CITY of CHARLOTTE
Pilot BMP Monitoring Program

Edwards Branch Wetland
Final Monitoring Report

January 2007

Prepared By:
Jon Hathaway, EI; *William F. Hunt* PE, PhD; *and Amy Johnson, PhD*
Department of Biological and Agricultural Engineering
NC STATE UNIVERSITY

Submitted To:
City of Charlotte-Storm Water Services

Purpose

The purpose of this report is to document monitoring and data analysis activities undertaken by the City of Charlotte, NC and NC State University to determine the effectiveness and stormwater treatment capabilities of the Edwards Branch Stormwater Constructed Wetland.

Introduction

Stormwater wetlands are designed for several reasons: improving water quality, improving flood control, enhancing wildlife habitat, and providing education and recreation. Wetlands in general, and stormwater wetlands in particular, use several mechanisms to remove pollutants. Stormwater wetlands employ perhaps more ways to remove sediment, nutrients, metals and chemicals, and even bacteria than any other structural BMP. These mechanisms include sedimentation, filtration, adsorption, microbial activity (nitrification and denitrification), and plant uptake. Where stormwater regulations are implemented, wetlands are often used to remediate the impact of newly constructed imperious area. In North Carolina, properly designed wetlands are an accepted BMP for the removal of total suspended solids (TSS), total nitrogen (TN), and total phosphorous (TP). NCDENR gives wetlands credit for 85% TSS removal, 40% TN removal, and 35% TP removal (NCDENR, 2006).

SITE DESCRIPTION

The Edward’s Branch wetland is an off-line stormwater system located in the Edward’s Branch watershed. The wetland was constructed in 2001 by Mecklenburg County in conjunction with a natural channel stream restoration of Edward’s Branch conducted by the City of Charlotte. An elevated walkway over the wetland provides citizen access to the nearby Sheffield Park. Located between the restored stream reach and the park, the wetland is approximately ½ acre in size with an average depth of approximately 1.5 ft (18 in.). Although the topography of Edward’s Branch wetland is typical of other stormwater wetlands, the vegetative coverage is typical of an innovative wet pond. The watershed, consisting of primarily single family residences on ¼ to ½ acre lots, is separated from the wetland by Edward's Branch. An innovative piping system was constructed to route water from the watershed to the wetland. Sizing and features of the wetland were selected to comply with state guidelines for constructed wetland design (NCDENR, 1996).

Stormwater runoff from the watershed is conveyed to the wetland through an inverted 8-in. ductile iron pipe running under Edward's Branch. Flows exceeding the capacity of the 8-in. pipe section discharge directly into Edward's Branch. Because the system is off-line, only a portion of stormwater runoff originating within the watershed is routed through the wetland system. Additionally, the hydraulics of the inlet system insures that the capacity of the wetland is not exceeded.

The wetland outlet is a 10-ft by 10-ft cast-in-place concrete riser with a 24-inch diameter RCP barrel discharging to Winterfield Tributary, which drains into Edward's Branch. A 12-in. diameter orifice cut in the face of the riser provides the outlet for the wetland. A ¼-in aluminum plate with a 2-in. diameter torch cut orifice is bolted to the face of the riser, controlling the outflow rate. Placement and sizing of the orifice plate determined the storage depth and drawdown rate of the water quality volume of the wetland. Adjustment of the drawdown orifice elevation required complete replacement of the orifice plate. Adjustments were only possible within the larger 12-in. orifice.

Due to the unique inlet configuration, monitoring of flow at the inlet proved to be very difficult. An ISCO low profile area-velocity probe was installed in the 8-in. pipe conveying water from the drainage network to the wetland inlet. During normal pool conditions, water within the wetland cell backed into the inlet pipe. During storm events the water level over the probe rose and then lowered slowly during the subsequent drawdown period. As a result of this condition, the area-velocity probe was submerged in slowly moving or static water during much of its operational time. Such conditions are less than ideal for these measurement devices.

The existing ¼-in. aluminum orifice plate on the wetland outlet was determined insufficient for monitoring due to the ragged edge of the orifice opening. In addition, it was determined that the drawdown time for the wetland exceeded 48 hours, which potentially had a negative effect on wetland plants. Water depth within the wetland exceeded what was typically accepted as ideal for plant establishment. As a result of these observations, a new orifice plate was installed with two 1.75-in. circular orifices. The orifice plate was precision-made to ensure accurate application of a stage discharge curve developed using standard orifice equations. An ISCO 730 bubbler flow module was utilized with an ISCO Avalanche sampler to collect flow-weighted outflow samples. The bubbler was welded to the orifice plate to ensure its stability. A debris screen was installed around the orifice outlet to keep dead vegetation and trash away from the orifice and to protect the sampler intake and bubbler (Figure 1).

Figure 1: Edward's Branch Outlet Structure with Debris Screen

MONITORING PLAN

Monitoring efforts were initiated in October 2003 and continued until June 2005, with twenty-three storm events being partially collected / measured. However, due to frequent failure of the inflow measurement system and other collection failures, only 16 of these storms provided sufficient inflow and outflow volumes for sample analysis of most pollutants. Additional manual grab samples, from which levels of fecal coliform, E. coli, and oil & grease were measured, were collected for nine of the 23 storm events.

Average inflow and outflow event mean concentration (EMC) values for each pollutant were used to calculate a BMP efficiency ratio (ER):

$$ER = (EMC_{inflow} - EMC_{outflow}) / EMC_{inflow}$$

where EMC_{inflow} and $EMC_{outflow}$ represent the mean BMP inflow and outflow EMCs across all storm events. Removal rates were also calculated on a storm-by-storm basis. Some authors have suggested that reporting BMP effectiveness in terms of percent removal may not give a completely accurate picture of BMP performance in some situations (Urbonas, 2000; Winer, 2000; Strecker et al., 2001; US EPA, 2002). For example, if the influent concentration of a pollutant is extremely low, removal efficiencies will tend to be low due to the existence of an “irreducible concentration”, lower than which no BMP can achieve (Schueler, 1996). For these relatively “clean” storms, low removal efficiencies may lead to the erroneous conclusion that the BMP is performing poorly, when in fact pollutant targets may be achieved. Caution should be used when interpreting BMP efficiency results that rely on a measure of percent or proportion of a pollutant removed. Therefore, we reported not only removal efficiencies, but also effluent “quality” for major pollutants, i.e. the concentration of pollutants in BMP outflow.

DATA ANALYSIS RESULTS

It should be reiterated that the inlet configuration of the wetland prevented accurate measurements of inflow. An example of the flow measurements that were collected can be seen in Figure 2. This hydrograph was produced on March 23, 2005, by a 0.8 – inch storm event. The dramatic fluctuations in inflow are due to the submerged conditions experienced at the inlet.

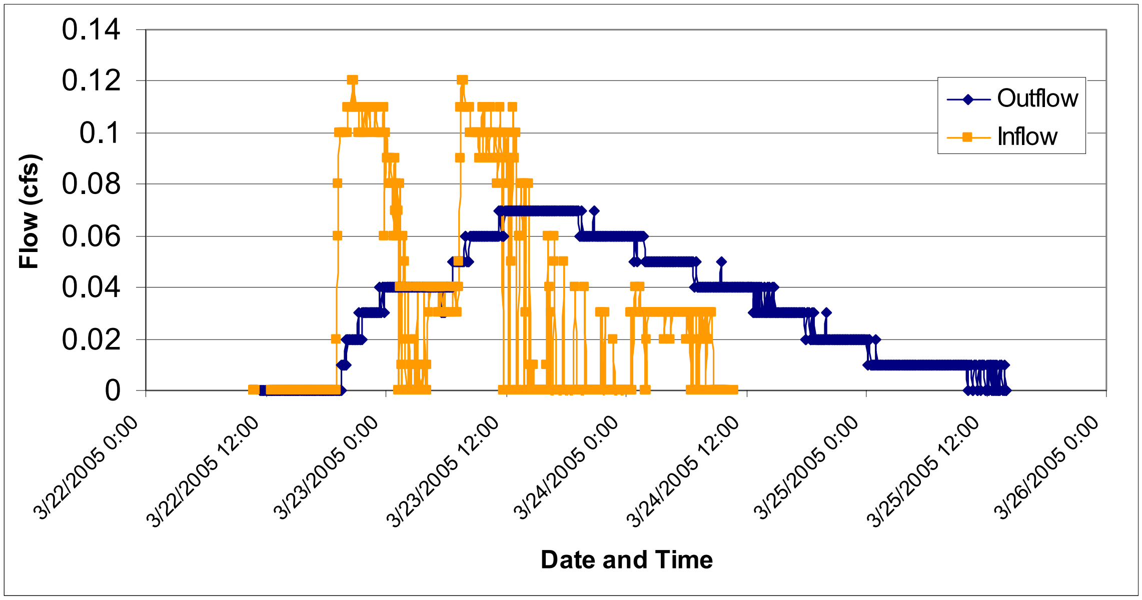

Figure 2: Example hydrograph from 0.8-inch storm on 3/23/2005

Due to the design of the wetland, however, the wetland did not have a significant amount of storage. Due to this lack of storage, it is assumed that is most cases the inflow to the wetland was equal to the outflow. Thus, estimates of concentration reductions (efficiency ratios) are assumed to be reasonable estimates of wetland function. Mass reduction calculations are not necessary if the wetland inflow is reasonably equal to the outflow.

Figure 3 and Table 1 illustrate the performance of the Edward's Branch constructed wetland on major pollutants, in terms of the efficiency with which the wetland removed a particular pollutant. A positive efficiency ratio (ER) indicates that the pollutant, which entered the wetland as stormwater runoff, was retained by the wetland. A negative ER represents a surplus of pollutant leaving the BMP, suggesting either internal production of nutrients within the wetland, or loss of stored pollutant from previous storm events. By this measure, the Edward's Branch wetland was successful in removing most pollutants, with the exception of oil & grease, iron, and manganese. Only the surplus in iron was statistically significant. In addition, turbidity increased from the wetland inflow to outflow, although not significantly.

According to statistical tests, the Edward's Branch wetland significantly ($p<0.05$) reduced the following pollutants in stormwater runoff: fecal coliform, *E. coli*, BOD_5, COD, NH_4-N, NO_x-N, TKN, TN, TP, copper, zinc and lead (Fig.2, Table A1, Table A2). With the exception of NH_4-N and NO_x-N, all of these pollutants tend to be associated with particulate matter, suggesting that settling/sedimentation is a dominant mechanism of pollutant removal in the Edward's Branch wetland. This makes sense as vegetative uptake from this wetland is likely limited due to the small amount of vegetative cover. When detention time is adequate (≥2 days), BMPs that slow water flow and promote settling, such as wetlands, can be effective at removing these types of pollutants (ITRC, 2003). Additionally, the wetland's shallow depth and long flow path likely contributed to the significant reduction observed for many of the pollutants.

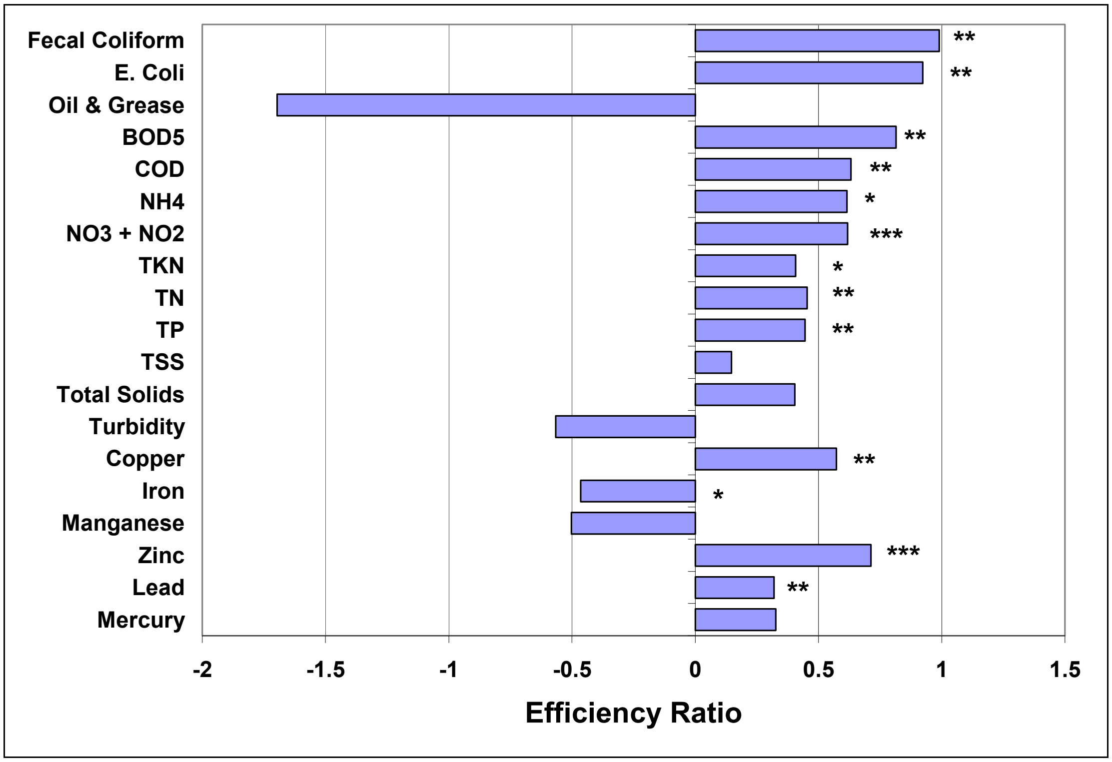

Figure 3: Efficiency ratios of selected pollutants based on pre- and post-BMP mean concentrations (EMCs) at Edward's Branch wetland.

Efficiency ratio (ER) = (EMC_{inflow} - $EMC_{outflow}$) / EMC_{inflow}.

Table 1: Summary of Water Quality Results

Parameter	Units	# of Samples	Influent EMC	Effluent EMC	ER	p-value	Significant ($p < 0.05$)
Fecal	col. / 100 ml	9	21033.3	213.3	99%	0.004	**yes**
E-Coli	MPN/100ml	6	2400.0	183.3	92%	0.031	**yes**
Oil & Grease	ppm	7	8.2	21.8	-168%	0.313	no
BOD	ppm	16	28.7	5.3	82%	0.001	**yes**
COD	ppm	16	67.4	24.8	63%	0.004	**yes**
NH_4	ppm	16	0.4	0.1	62%	0.020	**yes**
NOx	ppm	16	0.5	0.2	62%	0.003	**yes**
TKN	ppm	16	1.6	0.9	41%	0.021	**yes**
TN	ppm	16	2.0	1.1	45%	0.002	**yes**
TP	ppm	16	0.2	0.1	45%	0.002	**yes**
TSS	ppm	16	29.4	25.1	15%	0.193	no
Total Solids	ppm	16	214.3	127.8	40%	0.193	no
Turbidity	NTU	15	28.7	45.0	-57%	0.115	no
Copper	ppb	16	13.6	5.8	57%	0.001	**yes**
Iron	ppb	16	1419.3	2078.8	-46%	0.018	**yes**
Manganese	ppb	16	128.6	193.3	-50%	0.151	no
Zinc	ppb	16	92.8	26.7	71%	0.001	**yes**
Lead	ppb	16	7.6	5.2	32%	0.001	**yes**

Total Suspended Solids

Despite the high removal efficiencies for many particulate-associated pollutants, TSS removal for this study (~15%) was much lower than TSS removal efficiencies typically found for stormwater wetlands (Table 2). Turbidity, which is often purported to correlate reasonably well with TSS, showed a negative removal efficiency (-57%), although this reduction was not significant. The reason for this discrepancy is not clear. However, Burton and Pitt (2002) suggest that turbidity is generally associated with smaller particles than TSS, (1 μm vs. 10-100 μm, respectively). If this is the case, the above result indicates that there was sufficient time for larger particles to settle out of suspension but finer particles were not being retained in the wetland. The implications of this result for the Edward's Branch wetland, in terms of pollutant removal, do not seem to be severe as most particulate-associated pollutants had high removal efficiencies (Fig. 2), despite the fact that large amounts of sediment-bound pollutants have been shown to be associated with finer particle sizes (Vaze and Chiew, 2004; Hipsey, et al., 2006).

Table 2: Comparison of mean removal efficiencies for stormwater wetlands.

Parameter	Edward's Branch	US. EPA, 1999	Kadlec and Knight, 1996	Madge, 2004	Winer, 2000†	Urbonas, 2000	Van Buren et al., 1997
	%						
BOD_5	82	--	--	--	--	18	--
COD	63	--	--	--	--	--	38
NH_4	62	33	-44 – 79	--	--	--	23
NO_x	62	46	--	40	67†	--	44
TKN	41	7	--	--	--	--	33
Total N (TN)	45	24	24	19	30†	21	--
Total P (TP)	45	46	--	56	49†	-4 – 90	21
TSS	15	76	83 – 96	71	76†	40 – 94	42
Copper	57	39	--	--	40†	--	34
Zinc	71	54	--	--	44†	-29 – 82	45
Lead	32	63	54 – 96	--	--	27 – 74	28

†Median removals reported.

The reason for the low TSS removal rates compared to other monitoring studies may be related to the poor establishment and maintenance of wetland vegetation found at the Edward's Branch stormwater wetland. Wetland vegetation helps slow influent water and induce particulate settling, but difficulties pertaining to plant growth and maintenance are common obstacles reported for stormwater wetlands (US EPA, 1999; Muthukrishnan et al., 2004). The reason for the poor vegetative population throughout the study period at Edward's Branch was likely due to poor growing medium for the vegetation. The soils were highly acidic (pH < 5) and were exclusively mineral (no organics). This provided a poor environment for plant growth. In addition, the elevation of the orifice plate was approximately 6 in. higher than what would be optimum for wetland plant growth. Incorporating an adjustable outlet orifice into the wetland design would potentially improve the growth of wetland vegetation and, presumably, TSS removal rates.

Despite the lack of vegetative growth, the removal efficiency for TSS was much greater (58%) throughout much of the second year of the study (Fig. A1). Removal of many of the other pollutants that were monitored stabilized during the second year of the study as well; this may indicate a climatic reason for the greater removal efficiency during this period, such as less intense or less frequent storm events.

Nutrients and Organic Material

The removal rates for major nutrient pollutants and oxygen demanding material (organic carbon) were equal to or greater than that found by others (Table 2). Besides particulate settling, other processes are known to contribute to the high removal of these pollutants in wetland systems.

Oxygen Demand:

Biological oxygen demand (BOD_5) and COD are typical measurements of the amount of organic matter in stormwater runoff. Any wetland process that contributes to the decomposition of organic matter will cause a reduction of BOD_5 and COD. Physically, this can occur by adsorption onto particles and subsequent filtration and sedimentation. Microbial decomposition of organic material can also significantly reduce levels of BOD_5 and COD through respiration and the reduction of elements such as nitrate and iron. Removal efficiencies in the Edward's Branch wetland were high for both measurements (>80% and 60% for BOD_5 and COD, respectively). Knight et al., (1993) reported typical BOD_5 removal efficiencies near 70% and average outflow BOD_5 concentration from wetlands of 10.5 ppm with values ranging from 1 to 50 ppm. The Edward's Branch wetland had a higher removal efficiency for BOD_5 (Table 2) and a much lower mean effluent BOD_5 concentration (Table 3).

Table 3: Comparison of median effluent concentrations for stormwater wetlands.

Parameter	Edward's Branch	Madge, 2004	Winer, 2000	Schueler, 1996	Van Buren et al, 1997	GeoSyntec, 2006
	ppm					
BOD_5	4.10 (5.30)†	--	--	--	--	--
COD	20.70 (24.79)†	--	--	--	(15)†	--
NH_4	0.10 (0.14)†	--	--	--	(0.26)†	--
$NO_3 + NO_2$	0.14 (0.17)†	0.22	0.36	(0.35)†	(0.71)†	0.05
Total Kjeldahl N (TKN)	0.90 (0.94)†	--	--	(1.29)†	(0.74)†	1.09
Total N (TN)	1.05 (1.11)†	2.0	1.7	(1.63)†	--	1.22
Total P (TP)	0.09 (0.12)†	0.13	0.20	(0.19)†	(0.084)†	0.06
Suspended Residue (TSS)	21.50 (25.06)†	22	22	(32)†	(73)†	7.55
Copper	5.0 (6.0)†	3.9	7.0	--	(11)†	3
Zinc	21.0 (27.0)†	47	31.0	--	(42)†	18
Lead	5.0 (5.0)†	1.6	--	--	(11)†	1

†Values in parentheses are based on the mean effluent concentration.

Nitrogen:

Soluble pollutants are removed from treatment wetlands by chemical adsorption to suspended particles followed by sedimentation of those particles, and by plant uptake and microbial transformations. The major removal mechanism of the various forms of nitrogen present in a wetland is bacterial transformation. All nitrogen species can be incorporated into the wetland's biomass, where they are stored, through various biochemical reactions, such as mineralization by microbes in the case of organic N, as well as uptake of NH_4 and NO_3 by plants and microbes. During anoxic periods or in anoxic microsites within the wetland, nitrate (NO_3) can be reduced to gaseous nitrogen (denitrification) and removed from the system by the action of denitrifying microbes. Removal rates of inorganic nitrogen species (NH_4 and NO_3) were above 60%, within the range typical of stormwater wetlands (Table 2). Total Kjeldahl nitrogen (TKN) and total nitrogen (TN) had removal efficiencies above 40%, a level of removal greater than that reported by others (Table 2). Additionally, both mean and median concentrations of all nitrogen species in wetland effluent were 66 times less than that required by law (10 ppm NO_3).

Phosphorus:

Removal of total phosphorus (TP) from the Edward's Branch wetland (~45%) was within the range typical for stormwater wetlands (Table 2). The reduction of TP that occurs within the wetland is not entirely biologically-mediated, like nitrogen, and is mostly due to abiotic factors. Adsorption onto iron-oxide and aluminum-oxide surfaces and complexation with organic acids accounts for a large portion of phosphorus removal from the water column. Through sedimentation of these particles, phosphorus can accumulate in wetland sediments. This phosphorus is not technically removed from the system, but rather is stored at the bottom of the wetland. Potential release of this stored phosphorus can occur under specific conditions (see section on metals). Several other minor removal mechanisms exist for TP as well. When phosphorus is present in dissolved forms, it can be taken up by algae and plants. In addition, organic forms of P can be decomposed and used by microbial biomass, although phosphorus assimilation does not occur to the same degree as nitrogen assimilation. Less important are precipitation reactions with metals that may take dissolved P out of solution.

Pathogens and Hydrocarbons

The Edward's Branch wetland was very successful in removing *E. coli* and fecal coliform, achieving removal rates of greater than 90% for *E.coli* and 99% for fecal coliform entering the wetland. Few other wetland studies have reported removal rates for pathogens. In the NURP database, only a general "bacteria" category, which included fecal coliform and *E. coli* among other pathogens, was reported as having a 78% median removal (Winer, 2000). Where fecal coliform or *E. coli* were specifically measured, reports of >90% removal are seen for coliforms with vegetated wetland systems (Kadlec and Knight, 1996). Although bacteria can sorb to suspended particles and be removed through physical settling/sedimentation, other mechanisms of removal , such as photodegredation (UV radiation) and microbial attack may be equally, or more, important in treatment wetlands (Muthukrishnan et al., 2004).

The extremely low removal efficiency for oil and grease (-168%) suggests that the Edward's Branch wetland was acting as a source for these pollutants rather than a sink. This is unlikely and is probably related to the uncertainty involved in measuring this pollutant. The increase in oil and grease was not statistically significant due to the high variability in the values and the low number of storm events for which this parameter was measured. This study is inconclusive with respect to this wetland's ability to remove oil and grease. The removal efficiency of oil and grease could most likely be increased by the addition of a grease trap or other filtering device to the wetland inlet.

Metals

As for most of the other pollutants, trace metals can be removed from the water column through physical filtering and settling/sedimentation. Additionally, trace metals readily form complexes with organic matter, which can then become attached to suspended particles. As with phosphorus, the storage of metals on wetland sediments creates conditions under which the pollutant is susceptible to future loss/transformation. The Edward's Branch wetland exhibited high removal of copper (57%) and zinc (71%) and the moderate removal of lead (32%). The lead result was confounded by influent lead concentrations which were often at or below detection limits. In short, the inflow was often relatively "clean." Conversely, concentrations of iron and manganese increased from the wetland inflow to outflow by approximately 50%, although the increase of manganese was not significant at the $\alpha=0.05$ level. All other monitored metals were present in such small quantities, often below their detection limits, as to be of little concern.

Other mechanisms responsible for trace metal removal from treatment wetlands include uptake/assimilation by plants/microbes and oxidation/reduction processes for certain metals. Oxidation/reduction processes are primarily associated with iron and manganese and the occurrence of negative removal efficiencies of iron and/or manganese can be a good indicator that reductive processes are occurring in the wetland. When organic matter is plentiful and temperatures are warm, oxygen levels can become depleted as organic matter is decomposed. Under these reduced conditions, iron and manganese, which often occur in association with each other as iron- and manganese-oxide coatings, can be transformed from an oxidized particulate phase, to a reduced soluble phase. As seasonal cycles cause fluctuations in oxygen levels, both metals can be converted back to insoluble oxidized species (Moore, 1991). When reducing conditions are present, any substance associated with the iron-or manganese-oxides, such as copper, zinc or phosphorus, can also become soluble upon reduction of the iron-oxide material. Because phosphorus is often sorbed to sediments containing iron-oxide coatings, reducing conditions can lead to not only an increase in soluble iron but may also be accompanied by a loss of soluble phosphorus (Richardson and Craft, 1993). In the Edward's Branch wetland, however, either this association was not present, or any soluble phosphorus that was released upon reduction of iron-oxide particles was removed by other mechanisms because no loss of P was evident.

Although iron and manganese both occur as mineral coatings, changes in manganese concentrations during reduction/oxidation cycles are often not associated with similar changes in iron. Therefore, seasonal concentrations of manganese and iron will often be different. This result can be seen by examining the storm-by-storm fluctuations in iron and manganese concentrations shown in Figs. A2 and A3. Removal efficiencies of iron and manganese remain below 0% throughout the summer months, meaning effluent concentrations are greater than influent concentrations and anaerobic conditions most likely are present. Although removal efficiencies for manganese closely follow a seasonal trend, lower in the summer and higher in the winter, removal efficiencies for iron show more variability (Figs. A2 and A3). A reason for this may be that soluble manganese is supplied almost entirely from in-situ reduction in the water column; whereas, soluble iron is supplied by reduction in sediments (Moore, 1991).

CONCLUSIONS

- Monitored pollutants in urban runoff generally followed a log-normal distribution, especially those pollutants that tend to occur in association with solids or particulates.
- Pollutants that are generally associated with suspended particulate matter are susceptible to physical loss from the wetland through sedimentation and infiltration. This mechanism appears to have been a major factor in the high removal of pathogens, certain forms of N and P, organic material and certain heavy metals which are known to complex with organic matter. This result occurred despite the difficulty experienced with wetland vegetation growth and maintenance, the increase in turbidity and only a slight decrease in total suspended solids. One reason for this conclusion is that many of the monitored pollutants followed the same storm-to-storm patterns (Figs. A1-A5), indicating that a similar removal mechanism was involved.
- Redox (the cycling of reduction and oxidation) conditions may be important in wetlands because of their effect on certain transformations of iron- and manganese. This can potentially have implications for release of constituents associated with iron- and manganese-containing minerals, such as phosphorus. However, this did not appear to be the case in this study as almost half of the TP entering the Edward’s Branch wetland as stormwater runoff was retained in the wetland.
- Because pollutants are adsorbed to settled particles in the wetland sediment, they can potentially be released to the overlying water column under certain conditions. The long-term behavior of deposited sediment that is heavily loaded with pollutants is unknown and deserves further

study. Decay of vegetation, resuspension of sediments and mobilization of adsorbed ions could possibly contribute to the release of contaminants from wetland sediments in the future. However, because Edward's Branch wetland is off-line, the likelihood of a large event "blowing out" the pollutants from the wetland is minimal.

- Total nitrogen and total phosphorus removal by the Edward's Branch wetland, 45% TN and 45% TP, is at or above the State of North Carolina's standard for each, 40% TN and 35% TP. This finding is consistent with the data collected at Bruns Avenue wetland in Charlotte, North Carolina.
- The extremely high pathogenic bacteria efficiency ratios (>90%) indicate that a system like Edward's Branch may be very useful in watersheds with bacteria TMDL's. It should be noted, however, that this wetland had poor vegetative cover (estimated 15-20%) and had correspondingly limited fauna present. Thus, on-site pathogen sources may have been limited.

REFERENCES

Burton, Jr., G.A., and R.E. Pitt. 2002. Stormwater Effects Handbook: a Toolbox for Watershed Managers, Scientists, and Engineers. CRC Press., New York.

GeoSyntec Consultants. 2006. Analysis of treatment system performance. International Stormwater Best Management Practices (BMP) Database [1999-2005]. Water Environment Research Foundation. http://www.bmpdatabase.org/ [accessed May 1, 2006].

Interstate Technology and Regulatory Council. 2003. Technical and Regulatory Guidance Document for Constructed Treatment Wetlands. ITRC Wetlands Team.

Hipsey, M.R., J.D. Brookes, R.H. Regel, J.P. Antenucci, and M.D. Burch. 2006. *In situ* evidence for the association of total coliforms and *Escherichia coli* with suspended inorganic particles in an Australian reservoir. Water, Air and Soil Pollution. 170:191-209.

Kadlec, R.H. and R.L. Knight. 1996. Treatment Wetlands. Lewis Publishers, Inc. New York.

Knight, R.L., R.W. Ruble, R.H. Kadlec, and S. Reed. 1993. Wetlands for wastewater treatment: performance database. *In:* (ed) Moshiri, G.A. Constructed Wetlands for Water Quality Improvement. CRC Press, Boca Raton.

Madge, B. 2004. Effective use of BMPs in stormwater management (chapter 5). *In:* (eds.) Muthukrishnan, S., B. Madge, A. Selvakumar, R. Field, and D. Sullivan. The Use of Best Management Practices (BMPs) in Urban Watersheds. U.S. EPA. EPA/600/R-04/184. Washington, DC.

Moore, J.W. 1991. Inorganic Contaminants of Surface Water. Research and Monitoring Priorities. Springer-Verlag, New York.

Muthukrishnan, S., R. Field, and D. Sullivan. 2004. Types of best management practices (chapter 2). *In:* (eds.) Muthukrishnan, S., B. Madge, A. Selvakumar, R. Field, and D. Sullivan. The Use of Best Management Practices (BMPs) in Urban Watersheds. U.S. EPA. EPA/600/R-04/184. Washington, DC.

Richardson, C.J. and C.B. Craft. 1993. Effective phosphorus retention in wetlands: fact or fiction? *In:* (ed) Moshiri, G.A. Constructed Wetlands for Water Quality Improvement. CRC Press, Boca Raton.

Schueler, T.R. and M. Helfrich. 1988. Design of extended detention wet pond systems. *In:* (eds.) Roesner, L.A., B. Urbonas., and M.B. Sonnen. “Design of

Urban Runoff Quality Controls”. Proceedings of an Engineering Foundation Conference on Current Practice and Design Criteria for Urban Quality Control. Am. Soc. Civil Engs. pp. 180-202.

Schueler, T. 1996. Irreducible pollutant concentrations discharged from stormwater practices. Technical Note 75. Watershed Protection Techniques. 2:369-372.

Strecker, E.W., M.M. Quigler, B.R. Urbonas, J.E. Jones, and J.K. Clary. 2001. Determining urban stormwater BMP effectiveness. J. Water Resources Planning and Management. 127:144-149.

U.S. Environmental Protection Agency. 1993. Handbook for Urban Runoff Pollution Prevention and Control Planning. EPA-625/R-93/004. Office of Research and Development.

U.S. Environmental Protection Agency. 1999. Preliminary Data Summary of Urban Storm Water Best Management Practices. EPA-821-R-99-012. Washington, DC.

U.S. Environmental Protection Agency and Amer. Soc. Civil Engineers. 2002. Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater Database Requirements. U.S. EPA. EPA-821-B-02-001. Washington, DC.

Urbonas, B.R. 2000. Assessment of stormwater best management practice effectiveness (chapter 7). *In:* (eds). Heaney, J.P., R. Pitt, R. Field. Innovative Urban Wet-Weather Flow Management Systems. EPA/600/R-99/029. Washington, DC.

Van Buren, M.A., W.E. Watt, and J. Marsalek. 1997. Application of the log-normal and normal distributions to stormwater quality parameters. Water Research. 31:95-104.

Vaze, J. and F.H.S. Chiew. 2004. Nutrient loads associated with different sediment sizes in urban stormwater and surface pollution. J. Environmental Engineering. 130:391-396.

Winer, R. March 2000. National Pollutant Removal Performance Database for Stormwater Treatment Practices, 2nd Edition. Center for Watershed Protection. U.S. EPA Office of Science and Technology.

APPENDIX A

Table A1. Results of statistical comparisons between pre- and post-BMP concentrations of selected pollutants at the Edward's Branch wetland.

Parameter	**Assumed Distribution**	**Reject Based on K-S Test†**	**Paired *t*-Test‡**	**Wilcoxon Signed-Rank Test**
			***p*-value**	
Dissolved Oxygen	Lognormal	No	0.5794	1.0000
Temperature	Lognormal	No	0.7872	0.6377
Conductivity	Lognormal	No	0.0847	0.1563
pH	Lognormal	No	0.4939	0.5625
Fecal Coliform	Lognormal	**Yes**	**0.0001**	**0.0039**
E. Coli	Lognormal	No	**0.0017**	**0.0313**
Oil and Grease	Lognormal	No	0.1989	0.3125
BOD_5	Lognormal	No	**0.0040**	**0.0010**
COD	Lognormal	No	**0.0017**	**0.0040**
Alkalinity	Lognormal	No	0.3553	0.2078
NH_4	Lognormal	**Yes**	**0.0220**	**0.0195**
$NO_3 + NO_2$	Lognormal	No	**0.0007**	**0.0033**
Total Kjeldahl N (TKN)	Lognormal	No	**0.0183**	**0.0214**
Total N (TN)	Lognormal	No	**0.0020**	**0.0017**
Total P (TP)	Lognormal	No	**0.0011**	**0.0020**
Filterable Residue	Lognormal	No	0.2883	0.3750
Suspended Residue (TSS)	Lognormal	No	0.3499	0.1928
Total Residue	Normal	No	0.1058	0.0833
Specific Conductance	Lognormal	No	0.4398	0.6250
Turbidity	Lognormal	No	0.1416	0.1151
Copper	Lognormal	**Yes**	**0.0040**	**0.0013**
Iron	Lognormal	No	**0.0287**	**0.0181**
Manganese	Lognormal	No	0.1211	0.1514
Zinc	Normal	No	**0.0040**	**0.0020**
Lead	Lognormal	No	**0.0028**	**0.0010**

†Rejection (α=0.05) of Kolmogorov-Smirnov goodness-of-fit test statistic implies that the assumed distribution is not a good fit of the data.

‡Statistical tests were performed on log-transformed data except for total residue and zinc, in which case raw data was used.

Table A2. Pollutant removal efficiencies for the Edward Branch wetland based on pre- and post-BMP concentrations for individual storm events.

Parameter	**# of samples**	**Median BMP Removal Efficiency**	**Maximum BMP Removal Efficiency (Storm)†**	**Minimum BMP Removal Efficiency (Storm)†**
		%		
Dissolved Oxygen	6	-2	25 (16)	-7 (12)
Temperature	12	3	30 (5)	-43 (4)
Conductivity	6	-121	43 (12)	-338 (14)
pH	6	1	11 (17)	-6 (12)
Fecal Coliform	9	97	99.9 (14)	93 (5, 16)
E. Coli	6	94	99 (11)	77 (16)
Oil and Grease	7	0	41 (9)	-375 (11, 12)
BOD_5	16	49	98 (5)	-203 (3)
COD	16	54	91 (5)	-235 (3)
Alkalinity	15	-131	97 (5)	-847 (17)
NH_4	16	12	94 (5)	-74 (3)
NO_3+NO_2	16	63	91 (5)	-430 (3)
Total Kjeldahl N (TKN)	16	38	81 (5)	-56 (1)
Total N (TN)	16	44	85 (5)	-71 (3)
Total P (TP)	16	56	82 (5)	-100 (15)
Filterable Residue	7	-25	43 (3)	-208 (1)
Suspended Residue (TSS)	16	15	81 (15)	-343 (4)
Total Residue	16	-15	94 (13)	-237 (1)
Specific Conductance	4	-93	43 (3)	-346 (6)
Turbidity	15	-20	76 (3)	-769 (1)
Copper	16	42	94 (6)	-50 (1)
Iron	16	-61	71 (3)	-295 (2)
Manganese	16	-45	66 (4)	-1327 (6)
Zinc	16	75	92 (5)	-200 (3)
Lead	16	17	69 (5)	0 (5 events)
Mercury	16	0	85 (6)	0 (15 events)

†Number in parentheses represents the storm event for which the reported pollutant removal occurred.

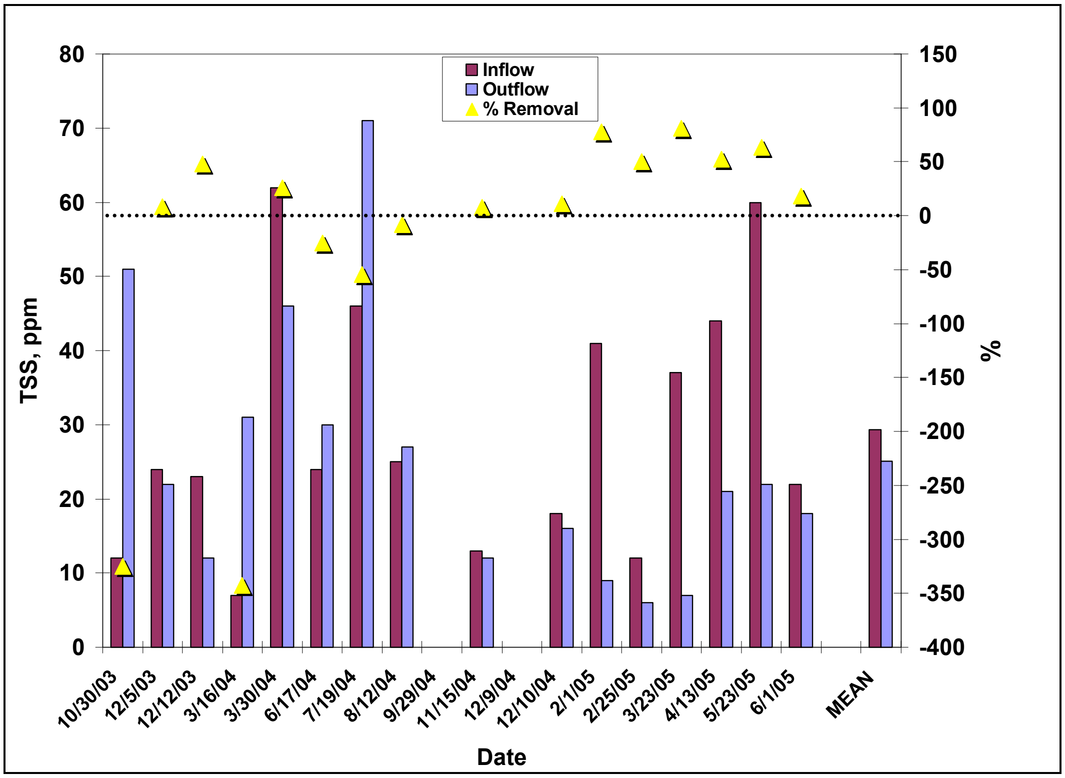

Fig. A1. Change in total suspended solids (TSS) due to BMP treatment by storm event.

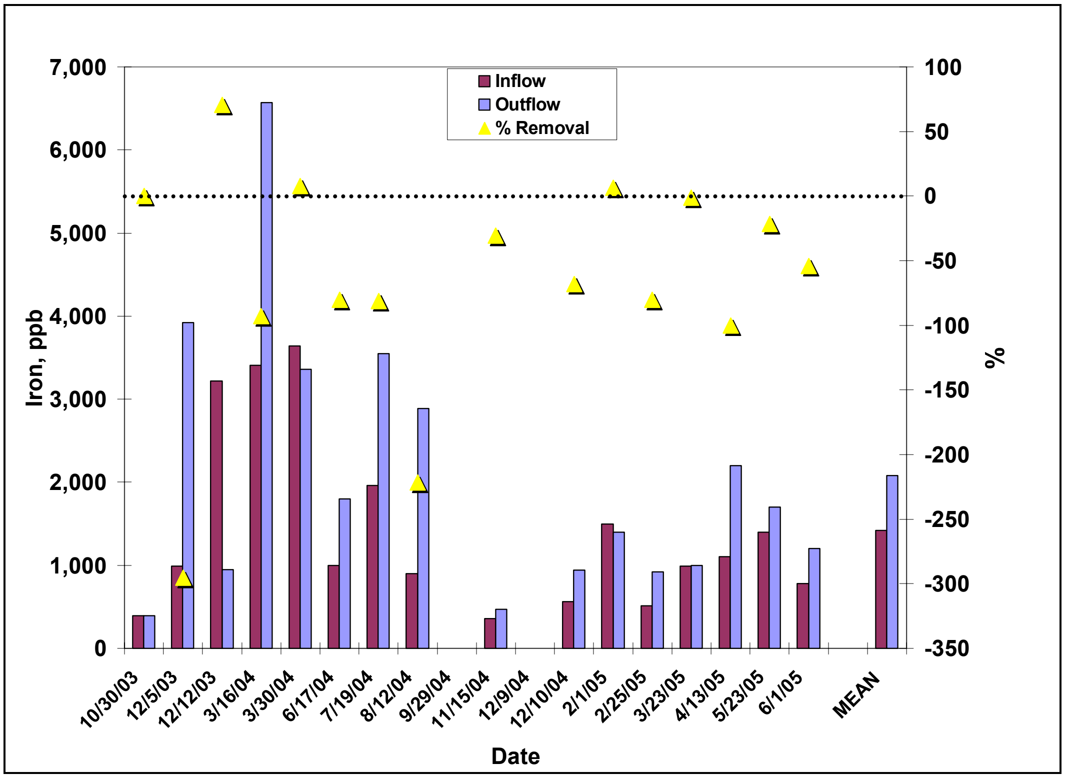

Fig. A2. Change in iron concentration due to BMP treatment by storm event.

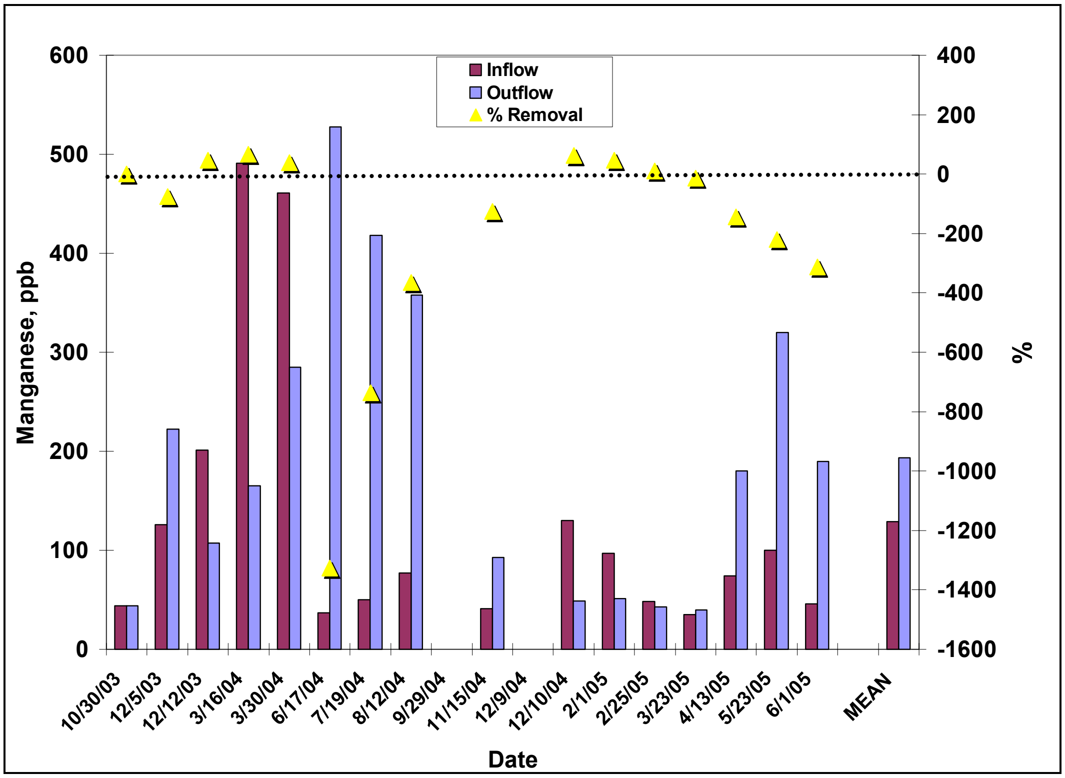

Fig. A3. Change in manganese concentration due to BMP treatment by storm event.

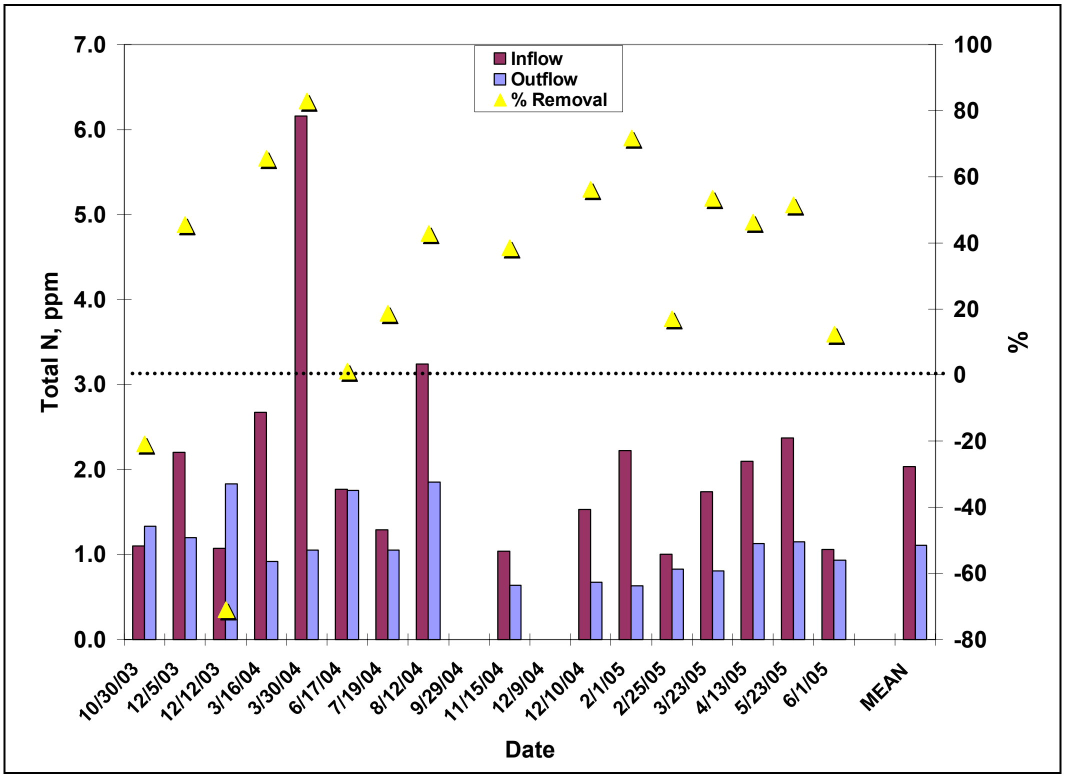

Fig. A4. Change in total nitrogen concentration due to BMP treatment by storm event.

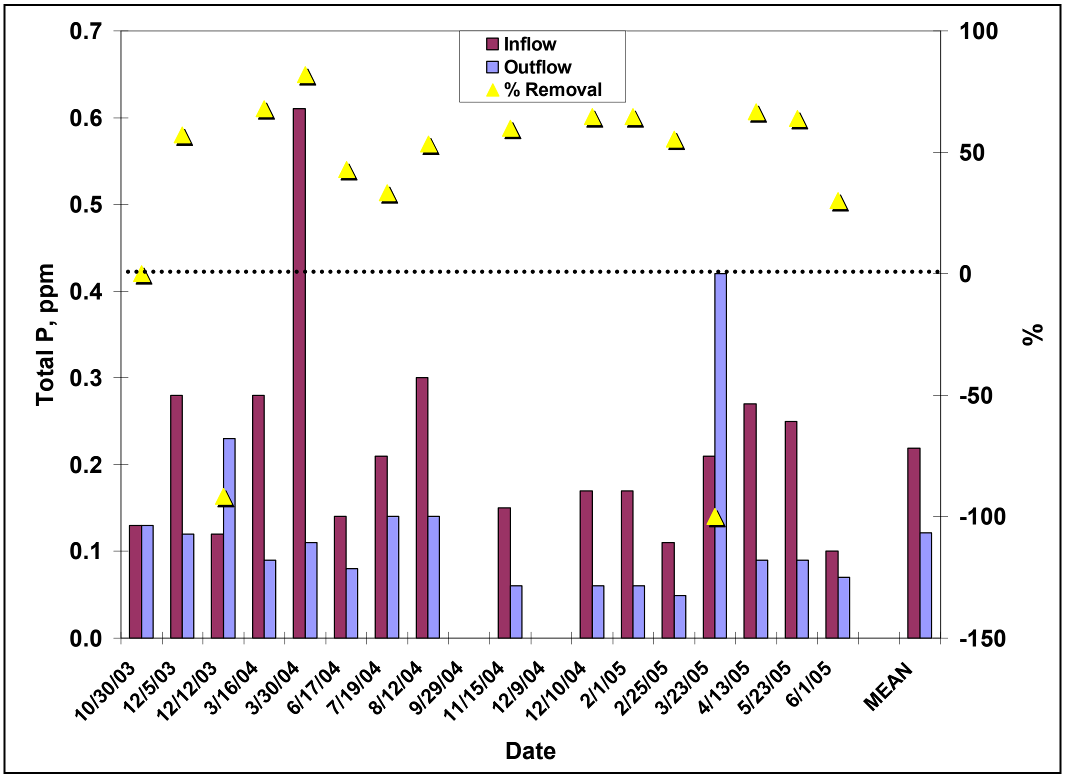

Fig. A5. Change in total phosphorus concentration due to BMP treatment by storm event.

APPENDIX B

Monitoring Protocol

Stormwater BMP performance Monitoring Protocol for:

Edwards Branch Wetland

Description of Site:

The Edwards Branch wetland is an offline stormwater wetland incorporating a flow splitter at its influent point to divert larger flows away from the wetland and into a nearby stream. The wetland utilizes an circular orifice to allow for drawdown of stormwater detained within. The site is still in the process of becoming fully vegetative. This process has been slowed by the recent excessively wet weather (summer 2003) which caused the water level in the wetland to remain high for long periods of time. Additionally a large amount of waterfowl frequent the wetland causing damage to young wetland plants.

Watershed Characteristics (estimated)

No watershed discretization has been undertaken at this time.

Sampling equipment

Inlet monitoring should take place in the 8” PVC pipe at the junction box near the inlet. During storm events this pipe will experience a tail water condition. As a result it is necessary to utilize an Area-Velocity meter at this location. Outlet detention is controlled by a circular orifice. Observation of the response of the system to storm events indicates that the orifice size should be increased and the invert lowered by several inches.

Addendum 3/17/04: single 2” orifice has been replaced with an orifice plate with two (2) 1.75” orifices installed approximately 2” lower to foster additional wetland plant growth. *JTS*

Inlet Sampler

Primary device:	8” diameter culvert
Secondary Device:	ISCO model 750 area-velocity meter
Bottle Configuration	24 1000mL Propak containers

Outlet Sampler

Primary Device:	2 1.75” diameter circular orifices
Secondary Device:	Model 720 Bubbler
Bottle Configuration	24 1000mL Propak containers
Rain gage	Nearby USGS gauging station used

Sampler settings

Inlet Sampler

Sample Volume	200 mL
Distribution	5/bottle
Pacing	25 cu ft
Set point enable	None

Outlet Sampler

Sample Volume	200mL
Distribution	5/bottle
Pacing	144 cu ft
Set point enable	> .06 cfs

As monitoring efforts continue it is very likely that the user will need to adjust the sampler settings based on monitoring results. The user should keep detailed records of all changes to the sampler settings. One easy way to accomplish this is to printout the settings once data has been transferred to a PC.

Sample Collection and Analysis

Samples should be collected and analyzed in accordance with the *Stormwater Best Management Practice (BMP) Monitoring Protocol* for the City of Charlotte and Mecklenburg County Stormwater Services.

General Monitoring Protocol

Introduction

The protocols discussed here are for use by City of Charlotte and Mecklenburg County Water Quality personnel in setting up and operating the stormwater BMP monitoring program. The monitoring program is detailed in the parent document “Stormwater Best Management Practice (BMP) Monitoring Plan for the City of Charlotte”

Equipment Set-up

For this study, 1-2 events per month will be monitored at each site. As a result, equipment may be left on site between sampling events or transported to laboratory or storage areas between events for security purposes. Monitoring personnel should regularly check weather forecasts to determine when to plan for a monitoring event. When a precipitation event is expected, sampling equipment should be installed at the monitoring stations according to the individual site monitoring protocols provided. It is imperative that the sampling equipment be installed and started prior to the beginning of the storm event. Failure to measure and capture the initial stages of the storm hydrograph may cause the “first flush” to be missed.

The use of ISCO refrigerated single bottle samplers may be used later in the study if future budgets allow. All samplers used for this study will be configured with 24 1000ml pro-pak containers. New pro-pak containers should be used for each sampling event. Two different types of flow measurement modules will be used depending on the type of primary structure available for monitoring

Programming

Each sampler station will be programmed to collect up to 96 individual aliquots during a storm event. Each aliquot will be 200 mL. in volume. Where flow measurement is possible, each sampling aliquot will be triggered by a known volume of water passing the primary device. The volume of flow to trigger sample collection will vary by site depending on watershed size and characteristic.

Sample and data collection

Due to sample hold time requirements of some chemical analysis, it is important that monitoring personnel collect samples and transport them to the laboratory in a timely manner. For the analysis recommended in the study plan, samples should be delivered to the lab no more than 48 hours after sample collection by the automatic sampler if no refrigeration or cooling of samples is done. Additionally, samples should not be collected/retrieved from the sampler until the runoff hydrograph has ceased or flow has resumed to base flow levels. It may take a couple of sampling events for the monitoring personnel to get a good “feel” for how each BMP responds to storm events. Until that time the progress of the sampling may need to be checked frequently. Inflow sampling may be completed just after cessation of the precipitation event while outflow samples may take 24-48 hours after rain has stopped to complete. As a result it may be convenient to collect the inflow samples then collect the outflow samples several hours or a couple of days later.

As described above, samples are collected in 24 1,000mL containers. In order for samples to be flow weighted these individual samples will need to be composited in a large clean container; however, future use of single bottle samplers will likely reduce the need for this step. The mixing container should be large enough to contain 24,000mL plus some extra room to avoid spills. Once the composited sample has been well mixed, samples for analysis should be placed in the appropriate container as supplied by the analysis laboratory.

Chain of custody forms should be filled in accordance with Mecklenburg County Laboratory requirements.

Collection of rainfall and flow data is not as time dependent as sample collection. However it is advised that data be transferred to the appropriate PC or storage media as soon as possible.

Data Transfer

Sample analysis results as well as flow and rainfall data should be transferred to NCSU personnel on a quarterly basis or when requested. Transfer may be completed electronically via email or by file transfer.