BIORETENTION COLUMN STUDY: FECAL COLIFORM AND TOTAL SUSPENDED SOLIDS REDUCTIONS

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ABSTRACT. *Surface water impairments for pathogens are a major problem in waterways throughout the United States, especially in New Jersey. Fecal coliform (FC) counts are commonly used as an indicator of pathogens. In this study, bioretention systems, which are stormwater best management practices, were modeled with columns. Unlike traditional detention basins, bioretention systems are meant to manage water quality in addition to quantity and peak flow rates. Typical rainfall conditions for New Jersey were mimicked in the laboratory with regard to rainfall intensity and stormwater composition (bacterial colony counts) using a diluted manure slurry. The applied influent flow rate was 77.0 mL/min, while the average leachate flow rate observed in the bottom spout was 20.8 mL/min. The hydraulic performance of the columns was adequate in that the influent completely infiltrated well before the New Jersey Department of Environmental Protection (NJDEP) performance standard of 72 h. However, ponding of more than 30.5 cm (the NJDEP performance standard for ponding) was observed in some of the simulations. The mean, median, and range of reduction coefficients for fecal coliform (FC) were 91.6%, 98.6%, and 54.5% to 99.8%, respectively, for 13 simulations. The mean, median, and range of reduction coefficients for total suspended solids (TSS) were 91.5%, 91.9%, and 81.0% to 99.4%, respectively, for 15 simulations. The average pH of the influent water was 6.87, while the average leachate pH was 4.61. It is likely that both adsorption and filtration were responsible for the FC and TSS reductions. Die-off factors that may have influenced FC reduction in addition to adsorption and filtration are discussed. Reduction coefficients were observed to not necessarily be the ultimate indicator of system performance or effectiveness, as they are conditional upon the leachate concentration.*

Keywords. *Animal wastes, Bacteria, Best management practices, Bioretention, Fecal coliform, Nonpoint-source pollution, Pathogens, Stormwater runoff.*

Currently, 8,560 water bodies in the nation (14.4% of all reported water bodies) are impaired for pathogenic bacteria, viruses, and/or parasites (USEPA, 2003). Impairments often result from nonpoint sources of pollution carried by urban and agricultural stormwater runoff (Irvine and Pettibone, 1996; Inamdar et al., 2002; Jeng et al., 2005; Tufford and Marshall, 2002; Characklis et al., 2005; George et al., 2004; Barrett et al., 1998; Sansalone and Buchberger, 1997; Wu et al., 1998). Other sources of contamination include combined sewer overflows, sewer leakages, septic fields, and wastewater treatment works (Marsalek and Rochfort, 2004). Epidemiological evidence shows that an increased risk of adverse health effects is associated with swimming in recreational waters that are contaminated with untreated urban stormwater (Haile et al., 1999). Gaffield et al. (2003) determined a link between contaminated stormwater runoff and public waterborne illness.

Submitted for review in August 2006 as manuscript number SW 6628; approved for publication by the Soil & Water Division of ASABE in May 2007.

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FC bacteria are commonly used as an indicator of pathogens and are used by governmental agencies to help manage drinking water quality and recreational activities such as swimming, boating, and fishing. While coliform bacteria themselves do not usually cause illness, they originate from the digestive tracts of warm-blooded animals, and their presence suggests the occurrence of pathogens from the same origin. *Escherichia coli* (*E. coli*), a type of FC bacteria, and organisms of the *Enterococci* genus are also used as bacterial indicators of pathogens. Coliphages, which are viruses that infect coliforms, are often used as viral pathogen indicators. Protozoan parasites, such as *Cryptosporidium parvum* oocysts, have not been shown to correlate well with coliforms or enterococci (Medema et al., 1997). Thus, the use of alternative indicators, such as *Clostridium perfringens*, has been suggested (Medema et al., 1997)

A bioretention system (fig. 1) is a structural stormwater best management practice (BMP) that is often used in suburban settings. The typical design for a bioretention system includes a sloped grass buffer strip, a ponding area with vegetation, a three-foot deep planting substrate, and a one-foot deep sand layer. Some systems include gravel and underdrain piping below the sand layer when soils are not appropriate for groundwater recharge. The soil planting layer: (1) acts as a primary filter to retain pollutants, (2) provides rapid infiltration of stormwater runoff (complete infiltration within 72 h to avoid mosquito breeding), and (3) sustains healthy vegetation at the surface. The planting substrate consists of a high sand content to achieve infiltration requirements. The sand layer acts as a secondary filter and transition

  ISSN 0001–2351

Figure 1. Schematic of a typical bioretention system (NJDEP, 2004b).

between the planting substrate and the underlying soil or under-drain system. A thin mulch layer can be applied to the top of the planting substrate to retain moisture and attenuate pollutants. The under-drain system can be connected to a stormwater sewer system, which eventually discharges into surface waters. Systems without an under-drain system are used to recharge groundwater through infiltration.

Plants in a bioretention system often consist of native water-tolerant grasses, shrubs, and trees (often of the facultative wetland variety) that are intended to adapt well to the soil and climate of the region in which they are planted. They must also tolerate pollutants and varied depths of water. The plants are intended to uptake water contaminated with excess nutrients; however, plant roots may also provide pore spaces that will provide a habitat for microorganisms, thus promoting biological degradation of some pollutants and predation of other bacteria (Davis et al., 2001).

Bioretention systems are intended to remove the typical pollutants found in stormwater such as suspended solids, nutrients, metals, hydrocarbons, and indicator bacteria (NJDEP, 2004a).

Past research on bioretention systems has investigated their infiltration capacity and their capacity to reduce pollutant concentrations in stormwater both in the laboratory and in the field (Davis et al., 2006; Hong et al., 2006; Dietz and Clausen, 2005; Hsieh and Davis, 2005a, 2005b; Morzaria-Luna et al., 2004; Davis et al., 2003; Kim et al., 2003; Davis et al., 2001). However, published data on the capacity of bioretention systems to reduce fecal coliforms or other bacteria indicators in stormwater are not extensive to date. On the other hand, other similar BMPs (namely detention ponds, constructed wetlands, and vegetative filter strips) have shown to be favorable in managing pathogen indicator organisms in water (Greenway, 2005; Roodsari et al., 2005; Stout et al., 2005; Birch et al., 2004; Solano et al., 2004; Hench et al., 2003; Mantovi et al., 2003; Nokes et al., 2003; Quininez-Diaz et al., 2001; Davies et al., 2003; Davies and Bavor, 2000; Newman et al., 2000; Perkins and Hunter, 2000; Bolton and Greenway, 1999; Gerba et al., 1999; Khatiwada and Polprasert, 1999; Lim et al., 1998; Chaubey et al., 1994).

The goal of this study was to examine whether bioretention systems can effectively reduce FC and TSS concentrations to acceptable levels. At the same time, hydraulic, pH, and temperature parameters were monitored. Bioretention systems are increasingly being considered for stormwater management projects nationwide, creating a demand for more extensive research. As such, another goal was to make recommendations for regulatory guidance and future research.

Materials and Methods

Bioretention Column Construction

Bioretention column models (fig. 2) were constructed using 15.2 cm diameter, clear PVC pipe cut into 152.4 cm lengths (Harvel Plastics, Inc., Easton, Pa.). One end of the pipe was fitted with a 15.2 cm to 10.1 cm PVC reducer coupling and capped with a 10.1 cm PVC cap that was drilled with a 1.3 cm diameter hole for collecting leachate. Three columns (named A, B, and C) were constructed in this manner and housed in a heavy-duty wooden workbench. From the top down, the columns were filled as follows: (1) a 30.5 cm ponding area was left unfilled in the topmost portion of the columns, (2) the next 91.4 cm of the columns were packed with the planting substrate at a bulk density of approximately 1.3 g/cm^3, (3) the next 30.4 cm of the columns were packed with clean medium aggregate concrete sand (ASTM C 101 33) at a bulk density of approximately 1.8 g/cm^3, (4) a sheet of perforated polyethylene filter fabric (Easy Gardener, Inc., Waco, Tex.) followed the sand (fig. 3a), and (5) the entire

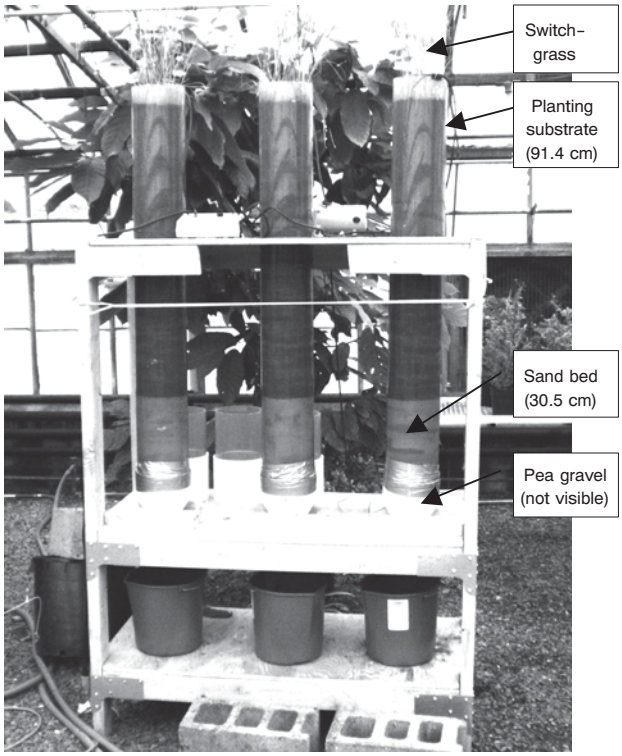

Figure 2. Photo of the bioretention columns housed in the workbench.

coupling was filled with clean pea gravel (AASHTO M-43) and was followed by the cap. The planting substrate consisted of three equal parts (by volume) of sphagnum peat, triple-shredded hardwood mulch, and medium aggregate concrete sand (ASTM C 101 33). The sand grains ranged in diameter from 0.3 to 1.0 mm (equal parts by volume). As of 2004, this mix was recommended for bioretention projects in Delaware (personal communication with Randell Greer, Delaware Division of Soil and Water Conservation). The planting substrate was mixed thoroughly by hand before packing. The columns were wrapped in heavy-duty aluminum foil after filling to prevent sunlight infiltration and algal growth.

Six 5 cm diameter seedling plugs of switchgrass (*Panicum virgatum*; Pinelands Nursery, Columbus, N.J.) were planted into the planting substrate in September 2004. The switchgrass was watered regularly and permitted to grow for six months before experimentation commenced. Tap water was used for watering only after being left in an open bucket (to promote residual chlorine diffusion) for at least one day. All stages of the experiment took place in a greenhouse that ranged in temperature from 25°C to 37°C. An additional 30.5 cm piece of clear PVC was affixed to the top of the columns after planting using a 15.2 cm diameter PVC coupler (fig. 3b). This provided a ponding area above planting substrate.

Preparation of Manure Water

Fresh horse manure (from animals not treated with antibiotics) was collected on experimentation days. A 200 g equal-parts-by-mass manure mixture (from three different horses) was added to 1,800 mL of sterile buffered dilution water (Clesceri et al., 2001) in a 6,000 mL Erlenmeyer flask. The mixture was then placed on a gyratory shaker (New Brunswick Scientific Co., Inc., Edison, N.J.) for 30 min at

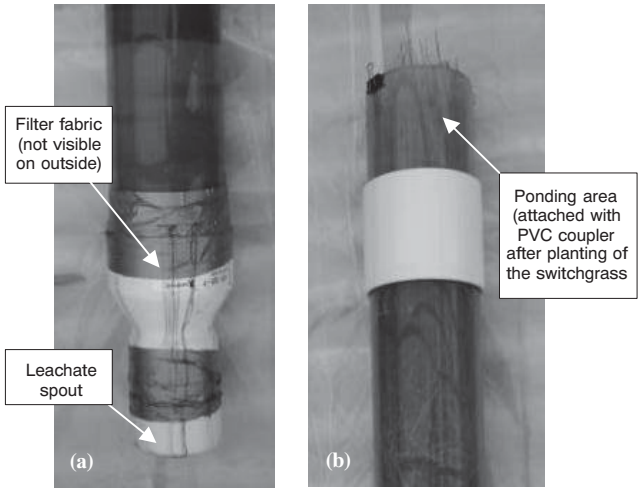

Figure 3. Close-up photos of the (a) bottom and (b) top sections of the columns.

Table 1. Expected FC concentrations associated with the dilution ratios.[a]

Dilution Ratio	Expected Concentrations of FC (CFU/100 mL)
9:1	2.37×10^8
19:1	1.18×10^8
99:1	2.37×10^7

[a] A CFU/gram horse manure estimate was calculated from literature values (*ASABE Standards*, 2005; USEPA, 2001) and multiplied by the respective dilution factor to obtain a concentration. These estimates do not reflect the fact that only the supernatant was used.

200 rpm. The slurry was allowed to settle for 20 min, and the supernatant was decanted. The supernatant was mixed with sterile dilution water to achieve concentrations of FC bacteria within a range of literature-supported values for stormwater and grazed pasture runoff. The target range for the influent was 1.2×10^2 to 4.3×10^6 CFU/100 mL (USEPA, 2001). Horse manure was used because it was more readily available than other types of manure, it provided more predictable FC concentrations, and it could be collected immediately after defecation. As suggested by ASCE (1999), experiments were run using different influent dilutions to examine the possible effect of influent concentration on the bioretention system. The dilutions were prepared at ratios of 9:1, 19:1, and 99:1 sterile dilution water to supernatant. Ranges of FC concentrations associated with each dilution were estimated according to literature values, as shown in table 1. The volume of one batch of diluted supernatant used for one simulated storm event was 10 L. All glassware was sterilized in a steam autoclave prior to use.

Experimental Methods

The manure water was delivered to the top surface of the bioretention column at a rate of 77 mL/min for 2 h using a peristaltic pump (Masterflex L/S, Cole-Parmer, Vernon Hills, Ill.) with 6.35 mm diameter sterile tubing (Masterflex Norprene, Cole-Parmer, Vernon Hills, Ill.). This rate was based on a 3.18 cm rainfall event over 2 h, the storm event recommended to be ideal for water quality research (NJDEP, 2004b). A runoff coefficient of 0.8 was assumed, and the bioretention area was assumed to be 5% of the drainage area (Davis et al., 2001). Seventeen simulated storm events were conducted over a period of nine months starting in March

2005. Each column received a differently diluted batch of manure water. New tubing was used for each simulated storm event. Simulated storm events were conducted at least one week after each other to allow for drainage and drying (Davis et al., 2001). Column A received the 19:1 dilution, column B received the 9:1 dilution, and column C received the 99:1 dilution.

The manure water was sampled just before it was applied to the column. This was considered the "influent" sample. "Leachate" grab samples were collected from the bottom spout after the time of first appearance. At least three grab samples were collected per simulation. Due to holding time limitations, some samples had to be analyzed immediately, disallowing a regular time period between grab samples. Samples were stored in an ice-filled cooler during transport to the laboratory. Samples for TSS analysis were collected in 500 mL high-density polyethylene bottles. Samples for FC analysis were collected in sterile 15 mL glass culture tubes with sterile high-density polyethylene screw caps. The instantaneous flow rate, pH, and temperature of the leachate from the bottom spout were determined at the time of each grab sample; a pH/temperature meter was used (Oakton, Cole-Parmer, Vernon Hills, Ill.).

Samples were analyzed for FC using the fecal coliform membrane filtration procedure (Clesceri et al., 2001) and sterile FC broth with rosolic acid (Difco, Detroit, Mich.). Because of low concentrations, leachate samples were filtered in a range of 0.01 to 10 mL volumes (in some cases after serial dilution). Samples were filtered in triplicate at each filtration volume. Samples were also analyzed in triplicate for TSS by the dry weight analysis procedure (Clesceri et al., 2001).

Post-Simulation Soil Analyses

After simulations were conducted, two columns were deconstructed for soil analysis according to Weaver et al. (1994). Column B was deconstructed 36 days after receiving its last storm simulation, while column A was deconstructed approximately 24 h afterwards. The gravel, sand, and planting substrate layers were collected and sealed in plastic freezer bags (S.C. Johnson Wax, Racine, Wisc.). Sampling from the bottom of the column first and moving upward, each 10.2 cm depth of material (approx. 1852 cc in volume) was sealed in a separate bag. The planting substrate/sand interface (at the 91.44 cm depth) was sampled to include approximately 459 cc above and below this point. The top one foot of the column was sampled at 5.1 cm depths rather than 10.2 cm.

For column B, three samples from the following depth ranges were analyzed for FC bacteria: 0 to 5.1 cm, 58.4 to 68.6 cm, and 88.9 to 94.0 cm. For column A, three samples from the following depths were analyzed for FC bacteria: 0 to 5.1 cm, 25.4 to 30.5 cm, and 50.8 to 61.0 cm. Samples were mixed by hand by manipulating the plastic bag. Using sterile instruments, a mixture was made from 90 mL of sterile dilution water and 10 g of a representative grab sample of the media. The mixture was placed on a gyratory shaker for 30 min at 200 rpm.

Data Reporting and Statistical Analyses

A reduction coefficient was calculated for each simulated storm event by subtracting the average leachate event mean concentration (EMC) from the influent concentration and dividing by the influent concentration. The EMC is defined as:

$$\mathrm{EMC} = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i} \quad (1)$$

where V_i is the volume of flow during period i, C_i is the concentration associated with period i, and n is the total number of measurements taken during an event. Since several filtrations were performed for each sample for FC and TSS analysis, the geometric mean was used as C_i. The value of V_i for the leachate was estimated using observed instantaneous flow rate values of the leachate at the bottom spout (ASCE, 1999).

FC concentrations were reported as the geometric mean of CFUs for each replicate of a sample dilution that yielded results within an ideal range of 20 to 60 (Clesceri et al., 2001). If values within this range were not met, then the geometric mean of the values within all the other ranges was used (unless the colonies were too numerous to count). For the TSS data, concentrations that were below detection were reported as one half of the detection limit of 0.1 mg/L for calculation purposes.

Outliers were determined using Chauvenet's criterion. Outliers were not included in statistical calculations reported in the results section. Regression analyses ($\alpha = 0.05$) were performed to compare the reduction coefficients for FC and TSS with other experimental data, respectively. A single-variable ANOVA test was performed to determine the significance, if any, of how three different preparations of the manure water dilutions affected the FC and TSS reduction coefficients, respectively. The data were grouped according to the small (9:1), medium (19:1), and large (99:1) dilutions. The null hypothesis was that differences in the dilutions do not change the resultant FC or TSS reduction. The alternative hypothesis was that differences in dilution will change the resultant TSS reduction, indicating that smaller dilutions result in larger reductions. The level of significance for this test was $\alpha = 0.1$, below which the null hypothesis was rejected.

Results and Discussion

Characterization of Plants

The switchgrass appeared to be an appropriate type of vegetation for these systems. It established quickly and heartily soon after initial planting of the seedling plugs. During the winter months, the switchgrass went into a dormant stage. During this time, the grasses were trimmed similarly to how they would have been in the field for maintenance of the bioretention system (NJDEP, 2004b). During the following growing season, the grasses in all three columns grew to approximately 56 cm height as of December 2005. The roots were easily observed through the transparent PVC column. All three columns possessed plant roots that extended to a depth of approximately 82 cm as of December 2005.

Hydraulics

During the simulated storm events, the flow characteristics could be observed through the transparent PVC columns. Preferential flow was observed along the thicker roots and adjacent large pores caused by the mulch. Leachate first appeared in the bottom spout within 55 to 100 min of the start

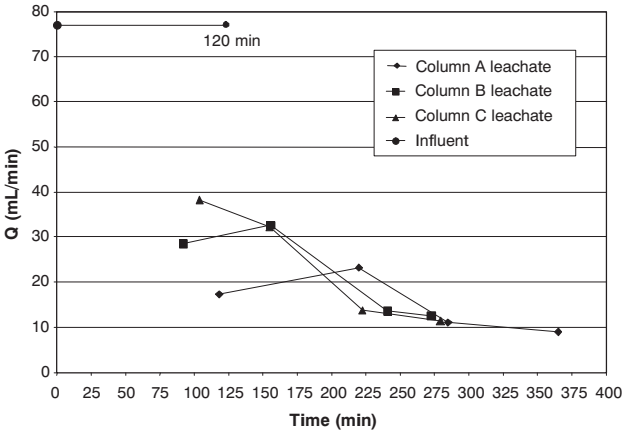

Figure 4. Average flow rate data from all simulations. The hydrographs were created by grouping and averaging data points within 60 min time intervals.

of pumping. Ponding was observed above the substrate surface in all columns, reaching 30.5 cm (maximum free depth in the column above the substrate surface) in some of the column A simulations. In such a case, the pump was turned off briefly and turned back on while the water was still ponded. The performance of column A stood out from the others in that it did not infiltrate water as quickly and the influent ponded to higher depths than in the other columns. These observations are supported by the leachate flow rate for column A, which had a more gradual, more delayed, and smaller peak flow rate than the other columns (fig. 4).

The infiltration rates of the columns were estimated using an average of the instantaneous flow rates and are summarized in table 2. The estimated infiltration rates found for this study are consistent with regulatory guidance for bioretention system performance. The New Jersey Department of Environmental Protection (NJDEP, 2004b) suggests that the captured water be fully infiltrated within 72 h with a maximum ponding depth of 30.5 cm. Of these criteria, the former was always met. The latter was always met for column B but only sometimes for columns A and C. Davis et al. (2001) reported infiltration flow rates (in a similar bioretention study) that ranged from 0.30 to 2.0 cm/h, rates that the authors classified as unacceptable for implementation in Maryland.

Table 2. Estimated infiltration rates.

Simulation	Column	Avg. Instantaneous Leachate Flow (mL/min)	Infiltration Rate (cm/h)
3/17/2005	B	25.90	8.35
3/25/2005	C	16.05	5.18
3/30/2005	B	21.65	6.99
4/21/2005	B	23.63	7.62
6/24/2005	B	16.25	5.23
7/21/2005	B	18.25	5.89
7/29/2005	C	24.58	7.92
8/4/2005	A	21.00	6.78
8/5/2005	C	23.00	7.42
8/11/2005	A	17.83	5.77
8/12/2005	C	30.75	9.93
8/25/2005	A	16.05	5.18
8/26/2005	C	28.25	9.12
9/20/2005	C	26.00	8.38
9/21/2005	A	13.00	4.19
9/22/2005	B	24.38	7.87
12/2/2005	A	6.50	2.11

FC AND TSS VALUES

Despite one FC reduction coefficient value of only 54.5% (3/17/2005 simulation), the columns consistently reduced bacteria counts at both high and low influent concentrations (table 3). The FC data for the 3/17/2005 simulation were not used in the subsequent statistical calculations since the reduction coefficient was determined to be an outlier using

Table 3. Summary of TSS and FC data.[a]

		TSS			FC			Maximum Water Temp. (°C)
Simulation	Column	Reduction Coefficient (%)	Influent Concentration (mg/L)	Leachate EMC (mg/L)	Reduction Coefficient (%)	Influent Concentration (CFU/100 mL)	Leachate EMC (CFU/100 mL)	
3/17/2005	B	88.6	185	21.1	54.6[b]	5.90E+03	2.70E+03	31.5
3/25/2005	C	93.5	71.6	4.69	--	--	--	21.6
3/30/2005	B	99.1	215	1.93	99.2	1.50E+05	1.20E+03	26.7
4/21/2005	B	97.1	306	9.03	75.7	1.50E+05	2.80E+02	28.1
6/24/2005	B	91.9	260	21.1	98.6	6.30E+06	8.90E+04	31.4
7/21/2005	B	96.6	273	9.19	91.3	2.90E+06	2.60E+05	--
7/29/2005	C	81	42	7.99	--	--	--	31.5
8/4/2005	A	91.8	80	6.6	99.2	2.30E+07	2.00E+05	38.5
8/5/2005	C	88.4	18	2.09	99.5	1.40E+06	7.00E+03	39.2
8/11/2005	A	--	--	--	98.7	5.70E+06	7.60E+04	--
8/12/2005	C	--	--	--	99.8	1.40E+07	2.40E+04	32.2
8/25/2005	A	95	83.3	4.16	98.5	2.20E+07	3.30E+05	--
8/26/2005	C	81.9	14.6	2.66	99.1	3.00E+06	2.60E+04	--
9/20/2005	C	91.9	25.3	2.06	--	--	--	27.9
9/21/2005	A	84.6	48.3	7.46	--	--	--	28.0
9/22/2005	B	99.2	390	3.03	91.7	2.30E+03	1.90E+02	--
12/2/2005	A	99.4	103	0.67	99.3	3.00E+03	2.00E+01	21.2
Mean		91.5 ±6.1			95.9 ±13.3			

[a] Congruent FC and TSS analyses could not be performed for all simulations.
[b] This value was determined to be an extreme outlier. The data corresponding to this simulation were not used in subsequent statistical calculations, including the geometric mean.

Chauvenet's criterion. The influent FC concentrations shown in table 3 do not reflect the estimates determined in table 1. It seems as though differently diluted slurries did not have a predictable effect on the influent concentrations (probably due to the high variability in FC die-off/growth rates). Future experiments can probably involve only one dilution factor rather than three.

It is likely that both adsorption and filtration were responsible for the FC reductions. Adsorption of bacteria is influenced by physical, chemical, and microbiological factors, including the size and texture of porous media, presence of organic matter and biofilm, temperature, flow rate, ionic strength, pH, hydrophobicity, chemotaxis, and electrostatic charge (Stevik et al., 2004). Bouwer (1984) reported that filtration generally occurs when the diameter of suspended particles is larger than 0.2 times the diameter of particles constituting the porous media. The sand used in the bioretention column ranged in diameter from 0.3 to 1.0 mm. This means that the diameter of suspended particles should be greater than 0.06 mm (or 60 μm) for filtration to occur. However, Davies and Bavor (2000) and George et al. (2004) observed bacteria on fine particles of diameters less than 2 μm and on particles of diameters greater than 5 μm, respectively. Thus, some of FC bacteria attached to particles might not have been filtered in the bioretention columns. In these cases, adsorption was probably the primary mechanism (Stevik et al., 2004). Additionally, filtration is less effective when transport takes preferential flow paths through the substrate (Stevik et al., 2004). The presence of macropores or channeling in the media would have reduced the filtration capacity of the bioretention column. Water that flowed along the sides of the bioretention column was also less effectively filtered. Macropores surrounding the mulch were observed through the clear PVC columns. In areas of the media where pore spaces are large, adsorption of smaller particles is the dominant physical mechanism for FC and TSS retention (Sharma et al., 1985).

A summary of statistical reporting is provided in table 4. A negative correlation (r = –0.622, p-value = 0.055) was observed between FC reduction and influent TSS concentration. This indicates that higher influent TSS concentrations will result in less FC reduction. On the other hand, a positive correlation (r = 0.640, p-value = 0.010) was observed between TSS reduction and influent TSS concentration. This indicates that a higher influent TSS concentration will result in a higher TSS reduction. The observed phenomenon that FC reduction is negatively correlated to influent TSS while TSS reduction is positively correlated suggests the need to study the more complex physical, chemical, and microbiological interactions between the FC, associated particulate matter, and the porous substrate during the retention time within the system.

It is important to note that while the EMC is a generally accepted reporting tool for the leachate concentrations, it does not fully describe the load reduction caused by the bioretention columns during a longer sampling window (ASCE, 1999). In fact, the total load of FC and TSS removed from the system is likely to be higher than that represented by the reduction coefficient, if samples from the tail-end (beyond approximately 400 min) of the leachate flow were included.

Table 4. Summary of regression statistics.

% FC reduction	Influent TSS concentration	r = –0.622	p-value = 0.055
% TSS reduction	Influent TSS concentration	r = 0.640	p-value = 0.010
Influent FC concentration	Leachate FC EMC	r = 0.682	p-value = 0.014

The NJDEP (2004b) recommends a 90% reduction coefficient for TSS as a performance standard. Using this standard as a measure of success for the bioretention columns, the columns were successful 10 of 15 times. It is important to note, however, that 4 of the 5 simulations with coefficients below 90% had influent concentrations of 49 g/L or less. Moreover, in some cases, these simulations yielded leachate concentrations less than simulations with higher reduction coefficients. Leachate concentrations can still be high and above water quality standards independently of a high reduction coefficient. Thus, reduction coefficients are not necessarily the ultimate indicator of system performance or effectiveness, and they are conditional upon the quality of the leachate discharged.

The finding regarding the reduction coefficient's inability to represent performance efficiency is also indicated in the positive correlation (r = 0.682, p-value = 0.014) between influent FC concentration and leachate FC EMC. This indicates that larger influent FC concentrations will result in larger leachate FC EMCs. A large influent FC concentration will result in a high FC reduction, but the leachate EMCs are also high in comparison. Currently, there is no bioretention performance standard for FC by the NJDEP or the USEPA. Depending on waterbody classification, the New Jersey Surface Water Quality Standards (N.J.A.C. 7:9-6) for FC range from 50 to 1500 CFU/100 mL. There are several instances in the data where the FC reduction was above 90%, but the leachate FC EMC was greater than the 50 CFU/100 mL standard. Again, just like with TSS, the FC reduction coefficients should not be the ultimate indicator of system performance or effectiveness.

The differences in how the manure water was diluted was found to be a significant (p-value = 0.075) factor of the percentage of TSS that was reduced. Thus, the alternative hypothesis that smaller dilutions result in larger reductions was accepted. It was not found to be a significant factor (p-value = 0.169) of the percent reduction of FC concentrations.

pH Values

The pH was observed to be significantly more acidic in the leachate than in the influent (table 5). The peat fraction of the bioretention planting substrate likely contributed to the acidity of the system. According to Sjogren (1994), bacterial survival decreases with pH values approaching acidic and basic extremes. Additionally, Sjogren (1994) reported decreased survival of *E. coli* bacteria in more acidic soils. The average observed pH value of the leachate was 4.61 compared with the influent average of 6.87, suggesting that some of the FC bacteria may have died from the acidity. However, correlations between FC and pH were not observed in the data. The very acidic pH values of the leachate water could impact the quality of the ground or surface water to which it discharges.

The water quality standard for pH, according to the New Jersey Ground Water Quality Standards (N.J.A.C. 7:9-6) and the New Jersey Surface Water Quality Standards (N.J.A.C. 7:9B), is 6.5 to 8.5. The observed leachate pH values are all below this standard. The bioretention systems, as designed in

Table 5. Average pH and temperature data (nd = no data).

Simulation	Column	Avg. Influent pH	Avg. Leachate pH	Avg. Water Temp. (°C)
3/17/2005	B	7	4.55	31.5
3/25/2005	C	7.45	4.75	20.6
3/30/2005	B	7.13	4.39	24.4
4/21/2005	B	7.13	4.34	28.1
6/24/2005	B	7.02	4.62	27.2
7/21/2005	B	nd	nd	nd
7/29/2005	C	6.43	4.41	24.7
8/4/2005	A	6.96	4.62	28.5
8/5/2005	C	7.01	4.39	29.5
8/11/2005	A	nd	nd	nd
8/12/2005	C	7.04	4.41	25.4
8/25/2005	A	nd	nd	nd
8/26/2005	C	nd	nd	nd
9/20/2005	C	5.98	4.82	26.3
9/21/2005	A	6.73	4.78	28.0
9/22/2005	B	nd	nd	nd
12/2/2005	A	6.57	5.23	20.4

this study, would improve the water quality for at least two parameters (i.e., FC and TSS), but they would impair water quality for pH. The planting substrate should be re-evaluated in future studies using a less acidic substrate.

Post-Simulation Soil Analyses

In the column deconstruction experiments, FC CFUs were observed only in the substrate from the topmost depths (0 to 5.1 cm) of the planting substrate for both columns A and B. For column A, the geometric mean of the three plate counts was 70 CFU/100 mL of the 9:1 dilution water to substrate mixture, which corresponds to 7 CFU per 10 g of substrate. For column B, FC growth was observed in the 99:1 dilution water to substrate mixture. However, because of the large amount of particulates on the filter, a CFU count was not possible. The influent from the final simulation of column B had approximately 75% of the FC concentration as that of column A. This, in addition to the time differences between the deconstructions and final simulations, may have been a factor in the difference in results between column A and B.

Conclusions and Recommendations

This study showed that a reduction of FC and TSS concentrations from diluted manure slurry was possible using bioretention columns. The concentration of FC bacteria in the diluted manure slurry was within ranges found in the literature for urban stormwater and pasture lands. The FC reductions were above 90% for all but two simulations. The columns performed successfully in reducing TSS concentration for 10 of the 15 simulated storm events, according to the accepted performance standard of 90% reduction (NJDEP, 2004b).

Future research can include the systematic investigation of the processes involved with reduction of FC within the bioretention system. Additionally, studying the relationship between FC reduction and FC bacteria association with certain particulate fractions would be valuable, considering that a negative correlation was shown between influent TSS concentration and FC reduction.

Since this experiment reduced FC from manure water, bioretention might be an effective tool for managing runoff from agricultural pasture lands. An in-field study of a bioretention system managing animal waste runoff from a farm would be an important next step. A long-term evaluation is also important in determining possible maintenance issues over time. This is especially true considering that the column deconstruction experiment showed the retention of viable bacteria in the substrate after the last simulations were conducted.

Optimization of the planting media substrate for FC will likely become a key issue in the near future. However, since bioretention is meant to treat a variety of contaminants, there needs to be a substrate that is effective for both FC and other parameters. For example, the bioretention columns performed well in reducing FC and TSS, but also significantly reduced the pH to values below NJDEP water quality standards. Thus, a substrate optimized for FC must subsequently be tested against other parameters.

The hydraulic performance of the columns was adequate in that the influent completely infiltrated well before the NJDEP (2004b) performance standard of 72 h. However, ponding of more than 30.5 cm, the NJDEP (2004b) performance standard for ponding, was observed in the column A simulations. Thus, amendment of the planting media substrate in combination with an overflow control system will be important in-field considerations for hydraulics when constructing bioretention systems in practice.

Acknowledgements

The authors would like to thank Lisa Evrard, Daniel Gimenez, Nicoletta Graf, Michael Mak, Robert Miskewitz, James Moore, Peter Strom, Christopher Uchrin, Sean Walsh, and Carey Williams of Rutgers University; Pinelands Nursery of Dayton, New Jersey, for in-kind materials; and Ricci Brothers, Inc., of Port Jarvis, New Jersey, for in-kind materials. Partial funding was provided by a grant from the New Jersey Water Resources Research Institute.

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