Indicator Bacteria Removal in Storm-Water Best Management Practices in Charlotte, North Carolina

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Abstract: Water quality degradation due to pathogen pollution is a major concern in the United States. Storm-water runoff is an important contributor to the transport of indicator bacteria from urbanized watersheds to nearby surface waters. With total maximum daily loads being established to reduce the export of indicator bacteria to surface waters, storm-water best management practices (BMPs) may be an important tool in treating indicator bacteria in runoff. However, the ability of these systems to remove indicator bacteria is not well established. A study in Charlotte, N.C., monitored nine storm-water BMPs (one wet pond, two storm-water wetlands, two dry detention basins, one bioretention area, and three proprietary devices) for fecal coliform and *Escherichia coli* (*E. coli*). A wet pond, two wetlands, a bioretention area, and a proprietary device all removed fecal coliform with an efficiency higher than 50%; however, only the wetlands and bioretention area had significantly different influent and effluent concentrations ($p < 0.05$). For *E. coli*, only one of the wetlands and the bioretention area provided a concentration reduction greater than 50%, both of which had a significant difference in influent and effluent concentrations ($p < 0.05$). Only one of the nine BMPs had a geometric mean effluent concentration of fecal coliform lower than the U.S. EPA target value, while four of the nine BMPs had geometric mean effluent concentrations lower than the U.S. EPA standard for *E. coli*. This study showed that some BMPs may be useful for treatment of indicator bacteria; however, other BMPs did not perform well. Because wet, nutrient-rich environments exist in many storm-water BMPs, there is a potential for indicator bacteria to persist in these systems.

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Introduction

Pathogen pollution is a contributor to water quality degradation and is an obstacle to the goal of the Clean Water Act "to restore and maintain the chemical, physical, and biological integrity of the nation's waters." In the U.S EPA's (U.S. EPA 2002) National Water Quality Inventory in 2000, 13% of the river and stream miles that were surveyed were impaired by indicator bacteria. Furthermore, of the stream and river miles designated as impaired, either unable or partially unable to meet their designated use, more were impacted by indicator bacteria than by any other pollutant or stressor (U.S. EPA 2002). In light of the negative impact that indicator bacteria and other pollutants have on surface waters in the United States, total maximum daily loads (TMDLs) have been established to reach water quality goals in impaired water bodies.

Indicator species are used to test for the presence of harmful pathogens in surface waters. While these species may not be harmful to humans themselves, their presence in surface waters can indicate contamination from the fecal matter of warm-blooded animals. Fecal matter can contain harmful intestinal viruses, bacteria, and protozoa (U.S. EPA 2001). Various indicator bacteria have been used to assess water quality degradation due to pathogens including: total coliform, fecal coliform, *Escherichia coli* (*E. coli*), and enterococci. In 1986, the U.S. EPA's Ambient Water Quality Criteria for Bacteria report (U.S. EPA 1986) discussed the merits of these various indicator species and set criteria whereby *E. coli* and enterococci were recommended for use as indicators in freshwater environments and enterococci was suggested as an indicator in marine environments. These criteria stated that for fresh waters designated for use as full body contact recreational waters, the geometric mean over a 30-day period should not exceed 126 /100 mL for *E. coli* and should not exceed 33 /100 mL for enterococci. For similarly designated marine waters, the geometric mean over a 30-day period should not exceed 35/100 mL for enterococci.

A literature review by Wade et al. (2003) concluded that the U.S. EPA bacteria standards set forth for marine waters was supported by the available literature. For fresh waters, Wade et al. (2003) indicated that *E. coli* was a more consistent predictor of gastrointestinal illness than any other indicator. Despite this, fecal coliform remains a commonly used bacteria indicator for surface waters. In 1976, the U.S. EPA recommended fecal coliform standards where the log mean over a 30-day period should not exceed 200 /100 mL (colony forming units per 100 mL) and no more than 10% of the samples should exceed 400 /100 mL. As of 2003, 18 states had adopted the *E. coli* standard for fresh water, six states adopted the enterococci standard for fresh waters, and nine

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states had adopted the enterococci standard for marine waters (U.S. EPA 2003a).

Storm-water runoff is an important transport mechanism for indicator bacteria to receiving waters. Indicator bacteria come from both human and animal (domestic and wild) sources, and are transported via runoff to nearby water bodies. A study by the Municipality of Anchorage Watershed Management Services (MOAWMS) (2003) found that these transport mechanisms vary based on land use, type of storm-water conveyance system, and the degree of stream modification. The study by MOAWMS indicated that fecal coliform loading was high in runoff that originates from landscapes associated with densely urbanized areas drained by curb and gutter. Schoonover and Lockacy (2006) showed a similar trend in a study of 18 mixed land use watersheds in west Georgia and indicated that watersheds consisting of greater than 24% imperviousness exhibit higher fecal coliform concentrations than watersheds with impervious percentages less than 5% during both base and storm flow.

Storm-water runoff from urbanized areas can increase indicator bacteria concentrations in nearby surface waters, suggesting an increased risk to public health. This is a concern in both freshwater and ocean environments. A substantial amount of research has examined the impact of bacterial pollution on ocean environments, likely due to the economic and public safety concerns associated with shellfish waters and recreational ocean beaches. In Santa Monica Bay, California, Haile et al. (1999) showed an increased risk of health effects to swimmers located closer to storm drain outlets, noting that higher levels of bacterial indicators were found near the storm drain.

Indicator bacteria can be removed from or inactivated in surface waters and storm water through a number of treatment mechanisms, such as ultraviolet light (from sunlight), sorption, sedimentation, and filtration. Additionally, as living organisms, various environmental factors, such as temperature, moisture conditions, and salinity, can impact the ability of indicator bacteria to survive in a given natural environment (U.S. EPA 2001; Schueler 2000; Arnone and Walling 2007; Davies-Colley et al. 1994). Urban storm water is commonly treated by storm-water best management practices (BMPs), each of which provides some combination of treatment mechanisms and provides a certain set of environmental conditions. Storm-water BMPs include wet ponds, dry detention basins, wetlands, bioretention areas, and proprietary devices. Proprietary, or manufactured, devices use some combination of baffles, swirl flow patterns, settling chambers, filtration, and other means to separate floatable and settleable solids from storm-water runoff.

Although BMPs have been studied in detail for many pollutants, little peer-reviewed literature is available which documents their ability to remove or inactivate indicator bacteria. The majority of the BMP data associated with indicator bacteria removal is available in a database format through the International Stormwater BMP Database (ISBD) (U.S. EPA 2003b). Based primarily on data entered into the ISBD, the U.S. EPA (2003b) concluded that BMP performance with respect to indicator bacteria is less understood than for other pollutants. The data that have been collected have been primarily for sand filters, wetlands, and wet detention ponds. Furthermore, the paper highlights the variable performance that initial studies have shown with respect to BMP indicator bacteria removal. This is a concern as storm-water BMPs are commonly used to achieve TMDLs in impaired surface waters. The functionality of storm-water BMPs for indicator bacteria removal is important in determining if nonpoint source indicator bacteria can be treated using these devices.

Although a number of studies have been performed on indicator bacteria removal in wetlands receiving wastewater (Karim et al. 2004; Vymazal 2005; Perkins and Hunter 2000; Ghermandi et al. 2007; Quiñónez-Diaz et al. 2001), few peer reviewed studies have been performed on indicator bacteria removal in wetlands receiving storm-water runoff. Birch et al. (2004) collected a limited number (four) of samples during high flow events at a storm-water wetland in Sydney, Australia. The mean fecal coliform removal in the wetland was 76% with a range of 26–98%. The average fecal coliform outflow concentration for each of the wetlands was higher than the U.S. EPA target value of 200 /100 mL. Similar mean removal was found by Davies and Bavor (2000) in a study of a storm-water wetland receiving residential storm water in New South Wales, Australia. The wetland mean removal of fecal coliform (called thermotolerant coliform in the study), enterococci, and heterotrophic bacteria was 79%, 85%, and 87%, respectively. The mean effluent concentration of fecal coliform was 3,600 col/100 mL. It should be noted that Sydney, Australia, and Charlotte, N.C., exhibit similar rainfall totals and distributions from month to month [Australian Bureau of Meteorology (ABM) 2008; State Climate Office of North Carolina (SCO-NC) 2008].

A wet pond receiving residential storm-water runoff was also monitored in the study by Davies and Bavor (2000). Mean removal of fecal coliform (thermotolerant coliform), enterococci, and heterotrophic bacteria was −2.5%, 23%, and 22%, respectively. Davies and Bavor (2000) associated the poor performance of the wet pond, relative to the wetland, to its poor removal of fine clay particles, to which the bacteria were "predominately absorbed." The mean effluent concentration of fecal coliform was 8,100 col/100 mL. Research was also performed on three wet ponds in Wilmington, N.C., by Mallin et al. (2002). The ponds were sampled monthly, regardless of whether the pond discharge was base flow or storm flow. The writers did not report the percentage of samples associated with wet weather. The average fecal coliform removal in the three ponds was 56%, 86%, and −13%, and a correlation was observed between fecal coliform concentrations and rainfall occurring within 24 h of a given pond being sampled. The average effluent fecal coliform concentrations for the three wet ponds was 70, 43, and 85 col/100 mL, respectively; however, only one of the wet ponds had an average influent fecal coliform concentration higher than the U.S. EPA targeted value of 200/100 mL (488 col/100 mL). These studies suggest some variability in wet pond performance with regard to indicator bacteria removal.

A more detailed study was performed by Struck et al. (2008) in an evaluation of indicator bacteria removal in wetlands and wet ponds using mesocosms. Results of the study suggested that indicator organism concentrations decreased exponentially over time in mesocosms subjected to storm water, which had been manipulated to increase bacterial concentrations. Struck et al. (2008) also examined factors contributing to this decay, indicating that temperature, light exposure, time, and other effects can impact indicator bacteria concentrations in simulated storm-water wetlands and wet ponds. Other effects included oxygen-reduction potential, pH, dissolved oxygen, and conductivity.

A study by California Department of Transportation (CALTRANS) (2004) evaluated the performance of five dry extended detention basins. Four of the dry detention basins were unlined and one was lined with concrete. The average fecal coliform concentration reduction was −122% for the unlined basins and −12% for the lined basin. Average effluent fecal coliform concentrations were 2,000 most probable number

Table 1. Watershed and BMP Summaries

Site	Watershed size (ha)	Description	Estimated curve number	Estimated BMP surface area (ha)
Dry Detention 1	2.4	Office park—buildings and parking	85	0.04
Dry Detention 2	1.5	Office park—buildings and parking	94	0.07
Pond	48.6	Residential	75	0.31
Wetland 1	21.0	Residential	80	0.25
Wetland 2	6.4	Residential and school	83	0.13
Bioretention	0.4	Municipal parking lot	98	0.02
Proprietary 1	0.3	Bus maintenance facility—parking and overhead shelters	98	n/a
Proprietary 2	0.9	Bus maintenance facility–parking and overhead shelters	98	n/a
Proprietary 3	0.9	Bus maintenance facility–parking and overhead shelters	98	n/a

Note: n/a=not applicable.

(MPN)/100 mL and 7,500 MPN/100 mL for the unlined and lined basins, respectively. Little discussion is provided as to the reason for the poor performance of these systems. Conversely, a study by Harper et al. (1999) evaluated the performance of a dry detention basin in Debary, Fla. The basin was drained via a perforated PVC pipe, which was surrounded by sand. The overall system showed a 98% removal of fecal coliform.

Bioretention areas have not been studied in detail with respect to indicator bacteria. The bioretention area studied as part of the City of Charlotte Pilot BMP Program was documented extensively by Hunt et al. (2008), and no other field studies were found in which bioretention indicator bacteria removal was evaluated. However, a bioretention column study performed by Rusciano and Obropta (2007) examined indicator bacteria removal in simulated bioretention areas. The bioretention columns were loaded with diluted manure slurry with influent fecal coliform concentrations ranging from 2.3×10^7 to 2.3×10^3 colony forming units (cfu)/100 mL. The average fecal coliform removal for 13 simulations over a 9-month period was approximately 96%, and leachate effluent mean concentrations ranged from 3.3×10^5 to 2.0×10^1 cfu/100 mL. Bioretention areas are expected to perform similarly to sand filters, which were evaluated for fecal coliform removal in a study by Barrett (2003). Five sand filters had a fecal coliform influent event mean concentration (EMC) of 11,200 MPN/100 mL and an effluent EMC of 3,900 MPN/100 mL, a reduction of 65%.

Zhang and Lulla (2006) studied two hydrodynamic separation devices in Providence, R.I., for 12 storm events. Indicator bacteria removal in Systems 1 and 2 were determined to be 42% and 62%, respectively, for *E. coli* and 73% and 39%, respectively, for fecal coliform. The study noted that sediments within the device had higher concentrations of indicator bacteria than the sump water, concluding that resuspension of indicator bacteria from captured sediments could occur, potentially reducing removal efficiency below that reported. Additionally, Zhang and Lulla (2006) concluded that low biochemical oxygen demand (BOD) concentrations (less than 10 mg/L), and thus low nutrient concentrations, in the sump water of the device would make indicator bacteria regeneration unlikely. A study by CALTRANS (2004) also evaluated the performance of a proprietary device, showing fecal coliform removal efficiencies of −121%. Little discussion is provided on the poor performance of the system.

Due to the limited amount of literature pertaining to indicator bacteria removal by storm-water BMPs, more research is needed to aid communities throughout the United States in reaching their target indicator bacteria TMDL. Determining which BMPs are capable of efficient indicator bacteria reduction will result in more effective watershed restoration programs. More specifically, if *E. coli* becomes established as the primary indicator bacteria in fresh water, *E. coli* sequestration and removal must be established for a suite of storm-water BMP types, including wet ponds, dry detention, storm-water wetlands, bioretention, and proprietary devices.

Materials and Methods

Description of Sites

The storm-water BMPs evaluated in this project were monitored as part of the Charlotte-Mecklenburg Stormwater Services (CMSS) Pilot BMP Program. This program was developed, in part, to evaluate various types of BMPs within the city of Charlotte, to gather local BMP performance data. As part of the Pilot BMP Program, grab samples were taken and analyzed for both fecal coliform and *E. coli* from 12 storm-water BMPs. A viable data set, chosen to be six or more storm events with paired influent and effluent samples, was collected for two dry detention basins, one pond, two storm-water wetlands, one bioretention area, and three proprietary BMPs. The characteristics of these BMPs are given in Table 1.

Storm-water BMPs are designed for a number of purposes. BMPs such as dry detention basins and ponds are normally designed to attenuate peak flows from larger storm events and are often constructed in relatively large watersheds. Bioretention areas and proprietary devices are often sited in small highly impervious watersheds. Bioretention areas offer little mitigation of peak flows during extreme storm events, but provide temporary capture and treatment of smaller "water quality" rain events. In North Carolina, and several other states, the water quality event is 2.5 cm (1 in.) of precipitation [North Carolina Department of Environment and Natural Resources (NCDENR) 2007]. This is a common design parameter for determining the capture volume required for a given storm-water BMP. Proprietary devices are commonly placed in storm-water conveyance pipes and provide some treatment of runoff over a wide range of storm events using methods that allow the water to flow through without being detained. Storm-water wetlands can be constructed to detain larger storm events in sizable watersheds; however, they are commonly designed to treat the water quality event, as was the case for the Charlotte storm-water wetlands. Due to variable intended function, design specifications for each type of BMP differ, making normalization problematic. However, these BMPs were selected because they were representative of the types of BMPs common to the city of Charlotte and elsewhere.

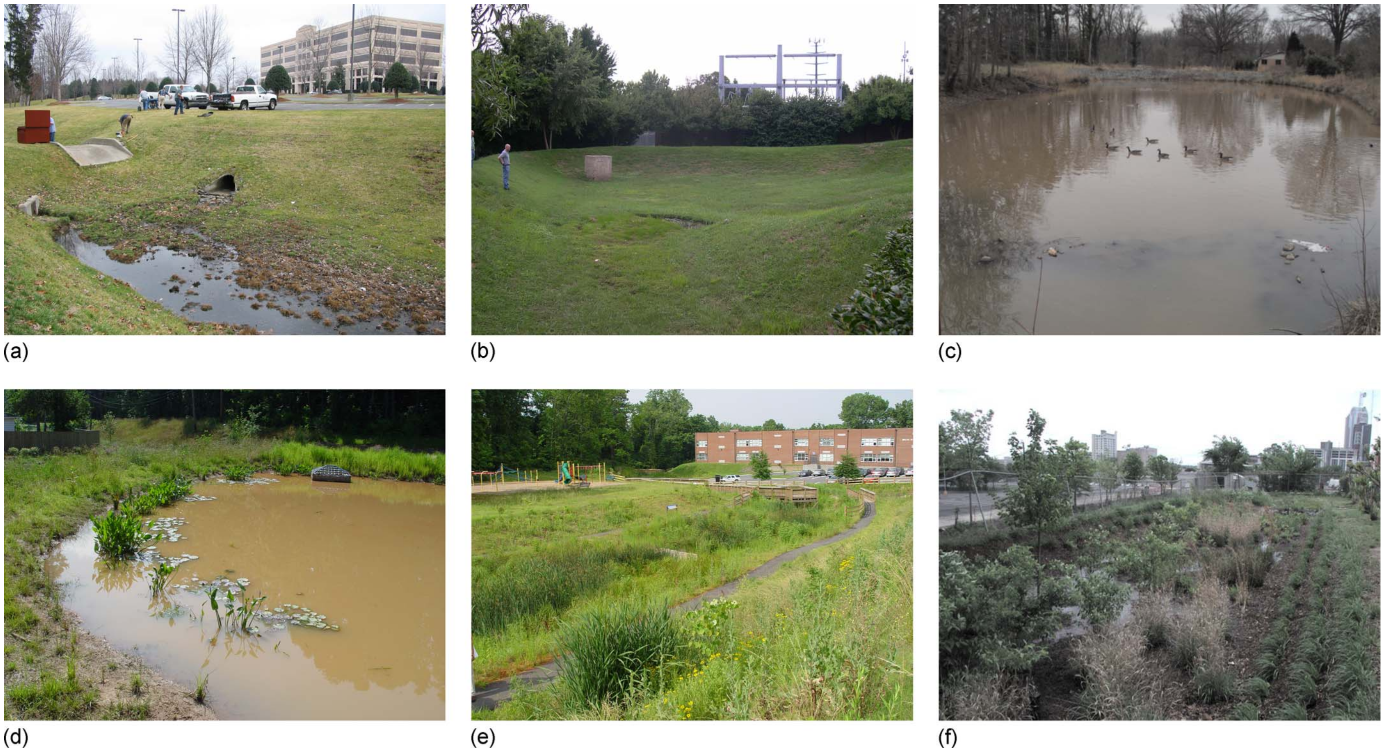

Fig. 1. Illustration of (a) Dry Detention 1 (DD1); (b) Dry Detention 2 (DD2); (c) wet pond (WP); (d) Wetland 1 (WL1); (e) Wetland 2 (WL2); and (f) bioretention (BR)

Dry detention basins fill with runoff during storm events and provide temporary detention while slowly draining in approximately 48 h. The primary pollutant removal mechanism in these systems is sedimentation. Dry detention 1 [Fig. 1(a)] received runoff from a 2.4-ha watershed comprised of an office park and its associated parking areas, landscape features, and buildings. The dry detention facility was well vegetated with grass and had good sun exposure. There was some evidence of erosion and sedimentation within the facility. Dry detention 2 [Fig. 1(b)] was sited in a similarly sized watershed, 1.5 ha, also comprised of an office park. Like Dry Detention 1, this facility had good sun exposure, was well vegetated with grass, and had evidence of some erosion and sedimentation. Both facilities appeared to be mowed frequently. CMSS staff noted the frequent presence of birds around the basins, with bird droppings found on the boxes which housed flow and water quality sampling equipment.

Wet ponds work on the principle of plug flow, whereby, influent runoff enters the pond and theoretically replaces captured runoff from prior events. Sedimentation in wet ponds is a major pollutant removal mechanism, but some treatment is also provided via other mechanisms such as oxidation-reduction reactions, plant uptake, and adsorption due to contact among the soils, vegetation and captured storm water. The wet pond that was monitored in this study [Fig. 1(c)] was fed by a small perennial stream. This pond received storm-water runoff from a 48.6-ha watershed that was primarily residential. This pond was likely not originally created for storm-water management and was constructed with no detention component. The estimated age of the pond was between 50 and 70 years old. Waterfowl were frequently observed at the pond during site visits. The pond was retrofitted in the late 1990s to include a littoral shelf; however, the shelf was not planted and exhibited little vegetation during the study period. Despite the presence of trees around the BMP, there was good sunlight exposure on the pond.

Wetlands are commonly installed as water quality devices, treating small (2.5 cm) storm events. These BMPs promote sedimentation like wet ponds, but provide more exposure of captured storm water to wetland soils and plants in a shallow system. Wetland 1 [Fig. 1(d)] received storm water from an approximately 21-ha residential area. This wetland exhibited common wetland topography, and consisted predominantly of shallow water depths averaging 18 cm. During the course of the study, however, there was very little vegetation in the wetland, likely due to poor soil conditions, prolonged periods of high water levels due to slow drainage after storm events, and the impact of waterfowl grazing. This lack of vegetation resulted in a larger amount of full sun exposure to water in the wetland than would typically be expected for wetlands. Waterfowl, particularly ducks, were commonly observed at this site. Wetland 2 [Fig. 1(e)] was constructed with similar topography, but exhibited exceptional plant growth. Wetland 2 received storm water from a 6.4-ha watershed consisting of residential area and a school. This wetland had two inlets, thus, average influent fecal coliform and *E. coli* concentrations were calculated by weighting the grab samples at each inlet based on the proportion of the total flow they contributed. A description of the flow monitoring at Wetland 2 is in the "Monitoring Methods" section of this paper. A portion of the watershed was localized, draining to the wetland via overland flow. This overland flow was not monitored, which could represent some errors for this site. Wildlife was observed at Wetland 2 during the study. Both wetlands were fed by watersheds containing a large amount of residential area, likely meaning the presence of domestic animals, and leading to a bacterial contribution from pet waste (Young and Thackston 1999; Mallin et. al 2000).

Bioretention areas function as filtration and infiltration BMPs. Storm water enters the system and passes through a permeable soil media where pollutants are filtered, as is seen commonly in sand filter systems. The system may pond water as much as 6–12 in.; however, it is drained within 12–24 h. The system is intended to dry out between storm events. The Bioretention monitored in this study [Fig. 1(f)] received runoff from a highly impervious 0.4-ha parking lot. The parking lot was used primarily as parking for employees and visitors of the Mecklenburg County (NC) Social and Environment Services. This bioretention cell was studied and described in detail by Hunt et al. (2008). On at least one occasion, a diaper was observed in the parking lot, providing a potential source of bacteria to the BMP. Additionally, trees in the parking lot attracted birds, and evidence of bird droppings were observed by CMSS staff. Sun exposure in the BMP was fair, as it was limited by fairly dense vegetation.

All three proprietary systems were installed at the Charlotte Area Transit System Bus Operations Maintenance Facility. The watersheds were small (Table 1) but highly impervious, and consisted of bus parking areas and some overhead metal shelters. These systems were underground and thus received no sunlight. Proprietary 1 worked by passing runoff through a system where floatable and settleable solids were separated and captured. Proprietary 2 worked by forcing influent flows into a swirl pattern where settleable and floatable solids were forced to the center of the system and into a separation chamber. Proprietary 3 worked by routing storm water through a series of chambers where floatable solids were captured and sedimentation occurred. In Proprietary 3, flows were controlled to allow treatment in each chamber during small storm events, while larger flows were treated only in one chamber before exiting the system.

Monitoring Methods

Due to the small sample hold times required of bacteriological samples, CMSS staff collected grab samples for fecal coliform and *E. coli* examinations (U.S. EPA and ASCE 2002) from each site during rainfall events. The only site with more than one inlet was Wetland 2, where the influent bacteria concentration was estimated by weighting the two influent grab samples based on approximate proportions of flow. One inlet was monitored for flow by monitoring stage changes over a 120° v-notch weir using an ISCO Avalanche automated sampler equipped with an ISCO 730 bubbler flow module (Teledyne ISCO, Lincoln , Nebraska). The second inlet was monitored for flow using an ISCO Avalanche automated sampler equipped with an ISCO 750 area velocity flow module installed in a 24-in. RC pipe.

Standard Method 9060 for microbiological examination [American Public Health Association, American Water Works Association, and Water Environment Federation (APHA, AWWA, and WEF) (1998)] was followed for sample collection. Samples were taken using disposable, sterilized sample bottles which contained tablets of sodium thiosulfate (a chlorine-neutralizing compound). A sample of at least 100 mL was taken and stored on ice while being transported to the Charlotte Mecklenburg Utilities Laboratory for analysis. A maximum hold time of 6 h between sample collection and delivery to the laboratory was adhered to. Samples were tested for fecal coliform using Standard Method 9222D, while *E. coli* was examined using Standard Method 9223B (American Public Health Association 1998). For fecal coliform, 12% of the influent samples and 21% of the effluent samples were either less than the limit of detection (LOD) or exceeded the maximum reporting limit (MRL). For *E. coli*, 38% of the influent samples and 33% of the effluent samples were either less than the LOD or exceeded the MRL.

One inherent source of error in analyzing samples for indicator bacteria is the dilution sometimes performed as part of the sample analysis procedure (U.S. EPA 2003c). Undiluted samples often contain indicator concentrations too high to be estimated using these analysis methods. To achieve test results which provide adequate readings of indicator bacteria, samples are often diluted to allow analysis of samples with higher concentrations. Unfortunately, storm-water samples have a wide range of indicator concentrations from storm to storm, as seen in this study. Therefore, a standard dilution is difficult to apply as the appropriate dilution differs among storms. For a given storm event, selecting the appropriate dilution is an iterative process, requiring that multiple analyses be performed. If an appropriate dilution is not selected, the analysis will provide some insight into actual concentration of a given pollutant, but the results will have a MRL or LOD meaning that the analysis can only conclude that the actual concentration is above or below some reporting limit as constrained by the dilution that was selected. For fecal coliform, the LOD was typically 100 col/100 mL and the MRL varied based on the dilution used for a given sample. For *E. coli*, the LOD was 10 MPN/100 mL and the MRL was 2,400 MPN/100 mL. Data are analyzed herein using the values at the reporting limit without manipulation.

Bacteria grab samples were collected at the various sites between March 2004 and October 2006. A grab sample was taken from both the inlet and outlet of each BMP per precipitation event. An effort was made to take grab samples during the rising limb of the storm event, but this was not always the case. The monitoring period and number of samples collected at each site varied (Table 2). *E. coli* was not initially tested for in the bacteria grab samples, but was later added as a parameter.

Statistical Analysis

To adequately describe the indicator bacteria sequestration and removal performance of each BMP, various analyses were performed. The mean concentration method was used to gain some understanding of each BMP's ability to remove the influent indicator bacteria. This method is similar to that used in determining the efficiency ratio; however, in determining the efficiency ratio, event mean concentrations are required (U.S. EPA and ASCE 2002). Obviously, when analyzing data generated from grab samples, this is not possible.

Although evaluating BMP efficiency based *solely* on methods such as the mean concentration method or the efficiency ratio is not suggested (Strecker et al. 2001; U.S. EPA and ASCE 2002), these methods do provide a simple estimation of the percent of a given pollutant treated by the BMP, on a concentration basis, relative to what the practice received during the storms that were monitored. There are inherent errors in these methods, as the data set may include samples from storm events that are abnormal in some manner, and thus artificially raise or lower the true BMP efficiency. Additionally, grab samples may not accurately portray BMP effectiveness if pollutant concentrations in the influent or effluent vary throughout the course of the storm. The mean concentration method was used to generate a concentration reduction efficiency (CR); however, geometric means were used in lieu of arithmetic means as is common in indicator bacteria data manipulation [Eq. (1)].

Table 2. Monitoring Period and Number of Samples Taken at Each Study Location

Site	Start	End	Number of samples tested for fecal coliform	Number of samples tested for *E. coli*
Dry Detention 1	February 2005	July 2006	9	9
Dry Detention 2	January 2005	December 2005	12	12
Wet Pond	August 2004	April 2006	14	10
Wetland 1	March 2004	June 2005	9	6
Wetland 2	September 2004	December 2005	15	10
Bioretention	August 2004	March 2006	19	14
Proprietary 1	October 2005	October 2006	7	7
Proprietary 2	October 2005	October 2006	6	6
Proprietary 3	October 2005	October 2006	6	6

$$CR = 1 - \left(\frac{\text{Geometric Average Outlet Concentration}}{\text{Geometric Average Inlet Concentration}}\right) \quad (1)$$

To supplement the mean concentration method, the effluent probability method was also employed (U.S. EPA and ASCE 2002). A Kolmogorov-Smirnov test was performed to determine a usable distribution of the data prior to additional statistical analysis. As part of the effluent probability method, data were transformed into the correct distribution and were tested for significant differences between the influent and effluent bacteria concentrations using a nonparametric Wilcoxon signed rank test. Probability plots were generated to evaluate BMP performance over the entire concentration spectrum that was observed in the data set (Burton and Pitt 2002). Lastly, the geometric mean effluent concentrations of fecal coliform and *E. coli* leaving each site were compared to the maximum 30-day geometric mean for each indicator as established by the U.S. EPA for full body contact (U.S. EPA 1986; U.S. EPA 1976).

The LOD and MRL present for the samples likely had some impact on the results of these analyses. In general, fecal coliform data were most often affected by the LOD, generally 100 col/100 mL as discussed earlier. *E. coli* data were most often affected by an MRL of 2,400 MPN/100 mL. The impact of these limits were more prevalent in some of the BMPs that others. The MRL associated with *E. coli* is considered more problematic, as there is no way to tell how high the actual indicator bacteria count is above 2,400 MPN/100 mL. For fecal coliform, the minimum reading must be somewhere between 0 and 100 col/00 mL. The use of geometric means and nonparametric statistics lessens the impact of the LOD and MRL, as they tend to be less sensitive to extreme observations. This is important as the LOD and MRL place lower and upper limitations on such observations.

Results and Discussion

Concentration Reduction Efficiency

CR values were developed for each site for both fecal coliform and *E. coli* (Table 3). The CR shows which BMPs were potentially adding bacteria to the storm-water drainage system. Any indicator bacteria increase was potentially due to either animal activity or from bacteria entering the flow stream from within the BMPs.

For the majority of BMPs, a similar reduction (or addition) in concentration was noted for both fecal coliform and *E. coli*; however, some BMPs exhibited dramatically different concentration reductions for these two indicators. This was possibly due, in part, to the difference in the number of samples taken for each indicator bacteria at a given site; however, even for sites with the same number of fecal coliform and *E. coli* samples, variations in the CR calculated for each indicator bacteria existed (such as Proprietary 1). This indicates that data generated for BMP removal of fecal coliform may not be consistent with BMP removal of *E. coli* in all cases. A study by Struck et al. (2008) on wetland and wet pond mesocosms showed various indicator bacteria may have different inactivation rates as a result of various environmental factors. These factors included temperature, sunlight, and sedimentation.

For fecal coliform, the wet pond, Wetland 1, Wetland 2, bioretention, and Proprietary 1 exhibited greater than 50% removal. The fecal coliform removal determined for Wetland 1 and Wetland 2, 0.98 and 0.56, was similar to that found by Birch et al. (2004). Conversely, only one of the three wet ponds studied by Mallin et al. (2002) showed fecal coliform removal equal to or greater than 70%. It should be noted that the fecal coliform CR determined for the bioretention (0.89) was higher than the reduction (65%) reported for sand filters by Barrett (2003). For *E. coli*, only Wetland 1 and the bioretention provided high (>50%) concentration reductions, with the wet pond providing slightly lower reductions with a CR of 0.46.

Overall, Wetland 1 and the bioretention seemed to be the most proficient at reducing influent concentrations of both kinds of bacteria. Wetland 1 had a substantial amount of sun exposure due to poor vegetation establishment, possibly leading to higher die

Table 3. Indicator Bacteria Concentration Reduction (CR) Efficiency for BMPs in Charlotte, N.C.

BMP type	Number of fecal samples	Efficiency fecal coliform (%)	Number of *E. coli* samples	Efficiency *E. coli* (%)
Dry Detention 1	9	−0.45[a]	9	−0.22
Dry Detention 2	12	−0.20	12	0.00
Wet Pond	14	0.70	10	0.46
Wetland 1	9	0.98	6	0.96
Wetland 2	15	0.56	10	0.33
Bioretention	19	0.89	14	0.92
Proprietary 1	7	0.59	7	−0.02
Proprietary 2	6	−0.57	6	−2.69
Proprietary 3	6	−0.62	6	−0.07

[a]Negative values indicate an increase in concentration.

Table 4. Wilcoxon Signed Rank Results for Fecal Coliform

BMP type	Distribution	Rank sign	Significant?
Dry Detention 1	Lognormal	0.1484	No
Dry Detention 2	Lognormal	0.4131	No
Wet Pond	Lognormal	0.1099	No
Wetland 1	Lognormal	0.0039	**Yes**
Wetland 2	Lognormal	0.0132	**Yes**
Bioretention	Lognormal	0.0001	**Yes**
Proprietary 1	Lognormal	0.1250	No
Proprietary 2	Lognormal	0.2500	No
Proprietary 3	Lognormal	0.3750	No

Table 5. Wilcoxon Signed Rank Results for *E. coli*

BMP type	Distribution	Rank Sign	Significant?
Dry Detention 1	Normal	0.1484	No
Dry Detention 2	Lognormal	0.4131	No
Wet Pond	Lognormal	0.1099	No
Wetland 1	Lognormal	0.0039	**Yes**
Wetland 2	Lognormal	0.4609	No
Bioretention	Lognormal	0.0015	**Yes**
Proprietary 1	Lognormal	0.1250	No
Proprietary 2	Lognormal	0.2500	No
Proprietary 3	Lognormal	0.3750	No

off rates. Additionally, storm-water wetlands and bioretention areas facilitate sedimentation and, in the case of bioretention, filtration and relatively low soil moisture. This assertion is supported by Kibbey et al. (1978) who showed that soils even at field capacity had higher rates of bacteria die off than those that stayed saturated.

The poorest performing BMPs were the two dry detention basins. Both basins showed negative removal of fecal coliform, similar results to those of CALTRANS (2004). Although the basins had good sun exposure, they remained moist for a substantial period of time after each rain event per observation by CMSS staff. It is possible that the wet soil provided an environment where the indicator bacteria could survive for an extended period of time, as was the case in a study performed by Karim et al. (2004) on wetlands receiving wastewater. Karim et al. (2004) found that sediments within the wetland provided an environment where bacterial survival was prolonged. Animal activity was also noted in the basins by CMSS staff, most notably, bird feces was observed. It was likely that the dry detention basins were attracting animals and potentially providing an environment where indicator bacteria could persist.

Due to the limited number of samples collected at the site, evaluation of the proprietary devices was minimal. Initial results showed an increase in fecal coliform at two of the three devices and increases in *E. coli* at each site. Similar fecal coliform increases were determined for a proprietary system monitored by CALTRANS (2004). There was a consistent source of water and nutrients in the two proprietary devices, which may have allowed the bacteria to persist and possibly be exported from the system during subsequent rain events. It should be noted that Proprietary 1 performed well with respect to fecal coliform concentration reduction and likely would have had significantly different influent and effluent concentrations if more storm events had been collected at the site. However, Proprietary 1 performed poorly from a removal efficiency standpoint with respect to *E. coli*. It should be noted that the proprietary devices, particularly Proprietaries 1 and 2, had low influent concentrations of both fecal coliform and *E. coli* relative to the other BMPs, potentially contributing to the low CRs for these systems. It should also be noted that these proprietary systems were not filter based, as is the case with some proprietary devices.

Wilcoxon Signed Rank Test

The results of the Wilcoxon signed rank test supported the CR observations with the exception of fecal coliform removal in Proprietary 1. For fecal coliform, the influent concentration was significantly higher ($p < 0.05$) than the effluent concentration for the two wetlands and the bioretention area (Table 4). For *E. coli*, only Wetland 1 and the bioretention had significantly ($p < 0.05$) higher influent than effluent concentrations (Table 5).

Influent and Effluent Probability Plots

Probability plots [Figs. 2(a–i) and 3(a–i)] were used to compare BMP performance (effluent concentration) for a wide range of influent concentrations. Fig. 2 shows the fecal coliform probably plots for each BMP. The plots for the Bioretention and Wetland 1 demonstrate the effectiveness of these BMPs over a wide range of influent concentrations. Samples at the outlet of the bioretention frequently were below the LOD. The effluent fecal concentrations of Wetland 1 were also consistently low. At very high influent concentrations, the bioretention seemed to show reduced performance; however, a similar trend was not observed in Wetland 1, which performed well at all influent concentrations.

The probability plots for the dry detention basins [Figs. 2(a and b)] showed inconsistent performance throughout most concentrations, with increases noted at low concentrations. Two of the proprietary devices also typically performed poorly [Figs. 2(h and i)], showing little to no difference between influent and effluent concentrations. At high concentrations, Proprietary 1 seemed to function effectively; however, Proprietary Devices 2 and 3 showed decreased performance at high concentrations. Probability plots for Proprietaries 1 and 2 [Figs. 2(g and h), respectively) showed that the fecal coliform influent concentration for each was much lower relative to the other BMPs tested, probably limiting the device's ability to improve concentrations. The wet pond [Fig. 2(c)] and Wetland 2 [Fig. 2(e)] exhibited modest fecal coliform concentration improvements throughout the entire plot, but the wet pond provided more consistent removal among the various influent concentrations, particularly at low concentrations. The Wet Pond and Wetland 2 generally produced effluent fecal coliform concentrations well above the 200/100 mL standard.

Probability plots were also generated for each BMP for *E. coli* (Fig. 3). These plots illustrate the difficulty of bacteria analysis when reporting limits exist. As seen on Plots 3a–3e, an MRL was normally present at an *E. coli* count of 2,400 MPN/100 mL. Reporting limits can make analysis difficult, particularly when influent and effluent concentrations are similar. On such plots, evaluating the performance of a system when receiving high *E. coli* concentrations can be difficult or impossible, as no distinction can be made between the influent and effluent concentrations.

Despite the reporting limits evident in these probability plots, the bioretention and Wetland 1 seemed to perform well with respect to *E. coli*, as was the case with fecal coliform. Both systems showed consistent performance over a range of influent *E. coli* concentrations. Wetland 1 received influent *E. coli* concentrations that were consistently at or above the reporting limit, whereas the

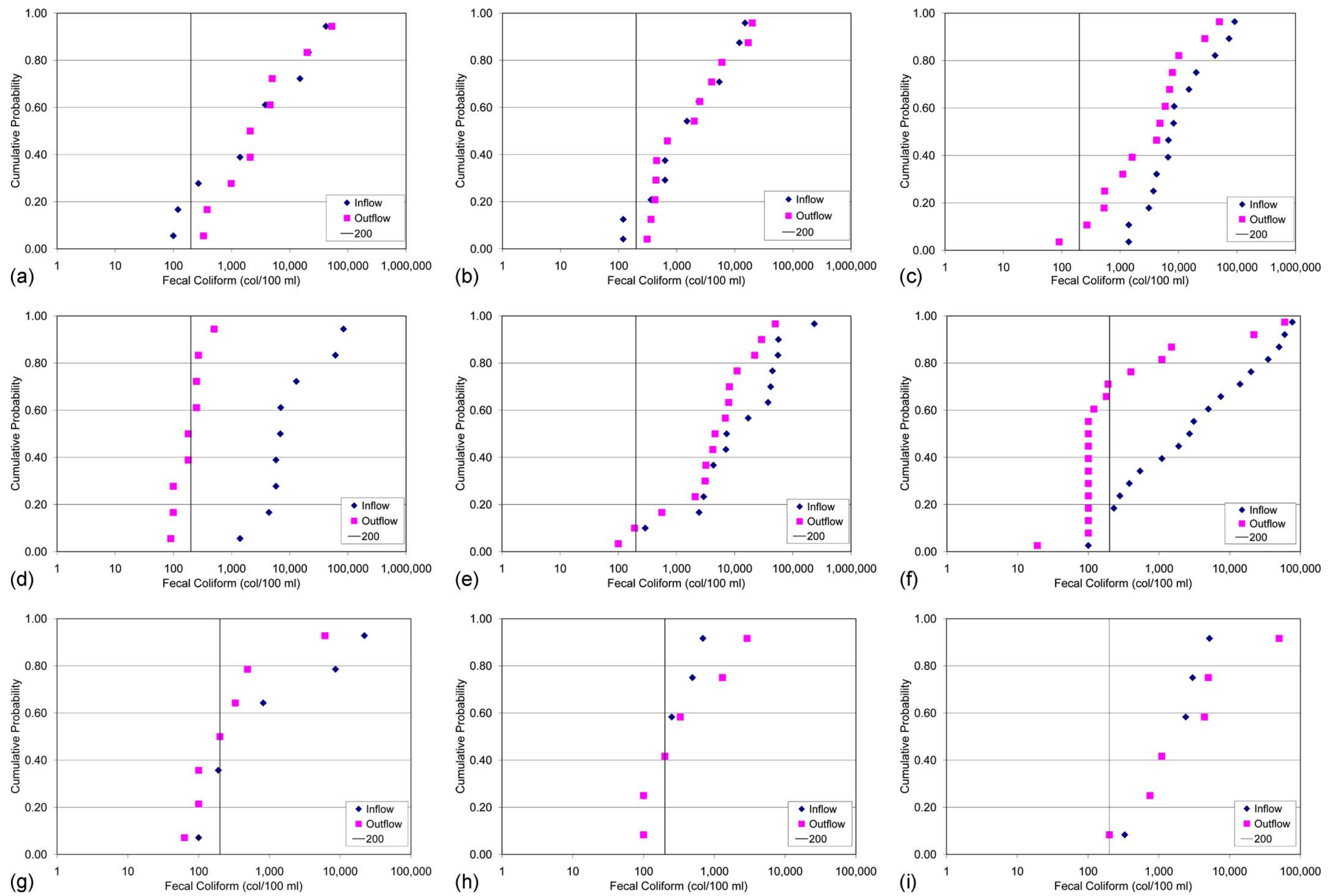

Fig. 2. Fecal coliform influent and effluent probability plots for (a) Dry Detention 1(DD1); (b) Dry Detention 2 (DD2); (c) wet pond (WP); (d) Wetland 1(WL1); (e) Wetland 2 (WL2); (f) bioretention (BR); (g) Proprietary 1 (P1); (h) Proprietary 2 (P2); and (i) Proprietary 3 (P3)

Bioretention received a more diverse set of influent concentrations. At higher concentrations, the Bioretention seemed to show some reduction in efficiency, also seen in the probability plots generated for fecal coliform. The wet pond performed well when receiving low influent *E. coli* concentrations; however, as influent concentrations increased to reporting limits, effluent flows increased toward reporting limits as well. The reporting limit made evaluation of this practice at high concentrations impossible. Generally, the dry detention basins, Wetland 2, and the three proprietary devices did not perform well with respect to *E. coli* sequestration and removal. Effluent *E. coli* concentrations were similar to or higher than influent concentrations for these BMPs. However, the findings for Proprietaries 1–3 must be tempered by low influent *E. coli* concentrations noted in the probability plots for each. Particularly for Proprietaries 1 and 2, influent *E. coli* concentrations were often below the regulatory standard of 126/100 mL.

Geometric Mean Effluent Concentration Analysis

Currently, water quality standards related to bacteria are concentration based. The U.S. EPA recommended standard for fecal coliform is 200 /100 mL. Likewise, the recommended standard *E. coli* concentration is 126/100 mL. BMP geometric mean effluent concentrations were compared to these target values (Table 6). For fecal coliform, only one BMP had a geometric mean effluent concentration below or equal to the target value, Wetland 1. Five of the nine effluent samples from Wetland 1 were at or below 200 col/100 mL. The bioretention performed fairly well in terms of this analysis (geometric mean effluent of 258 col/100 mL), with 14 of 19 samples being less than or equal to 200 col/100 mL. Although the geometric mean effluent of the bioretention did not meet targeted values, the median effluent fecal coliform concentration of the bioretention was calculated to be 100 col/100 mL, indicating some promise with respect to this system. Last, Proprietary 1 performed fairly well with a geometric mean effluent concentration of 277 col/100 mL. The median effluent concentration for Proprietary 1 was 200 mL/100 col, indicating relatively good performance. A small sample set for Proprietary 1 limits the ability to make generalizations about its ability to achieve targeted fecal coliform concentrations.

Four BMPs had geometric mean effluent *E. coli* concentrations below the U.S. EPA target value of 126 /100 mL, Wetland 1, bioretention, Proprietaries 1 and 2. Of these BMPs, only Wetland 1 and the bioretention had a geometric mean effluent concentration lower than its geometric mean influent concentration. Of the 14 samples taken from the bioretention, 12 had geometric mean effluent concentrations less than the target value. Of the 14 influent samples taken at the bioretention, six were below the U.S. EPA target value of 126/100 mL. For *E. coli*, the bioretention received relatively low influent concentrations. Wetland 1 also

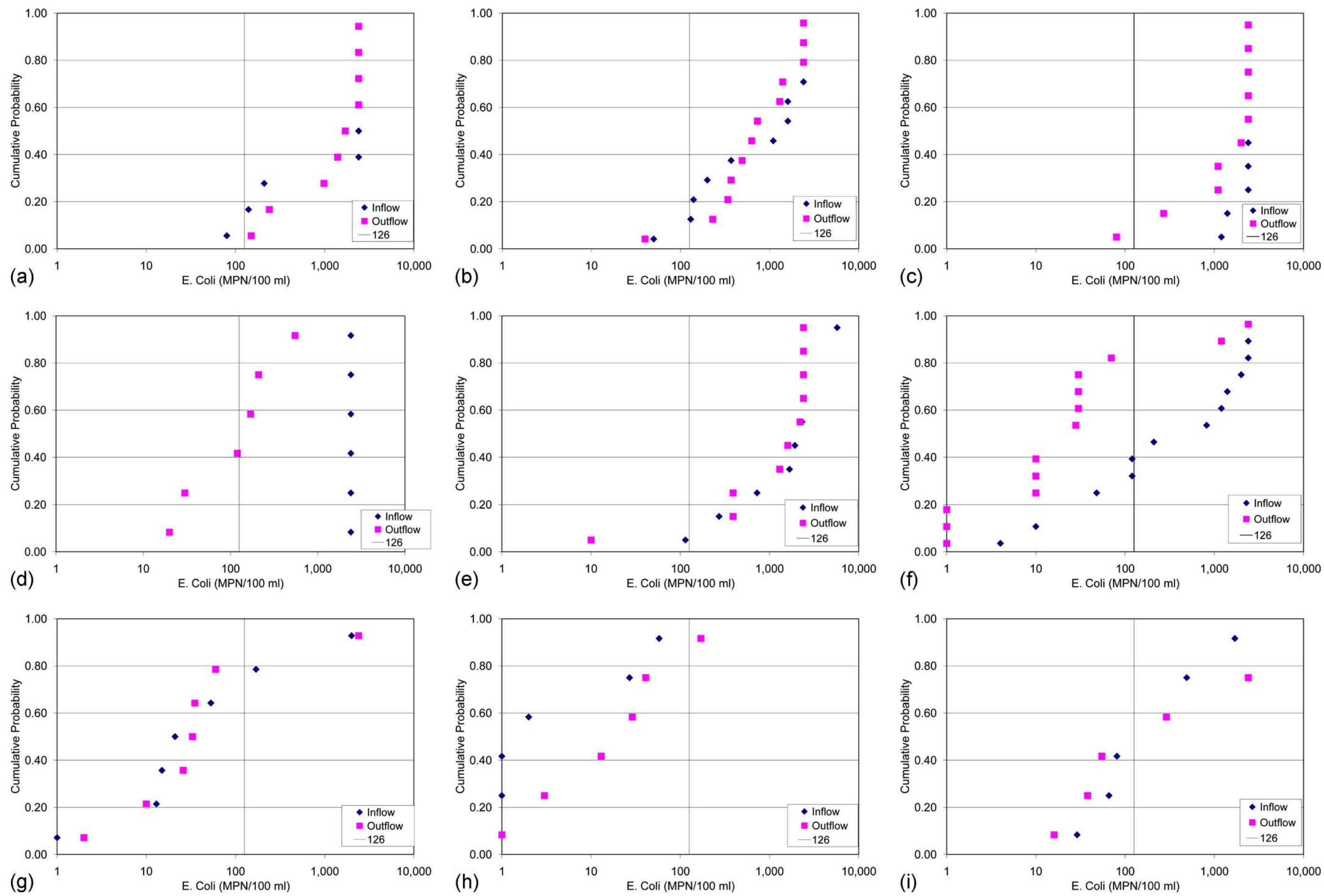

Fig. 3. *E. coli* influent and effluent probability plots for (a) Dry Detention 1 (DD1); (b) Dry Detention 2 (DD2); (c) wet pond (WP); (d) Wetland 1 (WL1); (e) Wetland 2 (WL2); (f) bioretention (BR); (g) Proprietary 1 (P1); (h) Proprietary 2 (P2); and (i) Proprietary 3 (P3)

exhibited the ability to reduce influent *E. coli* concentrations, with three of six samples being below the targeted value. Of the BMPs with geometric mean effluent concentrations lower than the standard, Wetland 1 had the highest geometric mean influent concentration. None of the influent samples taken from Proprietary 2 were higher than the target value, and only two of the seven samples taken at Proprietary 1 were higher than the target value, again highlighting the relatively clean quality of inflow to the proprietary devices, which potentially impacted the results for these systems. The small number of *E. coli* samples taken at Proprietary Devices 1–3 and Wetland 1 limited the ability to make generalizations on their performance.

Conclusions

The results of this study support others in literature that urban watersheds are a nonpoint source of bacterial pollution in surface

Table 6. Geometric Mean Influent and Effluent Fecal Coliform and *E. coli* Concentrations

	Fecal coliform concentrations (col/100 mL)			*E. coli* concentrations (MPN/100 mL)		
BMP type	Geometric mean influent	Geometric mean effluent	% of effluent samples under 200 col/100 mL	Geometric mean influent	Geometric mean effluent	% of effluent samples under 126 MPN/100 mL
Dry Detention 1	1,985	2,873	0	915	1,121	0
Dry Detention 2	1,327	1,590	0	655	658	8
Wet Pond	9,033	2,703	7	2,122	1,153	10
Wetland 1	9,560	184	56	2,400	106	50
Wetland 2	8,724	3,874	13	1,295	864	10
Bioretention	2,420	258	74	241	20	86
Proprietary 1	667	277	43	36	37	71
Proprietary 2	235	368	50	4	14	83
Proprietary 3	1,472	2,379	0	183	196	50

waters (Schoonover and Lockacy 2006; Mallin et al. 2000; Tufford and Marshall 2002). Even in watersheds consisting primarily of parking lots, concentrations of fecal coliform and *E. coli* entering BMPs can be higher than government (U.S. EPA 1976; U.S. EPA 1986) recommended maximum values, indicating the need for treatment. Although conclusions are limited somewhat by the LOD and MRL present in the data, the findings from this study suggest that some storm-water BMPs may effectively sequester and remove indicator bacteria. In particular, bioretention areas and some types of wetlands showed promise in bacterial treatment. A small-sized sample set, and low influent concentrations limited evaluation of the proprietary devices. Bioretention significantly ($p<0.05$) reduced both fecal coliform and *E. coli* concentrations from the inlet to the outlet with concentration reduction efficiencies of 0.89 and 0.92, respectively. Wetland 1, which performed better than Wetland 2, was atypical due to its lack of vegetative growth. The shallow water depths present in Wetland 1 (15–45 cm) and minimal vegetative coverage likely led to more sun exposure, and potentially ultraviolet light penetration, to the wetland bottom than would normally be expected in a storm-water wetland. This high sun exposure possibly led to increased inactivation of indicator bacteria in the wetland in between storm events and during the slow drawdown after an event.

If the proper environment exists, it is also possible that storm-water BMPs can be sources of indicator bacteria. This is likely due to both animal activity and to indicator bacteria persistence within BMPs. This was potentially the case for the two dry detention basins as well as two of the proprietary BMP systems. This was also likely the case in the wetlands and wet pond; however, removal mechanisms within these BMPs resulted in a net reduction of indicator organisms. It should be noted that relatively low concentrations of fecal coliform and *E. coli* entered two of the three proprietary systems, which likely reduced the ability of these BMPs to further lower indicator bacteria concentrations.

Although positive concentration reductions were achieved by BMPs for both fecal coliform (five of nine BMPs) and *E. coli* (six of nine BMPs), only Wetland 1 provided a positive concentration reduction and a geometric mean effluent concentration lower than USEPA targeted concentrations for both fecal coliform and *E. coli*. Good light exposure at this site likely contributed to this performance. Of the nine BMPs studied, only Bioretention employed a filtering removal mechanism. It also was the driest BMP. These two factors, along with sun exposure, seemed to indicate it as a potential option for treating indicator bacteria. Although geometric mean effluent concentrations of fecal coliform were higher than the standard, median effluent concentrations were lower, and both median and geometric mean effluent *E. coli* concentrations were lower than the government standard for this practice. Some bias might be present because the Bioretention received runoff with somewhat lower influent concentrations than either of the wetlands or the wet pond. The proprietary systems produced relatively low geometric mean effluent concentrations, but a small sample set and low influent concentrations of *E. coli* limited their analysis. Probability plots generated for both Wetland 1 and for Bioretention indicate that there may be reduced effectiveness of these practices at high inlet indicator bacteria concentrations.

While some conclusions can be drawn from this study, only one or two examples of each BMP type where monitored with grab samples, limiting the ability to make generalizations. Additional study should be performed to evaluate the effectiveness of various BMP types in detail. Further study is also necessary to determine if bioretention effluent can reach U.S. EPA targeted values when receiving high concentrations of indicator bacteria, and to evaluate proprietary systems with higher influent concentrations of fecal coliform and *E. coli* over a larger number of events. Analysis of proprietary systems which employ filtration would also be beneficial.

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