Environment and Natural Resources Research; Vol. 4, No. 3; 2014
ISSN 1927-0488 E-ISSN 1927-0496
Published by Canadian Center of Science and Education

Nutrient and *Escherichia coli* Attenuation in a Constructed Stormwater Wetland in the North Carolina Coastal Plain

Charles Humphrey[1], Nicholas Chaplinski[2], Michael O'Driscoll[3], Tim Kelley[1] & Stephanie Richards[1]

[1] Environmental Health Sciences Program, East Carolina University, Greenville, NC, USA

[2] Department of Environmental Health and Safety, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

[3] Department of Geological Sciences, East Carolina University, Greenville, NC, USA

Correspondence: Charles Humphrey, Environmental Health Sciences Program, East Carolina University, 3408 Carol Belk Building, Greenville, NC 27858, USA. Tel: 1-252-737-1479. E-mail: Humphreyc@ecu.edu

Received: April 14, 2014 Accepted: May 3, 2014 Online Published: May 13, 2014

doi:10.5539/enrr.v4n3p12 URL: http://dx.doi.org/10.5539/enrr.v4n3p12

Abstract

Stormwater best management practices (BMPs) are installed to reduce the delivery of pollutants to surface waters. The objective of this study was to determine the stormwater NO_3-N, PO_4-P, and *Escherichia coli* (*E. coli*) reductions in a constructed wetland in Greenville, North Carolina. Water samples were collected at the inlet and outlet of the wetland before, during, and after 11 storms for NO_3-N, PO_4-P, and *E. coli* analysis. Treatment efficiencies for NO_3-N (69%) and PO_4-P (63%) exceeded the nutrient credit reductions assigned to stormwater wetlands (40% for both) in North Carolina. The *E. coli* (59%) and PO_4-P (63%) concentration reductions in the wetland were similar to the reduction in specific conductivity (62%), possibly because of sedimentation in the wetland that reduced the suspended and dissolved solids with adsorbed *E. coli* and PO_4-P. The relatively large size of the wetland (7% of drainage area), and below average rainfall likely contributed to the exceptional pollutant reduction efficencies.

Keywords: bacteria, coastal, nutrients, stormwater, wetland, runoff

1. Introduction

1.1 Urban StormwaterManagement

Stormwater runoff from urban areas can lead to impairment of adjacent receiving waterways via rapid transport of pollutants such as nutrients, sediment, and bacteria that accumulate on impervious surfaces between storms (Davis et al., 2001; Tilley & Brown, 1998). Best management practices (BMPs) such as stormwater wetlands are created to reduce the transport of runoff and pollutants from urban areas to natural waters, thus protecting water quality. Stormwater wetlands are designed and constructed to mimic nutrient and pathogen treatment processes that occur in natural wetlands. Most stormwater wetlands consist of a forebay near the inlet, a shallow-water and shallow-land area, and another deep pool before the outlet (Hunt et al., 2007). The deep pool areas serve to dissipate the energy of influent, allowing sediment to settle and deep pools also provide open water aquatic habitat. Shallow water areas are vegetated channels that connect the deep pools, while shallow land areas are at higher elevations (than shallow water) and consist of different plant species (Hunt et al., 2007). Vegetation in the shallow water and shallow land areas uptake nutrients from runoff, and help slow the flow of influent, hence allowing sediment to settle (Gu & Dreschel, 2008). Constructed stormwater wetlands (CSWs) are often advantageous over other BMPs in that they tend to maintain a continuous flow, involving base flow and storm flow whereas other BMPs (retention ponds, etc.) may only be functioning as a treatment mechanism during and post storm events (Wadzuk et al., 2010).

Stormwater wetlands use physical, chemical and biological processes to treat stormwater. Stormwater wetlands are designed to remove pollutants from runoff via several mechanisms including: microbial breakdown and/or transformation of nutrients, plant uptake, settling, and adsorption (Johengen & LaRock, 1993: Martin & Reddy, 1997; USEPA, 2009). Stormwater wetlands may also reduce the concentration of pathogenic bacteria that can be harmful to public health (American Society of Meteorology, 1999). High concentrations of *E.coli* may indicate the presence of other disease-causing bacteria, and are a commonly used microbial indicator for non-saline surface waters (USEPA, 2008). High *E.coli* densities in recreational surface waters have been significantly correlated to human illness and thus threaten public health. Stormwater wetlands can reduce *E. coli* concentrations via adsorption to suspended sediment and later sedimentation, and/or inactivation from sunlight in open water areas.

The ability of wetlands to attenuate nutrients has been demonstrated for different pollutant sources including urban runoff, agricultural runoff, and wastewater treatment plant discharges (Reed at al., 1995; Raisen & Mitchell, 1995; Kadlec & Knight, 1996; Kovacic et al., 2000; Koskiaho & Puustinen, 2005). Wetland performance in treating stormwater is a function of numerous factors including, but not limited to hydraulic loading rate, detention time, storm intensity, runoff volume, wetland size (Carleton et al., 2001), season (Yousef et al., 1986; Hvited-Jacobsen et al., 1989), maintenance intensity (Hunt & Lord, 2007), and vegetative species and placement (Jenkins & Greenway, 2005). While most studies have shown that stormwater wetlands are effective at reducing nutrient and pathogen influent concentrations, the reported treatment efficiencies are often variable because of the many factors which influence pollutant treatment (Line et al., 2008; Hathaway et al., 2009; Wadzuk et al., 2010).

1.2 Eastern North Carolina Characteristics and Water Quality Issues

This study was conducted in the city of Greenville, which is in the central coastal plain of eastern North Carolina (NC). The geology of the area may be characterized as a gently southeastward dipping and thickening wedge of sediments resting on an underlying basement complex of Paleozoic age rocks (Lautier, 2001). The sediment is comprised of layers and lenses of sand, clay, silt, limestone, gravel, shell material and combinations of those materials (Lautier, 2001). Ground and surface water interact in a variety of physiographic and climatic landscapes creating the potential for exchange between the two components (Sophocleous, 2002). Therefore, groundwater quality and surface water quality are often linked. The mean monthly precipitation for Greenville ranges from 7.09 cm in November to 14.96 cm in August, and the mean annual precipitation is 106.93 cm (State Climate Office of North Carolina, 2014). Mean air temperatures are warmest in the summer months of July (26.5 °C) and August (25.6 °C) and lowest in the winter months of January (5.3 °C) and February (6.9 °C) (State Climate Office of North Carolina, 2014).

Groundwater and surface water resources in the coastal plain of eastern NC have been influenced by various sources of pollution including onsite wastewater systems, agriculture, and urban runoff (Hathaway et al., 2012; Humphrey et al., 2012). The state of NC enacted regulations (15A NCAC 2B.0258) to reduce the impact of stormwater runoff to nutrient sensitive waters from urbanizing areas such as Greenville, NC (North Carolina Department of Environment and Natural Resources, 2001). Developers must implement stormwater BMPs for construction projects in municipalities affected by stormwater regulations. Developers receive nutrient reduction credits for installing approved stormwater BMPs such as wetlands. However, since prior research has shown that pollutant treatment efficiencies of BMPs are variable, determining the treatment efficiency of common BMPs such as stormwater wetlands is important in ensuring that the regulations meet their intended purposes. The objective of this study was to determine if the NO_3-N, PO_4-P, and *E. coli* treatment efficiency of a constructed stormwater wetland was greater than or equal to the pollutant reduction credit established for the BMP by NC regulations.

2. Methods

2.1 Site Selection

The study site was located on the *Bellamy* student housing development, which was constructed in 2007 to serve students at East Carolina University in Greenville, NC. The *Bellamy* site consisted of 9.20 hectares (ha) of land. Upon completion of the first phase of development, the housing complex's total impervious area was 5.72 ha or 62% of the total property. Concurrent with the development at this site, NC general statutes (North Carolina Department of Environment and Natural Resources, 2001) required that a stormwater BMP be constructed to detain runoff and reduce nitrogen and phosphorus concentrations from the impervious surfaces before discharging to the existing stormwater conveyance system for the City of Greenville. Drainage from the site eventually discharges to the Tar River, which is classified as nutrient sensitive waters (North Carolina Department of Environment and Natural Resources, 2001).

The constructed stormwater wetland at the *Bellamy* occupies 0.68 ha or just over 7% of the watershed area (Figure 1). The wetland includes a forebay (influent pond), shallow water and shallow land area, an open water pool, and outlet. There were approximately 9200 plants were installed in the wetland including: Sweet Flag (*Acorus calamus*), Sawgrass (*Cladium jamaicense*), Arrow Arum (*Peltandra virginica*), Duck Potato (*Sagittaria latifolia*), and Softstem Bullrush (*Schoenoplectus tabernaemontani*). A wet hydro-seed mix was used to establish permanent vegetative cover in the buffer outside of the permanent pool.

A maintenance plan was developed and a landscaping company was contracted for general upkeep of the pond including trash removal, removal of common cattail (*Typha latifolia*), and removal of matted macrophyte matter that kept drainage at a maximum and deterred any obstruction to the concrete effluent structure.

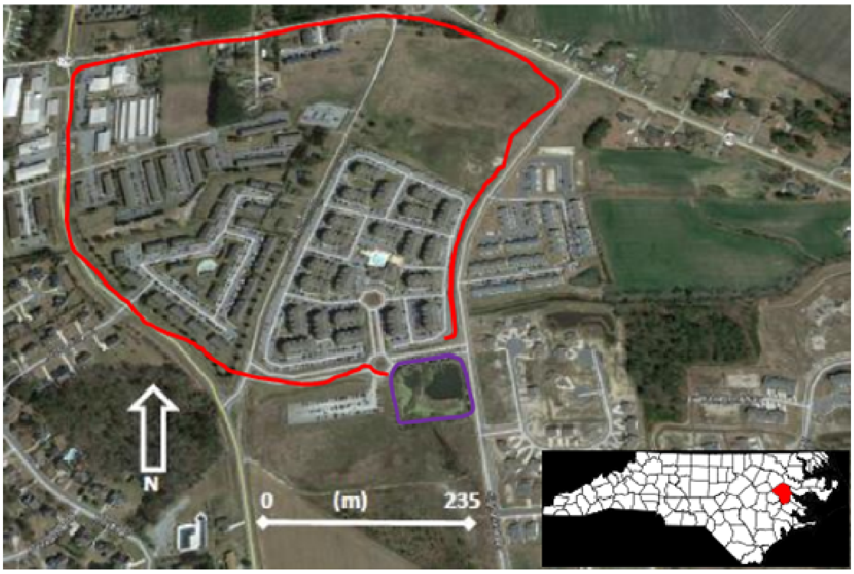


Figure 1. The *Bellamy* stormwater wetland (purple outline) that treats runoff from the apartments and other land. The red outline is the estimated watershed boundary. The site is located in Greenville, Pitt County, NC, USA

2.2 Instrumentation and Monitoring

Stilling wells constructed of 7.6 cm diameter PVC pipe were installed at the inlet and outlet of the wetland. Holes were drilled into the pipe to allow water to enter and exit, and the wells were driven in to the ground such that there was approximately 1 m of clearance from the top of the pipe to the high water level in the wetland. Automated *Aqua Troll® 200* loggers were placed in the wells and were programmed to record surface water specific conductivity and temperature every 0.5 hours over the duration of the study (10 months). The inflow and outflow mean readings were summarized for each month and for the entire study (10 month average) to determine if there were statisticial differences. Because of funding limitations we were not able to monitor beyond 10 months. Surface water samples were collected by dipping sterile bottles into the wetland near the influent and effluent wells before, during, and after 11 storms between June 2009 and March 2010 (Figure 2). Separate bottles were used for nutrient and *E. coli* analysis. Water samples were kept in an ice-filled cooler and transported to the East Carolina University Environmental Health Sciences Water Laboratory for analysis. Water samples were analyzed for NO_3-N, and PO_4-P using a *Hach DR 890* colorimeter. The NO_3-N tests were conducted using the cadmium reduction method with powder pillows. The PO_4-P tests were conducted using the PhosVer3 (Ascorbic acid) method with powder pillows. The *IDEXX® Colilert* with *Quanti Tray 2000* method was used for *E. coli* enumeration. The *E. coli* samples/trays were incubated at 35 °C for 24 hours, and then enumerated.

Figure 2. The consructed stormwater wetland with the location of the sampling points at the inlet (red circle) and outlet (green square) of the wetland. Treatment efficiency was determined by comparing the nutrients and *E. coli* concentrations at the outlet to the inlet

2.3 Statistical Analysis

Mann Whitney tests (for data that are not normally distributed) were used to determine if there were significant differences among inflow and outflow NO_3-N, PO_4-P, and *E.coli* concentrations (n = 11 for all), and specific conductivity readings (n = 14,400). Nutrient and *E. coli* reduction efficiencies from the inlet to outlet were calculated using equation (1) and compared to statutory reduction credits for stormwater wetlands. The statistical software *Minitab 16* and *Microsoft Excel* were utilized to create graphs and perform statistical tests to determine if differences between inflow and outflow concentrations and readings were statistically significant ($p \leq 0.05$). Rainfall data from a weather station in Greenville was obtained and compared to the long-term average (1971-2000) from the same station.

Treatment Efficiency = [(Inlet Concentration – Outlet Concentration) / Inlet Concentration] x 100% (1)

3. Results

3.1 Nitrate Treatment

The mean inflow NO_3-N concentrations were higher before (0.56 mg/L), during (0.61 mg/L) and after storms (0.57 mg/L) relative to outflow NO_3-N concentrations (before: 0.18 mg/L; during: 0.19 mg/L; after: 0.18 mg/L) (Figure 3). For NO_3-N analysis, the differences were statistically significant for each of the comparisons (before: $p = 0.01$; during: $p = 0.002$; after: $p = 0.004$). When pooling all the data, statistically significant differences ($p < 0.0001$) were also observed between the mean inflow (0.58 mg/L) and outflow (0.18 mg/L) NO_3-N concentrations. The mean NO_3-N concentrations for inflow and outflow samples were highest during storms.

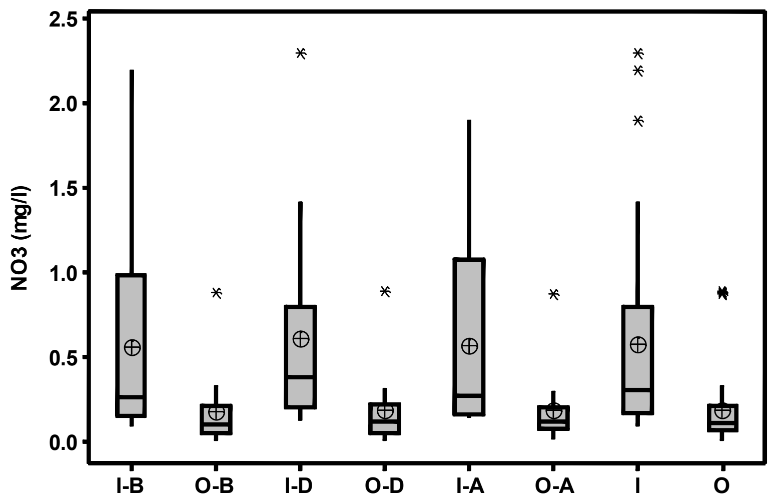


Figure 3. Nitrate concentrations before (B), during (D) and after (A) rain events for inlet (I) and outlet (O) sampling locations. Circles indicate the mean, stars indicate statistical outliers. Nitrate concentrations were always lower near the outlet relative to the inlet

3.2 Phosphate Treatment

The mean PO_4-P inflow concentrations were higher than outflow concentrations for each period of sample collection (Figure 4). The before storm inflow PO_4-P concentrations (0.19 mg/L) were elevated relative to outflow concentrations (0.07 mg/L), but the differences were not statistically significant (p = 0.08). Samples collected during storms for PO_4-P analyses had mean inflow concentrations (0.21 mg/L) that were significantly (p = 0.01) higher than outflow concentrations (0.07 mg/L). The after-storm PO_4-P concentrations were higher for inflow samples (0.18 mg/L) relative to outflow (0.07 mg/L), but the differences were not statistically significant (p = 0.11). When pooling all inflow phosphorus data (mean: 0.19 mg/L) and comparing to all outflow phosphorus data (mean: 0.07 mg/L) statistically significant differences (p = 0.0006) were observed. Mean inflow PO_4-P concentrations were highest during storms, but outflow PO_4-P concentrations were similar during each period of sample collection.

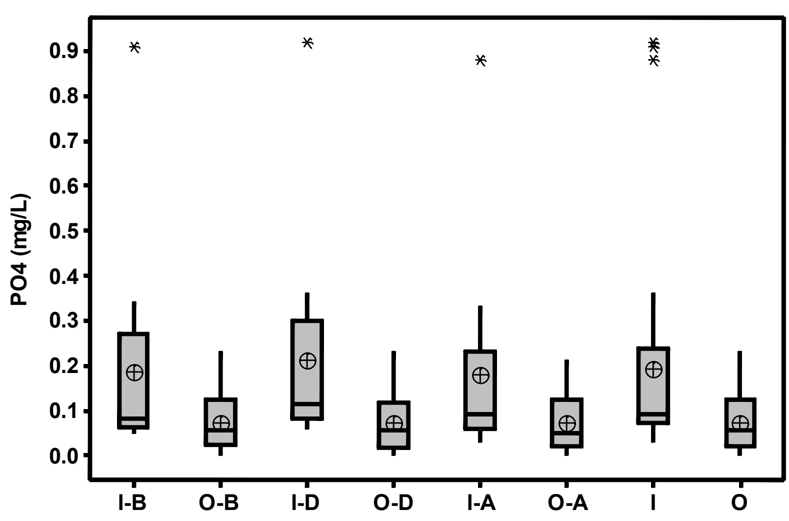


Figure 4. Phosphate concentrations before (B), during (D) and after (A) rain events for inlet (I) and outlet (O) sampling locations. Circles indicate the mean, stars indicate statistical outliers. Phosphate concentrations were always lower near the outlet relative to the inlet

3.3 E. coli Analysis

The geometric means of *E.coli* concentrations for inflow samples were elevated relative to outflow samples for each period of sample collection, and for all of the pooled inflow and outflow data (Figure 5). Geometric mean inflow *E. coli* concentrations before ($\log_{10}$ 2.95 or 887 MPN/100 mL), during ($\log_{10}$ 3.02 or 1036 MPN/100 mL), and after ($\log_{10}$ 2.89 or 784 MPN100 mL) storms were higher compared to outflow geometric mean concentrations (before: $\log_{10}$ 2.57 or 374 MPN/100 mL; during: $\log_{10}$ 2.62 or 413 MPN/100 mL; after: $\log_{10}$ 2.52 or 320 MPN/100 mL). These differences were not statistically significant, as the p-values exceeded 0.05 for each comparison. However, when all the data was pooled, the geometric mean inflow *E. coli* concentration ($\log_{10}$ 2.95 or 896 MPN/100 mL) was significantly (p = 0.03) higher than the geometric mean outflow concentration ($\log_{10}$ 2.56 or 367 MPN/100 mL). The geometric mean *E. coli* inflow and outflow concentrations were highest during storm events.

3.4 Nutrient and Bacteria Treatment Efficiency

The constructed stormwater wetland at the *Bellamy* reduced mean inflow NO_3-N concentrations by 69%, mean PO_4-P concentrations by 63%, and geometric mean *E. coli* concentrations by 59% before discharge. The treatment efficiency established by the state of NC was a 40% reduction for nitrogen and phosphorus, thus the wetland was performing well relative to the regulatory expectations. Also the mean inflow specific conductivity of stormwater was reduced by 62% before reaching the outlet.

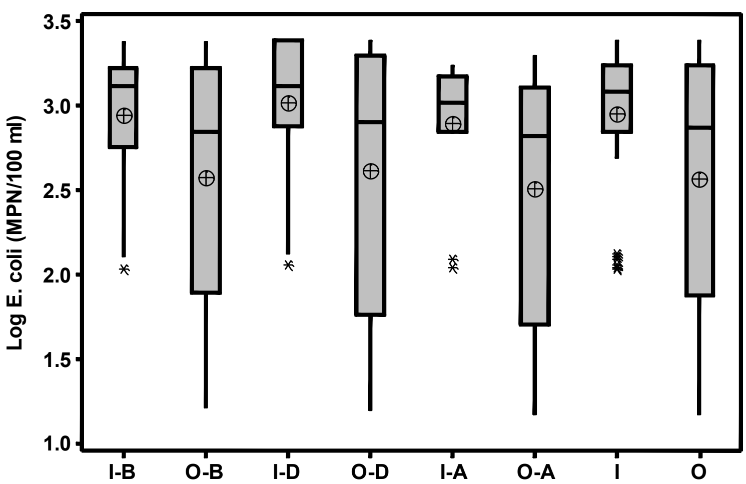


Figure 5. $\log_{10}$ *E. coli* concentrations before (B), during (D) and after (A) rain events for inlet (I) and outlet (O) sampling locations. Circles indicate the mean, stars indicate statistical outliers. *E. coli* concentrations were always lower near the outlet relative to the inlet

3.5 Specific Conductivity and Temperature

Similar to the nutrient and *E. coli* concentration trends, inflow specific conductivity was elevated relative to outflow specific conductivity for each month, and for the entire study (Figure 6). The mean monthly inflow specific conductivity was similar between July 2009 and March 2010 (range: 572 to 710 µS/cm), but lower at the start of the project in June 2009 (340 µS/cm). The mean monthly outflow specific conductivity was similar between June 2009 and January 2010 (range: 187 to 274 µS/cm), but increased during the winter months of February (329 µS/cm) and March (350 µS/cm).

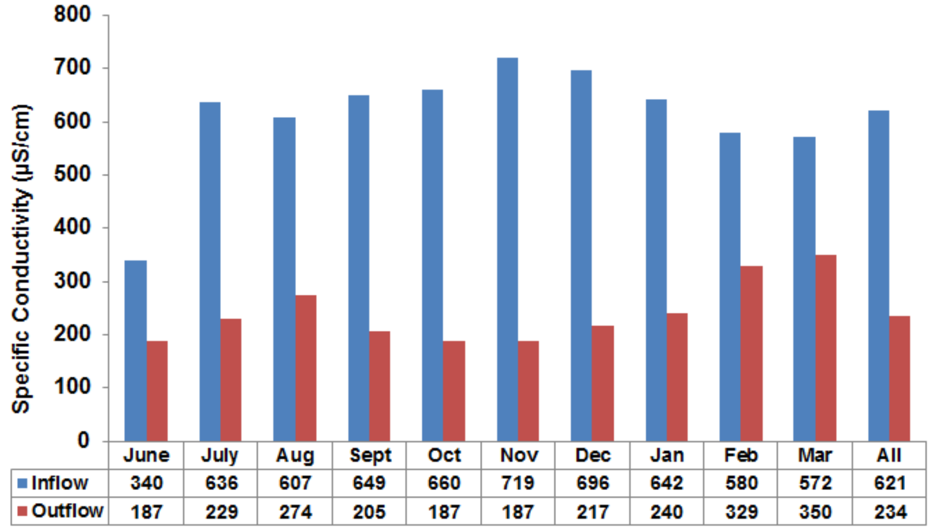


Figure 6. Mean monthly inflow and outflow specific conductivity (uS/cm), and pooled data (All). Outflow specific conductivity was always lower near the outlet relative to the inlet

Mean monthly inflow water temperatures during the summer months of June (21 °C), July (25 °C), and August (26 °C), were cooler than outflow water temperatures (June: 28 °C; July: 28 °C; August: 29 °C). During the winter, mean monthly inflow water temperatures were warmer (December: 13 °C; January: 10 °C; February: 9 °C; March: 10 °C) than outflow water temperatures (December: 10 °C; January: 7 °C; February: 7 °C; March: 9 °C). The other months had similar inflow and outflow water temperatures (Figure 7).

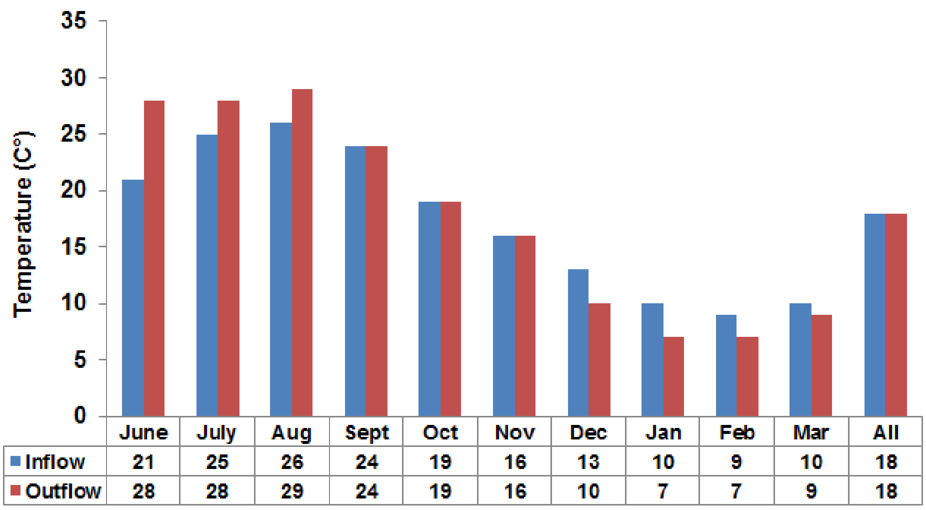
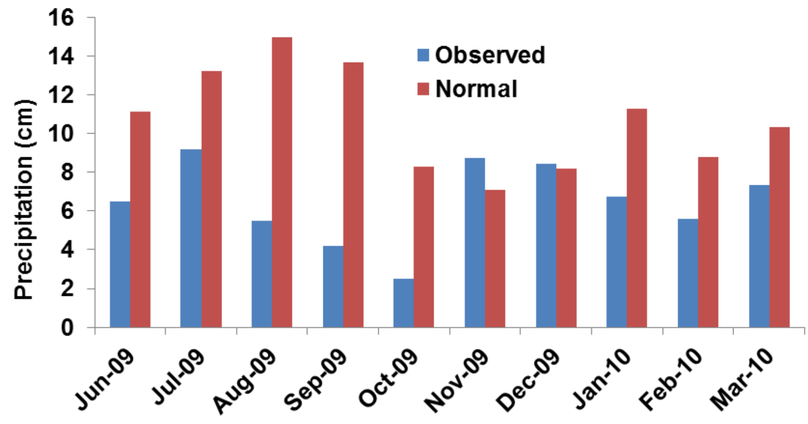


Figure 7. Mean monthly inflow and outflow water temperature (°C), and pooled data (All). During summer months, outflow was warmer than inflow, and during winter months outflow was cooler than inflow

3.6 Rainfall Data

Precipitation during the study totaled 64.75 cm or 39% less than the long-term average (106.93 cm) for the City of Greenville, NC (State Climate Office, 2014). November and December of 2010 were the only two months when the observed precipitation was greater than or equal to the long-term average (Figure 8).



	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10
Observed	6.48	9.19	5.51	4.22	2.49	8.74	8.46	6.73	5.61	7.32
Normal	11.13	13.21	14.96	13.69	8.31	7.09	8.20	11.25	8.76	10.34

Figure 8. Observed precipitation at the Airport in Greenville, NC during the study, as compared to the long-term monthly average (normal). The study period was relatively dry compared to the long-term average

4. Discussion

The mean NO_3-N and PO_4-P treatment efficiency for the wetland exceeded the nutrient treatment efficiency credit (40% for N and P) for each nutrient. The exceptional performance of the BMP may be due to the relatively large stormwater wetland area in relation to total drainage area. The *Bellamy* wetland encompassed 7% of the watershed, and thus was 2-4 percentage points larger than most constructed wetlands with similar sized drainage areas. Research has shown that wetlands with larger surface area to drainage area ratios can be more effective at reducing some nutrient concentrations than wetlands with smaller ratios (Line et al., 2008), possibly because the increased hydraulic residence time in larger wetlands allows more opportunity for pollutant removal via sedimentation, plant uptake and other processes (Carlton et al., 2001; Gu & Dreschel, 2008). The relatively low amount of precipitation may have also influenced the treatment efficiency, by providing more internal storage for stormwater and increased hydraulic retention time. If water levels in the wetland are low because of below average rainfall, when a storm event does occur, there may be little outflow because of the internal storage in the wetland, and evapotranspiration. Another potential contributing factor to the performance of the wetland was the maintenance intensity. A management company was contracted to maintain the stormwater wetland. Part of the maintenance agreement was the harvesting cattails to prevent the eventual loss of biodiversity. The harvesting of cattails was witnessed during data collection. Prior research has indicated that harvesting wetland plants may be beneficial to the treatment efficiency of the BMP (Lenhart et al., 2012). When plants are harvested and removed from the wetland, so are the nutrients within the plants and any sediment attached to the plants (Lenhart et al., 2012). The harvesting of wetland plants represented a mechanism for nutrient, sediment, and *E. coli* (sorbed to sediment or on harvested plants) reduction in the BMP. Also, by harvesting the wetland plants, there is a reduction in the potential mineralization and release of nutrients upon death of the plants (Lenhart et al., 2012). Other maintenance practices such as trash removal, preventing blockage of the inlet and outlet, and monitoring and removing excess sediment in the forebay, can improve the treatment efficiency and aesthetics of the wetland (Hunt & Lord, 2007). The *Bellamy* wetland was routinely maintained during the period of this study, and because the wetland was relatively new, the accumulated sediment did not need to be removed. These factors including a relatively large wetland area, below average rainfall, routine harvesting of wetland plants and other maintenance, may have contributed to the high nutrient and *E. coli* treatment efficiency of the wetland. As the watershed continues to develop, and the wetland ages and accumulates sediment, the nutrient and *E. coli* treatment efficiencies may decline.

The mean stormwater specific conductivity reduction from the wetland inlet to outlet (62%) was similar to the mean PO_4-P (63%) and geometric mean *E. coli* (59%) reductions, but lower than NO_3-N reduction (69%). Specific conductivity is influenced by the dissolved salt and solid content of waters (Allhajar et al., 1990), therefore as suspended and dissolved sediment moves from the inlet through the wetland towards the outlet, processes which remove sediment from the water such as sedimentation can also reduce the specific conductivity of water. Sedimentation may be a dominant removal mechanism for solids in the wetland, and a dominant mechanism for the reduction in specific conductivity of inflow stormwater. Both PO_4-P and *E. coli* can bind to solids, and thus be removed via sedimentation (Hunt, 1999; Davis et al., 2000; Characklis et al., 2005; Jamieson et al., 2005). The NO_3-N reduction efficiencies were higher (than PO_4-P, *E. coli*, and specific conductivity reductions) in the wetland possibly because of processes in addition to plant uptake and sedimentation acting to remove NO_3-N, such as denitrification (Bourgues & Hart, 2007). Denitrification is the microbial conversion of NO_3 to N_2 gas. Denitrification occurs in anaerobic environments such as natural and constructed wetlands, where labile carbon and NO_3 are abundant (Mitsch & Gosselink, 2000). This additional removal pathway for nitrogen in wetland environments, may explain why the NO_3-N reduction efficiencies were greater than PO_4-P and *E. coli* reduction efficiencies.

The mean inflow water temperatures were cooler during the summer months and warmer during the winter months than outflow water temperatures, possibly because of frontal systems that generated rainfall (Brooks et al., 2003). During the winter, the mean inflow water temperatures were warmer than outflow water temperatures possibly because of warm fronts that contribute relatively warm runoff to the wetland, while during the summer, cold fronts delivered relatively cool runoff to the wetland.

5. Conclusions

The stormwater wetland at the *Bellamy* housing complex was more efficient at reducing NO_3-N and PO_4-P than the reduction credits assigned by the State of NC. The high treatment efficiency of the wetland was most likely influenced by the large wetland to drainage area percentage (7%), the relatively low precipitation, the maintenance intensity, and age of the wetland. These factors most likely resulted in the wetland's high storage capacity and treatment efficiency for urban runoff. The PO_4-P and specific conductivity reduction percentages were similar (62 and 63%) possibly because sedimentation was a dominant reduction process for solids and PO_4-P. The NO_3-N treatment efficiency of the wetland exceeded the PO_4-P and *E. coli* treatment efficiency possibly because of the denitrification removal pathway that is specific to NO_3-N. A follow up study to monitor the wetland's nutrient and *E.coli* concentrations may be beneficial for determining the temporal variability of treatment.

Acknowledgments

The authors would like to thank the owners and managers of the *Bellamy* for allowing us to use their property for this study.

References

Alhajjar, B. J., Chesters, G., & Harkin, J. M. (1990). Indicators of chemical pollution from septic systems. *Ground Water, 28*(4), 559-568. http://dx.doi.org/10.1111/j.1745-6584.1990.tb01712.x

American Society for Microbiology. (1999). Microbial pollutants in our nation's water: Environmental and public health issues. *American Society for Microbiology*. Washington, DC.

Bourgues, S., & Hart, B. T. H. (2007). Nitrogen removal capacity of wetlands: sediment versus epiphytic biofilms. *Journal of Water Science and Technology, 55*(4), 175-182. http://dx.doi.org/10.2166/wst.2007.107

Brooks, K. N., Ffolliot, P. F., Gregerson, H. M., & DeBano, L. F. (2003). Hydrology and the management of watersheds (3rd ed.). 2121 Stave Avenue, Ames, Iowa, USA: Iowa State University Press.

Carleton, J. N., Grizzard, T. J., Godrej, A. N., & Post, H. E. (2001). Factors affecting the performance of stormwater treatment wetlands. *Water Research, 35*, 1552-1562. http://dx.doi.org/10.1016/S0043-1354(00)00416-4

Characklis, G. W., Dilts, M. J., Simmons III, O. D., Likirdopulos, C. A., Krometis, L. H., & Sobsey, M. D. (2005). Microbial partitioning to settleable particles in stormwater. *Water Research, 39*, 1773-1782. http://dx.doi.org/10.1016/j.watres.2005.03.004

Davies, C. M., & Bavor, H. J. (2000). The fate of stormwater associated bacteria in constructed wetland and water pollution control pond systems. *Journal of Applied Microbiology, 89*, 349-360. http://dx.doi.org/10.1046/j.1365-2672.2000.01118.x

Davis, A. P., Shokouhian, M., Sharama, M., & Minami, C. (2001). Laboratory study of biological retention for urban stormwater management. *Water Environmental Research, 73*, 5-14. http://dx.doi.org/10.2175/106143001X138624

Gu, B. H., & Dreschel, T. (2008). Effects of plant community and phosphorus loading rate on constructed wetland performance in Florida, USA. *Wetlands, 28*(1), 81-91. http://dx.doi.org/10.1672/07-24.1

Hathaway, J., Hunt, W., & Jadlocki, S. (2009). Indicator bacterial removal in storm-water best management practices in charlotte, North Carolina. *Journal of Environmental Engineering, 135*(12), 1275-1285. http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000107

Hathaway, J. M., Tucker, R. S., Spooner, J. M., & Hunt, W. F. (2012). A traditional analysis of the first flush effect for nutrients in stormwater runoff from two small urban catchments. *Water, Air and Soil Pollution, 223*, 5903-5915. http://dx.doi.org/10.1007/s11270-012-1327-x

Humphrey, C., O'Driscoll, M. A., & Armstrong, M. C. (2012). Onsite wastewater system nitrogen loading to groundwater in the Newport River watershed, North Carolina. *Environment and Natural Resources Research, 2*(4), 70-79. http://dx.doi.org/10.5539/enrr.v2n4p70

Hunt, W. F. (1999). *Urban waterways: urban stormwater structural best management practices*. North Carolina Cooperative Extension Service publication. AG-588.

Hunt, W. F., Burchell, M. R., Wright, J. D., & Bass, K. L. (2007). *Urban waterways: Stormwater wetland design and update: zones, vegetation, soil and outlet guidance*. North Carolina Cooperative Extension Service publication. AGW-588-12.

Hunt, W. F., & Lord, B. (2007). *Urban waterways maintenance of stormwater wetlands and wet ponds*. North Carolina Cooperative Extension Service publication. AGW-588-07.

Hvitved-Jacobsen, T., Yousef, Y. A., & Wanielista, M. P. (1989). Rainfall analysis for efficient detention ponds. Engineering Foundation Conference on Current Practice and Design Criteriafor Urban Quality Control. In L. A. Roesner, B. Urbonas, & M. B. Sonnen (Eds.), *Proceedings of the American Society of Civil Engineers* (pp. 214-222). Potosi, Missouri.

Jamieson, R., Joy, D. M., Lee, H., Kostaschack, R., & Gordan, R. (2005). Transport and deposition of sediment associated *Escherichia coli* in natural streams. *Water Research, 39*, 2665-2657. http://dx.doi.org/10.1016/j.watres.2005.04.040

Jenkins, G. A., & Greenway, M. (2005). The hydraulic efficiency of fringing versus bonded vegetation in constructed wetlands. *Ecological Engineering, 25*(1), 61-72. http://dx.doi.org/10.1016/j.ecoleng.2005.03.001

Johengen, T. H., & LaRock, P. A. (1993). Quantifying nutrient removal processes within a constructed wetland designed to treat urban stormwater runoff. *Ecological Engineering, 2*(4), 347-366. http://dx.doi.org/10.1016/0925-8574(93)90003-X

Kadlec, R. H., & Knight, R. L. (1996). *Treatment wetlands*. Boca Raton, Florida; CRC Press, Lewis Publishers.

Koskiaho, J., & Puustinen, M. (2005). Function and potential of constructed wetlands for the control of N and P transport from agricultural and peat production in boreal climates. *Journal of Environmental Science and Health, 40*, 1265-1279. http://dx.doi.org/10.1081/ESE-200055679

Kovacic, D. A., David, L. E., Gentry, K. M., Starks, K. M., & Cooke, R. A. (2000). Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. *Journal of Environmental Quality, 29*, 1262-1274. http://dx.doi.org/10.2134/jeq2000.00472425002900040033x

Lautier, J. C. (2001). *Hydrogeologic framework and ground-water conditions in the North Carolina central coastal plain* (p. 4). North Carolina Department of Environment and Natural Resources Division of Water Resources.

Lenhart, H., Hunt, W., & Burchell, M. (2012). Harvestable nitrogen accumulation for five storm water wetland plant species: Trigger for storm water control measure maintenance? *Journal of Environmental Engineering, 138*(9), 972-978. http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000550

Line, D. E., Jennings, G. D., Shaffer, M. B., Calabria, J., & Hunt, W. F. (2008). Evaluating the effectiveness of two stormwater wetlands in North Carolina. *Transactions of the ASABE, 51*(2), 521-528. http://dx.doi.org/10.13031/2013.24393

Martin, J. F., & Reddy, K. R. (1997). Interaction and spatial distribution of wetland nitrogen processes. *Ecological Modeling, 105*(1), 1-21. http://dx.doi.org/10.1016/S0304-3800(97)00122-1

Minitab Inc., State College, PA, 16801-3210, USA.

Mitsch, W. J., & Gosselink, J. G. (2000). *Wetlands* (3rd ed.). New York, NY: John Wiley & Sons Inc.

North Carolina Department of Environment and Natural Resources. (2001). *The Tar-Pamlico Stormwater Rule* (15A NCAC 2B .0258).

Raisen, G. W., & Mitchell, D. S. (1995). The use of wetlands for the control on non-point source pollution. *Water, Science and Technology, 32*, 177-186. http://dx.doi.org/10.1016/0273-1223(95)00618-4

Reed, S. C., Crites, R. W., & Middlebrooks, E. J. (1995). *Natural systems for waste management and treatment*. New York: McGraw-Hill.

Sophocleous, M. (2002). Interactions between groundwater and surface water: The state of the science. *Hydrogeology Journal, 10*, 52-67. http://dx.doi.org/10.1007/s10040-001-0170-8

State Climate Office of North Carolina. (2014). *Climate normals for Greenville, NC*. Retrieved November 10, 2013, from http://www.nc-climate.ncsu.edu/cronos/normals.php

Tilley, D. R., & Brown, M. T. (1998). Wetland networks for stormwater management in subtropical urban watersheds. *Ecological Engineering, 10*, 131-158. http://dx.doi.org/10.1016/S0925-8574(98)00010-X

United States Environmental Protection Agency. (2008). *Fecal coliform and E. Coli*. Retrieved November 21, 2013, from http://www.epa.gov/katrina/fecal.html

United States Environmental Protection Agency. (2009). *Macrophytes as indicators*. Retrieved November 6, 2013, from http://www.epa.gov/bioindicators/html/macrophytes.html

Wadzuk, B. M., Rea, M., Woodruff, H., Flynn, K., & Traver, R. G. (2010). Water-quality performance of a constructed stormwater wetland for all flow conditions. *JAWRA Journal of the American Water Resources Association, 46*(2), 385-394. http://dx.doi.org/10.1111/j.1752-1688.2009.00408.x

Yousef, Y. A., Wanielista, M. P., & Harper, H. H. (1986). *Best management practices-effectiveness of retention / detention ponds for control of contaminants in highway runoff*. Florida Department of Transportation, Gainesville, Florida.