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EVALUATION AND DEMONSTRATION OF THE USE OF PROCESSED FOREST BIOMASS IN BIORETENTION CELLS ALONG SOUTH CAROLINA'S HIGHWAYS

FINAL REPORT TO THE SOUTH CAROLINA FORESTRY COMMISSION

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Extended Abstract

Growth of developed areas and impervious surfaces in the U.S. has increased the environmental impacts of stormwater runoff and the public's interest in regulation of those who discharge it. Growth of communities in the urban-wildland interface is an important reason why risks of wildfire have increased and government agencies have undertaken new collaborative efforts to reduce them. A bioretention cell is a space-saving method to manage stormwater runoff from highways, streets, and parking lots. Widespread use of this structural practice could improve the quality of stormwater runoff and expand the market for small-diameter woody material. As a result, widespread use might also reduce risks of wildfire because mulch could be the source of the material, which provides carbon that the cell requires. The purpose of this project was to demonstrate a bioretention cell and the use of woody material in it along a major highway in South Carolina and evaluate the environmental performance and costs of this cell.

All storm water discharges from highways and other property of South Carolina's Department of Transportation (SCDOT) will be regulated under Phase I of the National Pollution Discharge Elimination System (NPDES) permit program for municipal separate stormwater sewer systems (MS4s). After consultation with and permission from officials of the South Carolina Department of Transportation (SCDOT), we selected a site for a bioretention cell in one part of the landscape at the interchange of Interstate 85 and South Carolina Highway 81, which is near Anderson, South Carolina. We also designed and managed the installation of the cell. The cell is 20' wide, 25' long, and 4' deep with a one-foot thick layer of single-ground pine mulch.

In general, the highway bioretention cell substantially reduced the peak discharge and total quantity of stormwater runoff to the existing storm sewer. The cell's efficiency of trapping zinc was five percent short of perfect and similar to the trapping efficiencies for zinc of previous

bioretention cells. Nitrate removal of this bioretention cell was appreciably higher than the nitrate removal of previous bioretention cells that had not been anaerobically enhanced. The efficiency with which the cell removed copper was, on average, 45% and substantially less than the trapping efficiencies for copper of previous bioretention cells. The efficiency with which the bioretention cell removed phosphates was extremely variable and, on average, negligible. Regardless of trapping efficiencies, concentrations of measured pollutants in the discharge were substantially below regulatory thresholds for water quality.

The highway bioretention cell near Anderson cost $9,250. This cost includes imputed expenses of project personnel who designed, engineered, and helped to install the cell and SCDOT workers who also helped to install the cell. These imputed expenses are based on typical hourly rates for similar types of work in Anderson. The largest portion of these costs, $5,489, was for the construction of the cell.

Bioretention cells appear to exhibit economies of water-quality size. If the volume of water that a cell treats for pollutants increases by one percent, the total costs of the cell increase by an estimated 0.74 percent in coastal areas of mid-Atlantic states, 0.63 percent in the Piedmont region, and 0.55 percent in the Sandhill region. Hence, costs per unit of water-quality volume decrease as the volume of water that a cell treats for pollutants increases.

Meaningful comparisons of costs of bioretention cells and stormwater ponds are difficult to make for a number of reasons. One reason is that stormwater ponds have been designed primarily to reduce stormwater runoff while most bioretention cells have been designed primarily to remove pollutants. Determination of the precise ranges of water-treatment and water-storage volumes over which bioretention cells are cheaper than stormwater ponds to meet regulatory standards for stormwater runoff remains an important question for research.

The South Carolina Department of Transportation has 93 county maintenance yards and section sheds with National Pollution Discharge Elimination System (NPDES) permits to discharge storm water. These permitted sites cover approximately 826 acres. Although obviously interested, SCDOT has not decided to what extent to use bioretention cells to remove pollutants in runoff from its yards and sheds. However, if SCDOT were to eventually retrofit all 93 sites with bioretention cells to treat one inch of storm water runoff, design the cells to have nine inches of ponding depth, and create a one-foot deep layer of ground woody material in the cells, this state organization would use 148,039 yd^3 of the material. If single-ground pine mulch costs \$14 per yd^3, then SCDOT would use \$2.1 million of this material in the bioretention cells.

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Background

Urbanization of land use occurs throughout the U.S. The area of developed land--urban, built-up, and rural transportation land--increased 47.4%, from 72.8 million acres to 107.3 million acres, during 1982-2002 in the 48 contiguous states (NRCS 2004, 3). In South Carolina, developed area increased 55.5%, from 1.3489 million to 2.0973 million acres, during 1982-1997 (NRCS 2000, 15). Land development also apparently accelerated. In the lower 48 states developed area increased 18.8% during 1982-1992 but 24.0% during 1992-2002 (NRCS 2004, 3). In South Carolina, the proportional growth rate of developed area was 12.2% during 1982-1987, 14.7% during 1987-1992, and 20.9% during 1992-1997 (NRCS 2000, 15).

Expansion of urban areas into natural forests and other rural areas in the U. S. has led to increases in potential damages of wildfires and, thus, costs of suppressing them during the last 20 years (DIDA, 5). Although they fluctuate yearly, real expenditures (2004 dollars) by federal agencies on wildland fire suppression have an estimated positive trend of $77.3 million per year during 1994-2004 and were $890.2 million in 2004 (BEA, NIFC). Regardless of suppression expenditures, property losses and other adverse impacts of wildland fire continue to grow because the communities in the wildland-urban interface also continue to increase in size and number (DIDA, 5). The U. S. Dept. of Agriculture's Forest Service and the Dept. of the Interior spent $2.295 million in 2002 for suppression (DOI-FS) of 3,161 fires that burned 26,256.3 acres in South Carolina (ORS). Research about promotion of markets for small-diameter, woody material that would otherwise be hazardous fuel are action items in a 10-year comprehensive strategy for collaboration between federal, state, and local governments and citizens to reduce risks of wildland fire to communities and the environment (DIDA, 1, 9, and 11).

Conversion of agricultural and other types of undeveloped land into residential, commercial, industrial, and other types of developed land is usually irreversible. Developed land has significantly more impervious surface than undeveloped land (Haan et al., 498-500). In 2000, the total area of impervious surfaces—e.g., roofs, sidewalks, driveways, parking lots, and paved roadways—in the conterminous U.S. was 112,610 km^2, which was 96.6% of the area of Ohio (Elvidge et al.). The substantial increases in impervious cover and temperature of this surface permanently alter atmospheric and hydrologic cycles.

Urbanized uses of land can adversely affect water quality because of these changed cycles and non-point source pollution (e.g., Arnold and Gibbons, 244-249; Heimlich and Anderson, 31-35). In particular, runoff from urban areas and storm sewers in 2000 was the most important source of impairment of waters along assessed ocean shoreline in the U.S. (EPA 2002, Ch. 4, 39) and the second most important source of pollutants that impaired waters of assessed shoreline of the Great Lakes (EPA 2002, Ch. 4, 35) and estuaries (EPA 2002, Ch. 4, 30). Urban and storm-sewer runoff was the third most important source of pollutants that impaired assessed lakes, reservoirs, and ponds (EPA 2002, Ch. 3, 22) and the fourth most important source of pollutants that impaired assessed rivers and streams (EPA 2002, Ch. 2, 14) in the U.S. in 2000. Runoff from impervious surfaces in urban areas and storm sewers may include sediment, bacteria from pet waste, and toxic chemicals (EPA 2002, Ch. 2, 15).

The U. S. Environmental Protection Agency (EPA) regulates discharges of storm water from urban areas. As required by 1987 amendments to the Clean Water Act, the EPA in Nov. 1990 promulgated Phase I of a comprehensive national program to address storm water discharges.

Phase I requires operators of construction sites that disturb five or more acres of land, facilities that engage in ten other types of industrial activities, and municipal separate storm sewer systems that serve at least 100,000 people in incorporated places or unincorporated urbanized areas of counties to obtain coverage under a National Pollutant Discharge Elimination System (NPDES) permit for discharge of storm water runoff (EPA 1999a, 68731; EPA 1996, 4). One type of activity that is covered by a NPDES general permit for industrial activity is transportation (EPA 2005). The EPA has assigned to South Carolina's Department of Health and Environmental Control (DHEC) the authority to issue this and all other NPDES permits.

At present, South Carolina's Department of Transportation (SCDOT) has coverage under a NPDES general industrial permit with individual numbers for 93 maintenance facilities in the state (Graham, Vaughan). Also, SCDOT operates under a NPDES general construction permit to discharge storm water from any bridge, rest area, or highway that is being built (Vaughan). DHEC has designated SCDOT as a large, municipal separate storm sewer system (MS4) under NPDES Phase I regulations (Vaughan). Thus, all post-construction storm water discharges will be covered by and subject to the requirements of the MS4 permit, once it becomes effective (Vaughan). SCDOT must develop and implement a storm water pollution prevention plan to reduce or prevent release of pollutants in storm water through management practices, such as infiltration and retention devices, so that storm water discharges meet water quality standards (DHEC 2004, pgs. 1-3, 10, 15, and 34).

A bioretention cell is one type of structural management practice that removes pollutants and can control water quantity. The cell captures runoff as sheet flow from parking lots or streets and moves the stormwater through vegetation or directly to swale-like prepared beds that serve as filters and ponding areas (e.g., Appendix A and EPA 1999b). Infiltrated water passes through layers of vegetation, soil or sand, and organic material all of which are above a gravel bed in a trench. In the case of rare, high runoff events, excess water exits through drains located in the cell. In a bioretention cell, the surface vegetation takes up nutrients contained in the dissolved fraction, the organic material adsorbs pollutants, and microbial activity within the soil removes nitrogen and organic matter (EPA 1999b, 2-3). The cell can have an anaerobic zone for denitrification (EPA 1999b, 2). The anaerobic zone can also retain some of the stormwater that flows into the cell and, thereby, reduce outflow.

In contrast to a stormwater pond, a bioretention cell is built into a landscape that serves other purposes, e.g., beautification and shade. Moreover, bioretention cells might remove pollutants more effectively than stormwater detention ponds (Appendix B, Table 7). Widespread use of bioretention cells would expand the market for ground-wood mulch and, to some extent, might reduce hazardous fuels for wildfire because mulch from wood debris could be the source of organic material that the cells require. Engineers and real-estate developers have begun to use bioretention cells in urban areas of the U. S. (e.g., EPA 1999b, 2 and Schueler 2000).

However, important questions about environmental performance and costs of bioretention cells remain unanswered. In particular, to what extent do pollutants adsorb to single-ground pine mulch? Given not-always-adequate removal of nitrates in previously designed bioretention cells, will an underground, rather than ground-level, layer of single-ground pine mulch and an anaerobic gravel layer that is immediately below the mulch adequately remove nitrates from the water that infiltrates or flows out of the cell? If drainage tiles are placed between the pine mulch and the gravel layer and if the gravel layer is sufficiently large, can the bioretention cell reduce the quantity of stormwater runoff? Do bioretention cells exhibit economies of size? Under what conditions, if any, are bioretention cells cheaper than stormwater ponds if they both meet regulatory standards or can reasonable comparisons even be made? Finally, how much processed pine biomass would be used if the South Carolina Department of Transportation were to use bioretention cells to manage stormwater discharges? The objectives of this project were to address these questions and demonstrate the use of single-ground pine mulch in a bioretention cell that treats runoff from a major highway interchange in South Carolina.

Demonstration of the Use of Processed Pine Biomass in a Bioretention Cell

After substantive consultation with and permission from officials of the South Carolina Department of Transportation (SCDOT), we designed a bioretention cell during late 2004 and early 2005 for the southeastern triangle--the blue shaded area in Figure 1--of the four-clover interchange at Exit 27 of Interstate 85 and South Carolina Highway 81 in Anderson County. We installed the cell with help from SCDOT personnel from the Anderson maintenance yard on May 25, 2005. Our collaboration with SCDOT personnel to select an appropriate site, discuss relevant storm water regulations, and install the cell on SCDOT property were three of our primary means of demonstrating the cell and the use of pine mulch in it. Our distribution of copies of this final report to our SCDOT collaborators will also contribute to their evaluation of the use of bioretention cells and pine mulch in them to manage storm water runoff.

The highway bioretention cell is approximately 20' wide, 25' long, and 4' deep with these four layers: 1) a top layer of Centipede sod, 2) an upper-middle layer of topsoil that is approximately 12 inches thick, 3) a 12 in. thick lower-middle layer of single-ground pine mulch, and 4) a bottom gravel layer that is 24" thick and comprised of ¾" washed stone, or American Society for Testing and Materials (ASTM) 6M washed gravel. In previous designs, bioretention cells have had a top layer of mulch, a middle layer of soil, and a bottom sand-gravel layer that removed excess water and kept the soil aerobic. Water could only leave the gravel layer by the process of infiltration. This produced anoxic conditions in the gravel layer after storm events. However, in this bioretention cell, the layer of ground woody material was put below ground and directly over the anaerobic gravel layer on the bottom to provide carbon for removal of nitrates from the water that infiltrates or flows out of the cell. Also, an under-drain, which consists of three four-inch corrugated, perforated, plastic pipes, was put below the pine mulch and above the gravel. The cell was designed so that storm water can pond nine inches on top of the cell.

Analysis of Inflow, Under-Drain Water, and Outflow at the Highway Bioretention Cell

The bioretention cell reduces the peak discharge and total quantity of stormwater runoff from SC Highway 81 at Exit 27 of Interstate 85 to the existing storm sewer. According to samples taken from June through August of 2005, the cell reduced the peak discharge, on average, by 82%. The total quantity of water outflow was 62% smaller, on average, than the total quantity of stormwater inflow.

The bioretention cell's efficiency of trapping zinc was high and similar to previous bioretention cells' trapping efficiencies of zinc. In particular, concentrations of zinc were, on average, 95% lower in the stormwater outflow than in the stormwater inflow. Concentrations of nitrates were, on average, 73% lower in the stormwater outflow than in the inflow. The nitrate removal of this bioretention cell was appreciably higher than the nitrate removal of previous bioretention cells that had not been anaerobically enhanced.

Concentrations of copper were, on average, 45% lower in the stormwater outflow than in the inflow to the cell. The efficiency with which the cell removed copper in stormwater was substantially lower than the trapping efficiencies for copper of previous bioretention cells. Although the bioretention cell completely removed phosphate in two instances, the cell actually added phosphate to stormwater outflow in another instance. Thus, the efficiency with which the cell 'trapped' phosphate was extremely variable and, on average, only four percent. Regardless of the cell's removal efficiencies, concentrations of measured pollutants in the discharge were substantially below the thresholds for water quality.

Costs of Bioretention Cells

The bioretention cell at Exit 27 of Interstate 85 cost $9,250 for engineering, other pre-construction activities, and construction (Table 1). This cost includes imputed expenses of project personnel who designed, engineered, and helped to install the cell and SCDOT workers who also helped to install the cell. These imputed expenses are based on typical hourly rates for similar types of work in Anderson, South Carolina. This figure does not include a land cost for the grassy surface area of the cell because this area is part of the existing landscape at the interchange. Construction expenses of $5,489 were the largest portion of the total cost.

Design and engineering were proportionately more costly in this project than in previous projects for which comparable data are available (Table 2). One possible reason why pre-construction activities accounted for a larger share of total costs in this project than in other projects and construction accounted for smaller share of total costs is that the biosystems engineers who worked on this project kept detailed and comprehensive records of hours spent on tasks related to designing the highway bioretention cell. Costs of the design and engineering of other bioretention cells might have been estimated with rules of thumb—for example 15 percent of construction costs—as the costs of design and engineering of stormwater ponds have been estimated (Brown and Schueler, pg. 15). Another reason is that the design and engineering costs of seven bioretention cells in Manassas, Virginia were only $2,000, just 2.23% of construction costs, and seem unreasonably small.

Design, engineering, and construction costs of a bioretention cell depend on the volume of water that is treated for pollutants, the volume of stormwater that can be instantaneously stored in the cell, the type of major land resource area where the cell is located, and the average wages of engineers and construction workers in or closest to the urban area where the cell is located (Appendix B, pg. 26, Models 2 and 3 in Table 4). If the volume of water that a cell treats for pollutants increases by one percent, the total costs of the cell increase by an estimated 0.74 percent in coastal areas of mid-Atlantic states, 0.63 percent in the Piedmont region of these states, and 0.55 percent in the Sandhill region, according to the best-fitting model (Appendix B, pg. 26, Model 2 in Table 4). In all models, costs per unit of water-quality volume decrease as the volume of water that a cell treats for pollutants increases (Appendix B, pg. 26, Table 4). Hence, bioretention cells exhibit economies of water-treatment size.

Design, engineering, and construction costs of a stormwater pond also depend on land prices, in addition to water-quality volume, water-quantity volume, and the average wage of engineers and construction workers in or closest to the urban area where the pond is located (Appendix B, pg. 27, Models 2 and 3 in Table 5). In the best-fitting model to date (Appendix B, pg. 27, Model 2 in Table 5), a one percent increase in land costs leads to a 0.21 percent increase in the total costs of a pond. In the same model, total costs increase 0.64 percent in response to a one percent increase in the water-storage volume of a pond in which the water-treatment volume is held constant. If water-treatment volume increases by one percent, the total costs of a stormwater pond increase by 0.67 percent in the Piedmont region and 0.86 in coastal areas of mid-Atlantic states. Hence, stormwater ponds exhibit economies of size of water treatment and storage.

Under what conditions is a bioretention cell cheaper than a stormwater pond? The answer to this question depends, in part, on whether treatment or storage is the basis of the comparison and the primary purpose of practice. In the past, stormwater ponds were designed primarily to reduce stormwater runoff and bioretention cells were designed to remove pollutants in the runoff. Distinct water-quality information exists for only four of the 27 cells in our sample. The highway bioretention cell and one adjacent to a shipping-receiving lot at an industrial park in Orangeburg, South Carolina are two of these four and were definitely designed to both treat and store stormwater runoff.

Under what conditions is a bioretention cell cheaper than a stormwater pond as a method of removing pollutants in stormwater runoff? In the unrestricted models (Appendix B, pgs. 26-27, Models 1 and 2), bioretention cells cost less than stormwater ponds at least for relatively small volumes of water storage, regardless of the region. Moreover, according to the estimates from Models 2 in Tables 4 and 5 (Appendix B, pgs. 26-27), a bioretention cell appears to be a cheaper method of treating runoff than a stormwater pond is for any observed storage volume in coastal areas of mid-Atlantic states. A bioretention cell is also a cheaper method of removing pollutants in runoff than a stormwater pond for storage volumes that are, on average, less than 141,682 ft^3 in the Piedmont region.

Our conclusions about the cost effectiveness of bioretention cells to treat stormwater runoff are not definitive for a number of reasons. First, whether a bioretention cell is, on average, cheaper than a stormwater pond depends on factors other than the water storage volume, such as unit costs of key inputs. As such, expected cost effectiveness is a function not a point. Second, a storage volume of 141,682 ft^3 is approximately seven times 19,874 ft^3, the largest observed water-storage volume of a bioretention cell in any mid-Atlantic state. Moreover, if the ponding depth and effective storage depth of the anaerobic gravel layer of a bioretention cell are 0.75 ft. and 1 ft., then the drainage area that would generate 141,682 ft^3 of runoff from the first inch flush of a rain event is approximately 16.7 acres, which is more than thrice 5 acres, the maximum recommended drainage area for typical bioretention cells (EPA 2004). Hence, the comparison of one stormwater pond to one bioretention cell might not be valid if the drainage area exceeds 5 acres or the water storage volume is designed to exceed 141,682 ft^3. The comparison would be between one stormwater pond and at least three bioretention cells. Third, water-quantity volumes were assumed, not measured, equal to water-quality volumes for 23 of the 27 bioretention cells in our database. Fourth, even if a bioretention cell and a stormwater pond are designed to have the same water-storage and water-treatment volumes, these two BMPs do not necessarily reduce equal amounts of runoff or have the same pollutant trapping efficiencies. At a particular location, a bioretention cell might be a cheaper way to remove a certain amount of pollutants in runoff whereas a stormwater pond might be cheaper way to reduce runoff to pre-development levels.

Maximum Possible Use of Processed Pine Biomass at Maintenance Yards and Section Sheds

The South Carolina Department of Transportation operates under a National-Pollution-Discharge-Elimination-System (NPDES) general industrial permit to discharge storm water from 93 county maintenance yards and section sheds. All post-construction storm water discharges from these yards, sheds, and other SCDOT properties will be covered by and subject to the requirements of a NPDES large municipal-separate-storm-sewer-system (MS4) permit, once it becomes effective (Vaughan). The general industrial permit currently requires and the new large MS4 permit will require that SCDOT uses ‘best’ management practices to control stormwater runoff and reduce pollution. Officials of SCDOT have not decided to what extent, if any, to use bioretention cells, one of these management practices, to remove pollutants in runoff from its yards and sheds.

Suppose that SCDOT were to retrofit all of the maintenance yards and section sheds that are covered by the general industrial permit with bioretention cells to treat storm water runoff. How much single-ground pine mulch would be used? According to analysis of aerial photographs, the average drainage area of a SCDOT maintenance yard or section shed is 8.88 acres (n=24, s.d. = 5.75). Greenville County's Department of Public Works recommends that a bioretention cell be designed so that the surface area of the cell equals one inch, or one-twelfth of a foot, of storm water runoff multiplied by the drainage area of the runoff divided by the average ponding depth above ground (SWD, pg. 9-277). Given the typical above-ground ponding depth of 0.75 foot, the estimated total surface area of bioretention cells at a maintenance yard or section shed would be, on average, 0.99 acre. If the mulch layer in each bioretention cell were ⅓ yard deep, as in the I85-SC81 cell, then the bioretention cell(s) at a maintenance yard or section shed would use, on average, 1,592 yds^3 of the single-ground pine material. SCDOT's 93 maintenance yards and sections sheds drain approximately 826 acres. Thus, the estimated amount of single-ground pine mulch that would be used in bioretention cells at these yards and sheds would be 148,039 yds^3.

The cost of the mulch for our highway bioretention cell was approximately $14 per cubic yard (Table 1). If the cost were to remain constant over time, SCDOT could use $2,072,533 of single-ground pine mulch as the carbon source in bioretention cells to manage the quantity and quality of stormwater runoff from its 93 maintenance yards and section sheds.

<u>Conclusions</u>

A highway bioretention cell with a ground cover of turfgrass and an underground layer of pine mulch above a bottom layer of gravel adequately removes nitrates and other pollutants from stormwater. The bioretention cell with drainage tiles below the single-ground pine mulch and above the gravel layer also significantly reduces the quantity of stormwater runoff. Bioretention cells exhibit economies of water-quality size and stormwater ponds exhibit economies of water-quality and water-quantity size. The challenge for future research is to estimate and use cost functions to determine the water-quality volume(s) at which, given local input prices, major land resource areas, and possible size constraints, a bioretention cell is a cheaper method than a stormwater pond to meet one or more regulatory standards for stormwater runoff. Given favorable assumptions, South Carolina's Department of Transportation might use 148,039 yds^3 or $2.1 million of single-ground pine material as the sole source of carbon in bioretention cells.

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Table 1: Costs of the Highway Bioretention Cell at the I 85–SC 81 Interchange

Type of Cost	Costs (Dollars)	Adjusted Costs (2003 $s in Baltimore MD)
1. Design and Engineering*	$3,761	$4,053
2. Construction	$5,489	$5,915
Labor*	$1,566	$1,687
Materials	$3,924	$4,228
Soil (500 ft^3)	$495	$533
Gravel (1000 ft^3)	$766	$825
Single-Ground Pine Mulch (500 ft^3)	$260	$280
Sod (2000 ft^2)	$532	$573
Pipes, Joints, and Rip-Rap	$485	$523
Sediment Controls	$68	$73
Machinery Rental* and Staples for Sod	$1,318	$1,420
Total	$9,250	$9,967

*These imputed costs equal hours spent by project personnel multiplied by typical hourly rates for similar types of work in Anderson, South Carolina. Imputed expenses for machinery rentals were the average daily rental of two dump trucks with 5-yd^3 beds ($251 each), one dump truck with an 8-yd^3 bed ($361), and one backhoe with a 24 in. bucket on a trailer ($440).

Table 2: Comparison of Cost Shares for Bioretention Cells

Type of Cost	Total Cost of I85 Highway Bioretention Cell	Percentage of Total Cost of I85 Highway Bioretention Cell	Percentage of Total Cost of Eleven Bioretention Cells in Maryland and Virginia
1. Design and Engineering	$3,761	41%	7%
2. Construction	$5,489[a]	59%	93%
Excavation and Grading	$1,024[b]	11%	22%
Drainage	$655[c]	7%	48%[e]
Cell Layers	$2,973[d]	32%	
Appurtenances	$0	0%	6%[f]
Landscaping	$763	8%	15%
Sediment Controls	$75[g]	1%	1%

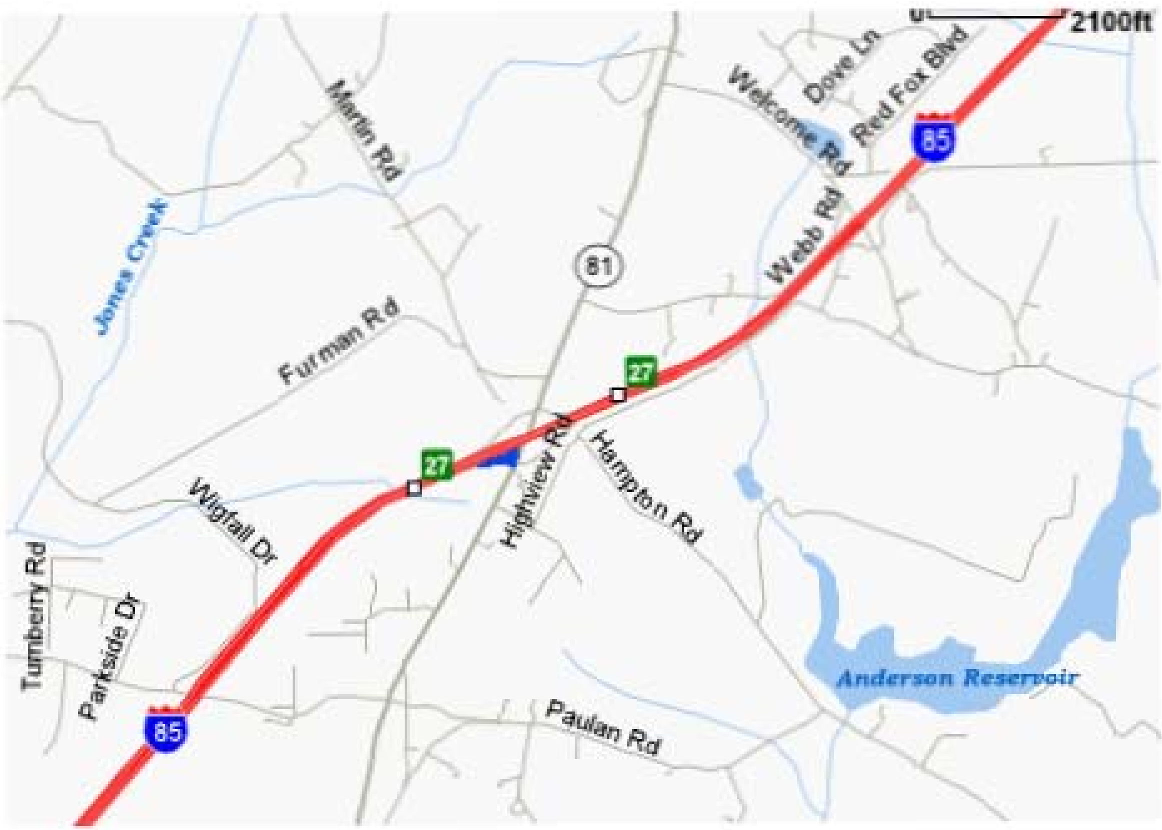
[a] Construction expenses for materials and labor, which includes supervision
[b] Includes mechanical removal of earth material and half-day rental of the backhoe
[c] Installation of overflow drainage and under-drain system
[d] Installation of gravel, mulch, and soil, rental of trucks for this installation, and half-day rental of the backhoe
[e] The control structure, which includes the riser and barrels (Brown and Schueler, pg. 3) but should also include trash racks, rip-rap, and any other relevant appurtenance
[f] Items not included elsewhere, such as rip-rap and trash racks (Brown and Schueler, pg. 3)
[g] Planting grass seeds and laying straw bales

Table 3: Water-Quality Volumes and Real Costs of Bioretention Cells in Maryland, Virginia, North Carolina, and South Carolina

ID (State Abbreviation and No.)	Water Quality Volume (ft^3)	Aggregated Major Land Resource Area	Unadjusted Total Cost (Current Dollars)	Adjusted Total Cost (2003 Dollars in Baltimore MD)	Adjusted Total Cost per Water Quality Volume ($/$ft^3$)
MD1	4,088	Piedmont	$21,708	$25,740	$6.30
MD2	7,014	Piedmont	$34,312	$42,926	$6.12
MD3	3,225	Piedmont	$21,454	$24,792	$7.69
MD4	332	Coastal	$41,518	$49,230	$148.17
MD5	19,874	Coastal	$152,314	$190,554	$9.59
VA1	1,260	Coastal	$7,838	$9,284	$7.37
VA2	1,290	Coastal	$6,961	$8,246	$6.39
VA3	2,423	Coastal	$19,638	$23,263	$9.60
VA4	930	Coastal	$7,861	$9,312	$10.01
VA5	2,775	Coastal	$19,000	$22,506	$8.11
VA6	1,170	Coastal	$6,778	$8,029	$6.86
VA7	3,870	Coastal	$23,531	$27,873	$7.20
NC1	272	Coastal	$920	$1,236	$4.54
NC2	1,089	Piedmont	$6,095	$8,052	$7.39
NC3	726	Piedmont	$2,070	$2,735	$3.77
NC4	10,890	Piedmont	$28,750	$37,980	$3.49
NC5	2,178	Piedmont	$14,260	$18,609	$8.54
NC6	2,087	Piedmont	$69,600	$88,480	$42.39
NC7	545	Piedmont	$1,725	$2,256	$4.14
NC8	2,360	Sand Hills	$2,070	$2,735	$1.16
NC9	17,061	Sand Hills	$6,900	$9,115	$0.53
NC10	908	Coastal	$1,150	$1,456	$1.60
NC11	2,360	Piedmont	$13,800	$18,271	$7.74
NC12	1,815	Piedmont	$11,385	$14,411	$7.94
NC13	1,398	Piedmont	$20,700	$26,315	$18.83
SC1	1,406	Coastal	$28,861	$35,505	$25.25
SC2*	375	Piedmont	$9,250	$9,967	$26.58
Average	3,471			$26,629	$14.72

*Highway bioretention cell at the I85 – SC81 interchange near Anderson, South Carolina

Figure 1: Location of Highway Bioretention Cell



The bioretention cell is the blue-shaded triangle at the interchange of Interstate 85 and South Carolina Highway 81.

APPENDIX A:

Analysis of the Quantity and Quality of Stormwater Inflow to and Outflow from a Highway Bioretenton Cell

by Bradley L. Weeber

(This appendix is Brad Weeber's draft of most portions of his thesis for a Master of Science in Agricultural and Biological Engineering.)

Introduction

Non-point source (NPS) pollution is the leading cause of water quality problems in the United States (EPA, 1994). NPS pollution occurs when water travels over land, accumulating pollutants and deposits them into rivers, lakes, estuaries, or groundwater. According to EPA, 1994, NPS pollution is the main cause for 40% of surveyed rivers, lakes, and estuaries not being clean enough for basic uses such as fishing and swimming.

This form of pollution is particularly important in urbanized areas because water that once infiltrated into the ground now flows over impervious surfaces. Runoff from urbanized areas has been found to contain heavy metals, nutrients, petroleum products, and other pollutants. Some research has found that pollutants in urban runoff concentrate in the first part of the hydrograph (Sansalone, 2004, Wanielista, 1999, Lee 2000, Deletic 1998). This is known as the first flush (FF) effect and has implications for the control of storm water pollutants.

Best management practices (BMPs) minimize adverse impacts to the environment. BMPs remove pollutants from storm water by physical methods such as floatation, filtering, and sorption and in some cases pollutants are chemically or biologically broken down. Some BMPs implement what is known as "local disposal," where the quantity of water released into surface waters is reduced by promoting infiltration and evapo-transpiration.

The bioretention cell (BRC) is a relatively new BMP that utilizes soil, organic materials, plants, microbes, and ponding to treat storm water runoff. Bioretention cells store water to reduce peak discharge, employ “local disposal” to reduce water volume discharged to surface waters, and utilize several mechanisms for pollutant removal.

BRCs have shown the potential for greater pollutant removal than other BMPs such as storm water ponds (EPA, 1999). One pollutant that BRCs have shown to be ineffective at removing is nitrate. In extreme cases nitrate levels have increased as a result of BRCs.

A possible solution to the nitrate problem is the anaerobically enhanced bioretention cell. The anaerobically enhanced BRC has a modified drainage system designed to create an anoxic zone. Anoxic conditions promote denitrification, the process by which nitrate is converted to nitrogen gas.

This study monitored the pollution in highway runoff and the performance of an anaerobically enhanced bioretention cell at reducing and treating this runoff. The objectives of this research were these:

1. Analyze highway runoff for pollution levels.
2. Analyze highway runoff for the presence of a first flush effect.
3. Evaluate the effectiveness of an anaerobically enhanced BRC as a storm water quantity BMP.
4. Evaluate the effectiveness of an anaerobically enhanced BRC as a storm water quality BMP.
5. Determine if denitrification occurs in the anoxic zone of the BRC.

These objectives were accomplished by installation of an anaerobically-enhanced BRC at the intersection of Highway 81 and Interstate 85 in Anderson, SC. The surface area of the cell was

20 by 25 feet. The depth of the cell was 4 feet. The BRC consisted of four layers; centipede sod layer, soil layer, single-ground pine mulch layer, and gravel layer. Water was allowed to pond nine inches over the BRC.

The sod layer filtered sediment and particulate pollutants. The soil supported sod growth, filtered pollutants, and acted as a sorbent for dissolved pollutants. The mulch layer served as a second sorbent (particularly for metals) and electron donor for the denitrification process. The drain system, located between the mulch and gravel layer, created aerobic conditions in upper layers and anoxic conditions in the gravel layer. The gravel layer served as water storage and anoxic layer for denitrification to occur.

Runoff entered the BRC by means of an 18-inch corrugated metal pipe. Discharge from the cell occurred through an 8-inch PVC pipe connected to the drainage system or an overflow weir. All three locations were monitored for discharge and sampled for water quality constituents.

Methods and Procedures

The bioretention cell (BRC) for this project was located near Anderson, SC within in the triangular area of land enclosed by I-85, South Carolina Highway 81, and the northbound exit ramp. This is a high traffic intersection that also contains businesses, which include a gas station and fast food restaurants. The drainage area was determined using GPS surveying equipment to be 0.443 acres (19,315 ft^2). The roadway runoff reached the BRC by means of an 18-inch corrugated metal pipe (CMP).

The BRC was designed to hold a half-inch of runoff. The calculation of BRC size can be found in Appendix A1: Calculation of BRC Size. The final dimensions of the BRC were 20 by 25 feet.

The total depth of the BRC was four feet. The bottom two feet consisted of ASTM 6M washed gravel. This gravel is approximately ¾ inch in diameter. Water could only leave the gravel layer by the process of infiltration. This produced anoxic conditions in the gravel layer after storm events. The drain system for the BRC was placed on top of the gravel layer. Directly above the drain system was one foot of single ground pine mulch. One foot of topsoil was placed above the mulch layer. The top layer of the BRC was centipede sod.

The drain system provided aerobic conditions in upper layers. The water entered the under drain system by means of three corrugated perforated 4 inch plastic pipes that ran the length of the BRC. These connected to an eight inch PVC main across the downstream side of the BRC. This PVC pipe was connected to another eight inch PVC pipe at a ninety degree angle to route the water out of the BRC.

Two soil samples were taken from different locations within the BRC and analyzed at the Clemson Entomology, Soil, and Plant Science Laboratory. Both samples were classified as a sandy loam. Table 1 provides a breakdown of the percent sand, silt, and clay for both soil samples.

Table 1. Analysis of Soil at Location of Highway Bioretention Cell

Category	Sample #1 (%)	Sample #2 (%)
Very Coarse Sand	6.8	8.2
Coarse Sand	13.3	13.2
Medium Sand	14.7	17.1
Fine Sand	16	16.2
Very Fine Sand	8.3	7.8
TOTAL SAND	59.1	62.3
SILT	21.6	19
CLAY	19.3	18.7

A berm was built around the entire BRC to allow for ponding. Once the water level exceeded 9 inches in the BRC, water flowed over a 120° V-notch weir for measurement. Riprap was used to stabilize this discharge point. A 2 inch slotted well casing was placed in the BRC to allow for samples to be taken in the gravel layer.

Flow and Depth Measurement

To determine a mass balance on pollutants from concentration, water quantity must be known. For this reason, the inflow, drain flow (also known as pipe flow), and overflow were measured. Rainfall directly onto the cell was neglected. For a given storm, the inflow minus the drain flow and overflow may be considered storage. Water stored in the BRC is eventually lost to infiltration from the bottom of the BRC and evapotranspiration.

The water entering the BRC from the 18 inch CMP was measured with an American Sigma Submerged Area/Velocity Sensor 88002. The sensor was mounted in the CMP three feet from the outlet in the "upstream" configuration.

The water discharge leaving the BRC from the drain system was measured with a 0.5 foot H flume. ASTM standard D 5640 was followed for the selection and use of the flume. The water level in the flume was measured with an American Sigma down looking ultrasonic sensor.

The water discharge leaving the BRC from the overflow was measured with a 120˚ V-notch weir. Equation 1 represents flow over a 120˚ V-notch weir (Grant and Dawson, 1995), where Q is discharge in cfs and H is head in feet. The head was measured 1.5 feet upstream from the weir in the stilling pool using an American Sigma down looking ultrasonic sensor.

$$Q = 4.330 * H^{2.5} \qquad (1)$$

To determine the time water remained standing in the BRC, a third ultra sonic sensor was installed approximately in the middle of the cell. A metal plate was buried beneath the sensor because grass was not sufficient to return the ultrasonic signal. All data from level and flow sensors was recorded with American Sigma 930 data loggers.

Water Sample Collection

Water samples were collected from the inflow CMP, drain system discharge, and overflow discharge using three ISCO 3700 discrete samplers. The samplers were powered by twelve-volt lead-acid batteries recharged by solar panels. The samplers were triggered with a liquid detector.

Once triggered, the sampler was programmed to pull a 350 mL sample into a separate bottle every five minutes for the first 30 minutes (7 bottles). After 30 minutes, the sampler was programmed to pull a 175 mL sample every five minutes. Two samples were then placed in each bottle for the remaining 17 bottles. This sampling scheme was used to provide higher resolution at the beginning of the storm where constituent values often changed rapidly. The program also rinsed the sample line between all samples. The program only ran as long as the liquid detector indicated liquid was present. This sampling program was used for all samplers.

Bottles 1, 3, 5, 7, 9, and 11 were glass in all samplers. A flow weighted composite was created from these samples for total petroleum hydrocarbon (TPH) and oil/grease analysis. Glass was necessary as the use of plastic bottles can increase TPH values. The sample volumes left in the glass bottles after the composite was made was sufficient for all other analyses. All other bottles in the samplers were HDPE.

The samples were collected the day of or the day after a storm event with the exception of storm seven. The samples were then delivered to the labs for immediate analysis. For this reason, no samples were collected for storms that occurred on Friday or Saturday.

Well samples were drawn from approximately three feet deep (the middle of the gravel layer) with a ¾ inch piece of tubing attached to a Buchner flask. A vacuum pump was used to draw water. Once a sufficient amount of water was collected, it was poured from the Buchner flask into a HDPE ISCO bottle. Well samples were obtained at the time of sample collection and daily for several days after the storm. .

Cleaning Procedure

Testing for trace constituents requires rigorous cleaning methods to avoid contamination of the sample. All sample bottles were soaked in a 2% Citranox® solution for one hour. Citranox® was used because it is phosphate free, free rinsing, and yields a pH of 2.5 in a 2% solution, thus effectively removing any metals.

After being soaked, the bottles were rinsed four times with de-ionized (DI) water. The bottles were then capped and stored until use. The cleaning procedure was repeated every time bottles were reused. For quality assurance, blanks (DI water) were analyzed twice during the project. On both occasions, all constituents were below the detection limits for the lab.

Sample Analysis

All samples were analyzed at the Clemson University Agricultural Service Laboratory. Mineral concentrations were determined with a TJA 61E induction-coupled plasma (ICP) spectrometer by Thermo Electron Corporation. Nitrate concentrations were determined with a nitrate meter and electrode by Thermo Orion. A Thermo Orion probe was also used to measure pH.

Samples were also analyzed at Texidyne, Inc. located in Central, South Carolina. This lab performed total petroleum hydrocarbons (TPH) and oil and grease analysis. Their methods conform to the *Standard Methods for the Examination of Water and Wastewater 19^th^ Edition.*

Data Analysis

Storm and Sample Information Sheets

The "Storm and Sample Information Sheets" were used to collect data in the field and summarize information after analysis. When collecting a sample; time of collection, start and stop times for all samplers, preservation method, and any comments about the sample were recorded. The comments section is where date and time of any samples drawn from the well can be found.

Once the data was retrieved from the data logger; the start time, stop time, and total rainfall amount were recorded. The date, time, and rainfall amount for any previous storm was also recorded. This was done to observe effects of the antecedent dry weather on constituent levels as well as possible effects on the BRC's removal efficiency.

After the sample data was returned from the lab, the Storm and Sample Information Sheets were filled out with event mean concentration (EMC), total load, and BRC removal efficiency for all constitutes. How these were determined is outlined in the "calculations" section.

Flow Data

The flow entering the BRC from the 18 inch CMP was measured with an American Sigma Submerged Area/Velocity Sensor 88002. This sensor measures depth with a pressure transducer and velocity with a Doppler sensor. The data logger then uses these two values and the known pipe diameter to determine the actual flow in cubic feet per second.

The CMP coming into the BRC was at a steep angle causing for low depth and high velocity flow. The Doppler velocity sensor had no trouble with these conditions, however the pressure transducer would often misread due to the highly turbulent shallow depth flow. For this reason, a regression was made between velocity and discharge to fill in the data points where depth data was erroneous. Regression analysis can be found in Appendix A3: Relationship between Inlet Velocity and Discharge. Any data points estimated in this way are shown in red.

The flow leaving the BRC through the drain system was measured with a 0.5 foot H flume. Discharge information for this type of flume was found in Grant and Dawson, 1995. Further explanation of the flow calculations for the flume can be found in Appendix D: Discharge Information for Outlet Flume.

The flow leaving the BRC from the overflow was measured with a 120° V-notch weir. A stilling basin was located before the weir to allow for an accurate depth measurement. The flow over the weir was determined by Equation 1 found in Grant and Dawson, 1995.

<u>Calculations</u>

Due to the large number of repetitive calculations required, most were performed in Microsoft Excel. Concentration and flow data were entered into a spreadsheet where the data was aligned corresponding to time. Flow rate for a sample was then converted to total flow by multiplying by the time the sample covered (five minutes for first seven bottles and ten minutes for all bottles thereafter). A conversion factor was used to obtain flow in liters.

Mass of constituent for each time period was then found by multiplying concentration in mg/L (ppm) times flow in liters. Mass for each time period was then summed over the entire storm duration to determine total mass for the storm. If the entire storm was not sampled (i.e. longer than three hours), the concentration data for the end of the storm was estimated from the existing concentration trends. Estimated data are shown in red.

First flush analysis was performed according to Sansalone and Cristina, 2004, description and equations 2 and 3.

$$V(t) = \frac{\int_0^k Q(t)dt}{\int_0^n Q(t)dt} \qquad \text{(Sansalone, 2004)} \qquad (2)$$

$$M(t) = \frac{\int_0^k Q(t)C(t)dt}{\int_0^n Q(t)C(t)dt} \qquad \text{(Sansalone, 2004)} \qquad (3)$$

Removal efficiency in percent for each constituent was determined by equation 4.

$$\text{Re}\,moval\ \% = \left(1 - \frac{mass\_in}{mass\_out}\right) * 100 \qquad (4)$$

Event mean concentration (EMC) was determined by equation 5.

$$EMC = \frac{total\_mass}{total\_volume} \qquad (5)$$

Results and Discussion of Anderson Bioretention Cell Study

Reduction of peak discharge is a common goal of storm water BMPs. Table 1 shows the peak discharge entering the BRC, exiting the BRC, and the percent reduction.

Table 1. Peak discharge information for Anderson BRC.

	Date	Peak Q in (cfs)	Peak Q out (cfs)	Reduction (%)
Storm 1	6/19/2005	0.077	0.0121	84.28571
Storm 2	6/27/2005	0.146	0.0118	91.91781
Storm 3	7/19/2005	0.108	0	100
Storm 4	7/28/2005	0.07	0	100
Storm 5	8/7/2005	0.1	0.043	57
Storm 6	8/18/2005	0.13	0.043	66.92308

Average		0.105667	0.02015	82.10034

No storms during the study exceeded the capacity of the BRC. Therefore, no flow or concentration data was collected from the overflow weir.

In recent years, there has been support for "local disposal" of storm water. Local disposal not only reduces peak discharge into receiving waters but quantity as well. This is achieved in a BRC through infiltration and evapotranspiration of stored water between storm events. Table 2 shows quantity data for the BRC and factors that may influence percent reduction of water quantity. Antecedent dry weather (ADW) is the time since the last runoff event. This is not necessarily the same as the last sampled storm.

Table 2. Water quantity information for Highway Bioretention Cell near Anderson SC

	Influent (l)	Effluent (l)	Reduction (%)	Rainfall (in)	ADW (days)
Storm 1	8906.1999	1369.98491	84.61762687	0.3	6
Storm 2	3952.7421	2377.1023	39.86194305	0.26	0.7
Storm 3	2187.9145	0	100	0.11	4
Storm 4	1905.2676	0	100	0.1	8
Storm 5	6501.2541	5388.6206	17.11413663	0.26	7
Storm 6	16081.111	11309.6543	29.67118707	0.53	4
Average	6589.0815	3407.56035	61.87748227	0.26	4.95

The amount of water the BRC can store for local disposal is dependent on how much water is in the cell at the time of a storm. Maximum storage will occur when the soil, mulch, and gravel layers are dry. A good indicator of dryness of the cell is antecedent dry weather (ADW). The longer it has been since the last rain the more storage space the BRC should have. The temperature, humidity, and other climatic conditions on the ADW days would also be important.

This relationship can be seen from storms 1 and 2 that have nearly equal rainfall. The BRC would have more storage capacity for storm 1 with 6 days ADW as opposed to storm 2 with less than a day ADW. The percent reduction of storm water for storms 1 and 2 are 85% and 40% respectively.

The storage capacity of the BRC is independent of the amount of water entering the cell. For this reason the percent reduction decreases with increasing storm size. This is demonstrated by the 100% volume reduction of the two smallest storms, storms 3 and 4, with 0.1 and 0.11 inches of rain respectively. One of the lowest volume reduction percentages is seen in storm 6, with 0.53 inches of rainfall.

The second concern of storm water runoff is quality. The BRC uses several different mechanisms to remove pollutants from runoff. To evaluate the effectiveness of a BMP, average concentration (EMC) and total load must be considered. Table 3 shows the EMC of the pollutants entering and leaving the cell. Table 4 shows the total load in, out, and removed from surface runoff. Table 5 shows the removal efficiency of the BRC for the four pollutants considered.

Table 3. Influent and effluent EMCs.

	PO_4-P	Zn	Cu	NO_3-N	PO_4-P	Zn	Cu	NO_3-N
	Mean Concentration IN (mg/l)				Mean Concentration OUT (mg/l)			
Storm 1	0.084	0.068	0.006	1.592	0.200	0.020	0.010	1.142
Storm 2	0.011	0.049	0.003	0.532	0.066	0.007	0.006	0

Storm 3	0.160	0.227	0.007	0.811	NA	NA	NA	NA
Storm 4	0.090	0.383	0.006	1.312	NA	NA	NA	NA
Storm 5	0.071	0.036	0.007	0.874	0.083	0.003	0.008	0.262
Storm 6	0.043	0.056	0.004	0.549	0.052	0.007	0.006	1.000
Average	0.077	0.137	0.006	0.945	0.100	0.009	0.008	0.601

Table 4. Mass loads of influent (In), effluent (Out), and net removal (Net)

Storm Number	PO_4-P (mg)			Zn (mg)			Cu (mg)			NO_3-N (mg)		
	In	Out	Net	In	Out	Net	In	Out	Net	In	Out	Net
S1	749	274	475	604	28	577	57.1	13.7	43.4	14180	1564	12616
S2	45	158	-113	196	17	179	13.3	15.3	-2.0	2103	0	2103
S3	349	0	349	497	0	497	16.4	0.0	16.4	1775	0	1775
S4	172	0	172	729	0	729	10.9	0.0	10.9	2500	0	2500
S5	464	448	16	231	18	213	44.0	44.2	-0.2	5681	1410	4272
S6	696	594	102	905	80	825	71.9	66.6	5.3	8826	11310	-2483
Mean	412	246	167	527	24	503	35.6	23.3	12.3	5844	2381	3464

Table 5. Mass basis removal efficiency of inflow vs. drain flow

	PO_4-P (%)	Zn (%)	Cu (%)	NO_3-N (%)
Storm 1	63.4	95.4	76.0	89.0
Storm 2	-252.5	91.3	-14.9	100.0
Storm 3	100.0	100.0	100.0	100.0
Storm 4	100.0	100.0	100.0	100.0
Storm 5	3.4	92.2	-0.5	75.2
Storm 6	14.7	91.2	7.3	-28.1
Mean	4.8	95.0	44.7	72.7

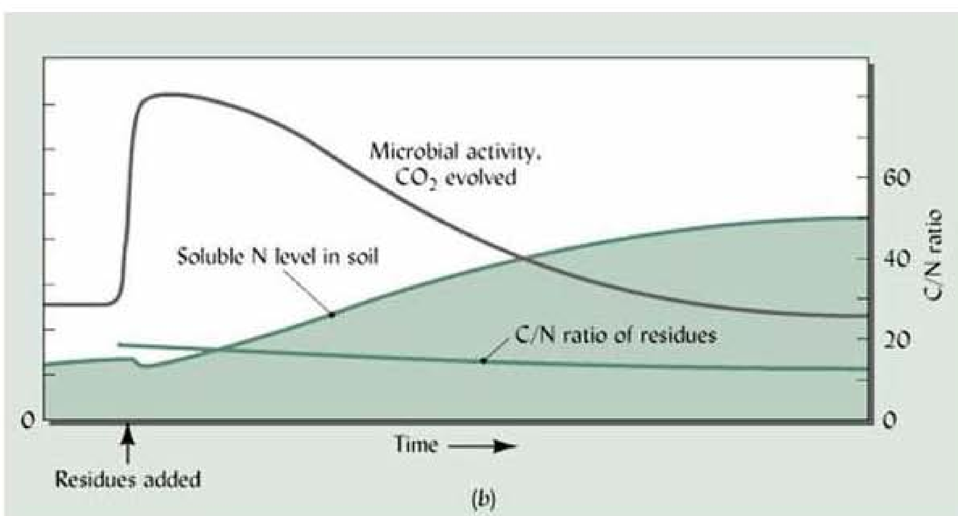
The average removal efficiency for all constituents analyzed was positive. This results from decreased water concentration after passing through the cell and/or a decrease in water volume. For instance, the average removal efficiency of phosphate and copper are 4.8% and 44.7% respectively despite the average EMC of these constituents increasing from influent to effluent. In both cases the reduction in total load was a result of the reduced flow.

The removal efficiency for inflow vs. drain flow of all constituents for storms 3 and 4 were 100%. This was due to no outflow resulting from these storm events.

The nitrate removal efficiency of the BRC was high for all storm events except storm 6 where nitrate increased. A likely explanation for this is the grass of the BRC was mowed August 15, three days before storm 6. The grass was not mowed at any other time during the study.

Grass clippings have a high nitrogen residue with an average carbon/nitrogen (C/N) ratio of 17 (Richard, 1992). Nitrogen-rich residues decompose rapidly (days) (Weil, 2002). Figure 1 shows effect of low C/N (less than 20) residues on soluble nitrogen levels in the soil. Soluble nitrogen is primarily nitrate (Weil, 2002).

Figure 1. Effect of low C/N ratio residues on soluble nitrogen levels (Weil, 2002)



The BRC for this project was anaerobically enhanced. The goal of this modified drainage system was to improve nitrate removal. It was expected that the removal efficiency of other constituents would be near that of previous BRCs. Table 6 compares the removal efficiencies of the Anderson BRC to that of previous, standard drainage, BRCs.

Table 6. Removal Efficiencies of Highway Bioretention Cell and Other BRCs

Pollutant	Average BRC removal (%)	Anderson BRC removal (%)
Nitrate	18.3	72.7
Zinc	90.7	95.0
Copper	86.0	44.7

As can be seen from Table 6, the highway bioretention cell in Anderson outperforms the standard drainage bioretention cells in the removal of nitrate with 72.7% and 18.3% removal efficiency respectively. It is likely that this is due to the Anderson BRC's anaerobically-enhanced design. Confirmation of this could only come from a similar BRC in the same location that was not anaerbically enhanced.

The zinc removal efficiency of the Anderson BRC and standard drainage BRC were similar at 95.0% and 90.7% respectively. This result was anticipated because the major zinc removal mechanism is sorption which is unaffected by the anaerobically enhanced design.

The copper removal efficiency of the Anderson BRC was substantially lower than that of the standard drainage BRCs with 44.7% and 86.0% respectively. It is believed that this is not due to the Anderson BRC having less capability to remove copper, but rather the extremely low concentration of copper entering the cell. Table 7 shows a comparison between common concentrations of pollutants found in urban runoff (Davis et al., 2003) and the runoff entering the highway bioretention cell.

Table 7. Comparison between typical runoff concentrations and Anderson concentrations.

Pollutant	Pollutant Concentrations in Typical Runoff (Davis et al, 2003) (mg/l)	Pollutant Concentrations in Anderson Runoff (mg/l)
Nitrate	2	0.945
Phosphorus	0.6	0.077
Copper	0.08	0.006
Zinc	0.6	0.137

The concentrations of pollutants in the runoff at the I85-SC81 interchange are less than concentrations of 'typical' runoff for all pollutants considered. The most extreme case is copper where the Anderson runoff concentration is more than an order of magnitude less than typical runoff. Sorption is controlled by concentration gradients. Extremely low concentrations coming into the cell does not enable the soil and mulch to sorb copper. In such a situation, the soil and mulch may leach copper.

Oil and grease and total petroleum hydrocarbon (TPH) analysis was also performed. Due to the expense of the analysis a single flow weighted composite for the inflow and outflow of each storm was analyzed. Table 8 shows the data for the composite samples.

Table 8. Oil and Grease and TPH average concentrations.

	Influent		Effluent	
	Oil and Grease	TPH	Oil and Grease	TPH
Storm 2	5.2	<1*	12.4	<1*
Storm 3	3.4	<1*	-	-
Storm 5	<1*	<1*	<1*	<1*

Storm 6	2.4	<1*	<1*	<1*
Storm 7	8.8	2.4	-	-
Storm 8	3.4	<1*	-	-

* Indicates data reported as 1:2 dilution

All samples were sent to the lab as a 1:2 dilution. The dilution was required to leave enough water for other analyses. Values of less than one were reported in Table X as the dilution value because it could not simply be doubled.

Due to the limited data and data less than one mg/l, it is difficult to draw any conclusions about the BRC's removal characteristics of oil and grease and TPH. There is only one storm with inflow and outflow that showed a reduction in oil and grease, storm 6. Storm 7 did produce inflow and outflow from the BRC; a power failure in the pipe sampler is the reason for no effluent data. Unexpected data is seen from storm 2, where the oil and grease value is shown to double passing through the BRC. No explanation for this has been found.

Well samples were drawn from the anoxic gravel layer by means of a 2-inch slotted well pipe. Samples were drawn after storms to observe the changing constituent values. Nitrate was of particular concern as the anoxic zone was specifically designed to reduce nitrate levels. Table 9 shows concentration values in well samples taken after the storm. The "elapsed time" column indicates the time after (or before) the beginning of the storm that the sample was collected.

Table 9. Well sample data.

	Sample	Date	Time	Elapsed Time (hr)	NO_3-N (mg/l)	Zn (mg/l)	Cu (mg/l)	PO_4-P (mg/l)
Storm 3	Well 1	7/20/2005	13:05	8	0	0.044	0	0.06
	Well 2*	7/21/2005	8:06	27	0	0.014	0	0.041
	Average				0	0.029	0	0.0505
Storm 5	Well 1	8/8/2005	9:00	25	0	0.0086	0.0057	0.0959
	Well 2	8/9/2005	12:00	52	0	0.0114	0.0063	0.135

	Well 3	8/10/2005	15:00	79	0	0.008	0.0041	0.0593
	Average				0	0.0093	0.0054	0.0967
Storm 7	Well 1	8/22/2005	9:00	-8	0	0.0051	L.0008	L.0123
	Well 2	8/24/2005	13:30	45	0	0.0482	0.0048	0.0673
	Well 3	8/25/2005	9:00	64.5	0	0.0111	0.014	0.1284
	Average				0	0.021467	0.0094	0.09785

* Low well level. Sample drawn from bottom, with large amounts of sediment

L Concentration below equipment rating

As can be seen in Table 9, no detectable nitrate levels were found in any well samples. It is known that detectable levels of nitrate entered the BRC for each of the storms in Table X. Therefore, for no nitrate to be found in the well samples, the nitrate is either adsorbed completely in the upper layers or is being reduced in the anoxic zone. Effluent samples also contained detectable levels of nitrate in all but one case. This implies that complete adsorption of nitrate in upper layers is not occurring.

Therefore, it appears that denitrification is occurring in the anoxic gravel zone. Privette, 2005, showed denitrification in an anoxic zone to be a fast process, approaching 100% reduction in less than 48 hours. The nitrate levels entering and leaving the BRC were just above the detectable limit of 1 mg/l. The shortest time between the start of a storm and a well sample was 8 hours. With the rate of denitrification shown in Privette, 2005, it is likely that 8 hours was sufficient time to reduce nitrate levels below the detection limit.

It was observed that in most cases the concentrations of zinc, copper, and phosphate also dropped with time and increased when runoff entered the cell. Well 1 of storm 7 was taken before the storm. Well 2 of storm 7 was taken after the storm and had higher pollution concentrations. A runoff event occurred between well 1 and well 2 samples of storm 5. This explains the increase in concentration of zinc, copper, and phosphate. No explanation was found for the increase in copper and phosphate between storm 7 well 2 and 3 samples.

Another goal of this research was to investigate the first flush phenomenon. If a strong FF is present for a watershed, a BMP would not need to treat the entire runoff volume to make significant improvements in water quality. An analysis of FF was performed for zinc, copper, nitrate, and phosphate for the influent and effluent according to the method described by Sansalone, 2004. Figure 2 shows the different types of FF and delayed loadings that can occur.

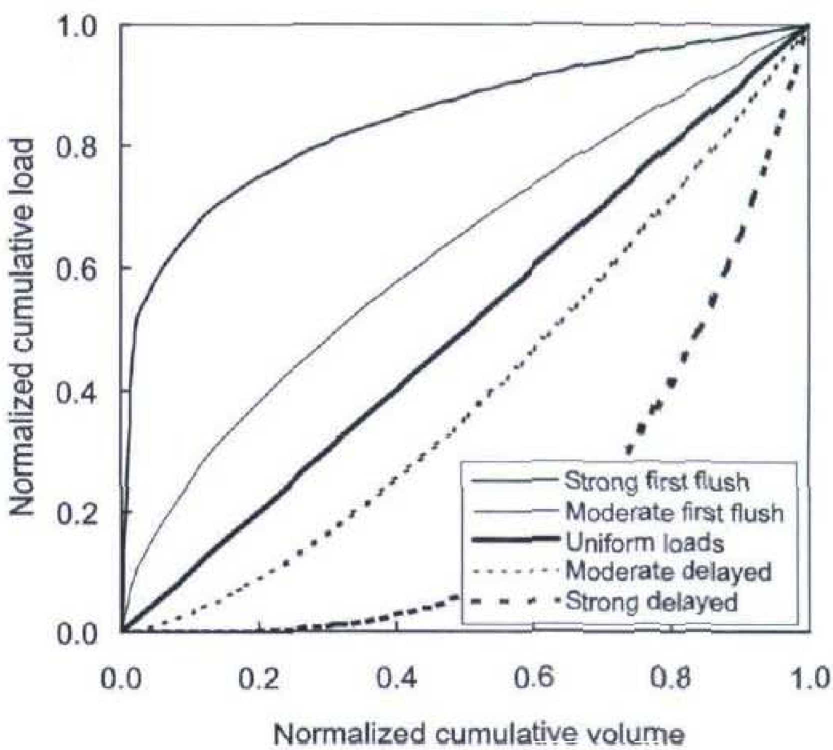


Figure 2. Normalized pollution load curves (Taebi, 2004).

Figure 3 shows the normalized curves for influent zinc. Figure 4 shows the normalized curves for effluent zinc.

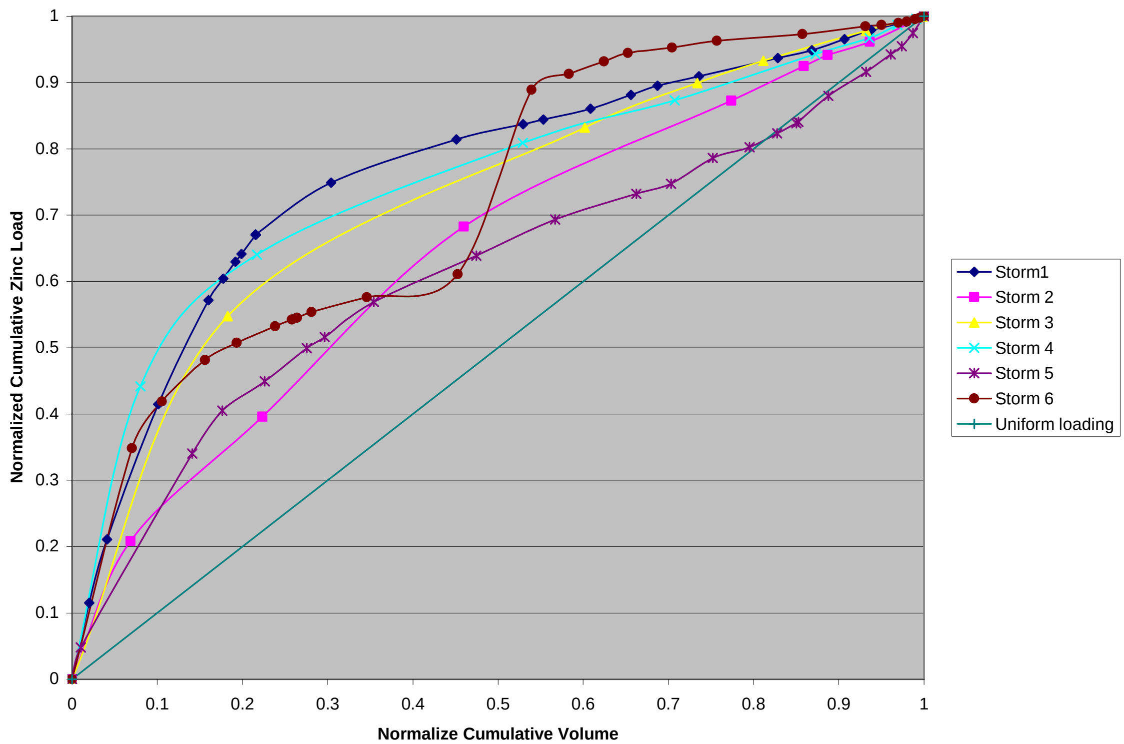


Figure 3. Normalized pollution curves for influent zinc.

The influent zinc pollution curves ranged from moderate to strong first flush. The weakest FF was observed in storm 2 with approximately 40% of the zinc load occurring in the first 20% of volume. The strongest FF was observed in storm 1 with approximately 65% of the zinc load occurring in the first 20% of volume.

Storms 1 and 4 demonstrated strong first flush (FF) characteristics; they also had two of the longest ADW, 6 and 8 days respectively. Storm 3 also demonstrated a strong FF effect. Storm 3 had a moderate ADW of 4 days, however; the rain was the second most intense. While intense, storm 2 had less than a day ADW, a likely cause for the only moderate FF effect. Storm 5 also had a moderate FF effect. While it had long ADW of 8 days, it was the second least intense storm.

The general finding of increased FF effect with increased rainfall intensity corresponds to Sansalone, 1998, Cristina, 2003, Lee, 2003, Taebi, 2004, and Gupta, 1996. The general finding of increased FF effect with increased ADW corresponds to Gupta, 1996. A more advanced statistical analysis of the correlation between ADW, rainfall intensity, rainfall duration, and FF effect was not performed.

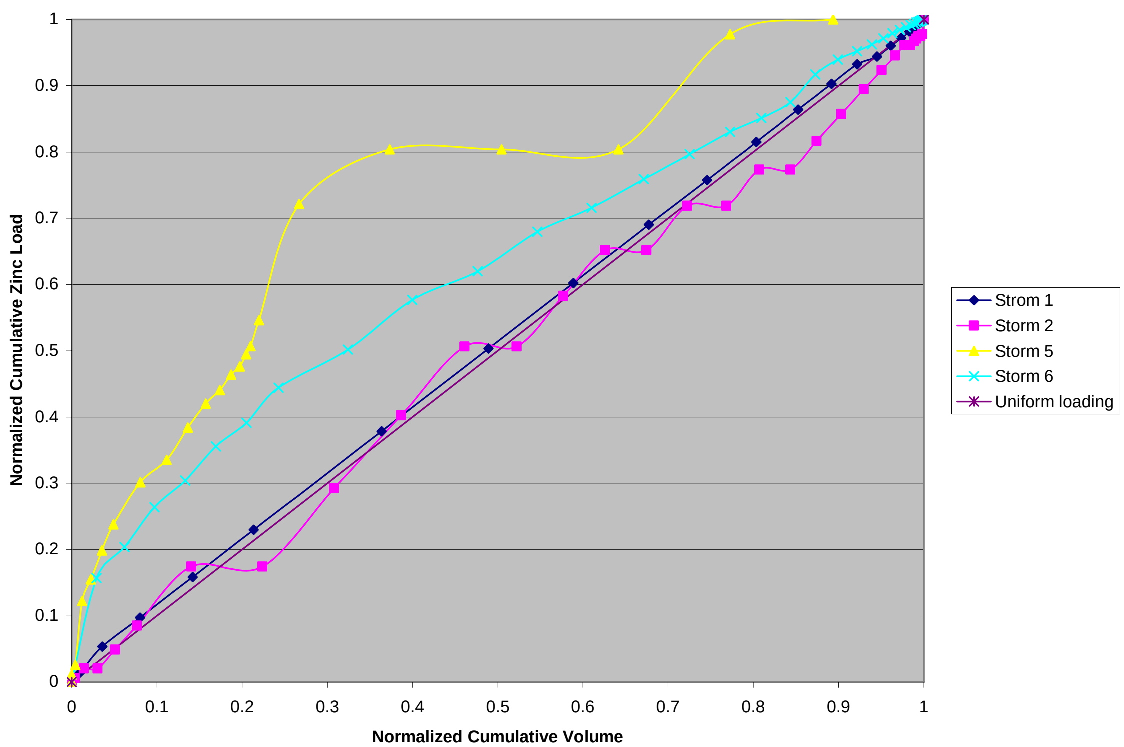


Figure 4. Normalized pollution curves for effluent zinc.

Storms 1 and 2 show no FF effect for effluent zinc. Storms 5 and 6 both show a moderate FF effect for zinc effluent. It should be noted that the zinc removal efficiency for storms 5 and 6 were still high at 92.2% 91.2% respectively.

Figure 5 shows the normalized curves for influent copper. Figure 6 shows the normalized curves for effluent copper.

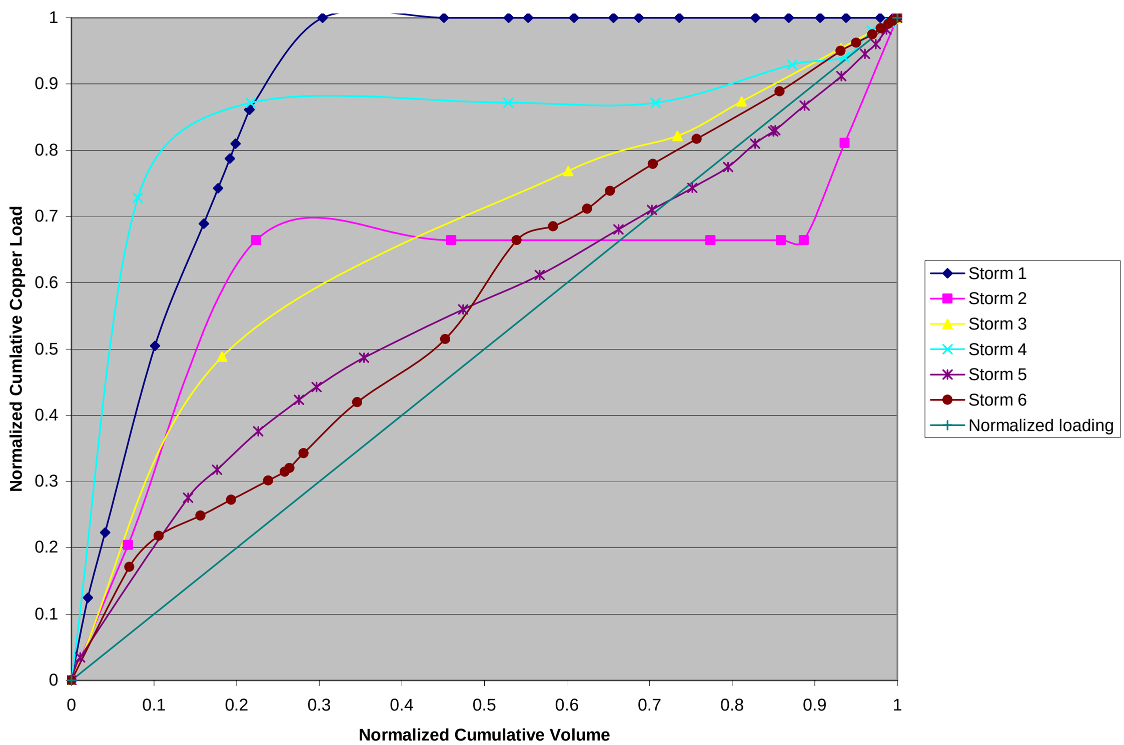


Figure 5. Normalized pollution curves for influent copper.

Like zinc, copper showed the strongest influent FF effect for storms 1 and 4. Storm 6 has the smallest FF for copper influent. It is almost normalized loading with approximately 27% of the copper load occurring in the first 20% of volume load.

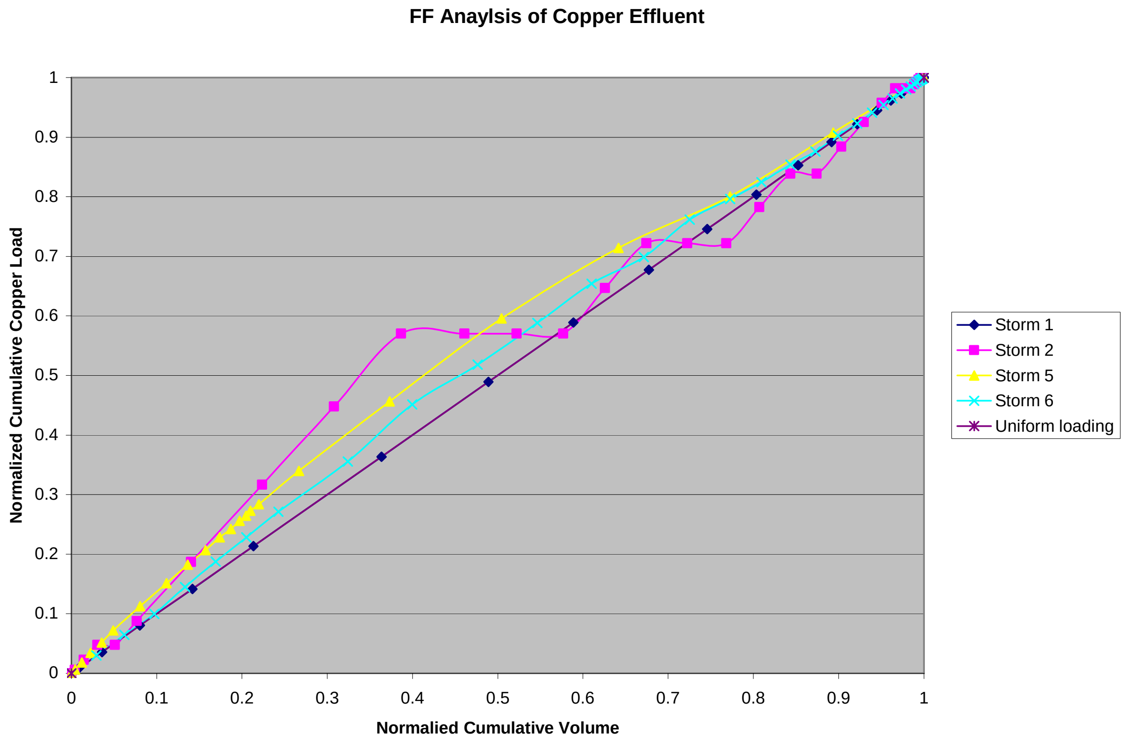


Figure 6. Normalized pollution curves for effluent copper.

Unlike zinc, copper shows no appreciable effluent FF effect. A possible explanation is that copper entered the cell in such low concentrations, that it did not build up substantial as zinc is theorized to have done during storms 3 and 4, where no outflow occurred.

Figure 7 shows the normalized curves for influent nitrate. Figure 8 shows the normalized curves for effluent nitrate.

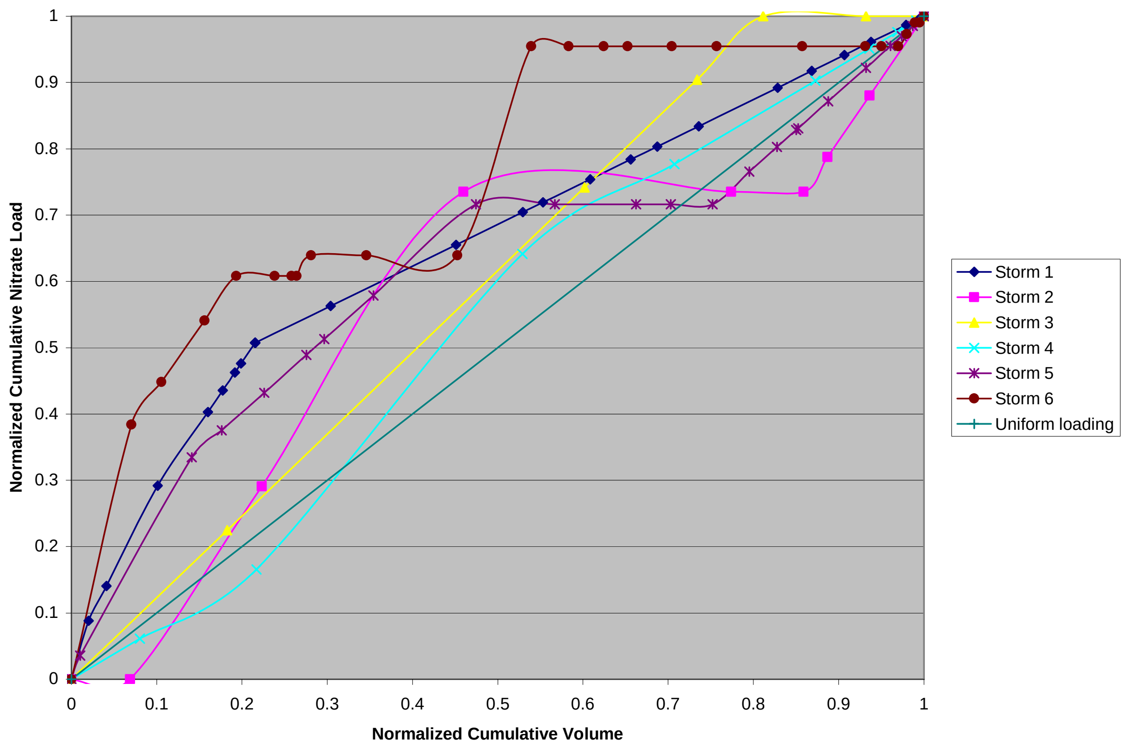


Figure 7. Normalized pollution curves for influent nitrate.

As can be seen from Figure 7, nitrate does not appear to have as strong of FF effect as the metals. Also, when influent nitrate FF occurs, does not appear to correspond to when influent metals FF occurs. For instance, storm 6 had little FF for both metals however it is the strongest FF for nitrate with approximately 60% of the nitrate load occurring in the first 20% of volume. Storm 4 had a strong FF for metals however storm 4 is nearly uniform loading for nitrate with a moderate delay at the beginning.

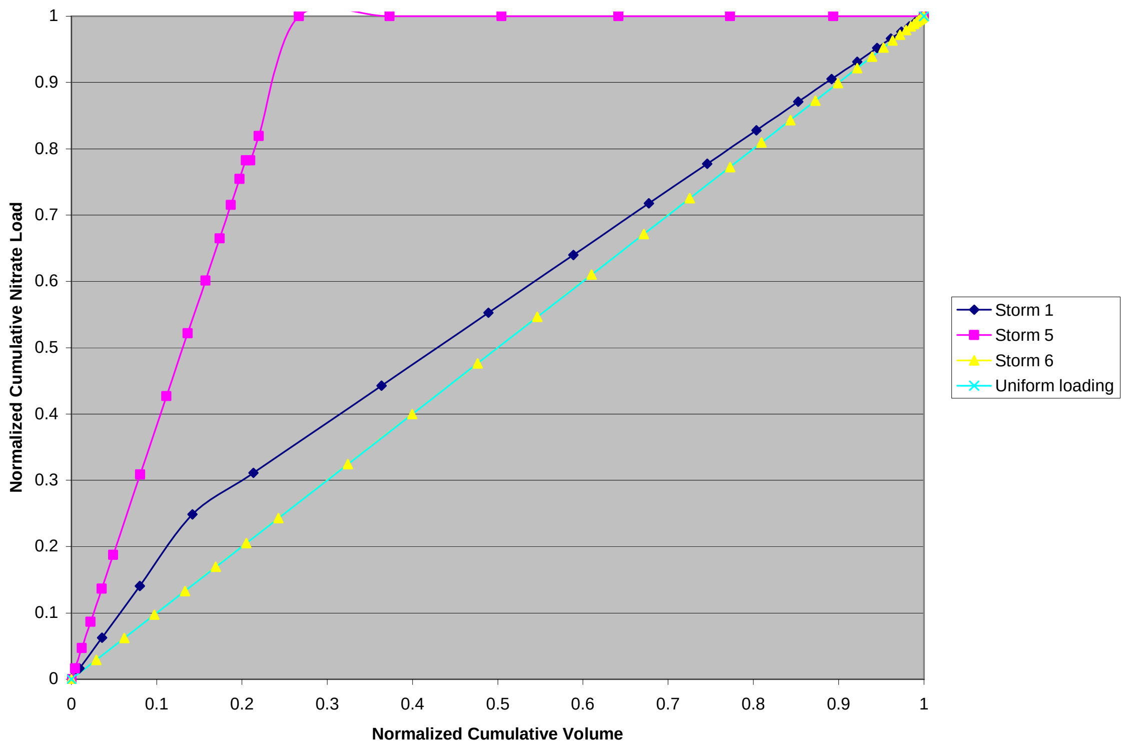


Figure 8. Normalized pollution curves for effluent nitrate.

As can be seen in Figure 8, storms 1 and 6 demonstrate no appreciable FF for nitrate effluent. Storm 5, however, appears to have a very strong FF effect. This may be due in part to accumulation of nitrate from storms 3 and 4 where no outflow occurred. It is likely that the FF effect is exaggerated due to concentration levels being at the very bottom of the detection limit. The sloped part of the storm 5 line is where all samples had 1 mg/l nitrate, the lowest non-zero value the testing method allowed for. The horizontal part of the storm 5 line corresponds to all zero mg/l of nitrate. If testing procedures allowed for higher resolution at low concentration, the apparent FF effect would likely be less extreme.

Figure 9 shows the normalized curves for influent phosphate. Figure 10 shows the normalized curves for effluent phosphate.

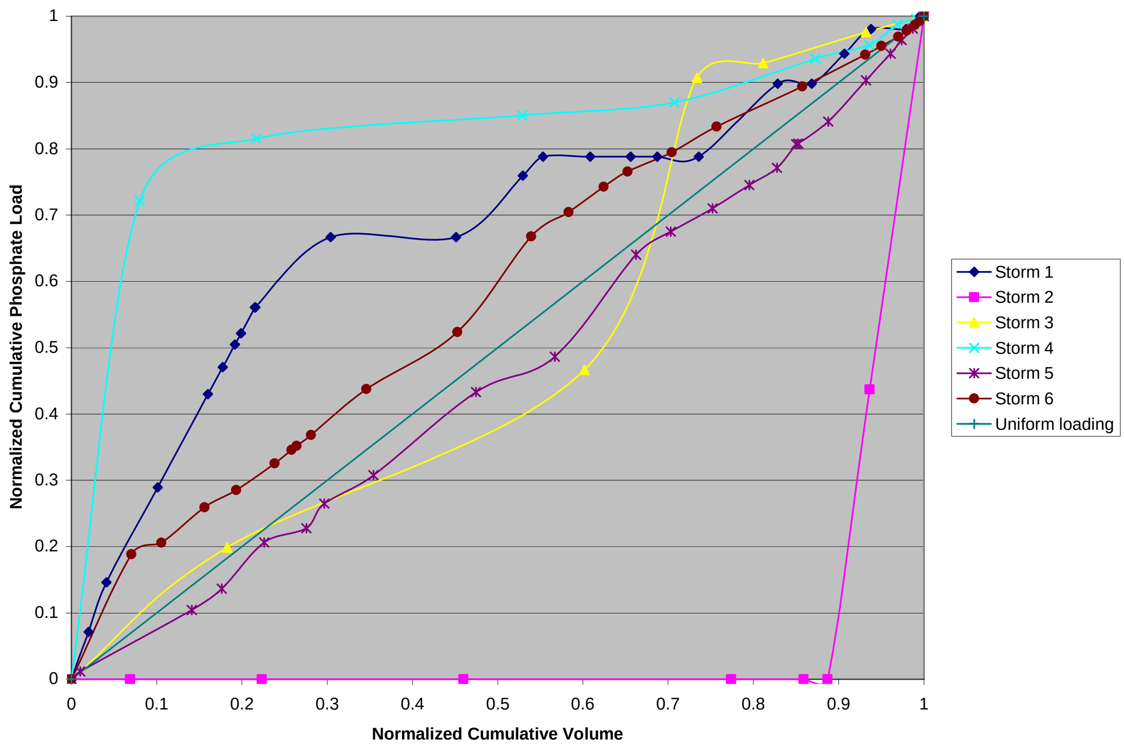


Figure 9. Normalized pollution curves for influent phosphate.

Like zinc, storms 1 and 4 produced the strongest FF for influent phosphate. Storms 3, 5, and 6 are approximately uniform loading. Storm 2 appears to have a very strong delay for influent phosphate. Again, this is likely exaggerated due to concentration levels being at the lower detection limit for storm 2. Storm 2 had the lowest phosphate load and EMC. This is probably due to the short ADW.

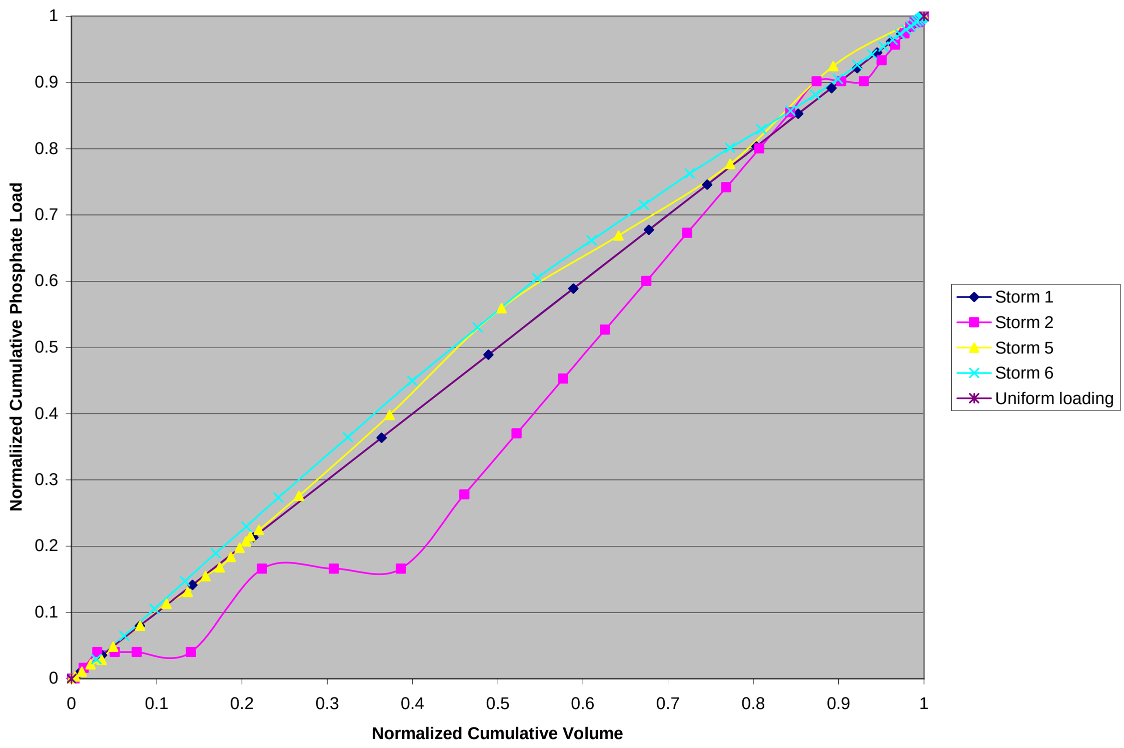


Figure 10. Normalized pollution curves for effluent phosphate.

Storms 1, 5, and 6 show near uniform loading of phosphate effluent. Storm 2 shows a moderate delay in phosphate loading. This is consistent with the finding that phosphate influent for storm 2 was delayed.

A comparison between the FF characteristics of zinc, copper, nitrate, and phosphate was achieved by fitting a third order polynomial to all storm data for each pollutant. A third order polynomial was used due to the research by Taebi, 2004, and Lee, 2003, indicating their usefulness in modeling FF normalized curves. The average normalized curve for each pollutant can be seen in Figure 11.

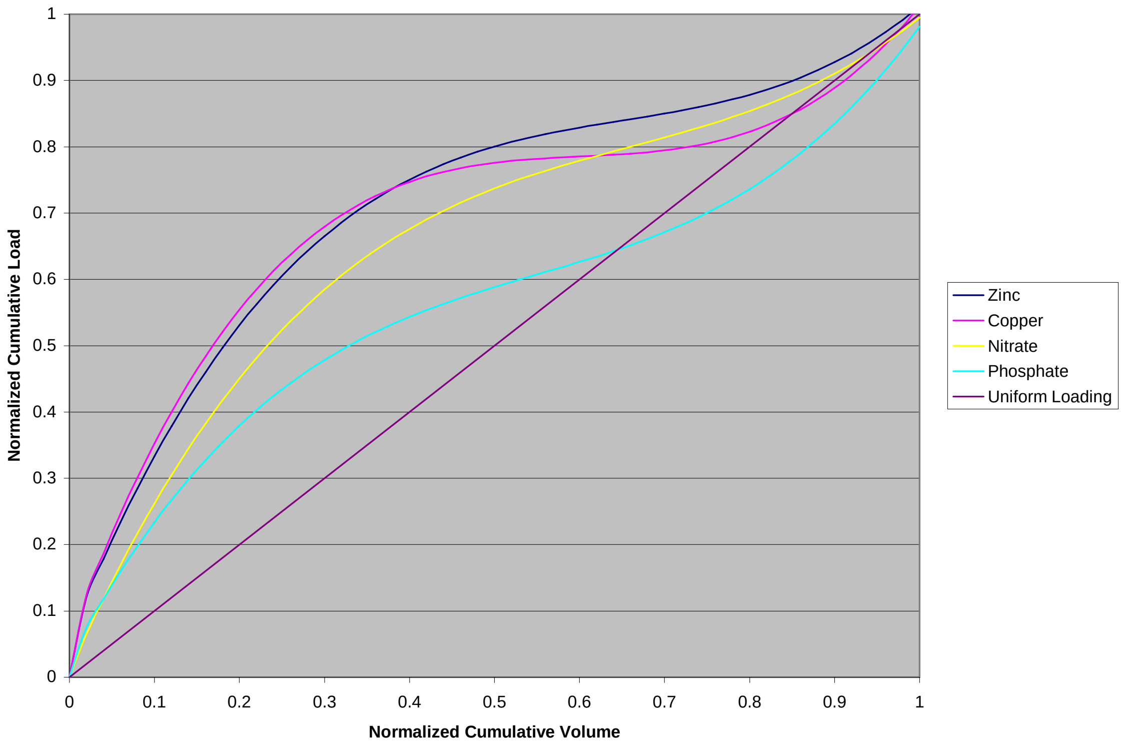


Figure 11. Average normalized curves for zinc, copper, nitrate, and phosphate.

As can be seen from Figure 11 zinc and copper have the strongest FF effect. It is also seen that zinc and copper have very similar FF characteristics. Nitrate has the next strongest FF normalized curve. Phosphate has the weakest FF normalized curve. The average phosphate normalized curve changes from FF to delay at about 63% of volume. This is primarily due to the exaggerated storm 2 delay mentioned above.

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<u>Appendix A1: Calculation of the Size of the Bioretention Cell</u>

The bioretention cell was designed to treat the first half-inch of runoff from the highway interchange. According to a global positioning system survey, the roadway drainage area was 19,315 square feet. The design volume for the BRC is the drainage area multiplied by design runoff. Equation A1 determines design volume based on drainage area and runoff.

$$19{,}315\,ft^2 * \frac{1/2}{12}\,ft = 805\,ft^3 \qquad \text{(A.1.1)}$$

Storage depth per unit area was then determined for the BRC design. The soil and mulch storage capacity was ignored for this estimation. The gravel layer within the BRC was designed to be 2-feet deep with a porosity of 0.5. The designed ponding depth of 9-inches was considered 100% storage. Equation A2 shows the estimation of storage depth per unit area.

2 ft gravel*0.5+0.75 ft ponding depth = 1.75 ft of storage per unit area (A1.2)

The required surface area of the BRC was determined by dividing the design volume, Equation A1, by the storage depth per unit area, Equation A2. Equation A3 shows the required surface area of the BRC to meet the runoff storage criterion.

$$\frac{805\,ft^3}{1.75\,ft} = 460\,ft^2 \qquad \text{(A1.3)}$$

A 20’ wide by 25’ long bioretention cell fits the topography of the area well and provides the necessary storage.

Appendix A2: Pictures of the Construction of the Highway Bioretention Cell

Figure A2.1. Initial Excavation

Figure A2.2. Running of levels to ensure proper depth of layers

Figure A2.3. Pouring of gravel into bottom of the bioretention cell with well pipe in place

Figure A2.4. Installation of drain system over two feet of gravel

Figure A2.5 Spreading of processed forest biomass over gravel and drain system

Figure A2.6 Final grading and installation of sod

Figure A2.7 Complete bioretention cell

Appendix A3: Estimation of Discharge of Stormwater to Bioretention Cell from Inlet

A model of stormwater discharge to the bioretention cell as a quadratic function of the velocity of the discharge from the corrugated metal pipe was estimated with data that were collected in June from readings of the Doppler velocity sensor and the pressure-transducer depth sensor. Figure A3.1 depicts these actual discharges and estimated discharges as a function of velocity. Table A3.1 is a tabular presentation of the estimates of discharges for given velocities.

Figure A3.1. Actual and Estimated Discharges (ft^3/sec) as Functions of Velocity (ft/sec)

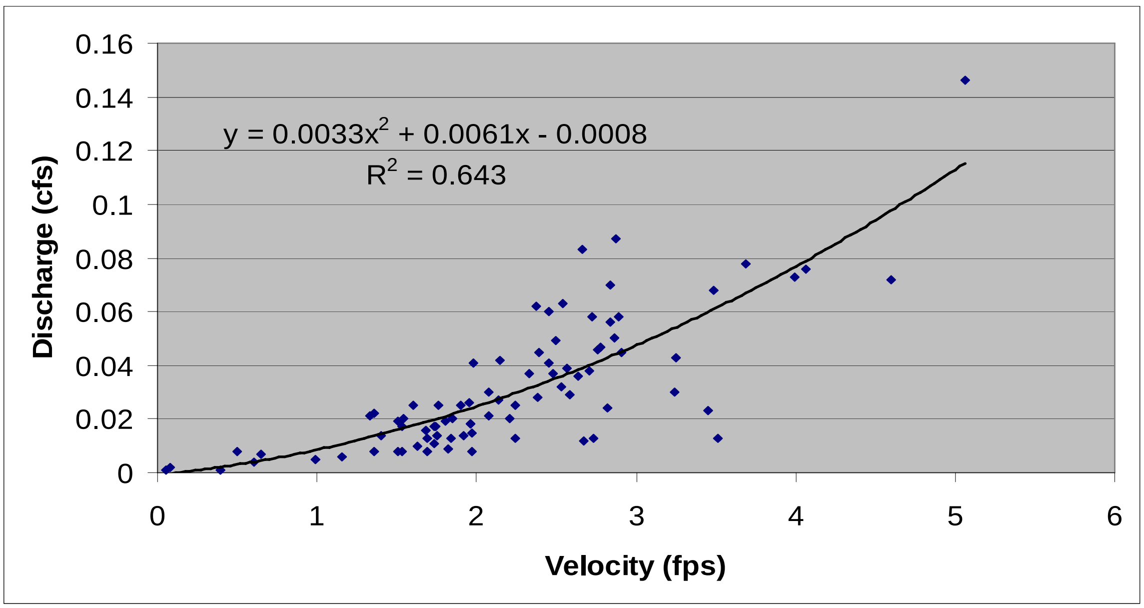


Table A3.1. Estimates of discharges (edischarge) from the quadratic least-squares model

velocity	Edischarge	velocity	edischarge	velocity	edischarge	velocity	edischarge
0	-0.0008	1	0.008600	2	0.024600	3	0.047200
0.1	-0.00016	1.1	0.009903	2.1	0.026563	3.1	0.049823
0.2	0.000552	1.2	0.011272	2.2	0.028592	3.2	0.052512
0.3	0.001327	1.3	0.012707	2.3	0.030687	3.3	0.055267
0.4	0.002168	1.4	0.014208	2.4	0.032848	3.4	0.058088
0.5	0.003075	1.5	0.015775	2.5	0.035075	3.5	0.060975
0.6	0.004048	1.6	0.017408	2.6	0.037368	3.6	0.063928
0.7	0.005087	1.7	0.019107	2.7	0.039727	3.7	0.066947
0.8	0.006192	1.8	0.020872	2.8	0.042152	3.8	0.070032
0.9	0.007363	1.9	0.022703	2.9	0.044643	3.9	0.073183

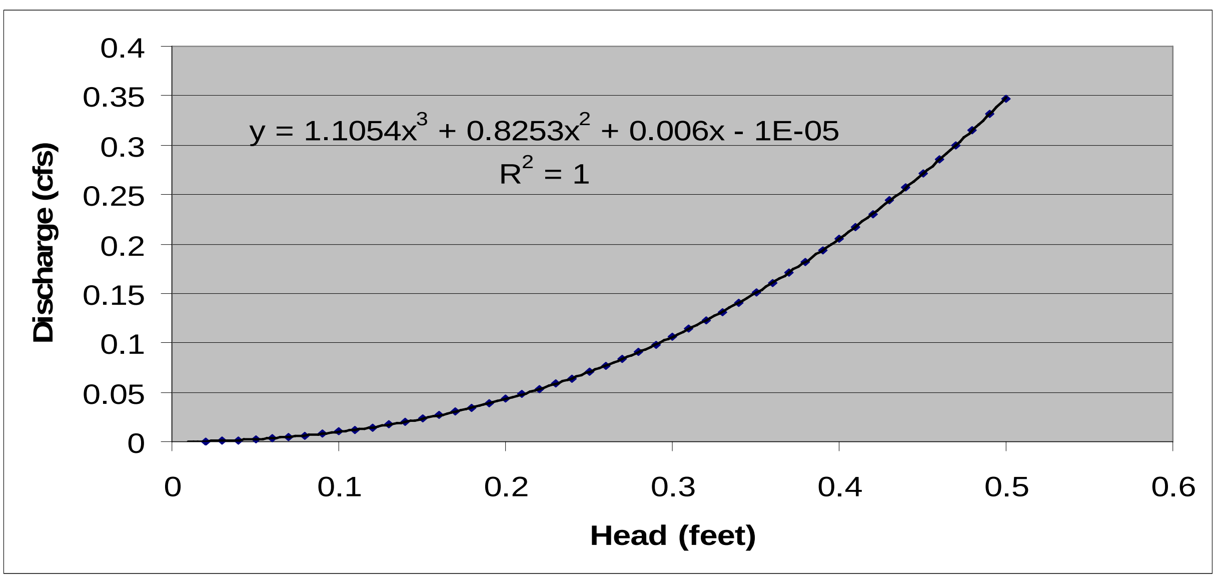
Appendix A4: Discharge Information for Outlet Flume

Table A4.1 shows head in feet and published estimates of discharges in cubic feet per second for a 0.5 foot H flume (Grant and Dawson, 1995). Figure A4.1 depicts the published estimates in Table A4.1 as a function of a perfectly fitted third-order polynomial of the flume head.

Table A4.1. Discharge for 0.5 foot H flume.

H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)	H (ft)	Q (cfs)
0.01	-	0.11	0.0122	0.21	0.0479	0.31	0.1139	0.41	0.217
0.02	0.0004	0.12	0.0146	0.22	0.053	0.32	0.1224	0.42	0.23
0.03	0.0009	0.13	0.0173	0.23	0.0585	0.33	0.1314	0.43	0.244
0.04	0.0016	0.14	0.0202	0.24	0.0643	0.34	0.1407	0.44	0.257
0.05	0.0024	0.15	0.0233	0.25	0.0704	0.35	0.1505	0.45	0.271
0.06	0.0035	0.16	0.0267	0.26	0.0767	0.36	0.1607	0.46	0.285
0.07	0.0047	0.17	0.0304	0.27	0.0834	0.37	0.1713	0.47	0.300
0.08	0.0063	0.18	0.0343	0.28	0.0905	0.38	0.1823	0.48	0.315
0.09	0.008	0.19	0.0385	0.29	0.0979	0.39	0.1938	0.49	0.331
0.10	0.0101	0.20	0.0431	0.30	0.1057	0.40	0.205	0.50	0.347

Figure A41. Estimates of discharges for 0.5 foot H flume and third order polynomial model



Appendix B:

An Economic Analysis of Costs of Three Stormwater Management Practices

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Abstract

The degradation caused by urban stormwater runoff can be serious. Land-use change and the concomitant increase in impervious cover can cause flooding, erosion, habitat degradation, and water quality impairment. Bioretention cells, stormwater ponds and grass swales are three 'best' management practices (BMPs) that can reduce the quantity and improve the quality of stormwater runoff. To analyze the costs of these three practices information was collected from the Center for Watershed Protection, University of North Carolina's Water Resource Research Institute, the Engineering Resource Corporation and Clemson University in South Carolina, Montgomery County Department of Environmental Protection in Maryland and California Department of Transportation. To make reliable and meaningful comparisons, design and construction costs of bioretention cells, stormwater ponds and grass swales were adjusted for purchasing-power differences in time and space. In addition to the effects of water-quality and water-quantity volume, the time- and space-adjusted effects of engineering and construction wages and land prices were also analyzed. Engineering wage was significant for bioretention cells and land value was significant for stormwater ponds. All the three BMPs exhibit economies size. Design and construction of bioretention cells is cheaper in the Sandhill region and more expensive in the coastal region than the piedmont region of the middle and southern Atlantic states. Bioretention cells are a cheaper method to remove pollutants than stormwater ponds for any reasonable volume of stormwater in coastal areas and for volumes of stormwater less than 141,682 cubic feet in the Piedmont region.

An Economic Analysis of Costs of Three Stormwater Management Practices

Background

Urban stormwater is a leading contributor to degradation of water quality in estuaries, lakes, rivers, and bays. In particular, runoff from urban areas and storm sewers in 2000 was the most important source of impairment of waters along assessed ocean shoreline in the U.S. (EPA 2002a) and the second most important source of pollutants that impaired waters of assessed shoreline of the Great Lakes (EPA 2002a) and estuaries (EPA 2002a). Urban and storm-sewer runoff was the third most important source of pollutants that impaired assessed lakes, reservoirs, and ponds (EPA 2002a) and the fourth most important source of pollutants that impaired assessed rivers and streams (EPA 2002a) in the U.S. in 2000. Runoff from impervious surfaces in urban areas and storm sewers may include sediment, bacteria from pet waste, and toxic chemicals (EPA 2002a).

The U. S. Environmental Protection Agency (EPA) regulates discharges of storm water from urban areas. As required by 1987 amendments to the Clean Water Act, the EPA in Nov. 1990 promulgated Phase I of a comprehensive national program to address storm water discharges. Phase I requires operators of construction sites that disturb five or more acres of land, facilities that engage in ten other types of industrial activities, and municipal separate storm sewer systems that serve at least 100,000 people in incorporated places or unincorporated urbanized areas of counties to obtain coverage under a National Pollutant Discharge Elimination System (NPDES) permit for discharge of storm water runoff (EPA 1999b; EPA 1996). Promulgated in Dec. 1999, Phase II expands the requirement of permit coverage to operators of municipal separate storm sewer systems that serve less than 100,000 people in urbanized areas, known as small MS4s, and sites of construction activities that disturb between one and five acres of land (EPA 1999b). Regulated dischargers must develop and implement storm water management programs, called 'storm water pollution prevention plans' in the permits, to reduce pollutants in runoff through a combination of structural and non-structural best management practices (e.g., EPA 1999b).

The federal government has given states the responsibility to administer NPDES permit applications and certain federal water quality programs (EPA, 1999a). In South Carolina, operators of construction sites that disturb at least five acres must, during construction, install structural best management practices that remove at least 80 percent of the average annual load of pollutants in storm water discharges that will occur after construction has finished and will cause or contribute to cause violations of water-quality standards (Sadler).

Apart from these federal rules and regulations, the state of South Carolina has its own policies that regulate dischargers of stormwater runoff. A water-quantity standard for stormwater runoff is set by the Stormwater Management and Sediment Reduction Act of 1991. In particular, "post-development peak discharge rates shall not exceed pre-development discharge rates for the 2- and 10-year frequency 24-hour-duration storm event" (SCDHEC, 2003b). Land disturbing activities which are not part of the larger common plan of development or sale and disturb more than two acres and less than five acres of land require the use of BMPs to control the stormwater runoff. BMPs other than ponds are recommended to achieve water-quality improvements on sites which disturb less than ten acres of land (SCDHEC, 2003b).

Implementation of these federal and state regulations requires the use of best management practices (BMPs). There are two basic types of BMPs: non-structural and structural. Non-structural BMPs consist of administrative, regulatory or management practices that have positive impacts on non-point source runoff. Structural BMPs are designed facilities or modified natural environments that help clean the stormwater quality. These include various types of stormwater ponds, such as dry extended detention ponds and wet ponds, bioretention cells and grass swales (SMRC). The focus of this paper is on the costs and cost effectiveness of these BMPs.

Bioretention cells, specially designed landscaping area adapted to treat stormwater runoff, are most commonly found along the edges or medians of parking lots and residential streets (SMRC). They are usually built into and under landscapes that serve other purposes, such as beautification and shade. In contrast, stormwater ponds, basins whose outlets are designed to detain stormwater runoff from a storm for some minimum duration and allow sediments and associated particles to settle out, require surface area that typically becomes unavailable for other uses. Although stormwater ponds typically been the structural BMP of choice, public works officials and real-estate developers have begun to use these cells in the mid-Atlantic region and elsewhere (e.g., EPA 1999d and Schueler). Like bioretention cell, grass swales- modified traditional drainage ditches, are suitable for small drainage areas (less than 5 acres) treating stormwater runoffs from the highways or the residential roads (SMRC). They are commonly found on the side of the roads or the highways and do not interfere with the development of the surrounding areas (SMRC).

To decide which BMP is most suitable in a given area, one must estimate the cost of designing, installing and maintaining BMPs and the amounts of pollutant that they can remove. In a report submitted to the Chesapeake Research Consortium in 1997, Brown and Schueler examined the relationship between storage volume and construction costs of the BMPs. Koustas and Selvakumar estimated models of capital and maintenance costs of the most frequently used BMPs. A study conducted in North Carolina (Wossink and Hunt) focused on selecting the most effective BMP for the removal of a class of pollutants and its associated cost. They analyzed construction and annual operating costs of various BMPs.

This paper differs from previous research on the costs of BMPs for stormwater management in three ways. First, costs of bioretention cells, stormwater ponds and grass swales are adjusted for purchasing-power differences in time and space. Second, the effects on real costs of factors other than water-quality or water-quantity volume are estimated. In particular, the cost of land is counted as a cost of a stormwater pond because the surface area of a pond is no longer available for another land use. Also, the effects of two additional input costs—engineering and construction wages--on the combined design and construction costs of the three BMPs are estimated. Third, a comparative study of the volume-to-cost relationship is presented for all the three BMPs. In particular, we determine the storage volume below which a bioretention cell is cheaper than a stormwater pond to remove pollutants.

Data Sources and Variables

The dataset primarily includes information collected from two different sources: a study conducted by Brown and Schueler at the Center for Watershed Protection (CWP) and Report No. 344 (Wossink and Hunt) of the Water Resource Research Institute. The CWP data were collected from a survey of local engineers and planners. Fourteen different organizations contributed information. Additional entries were also obtained from the other BMP studies and visits to local stormwater management departments (Brown and Schueler). In the report by Wossink and Hunt, information about the costs of the different BMPs was collected through phone surveys and site contacts with designers and property owners in 1999-2001. The data collected was either the bid price or the known amount spent by the granting agencies (Wossink and Hunt). Other than the two primary sources of data mentioned above, data on a stormwater pond and two bioretention cells in South Carolina were collected personally from the

Engineering Resource Corporation and Clemson University in South Carolina. Data on three stormwater ponds were provided by the Watershed Restoration Program of the Montgomery County Department of Environmental Protection and one of the data was collected from the Seattle Public Utilities Department of Seattle. Data on six grass swales and two stormwater ponds were collected from a document of the California Department of Transportation (CALTRANS).

The CWP dataset consists of thirty-seven stormwater ponds which included eighteen dry extended detention ponds, eleven wet extended detention ponds, and eight wet ponds. Extended detention ponds are those which incorporate additional features to improve water quality along with the usual water quantity control. All the stormwater ponds from the other sources are wet ponds. Two of the twenty-six bioretention cells in the dataset are cells with underground detention taking care of both water-quality and -quantity control and two are organic filters. Two of the grass swales data include grass channels having a flat surface with no capacity to hold runoff.

Information about construction and engineering wages was collected from the Bureau of Labor Statistics (BLS, 2000a). These wages are the average dollar amount earned in a week. Standard Industrial Code (SIC) 162 (similar to North American Industry Classification System (NAICS) 234) was used to get construction wage (CONWAGE) data, which included heavy construction, construction of water and sewer mains, pipelines, power lines and construction of heavy projects which were not specified elsewhere. Engineering wages (ENGWAGE) reflected data from SIC code 8711 (NAICS 541330), which consists of engineering services like designing ship boats, industrial, civil, electrical and mechanical engineers, machine tool designers, marine engineering services and petroleum engineering services. Information about the national average annual hours worked, for each of these job categories, were collected from the Bureau of Labor Statistics (BLS, 2000b). The weekly averages of the hours worked were calculated from these data. These weekly averages were then used to calculate the hourly wage appropriately adjusted, using the historical cost indices (Murphy), to correspond to Baltimore Maryland in 2003. The historical cost indices represent a composite model of nine different types of buildings constructed in the US and Canada closely representing the usage of materials labor and equipments used in the North American Building Construction Industry.

Data on the land price (LANDVAL) of ten randomly selected residential or commercial properties on the outskirts of the particular city in which a stormwater pond was located were collected for the specified residential or commercial use of the land, using the tax assessors database (Pulawski). For Greenville, North Carolina, where the uses of the land for the BMPs were both residential and commercial, five random real-estate land values of each type were used. The averages of these values were then appropriately adjusted to correspond to Baltimore Maryland in 2003 (LANDVAL). Land cost constituted, on average, 63 percent of the total adjusted cost of a stormwater pond.

Brown and Schueler calculated the water-quantity volume (QUANVOL) of stormwater ponds and bioretention cells in the CWP dataset as the volume of the runoff from the drainage area of a ten-year storm event. The water-quality volume (QUALVOL) for the stormwater ponds is the responses given in the survey and is 0.75 ft times the surface area for the bioretention cell. For the data points of the study by Wossink and Hunt, QUANVOL was measured as 0.5 inch times the drainage area of both the BMPs and QUALVOL was measured as 0.24 inch times the drainage area for the stormwater ponds. Water-quantity volumes were assumed, not measured, equal to water-quality volumes for 23 of the 26 bioretention cells in our database. The QUALVOL of the grass swales was calculated as the first one inch of runoff during any given storm event times the drainage area (SWDMM).

The data points were also classified into major land resource areas according to their locations (NRCS). Three different classifications were noted for the bioretention cells, namely the piedmont region, the coastal plains and the Sandhill region. The stormwater pond however had only the piedmont region and the coastal plains classification. For the stormwater ponds and the grass swales classification was also done for the BMPs on the west coast.

The estimated total cost (ESTTOTCST) consisted of design and engineering and construction cost. Construction costs includes excavation and grading cost, cost of materials, cost of the control structures, e.g. risers, barrels etc., cost of the sediment control practices put in place during construction of the practice, landscaping cost including labor directly related to BMP and the appurtenance cost which included cost of additional items not included elsewhere (Brown and Schueler). The total cost in this report pertains to the year in which the BMP was established. In order to facilitate comparison the cost data was adjusted with respect to time and geographical location. The nominal total costs were thus converted to real costs by incorporating the price adjustment using the historical cost indices (Murphy). The adjusted costs correspond to the year 2003 and to Baltimore in Maryland which was chosen as the point of reference because of its frequent use as a central location in the study. In the case of stormwater ponds, the estimated total cost (ESTTOTCSTLND) includes the total adjusted land cost calculated using the land value of the BMP surface area.

Pollutant removal data for the ponds and grass swales were collected from the National Best Management Practice Database (EPA, 1999a) and the Final Report prepared by the California Department of Transportation (CALTRANS). For bioretention cells, these data were collected from five different sources: study done on Monticello High School (Yu et al.) in VA, Inglewood Demonstration Project (EPA, 2000a), Greenbelt and Landover field study in Maryland (Davis) and results stated in Table 14 of the Report No. 344 (Wossink and Hunt).

Econometric Model and Estimation Procedures

Along the lines of the study conducted by Wossink and Hunt, the Cobb Douglas cost curve is specified as follows:

$$ESTTOTCST = aWQV^{b}e^{u},$$

where e^{u} is the error term. The logarithmic transformation of the preceding equation is

$$LESTTOTCST = \ln(a) + b\ln(WQV) + u \quad \text{(Model 1)}$$

PROC REG procedure in SAS is used to perform simple linear regression based on the equation above for bioretention cells, grass swales (using QUALVOL) and the stormwater ponds (using QUANVOL) separately. Positive and less than one values of ‘b’ imply that the cost increase less than proportionately for every one percent increase in the water quality/quantity volume indicating the presence of economies of size.

The more complicated model (model 2) is then considered by incorporating the input prices and the regional differences in the costs of the three BMPs. The stormwater ponds were classified as dry or wet extended detention ponds and wet ponds. The adjusted opportunity cost of land is added to ESTTOTCST, to give the total adjusted cost for the stormwater ponds (ESTTOTCSTLND). The effect of the type of region on cost is considered by using coastal and Sandhill region dummies (base piedmont region) interacted with the water quality/quantity volume. Engineering and construction wages were then integrated into the total adjusted cost model. Land value is the additional independent variable incorporated into the model for stormwater ponds. QUALVOL was incorporated for stormwater ponds and QUANVOL for bioretention cells. Dummy variable for grass channel was interacted with QUALVOL to identify the difference in the cost of a grass swale (GRCHANQLV). Dummy variable for the grass swales and the stormwater ponds located on the west coast were interacted with the QUALVOL (CAQLV) and the QUANVOL (CAQNV) respectively to capture the coastal difference in cost. Lack of sufficient information prevented the incorporation of QUANVOL in the model for grass swales. The logarithmic transformation of the model can now be written as follows:

$$LESTTOTCSTLND = Intercept + cLQUANVOL + dLCOASTQNV + eLCAQNV + fLQUALVOL + gLLAND + hLENGWAGE + iLCONWAGE + u_1$$

(stormwater ponds)

$$LESTTOTCST = Intercept + jLQUANVOL + kLQUALVOL + lLCOASTQLV + mLSANDHILLQLV + nLENGWAGE + oLCONWAGE + u_2$$

(Bioretention cells)

$$LESTTOTCST = Intercept + pLQUALVOL + qLGRCHANQLV + rLCAQLV + sLENGWAGE + tLCONWAGE + u_3$$

(Grass Swales)

To test for the economies of size in these models, the water quantity volume of a BMP is assume to increases by the same amount as the increase in the water-quality volume. The economies of water-quality size for bioretention cells located in the piedmont region is as follows:

$$\frac{\partial LESTTOTCST}{\partial LQUALVOL} = k + j\frac{QUALVOL}{QUANVOL} \text{ (Piedmont region)}$$

The average of the ratio of QUALVOL to QUANVOL for those cells located in the piedmont region is considered for the above equation. Similar calculations are done for the cells located in the coastal region and the Sandhill region.

The models were tested for heteroskedasticity with SPEC option in SAS. No evidence of this problem was found; the Chi-Square = 24.30 for bioretention cells, 43.74 stormwater ponds and 8.49 for grass swales. They were also tested for spatial correlation with the moran function in MATLAB. In light of Moran's I-statistic = 0.09 for bioretention cells and 0.51 for stormwater ponds, we conclude that no spatial correlation exists.

The equations are then compared to determine the conditions under which a particular BMP is cheaper than the other to remove pollutants.

In theory, cost functions are homogenous of degree one in their factor prices (Varian). This criterion was next incorporated in the restricted form of the model (Model 3) in the three BMPs with the RESTRICT option in SAS. Model 3 is the restricted version of model 2 mentioned above. Translog specifications of the cost functions were also estimated. However, the maximum likelihood ratio test indicated that the Cobb Douglas cost function is appropriate. The results of the translog model are therefore not reported.

Results and Interpretations

Costs of Bioretention Cells

The results of the regression analysis for the various models of the bioretention cells are shown in table 4. Model 1 shows the results of regression of the total adjusted costs on the volume of water treatment of a cell. In model 2, the effect of the type of region on total adjusted costs is studied along with the input prices. We also study the effect of including QUANVOL in the model. Model 3 gives the results of imposing the homogeneity restriction on Model 2.

In model 1, a one-percent increase in the water-quality volume increases the total adjusted costs by 0.66 percent. Thus, the total adjusted costs increase proportionally at the lower rate compared to the volume of the cell. Model 1 however, explains only around 30 percent of the variation in the total adjusted costs.

The dummies for the coastal and the Sandhill region are next incorporated into the regression along with the various input costs and QUANVOL. The inclusion of these exogenous variables in the analysis improves the adjusted R-square value by 43 percent. In this model QUANVOL is a significant determinant of the total adjusted cost of a cell. QUALVOL is significant for the coastal and Sandhill regions but not for the Piedmont region. This insignificance of QUALVOL is difficult to interpret as bioretention cells' pollutant removal capacity is expected to be significant. This suggests a lack of sufficient data or the presence of measurement error. QUALVOL is part of the QUANVOL of a bioretention cell.

The effect of the water-quality volume on the cost is less by about 0.17 percent (Model 2, Table 4) when the cell is located in the Sandhill region.

For every one percent increase in the QUANVOL of the cell, holding the QUALVOL constant, the total cost increases by 1.09 percent. As the QUALVOL of the cell increases the QUANVOL also increases by at least the same amount. Therefore, for every one percent increase in QUALVOL the total costs of the cell increase by an estimated 0.74 percent in the coastal region of the mid-Atlantic states, 0.63 percent in the Piedmont region of these states and 0.55 percent in the Sandhill region. The cells exhibit economies of water-quality size in all the regions.

Pre-construction and construction costs of a bioretention cell depend not only on the volume of water that is treated for pollutants, QUALVOL and, the type of major land resource area in which the cell is located, but also on the average wage of engineers and construction workers in or closest to the urban area where the cell is located. The effects of incorporating the different wages are also studied in model 2. Engineering wage is a significant determinant of the total adjusted costs of a bioretention cell. Construction wage is however statistically insignificant. Construction cost constitutes major portion of the total adjusted costs (90 percent approximately). Construction wage however does not contribute significantly to the cost variability, reflecting the possibility of some missing variables in the model.

A typical bioretention cell that can fit into a parking lot or a residential complex requires a high level of engineering sophistication for its construction. Results shown in table 4 indicate that a unit percentage increase in the engineering wage results in a 7 percent increase in the total cost, suggesting the high elasticity of engineering wage. A highly paid engineer is likely to employ more sophisticated technologies to obtain superior results. The rise in costs in the proposed model (Model 2) can be attributed to higher engineering wage and higher costs associated with increase in sophistication. Since the model does not consider material cost separately, a 7 percent increase in the costs maybe due to the better quality materials used by a highly skilled engineer.

The highly negative and significant intercept implies negligible fixed costs of a bioretention cell. Though this result does not seem very plausible it might be the result of the measurement error our data.

In model 3 the homogeneity restriction was incorporated into the cost function of model 2. The incorporation of the restriction causes the engineering wages to be insignificant making it easier to be interpreted than the estimate in model 2. The likelihood ratio test indicates that the restriction is valid and should be incorporated in the model. Both the models however indicate that a bioretention cell is cheaper to build in the Sandhill region, whenever the regional differences are considered.

<u>Costs of a Stormwater Pond</u>

The results of the regression analysis of the stormwater ponds with three different model specifications are shown in table 5. In model 1 one percent increase in the storage volume of a stormwater pond increases the total adjusted costs by only 0.62 percent. Hence, stormwater ponds exhibit economies of water-quantity size. The adjusted R-square for this model is 61 percent.

Land value, the two types of wages mentioned earlier, the QUALVOL, the dummies for the coastal region, the extended detention ponds and the Californian coastal plains are used as the explanatory variables in model 2 along with the QUANVOL. The engineering wage and the construction wage are both insignificant.

For every one percent increase in the QUANVOL of the pond, assuming that the QUALVOL does not change, the total costs of the pond increase by an estimated 0.64 percent in the piedmont region, suggesting economies of water-quantity size. QUALVOL in model 2 also has a statistically significant effect on costs. For every one percent increase in the QUALVOL of stormwater pond the total adjusted cost increase by 0.67 percent in the piedmont region and 0.86 percent in the coastal region, indicating the presence of economies of water-quality size along with economies of water-quantity size.

The land value, as expected, is highly significant. As the land which is used as a stormwater pond usually cannot be utilized for any other purpose, the opportunity cost of land is a significant cost in constructing a stormwater pond. If the value of a unit of land increases by one percent the total costs of the stormwater pond increase by 0.33 percent.

Results indicate that the increase in the costs of a stormwater pond for every one percent increase in the QUANVOL of the pond, assuming QUALVOL does not change, would be lower by 0.06 percent in case of extended detention ponds when compared to the wet ponds. As the extended detention ponds are purposely designed for both quality and quantity control, they are expected to be deeper with smaller surface area than a wet pond having the same amount of water quantity volume.

The cost to build a stormwater pond is .09 percent higher on the west coast as compared to the east as LCAQNV is almost significant at 10 percent level of significance.

Restricting Model 2 to be homogeneous of degree one in prices makes LCAQNV significant, emphasizing the higher cost of building a stormwater pond on the west coast. Other than this the restriction had no significant changes in the parameter estimates or their significance level. The likelihood ratio test however indicates that the homogeneity restrictions are not valid and should not be a part of the model.

Costs of Grass Swales

The results of the regression analysis for the various models of the grass swales are shown in table 5. The QUANVOL is barely significant in model 1 and 3 insignificant in model 2, implying that water quality does not play an important role in determining the total adjusted cost of a grass swale. Model 1 explains only 25% of the variation in the total adjusted cost. Model 2 incorporates the difference in the total adjusted costs due to the presence of grass channels and the location of the BMP on the west coast along with the input prices. The homogeneity restrictions are not valid in model 3.

A grass swale can be designed as a grass channel, a dry swale and a wet swale. A dry swale is little similar to a bioretention cell with soil bed and underdrain system. A wet swale is more like a longitudinal wetland with permanent pool of water and a grass channel is a ‘conventional drainage ditch’ with flatter side slopes and minimal water quality treatment (SMRC). Grass channel is the cheapest to build among the three types mentioned above with minimum pollutant removal capacity (SMRC). This difference in cost is incorporated by considering the estimate of the dummy for grass channels interacted with the QUALVOL as one of the independent variable in model 2. Dry swale and wet swale distinction could not be made due to lack of sufficient data. The inclusion of this dummy and the three wages in the analysis improves the adjusted R-square value by 63 percent.

In model 2 QUALVOL also has a statistically insignificant effect on the costs of grass swale and channels. Model 2 also indicates that both the wages are insignificant determinants of the grass swales. The intercept, however is a large significant estimate indicating that the fixed costs involved in building a grass swale is an important part of the total adjusted cost.

After the incorporation of the homogeneity restriction in model 3 the QUALVOL for the grass swales becomes significant, but is still insignificant for the grass channel. The intercept term however still remains significant reiterating the importance of fixed cost in the building of a grass swale. Results in model 3 indicate that is it significantly costlier to build a grass swale on the west cost (by 0.24 percent) as compared to the east coast. In this model both the engineering and the construction wages are significant but their signs and magnitude are difficult to interpret. The likelihood ratio test however indicates that the homogeneity restrictions are not valid. All of the three models indicate that the fixed costs are an important part of the total adjusted cost of a grass swale.

<u>Comparison between Bioretention Cells, Stormwater Ponds and Grass Swales</u>

Meaningful comparisons of costs of bioretention cells, stormwater ponds and grass swales that account for both water-treatment and water-storage volumes are difficult to make. In the past, stormwater ponds were designed primarily to reduce stormwater runoff. Bioretention cells and grass swales were designed primarily to remove pollutants in the runoff. We use model 2 from Table 4, 5 and 6 for comparison because these models have almost similar specifications.

Stormwater ponds have higher estimated fixed costs than bioretention cells. Costs of stormwater ponds increase at a slower rate for every one percent increase in the water-quantity volume compared to the bioretention cells. In the Piedmont region, the water storage volume for which bioretention cells and stormwater ponds have the same cost is 141,682 ft^3. Thus, a bioretention cell is a cheaper management practice than a stormwater pond in the Piedmont region for storage volumes less than 141,682 ft^3. For the coastal region however, the cross-over volume is 26,180,952,710,364,100 ft^3. The mean water-quantity volume of stormwater ponds is 327,201 ft^3, so a BMP with QUANVOL greater than 26,180,952,710,364,100 ft^3 is impossible to imagine. In other words, a bioretention cell is a less expensive method of removing pollutants in any feasible volume of water than a stormwater pond in mid-Atlantic coastal areas.

If one ignores water-quality and water-quantity volumes, bioretention cells appear to remove more pollutants per liter of runoff than a stormwater pond or a grass swale. In particular, more copper, lead, zinc, phosphorus, and nitrogen are removed, on average, by a bioretention cell than a stormwater pond or grass swale. Stormwater ponds on an average remove more pollutants than a grass swale (Table 7). Table 8 shows the cost per unit of pollutant removed by stormwater ponds, bioretention cells, and grass swales. The bioretention cells have, on average, the lowest costs of pollutant removal.

Conclusions

Bioretention cells, stormwater ponds and grass swales all exhibit economies of size. These results reflect estimates of parameters in models that differ from those in previous studies because costs are adjusted for purchasing-power differences in time and space and depend on input prices, in addition to water storage volume, treatment volume, or both. Bioretention cells or grass swales are likely to be cheaper than stormwater ponds as land price increases. Engineering wages are a significant determinant of the costs of bioretention cells. Future research is needed to determine whether the high estimated effect of these wages represents the use of higher quality inputs or a statistical aberration.

Bioretention cells are cost effective in the coastal region but stormwater ponds are cost effective for most volumes of water treatment in the piedmont region. Estimated cross-over volumes in this paper depend on average values of input prices, rather than prices in specific locations; do not but should depend on maintenance costs. Determination of the precise ranges of water-quality and water-quantity volumes over which bioretention cells are cheaper than stormwater ponds to remove pollutants and reduce stormwater runoff according to regulatory standards remains an important question for future research.

Lack of sufficient information on maintenance costs notwithstanding, our models can be used by the EPA to improve the accuracy of its estimates of design- and construction-related costs of compliance with water quality regulation (e.g., EPA 2002b). Engineers could also use our model to help them decide whether bioretention cells or stormwater ponds are cheaper methods of attaining water-quantity and water-quality standards.

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Table 1: Descriptive Statistics for Bioretention Cells (n=27)

Variable	Mean	Standard Deviation	Minimum	Maximum
ESTTOTCST (2003 $s in Baltimore)	26,631	37,836	1,236	190,554
QUALVOL (cubic feet)	3,471	4,884	272	19,874
COASTQLV (cubic-feet)	1,352	3,836	0	19,874
SAHILQLV (cubic-feet)	719	3,297	0	17,061
QUANVOL (cubic-feet)	3,734	4,902	272	19,874
ENGWAGE (2003 $s in Baltimore /hour)	31	3	25	36
CONSWAGE (2003 $s in Baltimore /hour)	19	2	13	22
LANDWAGE (2003 $s in Baltimore /hour)	14	2	8	15

Table 2: Descriptive Statistics for Stormwater Ponds (n=53)

Variable	Mean	Standard Deviation	Minimum	Maximum
ESTTOTCST (2003 $s in Baltimore)	360,985	1,044,380	6,881	7,418,342
ESTTOTCSTLND (2003 $s in Baltimore)	751,328	1,838,554	12,638	9,084,534
QUANVOL (cubic feet)	327,201	783,820	671	4,126,003
COASTQNV (cubic feet)	149,786	566,122	0	2,962,080
QUALVOL (cubic feet)	298,424	1,123,999	322	6,493,925
LANDVAL (2003 $s in Baltimore/acre)	323,987	326,553	5,443	1,915,585
ENGWAGE (2003 $s in Baltimore/hour)	31	4	19	41
CONSWAGE (2003 $s in Baltimore/hour)	19	2	13	22
LANDWAGE (2003 $s in Baltimore/hour)	14	2	8	16

Table 3: Descriptive Statistics for Grass Swales (n=9)

Variable	Mean	Standard Deviation	Minimum	Maximum
ESTTOTCST (2003 $s in Baltimore)	40,849	29,534	4,962	95,017
QUALVOL (cubic-feet)	37,414	95,253	728	291,000
ENGWAGE (2003 $s in Baltimore /hour)	29	8	11	3
CONSWAGE (2003 $s in Baltimore /hour)	16	3	10	21
LANDWAGE (2003 $s in Baltimore /hour)	10	2	7	15

Table 4: Factors that Affect the Costs of a Bioretention Cell

Estimate, (Standard Error), and *p-value*			
Variable Name	Model 1	Model 2	Model 3 (Restricted)
Intercept	4.56748 (1.44624) *0.0041*	-22.87524 (7.21434) *0.0048*	-0.48399 (1.39818) *0.7327*
LQUALVOL	0.65786 (0.18955) *0.0019*	-0.37483 (0.34823) *0.2946*	-0.29004 (0.41424) *0.4915*
LCOASTQLV		0.14389 (0.05501) *0.0165*	0.00869 (0.04095) *0.8340*
LSANDQLV		-0.16944 (0.06204) *0.0129*	-0.24520 (0.06821) *0.0017*
LQUANVOL		1.09455 (0.34550) *0.0048*	1.18367 (0.41083) *0.0089*
LENGWAGE		7.00712 (2.25061) *0.0055*	0.74475 (1.25223) *0.5584*
LCONSWAGE		0.82643 (1.06514) *0.4469*	0.25525 (1.25223) *0.8404*
Adj. R-Square	0.2981	0.7366	0.6250

Table 5 Factors that Affect the Costs of a Stormwater Pond

	Estimate, (Standard Error), and *p-value*		
Variable Name	Model 1	Model 2	Model 3(Restricted)
Intercept	4.62935 (0.76656) *<.0001*	-0.14953 (2.24084) *0.9471*	-2.55864 (1.21616) *0.0410*
LQUANVOL	0.62390 (0.06804) *<.0001*	0.64450 (0.11019) *<.0001*	0.62093 (0.10939) *<.0001*
LCOASTQNV		0.01918 (0.01630) *0.2458*	0.02100 (0.01635) *0.2057*
LEXTDEQNV		-0.05860 (0.02083) *0.0073*	-0.05754 (0.02096) *0.0087*
LCAQNV		0.09143 (0.05454) *0.1007*	0.10312 (0.05414) *0.0632*
LQUALVOL		0.19757 (0.10728) *0.0723*	0.22087 (0.10727) *0.0453*
LLANDVAL		0.21207 (0.10675) *0.0532*	0.29383 (0.10396) *0.0070*
LENGWAGE		-0.06344 (0.86188) *0.9417*	0.32264 (0.81267) *0.6932*
LCONSWAGE		-0.16828 (0.90302) *0.8530*	0.38352 (0.79833) *0.6333*
Adj. R-Square	0.6150	0.8369	0.8346

Table 6: Factors that Affect the Costs of a Grass Swale or Channel

	Estimate, (Standard Error), and *p-value*		
Variable Name	Model 1	Model 2	Model 3(Restricted)
Intercept	12.91245 (1.38378) *<.0001*	13.65430 (1.91578) *0.0057*	11.85939 (1.63976) *0.0019*
LQUALVOL	-0.29817 (0.19906) *0.0986*	0.14532 (0.39475) *0.7372*	-0.38129 (0.16814) *0.0859*
LGRCHANQLV		-0.19747 (0.13961) *0.2522*	-0.01342 (0.06350) *0.8429*
LCAQLV		0.11548 (0.10200) *0.3399*	0.24507 (0.05420) *0.0106*
LENGWAGE		-1.52359 (2.07636) *0.5162*	-4.16826 (1.09387) *0.0189*
LCONSWAGE		0.13236 (3.62716) *0.9732*	5.16826 (1.09387) *0.0091*
Adj. R-Square	0.2471	0.8768	0.8437

Table 7: Pollutant Removal Effectiveness

Type of pollutant	Average Amount of Pollutant Removed by Stormwater Ponds (mg/L)	Average Amount of Pollutant Removed by Bioretention Cells (mg/L)	Average Amount of Pollutant Removed by Grass Swales (mg/L)
Copper	0.0228	17.03854	0.0165
Lead	0.0663	12.69257	0.0377
Zinc	0.1577	0.60375	0.1411
Phosphorus	0.1144	0.5934	-0.2330
Nitrates and Nitrites	0.4492	0.1493	0.5816
Nitrogen	0.7222	3.6810	0.2424

Source for stormwater ponds: National Best Management Practice Database (EPA, 1999)

Sources for bioretention cells: Inglewood demonstration project (EPA, 2000a) and Maryland's Greenbelt and Landover field study (Davis).

Table 8: Average Cost of One Milligram of Pollutant Removed per Liter

Type of pollutant	Costs for Stormwater Ponds without land cost	Costs for Bioretention Cells without land cost	Costs for Grass Swales without land cost
Copper	$15,476,982.52	$1,600	$2,482,773.94
Lead	$5,313,051.86	$2,148	$1,084,449.73
Zinc	$2,234,579.56	$45,161	$289,547.61
Phosphorus	$3,079,489.95	$45,951	-$175,313.08
Nitrates and Nitrites	$487,851.25	$7,407	$70,238.77
Nitrogen	$784,219.32	$182,666	$168,516.40

Source for stormwater ponds: National Best Management Practice Database (EPA, 1999)

Sources for bioretention cells: Inglewood demonstration project (EPA, 2000a) and Maryland's Greenbelt and Landover field study (Davis).