, outflow, precipitation and potential evapotranspiration (PET). A comparison between expected drainage and runoff from the watershed and measured wetland outflow volumes lead to the conclusion that the overall flows observed were reasonable for use with concentration data to predict nutrient mass transport.
Introduction

This project involved the evaluation of a free water surface in-stream constructed wetland. An important component in determining the impact of water quality improvement projects is flow measurement. Flowrates are used for creating mass balances and loadings. This paper describes the flow monitoring plan, techniques used, and results achieved for this study.

Site Background

The one hectare (2.4 ac) wetland was constructed in April-May, 1997. The wetland intercepts two main streams which carry drainage and runoff from approximately 240 ha (600 ac) of agricultural and urban watershed. One hundred and sixty hectares are attributed to agricultural and natural forested area, sixty hectares to urban area, and twenty hectares to intensive commercial areas. In addition to the two main inlets, a side ditch, one storm drain, and surface runoff from the immediate area contribute flow and pollutants to the site. The wetland was built by excavating the hydraulically dysfunctional floodplain, and lowering it to the chanelized stream level and raising the stream bottom. A low head, wooden bulkhead installed at the outlet holds water in the wetland at depths of 0.1m to 0.5m (6-18”). Two islands were built in the interior to add sinuosity to the flow path and to minimize transportation of cut/fill during construction. A complete site description is given in Chapter I with pictures included in Appendix C. A schematic of the site monitoring locations is shown in Figure 1.
Figure 1. Edenton wetland schematic, including pre and post construction cross sections.

Flow Monitoring Plan

A monitoring plan was implemented that measured flows at each inlet and at the outlet. The two main inlets carry waters partially from urban or commercial areas. Flow measuring devices were used that respond to the rapid flow changes that were expected to occur in urban watersheds. Continuous water level recorders utilizing a pulley float mechanism were chosen for their flexibility and accuracy over a range of flow stages.
Water Level Recorders

Water level recorders were installed at the two main inlets and at the wetland outlet (Fig. 2). The recorders operate on a pulley/float mechanism. A weighted float is attached to a pulley and a counter weight. Changes in water level turn the pulley and change the resistance on a connected potentiometer. Voltage changes are measured by a Blue Earth® microprocessor and the stage determined using referenced equations. The devices can be customized for the desired recording frequency. Initial calibration is performed prior to field installation. The complete unit was constructed at N.C. State’s Department of Biological and Agricultural Engineering.

Figure 2. Top view of a water level recorder with the pulley visible at the top, microprocessor mounted at the bottom, and palmtop computer downloading.
A four inch PVC pipe installed in the channel served as the housing for a weighted float and a smaller 1¼ inch pipe placed next to it protected the counter weight. A watertight PVC box placed on top of the pipes housed the recording device. Once installed, the unit was referenced to the surveyed outlet elevation.

The devices were managed by microprocessors, which were programmed to check the water level every three minutes and record a change of 1mm or more. If no change occurred, a data point was recorded each hour. In either case, the date, time, and stage were logged to memory. Manually read gages were installed to routinely check the accuracy of the readings and to provide discrete measurements when malfunctions occurred. The data was downloaded bi-weekly using a palmtop computer. Backups were filed on disk and the data analysis was performed at the office.

**Rainfall and Air Temperature**

A tipping bucket rain gage was installed on the downstream island. The device was mounted and leveled. Rainfall amounts were recorded using a Hobo® event logger. Rainfall of 0.01 inch triggered a log of the time and amount of precipitation. Data was downloaded using a Hobo® data shuttle and brought back to the department for analysis. Monthly mean air temperature data was available from a local weather station. Potential evapotranspiration was determined from the monthly mean temperature using the Thornwaith’s equation with monthly correction factors for eastern North Carolina (Thornwaith, 1957, Amatya et. al., 1995).
Agricultural and Commercial inlet

The agricultural/commercial inlet (E2) (Fig. 1) drains approximately 160 ha (400 ac) of agricultural and commercial watershed. It was the larger of the two inlets and due to the downstream bulkhead, the channel is about 0.5m deep at baseflow conditions. A continuous water level recorder was installed in the channel and stage height referenced to the wetland outlet. A staff gage was also installed and surveyed at this location to provide backup and calibration. At each visit to the site, the water level reading was matched with the gage height to confirm accuracy, and adjustments were made when differences were detected.

A culvert downstream from the recorder device was used for generating a stage-discharge curve. An ultrasonic doppler flowmeter was installed in the culvert. This device recorded the velocity and height of flow through a range of stages. Measurements were made from December, 1998 through May, 1999 resulting in over 3500 data points. Baseflow or low stage conditions were highly variable. Factors such as wind, debris, and/or wildlife can have considerable effect on acoustic instruments, especially at low flow conditions. For example, as the wetland was built in a perennial stream, there was always a drainage component of flow and therefore always some flow over the outlet. However, at low stages, frequent changes in wind speed and direction resulted in rapid shifts in velocity through the culvert making it difficult to accurately measure the net velocity. Therefore, flow measurements made at low stage (<8.7cm) conditions were not used in creating the stage/discharge curve. Flows above baseflow levels exhibited a clear
The stage/discharge relationship for low flow conditions (stage<8.7cm) was assumed to be linear and was forced to equal zero when the stage was equal to the level of the outlet weir. The composite graph depicting the values for higher flows with the linear estimation of low flows was created (Fig. 4). Baseflow estimates yielded that the
linear prediction for low flows was higher than actual conditions. A further polynomial curve was fitted to this data to create a continuous function that would lower baseflow estimates to a more realistic level (Fig. 4).

Figure 4. Curves and Equation for Flow Estimation at the Agricultural/Commercial Inlet.
Urban Inlet

The urban inlet (E3) was the smaller of the two main inlets and carries drainage from about 60 ha (150 ac) of urban area. The channel was small enough to install a V-notch weir. A continuous recorder was installed to record the head above the weir and a measuring tape attached to the weir for visual verification and calibration of the recorder. Combining weir equations with stage measurements provided a continuous flow record.

The urban nature of the watershed caused the level in this ditch to rise rapidly during storm events. Although the V-notch weir was sufficient for low flows, it was frequently overtopped during mid sized events. High flows combined with sandy soils caused erosion and leakage around the weir after several storms. Repairs were made, but data recorded prior to repairs was not an accurate representation of flow. To create an appropriate estimate of flow during leaking periods, several steps were taken. Under the assumption both inlets were subject to approximately the same rainfall conditions, the most accurate measurements were compared to determine if there was a significant relationship between them (Fig. 5).
A linear relationship ($R^2=0.71$) was found between the inlets and was used to correct measurements at E3 following washout periods. The statistical program used to create these estimates is presented in Appendix A.

**Other Inputs**

Two other inputs (side ditch and storm pipe, Fig. 1) were considered. Pipe elevations were surveyed to determine their slope and measured water levels were used with the Manning formula to estimate the contribution of these inlets (Manning, 1891, Grant, 1989). The watersheds for these inputs were primarily urban. Continuous measurements were not made at these locations, however, discrete flows were compared to the concurrent measurements from the urban inlet (E3). From these observations, it
was determined that the flow entering the wetland from these two urban locations was very close to the flow entering through E3. Therefore, the measurements at E3 were doubled to account for the total urban inflow.

**Wetland Outlet**

The outlet (E1, Fig. 1) was difficult to describe hydraulically. The outlet structure is a 21m (70 ft.) long wooden bulkhead. As installed, the weir was designed for water level control and not as a flow measurement device. Even though the structure was fairly level, the flow depth was not constant at low stages. Therefore, a smaller 1.2m (4 ft.) rectangular weir was placed approximately in the center and 5cm (2in.) below the top of the bulkhead to facilitate low flow determinations. A continuous water level recorder was installed to record the stage above the outlet.

Flow prediction at the outlet had several challenges. Leakage around the ends and below the bulkhead was particularly significant during low flow periods. Repairs were made, but some flow was not measured. Changing outlet conditions such as blockage of the 1.2m weir by plant debris further contributed to errors. At low flow conditions, head on the 1.2m (4 ft.) weir was typically less than the recommended level of 0.2 times the weir length (0.24m, 9in) (Grant, 1989). At high flow conditions (stage>5cm), outlet and tail water conditions made standard weir equations inaccurate. The length (21m) of the weir during higher flows magnifies the lack of precision with using the weir equation for outlet flow determination. Analysis of input flow rates versus calculated outlet rates showed that the weir equation overestimated flow during high stages. It was determined
that a linear adjustment ($R^2=0.86$) to the weir equation at high stage conditions would result in flowrates more comparable to input rates (Fig. 6).

![Outlet weir equation calibration](image)

Figure 6. Regression analysis to calibrate the outlet weir equation to inlet flowrates at high stages.

**Results and Discussion**

A monthly water balance was computed including inflow, outflow, precipitation, and potential evapotranspiration (PET). At the time of this analysis, the monthly mean air temperature information required for estimating PET was only available for a 15 month period from February, 1998 through May, 1999. Due to the size of the wetland
compared to the size of the watershed, the flux of precipitation/evapotranspiration on the wetland is negligible compared to the total flow entering and leaving.

After adjustment of the data as described in the preceding sections, the total water balance over the monitoring period between inflows and outflows was in good agreement (Fig. 7). Over the entire evaluation period, the agricultural/commercial inlet contributed 80% of the total flow volume and the sum of the smaller urban inlets including E3, the side ditch, and the storm pipe averaged 20% of the total monthly inflow.

![Figure 7. Monthly flow volumes entering and leaving the wetland.](image)
Further analysis was done to verify that flow determinations were comparable to expected watershed dynamics (Table 1). Drainage volumes were predicted separately for agricultural and urban land uses. A water balance using precipitation, PET, and deep seepage was used to estimate drainage volume from the 160 ha (400 ac) of agricultural lands. A constant deep seepage rate of 2.54 cm (1 in) per year was used for agricultural areas (Heath, 1980). Runoff from the 80 ha (200 ac) of urban and commercial areas was predicted using the Natural Resources Conservation Service (NRCS) curve number method. A weighted curve number of 75 was determined by combining estimates of the watershed area in commercial, urban and residential use. These procedures yielded a combined drainage and runoff volume that was 36% of the total precipitation falling on the watershed. Outflow, as measured at the wetland outlet, totaled 31% of the volume of rainfall measured (Table 1).

Table 1. Watershed analysis to compare predicted drainage and runoff to measured wetland outflow. Negative drainage indicates PET exceeded rainfall in that month.

<table>
<thead>
<tr>
<th>Watershed Analysis</th>
<th>Total=240 hectares</th>
<th>Curve Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ag./Forest=160 ha</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Urban/Commercial=60 ha</td>
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<table>
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<tr>
<th>Input</th>
<th>Ag/Forest</th>
<th>Urban/Comm</th>
<th>PET volume</th>
<th>Total Drained</th>
<th>Runoff Volume</th>
<th>TOTAL DRAINAGE +RUNOFF</th>
<th>TOTAL WETLAND OUTFLOW MEASURED</th>
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<tbody>
<tr>
<td>Volume</td>
<td>(m^3)</td>
<td>(m^3)</td>
<td>(m^3)</td>
<td>(m^3)</td>
<td>(m^3)</td>
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<td>rainfall Ag/Forest</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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26
Summary and Conclusions

Continuous stage measurements were made at the two main inlets and at the wetland outlet from September, 1997 through December, 1999. Flowrates were determined by combining stage measurements with weir equations and stage/discharge curves. Flows at high stage conditions at the wetland were calibrated with inlet flowrates because the assumptions necessary for using the weir equation were not met. The total volume of flow at the wetland outlet was comparable to the expected volume of drainage and runoff from the watershed. Based on the analysis presented in this chapter, flow data was deemed reasonable for use with water quality data.
References:


Chapter III

Water Quality Improvement by an In-stream Constructed Wetland in North Carolina’s Coastal Plain

K.L. Bass and R.O. Evans

Abstract

Wetlands have shown promise as a stormwater best management practice (BMP). Current recommendations suggest design surface areas be at least 1% of the contributing watershed area to ensure significant water quality improvement. Most urban areas are severely limited with regard to available land areas for wetland creation, thus, to be practical, smaller wetland:watershed area ratios will be necessary in many locations.

A one ha (2.4 acre), in-stream constructed wetland was built to intercept drainage waters from approximately 240 hectares (600 acres) of agricultural and urban watershed. The wetland was instrumented to monitor hydrology and water chemistry. Monitoring began in early 1996 and continued through December of 1999. Water quality samples were analyzed for total Kjeldahl nitrogen (TKN), ammonium-nitrogen (NH₄-N), nitrate-nitrogen (NO₃-N), total phosphorus (TP), and ortho-phosphorus (OP). Over the monitoring period, NO₃-N concentrations were reduced by 60%, NH₄-N by 30%, and TKN by 9.5% for a total nitrogen drop of 20%. Total and ortho-phosphorus levels increased 55%. Significant improvements in NO₃-N and NH₄-N concentrations were achieved in the first full growing season.
Introduction

The use of in-stream wetlands is a growing practice being used to mitigate the impacts of non-point source (NPS) pollution. Wetlands promote physical, chemical, and biological processes that attenuate and convert nutrients which can lead to improved water quality. Wetland effectiveness is sensitive to site conditions, making it difficult to precisely quantify their possible impacts. Factors such as site specific soil, hydrologic, and vegetative characteristics influence wetland performance. Typical design criteria include surface area/depth, hydraulic retention time, and plant coverage recommendations. For example, Schueler (1992) suggests a minimum 1% wetland/watershed area ratio to ensure water quality benefits in stormwater wetlands.

Constructed wetlands have been reported to reduce total suspended solids by 60% or more, phosphorus by 37-90%, and nitrogen by 40-60% (Kent, 1994). Mitsch (1992) reported in-stream wetlands to reduce phosphorus by 63-96% and sediment by 88-98%. Data reviewed from fifteen constructed wetland sites in a variety of locations were presented by Strecker et al. (1992). They reported median solids removal of 80%, total phosphorus removal of 58%, lead of 83%, and zinc of 42%. Included with those data were coefficients of variation from 28-56%. Although differences in site design, location, and monitoring make comparison and combination of data from various sites difficult, their review gives a reasonable indication of the potentials for wetlands. Data compiled by Kent (1994) on several sites indicated that constructed wetlands could perform as well as natural wetlands. The review by Strecker et al. (1992) showed greater removal effectiveness in constructed wetlands and lower variability (higher consistency)
when compared to natural systems. Three sites ranging from 0.7-5 acres monitored in Virginia showed reductions as high as 68% for TP and 81% for OP. Total nitrogen was reduced by 18%, NO₃ by 54% and fecal coliforms by 75% (Yu et. al., 1997). Results compiled by Yu et. al. (1997) from several constructed wetlands used to mitigate NPS pollution showed nitrogen removals from 10-50% and phosphorus removals ranging from 16-70% (Kappel et. al. 1985, Martin and Smoot 1986, Athanas 1988, and Linker 1989). Scheuler (1992) found evidence that wetland removal potentials for some constituents increase as a wetland gets older. Increased carbon sources from organic matter build up and higher plant densities were cited as the main factors.

Some phosphorus findings have not been as encouraging. Raisin and Mitchell (1998) found the sorption potential of phosphorus in wetland soils to be very low. Kadlec (1995) reports that only a few months of phosphorus can be bound by wetland soil. One study showed phosphorus removals of 40%, but decreasing to nearly zero within four months (Stein et. al., 1998). Other research has shown sorption capacity to be 35% lower under anaerobic conditions. Further analysis showed that surface layers had higher adsorption potential than deeper layers (Reddy et. al., 1998). A small wetland with a wetland/watershed area ratio of 0.0095:1 showed a 10% increase in phosphorus levels at the outlet (Yu et. al., 1997). In mineral wetland soils, phosphorus losses are attributed to the reduction of iron phosphate complexes. However, in organic soils, much of the soil phosphorus content is bound in organic material. Golterman (1991) found that higher release rates of phosphorus from organic soils under anaerobic conditions were
associated with mineralization of organic matter rather than with dissolution of iron complexes.

Site Background

A one ha (2.4 ac) wetland was constructed in April-May, 1997. The wetland intercepts waters from approximately 240 hectares (600 ac) of surrounding watershed. One hundred and sixty hectares are attributed to agricultural and natural forested area, sixty ha to urban area, and twenty ha to intensive commercial development. Pollution threats include agricultural sources such as fertilizers, urban sources such as roads and parking lots (oil and grease), lawns, leaking sewage pipes, improperly functioning on-site septic systems, solid waste storage and processing sites, and commercial properties.

The wetland was built by lowering the floodplain area down to the original stream level and raising of the channelized stream. The soils found in the floodplain and used for the wetland substrate were variable, with some reduced and high in organic matter and others clayey in content. A low head, wooden bulkhead was installed at the outlet to maintain water depths of 0.1m to 0.5m (6-18”). A more complete site description is given in Chapter I and pictures are presented in Appendix C. A schematic of the site is shown in Figure 1.
Flow Monitoring

Water flow measurements at this site were made at the two main inlet streams (E2 and E3) and at the wetland outlet (E1) using continuous water level recorders. Stage measurements were combined with weirs and calibrated discharge curves to generate a continuous mass flow record. A monthly water balance was conducted considering inflow, outflow, precipitation and evapotranspiration. Detailed flow monitoring descriptions and results are presented in Chapter II.
Water Quality Monitoring

Water quality samples were taken over time and at various flow stages. Background water samples were acquired from January 1996 until the construction began in May, 1997. After planting in mid-summer, grab samples were taken on bi-weekly intervals at six locations throughout the wetland and at 5 impact areas up and downstream. Automatic water samplers were utilized at the two main inlets and at the outlet. Over 1000 samples were acquired during the monitoring period. Water quality samples were analyzed at the North Carolina State Soil Science laboratory for sediment and nutrients (NO₃-N, NH₄-N, TKN, TP, & OP).

Sampling Protocol

Grab samples were taken by submerging the container to about the middle of the water column making sure the container did not touch the sides or bottom of the stream. Automatic samples were suctioned from the middle of the water column and suction lines were replaced regularly. The laboratory analyzed samples using standard EPA protocols. All nutrient samples were treated with sulfuric acid prior or immediately after sampling to prevent degradation or conversion of the nutrients. Acquired samples were kept on ice during transport and were stored at 4°C prior to analysis at the Soil Science Department. Sample date and location was labeled on the sample container and recorded. Duplicates of sample records were kept in a field notebook and given to the laboratory manager.
Automatic Samplers

Isco® automatic samplers were installed at the two main inlets and at the outlet. The samplers can obtain and store up to 24 samples. Suction lines from the samplers were placed in the middle of the water column and inspected regularly. Pumping was calibrated to make sure 500 mL sample volumes would be acquired for analysis.

Originally, the samplers were programmed to take a sample each day. A mixture of discrete and combined samples was kept based on the stage at which the sample was collected. Automatic samplers and water level recorder microprocessors were housed together in a protective sampling box. The devices were both powered by a 12V car battery which was maintained by a solar recharger. Pictures of water level recorders and samplers are shown in Appendix C.

Statistics

Data were analyzed using appropriate statistical procedures. Analysis of variance was used to determine the effects of wetland variables. Least square means were tested for differences using a Tukey-Kramer adjustment (Tukey, 1953, Kramer, 1956). All analysis was computed using SAS® and are reported at the 0.05 significance level. Inlet concentrations were flow weighted and combined to create a single inlet concentration.
Results and Discussion

Pre-Construction

Baseline concentration data was not statistically different between inlet and outlet locations. Inlet means were 0.6mg/l NO₃-N, 0.4mg/l NH₄-N, 1.7mg/l TKN, 0.52mg/l TP, and 0.29mg/l OP. Mean outlet concentrations were 0.5mg/l NO₃-N, 0.3mg/l NH₄-N 2.0 mg/l TKN, 0.52 mg/l TP, and 0.30 mg/l OP.

Overall Concentration Results

After wetland construction, referred to as the evaluation period, the mean inlet NO₃-N concentration was not significantly different from pre-construction levels at 0.6 mg/l. The mean outlet level tested significantly lower at 0.2 mg/l indicating an overall drop in concentration greater than 60%. Ammonium-nitrogen inlet concentrations were 0.6 mg/l. The mean outlet concentration was significantly lower (30%) at 0.4 mg/l. Mean TKN levels tested significantly different at the 0.10 significance level with inlet concentration 2.1 mg/l and outlet level 1.9 mg/l for a 9.5% reduction. Total nitrogen (nitrate+TKN) concentration was 20% lower with 2.1mg/l at the outlet and 2.7mg/l at the inlet. Data collected throughout the evaluation period for phosphorus showed significant increases between the inlets and the outlet. Total phosphorus levels increased 55% from 0.37 mg/l to 0.57 mg/l. Ortho-phosphorus concentrations also rose 55% from 0.27 mg/l to 0.42 mg/l (Table 1).
Overall Mass Loadings

Mass loadings were computed by combining concentration data with flow measurements. Over the evaluation period, NO$_3$–N load was lowered 55% with a total of 1,089 kg of nitrate nitrogen entering the wetland and 490 kg leaving through the wetland outlet. Sixteen percent of the ammonium nitrogen entering the wetland was removed with 797 kg at the inlet and 673 kg at the outlet. TKN input was measured to be 3,416 kg and output 3,212 kg for a 6% reduction. A total of 4505 kg of nitrogen entered the wetland and 3707 kg left for 18% drop. Total phosphorus and ortho-phosphorus leaving the wetland increased 50% with inputs of 687 kg and 496 kg, and 1,015 kg and 749 kg at the outlet.

Table 1. Overall nutrient reductions on concentration and mass basis.

<table>
<thead>
<tr>
<th></th>
<th>NO$_3$-N</th>
<th>NH$_4$-N</th>
<th>TKN</th>
<th>TN</th>
<th>TP</th>
<th>OP</th>
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</thead>
<tbody>
<tr>
<td>Concentration basis</td>
<td>60%</td>
<td>30%</td>
<td>9.5%</td>
<td>20%</td>
<td>-55%</td>
<td>-55%</td>
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<tr>
<td>Mass basis</td>
<td>55%</td>
<td>16%</td>
<td>6%</td>
<td>18%</td>
<td>-50%</td>
<td>-50%</td>
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</table>

Initial soil phosphorus content could have been a factor causing the observed increase through the wetland. Soils in the floodplain that accumulated organic matter under anaerobic conditions were uncovered during the excavation process. Mineralization of phosphorus from this organic matter could have caused an increase. Clayey substrate layers and sediment delivered to the wetland from highway construction upstream may have also been sources. Reduction of these clay soils and sediments under
anaerobic conditions could have liberated phosphorus associated with iron complexes.

The reduced nature of the wetland substrate also limits available binding sites for incoming phosphorus.

**Annual Concentration Analysis**

The change in nutrient concentrations on a yearly basis was also evaluated (Table 2). As planting took place mid-summer, 1997 means represent a shortened growing season and part of the first dormant season.

**Table 2. Mean nutrient concentrations at the wetland inlet and outlet.**

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>1997 Inlet</th>
<th>SD†</th>
<th>Outlet</th>
<th>SD†</th>
<th>1998 Inlet</th>
<th>SD†</th>
<th>Outlet</th>
<th>SD†</th>
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<tr>
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<td>0.4</td>
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<td>TKN</td>
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<tr>
<td>NH₄-N</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4*</td>
<td>0.3</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4*</td>
<td>0.4</td>
</tr>
<tr>
<td>TKN</td>
<td>2.4</td>
<td>0.8</td>
<td>2.1</td>
<td>0.7</td>
<td>2.1</td>
<td>0.8</td>
<td>1.9*</td>
<td>0.8</td>
</tr>
<tr>
<td>TP</td>
<td>0.47</td>
<td>0.23</td>
<td>0.64*</td>
<td>0.29</td>
<td>0.37</td>
<td>0.20</td>
<td>0.57*</td>
<td>0.34</td>
</tr>
<tr>
<td>OP</td>
<td>0.34</td>
<td>0.17</td>
<td>0.45*</td>
<td>0.21</td>
<td>0.27</td>
<td>0.14</td>
<td>0.42*</td>
<td>0.22</td>
</tr>
</tbody>
</table>

* Denotes a significant difference was detected between means within years.
† SD is the standard deviation
Data combined in 1997 did not exhibit significant differences in mean levels of any nutrients between the inlet and the outlet. Nitrate-nitrogen concentrations were 0.6 mg/l and 0.5 mg/l at the inlets and outlet, respectively. Mean NH₄–N levels were 0.4 mg/l at both the inlets and outlet. Total and ortho-phosphorus levels were at 0.31 mg/l and 0.2 mg/l at the inlet and 0.36 mg/l and 0.28 mg/l at the outlet.

Significant differences were found for all nitrogen forms except TKN in 1998 and 1999. In 1998, NO₃–N inlet concentrations were 0.7 mg/l while outlet levels were 0.2 mg/l for a 70% reduction. Mean NH₄-N concentrations in 1998 were 0.6 mg/l at the inlets and 0.4 mg/l at the outlet and a 33% reduction. Selection of native plants promoted quick growth and plant populations spread quickly in the first full growing season. Even though input levels of NO₃–N increased compared to 1997, outlet levels remained the same.

Canopy coverage, estimated at 90% in 1998, declined to approximately 50% in 1999. On-site visual observations led to the conclusion that a contaminant input from the urban inlet, possibly due to an upstream solid waste transfer station was the most likely cause. Severe burns of young leaves and buds during the emergent stage of growth were observed. Even though plant populations suffered, NO₃–N and NH₄–N removals were detected. In 1999, inlet NO₃–N levels were reduced 60% from 0.6 mg/l at the inlet to 0.2 mg/l at the outlet. Ammonium-nitrogen levels decreased 20% in 1999, from 0.5 mg/l at the inlet to 0.4 mg/l at the outlet.

Total Kjeldahl nitrogen concentrations (ammonium +organic) between the inlets and the outlet were not significantly different on a yearly basis. Inlet concentrations were
1.3 mg/l in 1997, 2.0 in 1998, and 2.4 in 1999. Outlet concentrations were slightly lower at 1.2 mg/l, 1.9 mg/l, and 2.1 mg/l. Each year, TKN concentrations increased while NH₄–N stayed fairly constant. This increase was likely due to organic matter build up in the wetland.

Total phosphorus levels in 1998 and 1999 were 0.32 and 0.47 mg/l at the inlet and 0.56 and 0.64 mg/l at the outlet. Inlet concentrations of ortho-phosphorus were 0.24 mg/l and 0.34 mg/l respectively, with outlet concentrations of 0.41 mg/l and 0.45 mg/l.

Seasonal Concentration Analysis

The mean concentrations of NO₃–N and NH₄–N for various periods are presented in Figure 2. A small concentration reduction through the stream reach was found prior to wetland construction. During this time, baseflow was confined primarily to a small, 0.5m wide by 0.15m deep, incised stream within the 2m wide channel (Fig.1). Vegetation established on the remaining 1.5m, which we believe functioned as a small floodplain system for low flows. During the winter and spring, higher flows resulted in inundation of the entire channel bottom, but the stage was not high enough to induce a hydrologic connection between the stream and original floodplain. This limited opportunity for assimilation of nutrients during larger baseflow conditions and storm events.

The increased contact area and residence times after wetland construction enhanced the potential for nutrient removals. An immediate decline in NO₃–N concentrations through the wetland was seen in the initial growing season. Significant differences were detected during the first winter and stayed fairly constant over the rest of
the evaluation period. Ammonium-nitrogen levels did not show improvements as quickly and actually increased during the first winter. Concentration reduction began to show in the second growing season and remained constant in the following seasons.

![Mean NO₃ and NH₄ Concentrations over time](image)

**Figure 2.** Mean Concentrations of NO₃–N and NH₄–N at the wetland inlet and outlet for several seasons.

**Spatial Analysis**

Although the wetland was designed to maximize flow paths and mixing of input waters, preferential flow paths developed. Observations of plant populations and organic matter build-up supported this conclusion. In early spring of 1999, an unknown contaminant detected by smell and very low dissolved oxygen readings entered the wetland at E3 (urban inlet). Subsequent plant damage was concentrated on the south side
of the wetland. This led to the conclusion that waters from the urban inlet (E3) primarily flows towards the south side of the wetland. Waters from the agricultural/commercial inlet (E2) drift toward the north side of the wetland. Based on these observations, an analysis was done to determine if a concentration gradient existed based on the preferential flow path of each inlet (Fig. 3 and Fig. 4).

Although only NO$_3$–N concentrations tested significantly different, nutrient concentrations at the first sampling location (E9) were slightly lower than at the agricultural/commercial inlet (Fig. 3). A subsequent increase of all nutrient forms except nitrate nitrogen occurred at the next location (E8). This increase may be due to the input of a small storm drain, with a high proportion of impervious surface, entering the wetland upstream of this location (Fig. 1). Waste from wildlife may also contribute, as this was a popular lounging area for ducks. Nitrate-nitrogen levels did not increase at E8 leading to the conclusion that waste may be the primary cause of this spike. Due to the general trend of NH$_4$–N and TKN levels declining between other locations, the overall removal between E2 and E1 may be underestimated.
Figure 3. Mean nutrient concentrations on the north (agricultural) side of the wetland.

Figure 4. Mean nutrient concentrations on the south (urban) side of the wetland.
As with NH$_4$–N and TKN, an increase in phosphorus occurs at E8. Overall phosphorus results could be influenced by this increase. However, conversely to NH$_4$–N and TKN trends, phosphorus levels did not exhibit significant changes between other locations and actually increased between the last two sampling points and the outlet. This increase suggests that some phosphorus observed at the outlet originated within the wetland. The increase at E8 may have biased the magnitude of phosphorus observations, but it is clear that no overall reduction was achieved.

Mean concentrations at the urban inlet were higher than at the agricultural/commercial inlet (Table 3). NO$_3$-N, NH$_4$-N, and TKN levels at locations E7 and E5 were significantly different from E3. Nitrate-nitrogen concentrations dropped 50% and NH$_4$-N levels were lowered 70% between the inlet and the first within wetland sampling point. The sudden drop was likely due to mixing and dilution from E2 and wetland processes. Outlet levels of TP and OP were higher than at either of the two downstream sampling locations.
Table 3. Nutrient concentrations (mg/l) at wetland inlets and locations along preferential flow paths.

| Nutrient | Agricultural/Commercial Inlet | | | | | Urban Inlet | | Wetland Outlet | |
|----------|--------------------------------|---|---|---|---|---|---|---|---|---|---|---|
|          | E2 N=285 SD† | E9 N=35 SD† | E8 N=38 SD† | E6 N=34 SD† | E3 N=211 SD† | E7 N=36 SD† | E5 N=34 SD† | E1 N=284 SD† |
| NO₃-N    | 0.6 0.4 0.4* 0.2 0.3** 0.2 0.3** 0.3 | 0.8 0.8 0.4* 0.5 0.4** 0.5 0.2 0.3 | |
| NH₄-N    | 0.3 0.4 0.2 0.2 1.7* 2.0 0.5* 0.7 | 1.5 1.7 0.3* 0.4 0.4** 0.4 0.4 0.4 | |
| TKN      | 1.7 0.8 1.3 0.4 3.5* 2.9 2.2** 1.7 | 3.7 3.1 1.8* 1.3 1.9** 0.9 1.9 0.8 | |
| TP       | 0.32 0.19 0.29 0.14 0.69* 0.70 0.53** 0.38 | 0.59 0.46 0.44 0.27 0.50 0.28 0.57 0.34 | |
| OP       | 0.24 0.14 0.21 0.11 0.36* 0.26 0.35** 0.22 | 0.35 0.22 0.30 0.16 0.33 0.15 0.42 0.22 | |

* Indicates the mean is significantly different from the location preceding it. For example, NO₃-N is significantly different between E3 and E7, but OP is not. Concentrations at the outlet are not different from either location E5 or E6.

** Indicates the mean is different from the inlet mean.

† SD is the standard deviation.

Summary and Conclusions

Concentrations of all nitrogen forms were reduced significantly between the inlets and the wetland outlet over the evaluation period. The highest drop in concentrations was achieved for NO₃-N (60%) with lower declines for NH₄-N (33%) and TKN (9.5%) levels. Total nitrogen concentrations were 20% lower at the wetland outlet. These results show that wetlands with small wetland/watershed area rations can provide
significant water quality benefits for nitrogen. Actual concentration drops through the wetland may have been greater than presented due to possible unaccounted for input near sampling location E8.

Phosphorus levels increased 55% between the inlets and the outlet. Although the nutrient increase at E8 was a factor, phosphorus concentration reduction between the inlet and the outlet would not have been achieved. The liberation of phosphorus bound in the wetland substrate and organic matter apparently negated any sorption or uptake occurring within the wetland. At some point in the future, phosphorus equilibrium may be reached leading to no net increase at the outlet, but thus far no decline has been observed.

Although the first growing season was shortened due to the time of planting, concentrations of NO$_3$-N and NH$_4$-N levels dropped between the inlets and wetland outlet. Significant concentration reduction was detected during the first winter for NO$_3$-N and removal of other nitrogen forms began in the first full growing season. Although plant populations suffered in the wetland’s second year, organic matter build up was sufficient to support microbial growth and removal conversion processes. Data from interior wetland sampling locations showed that nutrient variations can occur over small distances.
References:


Chapter IV

Seasonal and Temporal Effects on Nutrient Removal in an In-Stream Constructed Wetland

K.L. Bass and R.O. Evans

Abstract

A free water surface constructed wetland was built to intercept drainage from approximately 240 hectares (600 ac) of agricultural and urban watershed. The two year evaluation of the wetland included investigating seasonal nutrient fluctuations and the impacts of temperature and dissolved oxygen on nutrient concentration changes. Mean nitrate nitrogen (NO$_3$-N) concentrations were 60% lower at the wetland outlet than at the inlet throughout the year. Ammonium nitrogen (NH$_4$-N) levels dropped 30% through the wetland during the growing season and 20% during dormant months. Mean total Kjeldahl nitrogen (TKN) concentrations at the outlet were 15% lower than at the inlet during the winter, but were unchanged during the growing season. Phosphorus concentrations at the wetland outlet were higher than inlet levels throughout the year, but the increase was greater during the growing season.

The difference in nutrient levels through the wetland was compared to the monthly average water temperature. Higher temperatures resulted in greater reduction of NO$_3$-N and NH$_4$-N concentrations through the wetland. Also as temperatures rose, TKN and phosphorus levels increased more between the wetland inlets and outlet.
Introduction

Wetland conditions promote physical, chemical, and biological processes that can lead to improved water quality. The use of wetlands to mitigate the impacts of non-point source (NPS) pollution has been used in N.C. coastal plain, piedmont, and mountain regions.

One advantage of constructed wetland designs is that they can be tailored to work in a variety of conditions. However, variables that can influence wetland functions, such as temperature, are difficult to control. Biological and chemical processes that affect wetland performance in terms of water quality are temperature dependent. Microbial driven nutrient removals are expected to be higher during the growing season, while low temperatures during the winter may inhibit reduction processes such as denitrification. The effect of temperature on plant processes is complicated. Research indicates that the effect of plants on wetland functions is related to season and growth (Stein et al., 1998). Removal through plant uptake is maximized during the growing season, however, mineralization associated with the decay of plant matter is also higher. Scheuler (1992) reported that wetland performance may decline during the winter months when algae and microbes are less active. Dahab and Vanier (1998) found that removal of contaminants such as total suspended solids (TSS), fecal coliforms, nitrogen, and phosphorus varied seasonally in a subsurface wetland. Total Kjeldahl nitrogen concentration reduction was lowered from 39.3% in the summer to 27.3% in the winter. Ammonia nitrogen removals lowered from 30.6% to 12.3% while the drop in NO$_3$-N levels decreased from 62.5% to 27.3%. Total phosphorus concentrations declined 26.6% in the summer and 15.9% in the
winter months. Temperature variations within the summer did not affect removals while variability in the winter did have an effect (Dahab and Vanier, 1998). Some wetlands have shown increases in concentrations due to the decay of organic matter during the winter. Brusch and Nilsson (1993) found denitrification capacity to be positively related to mean daily temperature. In their study of a constructed wetland, denitrification rates changed rapidly at air temperatures between 5°C and 10°C, but remained constant above or below those temperatures. Research done by Hill and Payton (1998) showed little effect of temperature on wetland contaminant removals. Of 27 cases, they found only 3 to exhibit significant changes due to temperature. Of those significant cases, higher temperatures were related to increases in concentrations of total and ortho-phosphorus. The increased decay of plant material associated with higher temperatures was cited as a probable factor. In other cases, winter build up of organic material and subsequent decay during the spring was thought to neutralize significant temperature effects. Hill and Payton (1998) hypothesized that plant harvesting may help alleviate this problem.

**Site Background**

A one ha (2.4 ac) wetland was constructed in April-May, 1997. The wetland intercepts waters from approximately 240 hectares (600 ac) of surrounding watershed. One hundred and sixty hectares are attributed to agricultural and natural forested area, sixty ha to urban area, and twenty ha to intensive commercial development. Pollution threats include agricultural sources such as fertilizers, urban sources such as roads and parking lots (oil and grease), lawns, leaking sewage pipes, improperly
functioning on-site septic systems, solid waste storage and processing sites, and commercial properties.

The wetland was built by lowering the floodplain area down to the original stream level and raising the channelized stream. The soils found in the floodplain and used for the wetland substrate were variable, with some reduced and high in organic matter and others clayey in content. A low head, wooden bulkhead was installed at the outlet to maintain water depths of 0.1m to 0.5m (6-18”). A more complete site description is given in Chapter I and pictures are presented in Appendix C. A schematic of the site is shown in Figure 1.

Figure 1. Edenton wetland schematic, including pre and post construction cross sections.
Flow Monitoring

Measurements at this site were made at the two inlet streams (Fig. 1) and at the wetland outlet using continuous water level recorders. Detailed descriptions of flow determinations were presented in Chapter II. A monthly water balance was computed using inflow, outflow, precipitation, and evapotranspiration. Flow data collection began in the fall of 1997 and continued through December of 1999.

Water Quality Monitoring

Water quality samples were taken over time and at various flow stages. Descriptions of the sampling schemes are given in Chapter III.

Measurements of dissolved oxygen, temperature, and conductivity were made at several locations within the wetland using a Hydrolab® multimeter. The device was calibrated regularly for dissolved oxygen using a 100% saturation reference. Before taking a measurement, the dissolved oxygen probe was checked for accuracy in air. The conductivity probe was calibrated using a 0.01M KCL solution. Measurement was initialized by submerging the probe to the center of the water column and held until levels stabilized. The resulting measurements were then logged to internal memory and brought back for analysis. The probes were rinsed between measurements and inspected regularly.

Continuous water temperature measurements were made at interior wetland locations and at the outlet using submersible loggers. Sinkers held the loggers in the
middle of the water column and they were programmed to record on an hourly basis. Temperature data began in Dec. 1998 and equipment failure in May of 1999 prevented further measurement. Records of all monitoring, downloads, and measurements were recorded in a project notebook. Hourly air temperatures were downloaded off the internet as measured at the USDA Tidewater Research Station in Plymouth, NC, located approximately 30km from the study site.

Data was analyzed using an analysis of variance. Least square means were tested for differences using a Tukey-Kramer adjustment (Tukey, 1953, Kramer, 1956). All analysis was computed using SAS® and are reported at the 0.05 significance level. A paired sample t-test (\( \alpha =0.05 \)) was also used to analyze water and air temperature data. Inlet concentrations were flow weighted and combined to create a single inlet concentration for comparison with outlet concentrations.

**Impact on Water Quality**

Overall wetland performance was presented in the Chapter III. The wetland reduced concentrations of NO\(_3\)-N by 60%, NH\(_4\)-N by 30%, and TKN by 9.5%, for a total nitrogen drop of 20%. Total phosphorus (TP) and ortho-phosphorus (OP) levels increased by 55%. Phosphorus increases were attributed to dissolution of iron-phosphate complexes and liberation of phosphorus bound in organic material.
Results and Discussion

Seasonal Fluctuations

Further testing was done to determine if concentrations were subject to seasonal fluctuations. The inlet and outlet concentrations for three growing seasons (March – September) and two dormant periods (October-February) were averaged and evaluated (Table 1 and Fig. 2).

Table 1. Nutrient concentrations (mg/l) for the growing season and winter months.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Inlet, Growing N=98</th>
<th>SD†</th>
<th>Outlet, Growing N=108</th>
<th>SD†</th>
<th>Inlet, Dormant N=80</th>
<th>SD†</th>
<th>Outlet, Dormant N=174</th>
<th>SD†</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₃-N</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2*</td>
<td>0.5</td>
<td>0.7</td>
<td>0.3</td>
<td>0.3*</td>
<td>0.2</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5*</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.4*</td>
<td>0.2</td>
</tr>
<tr>
<td>TKN</td>
<td>2.1</td>
<td>1.0</td>
<td>2.2</td>
<td>1.0</td>
<td>2.1</td>
<td>0.6</td>
<td>1.8**</td>
<td>0.5</td>
</tr>
<tr>
<td>TP</td>
<td>0.39</td>
<td>0.19</td>
<td>0.68**</td>
<td>0.32</td>
<td>0.33</td>
<td>0.17</td>
<td>0.50**</td>
<td>0.33</td>
</tr>
<tr>
<td>OP</td>
<td>0.29</td>
<td>0.13</td>
<td>0.52**</td>
<td>0.23</td>
<td>0.24</td>
<td>0.13</td>
<td>0.35**</td>
<td>0.19</td>
</tr>
</tbody>
</table>

* denotes a significant difference between inlet and outlet means within seasons. ** designates the concentration change between seasons was significantly different. For example, TP conc. Increased significantly more during the growing season than in dormant periods. †SD is the standard deviation.
Figure 2. Mean nutrient concentrations at wetland inlets and outlets for growing and dormant seasons.

NO$_3$-N levels during the growing season dropped 60% between the inlets and the outlet from 0.6 mg/l to 0.2 mg/l, respectively. The mean dormant season concentration at the outlet was also lower at 0.3 mg/l than the mean inlet level of 0.7 mg/l. Comparison of the reduction in NO$_3$-N concentrations through the wetland between seasons indicated no statistical difference.

Growing season outlet concentrations of NH$_4$-N were 30% lower at 0.5 mg/l than the mean inlet concentration of 0.7 mg/l. Dormant season levels declined significantly with a 20% drop from 0.5 mg/l at the inlet to 0.4 mg/l at the outlet. Although NH$_4$-N removal seems greater in the growing season, the differences between seasons were not statistically significant. Total Kjeldahl nitrogen (TKN) concentrations during dormant
periods were 2.1 mg/l at the inlet and 1.8 mg/l at the outlet for a 15% decrease. However, inlet and outlet growing season levels were unchanged at 2.1 mg/l and 2.2 mg/l, respectively.

Phosphorus concentrations increased significantly between the inlet and outlet throughout the year. Mean growing season concentrations of total phosphorus increased 70% with 0.39 mg/l at the inlet and 0.68 mg/l at the outlet. The 50% gain in TP concentrations through the wetland in the dormant season was significantly lower than in the growing season with inlet and outlet levels of 0.33 and 0.50 mg/l, respectively. Ortho-phosphorus means exhibited a similar trend. Outlet concentrations during the growing season were 80% higher than inlet levels with means of 0.29 mg/l and 0.52 mg/l, while winter levels increased 50% through the wetland from 0.24 mg/l to 0.35 mg/l.

Water Temperatures

Although variations exist between depth, shading, and vegetation density around the loggers, water temperatures were not found statistically different between locations. Hourly measurements made between December, 1998 and May, 1999 ranged from 3.2°C to 24.9°C. Less than 7% of the daily averages during this time were lower than 10°C and less than 1% were lower than 5°C.

Daily average air temperatures at the Tidewater research station ranged from –5.7 to 24.2 degrees. Corresponding average water temperatures at the wetland outlet were higher than air temperatures (Fig. 3). Water temperatures are also not changing as rapidly as the air temperatures.
A statistical t-test showed mean water temperature to be significantly different than the mean air temperature during this five month period. The mean water temperature was 14 degrees and mean air temperature was 10 degrees. Another t-test confirmed that air temperature changes were greater than wetland water temperature changes. Water temperatures above the 5-10 degree range in cooler months are conducive for microorganisms and processes such as denitrification.

Regression analysis found water and air temperature changes to be positively correlated (Fig. 4). The equation indicates that the daily mean water temperature will stay higher at low air temperatures and be cooler when air temperature exceeds 24 degrees Celsius.
Temperature Impact on Nutrient Concentrations

Daily average water temperatures did not significantly effect either nutrient concentrations at the wetland outlet or the change in concentrations through the wetland. However, a general trend was found between average monthly concentration changes through the wetland and outlet water temperature (Fig. 5).
The reduction of NO$_3$–N and NH$_4$–N concentrations through the wetland increased with higher temperatures. The percent removal of TKN, TP, and OP concentrations showed an inversely proportional relationship to temperature. As temperatures increased, levels of these nutrients increased more through the wetland. The upward trend of TKN (ammonium + organic nitrogen) concentrations with temperature compared to the declining trend of NH$_4$-N levels leads to the conclusion that the decay of organic material is the most likely cause of these increases.
Dissolved Oxygen

Dissolved oxygen concentrations were measured at the wetland interior sampling locations (E7,E8,E9,E5,E6) and are presented in Figure 6. Levels were highly variable over time, but seemed similar between locations. Mean values at each location were not significantly different. Also, no correlation was found between temperature observations and the corresponding dissolved oxygen concentration. Mean levels were high suggesting aerobic conditions may be present near the soil surface (Table 2). This is important for nitrification and for limiting losses of phosphorus attached to incoming sediment. However, high oxygen levels may enhance the decay and mineralization of organic matter.

![Dissolved Oxygen Levels](image)

**Figure 6.** Dissolved oxygen levels at interior wetland sampling locations
Table 2. Mean dissolved oxygen and temperature levels at various locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number Obs.</th>
<th>Dissolved Oxygen (mg/l)</th>
<th>Temperature (°C) spot measurement</th>
<th>Temperature (°C) logged average</th>
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</thead>
<tbody>
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<td>E5</td>
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<td>7.2</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>E6</td>
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<tr>
<td>E8</td>
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<td>6.8</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>E9</td>
<td>6</td>
<td>5.3</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

Summary and Conclusions

Nitrate and ammonium nitrogen concentrations dropped as much through the wetland during the dormant months as during the growing season. TKN concentrations were lowered only during the winter months. The increase in phosphorus concentrations between wetland inlets and the outlet observed was significantly larger during the summer months than in dormant periods.

More than 90% of the hourly water temperatures measured between December, 1998 and May, 1999 were above 10 degrees Celsius. Water temperatures were also higher than air temperatures and did not change as rapidly. Temperature buffering and values above the 5-10 degree range is conducive to nutrient removal processes such as denitrification.

General trends between average monthly temperature and nutrient changes were observed. As temperatures increased, nitrate nitrogen and ammonium nitrogen removals also increased. Conversely, larger increases in TKN and phosphorus concentrations were associated with higher temperatures.
References:


Appendix A

Statistical programs and example results
Statistical Models to Estimate Stages at the Urban Inlet and at the Outlet using data from the Agricultural/Commercial Inlet.

The resulting models were used to predict stages when data was inaccurate due to significant leaks, etc.

```plaintext
/* Model the Stage at the Urban Inlet and at the Outlet using data from E2*/

data E1all;
infile 'k:\res3\edenton\analysis\flow\E1all.prn' ;
input dtime datetime15.
E1read 19-23 @@;
date=datepart(dtime);
proc sort;
by dtime;

data E2all;
infile 'k:\res3\edenton\analysis\flow\E2all.prn' ;
input @3 dtime datetime15.
E2read 19-25;
date=datepart(dtime);
proc sort;
by dtime;

data E3all;
infile 'k:\res3\edenton\analysis\flow\E3all.prn' ;
input dtime datetime15.
E3read 16-22 @@;
date=datepart(dtime);
proc sort;
by dtime;

merge E1all E2all E3all;
by dtime;

/*Jan 99*/
if date>14290 then E2=E2read;
if date>14290 then E3=E3read;

title 'Modeling Outlet Stage from Ag./Comm. Inlet';
proc glm data=all ;
model E1read=E2read;
output out=E1read predicted=pE1;

proc gplot data=E1read;
plot E1read*dtime=1
pE1*dtime=2/overlay;
symbol1 v=none i=join c=black;
symbol2 v=none i=join c=red;

proc glm data=all ;
model E3=E2read;
output out=E3read predicted=pE3;
proc gplot;
plot E3*dtime=1
pE3*dtime=2/overlay;
symbol1 v=none i=join c=black;
symbol2 v=none i=join c=red;
run;
```
### Results of Outlet Stage Modeling

The SAS System 10:49 Monday, March 6, 2000

General Linear Models Procedure

Number of observations in data set = 37221

**NOTE:** Due to missing values, only 5799 observations can be used in this analysis.

The SAS System 10:49 Monday, March 6, 2000

General Linear Models Procedure

Dependent Variable: E1READ

<table>
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<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
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<td>0.00129810</td>
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<td>35.90462502</td>
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</table>

R-Square: 0.790415, C.V: 49.96209, Root MSE: 0.0360291, E1READ Mean: 0.07211295

<table>
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<tr>
<th>Source</th>
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<th>Mean Square</th>
<th>F Value</th>
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<td>1</td>
<td>28.37954725</td>
<td>28.37954725</td>
<td>21862.40</td>
<td>0.0001</td>
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<th>Pr &gt; F</th>
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<tr>
<td>E2READ</td>
<td>1</td>
<td>28.37954725</td>
<td>28.37954725</td>
<td>21862.40</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Std Error of T for H0:

| Parameter   | Estimate | Std Error of Estimate | T for H0: Parameter=0 | Pr > |T| |
|-------------|----------|-----------------------|-----------------------|-------|------|
| INTERCEPT   | 0.0197609540 | 33.44               | 0.0001      | 0.00059094 |
| E2READ      | 0.3653972725  | 147.86              | 0.0001      | 0.00247125 |
Figure A1. Measured stages at the wetland outlet over time and the predicted stage calculated using the level at the ag./commercial inlet.
Flowmeter Data Analysis
Statistics to Generate Stage Discharge Curve for the Agricultural/Commercial Inlet

/* Creation of Stage/Discharge Curve for Agriculture/Commercial Inlet (E2) Using flowmeter data*/
data flow;
infile 'k:\res3\edenton\flow\E2\E2flow99.in';
input DR VR AR FlwRtR FlowR TFlowR DMX VMX DM VM DAVE TempAVE VAVE AreaAV 109-112;
depth=DR/1000;
depth2=depth*depth;
flwavg=VAVE/1000*AreaAV;
title 'E2 Flow Modeling-Discharge vs. depth curve all data';
/*Create a model using all the data and determine the appropriate level*/
proc glm; model FlwRtR=depth;
proc glm; model FlwRtR=depth depth*depth;
proc glm; model FlwRtR=depth depth*depth depth*depth*depth;
proc glm noprint;
model FlwRtR=depth depth*depth;
output out=out1 predicted=p;
proc gplot data=out1;
plot depth*p=1 depth*FlwRtR=2/overlay;
title 'E2 Flow Modeling-Discharge vs. depth curve';
symbol1 v=none i=join c=black;
symbol2 v=diamond i=none c=green;
/* Try a model without low flow data*/
data gt875;
set flow;
flwavg=VAVE/1000*AreaAV;
if DR>875 then adepth=DR/1000;
if DR>875 then aflow=FlwRtR;
title 'E2 Flow Modeling-Discharge vs. depth curve-depth>875mm';
proc glm; model aflow=adepth adepth*adepth;
proc glm noprint;
model aflow=adepth adepth*adepth;
output out=out2 predicted=p2;
proc sort; by p2;
proc gplot data=out2;
plot depth*p2=1 adepth*aflow=2/overlay;
title 'E2 Flow Modeling-Discharge vs. depth curve-depth>875mm';
symbol1 v=none i=join c=black;
symbol2 v=diamond i=none c=green;

/* Generate a model without the low flow data or negative flow values */
data nonneg;
set flow;
flwavg=VAVE/1000*AreaAVE;
if FlwRtR>0 and DR>875 then
    adepth2=DR/1000;
if FlwRtR>0 and DR>875 then
    aflow2=FlwRtR;
if flwavg>0 and DAVE>875 then
    adepth5=DAVE/1000;
if flwavg>0 and DAVE>875 then
    aflow5=flwavg;

title 'E2 Flow Modelling - depth>875mm and no negative flows';
proc glm; model aflow2=adepth2 adepth2*aadepth2;
proc glm noprint;
    model aflow2=adepth2 adepth2*aadepth2;
    output out=out3 predicted=p3;
proc sort; by p3;
proc gplot data=out3;
plot adepth2*p3=1 adepth2*aflow2=2/overlay;
title 'E2 Flow Modelling - depth>875mm and no negative flows';
symbol1 v=none i=join c=black;
symbol2 v=diamond i=none c=green;
run;
### Results

**E2 Flow Modelling-depth>875mm and no negative flows**

23:00 Sunday, March 5, 2000

**General Linear Models Procedure**

Number of observations in data set = 3931

**NOTE:** Due to missing values, only 1207 observations can be used in this analysis.

**E2 Flow Modelling-depth>875mm and no negative flows**

23:00 Sunday, March 5, 2000

**General Linear Models Procedure**

**Dependent Variable: AFLOW2**

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<th>F Value</th>
<th>Pr &gt; F</th>
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<td>5.81782511</td>
<td>2434.78</td>
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<td>Error</td>
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<td>2.87691730</td>
<td>0.00238947</td>
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<td></td>
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<tr>
<td>Corrected Total</td>
<td>1206</td>
<td>14.51256752</td>
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<td></td>
</tr>
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</table>

R-Square: 0.801764  C.V.: 25.07790  Root MSE: 0.04888217  AFLOW2 Mean: 0.19492129

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<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
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<tbody>
<tr>
<td>ADEPTH2</td>
<td>1</td>
<td>10.42023966</td>
<td>10.42023966</td>
<td>4360.91</td>
<td>0.0001</td>
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<tr>
<td>ADEPTH2*ADEPTH2</td>
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<td>1.21541056</td>
<td>1.21541056</td>
<td>508.65</td>
<td>0.0001</td>
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<th>Pr &gt; F</th>
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<tbody>
<tr>
<td>ADEPTH2</td>
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<td>0.92892050</td>
<td>0.92892050</td>
<td>388.76</td>
<td>0.0001</td>
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<tr>
<td>ADEPTH2*ADEPTH2</td>
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<td>1.21541056</td>
<td>1.21541056</td>
<td>508.65</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

**Std Error of T for H0:**

| Parameter               | Estimate | Estimate Parameter=0 | Pr > |T| |
|-------------------------|----------|----------------------|-------|
| INTERCEPT               | 3.598578405 | 17.73 | 0.0001 | 0.20297268 ADEPTH2 |
| -7.950765937            | -19.72   | 0.0001 | 0.40324607 ADEPTH2*ADEPTH2 |
| 4.495842895             | 22.55    | 0.0001 | 0.19934258 |
Concentration Analysis

Statistical Analysis Program

/* Read the Input File*/
data normal;
infile 'k:edenton4.prn' missover pad;
input loc$ @14 date DATE9. q 25-35 NO3 41-45
NH4 49-53 TKN 56-61 TP 62-69
OP 70-77 Sed 79-85
pH 87-93 @95 month MONYY6.
year 104-109 season period
rseas$;
format date DATE9.;
format month MONYY6.;

/* Set NO3 and NH4 levels to a minimum of 0.05 mg/l/*/ if NO3=0 then NO3=0.05;
if NH4=0 then NH4=0.05;
if TKN=0 then TKN=.05;

/* Check to see if the data is normal */
proc univariate normal plot
noprint;
var NO3 NH4 TKN TP OP
logNO3 logNH4 logTKN logTP
logOP;
by loc;

/* Comparing Inlet and Outlet Concentrations*/
data sub; set normal;
if loc in('IN','E1');
proc glm;
class loc period;
model NO3 = period loc
period*loc/solution;
lsmeans period*loc/ pdiff
adjust=tukey;
run;
proc glm;
class loc period;
model TKN = period loc
period*loc/solution;
lsmeans period*loc/ pdiff
adjust=tukey;
run;
proc glm;
class loc period;
model TP = period loc
period*loc/solution;
lsmeans period*loc/ pdiff
adjust=tukey;
run;
proc glm;
class loc period;
model OP = period loc
period*loc/solution;
lsmeans period*loc/ pdiff
adjust=tukey;
run;
title 'Modelling the effects of Period and Location and their interaction';

/* Testing for Seasonal Effects*/
data sub2; set sub;
if period in(2);
proc glm;
class loc season;
model NO3 = season loc
season*loc/solution;
lsmeans season*loc/pdiff
adjust=tukey;
run;
proc glm;
class loc season;
model NH4 = season loc
season*loc/solution;
lsmeans season*loc/pdiff
adjust=tukey;
run;
proc glm;
class loc season;
model TKN = season loc
season*loc/solution;
lsmeans season*loc/pdiff
adjust=tukey;
run;
proc glm;
class loc season;
model TKN = season loc
  season*loc/solution;
  lsmeans season*loc/pdiff
  adjust=tukey;
proc glm;
  class loc season;
model TP  = season loc
  season*loc/solution;
  lsmeans season*loc/pdiff
  adjust=tukey;
proc glm;
  class loc season;
model OP  = season loc
  season*loc/solution;
  lsmeans season*loc/pdiff
  adjust=tukey;
proc glm;
  class loc season;

/* Analysis of Interior Wetland Locations*/
data inner; set normal;
if loc in('E10', 'E11', 'E0', 'E4', 'E31', 'E3fs') then delete;
if period in(2);
proc sort; by loc;
proc glm;
  class loc;
model no3=loc;
  lsmeans loc/pdiff
  adjust=tukey;
  means loc/tukey;
proc glm;
  class loc;
model nh4=loc;
  lsmeans loc/pdiff
  adjust=tukey;
  means loc/tukey;
proc glm;
  class loc;
model tkn=loc;
  lsmeans loc/pdiff
  adjust=tukey;
  means loc/tukey;
proc glm;
  class loc;
model tp=loc;
  lsmeans loc/pdiff
  adjust=tukey;
  means loc/tukey;
proc glm;
  class loc;
model op=loc;
  lsmeans loc/pdiff
  adjust=tukey;
  means loc/tukey;
/* Yearly Analysis */
data year; set sub;
if period in(2);
proc sort; by loc year;
proc glm;
  class year loc;
model NO3=year loc year*loc;
  lsmeans year*loc/pdiff
  adjust=tukey;
  proc glm;
  class year loc;
model NH4=year loc year*loc;
  lsmeans year*loc/pdiff
  adjust=tukey;
  proc glm;
  class year loc;
model TKN=year loc year*loc;
  lsmeans year*loc/pdiff
  adjust=tukey;
  proc glm;
  class year loc;
model TP=year loc year*loc;
  lsmeans year*loc/pdiff
  adjust=tukey;
  proc glm;
  class year loc;
model OP=year loc year*loc;
  lsmeans year*loc/pdiff
  adjust=tukey;
run;
proc glm;
  class year loc;
model OP=year loc year*loc;
  lsmeans year*loc/pdiff
  adjust=tukey;
  proc glm;
/* Separated into Each Season*/
data rseas; set normal;
if loc in('E1', 'IN');
proc sort;
  by rseas loc;
proc glm;
class loc;
model NO3=loc;
by rseas;
lsmeans loc/pdiff adjust=tukey;
proc glm;
class rseas loc;
model NH4=loc;
by rseas;
lsmeans loc/pdiff adjust=tukey;
proc glm;
class rseas loc;
model TKN=rseas loc rseas*loc;
lsmeans rseas*loc/pdiff adjust=tukey;
proc glm;
class rseas loc;
model TP=rseas loc rseas*loc;
lsmeans rseas*loc/pdiff adjust=tukey;
proc glm;
class rseas loc;
model OP=rseas loc rseas*loc;
lsmeans rseas*loc/pdiff adjust=tukey;

/* Temperature Analysis*/
data temp;
infile 'k:TEMP.prn' ;
input loc$ @11 date DATE9. tempC tempF 32-35;
proc sort; by loc date;
data inner2;set inner;
proc sort; by loc date;
data temp2;
merge inner2 temp;
by loc date;
if loc in('E1');
proc sort; by loc tempC;
proc glm;
model NO3=tempC/solution;
proc glm;
model NH4=tempC/solution;
proc glm;
model TKN=tempC/solution;
proc glm;
model TP=tempC/solution;
proc glm;
model OP=tempC/solution;
run;
Example Output

Modelling the effects of Period and Location and their interaction
1
10:16 Friday, March 3, 2000

General Linear Models Procedure
Class Level Information

<table>
<thead>
<tr>
<th>Class</th>
<th>Levels</th>
<th>Values</th>
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<td>LOC</td>
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<td>E1 IN</td>
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<tr>
<td>SEASON</td>
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Number of observations in data set = 460

Modelling the effects of Period and Location and their interaction
2
10:16 Friday, March 3, 2000

General Linear Models Procedure

Dependent Variable: NO3

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<tr>
<td>Model</td>
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<td>18.41919917</td>
<td>6.13973306</td>
<td>50.14</td>
<td>0.0001</td>
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<td>55.83764322</td>
<td>0.12245097</td>
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<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>459</td>
<td>74.25684239</td>
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</table>

R-Square  C.V.    Root MSE    NO3 Mean
0.248047  91.17405  0.34992995 0.38380435

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<tr>
<td>SEASON</td>
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<td>0.01237226</td>
<td>0.01237226</td>
<td>0.10</td>
<td>0.7507</td>
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<td>18.39525367</td>
<td>18.39525367</td>
<td>150.23</td>
<td>0.0001</td>
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<tr>
<td>LOC*SEASON</td>
<td>1</td>
<td>0.01157324</td>
<td>0.01157324</td>
<td>0.09</td>
<td>0.7587</td>
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<th>F Value</th>
<th>Pr &gt; F</th>
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<td>SEASON</td>
<td>1</td>
<td>0.26745135</td>
<td>0.26745135</td>
<td>2.18</td>
<td>0.1401</td>
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<tr>
<td>LOC</td>
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<td>18.40555462</td>
<td>150.31</td>
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<tr>
<td>LOC*SEASON</td>
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<td>0.01157324</td>
<td>0.01157324</td>
<td>0.09</td>
<td>0.7587</td>
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Modelling the effects of Period and Location and their interaction

10:16 Friday, March 3, 2000

General Linear Models Procedure
Least Squares Means
Adjustment for multiple comparisons: Tukey-Kramer

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<tr>
<th>LOC</th>
<th>SEASON</th>
<th>NO3</th>
<th>Pr &gt;</th>
<th>Pr &gt;</th>
<th>HO: LSMEAN(i)=LSMEAN(j)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>i/j</td>
</tr>
<tr>
<td>E1</td>
<td>1</td>
<td>0.19045455</td>
<td>1</td>
<td>0.4850</td>
<td>0.0001 0.0001</td>
</tr>
<tr>
<td>E1</td>
<td>2</td>
<td>0.25114943</td>
<td>2</td>
<td>0.4850</td>
<td>0.0001 0.0001</td>
</tr>
<tr>
<td>IN</td>
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<td>0.61770833</td>
<td>3</td>
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<td>0.0001 0.8762</td>
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<td>0.65750000</td>
<td>4</td>
<td>0.0001</td>
<td>0.0001 0.8762</td>
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</table>
Appendix B

Plots of stage, nutrient, and temperature data.
Figure B1. 1997 stages at the two main inlets and at the wetland outlet.
Figure B2. 1998 stages at the wetland inlets and outlet.
Figure B3. 1999 stages at the wetland inlets and outlet.
Figure B4. Monthly precipitation measured at the site and at the Edenton weather station.
Figure B5. Nitrate-nitrogen concentrations over time.
Figure B6. Total Kjeldahl Nitrogen concentrations over time.
NH4-N Concentrations over time

Figure B7. Ammonium-nitrogen concentrations over time.
Figure B8. Total Phosphorus concentrations over time.
Ortho-Phosphorus Concentrations over time

Figure B9. Ortho-phosphorus concentrations over time.
Figure B10. Water temperatures at the wetland outlet from Dec. 1998 to May of 1999.
Figure B11. NO₃-N and NH₄-N concentrations and the corresponding average water temperature of the day the sample was taken.
Figure B12. Total Kjeldahl nitrogen concentrations over time and with the average water temperature on the day the sample was taken.
Figure B13. Total and ortho-phosphorus concentrations at the wetland outlet and the average water temperature of the day the sample was taken.
Appendix C

Pictures
Pre Construction

Figure C1. Pre-construction view of the site from the south side. The hospital is in the background.

Figure C2. View from upstream of the site after initial clearing.
Construction

Figure C3. Site excavation.

Figure C4. Further excavation. Island in the foreground with cover.
Figure C5. View of the main bulkhead and island from the wetland outlet.

Figure C6. Planting bur reed. 3’ x 3’ spacing.
Figure C7. View from the outlet in the 1st full growing season.

Figure C8. Cattails (*typha latifolia*)
Figure C9. Lilies (*nuphar variegatum*)

Figure C10. Bur reed (*sparganium americanum*)
Figure C11. Pickerelweed (*pontedaria cordata*)

Equipment

Figure C12. Water level recorder at the wetland outlet
Figure C13. Automatic sampler at the outlet

Figure C14. Weir at the urban inlet (E3).
Figure C15. On-site rain gage.

Figure C16. Ducks love this place! Muskrat on the right.
Figure C17. from left: Jonathan Smith, Kris Bass, Kevin Tweedy, Robert Evans