

Final Report:

Pathogenic Bacteria in Coastal Waters, BMP Model Development, and Grassed Bioretention Research

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Principal Investigators:

William F. Hunt, III

Assistant Professor and Extension Specialist, NCSU Biological & Agricultural Engineering
and

Jon M. Hathaway,

(former) Extension Associate, NCSU Biological & Agricultural Engineering

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Executive Summary

This project was comprised of three distinct parts: (1) monitoring of six stormwater BMPs in Wilmington for pathogenic bacteria indicator species, (2) monitoring of two grassed bioretention cells in Graham, NC, and (3) the development of three spreadsheet based models to assist BMP designers. The models created were for bioretention, permeable pavement, and green roof design.

Six BMPs, including 2 bioretention cells, 2 wet ponds, and 2 stormwater wetlands were monitored in Wilmington, NC from mid June 2007 through mid August 2008. Surprisingly, due in great part to two factors: a substantial drought and limited laboratory hours, far fewer samples were collected than originally estimated. The median number of events sampled was 6 for the sites. Because of the limited data, we were unable to draw definitive conclusions about the performance; however, one of the two bioretention cells and one of the wet ponds appeared to perform the best. When pooling the data collected earlier in the City of Charlotte (Hathaway et al., 2008), *it does seem that deeper media bioretention cells provide the most pathogenic bacteria removal benefit of any BMP*. It needs to be noted, however, that the worst performing BMP in Wilmington was also a bioretention cell, but this cell had abnormally shallow soil media (approximately 12 inches).

The grassed bioretention cells examined in Graham were the first of their kind studied in the United States and their performance has garnered a substantial amount of international interest. Both of the cells studied, which were side-by-side performed extremely well with respect to TN and TP removal. Using two different metrics, percent removal and effluent concentrations, the two grassed cells in Graham performed as well or better than any bioretention system studied in North Carolina to this point. The percent TN removal for both cells was 54% and the two cells' TP removal were 58% and 63%. These removals are all the more impressive when considering the relatively clean inflow concentrations. *Based on this study, the tentative recommendation from NCSU to NC DENR is to allow grassed bioretention cells to be used in North Carolina*. One word of caution, however, is to make sure grassed bioretention cells do not fall victim to overzealous fertilizer applicators, who mistake them for “ordinary” grassed landscapes.

The final portion of the project was to develop three models to assist designers. The models were produced in summer 2007 by Dr. Albert Jarrett (Green Roofs), Mr. Ryan Smith (bioretention), and Ms. Kelly Collins (Permeable Pavement). That latter model has since been refined by Mr. Matthew Jones. All the models have been used as training tools at NC Cooperative Extension workshops and are available at www.bae.ncsu.edu/stormwater/downloads.

Project Deliverables

The project was comprised of four deliverables, all of which are listed below. Additionally, a brief description of how each was accomplished is given.

1. A report for NC DENR will detail the findings on pathogenic removal. If possible, i.e., if the data are conclusive, recommendations will be made regarding pathogenic bacteria removal abilities of each stormwater practice examined (stormwater wetlands, wet ponds, and bioretention).

The report is contained herein.

2. Two presentations at a local conference (e.g., WRI annual conference) and at a National Meeting (e.g., StormCon or ASCE-EWRI) will be made.

Two presentations were given in summer 2008 featuring work researched as part of this deliverable. One was delivered to the American Society of Civil Engineers – Environmental and Water Resources Institute in May and the second was given to the American Society of Agricultural and Biological Engineers in July. Dr. Hunt presented many of the findings at the NC Chapter of the American Public Works Association in Wilmington in September 2008.

3. A report on the performance of the two grassed bioretention cells will be provided to NC DENR-DWQ toward the end of Spring 2007. In it, BAE faculty will potentially recommend nutrient and fecal coliform removal efficiencies for grassed bioretention cells

NC DWQ officials were briefed on the project throughout the study and actually amended the BMP Design manual to include grassed bioretention cells, in part based on this research, in 2007. A journal article (which has since been accepted for publication in the ASCE Journal of Irrigation and Drainage Engineering) was given to Mr. Bradley Bennett and his colleagues in Summer 2007. The most recent copy is an appendix to this report.

4. Three models, made available on-line, that are design support tools for bioretention, permeable pavement and green roofs will be produced.

This was accomplished by October 2007. However, since then, the permeable pavement model has undergone some revision due to user feedback. All the models are available at www.bae.ncsu.edu/stormwater/downloads.

Project Component Discussion

The first and third objectives of the project are discussed in some detail below. The entire journal article that has been accepted by the *Journal of Irrigation and Drainage Engineering* is also attached as an appendix.

Pathogenic Bacteria Study in Wilmington, NC.

Background and Introduction

In the United States Environmental Protection Agency's National Water Quality Inventory in 2000, 13% of the river and stream miles that were surveyed were impaired by pathogen indicator bacteria (USEPA 2002). Pathogen transport from urbanized areas to nearby surface waters increases the risk to public health. This is a concern in both freshwater and marine environments. Many studies have examined the impact of bacterial pollution on ocean and estuarine environments, where pathogens transported in stormwater and polluted streams can persist long enough to be consumed in contaminated shellfish or ingested by swimmers. This results in an economic and public safety concern along North Carolina's coast (Figures 1a and 1b). For instance, according to the North Carolina Division of Marine Fisheries, over 32 million pounds of shellfish were commercially fished from North Carolina in 2007, a value of over 46 million dollars. Likewise, water quality is important in maintaining quality recreational beaches, as the North Carolina Department of Commerce estimated that 13% of the visitor activities in North Carolina in 2007 were beach visits.



Figure 1: (a) Closed shellfish waters in North Carolina (b) Posted warning sign at a North Carolina beach

Stormwater runoff is an important transport mechanism for pathogens to receiving waters. A study performed in North Carolina by Mallin et al. (2000) indicated that as the amount of impervious area in a watershed increases, the amount of indicator bacteria monitored in nearby receiving waters seems to increase. Impervious areas represent the presence of human activity and the associated

presence of pet and vermin waste. Impervious areas also generate large amounts of runoff that is quickly transported to nearby surface waters, carrying pathogens with it.

Urban stormwater is commonly treated by stormwater Best Management Practices (BMPs), each of which provides some combination of natural treatment mechanisms and fosters certain environmental conditions. Although BMPs have been studied in detail for many pollutants, little peer-reviewed literature is available which documents their ability to remove or inactivate pathogens. The majority of the BMP data associated with pathogen removal is available in a database format through the International Stormwater BMP Database (ISBD) (USEPA 2003; USEPA 2006). Based primarily on data entered into the ISBD, the USEPA (2003) concluded that pathogen removal is less understood than removal of other pollutants in stormwater BMPs. The data that have been collected have been primarily for sand filters, wetlands, and wet detention ponds. Further, the report highlights the variable performance that initial studies have shown with respect to BMP pathogen removal.

Monitoring Locations

This research project involved the monitoring of 5 stormwater BMPs in Wilmington, N.C., including a bioretention area (both shallow and deep underdrains were monitored), two wet ponds, and two wetlands. Illustrations of each BMP are provided in Figure 2. A summary of the watersheds being treated by the BMPs is provided in Table 1.

Port City Java Bioretention

This bioretention area services a small parking lot associated with a coffee shop and office building. The watershed is highly impervious and approximately 0.3 acres. Runoff is directed via sheet flow to two bioretention cells, one with an average media depth of approximately 12 inches (labeled “shallow”), and one with an average media depth of approximately 24 inches (labeled “deep”). Influent samples were taken from a small flume installed at the parking lot edge. Effluent samples were taken from 2 underdrains, each collecting drainage from one of the cells.

Stonestrow Stormwater Wetland

This stormwater wetland services a multi-unit residential watershed which contains substantial amounts of parking lot and roof top. The watershed is approximately 5 acres. The wetland has good vegetative growth and has a very low water level in between rain events, commonly only having ponded water in deep pools.

Laney Stormwater Wetland

Laney stormwater wetland receives runoff from approximately 31.4 acres of a school campus. This watershed contains sports fields, parking areas, and roof tops. This wetland has very good vegetative growth and does not dry out in between rain events as at Stonestrow. A normal pool is consistently maintained in this system.

Cinema Wet Pond

Cinema wet pond treats an approximately 11.6 acre watershed consisting primarily of a movie theater and its associated parking areas. Runoff also enters from a small building and parking lot alongside the pond. Inlet samples are collected from a well mixed area where the primary inlet from the movie theater and the secondary inlet from the adjacent building enter. Effluent samples

are taken from the riser structure of the pond. The drainage gradient away from the pond appears to be poor, resulting in the outlet structure having backwater and not maintaining a proper normal pool. Vegetative growth in the wetland is poor, with little observed around the perimeter.



Figure 2 – Illustrations of BMPs: Port City Java Bioretention (a), Stonestrow Stormwater Wetland (b), Laney High School Stormwater Wetland (c), Cinema Wet Pond (d), and Residential Wet Pond (e)

Residential Wet Pond

The Residential wet pond services an estimated 17.9 acres of residential watershed. The housing community which is treated by this pond asked to remain anonymous. The pond has a clearly

defined inlet and outlet from which samples were taken. There is little vegetation around the pond, which has maintained grass all the way down to the normal pool elevation along its banks.

Table 1: BMP Watershed Descriptions

BMP	Type	General Watershed Description	Approximated Watershed Area (acre)
Port City Java	2 Bioretention Cells	Commercial	0.3
Stonesthrow	Stormwater Wetland	Multi-unit Residential	5
Laney High School	Stormwater Wetland	Institutional	31.4
Cinema Pond	Wet Pond	Commercial	11.6
Residential Pond	Wet Pond	Residential	17.9

Monitoring Procedure

All monitoring for indicator bacteria was performed using grab samples. Sterilized bottles were obtained from Tritest™, a water quality analysis company with a branch office in Wilmington, NC. Samples were taken while flow from a given rain event was still occurring into and out of each BMP. For the wetlands and wet ponds, a sample collection was attempted in a well mixed location at both the inlet and outlet. The bioretention area inlet was sampled at either the parking lot edge or installed flume, whichever was most easily accessed. The bioretention effluent was sampled from the underdrain of each cell. Samples were placed on ice and delivered to the laboratory within 6 hours for analysis. *E. coli* and Enterococci were measured using the IDEXX defined substrate assay method. *E. coli* analysis using this procedure is based on standard method 9223B (APHA, 1998).

Problems Encountered

Numerous problems were encountered during the length of this study. The primary issue was the drought which was ongoing during much of the initial part of the study in the fall and winter of 2007, this left monitoring at a stand still for months. Compounding the effect of the drought was the stringent grab sampling and delivery requirements set established for this grant. Particularly for the bioretention area's watershed, where flows occur and subside quickly, it was important to reach the site during or immediately after a fairly sizable storm event. This was not always possible. When storms did occur, the 6 hour hold time set for the study, combined with the lab only operating during normal working hours, further restricted collection.

A number of changes were made during the course of the study also limited data collection. Fecal coliform was replaced with *E. coli* as an analyzed parameter to represent current EPA suggestions for indicator bacteria in both marine and fresh water systems. This resulted in a number of fecal coliform samples which had been taken being disregarded for the study. The laboratory also had to be directed to dilute samples from the BMPs, as an unacceptable reporting limit was originally present in the data set. Samples with this original reporting limit were also disregarded. Lastly, two sampling locations were removed and replaced during the course of the study. One of the original stormwater wetlands was found to potentially have reverse flow from an adjoining stream during storm events, thus providing an undesirable source of error in the study. Likewise, one of the original stormwater wet ponds did not have a consistent normal pool, having substantial infiltration

in between rain events. This resulted in infrequent outflow from the pond during rain events. Thus, outflow was not readily sampled and a replacement pond was chosen.

Results and Discussion

The number of samples collected for each site is summarized in Table 2. Samples which were analyzed under the original reporting limit (minimum = 1, maximum = 2420) were not considered for analysis. The reporting limits (once changed by diluting samples) were a minimum of 10 MPN / 100 ml and a maximum of 24200 MPN / 100 ml. If a reporting limit (maximum or minimum) was present in a given sample, the reporting limit was used as the sample value during the analysis. Statistical analysis was not performed as 8 or more samples (considered a reasonable data set) were not taken at any site for either indicator bacteria. Also, a sample event was only included in the sample set if a paired influent and effluent sample was taken.

Table 2: Sample Collection Locations – Number of Valid Samples

BMP	Type	Number of Samples Collected per NC DENR – DWQ	
		<i>E. coli</i>	Enterococci
Port City Java	2 Bioretention Cells	5	5
Stonethrow	Stormwater Wetland	6	6
Laney High School	Stormwater Wetland	6	7
Cinema Pond	Wet Pond	6	6
Residential Pond	Wet Pond	3	3

Removal efficiencies and geometric mean effluent concentrations were computed for each BMP (influent and effluent geometric means were used to calculate efficiency). Results of the efficiency analysis show that most of the BMPs had positive removal of both *E. coli* and enterococci. The Cinema wet ponds showed good removal of both indicator bacteria, having an efficiency of 87% and 82% for *E. coli* and enterococci, respectively. The shallow bioretention cell at Port City Java (average media depth approximately 12 inches) had the poorest performance, with negative removal of both *E. coli* and enterococci. This indicates that either bacteria being stored from previous rainfall events is persisting in the system or that bacteria are regenerating within the cell. In either case, there is an apparent flushing of bacteria during rain events. Laney wetland showed inconsistent performance, removing enterococci, yet increasing *E. coli* concentrations. Other BMPs (Port City Deep, Stonethrow, and the residential pond) showed a fair ability to treat stormwater for indicator bacteria, with greater than 35% removal in all cases. Only the Port City Deep bioretention and the Cinema Wet Pond had effluent concentrations below government-established means.

Table 3: Data Analysis Results

BMP	Type	Efficiency (%)		Geometric Mean Effluent (MPN / 100 ml)	
		<i>E. coli</i>	enterococci	<i>E. coli</i>	enterococci
Port City (Shallow)	Bioretention	-1493	-105	1273	776
Port City (Deep)	Bioretention	52	91	38	35
Stonesthrow	wetland	55	68	429	609
Laney	wetland	-31	41	269	770
Cinema	pond	87	82	169	95
Residential	pond	89	38	450	2517

These data can be compared to a similar study performed on stormwater BMPs in Charlotte, NC (Table 4) (Hathaway and Hunt, *in review*). The data from Charlotte were reevaluated, calculating removal efficiencies using geometric means as was done with the Wilmington data. There are some differences between the results of the two studies, with Laney performing worst for *E. coli* of all the wetlands evaluated. Stonesthrow wetland showed adequate (similar) removal compared to the BMPs in Charlotte, performing better than one wetland and worse than the other. The wet ponds in Wilmington performed better than the wet pond evaluated in Charlotte based on removal efficiency. The two Port City bioretention cells performed worse than the cell in Charlotte; however, the deep cell showed promise in removing greater than 50% of *E. coli* and very high removal of enterococcus.

Table 4: Data From Charlotte BMPs Evaluated for *E. coli*

Site	BMP Type	Efficiency (%)	Geometric Mean Effluent
Pierson	Wet Pond	46	1153
Edwards	Wetland 1	96	106
Bruns	Wetland 2	33	864
Hal Marshall	Bioretention	92	20

Analysis of the geometric mean effluent concentrations from these BMPs indicates that although there is positive removal of indicator bacteria in many of the BMPs, EPA target concentrations may not be met. The targeted *E. coli* concentration in fresh waters is 126 CFU / 100 ml. Only the deep bioretention cell was able to achieve a geometric mean effluent lower than this value. These results are similar to that of the BMPs studied in Charlotte, where only the bioretention area and one of the wetlands met the EPA criteria. For enterococci, the EPA standard is 33 CFU / 100 ml for fresh water and 35 CFU / 100 ml for marine waters. Although the deep bioretention cell was slightly higher than the fresh water standard, it was in the range of the standard for marine waters. Only one other practice (Cinema Wet Pond) had an effluent concentration within a factor of 3 of this standard.

Conclusions

The authors wish to remind the reader that fewer samples were collected and analyzed than initially expected. Because of the lack of data, we are unable to make definitive conclusions. However, there are some general trends that can be highlighted and agree with previously collected data from Charlotte, NC. The results of this study indicate that some stormwater BMPs are able to remove indicator bacteria from stormwater runoff. The variability in results from BMP to BMP is similar to that seen in the study performed in Charlotte, indicating that some BMPs may perform better than others and that there may be design characteristics which maximize removal of indicator bacteria. Unfortunately, little research has been performed on stormwater BMPs to determine what design features may be manipulated to increase indicator bacteria removal.

This study also indicates that although some BMPs provide positive removal of indicator bacteria, EPA standards may be difficult to achieve using many stormwater BMPs. This is evidenced by the small number of BMPs able to achieve water quality standards in both the Wilmington and Charlotte studies (2 total of 10 presented herein). Although bioretention areas show promise in both removing indicator bacteria and in achieving water quality goals, as evidenced in the deep port city cell and the Charlotte cell, the data collected from the shallow port city cell illustrate that design features may need to be adjusted to provide good removal. *In short, media depths greater than one foot may be needed for bacteria removal.*

Lastly, stormwater BMPs may be sources of indicator bacteria if conditions within the BMP are conducive for regrowth and persistence. Also, stormwater BMPs commonly attract wild and domestic animals, potentially adding another input to the system. This was noted in the Charlotte study and the Wilmington study for a number of BMPs.

Research regarding pathogen indicator bacteria transport, fate, and removal from urban environments is ongoing not only in North Carolina, but worldwide. Although some BMPs have shown promise in removing indicator bacteria, results are variable not only among various types of BMPs, but even between BMPs of similar classification. This highlights the need for more research on this subject which will further define what removes indicator bacteria in stormwater BMPs, and how design features can be manipulated to enhance removal of this pollutant.

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Grassed Bioretention Field Study in Graham, NC

Background

Many BMPs are able to reduce peak flows, runoff volumes and ground or surface water pollution by increasing evapotranspiration, infiltration while also providing pollutant removal processes. A type of BMP, the bioretention cell is used for infiltration, filtration and evapotranspiration. Bioretention is generally a shallow depression in the landscape acting as a vegetated soil filter. These cells are commonly covered with hardwood mulch and planted with different kinds of vegetation to meet aesthetic needs. Sub-surface underdrains facilitate infiltration through a fill media preventing the cells from being flooded for a long time. Bioretention cells have been found to substantially capture oil, grease, total suspended solids and heavy metals (Davis et al. 2001, Dietz and Clausen 2005, Hsieh and Davis 2005). Nutrient removal of bioretention systems is less systematically high (Hsieh and Davis 2005, Birch et al. 2005, Dietz and Clausen 2005, Hunt et al. 2006). Phosphorous desorption was found to occur for high phosphorus index (P-Index) fill media (Hunt et al. 2006). Up-turned underdrains can force water to remain longer in the fill media thus creating internal storage zones (ISZs). ISZs were previously shown to enhance nitrate reduction on column studies (Kim et al. 2003). This effect was not significant in a North Carolina field study (Hunt et al. 2006); whereas, Dietz and Clausen (2006) found that the presence of an ISZ could reduce TN and TP concentrations, but no effect was found for nitrate concentrations.

Grass has been increasingly considered as an alternative cover, for a different aesthetic value, simpler maintenance, and reduced installation costs. However, a lack of research data on a turf-vegetated bioretention system's pollutant removal efficiency generally prevents grass cover from being accepted by regulators, like NC DENR-DWQ. The objectives of this study were to analyze preliminary results on the efficiency of two grassed bioretention cells utilizing ISZs to capture nutrients and fecal coliform.

Methods

Two grassed (bermuda sod) bioretention cells (Fig. 1) were constructed in summer 2005 at Graham High School (Alamance County, North Carolina) and monitored from September 2006 to August 2007. Table 1 contains watershed and bioretention cell details. The 7100 m² drainage area was 40% impervious (primarily an asphalt parking lot) and included a large lawn portion (60%) separated from the cells by the parking lot. The BMP surface area to watershed area ratio was approximately 3.2%. Runoff from the drainage area collected in a forebay (Figure 2) and flowed over identical rectangular weirs into the northern (North) and southern (South) cells. Engineered fill media (80% Expanded slate from Carolina Stalite, 15% sand and 5% topsoil) depths were 0.75 and 1.05 m, for the North and South cells, respectively.



Figure 1. Grassed bioretention cell during a rain event.

Table 1. Watershed and bioretention cell characterization

Project Location	Graham, NC
Watershed	Cape Fear River/ Jordan Lake
Total catchment area	0.69 ha
Catchment % impervious	40 %
Catchment Composition	Student Parking Lot for Graham, NC, High School (35%) and a residential property (65%)
Individual bioretention cell surface area	102 m ²
Bioretention ponding depth	23 cm
Media depth	0.6 m – North Cell 0.9 m – South Cell
Depth of IWS	0.3 m – North Cell 0.6 m – South Cell
Media composition	80% Expanded Slate fines (Carolina Stalite) 15% Sand 5% Organic Matter (yard waste)
Surface cover type	Bermuda grass
Underlying Soil Type	Loamy Clay – North Cell Sandy Loam – South Cell
Underdrain outlet depth	30 cm below grass surface

Underdrains discharged water from the cells to a downstream creek. Both cells had media with a low phosphorus index (P-Index) of 5 (North) and 8 (South). Low values were also found for the cation exchange capacity (CEC, 6.0 (North) and 6.4 (South)) and the percent humic matter (%HM, 0.18% for both (North) and (South)). The native subsoils were loamy clay (North) and sandy loam (South). Up-turned underdrains were designed to force water to remain high in the fill

media; thus, inducing ISZs in all but the top 30 cm of the cells (Fig 3). The surface ponding of the cell was approximately 23 cm, and the surface hydraulic conductivity was approximately 15 cm/hr.



Figure 2. Forebay serving both of the bioretention cells. In the foreground (right) is one of the concrete weirs.



Figure 3. The upturned elbow flowing during a storm event. This designed allowed for more water capture and infiltration to the in situ soil.

ISCO 730 bubbler modules were used to collect 2-min interval water depth measurements at the two outlet 90 degree V-notch weirs and at the inlet 0.915 m long rectangular weir. Standard weir equations were used to determine the discharge rate from water depth. Bubbler modules at the inlet rectangular weirs helped measuring inflow volumes from September 24, 2006; it was

estimated by NRCS CN ($\lambda=0.05$) methodology (Mishra and Singh 2003; Woodward et al. 2003; Lim et al 2006) beforehand. Rainfall was measured on site by an ISCO tipping bucket rain gauge placed at a 2 m height. Bioretention cell hydrology was characterized by analyzing inflow and outflow volumes and antecedent dry periods. ISCO 6712 automated samplers collected flow-weighted composite samples to determine event mean concentrations (EMCs). The inlet sampler was triggered by a 5.1mm/6 hr rainfall intensity. Samples were analyzed for nitrate plus nitrite ($\text{NO}_{2,3}\text{-N}$), ammonia ($\text{NH}_4\text{-N}$), total Kjeldahl nitrogen (TKN), total nitrogen (TN), ortho-phosphorus ($\text{OPO}_4\text{-P}$) and total phosphorus (TP). Analytical methods followed U.S. EPA (U.S. EPA 1993) or APHA Standard Methods (APHA et al. 1998).

Organic nitrogen (ON) concentrations were estimated by subtracting $\text{NH}_4\text{-N}$ from TKN. For 7 storm events, grab samples were collected during the storm and immediately analyzed by the City of Graham Wastewater Treatment Plant to determine the amount of fecal coliforms (FC). For every pollutant (i) other than fecal coliform and for every storm event (j), loads (L_{ij} , mg/m^2) were calculated by equation (1):

$$L_{ij} = \text{EMC}_{ij} * \text{ROvolume}_j * 10^{-3} \quad (1)$$

where:

EMC_{ij} is the event mean concentration of pollutant i for storm event j (mg/L),
 ROvolume_j is the total runoff volume on a per m^2 basis for storm event j (m^3/m^2),

As suggested by Strecker et al. (2001), bioretention cell efficiencies were determined not only by calculating removal rates (η_i) for both EMCs and loads (equation (2)), but by providing and discussing effluent quality for EMCs and loads as well:

$$\eta_i = ((X_{in_i} - X_{out_i}) / X_{in_i}) * 100 \quad (2)$$

where X_{in_i} and X_{out_i} are the means of EMCs or loads for the inlet and the outlets (North or South), respectively, for constituent i.

During the monitoring period, the wettest months were June, November and July 2006 with 195, 127 and 140 mm, respectively; whereas, May 2006, May 2007 and August 2007 were the driest months with 46, 17 and 13 mm of rainfall, respectively. The monitoring period precipitation records were relatively similar to, though slightly drier than, normal rainfall data.

Multi-comparison tests (Ryan-Einot-Gabriel-Welsch REGWQ tests) were performed with SAS 9.1.3 w/SPATM software to detect potentially significant differences between concentrations and loads for North versus South cell effluents, inlet versus outlets and seasons. A level of significance (α) of 0.05 was considered. Concentration and load log-normality was assessed by Cramer-von Mises tests and probability plot observations. To avoid log-transformation problems, a 0.001 mg/L value (which is 5 times lower than the lowest value recorded) was substituted for values below detection limit.

Results and discussion

Hydrology

Inflow volumes, the sum of direct rainfall and runoff volumes, were not significantly higher than the sum of North and South outflow volumes. However, for most of the events, the

bioretention cells reduced the volumes between the inlet and both outlets. This difference is attributed to water storage in the fill media, exfiltration below the underdrains and evapotranspiration. Overall, 2-minute peak inflows were reduced by the bioretention cells probably due to water storage in the fill media, which dampened flow rates.

Outflow rates were calculated for 16 (North) and 13 (South) storm events. For three storm events which occurred in March and April 2007, outflow peaks were higher than inflow peaks. For short antecedent dry periods, some water still remaining in the fill media could have been flushed from the system. For large storm events (e.g. the 60.2 mm rainfall event of April 17, 2007), an under-estimation of inflow peak could have occurred. Overall, low (18 (North) and 14 (South) %) average peak reductions were found.

Water Quality

Table 2 summarizes water quality and statistical results for the inlet and the two outlets of the bioretention cells.

Table 2. Influent and effluent EMCs (mg/L) and loads (mg/m²) and significant differences

Constituent		Average EMCs or Loads			Inlet Log- normal.	Significant differences			%reduc	
		IN	N	S		Inlet/N	Inlet/S	N/S	N	S
TKN	EMCs	1.106+/- 0.78	0.567+ /-0.25	0.452+ /-0.05	Log	Yes p<0.0001	Yes p<0.0001	No	49	59
	Loads	6.917+/- 7.49	3.564+ /-1.97	2.208+ /-5.18	Log	Yes p<0.0001	Yes p<0.0001	No	48	68
NH ₃ -N	EMCs	0.342+/- 0.28	0.103+ /-0.1	0.055+ /-0.05	Log	Yes p=0.0003	Yes p=0.0003	No	70	84
	Loads	1.967+/- 2.73	0.439+ /-0.52	0.241+ /-0.54	Log	Yes p<0.0001	Yes p<0.0001	No	78	88
NO _{2,3} -N	EMCs	0.419+/- 0.23	0.281+ /-0.17	0.384+ /-0.19	Not log	Yes p=0.0036	No	No	33	8
	Loads	3.150+/- 3.06	1.781+ /-3.23	3.108+ /-7.81	Not log	No	No	No	43	1
TN	EMCs	1.662+/- 0.97	0.759+ /-0.33	0.757+ /-0.29	Log	Yes p<0.0001	Yes p<0.0001	No	54	54
	Loads	11.077+/ -10.92	4.831+ /-7.46	5.887+ /-13.12	Log	Yes p<0.0001	Yes p<0.0001	No	56	47
TP	EMCs	0.137+/- 0.10	0.051+ /-0.02	0.058+ /-0.02	Log	Yes p<0.0001	Yes p<0.0001	No	63	58
	Loads	0.850+/- 0.82	0.399+ /-0.63	0.273+ /-0.58	Log	No	No	No	53	68
OPO ₄ -P	EMCs	0.057+/- 0.07	0.013+ /-0.004	0.015+ /-0.001	Log	Yes p=0.0009	Yes p=0.0009	No	78	74
	Loads	0.259+/- 0.26	0.124+ /-0.25	0.061+ /-0.17	Log	No	No	No	52	77
FC	Concent.	4172+/- 7141	125+/- 171	646+/- 849	-	-	-	-	95	85

NH₄-N, NO_{2,3}-N and TN concentrations and loads were analyzed for 26 and 18 storm events, for the North and South cells, respectively; whereas, TKN and TP results were both based on 13 (North) and 10 (South) storms. Apart from NO_{2,3}-N EMCs, all inlet nutrient EMCs and loads were log-normally distributed ($\alpha=0.05$).

Ammonia

Ammonia EMC removal rates were 70 and 84 % and load reductions were 78 and 88% for the North and South cells, respectively. Mean effluent EMCs and loads were significantly lower (0.103 (North) and 0.055 (South) mg/L) than those measured in the runoff (0.342 mg/L). If the fill media had had a high organic matter content (OM), the media could have been a source of ammonia created by OM decomposition. This was not noticed in this study, reaffirming that the soil had a low OM content. NH₄-N was probably removed by nitrification suggesting that aerobic biological processes took place in the fill media. The top portion (30 cm) of the fill media was not impacted by the ISZ. Therefore, it presented less frequent and shorter saturation periods. Consequently, nitrification would have easily occurred on this portion. These results were higher than those found by Hsieh and Davis (2005) who reported a maximum of 49% ammonia EMC reduction in a field bioretention cell, but they are similar to those found studying large pilot bioretention systems (Davis et al. 2001) (79 %) and a field rain garden monitored by Dietz and Clausen (2005) (84.6 %).

Total Kjeldhal Nitrogen

Effluent TKN EMCs (0.567 (North) and 0.452 (South) mg/L) and loads were significantly lower than runoff TKN values (inlet EMCs was 1.106 mg/L). Average TKN concentration reductions were 49 (North) and 59 (South) %, and TKN load removal rates were 48 (North) and 68 (South) %. Moreover, median effluent TKN EMCs (0.460 (North) and 0.459 (South) mg/L) were one order of magnitude lower than those presented in the international BMP database (GeoSyntec Consultants and Wright Water Engineers, Inc. 2006). Previous studies found moderate TKN EMC and load removal rates ranging from 50 to 65% (Davis et al. 2006, Birch et al. 2005); whereas, other studies' results were lower (Hunt et al. 2006). TKN reduction is partially due to the high NH₄-N conversion to NO_{2,3}-N. In addition, the results showed that organic nitrogen concentrations decreased by 39 (North) and 48 (South) %. It indicates that little ammonification, the generation of additional NH₄-N, took place into the soil.

Nitrate-Nitrite

Average removal rates of NO_{2,3}-N EMCs were approximately 33 % for the North cell, leading to significantly lower effluent EMCs (0.281 mg/L) than those of the influent (0.419 mg/L). However, the South cell removal rates were not as pronounced with 8% (EMCs) and 1 % (loads) and did not show any significant different. The trend showing higher removal rates found for the North cell may be partly attributed to North cell in-situ soil (clay) which was expected to provide a wetter fill media than the South cell (sandy loam in-situ soil), thus being more likely to retain anaerobic conditions for longer periods of time. Carbon sources in each cell were the same, eliminating this as a factor to explain the differences. Moreover, nitrate reduction by denitrification requires organic matter as an energy source for microorganisms and an anaerobic environment. It was previously shown that little organic matter was present in the fill media. Hunt et al. (2006) found 75 and 13 % nitrate concentration reduction in two conventionally drained bioretention cells with high and low OM content, respectively. Kim et al. (2003) studied nitrate reduction through

column experiments including a submerged zone. These experiments were conducted at 22°C with seven types of electron donors (alfalfa, newspapers, leaf mulch compost, sawdust, wood chips, wheat straw and sulphur). The authors showed the importance of the presence of an easily metabolizing carbon source for nitrate removal. Several laboratory (Davis et al. 2001 and 2006) or field studies (Dietz and Clausen 2005, Hsieh and Davis 2005, Birch et al. 2005 and 2006) also found little nitrate removal and in some cases nitrate exportations by bioretention systems. Median effluent NO_{2,3}-N EMCs (0.275 (North) and (0.402 (South) mg/L) were lower than those of the international BMP database (GeoSyntec Consultants and Wright Water Engineers, Inc. 2006). This indicates that the grassed bioretention cells, probably partly due to the presence of ISZs, were able to improve NO_{2,3}-N effluent quality.

Total Nitrogen

TN concentration average removal rates were 54% for both cells and mean effluent EMCs were 0.759 (North) and 0.757 (South) mg/L. Median effluent concentrations (0.729 (North) and 0.778 (South) mg/L) were in the range of TN median EMCs presented in the international stormwater BMP database (GeoSyntec Consultants and Wright Water Engineers, Inc. 2006). EMCs and loads from the underdrains were significantly lower than those of TN influent. TN reduction is mainly explained by TKN capture and NO_{2,3}-N conversion in the North cell.

Phosphorous species

Average TP EMC reductions were close to 60 % for the whole monitoring period and mean effluent concentrations were 0.051 (North) and 0.058 (South) mg/L both being significantly lower than influent EMC (0.137 mg/L). Phosphorous removal occurs in the top soil media layer which was essentially the same in the North and South cells. This is the reason why effluent concentrations were so similar. Median TP concentrations (0.049 (North) and 0.056 (South) mg/L) were one order of magnitude lower than those presented in the international stormwater BMP database (GeoSyntec Consultants and Wright Water Engineers, Inc. 2006). It therefore shows that even with relatively clean influent (0.137 mg/L), the bioretention cells were able to sequester TP. OPO₄-P concentrations were also significantly reduced between the inlet and both outlets with mean removal rates of 78 and 74% for the North and South cells, respectively. In addition, effluent mean OPO₄-P EMCs remained relatively low (0.013 (North) and 0.015 (South) mg/L). This is mainly due to the bioretention fill media's low P-Indices indicating that adsorption sites are still available for OPO₄-P immobilization.

Table 3. Comparison of effluent concentrations from select studies in North Carolina¹. All units in mg/L.

	Graham N	Graham S	Charlotte	Louisburg 1	Louisburg 2	Greensboro 1	Greensboro 2
TN	0.759	0.757	1.14	1.32	1.16	4.38	5.23
TP	0.051	0.058	0.13	0.24	0.25	0.56	3.00

¹ All cells examined, except those in Graham, were vegetated by trees and shrubs and covered in hardwood mulch.

Table 3 summarizes previous studies' outflow concentrations for TN and TP found for conventionally vegetated (trees, shrubs and mulch) bioretention cells in North Carolina. Compared to these studies, the Graham, NC, cell effluent concentrations were low suggesting that this system,

including a grass cover, a stalite fill media and an ISZ, seems to be at least as able as mulch and vegetation to reduce nutrient species.

Overall, the results showed that the North cell trended to be slightly more efficient than the South cell to reduce concentrations of nitrogen and phosphorous species. This is counter-intuitive to the fact that the North cell fill media depth (0.75m) is shallower than that of the South cell (1.05m). Bioretention depth was demonstrated to be an important parameter of phosphorous removal (Davis et al. 2001), when under approximately 0.6 to 0.8 m (Davis et al. 2006). However, overall North outflow concentrations presented herein (from a 0.75 fill media depth) were not significantly different ($\alpha=0.05$) from S outflow concentrations (from a 0.75 fill media depth). Moreover, it should be noted that fewer samples were collected from the North cell during the fall 2006 due to the absence of outflow or because of equipment malfunction. When only considering the storms producing water quality results for both cells, it appeared that South cell efficiencies were generally lower than those found for the North cell. Therefore, it seems that a 0.75 m depth above a clayey soil, could provide at least comparable if not more nutrient removal than a 1.05 m depth placed on a sandy loam soil, probably due to longer periods of saturation.

Fecal coliform

Fecal coliform grab samples were collected during 7 and 4 storm events for the North and the South cells, respectively. Inflow concentrations ranged from 220 to more than 20,000 col/100 mL and effluent concentrations ranged from 2 to greater than 1890 col/100mL. Individual event removal rates ranged from 13 to nearly 100% for both cells and the average fecal coliform concentration reductions were 95 (North) and 85 (South) %. Outflow concentrations exceeded the standard limit of 200 col/100 mL (USEPA 2006) for 3 of the 4 samples for the South cell and for one of the 7 samples of the North cell. Fecal coliform die-off is expected with sunlight and dry soils. The grassed cells, contrary to commonly vegetated bioretention systems, were nearly never shaded. Moreover, the cells rapidly drained at the surface. Few studies have assessed bioretention cell efficiencies to remove FC. Some published results also indicated moderate (Birch et al. 2006) to high (Birch et al. 2005, Hunt et al. 2008) reduction of FC. Other studies (Harrison et al. 2000, Barrett 2003) show very high FC sequestration for sand filter systems, which are related to bioretention. Due to the limited number of samples coupled the inherent variability on the enumeration method, the fecal coliforms sequestration results could not be stated with any statistical certainty. However, the study shows promising results for the ability of grassed bioretention cells to reduce fecal coliforms and pathogenic bacteria as a whole.

Conclusions

These preliminary results showed that, despite the likely source of nutrients due to grass decay and mowing, both grassed bioretention cells effectively removed nutrient species when using either an EMC reduction or effluent quality metric. The observed ammonia reduction bodes well for fill media mainly comprised of material like expanded slate that contain a low OM content. Because it has limited OM content, this media is unlikely to generate additional minerals. The grassed bioretention cells had promising fecal coliform reduction rates but some effluent concentrations were higher than the state limit. Overall, volumes and peak flows were reduced through the bioretention systems, but this was not systematic. The ISZ seemed to improve expected denitrification, particularly during the warm and humid seasons. However, under fall and winter climatic conditions, this effect is less evident and a higher hydraulic contact time could probably

provide better NO_{2,3}-N removal. The importance of the underlying, in situ, soil needs to be further explored. The shallower cell (North, 0.75 m fill media depth) overlaying a tighter clay soil provided better pollution abatement than a 1.05 m deep (South cell) overlying a sandy loam in situ soil. It is probable that the ISZ in the former bioretention cell stayed saturated, and therefore anaerobic, for a longer duration explaining why NO_{2,3}-N concentrations were substantially lower leaving the North cell. The probable lack of an anaerobic zone may explain why influent and effluent NO_{2,3}-N concentrations were roughly the same for the South cell. Increasing the media depth from 0.75 to 1.05 m did not further reduce nutrient concentrations. When comparing effluent concentrations, the system of a grass vegetated bioretention cell with an expanded slate fill media containing ISZs performed favorably to other conventionally vegetated (trees, shrubs and mulch) bioretention cells studied in North Carolina.

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Outcomes and Conclusions

The main outcomes and conclusions are segregated by theme: pathogen research in Wilmington, grass-covered bioretention in Graham, and the development of computer simulation design models. Certain "key" points for each study are emphasized with italics.

Pathogens in Stormwater:

- Not enough data were collected in Wilmington to make definitive recommendations.
- The bioretention cell classified as "deep," that is, it nominally had 2 ft of fill depth and one of the two wet ponds appeared to work the best at pathogen reduction.
- The poorest performance of any BMP was the "shallow" bioretention (1 ft of fill depth). *This indicates that there may be a minimum fill media depth required for pathogen treatment.*
- Only one of the six BMPs studied had effluent with pathogen concentrations at or below government-recommended standards ("deep" bioretention cell). *This indicates it might be difficult for BMPs to fully meet government prescribed standards.*
- Clearly, more research is needed and is intended to be conducted with a subsequent grant funded by WRRI's stormwater consortium.

Grassed Bioretention

- Grassed bioretention cells studied in Graham performed at least as well as (if not better than) other bioretention cells with documented performance in North Carolina. In addition to the grass/turf covering, the cells were comprised of Carolina Stalite fill and had a pair of Internal Water Saturation zones.
- *NC State cautiously recommends NC DENR allow bioretention to be turf covered; although, some concerns remain with long term maintenance and the potential for grassed cells to be inadvertently fertilized.*
- The presence of IWS appeared to improve the performance of bioretention in Graham. While earlier study in Greensboro did not indicate a benefit to having IWS, *this study does imply that the presence of an IWS will improve reduction of most pollutant loads.*
- The Graham cells reduced fecal coliform concentrations to a substantial degree, echoing earlier findings from a cell in Charlotte, NC.

Model Development

- Three models have been developed and have since been employed, to varying degrees, across North Carolina.

- The permeable pavement model has gained the most acceptance, and is used by several communities to verify that proposed applications earn runoff reduction credit. The city of Wilmington, for example, has used the model to verify the designs of at least 35 permeable pavement applications since January 2008.

Budget

Projected Budget

Item	Descriptions	319 (h) Funds Requested*	Non- federal Match	Total
Salary/fringe	<u>Grant Supported:</u> Mr. Jon Hathaway Ms. Kelly Collins Ms. Elodie Passeport Dr. Albert R. Jarrett Mr. Shawn Kennedy Mr. Robert A. Brown Mr. Matthew P. Jones Mr. Jason D. Wright <u>Match:</u> William F. Hunt Dwane L. Jones Mitchell Woodward	37,480	22,423	59,903
Fringe	25% of above	9,370	5,606	14,976
Travel	Travel to/from project sites (Wilmington, Graham). Conference presentations	4,475		4,475
Supplies & Materials	Wood and metal for monitoring assemblies	200		200
Laboratory Analysis	Water quality sample analysis for projects in Graham and Wilmington	11,229		11,229
Direct charges		62,754	28,029	90,783
Match indirect (10%)* NCSU portion			\$2803	\$2803
Indirect charges (10%)		6,275		\$6275
Under recovered indirect (17.3%)			\$10,857	\$10,857
Total		\$69,029	\$41,689	\$110,718

Actual Budget (please note that this project was under-budget.)

Item	Descriptions	319 (h) Funds Applied*	Non-federal Match	Total
Salary/fringe	<u>Grant Supported:</u> Mr. Jon Hathaway (Wilmington project management and bioretention model design) Ms. Kelly Collins (Permeable pavement model design) Ms. Elodie Passeport (Graham project data collection and analysis) Dr. Albert R. Jarrett (Green Roof model design) Mr. Shawn Kennedy (data collection and monitoring support) Mr. Robert A. Brown (Graham project data collection) Mr. Matthew P. Jones (Permeable Pavement model revision) Mr. Jason D. Wright (Initial Wilmington project management) <u>Match:</u> William F. Hunt (Overall project manager) Dwane L. Jones (assistance in Wilmington) Mitchell Woodward (assistance in Graham)	\$29,186	\$22,423	\$51,609
Fringe	25% of above	\$3,749	\$5,606	\$9355
Travel	Travel to/from project sites (Wilmington, Graham). Conference presentations	\$3,595		\$3595
Supplies & Materials	Wood and metal for monitoring assemblies	\$304		\$304
Laboratory Analysis	Water quality sample analysis for projects in Graham and Wilmington	\$7,116		\$7,116
Direct charges		\$43,951	\$28,029	\$90,783
Match indirect (10%)* NCSU portion			\$2803	\$2803
Indirect charges (10%)		\$4,395		\$6275
Under recovered indirect (17.3%)			\$7603	\$7603
Total		\$48,346	\$38,435	\$85,780