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DEMONSTRATION AND EVALUATION OF PROCESSED FOREST BIOMASS IN BIORETENTION CELLS FOR REDUCTION OF WILDFIRE HAZARD AND TREATMENT OF STORMWATER RUNOFF

FINAL REPORT TO THE SOUTH CAROLINA FORESTRY COMMISSION

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Extended Abstract

Growth of urban 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 streets and parking lots. Widespread use of this structural best management practice could expand the market for small-diameter woody material and might reduce risks of wildfire because processed residues from logging decks could be the source of organic material that the cell requires. The purpose of this project was to demonstrate the use of processed forest biomass in a bioretention cell at an industrial park in a developing area of South Carolina and evaluate the environmental performance and costs of this cell.

A bioretention cell, approximately 25' wide, 75' long, and 4' deep with a 12" layer of chipped logging residue, was designed and installed at the Orangeburg County and City Industrial Park. The cell and the use of processed forest biomass in the cell were publicized in a newsletter of the state's environmental regulatory agency, are publicized by an on-site sign, and will be publicized by a magazine article for Clemson University.

Aged chips of woody forest residues remove positive amounts of nitrate nitrogen, zinc, and copper from polluted solutions in laboratory tests, even though the removal efficiencies never exceed the efficiencies of at least one of the two commercial hardwood mulches. This chipped woody material does not add more phosphorous than the two commercial mulches. Although the level of total organic carbon decreases slightly over time as pine chips age, this type of processed forest biomass can serve as an adequate source of carbon for denitrification within the bottom

chamber of a bioretention cell.

In general, the bioretention cell in Orangeburg reduces the quantity of runoff to the existing storm sewer. Ninety four percent of the first inch of runoff enters and is treated by the cell. The cell apparently removes zinc and copper. Although the cell did not always remove phosphate and nitrate, removal of these pollutants improved as time passed. Concentrations of measured pollutants in the discharge were substantially below regulatory thresholds for water quality.

The bioretention cell in Orangeburg cost $28,860. The largest portion of these costs was $23,500 for the contractor, his sub-contractor, and their materials. Unusually but justifiably large excavation and grading expense for innovative design, insufficient bid competition, and contractor inexperience are reasons why the costs per unit of water-quality volume were higher in this project than the average of others.

Bioretention cells 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 0.765 percent in coastal areas of mid-Atlantic states, 0.734 percent in the Piedmont region, and 0.629 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. Regardless of region, a one percent increase in the hourly wage of engineers in the area where a cell is located leads to a 6.69 percent increase in the total costs of the cell.

Meaningful comparisons of costs of bioretention cells and stormwater ponds are difficult, if not impossible, to make because 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-quality volumes and drainage areas over which bioretention cells are cheaper than stormwater ponds to meet regulatory standards for quality and quantity of stormwater runoff remains an important question for research.

In August 2004 South Carolina had 803 industrial sites and 241 industrial parks that covered 189,605 undeveloped acres. If owners or tenants of these industrial parks and sites eventually develop all of the land, manage stormwater exclusively with bioretention cells, allocate an average of 0.0525 of each developed acre for the surface area of cells, and use one foot of chipped woody material in the cells, they would use 16.06 million yds^3 or 4.553 million tons of this material. If the real cost were to remain \$22 per delivered ton, then developers of these parks and sites would spend \$100.2 million over time to use the material in 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, range lands, and other rural areas has led to increases in potential damages of wildfires and, thus, costs of suppressing them during the last 20 years (DIDA, 5). Real expenditures (2003 dollars) by federal agencies on wildland fire suppression grew from $992.7 million in 1994 to $1.326 billion in 2003, or approximately 3.3% during the period (NIFC). Yet, in spite of the increase in 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). In the FY 2001 Interior and Related Agencies Appropriations Act (P.L. 106-291), Congress directed the Secretaries of the Interior and Agriculture to develop 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). Research about reduction of hazardous fuels and promotion of markets for small-diameter, woody material that would otherwise be hazardous fuel are action items in this 10-year strategy (DIDA, 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., pgs. 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, pg. 68731; EPA 1996, pg. 4).

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 1999a, pgs. 68722-68723). 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 2000, pg. 64764; EPA 1999a, pgs. 68736, 68754, and 68758-68760; EPA 1996, pgs. IV-4, VI-4, and VIII-2). In South Carolina, operators of construction sites that disturb at least five acres must install during construction 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, pgs. 14-15).

Although the regulations emphasize water quality, NPDES permit holders must also address water quantity. For example, under Phase II, operators of small municipal separate storm sewer systems must use a local ordinance or regulation and any locally appropriate combination of structural and non-structural best management practices at new development and redevelopment projects that have disturbed more than one acre to attempt to maintain pre-development runoff conditions after construction (EPA 1999a, pgs. 68759 and 68760). South Carolina's standards for stormwater management and sediment reduction explicitly address water quantity. 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" (DHEC 2003, 21).

A bioretention cell is one type of structural best management practice (BMP) 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 planted landscape that serves another purpose, e.g., beautification or shade. Moreover, bioretention cells can remove pollutants more effectively than stormwater detention ponds (Appendix F, Table 3). Widespread use of bioretention cells would expand the market for wood chips and, to some extent, might reduce hazardous fuels for wildfire because processed residues from logging decks could be the source of organic material that the cells require. Public works officials and real-estate developers have begun to use bioretention cells in the mid-Atlantic region and elsewhere (e.g., EPA 1999b, pg. 2 and Schueler 2000).

However, important questions about environmental performance and costs of bioretention cells remain unanswered. In particular, does chipped woody material from logging decks adsorb pollutants as well as commercial mulches or at least adequately? Given not-always-adequate removal of nitrates in previously designed bioretention cells, will an underground, rather than ground-level, layer of chipped small-diameter logging residue and an anaerobic gravel layer that is immediately below the chips adequately remove nitrates from the water that infiltrates or flows out of the cell? If drainage tiles are placed between the chipped woody material 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 be made? Finally, how much processed forest biomass would be used if industrial parks and sites in South Carolina were to use bioretention cells to manage stormwater discharges? The objectives of this project were to address these questions and demonstrate the use of processed pine residue from a logging deck in a bioretention cell that treats runoff from a parking lot in an industrial park.

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

A bioretention cell was designed in during 2002-2003 and installed in the late fall of 2003 next to the shipping-receiving lot of Dana Corporation's Torque Traction Integration Technologies, Inc. at the Orangeburg County and City Industrial Park (Appendix A). The Orangeburg County and City Industrial Park is newly built, covers 443 acres, and is located at the interchange of I-26 and US-301 in Orangeburg County, South Carolina (Figure 4 in Appendix A). The bioretention cell is approximately 25' wide and 75' long with these four layers: 1) a top layer of sod of Centipede sod, 2) an upper-middle layer of soil that is 12 inches thick, 3) a 12 in. thick lower-middle layer of chipped logging residues, and 4) a bottom gravel layer that is 24" thick and comprised of ¾" washed stone. In previous designs, bioretention cells have had a top layer of mulch, a middle layer of soil, and a sand-gravel layer on the bottom that removes excess water and keeps the soil aerobic. In this bioretention cell, the layer of chipped woody material was put below ground, 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.

This bioretention cell and the use of processed forest biomass in it were publicized or will still be publicized in various ways. First, the Bureau of Water of the South Carolina Department of Health and Environmental Control published an article in early 2003 about the project (Appendix B.) Second, a sign was designed (Appendix C) in Aug. and installed at the site of the cell in Oct. 2004. Third, Peter Kent, Public Information Director for Clemson University's College of Agriculture, Forestry, and Life Sciences, interviewed all participants about the project in June 2004. The interviews and project documentation will be the basis of at least one newspaper- or magazine-style article that he will finish writing in November.

<u>Laboratory Tests of Pollutant Removal Efficiencies of Chipped Pine Logging Residues</u>

One way to ascertain environmental performance of chipped pine material from logging decks is to conduct laboratory tests of pollutant removal efficiencies of this material and compare them to the removal efficiencies of two commercial hardwood mulches. The specific methods and test results are presented in Appendix D. Highlights of the results are now presented.

Aged and fresh chipped pine residue remove, on average, the same percentage of nitrate nitrogen that single-ground hardwood mulch removes but less than the double-ground hardwood removes from polluted water. Fresh chipped pine residue and the two hardwood mulches add, on average, the same amount of phosphorous. Aged chipped pine material and single-ground hardwood mulch add less phosphorous, on average, than double-ground hardwood mulch.

Aged chipped pine biomass removes less zinc, on average, than the single or double-ground hardwood mulch removes. Also, fresh chipped pine material and the single-ground mulch remove less zinc, on average, than the double-ground mulch removes. Aged chipped pine material and the double-ground mulch remove less copper, on average, than the single-ground mulch. Fresh chipped logging residues remove less copper, on average, than single-ground hardwood mulch, which removes less, on average, than double-ground mulch removes.

The level of total organic carbon decreased slightly as the chipped pine material and hardwood mulches aged. However, any of the three types of woody biomass could serve as a carbon source for denitrification within the bottom chamber of a bioretention cell.

<u>Analysis of Inflow, Under-Drain Water, and Outflow at the Orangeburg BRC (Appendix E)</u>

In general, the bioretention cell reduces the quantity of runoff to the existing storm sewer. Runoff from the parking lot enters the cell, is filtered, and then is infiltrated or internally drained to the storm sewer or flows over the cell to the storm sewer. All runoff becomes inflow to the cell and is filtered--that is, no runoff overflows to the existing stormwater system--for any rain event of 1.2 inches or less. Fifty percent of the runoff, all of which enters the cell, is infiltrated and 50% of the filtered runoff passes though the cell's internal drainage for a 1-inch rain. All runoff, which is filtered by the cell, infiltrates for rain events of 0.20 inch or less.

Thirty six to 38 percent of the first 1 inch of runoff from the parking lot infiltrates and 56-58% of the first flush is discharged from the cell as drain flow. Thus, 94% of the first inch of runoff enters the bioretention cell and only six percent of the first flush is overflow and discharged downstream without treatment by the cell.

The bioretention cell appears to adequately remove zinc and copper from runoff that infiltrates to groundwater and flows to the storm sewer, given a limited number of observations.

In the last of two rainfall events when an adequate amount of the first flush was sampled, the cell removed phosphorus and nitrates. 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 the Orangeburg County and City Industrial Park cost $28,860 for engineering, other pre-construction activities, and construction (Table 1). This figure does not include a cost for the grassy surface area of the cell because this area is part of the existing landscape that surrounds the shipping-receiving lot of the plant. The largest portion of these costs was $23,500 for the contractor, his sub-contractor, and their materials.

Design and engineering accounted for a larger share of costs of this project than previous projects for which comparable data are available (Table 2). The engineering plans for the Orangeburg bioretention cell had to be redone twice because the originally planned location of the cell was changed and the original stormwater plans differed from the as-built plans. Excavation and grading's share of total costs was more than twice as large in this project as in others (Table 2). Thirty eight percent of the excavation—approximately 174 yds^3 of soil—for the Orangeburg cell was done to put the top of the cell slightly below the parking lot, which had been built below grade. Thirty one percent of the excavation—approximately 139 yds^3 of soil—was done to enable the cell to retain and, thus, reduce stormwater runoff. All but two of the previous cells for which information is available were not designed to reduce the quantity of runoff. Two contractors bid for the work and neither bidder had any previous experience with installation of bioretention cells. The bidders probably included a premium for unexpected problems. Large but justifiable excavation and grading expense, insufficient bid competition, and contractor inexperience are also reasons why the costs per unit of water-quality volume were higher in this project than the average of all others (Table 3).

Design, engineering, and construction costs of a bioretention cell depend on the volume of water that is treated for pollutants, or water-quality volume, the volume of stormwater that can be instantaneously stored in the cell, or water-quantity volume, the type of major land resource area where the cell is located, and the average wage of engineers, construction workers, and landscape workers in or closest to the urban area where the cell is located (Model 4 in Table 3, Appendix F). In this model, a one percent increase in the hourly wage of engineers in the area where a cell is located leads to a 6.69 percent increase in the total costs of the cell. In the same model, 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 0.765 percent in coastal areas of mid-Atlantic states, 0.734 percent in the Piedmont region of these states, and 0.629 percent in the Sandhill region. In this and three simpler models (Models 1, 2, and 3 in Table 3, Appendix F), costs per unit of water-quality volume decrease as the volume of water that a cell treats for pollutants increases. Hence, bioretention cells exhibit economies of water-quality size.

Design, engineering, and construction costs of a stormwater pond depend on land prices, in addition to water-quantity volume, water-quality volume, and the average wage of engineers, construction workers, and landscape workers in or closest to the urban area where the pond is located (Model 3 in Table 4, Appendix F). In this model, a one percent increase in land costs leads to a 0.426 percent increase in the total costs of a pond and a one percent increase in the wage of construction workers induces a 5.10 increase in total costs. In the same model, total costs increase 0.340 percent in response to a one percent increase in water-quality volume and 0.842 percent in response to a one percent increase in water-quantity volume. In two other models in which water-quality volume is not included as an exogenous variable (Models 1 and 2 in Table 4), a one percent increase in the storage volume of stormwater leads to a 0.616 percent and 0.854 percent increase in costs of design, engineering, and construction. Hence, stormwater ponds exhibit economies of water-quality and water-quantity size.

Estimated fixed costs are higher for stormwater ponds than bioretention cells in all model specifications (Tables 3 and 4, Appendix F). The costs per unit of water-quantity volume of stormwater ponds decrease more in absolute value than the costs per unit of water-quality volume of bioretention cells decrease, according to estimates from two specifications of cost models that lack any input price (Models 1 and 2 in Table 3 and Model 1 in Table 4, Appendix F). In the model of bioretention-cell costs with wages of engineers, construction workers, and landscape workers (Model 3 in Table 3, Appendix F) and the model of stormwater-pond costs with these three wages and land prices (Model 2 in Table 4, Appendix F) this relationship still holds in the coastal region. However, in the Sandhill and Piedmont regions, the costs per unit of water-quality volume of bioretention cells decrease more in absolute value than the costs per unit of water-quantity volume of stormwater ponds decrease.

Meaningful comparisons of costs of bioretention cells and stormwater ponds that account for both water-quality and water-quantity volumes are difficult, if not impossible, to make. 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-quantity information exists for only three of the twenty six cells in our sample because the Orangeburg cell was also designed to reduce stormwater runoff and the other two might have been so designed.

According to the estimates from two simple models in which costs depend exclusively on water-quality volume (Table 5, Appendix F), a bioretention cell is a cheaper method than a stormwater pond to remove pollutants in volumes of stormwater below 112,536 ft^3, regardless of the region According to the estimates from two models in which costs also depend on input prices and regions, in addition to water-quality volume (Table 5, Appendix F), a bioretention cell is a more expensive method of removing pollutants from any volume of water than a stormwater pond in mid-Atlantic coastal areas. However, according to the same two models (Table 5, Appendix F), a bioretention cell is a cheaper management practice than a stormwater pond in the Piedmont region for volumes of stormwater less than 359,017 ft^3.

These estimated volumes illustrate but do not unambiguously define turning points of cost effectiveness of the two BMPs. Although 112,536 ft^3 and 359,017 ft^3 are within one half of a standard deviation from 301,338 ft^3, the mean water-quality volume of stormwater ponds, these turning points substantially exceed 19,874 ft^3, the largest observed water-quality volume of a bioretention cell. Moreover, the drainage areas of a South Carolina industrial park or site that would generate 112,536 ft^3 and 359,017 ft^3 of runoff from the first flush of a rain event are 65.6 and 209.3 acres, which are 13 and 42 times larger than 5 acres, the maximum recommended drainage area for typical bioretention cells (EPA 2004). Furthermore, the two sets of models on which these turning points are based ignore water-quantity volume as a determinant of costs.

Models of costs of bioretention cells and stormwater ponds that depend on water-quality and water-quantity volumes, in addition to input prices and regions, were estimated (Model 4 in Table 3 and Model 3 in Table 4, Appendix F). However, water-quantity volumes were assumed, not measured, equal to water-quality volumes for 23 of the 26 bioretention cells in our database. Even if measurements existed, these 23 bioretention cells were not designed to reduce stormwater runoff. Hence, even if a bioretention cell and a stormwater pond have the same water-quantity volume, these two BMPs do not necessarily reduce equal amounts of runoff. Similarly, even if a bioretention cell and a stormwater pond have the same water-quality volume, they do not necessarily have the same pollutant trapping efficiencies. Determination of the precise ranges of water-quality and water-quantity volumes over which, given local input prices and land resource areas, a bioretention cell is a cheaper method than a stormwater pond to meet regulatory standards for stormwater runoff remains an important question for future research.

Maximum Possible Use of Processed Forest Biomass at Industrial Parks and Sites

Industrial parks and sites that have on-going or future construction activities, such as the one in Orangeburg, are required by the South Carolina Stormwater Management and Sediment Reduction Act and by amendments to the Clean Water Act to use best management practices (BMPs) to control stormwater runoff and reduce pollution. Industrial parks that are not involved in construction activities but discharge runoff into municipal separate stormwater systems (MS4s) or directly into water bodies of the U. S. are also required under Phase I to use BMPs. How much chipped pine material would these industrial parks and sites use if they were to exclusively adopt bioretention cells to manage stormwater runoff?

In August 2004 South Carolina had 803 industrial sites and 241 industrial parks, according to information that South Carolina's Dept. of Commerce provided. Most of these parks and sites are located along or near interstate highways (Figure 1). An 'industrial site' is a property for manufacturers and other businesses that has expandable boundaries and is zoned the same as the surrounding land is (Beesley). An 'industrial park' is a property for manufacturers and other businesses that has a non-expandable boundary and individual lots that are zoned specifically for the park (Beesley). The Palmetto state's industrial sites had a reported 148,629 acres available for development, or 185 acres per site. South Carolina's industrial parks had a reported 40,976 acres available for development, or 175 acres per park.

The surface area of a bioretention cell depends on the drainage area and the runoff from the area (EPA 1999b, 3). In particular, the surface area should be 7% of drainage area, if the cell has no sandy pre-filtering bed, multiplied by the rational method's runoff coefficient, C, for the land use (EPA 1999b, 3). In our judgement, industrial parks and sites are more similar to heavy industrial areas than any other type of land use for which runoff coefficients are available. The runoff coefficient for heavy industrial areas falls within the range of 0.6 to 0.9 and, thus, the median value is 0.75 (Haan et al. 1994, pg. 84). Given a C-value of 0.75, the surface area of a bioretention cell at an industrial park or site in South Carolina should, on average, be 0.0525 (= 0.75*0.07) acre, or 254.1 square yards, per acre of drainage.

If the layer of chipped woody forest residue in each bioretention cell were ⅓ yard deep, as in the Orangeburg cell, then 84.7 cubic yards (=254.1 ÷ 3) of processed forest biomass per acre of drainage would be required. If owner or tenants of industrial parks and sites eventually develop all of their land, manage stormwater runoff only with bioretention cells, and use chipped woody material as the sole source of carbon in the cells, the total volume of chipped woody residue in the cells would be 16.06 million cubic yards, given the total drainage area of 189,605 acres.

The actual weight of a cubic yard of chipped woody material depends on the type and moisture content of wood. Oven-dried wood chips weigh 9 – 12 lbs. per cubic foot (Johnson 1987). Given moisture content of 100% of dry weight in newly chipped material from southern softwood forests (Rummer) and a median dry weight of 10.5 lbs per cubic foot, there is an estimated 21 lbs. per cubic foot, or 0.2835 tons per cubic yard, of green chipped woody material. In comparison, chipped brush weighs, on average, 0.25 ton per cubic yard (EPA 1994, pp. 162). Given this conversion factor, 16.06 million cubic yards of chipped woody material are equivalent to 4.553 million tons, which exceeds the 4.1 million tons of annual biomass residual of harvesting pine timber in the 1990s (Harper 2001). If the real cost of a delivered green ton of chipped woody material were to stay constant at $22, then developers of South Carolina's industrial parks and sites would spend $100.2 million over time to use this processed forest biomass as the carbon source in bioretention cells to manage stormwater quantity and quality.

Conclusions

Chipped woody material from logging decks adequately adsorbs pollutants, sometimes as well as or better than commercial mulches do. Additional tests are needed to confirm that a bioretention cell with an underground layer of chipped logging residue above a gravel layer adequately removes nitrates from stormwater. The bioretention cell with drainage tiles below the chipped woody material and above the gravel layer in Orangeburg 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 determine the exact quantitative range of water-quality volumes and associated drainage areas where bioretention cells are cheaper than stormwater ponds, given that, with the exception of the Orangeburg cell and two others, cells for which data are available were not engineered to reduce stormwater runoff and size constraints on both cells and ponds reportedly exist (EPA 1999b). Given favorable assumptions, developers of South Carolina's industrial parks and sites could spend $100.2 million over time to use at most 16.06 million cubic yards of chipped woody material as the sole source of carbon in bioretention cells.

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Table 1: Itemization of Total Costs of the Orangeburg Bioretention Cells

Type of Cost	Costs (Dollars)	Adjusted Costs (2003 $s in Baltimore MD)
1. Design and Engineering*	$2,999	$3,689
2. Construction	$25,862	$31,816
Contractor and Sub-Contractor	$15,300	$18,822
Materials	$10,562	$12,993
Contractor Material	$8,200	$10,088
Chipped Woody Material (15 tons)	$385	$474
Sod (8000 sq. ft.)	$1,977	$2,432
Total	$28,861	$35,505

*These costs equal hours spent by project personnel multiplied by typical hourly rates for similar types of work in Orangeburg SC.

Table 2: Comparison of Cost Shares

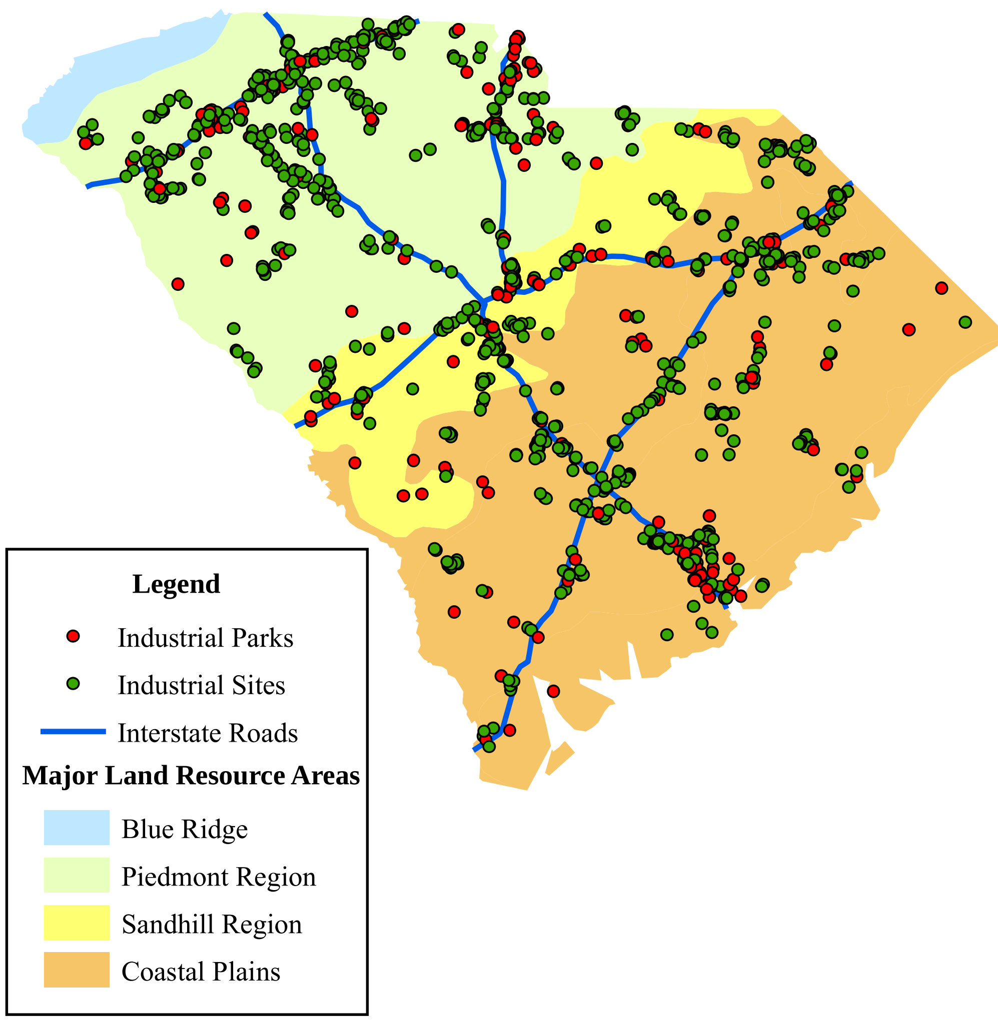
Type of Cost	Total Cost of Orangeburg Bioretention Cell	Percentage of Total Cost of Orangeburg Bioretention Cell	Percentage of Total Cost of 11 Other Bioretention Cells in Maryland and Virginia
1. Design and Engineering	$2,999	10%	7%
2. Construction	$25,861	90%	93%
Excavation and Grading	$14,300	50%	22%
Control Structure	$6,055	21%	48%
Sediment Control	$0	0%	1%
Appurtenances	$2,530	9%	6%
Landscaping	$2,977	10%	15%

Table 3: Water-Quality Volumes and Costs of Bioretention Cells in Maryland (MD), Virginia (VA), North Carolina (NC) and South Carolina (SC)

Location ID No.	Water-Quality Volume (cubic ft.)	Aggregated Major Land Resource Area	Unadjusted Total Cost (Dollars)	Adjusted Total Cost (2003 $s in Baltimore MD)	Adjusted Total Cost per Water-Quality Volume ($/cubic ft.)
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
Average	3,817			$26,936	$14.00
SC1*	1,406	Coastal	$28,861	$35,505	$25.25

*Bioretention Cell in Orangeburg, South Carolina

Figure 1: Locations of Industrial Parks and Sites in South Carolina, August 2004



Appendix A:

Design of Bioretention Cell in Orangeburg County and City Industrial Park

As the bioretention cell plan indicates (Figure 1), this BRC will be 25' x 75'. There are four layers of this BRC (Figure 2): 1) a top layer of sod of Centipede grass, 2) an upper-middle layer of soil that will be 18 inches thick, 3) a lower-middle layer of processed forest biomass will be 6 in. thick, and 4) a bottom gravel layer that will be 24" thick. The bottom layer will be comprised of washed ¾" stone. There will be a synthetic fabric membrane between the layers of gravel and processed forest biomass. The outlet from Dana Corporation's shipping-receiving lot to the bioretention cell shall be protected with a synthetic liner followed by one man riprap.

Overflow from the cell will be directed to a proposed junction box as shown on attached sketches (Figures 1 and 3). Overflow from the cell will enter this junction box through grate inlets located on the top. The overflow channel, with sod similar to the bioretention cell, shall be constructed so as to allow the overflow from the BRC to flow directly to the grate inlet.

The entrance to the overflow channel will be located at the downstream side of the bioretention cell. The channel base is 10 feet wide at the inlet side. The channel will be trapezoidal in shape with 3:1 side slopes. The top of the channel will be at elevation 170.5 feet to correspond with the top edge of the bioretention cell. The invert elevation at the entrance will be 167.75 feet. This will provide 9" of ponding depth within the bioretention cell and a 3" freeboard depth. This will allow overflow to be routed from the bioretention cell and not cause flooding of the shipping-receiving lot of the Dana Corp. At the downstream end of the overflow channel, the new junction box with a top grate inlet will be located. At the end of the channel, where the junction box is located, the land shall be graded at a 3:1 slope to match the surrounding profile as shown in Figures 1 and 3.

This junction box will also allow for the connection of the existing stormwater drain pipe as well as a newly installed 8" corrugated plastic drain that will convey overflow from within the mulch layer of the bioretention cell.

Within the bottom mulch layer of the bioretention cell, a drain system consisting of 4" slotted corrugated drain pipe will be installed on a 0.1% slope. This system is shown on the attached sketches for the bioretention cell (Figures 1 and 2). The 4" pipes will connect to an 8" drain pipe that will carry any overflow from within the cell to the proposed junction box noted above.

Description:	**Design**	**Installed**
Existing land elevation:	~170 feet	
Top rim of bioretention cell:	170.5 feet	not applicable
Side slopes from cell surface to rim:	3:1	~2.5:1
Cell surface elevation:	167.0 feet	167.00'
Bottom soil elevation	165.5 feet	166.00'
Bottom mulch elevation:	165 feet	165.00'
Synthetic fabric elevation:	165 feet	165.00'
4" CPP invert elevation:	165 feet	165.00'
Bottom rock elevation:	163 feet	163.00'
8" CPP pipe invert at proposed junction box:	164 feet	not applicable
Junction box invert elevation:	163 feet	163.71'
Junction box top elevation:	167 feet	165.71'
Overflow elevation	167.75 feet	167.75'

Installed drain lines (west to east) had slopes of 0.11, 0.12, 0.17, and 0.21% respectively.

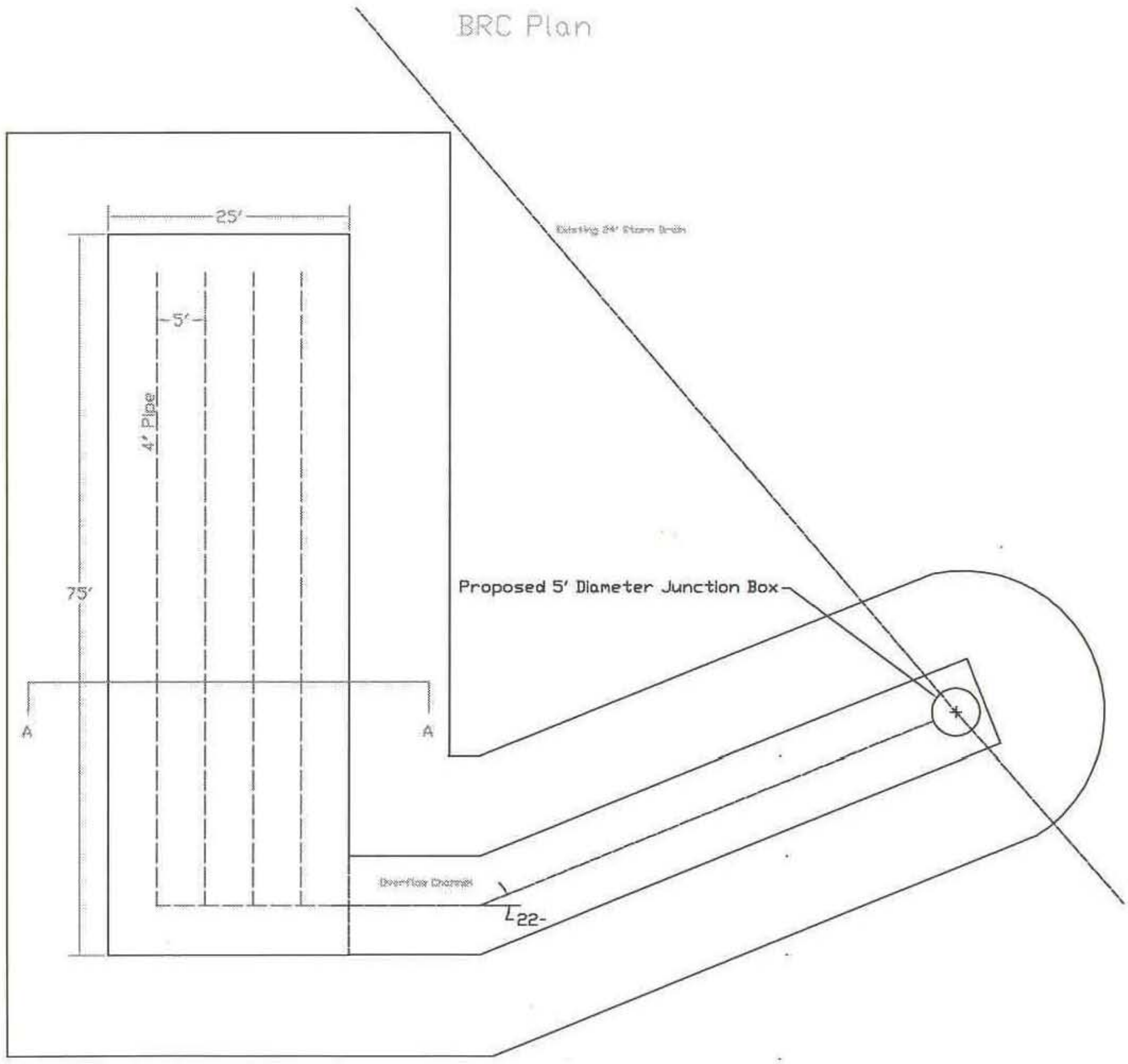


Figure 1. Bioretention Cell Layout and Overflow Channel

Section A-A

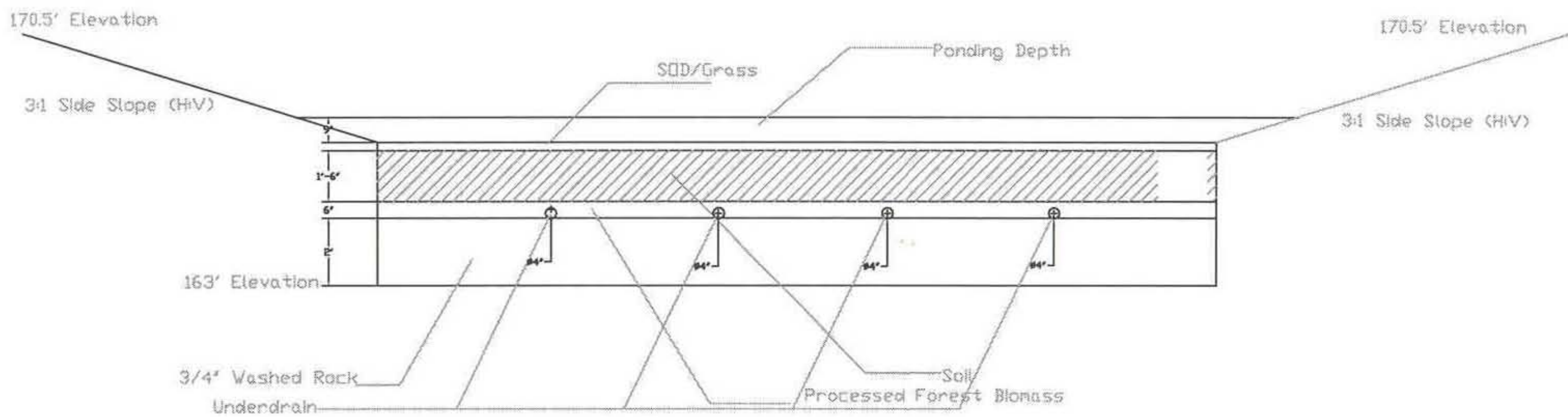
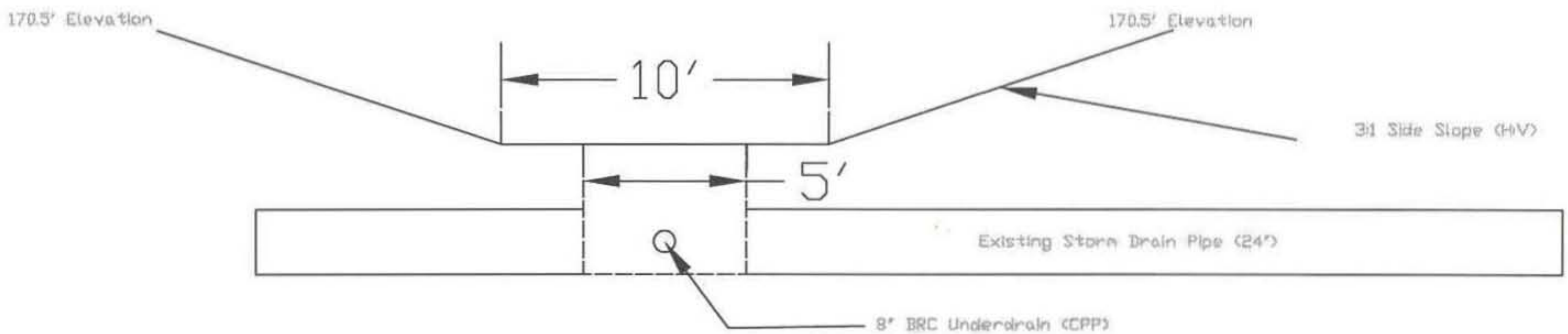


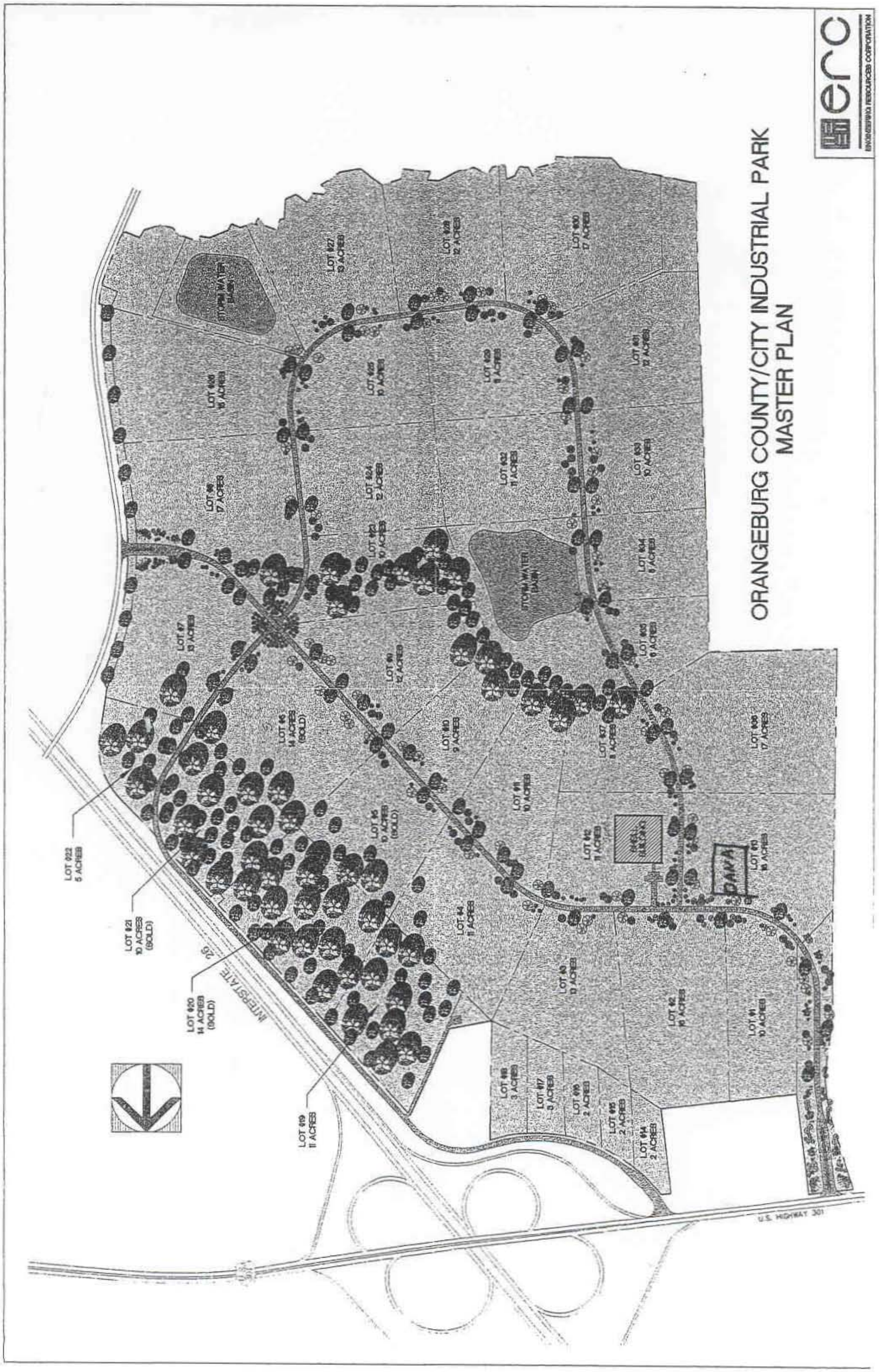
Figure 2. Bioretention Cell Cross Section

Channel Detail



Overflow Elevation from BRC 167.75' (Channel Bottom)
Elevation at Grate Inlet 167' (Channel Bottom)

Figure 3. Overflow Channel Cross Section w/ New Junction Box


ORANGEBURG COUNTY/CITY INDUSTRIAL PARK
MASTER PLAN
INTERSTATE 26

Appendix B:

Bioretention Cell Study Underway

by Charles Privette III, Extension Associate, Dept. of Agricultural and Biosystems Engineering

and Scott R. Templeton, Assistant Professor, Dept. of Applied Economics and Statistics,

Clemson University

(This article appeared in the Spring 2003 issue of *Turning the Tide*, which is published by the Bureau of Water of the South Carolina Department of Health and Environmental Control.)

Managing stormwater runoff is now more challenging than ever as regulations become stricter and urbanized areas continue to grow. Water that once infiltrated into soil now flows over mostly impervious surfaces in urban areas and washes pollutants from these surfaces into nearby streams and lakes. Enter bioretention cells (BRCs), a relatively new, but promising method of managing stormwater runoff. BRCs work by capturing runoff as sheet flow and directing it to prepared beds and ponding areas for infiltration and evaporation. BRCs also treat runoff because surface vegetation takes up nutrients contained in the dissolved fraction and chemically and biologically active organic material absorbs other pollutants.

This BRC pilot project, funded by the US Forest Service and conducted by a multi-disciplinary team of researchers from Clemson University, will evaluate the use of bioretention cells to manage both the quantity and quality of stormwater runoff and the use of processed forest biomass (chipped on-site logging debris) as the source of organic material for them. In previous designs, bioretention cells have had a top layer of mulch, a middle layer of soil, and a sand-gravel layer on the bottom that removes excess water and keeps the soil aerobic. However, their capacity to remove nitrogen has not always been adequate. To improve denitrification, the bioretention cell in this project will include a layer of processed forest biomass between the soil and rock layers.

The bioretention cell will be located at the DANA Corporation's new facility at the Orangeburg City and County Industrial Park where it will collect and treat stormwater runoff from the shipping-receiving lot. Biosystem engineers will use water quality samples to estimate pollutant removal efficiencies. They will also measure rainfall, inflow, and outflow to develop a model that determines minimum sizes of cells to meet environmental performance criteria. An economist will analyze the conditions under which BRCs are a cost-effective, better management practice.

This project also involves participation from the Cooperative Extension Service of Clemson University, South Carolina Forestry Commission, University of South Carolina, Engineering Resources Corporation, Orangeburg County Development Commission, Orangeburg City and County Industrial Park Commission, and Pattillo Construction Co. Project results will be presented in a future issue of *Turning the Tide*. For additional information, contact Charles Privette at privett@clemson.edu or 864-656-6247.

APPENDIX C: Sign for Bioretention Cell

Bioretention Cell
to Utilize Processed Forest Biomass and Manage Stormwater Runoff

A Project of
Clemson University

funded by
USDA Forest Service through South Carolina Forestry Commission

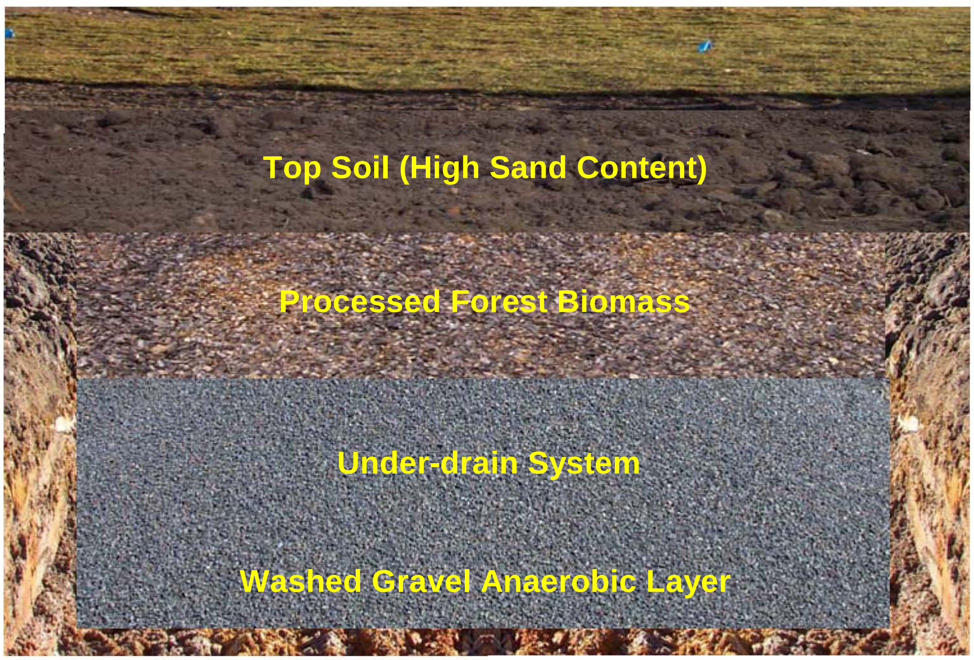
in partnership with

cooperation from

and materials donated by

For more information call 864-656-6247

Purposes of this Bioretention Cell



Project Objectives

APPENDIX D:

Removal Efficiencies of Woody Pine Chips and Two Commercial Hardwood Mulches

by Charles Privette

(This paper is a draft of a chapter of Charles Privette's dissertation for his Ph.D.)

BACKGROUND

Davis et al. (2001a) found that significant metal uptake occurred on the mulches in a bioretention system. Experiments showed reductions of copper, lead, and zinc that exceeded 92 percent. The experiments also showed a moderate reduction in phosphorus, 80 percent. Davis et al. (2002) determined in bioretention cells (BRCs) that a pH between six and eight did not affect removal results and concluded that the buffering capacity of the soil negates major effects from pH influent variations. Very little nitrate was removed by this system. Some results in fact even showed an increase in nitrate levels (Davis et al, 2001a).

One of the key aspects to the bioretention system is the use of multiple layers. This aspect sets bioretention areas apart from traditional filters. There typically exists an organic mulch layer within a bioretention cell that mimics the look of a typical landscaped area. The mulch layer is located on the surface of the cell is a few inches thick and is esthetically pleasing in appearance. The organic mulch layer serves as an organic filter for pollutants, provides an environment conductive to microbial growth/activity that can degrade petroleum-based solvents and other organic compounds, and prevents the soil from eroding (Bitter and Bowers, 2000, EPA, 1999, ARC, 2001, and PGCDER, 1993). Research has shown that double shredded hardwood mulches are less prone to float while pine mulches float well. Since the bioretention area is designed to flood, mulch that floats can be potentially transported off the area (Hunt and White, 2001).

Determining if an organic material is appropriate for adsorption is critical in the removal of pollutants from stormwater runoff. Currently mulch is being used as a surface layer in bioretention systems. Wood chips are waste products that are readily available and are cellulose-rich substrates that are abundant and renewable resources. Timber harvesting in South Carolina generates approximately 9.3 million tons of cellulose biomass, 4.1 million from pine and 5.2 million from hardwoods (Harper, 2000). Many types and sizes exist; hardwoods to softwoods, course to finely shredded, with in the realm of mulch. This study looks at two common mulches that are readily available; a single ground hardwood and a double ground hardwood, as well as an unprocessed logging residue that has been chipped.

These three products were analyzed to determine how well they adsorb several key compounds: zinc, copper, phosphorus, and nitrate nitrogen. The mulches were also analyzed to see what if any compounds/elements are leached. Total organic carbon was also analyzed to determine if the mulch could serve as a carbon source within the bioretention system.

OBJECTIVES

1. Determine the metal removal efficiencies of various mulches.
2. Determine the nutrient removal efficiencies of various mulches.
3. Determine which elements or compounds leach from various mulches.
4. Determine whether adsorptions and leachates of various mulches differ.
5. Determine whether various mulches could serve as carbon sources.

METHODS

Three separate tests were conducted in order to determine how the various mulches behave. The first behavior explored was which elements or compounds the various mulches leach. Information about the leachate from mulch will help determine the net adsorption rate of the mulch. The second set of experiments test a known solution entering a mulch column to determine what elements/compounds are adsorbed or removed in the process. Finally, the third test looked to determine how the adsorption rates change if the mulch has been washed before a test solution is passed through the column of mulch. This process will simulate aged mulch.

An adsorption test was then performed on the three mulches. Similar procedures to the leach test were performed with the exception of the solution passing through the column test. A synthetic pollution solution containing nitrate nitrogen, phosphorus, copper, and zinc were used for this test. The synthetic runoff solution was passed through the mulch at a flow rate 57 ml/min. Test samples were taken just as they were in the leach test with the exception that an initial sample was taken of the pollution solution. The results from this study were used along with the results from the leach study to determine the overall adsorption of the three mulches.

The last test dealt with adsorption capacities of washed mulches. Washing removes water-soluble surface debris that might interfere with the material's adsorptive properties (Vaughan et al. 2001). The difference between this study and the previous study was that the mulch went through a washing procedure before it was tested with the synthetic pollution solution. The washed mulch was allowed to air dry before it was tested for adsorption characteristics. Adsorption test procedures and methods for the washed tests were the same as that of the adsorption test. This can be representative of aged mulch. Washing procedures are described below. The results of the washed samples were then compared to the adsorption test samples.

The set-up for this study used a five gallon reservoir connected to a peristaltic pump that delivered the test solution through the bottom side of the test column. The effluent line was then connected to the top of the test column where the effluent discharge was pumped into a 3.75 liter plastic jug. The pump was calibrated to deliver 57 ml/min of solution to the test column. Figure

1 shows this arrangement.

Figure 1: Experimental set-up.

Test Solutions

A synthetic pollution solution containing nitrate nitrogen, phosphorus, copper, and zinc were used for the column studies. Davis et al, 2001a, found from research that the concentrations of these elements in storm water runoff were on the range of 2 mg/L of nitrate nitrogen, 0.6 mg/L phosphorus, 0.08 mg/l copper, and 0.6 mg/l zinc while Pitt, 2000, reported average concentrations of 15 μg/L copper and 110 μg/L zinc in storm water runoff from parking lots. The Davis et al, 2001a synthetic solution was chosen to be used in order to compare this study's results with other similar studies. Table 2 shows the concentrations used for testing.

Table 2. Stormwater runoff pollutant concentrations

Pollutant	**Concentration (mg/L)**
Phosphorus	0.6[a]
Nitrate Nitrogen	2 [a]
Copper	0.08 [a]
Zinc	0.6 [a]

The concentration of the batch solution is 1000 times the standard stormwater runoff concentrations as reported by Davis et al, 2001a. This was carried out to ensure that the same solution was used for each test. This sample was then frozen in 125 ml HPDE bottles. The solution was made as follows:

Nitrate Nitrogen (2 g/L)

Sodium Nitrate was used as the compound ($NaNO_3$). The molecular weight of $NaNO_3$ is 84.99 grams. In order to get 2 g/l of nitrate nitrogen 12.14 g of $NaNO_3$ was mixed with 1liter of deionized water.

Phosphorus (0.6 g/l)

Sodium Phosphate was used as the compound (Na_2HPO_4). The molecular weight of Na_2HPO_4 is 141.96 grams. In order to get 0.6 g/l of phosphorus, 2.75 g of Na_2HPO_4 was mixed with 1 liter of deionized water.

Copper (0.08 g/l)

Cupric Sulfate was used as the compound ($CuSO_4$). The molecular weight of $CuSO_4$ is 159.6 grams. In order to get 0.08 g/l of copper, 200 mg of $CuSO_4$ was mixed with 1 liter of deionized water.

Zinc (0.6 g/l)

Zinc Sulfate was used as the compound ($ZnSO_4$). The molecular weight of $ZnSO_4$ is 287.54 grams. In order to get 0.6 g/l of zinc, 2.640 g of $ZnSO_4$ mixed with 1 liter of deionized water.

These test solutions were kept frozen in HDPE bottles. The solution was thawed and stirred when a test was run. This ensured a homogeneous solution. Proper dilutions were made corresponding to the test that was performed. The remaining solution was then re-frozen for future use. The remaining solution was discarded in accordance with University procedures after test runs were completed.

Washing Procedure

The washing procedures started with the mulch leach test in which the mulch was washed with a continuous flow of deionized water (57 ml/min) through the test columns. The flow was stopped after approximately three hours of continuous flow (five pore volumes). The mulch was then allowed to soak twenty-four hours whereby the water was then removed. More deionized water was then applied and the mulch/water mixture was mixed thoroughly. This mixture was then allowed to sit for four days. The mulch was then strained and allowed to dry. Samples of the wash water were taken during the leach test as well as after the twenty-four hour and four day resident periods.

Sample Collection Technique

All water samples were collected in high-density polyethylene (HPDE) 125 ml bottles with polyethylene caps. Water samples that were analyzed immediately were not treated. Water samples that were stored in refrigerators/freezers for a period of time were treated as follows. Water samples that were tested for nitrate nitrogen were acidified to a pH <2 with concentrated sulfuric acid (H_2SO_4) (APHA, 1992 and HACH, 1999). All other water samples (phosphorus, carbon, zinc, and copper) were acidified to a pH <2 with concentrated nitric acid (HNO_3) (APHA, 1992, and HACH, 1999). According to APHA, 1992, samples containing low concentrations of phosphorus should not be stored in plastic bottles unless they are kept frozen because phosphorus may absorb onto the walls of the bottles. Samples that were to be stored were frozen after acidifying. Samples with metal concentrations are stable for up to 6 months under these conditions (APHA, 1992).

Sample Analysis

Water samples were analyzed at the University of South Carolina's Civil and Environmental Engineering Department's wastewater lab and through the Clemson University Extension Service's Agricultural Service Laboratory. HACH kits were used in the wastewater laboratory for analysis of nitrate nitrogen. HACH Procedure's Method 10020 states that before running test on samples, allow sample to warm to room temperature. Samples that were acidified were then neutralized using 5.0N sodium hydroxide solution. HACH Method 10020 Nitrate, High Range, Test 'N Tube procedures were followed for nitrate nitrogen sample analysis. Method 10020 uses the Chromotropic Acid method. This method is appropriate for nitrate nitrogen concentrations ranging from 0.0 to 30.0 mg/l NO_3^-N. The Chromotropic Acid method is based on nitrate in the sample reacting with chromotropic acid under strongly acidic conditions to yield a yellow product with a maximum absorbance at 410 nm. The Clemson University Extension Service's Agricultural Service Laboratory used a Thermo Jarrell Ash model 61E sample analyzer for sample analysis for zinc, copper, and phosphorus measurements.

Total Organic Carbon (TOC) analysis samples were analyzed in the University of South Carolina's Civil and Environmental Engineering Department's wastewater lab. Samples were first placed in test tubes and centrifuged for 15 minutes at 4000 RPMs. Six ml of each sample were then placed in TOC vials and labeled. The TOC vials were then placed in a TOC analyzer that had been calibrated. The TOC analyzer was programmed based on the number of samples and allowed to run.

RESULTS

Figures 2, 3, 6, and 7 show the removal ratios that the individual mulches have on nutrient removal over time. Figures 2 and 3 show the results of the adsorption test on the raw, un-aged mulch. Figures 6 and 7 show results for the washed, aged mulch that are similar. Mulch A represents the unprocessed logging residue that had been chipped, mulch B represents a double ground hardwood, and mulch C represents a single ground hardwood.

The average nitrate removal ratio for mulch A for all 5 time periods of the adsorption test was 0.70. Mulch B and C had ratios of 0.81 and 0.51 respectively. The washed test ratios for nitrate removal were slightly lower. The respective removal ratios for mulch A, B, and C were 0.50, 0.64, and 0.46. Phosphorus removal ratios for the washed test on mulch A, B, and C were -0.32, -0.62 and -0.27. The adsorptive test for phosphorus was significantly lower. Mulch A, B, and C had removal ratios of -2.88, -4.00, and -3.21 respectively.

Figures 4, 5, 8, and 9 show the metal removal ratios of individual mulches over time. Figures 4 and 5 show the results of the adsorption tests on the raw, un-aged mulch. Figures 8 and 9 show results for the washed, aged mulch that are similar. Mulch A had a removal ratio of 0.69 while mulch B and C had ratios of 0.81 and 0.81 respectively for the washed test. The removal of zinc using the adsorption test resulted in removal ratios are 0.67 and 0.65 for mulches A and C respectively. Mulch B removal ratio for zinc was higher at 0.83. The washed test for copper showed that mulch A and B had a removal ratio of 0.56 and 0.56 respectively. Mulch C was higher with a removal ratio of 0.69. The adsorption test for copper resulted in removal ratios for mulch A, B, and C of 0.37, 0.69, and 0.50 respectively.

Figures 10, 11, 12, and 13 show the total masses of nitrate, phosphorus, zinc and copper that the individual mulches leach. The average nitrate amount leached for all 5 time periods for mulch A, B, and C was 1113 mg, 1231 mg, and 1188 mg respectively. The average phosphorus amount leached for mulch A, B, and C was 3826 mg, 4231 mg, and 4193 mg respectively. The average copper amount leached for mulch A, B, and C was 20.7 mg, 20.1 mg, and 23.5 mg respectively. Mulch B leached only 28.4 mg of zinc in comparison with 92.0 mg for mulch A and 107 mg for mulch C.

Removal ratios were calculated by mass balance by recording input and effluent mass concentration and total flow volume for the given time period. In particular, $M_I = V_I C_I$, in which M_I is input mass, V_I is total flow volume, and C_I is input concentration. Also, $M_O = V_O C_O$, which where M_O is effluent mass, V_O is total flow volume, and C_O is input concentration. Total mass removal ratios for each subsequent time period was then determined by: $RR_{Tp} = \frac{\sum_{Tp_i}^{Tp} M_I - \sum_{Tp_i}^{Tp} M_O}{\sum_{Tp_i}^{Tp} M_I}$, in which RR_{Tp} is the removal ratio for a given element/compound at the given time period Tp and Tp_i is the initial time period. Leach total was determined by: $LT_{Tp} = \sum_{Tp_i}^{Tp} M_O$, in which LT_{Tp} is the total mass of a given element or compound.

Figure 2. Cumulative average nitrate nitrogen removal efficiencies of the three test mulches using the adsorption test procedures.

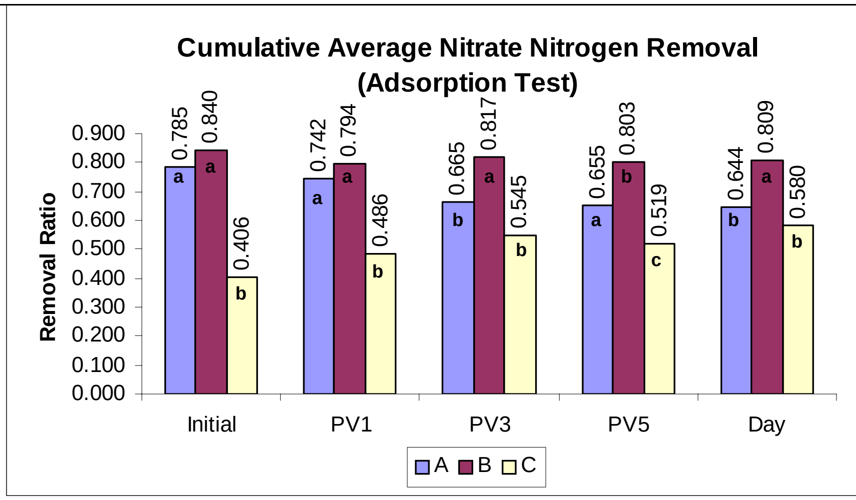


Figure 3. Cumulative average phosphorus removal efficiencies of the three test mulches using the adsorption test procedures

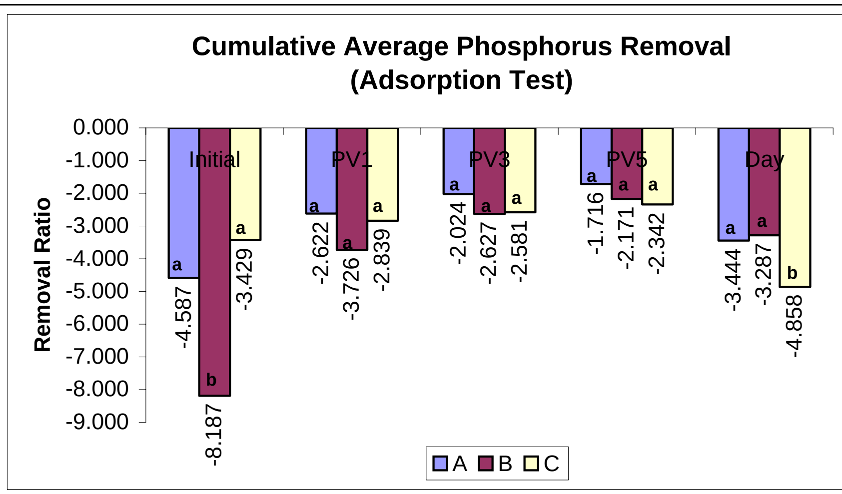


Figure 4. Cumulative average zinc removal efficiencies of the three test mulches using the adsorption test procedures

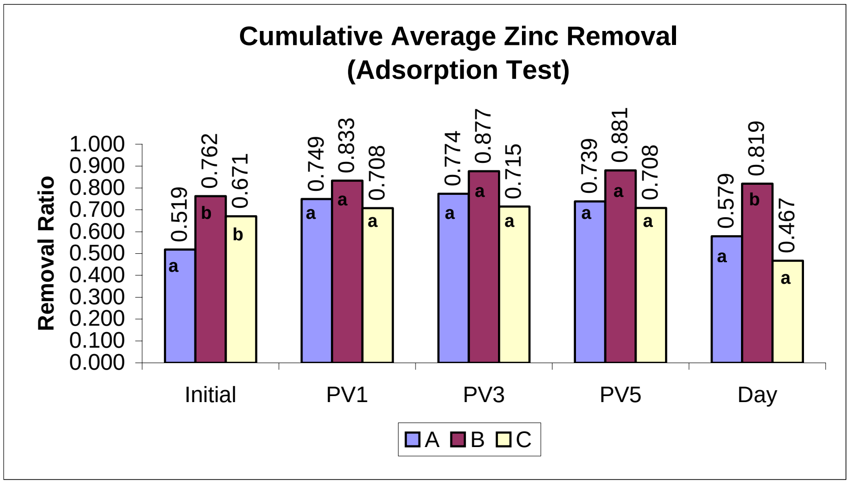


Figure 5: Cumulative average copper removal efficiencies of the three test mulches using the adsorption test procedures

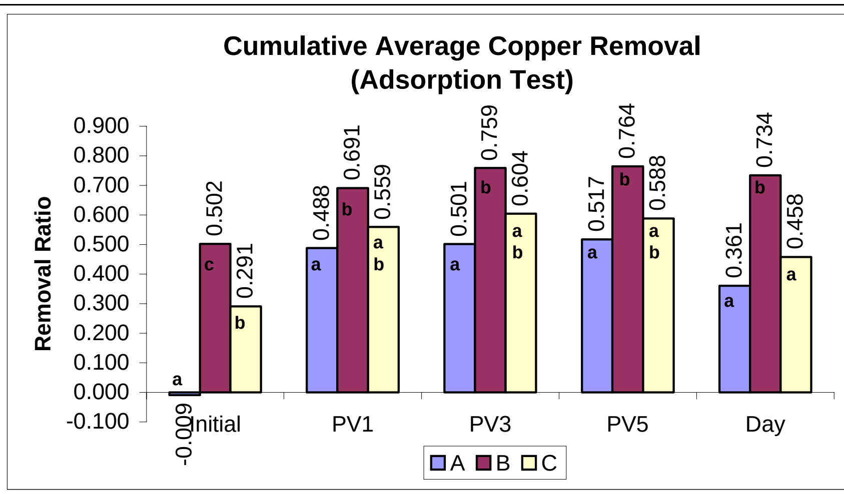


Figure 6. Cumulative average nitrate nitrogen removal efficiencies of the three test mulches using the washed mulch test procedures

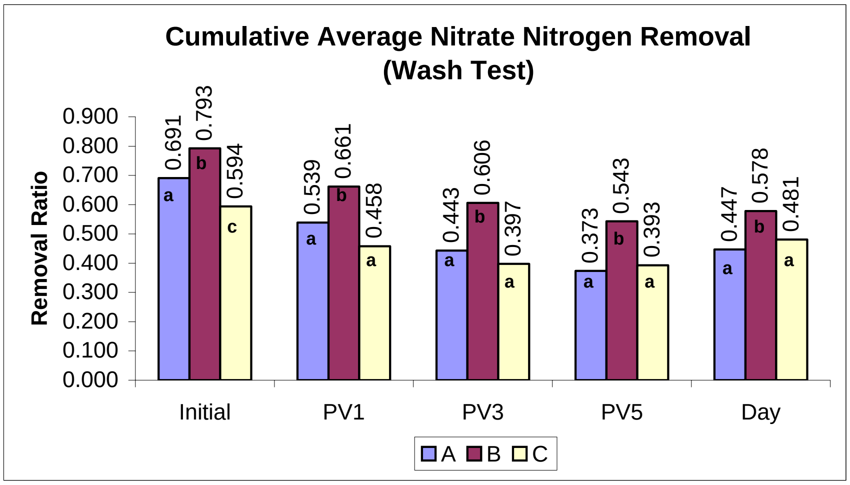


Figure 7. Cumulative average phosphorus removal efficiencies of the three test mulches using the washed mulch test procedures.

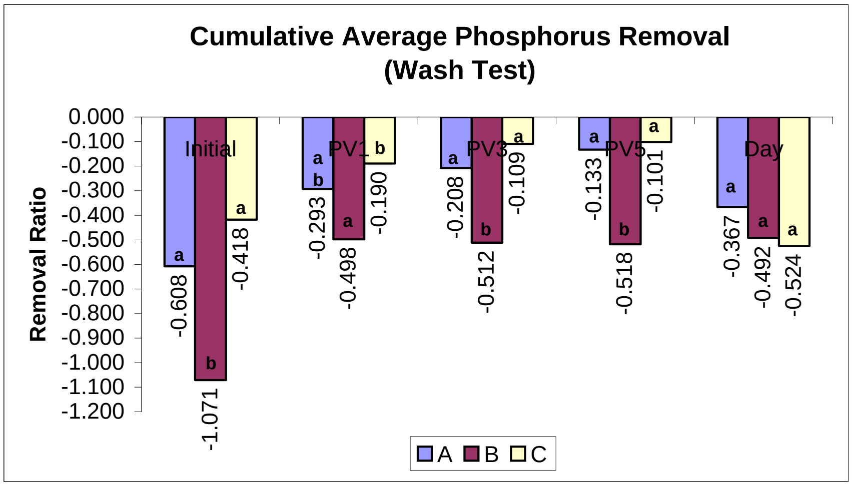


Figure 8. Cumulative average zinc removal efficiencies of the three test mulches using the washed mulch test procedures

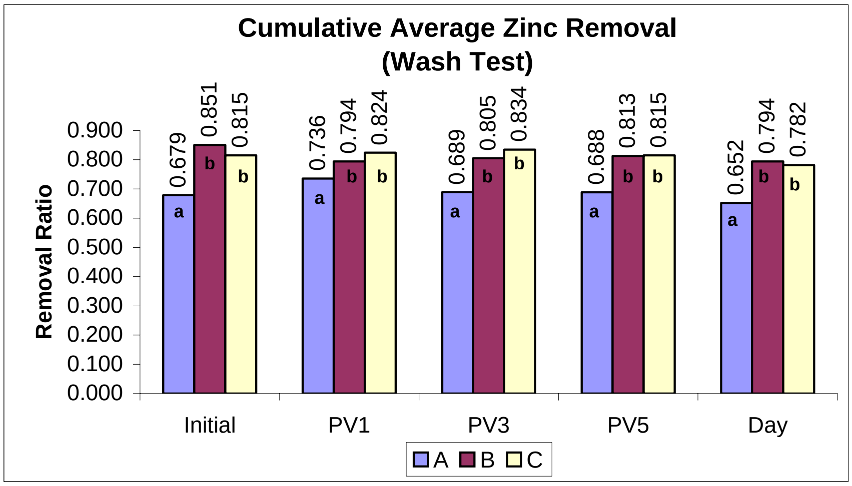


Figure 9. Cumulative average copper removal efficiencies of the three test mulches using the washed mulch test procedures

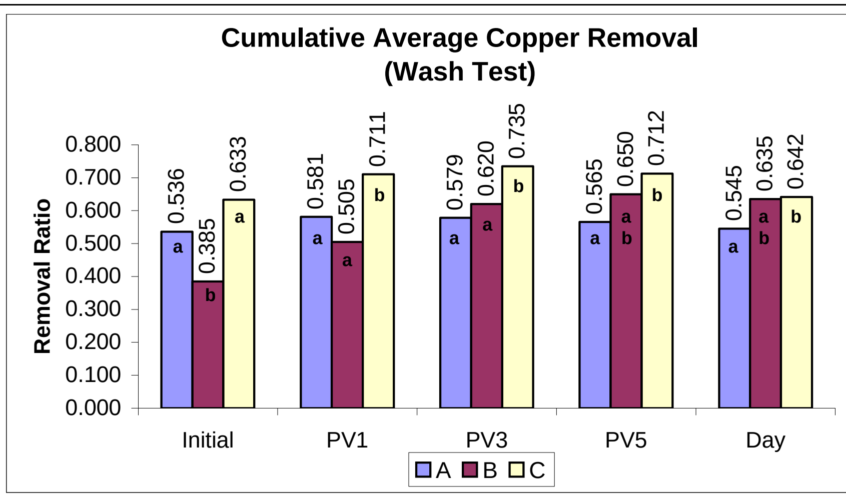


Figure 10. Cumulative average nitrate nitrogen leached from the three test mulches

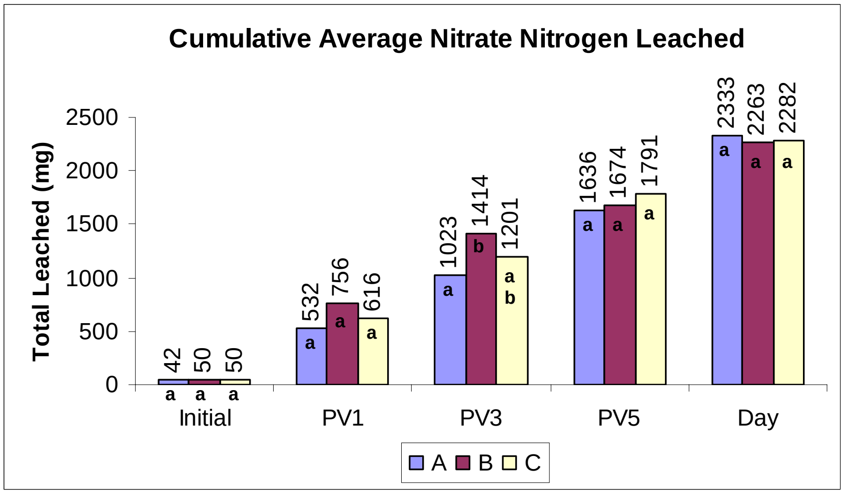


Figure 11. Cumulative average phosphorus leached from the three test mulches

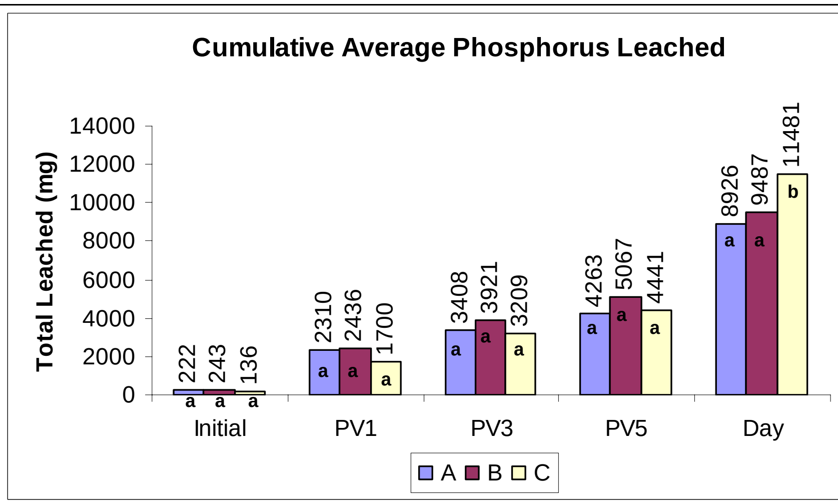


Figure 12. Cumulative average zinc leached from the three test mulches

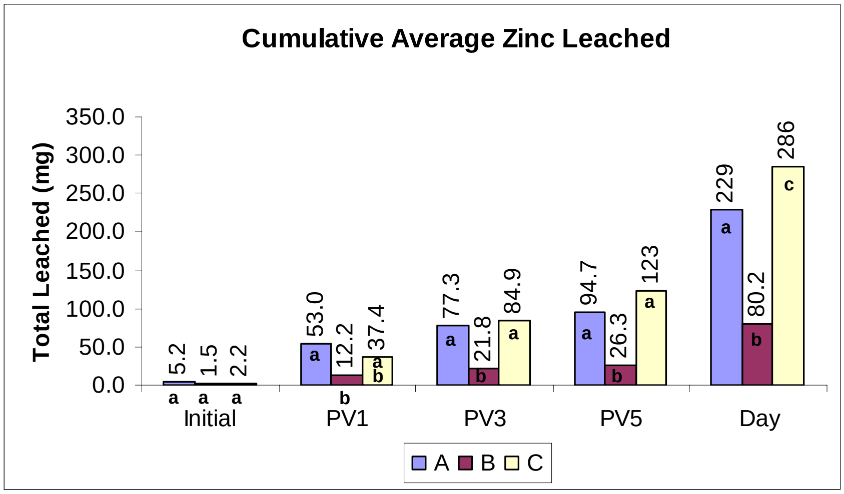
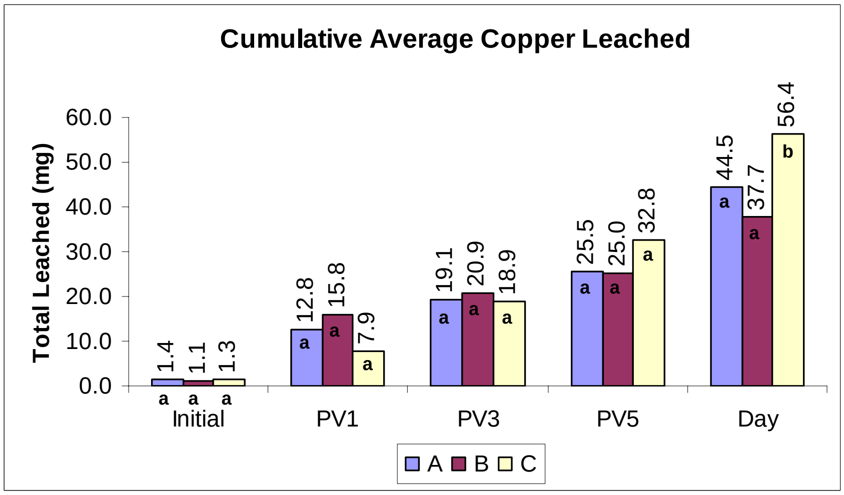


Figure 13. Cumulative average copper leached from the three test mulches



The amount of total organic carbon leached during the adsorption, washed, and leach tests was also measured. Table 3 gives a breakdown for the amount of total organic carbon leached for all three tests. The adsorption and leach results are similar in magnitude. These two tests originated with raw material that had not been tested. The washed test however does show slightly lower TOC values than its counterpart adsorption and leach test. The level of TOC does drop off slightly over time as the mulch is aged.

Table 3. Total organic carbon concentrations of mulch effluent.

	Total Organic Carbon (TOC) (mg/l)			
	Mulch	Adsorption Test	Washed Test	Leach Test
Continuous Flow	A	30-80	15-50	30-85
	B	20-100	10-75	40-95
	C	45-100	15-40	30-50
Stagnant (24 hours)	A	355-380	125-175	390-415
	B	280-435	55-75	190-260
	C	470-530	N/A	210*
*Only one data point recorded.				

Measurements were made for pH while samples were taken. Samples taken during the leach tests revealed an effluent pH reading of 5.5, 5, and 5 for mulches A, B, and C respectively. A pH reading of 5.5 was made for all three mulches during both the adsorption tests and washed tests. The original pH of the pollution solution was recoded as being 6.0 during these two tests. No noticeable increase or decrease in pH was observed during the column test.

DISCUSSION

Hsieh and Davis, 2002, found that mulch does not play an important role in total phosphorus removal. They did however find that mulch played a critical role in the removal of nitrate nitrogen. Findings from these tests correspond with the results that Hsieh and Davis found. The mulches actually added phosphorus to the system for both the washed and adsorption test. Nitrate nitrogen had removal ratios on the order of 0.46 to 0.80 for the two tests.

Unlike results found by Yu, 2001, in Table 4, results from these test showed removal ratios for copper to be in the range of 0.37 to 0.69 depending on the test and the mulch. Mixed results can be seen when comparing the removal ratios of mulch versus compost as seen in Table 5. The removals of nutrients are inversely proportional when comparing these two media. Mulch removal ratios were on the order of 0.46 to 0.80 for nitrates while compost showed negative removal ratios (-0.34). Mulch had ratios between -0.27 and -4.00 for phosphorus. Mulch removal ratios are equal or slightly lower than compost in respect to metal uptake. Zinc removal ratios for mulch were between 0.65 and 0.83 and copper ratios were 0.37 to 0.69, while compost showed 0.67 and 0.88 for copper and zinc respectively.

Table 4: Percent removal of Cu (II) using untreated sawdust[a] (Yu, 2001).

Initial Concentration (mg/l)	Cu (% Removal)
5	94.4
10	92.2
25	85.4
50	78.6

[a]Sawdust concentration equaled 20 g/l.

Table 5. Removal Efficiencies for compost filters (Stewart, 1992).

Pollutant	Removal Rate (%)
Nitrate	-34
Total Phosphorus	41
Copper	67
Zinc	88

The adsorption test and washed test showed that the nitrate nitrogen removal efficiencies differ across the individual mulches ($\alpha = 0.05$). No statistical difference exists between mulch A and C for the washed test. There is however a difference between mulches A or C and mulch B for the washed tests. Mulch B performed better in the removal of nitrates with a rate of 0.81 and 0.64 for both the adsorption and washed tests respectively.

The washed test showed that the individual mulches had differing effects while the adsorption test showed no difference in mulch type for phosphorus removal ratios at an alpha level of 0.05. Mulch A resulted in the best removal rate with a ratio of -2.88 even though there is not a statistical difference between mulches for the adsorption test. There is no statistical difference in phosphorus removal between mulch A and C for the washed test. There was however a difference between mulches A/C and mulch B. There were no statistical differences between mulch A and C in the removal of phosphorus for both test. Mulch A and C did perform better than mulch B.

The amount of phosphorus leached is critical in understanding why the phosphorus removal ratios were so low. Table 6 shows the approximate input concentration of phosphorus and the effluent concentration of phosphorus during the leach study. The amount of phosphorus leached is anywhere from a 1:1 to a 1:3 ratio of the tested concentration to leached concentration. The concentration of leachate dominated the removal process. The removal ratios for phosphorus were negative due to this difference.

Table 6: Concentration of element or compound in the pollution solution and the effluent of the leach test.

Element/Compound	**Concentration (mg/l)**	
	Pollution Solution	**Leach Test Effluent**
Nitrate Nitrogen	~ 2.0	0.2 – 0.4
Phosphorus	~ 0.6	0.5 – 2.0
Zinc	~ 0.2 – 0.4	0.01- 0.05
Copper	~ 0.01 – 0.05	0.005 – 0.02

It was determined that for both zinc and copper removal, the adsorption and washed tests showed that the individual mulches had differing results statistically. The washed test results showed that mulch A was different from B and C, which were not statistically different in the removal of zinc. There is no statistical difference between mulch A and C for the adsorption test on removal of zinc. There was however a difference between mulches A or C and mulch B. The washed test for copper showed that mulch A and B were not significantly different while mulch C was different. The adsorption test for copper showed that all three mulches were different. Mulch B had the highest removal ratio for both zinc and copper for the adsorption test with ratios of 0.83 and 0.69 respectively. Mulch C had the highest removal ratio for both zinc and copper for the washed test with ratios of 0.81 and 0.69 respectively. Mulch B also had a removal ratio of 0.81 for the washed zinc test.

The letters a, b, and c represent significantly different or similar results between the mulches for a given time period in Figures 1 through 12. For example, in the adsorption test for nitrate nitrogen, mulch A and mulch B results can not be defined as different based on an alpha of 0.05. Results are statistically different between mulch B and mulch C as well as between mulch A and mulch C at the 0.05 alpha level. Similar comparisons can be made between each mulch for each time period in a given test.

The individual mulches did not have differing effects statistically on what was leached except for zinc. Mulch B exhibited substantially less leachate of zinc than mulch A and C. Mulch A and mulch C were not significantly different with respect to zinc leachate.

Table 7 shows the overall removal ratios for each element/compound based on either the adsorption test or the washed test. There is a difference between the washed test and adsorption test based on an alpha level of 0.05. Nitrate nitrogen is the only category where the washed test resulted in a removal ratio that was less than its adsorption test counterpart. The washed test resulted in higher removal ratios for the other three elements.

Table 7: Removal ratios for both the adsorption and washed test on nitrate nitrogen, phosphorus, zinc, and copper.

Study	**Removal Ratios**			
	Nitrate Nitrogen	**Phosphorus**	**Zinc**	**Copper**
Adsorption	0.67	-3.36	0.72	0.52
Washed	0.53	-0.40	0.77	0.60

TOC concentrations on the range of 10 – 100 mg/l would be available for the denitrification process under continuous flow conditions. Stagnant conditions for a period of 24-hours resulted in a wide range of TOC values; 55 – 530 mg/l.

CONCLUSIONS

For nitrate nitrogen removal, the adsorption test and washed test showed that the individual mulches had differing results. The double ground hardwood (mulch B) performed better in the removal of nitrates with a rate of 0.81 and 0.64 for both the adsorption and washed tests respectively. There was no statistical difference between the raw forest biomass (mulch A) and the single ground hardwood (mulch C) for the washed test.

The washed test showed that the individual mulches had differing effects while the adsorption test showed no difference in mulch type for phosphorus removal. The raw forest biomass (mulch A) resulted in the best removal rate with a ratio of -2.88 even though there was not a statistical difference between mulches for the adsorption test. There also was no difference in phosphorus removal between the raw forest biomass (mulch A) and the single ground hardwood (mulch C) for the washed test. There was however a difference between these two mulches and the double ground mulch. The raw forest biomass (mulch A) and the single ground hardwood (mulch C) did perform better than the double ground (mulch B). The amount of phosphorus leached dominated the removal process. The removal ratios for phosphorus were negative due to this difference.

It was determined that for both zinc and copper removal, the adsorption and washed tests showed that the individual mulches differed. The washed test results showed that raw forest biomass (mulch A) was different the other two, which were not statistically different in the removal of zinc. There was no difference between the raw forest biomass (mulch A) and the single ground hardwood (mulch C) for the adsorption test on removal of zinc. There was however a difference between these two and the double ground mulch. The washed test for copper showed that the raw forest biomass and the double ground mulch were not different while the single ground mulch was different. The adsorption test for copper showed that all three mulches were different. The double ground mulch had the highest removal ratio for both zinc and copper for the adsorption test with ratios of 0.83 and 0.69 respectively. The single ground mulch had the highest removal ratio for both zinc and copper for the washed test with ratios of 0.81 and 0.69 respectively.

The level of total organic carbon decreased slightly over time as the mulch aged. However, any of the three mulches could serve as a carbon source for the designed denitrification process within the bottom chamber of a bioretention cell. There also was a difference between the washed test and adsorption test on removal efficiencies. Nitrate nitrogen was the only category where the washed test (aging process) resulted in a removal ratio that was less than its adsorption test counterpart. The washed test (aging) resulted in higher removal ratios for the other three elements. No noticeable increase or decrease in pH was observed during these tests.

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APPENDIX E:

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

by Charles V. Privette, III

(This paper is a draft of a chapter in Charles Privette's dissertation for his Ph.D.)

Water resources protection at the local level is becoming more complicated, largely due to non-point source pollution, or polluted runoff. Land use changes have led to increases in stormwater runoff that once infiltrated into the soil but now flows over mostly impervious surfaces into nearby streams and lakes. While flowing from the source areas to the receiving water bodies, the runoff washes pollutants from the land surface, thereby becoming polluted and requiring treatment. This diffuse form of pollution is now the nations leading threat to water quality. Urban runoff also ranks as the 2nd most common source of water pollution for lakes and estuaries and 3rd most common source of pollution for rivers (EPA, 1994).

The bioretention cell (BRC) offers a great means for reducing this pollution load by treating stormwater runoff before it reaches streams and lakes. BRCs capture runoff as sheet flow and direct it to prepared beds and ponding areas for infiltration and evaporation. The BRC treats runoff through nutrient uptake by surface vegetation and absorption of pollutants in an organic material layer. The system enables reactions in which other pollutants attach to chemically and biologically active organic matter.

Bioretention cells have been in use now for over ten years. They have been used extensively in Prince George's County, Maryland. Bioretention cells have been primarily constructed into urban landscapes of turf and trees. These cells are a relatively new, but promising method of treating stormwater runoff. Bioretention cells are built into landscapes that serve other economic uses, rather than taking up land area that precludes those uses, as detention ponds. Real-estate developers and public works officials have begun to use these cells in the mid-Atlantic region but not yet in other parts of the country (Schueler 2000). Important questions about environmental performance remain to be answered. In this study testing will be performed to evaluate bioretention cells and the use of processed forest biomass as the source of organic material for their use in South Carolina as a means of treating stormwater runoff. One of the underlying reasons for this study was to determine whether a more effective method could be developed for the removal of nitrates from bioretention cells. Traditionally, bioretention cells have contributed nitrates to the system. Another reason for this study was to determine whether a bioretention cell could be designed to reduce the quantity of stormwater discharge.

A field scale bioretention cell was constructed at the DANA Corporation in Orangeburg, South Carolina. The bioretention cell was located beside a shipping/receiving lot of the DANA Corporation. The stormwater runoff from both the parking/shipping/receiving lot and the roof top of the DANA facility was diverted directly to the bioretention cell. This cell monitoring was designed to demonstrate and evaluate effective environmental performance of the bioretention cell using processed forest biomass as an underlying mulch layer. Data from this monitoring project were used to calculate reduction rates for stormwater quantity control and identified pollutants in the stormwater runoff.

Bioretention cell design dimensions for this study were 75’ x 25’ x 4’ with a 9-inch ponding depth and 3–inch freeboard. The cell was comprised of four layers, with the top layer being centipede sod. Centipede grass is typical for this Orangeburg area. The second layer was a one-foot thick layer of native Goldsboro top soil that had been stockpiled during excavation of the bioretention cell. This soil contained 83% sand, 8.5% silt, and 8.5% clay and was classified as a loamy sand. Below this second layer was an organic layer, one-foot thick, comprised of processed forest biomass. This material was readily available chipped pine residue from a wood chipper, with the average size chip approximately 1-inch. This third layer contained the modification made to the usual bioretention cell. The third layer was separated from the bottom gravel layer by a synthetic geotextile membrane. The bottom layer was comprised of ¾ inch washed gravel (granite) and two-feet in depth.

For the bioretention cell in this study, flow measurements were obtained at the locations of the curb cut where the runoff exited the shipping/receiving lot, where the flow entered the overflow channel, and within the 8-inch drain line that connected the internal 4 inch drains. Flow measurements were obtained utilizing a constructed, compound, rectangular shape, sharp-crested weir and an American Sigma 75 kHz ultrasonic sensor connected to a flow meter on both the entrance to the bioretention cell and the overflow channel. The depth of flow was recorded using the ultrasonic sensor and then converted to a flow rate.

Flow measurements were also taken from within the 8-inch drain line. Since flow was confined to a pipe, an area velocity sensor was selected as the means of determining discharge flow rates. This sensor was also connected to the flow meter. The flow meter was calibrated for an 8-inch pipe so that the meter would calculate flow rate based on both mean velocity and depth of flow.

Separate water samplers were located at the inflow and the outflow weirs to record quality of surface flow that entered the bioretention cell and excess water that overflowed from the bioretention cell. Another sampler was located to retrieve samples on the under drain system. The forth sampler was located to record values within the bottom of the bioretention cell. (During construction of the bioretention cell, test wells were installed so that samples could be obtained from this anaerobic zone of the cell.)

Water samples from all samplers were collected either the day of a storm event or the next day. Bottles containing collected water samples were packed in a cooler and immediately shipped to the Clemson University Extension Service Agricultural Service Laboratory for analysis. Laboratory analyses were performed on these samples for suspended solids, nutrients, metals and other common pollutants. Pollutants predominately investigated were nitrate nitrogen, phosphorus, zinc, and copper. Results of these analyses then determined pollutant removal efficiencies of the bioretention cell. Data was thus analyzed to determine effectiveness of the bioretention cell for a given storm size.

For each pollutant, total mass for each storm event was calculated using:

$$M = \int_0^T QCdt \qquad \text{EQ Pollutant Load (B-4)}$$

where M is mass of pollutant, Q is measured stormwater flow rate, C is pollutant concentration, and t is event duration. This method was used by Weinstein et al (2001) to monitor bioretention systems in Maryland.

FLOW DATA ANALYSIS

Flow data from the flow meter was obtained periodically over the course of the experiment. This periodic data was compiled into one spreadsheet that was divided into the following categories: date, time, rain amount (in), water level in the overflow weir (in), water level in the inflow weir (in), and drain pipe flow (cfs). After the flow database was developed from January 20, 2004 to August 4, 2004, analysis was required to determine flow characteristics of the bioretention cell.

This database also included the number of days between events. Weather data for the area was also obtained to provide evaporation rates (see Appendix Weather Data). Since local data for evaporation rates was not available from the Orangeburg Airport weather data, the next closest location containing solar radiation data was used. This solar radiation data came from Blackville, SC, located approximately 30 miles from Orangeburg. Using solar radiation data from Blackville and mean temperature data from Orangeburg, evaporation rates were calculated based on the Jensen-Haise (Pair etal, 1969, p 106) formula:

$$ER = (0.014T_{AV} - 0.37)\frac{R}{1485.9} * 23.889 \quad \text{(B-12)}$$

where ER is evaporation rate in inches, T_{AV} is mean daily temperature in Fahrenheit, and R is total solar radiation in $MJ/m^2/day$.

Once this data was added to the flow database, the statistical program SAS (Statistical Analysis Software) was employed to evaluate the data. The first step in data analysis consisted of standardizing the data by using the equation:

$$X = \frac{X_i - \overline{X}}{STD_X} \quad \text{(B-13)}$$

where X_i is the original data value, $\overline{X}$ is the mean for the X data, and STD_x is the standard deviation of the data.

By standardizing collected data, the new data set has a mean of zero and a standard deviation of one. Dependent variables were defined to be runoff, drain flow, overflow, and total flow. Independent variables were identified as rainfall amount, rainfall intensity, days between rain, and evaporation. Based on the dependent variable, the significant independent variables were identified using the Stepwise procedure in SAS. This analysis was based on an 85% confidence measure. Variables that were identified as having a large F-value and a probability of exceeding this F-value of less than 0.15 were kept.

Stepwise analysis on the dependent variables runoff, drain flow, and total flow determined that the only significant independent variable was rainfall. Overflow determined rainfall as the most significant variable but indicated that evaporation and days between rains possibly had some effect. This analysis can be found in Appendix DATA ANALYSIS.

The next step in data analysis was to look at possible interactions or roots of variables and their interactions. This analysis was achieved by using the GLM procedure in SAS. Based on the stepwise results, various combinations of the significant variables were investigated as to their effect on the dependent variable in achieving a best fit representation of the data. The best fit results for this analysis can be found in Table DATA ANALYSIS below.

Table DATA ANALYSIS.

Dependent	R-Square	Source	Parameter	Type I		Type II		Estimate	t-value	Pr > | t |
				F-value	Pr > F	F-value	Pr > F			
Runoff	0.8906	R		395.09	<.0001	3.92	.0534			
		R^2		3.92	.0534	20.57	<.0001			
			Intercept					94.652	1.35	.1828
			R					524.762	1.98	.0534
			R^2					676.248	4.54	<.0001
OverFlow	0.9572	R		359.48	<.0001	74.66	<.0001			
		R^4		737.39	<.0001	737.39	<.0001			
			Intercept					23.340	4.06	.0002
			R					-113.345	-8.64	<.0001
			R^4					53.507	27.16	<.0001
DrainFlow	0.6953	R		104.83	<.0001	13.72	.0006			
		R^4		2.43	.1258	2.43	.1258			
			Intercept					-92.101	-1.52	.1353
			R					683.756	3.70	.0006
			R^4					98.491	1.56	.1258
TotalFlow	0.7107	R		112.49	<.0001	13.95	.0005			
		R^4		3.00	.0900	3.00	.0900			
			Intercept					-90.336	-1.52	.1342
			R					674.439	3.74	.0005
			R^4					106.992	1.73	.0900

From these results, the following models were determined for each dependent variable:

$$Runoff = 94.6518191 + 524.7615287R + 676.2482016R^2 \qquad \text{EQUATION RUNOFF (B-14)}$$

The stepwise procedure determined that rainfall amount was the only significant variable at the

0.15 level. From this analysis, the best fit model for runoff as a function of rainfall amount was equation RUNOFF (B-14). The variable rainfall amount had an F-Value of 3.92 with a greater than 86% confidence level. The variable rainfall amount^2 had an F-Value of 20.57 with a greater than 99% confidence level. The traditional equation for calculating runoff is based on a numerator that is a function of rainfall amount squared and a numerator of rainfall amount, thus a model equation that contains a rainfall amount and rainfall amount squared term seems reasonable.

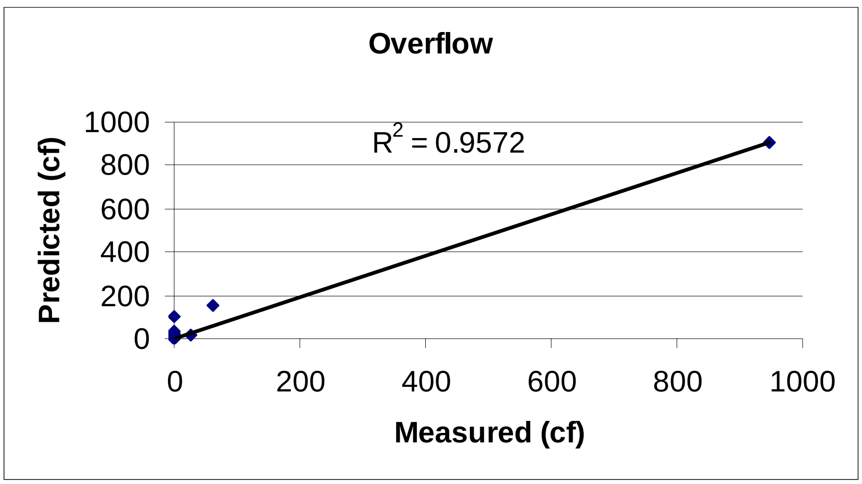


Figure Runoff.

$$Overflow = 23.3400152 - 113.3447819R + 53.5073516R^4 \quad \text{EQUATION OVERFLOW (B-15)}$$

The stepwise procedure determined that rainfall amount, evaporation, and days between were all significant variables at the 0.15 level. From this analysis, the best fit model for runoff as a function of rainfall amount was equation OVERFLOW (B-15). From the analysis of variables and their interactions, rainfall amount was the only highly significant variable. The variable rainfall amount had an F-Value of 74.66 with a greater than 99% confidence level. The variable rainfall amount^4 had an F-Value of 737.39 with a greater than 99% confidence level. The stepwise analysis revealed that runoff squared had a strong significance in predicting overflow.

Since runoff is a function of rainfall amount squared, rainfall amount quadrupled fits the model.

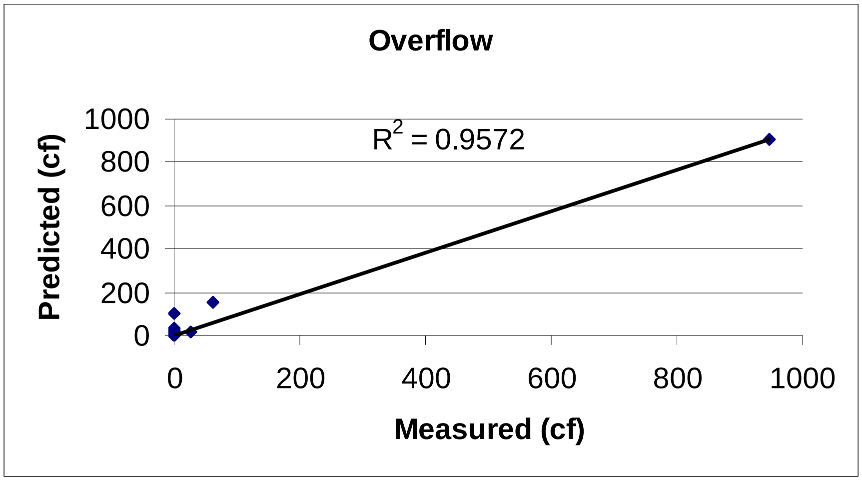


Figure Overflow

$$DrainFlow = -92.1016558+638.7564042R + 98.4912948R^4 \qquad \text{Equation DRAIN (B-16)}$$

The stepwise procedure determined that rainfall amount was the only significant variable at the 0.15 level. From this analysis, the best fit model for runoff as a function of rainfall amount was equation Drain (B-16). The variable rainfall amount had an F-Value of 13.72 with a greater than 99% confidence level. The variable rainfall amount^4 had an F-Value of 2.43 with a greater than 87% confidence level.

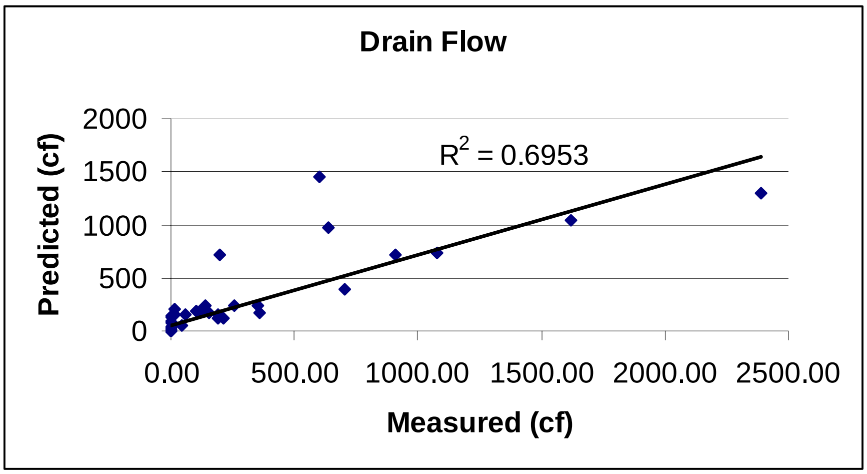


Figure DRAIN

$$TotalFlow = -90.3355078 + 674.4393996R + 106.9917035R^4$$ Equation TOTAL (B-17)

The stepwise procedure determined that rainfall amount was the only significant variable at the 0.15 level. From this analysis, the best fit model for runoff as a function of rainfall amount was equation TOTAL (B-17). The variable rainfall amount had an F-Value of 13.95 with a greater than 99% confidence level. The variable rainfall amount^4 had an F-Value of 3.00 with a greater than 91% confidence level.

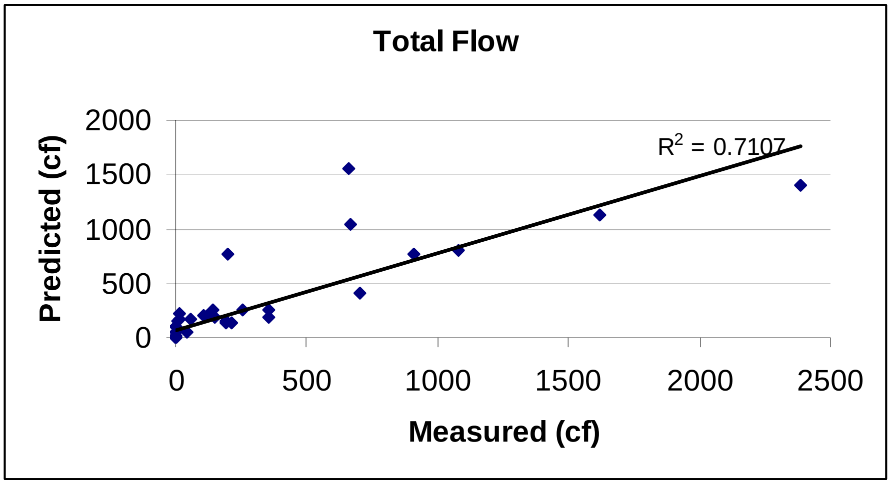


Figure TOTAL

These equations are valid up to a rainfall amount of 2.14 inches. From analysis of predicted results above this point, Equation OverFlow, DrainFlow, and TotalFlow over predict the flow amounts. In comparing Equation Runoff to the NRCS Curve Number Method, the equation typically under predicted the runoff amount for smaller rainfall events.

SAMPLE DATA ANALYSIS

Following analysis of water samples by the lab, results were compiled into a dataset based on time of sample event. Then the corresponding flow data on which the sample event occurred was added to the data set. Each sample event and its corresponding rainfall/runoff data was developed as a separate data entry. Equation Pollutant Load (B-4) was employed to determine total mass of sampled "pollutant" that entered the bioretention cell from runoff. Once the total mass of sampled "pollutant" that entered was computed, the average inflow concentration could be determined. Table INFLOW OUTFLOW CONC shows these values.

For those days when pipe flow samples were obtained, average outflow concentration was determined. This determination was performed due to situations in which the drain pipe sample scheme ended before all pipe flow ceased. Average outflow concentration was computed based on concentrations of the 24 samples that were taken either at 15-gallon or 30-gallon intervals. Average outflow concentration was then used to compute total mass of "pollutant" leaving by multiplying average outflow concentration by total outflow volume. Table INFLOW OUTFLOW CONC shows these values.

Table INFLOW OUTFLOW CONC.

	PO4-P	Zn	Cu	NO3-N	PO4-P	Zn	Cu	NO3-N
	Average Concentration IN (mg/l)				Average Concentration OUT (mg/l)			
2-Jun	0.072	0.313	0.023	1.338				
9-Jun	0.025	0.018	0.003	1.000				
20-Jun	0.000	0.017	0.000	0.075	0.035	0.019	0.004	0.826
28-Jul	0.163	0.027	0.001	0.029				
2-Aug	0.204	0.001	0.001	1.000	0.113	0.001	0.001	1.000
Average	0.093	0.075	0.006	0.688	0.074	0.010	0.002	0.913

Analysis of this data revealed the presence of only two events in which inflow sample data and outflow sample data occurred. These results may be due to rain events (lack of overflow), sampling errors, shortened sampling time frame, and budget constraints. Four of the five events had corresponding well data recorded. Assumptions were made that concentrations in bottom of the cell (well) were equal to concentrations leached through upper layers. Based on this assumption, reduction rates were computed based on inflow concentration versus well concentration. These results can be seen in Table Removal Rates Below.

Table Removal Rates

	PO4-P	Zn	Cu	NO3-N	PO4-P	Zn	Cu	NO3-N
	Removal Efficiency (%) IN vs OUT				Removal Efficiency (%) IN vs WELL			
2-Jun					(175.94)	100.00	100.00	(124.22)
9-Jun					(13100)	(2338)	100.00	(600.00)
10-Jun					(300.00)	(170.991)	100.00	(900.00)
20-Jun	(15363)	42.25	(4761)	(467.45)				
28-Jul					38.77	100.00	100.00	100.00
2-Aug	82.45	69.59	69.59	68.16	51.00	100.00	100.00	0.00

As seen from Table Removal Rates, results of the two inflow-outflow events are inconclusive. Data for August 2, 2004 demonstrate favorable gains that may be due to the percentage of runoff that never leaves the cell. Data from June 20, 2004 demonstrate very poor performance of the bioretention cell that may be due to a higher outflow percentage as well as a very low inflow mass amount. Virtually no phosphate or copper entered the cell from the runoff, resulting in a negative removal rate and very low outflow concentrations.

Another difference between these dates was the sampling scheme. On June 20th, the sampler was configured to sample every 15 gallons and only sampled for the first 6.6 percent of the drain event. During August 2nd, the sampler was configured to sample every 30 gallons which represented 49.8 percent of this drain event. If a first flush theory holds true for a bioretention system, the June 20th drain results would represent this phenomena and greatly reduce the removal efficiency of the cell if this concentration was used to determine the total mass that left the system. Even with poor removal rates for the June 20th date, outflow concentrations as seen in Table INFLOW OUTFLOW CONC are still low.

Results of the inflow/well concentrations are also inconclusive except for the removal of copper. In all tests, copper was eliminated. One note of interest with this data was the effects of the underlying gravel layer. Between June 9th and 10th, the overall removal efficiencies for the bioretention cell went up dramatically in terms of phosphate and zinc. Nitrate, however, decreased by 50 percent.

One of the underlying reasons for this study was to determine whether a more effective method could be developed for the removal of nitrates from bioretention cells. Traditionally, bioretention cells have contributed nitrates to the system as demonstrated on June 2nd, June 9th, and June 20th. The well samples that were taken were used to determine what was occurring in the bottom of the cell in the designed anaerobic gravel layer. The results of the well sample data can be seen in Figures Well DATA Labeled Nitrate, Phosphate, Zinc, and Copper. Also included within this data are the rain events that occurred including the rain amounts.

Figure Well DATA Nitrate.

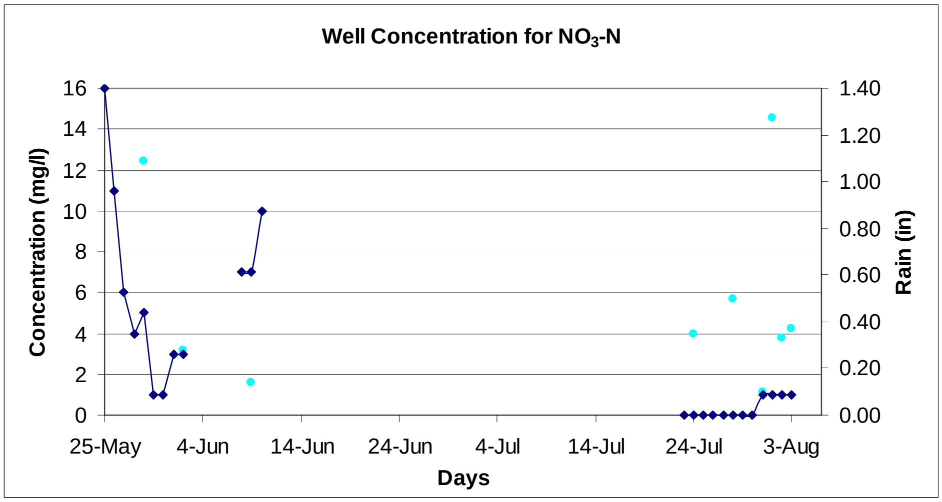


Figure WELL DATA Phosphate

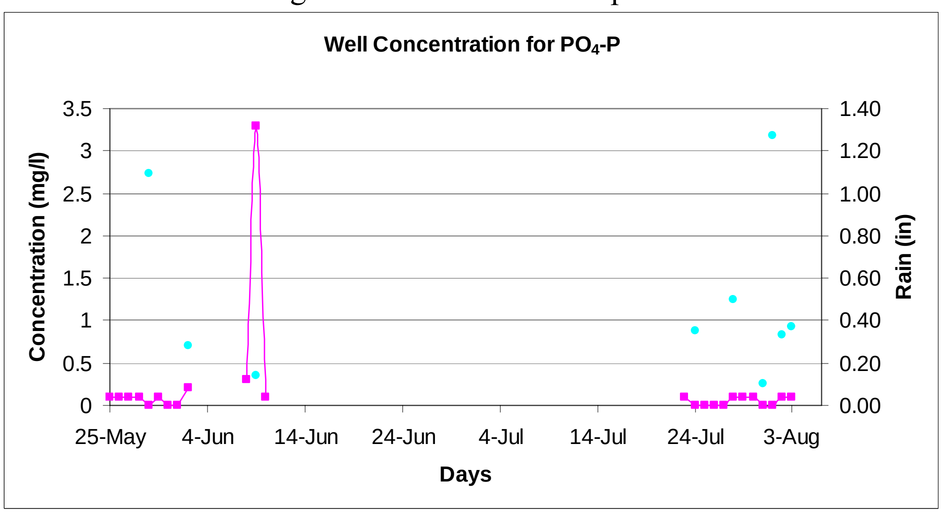


Figure WELL DATA Zinc.

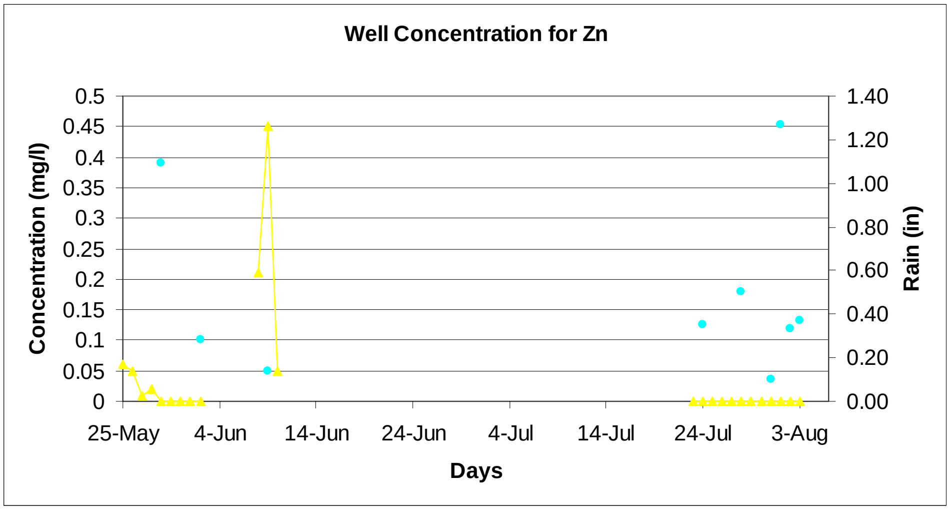
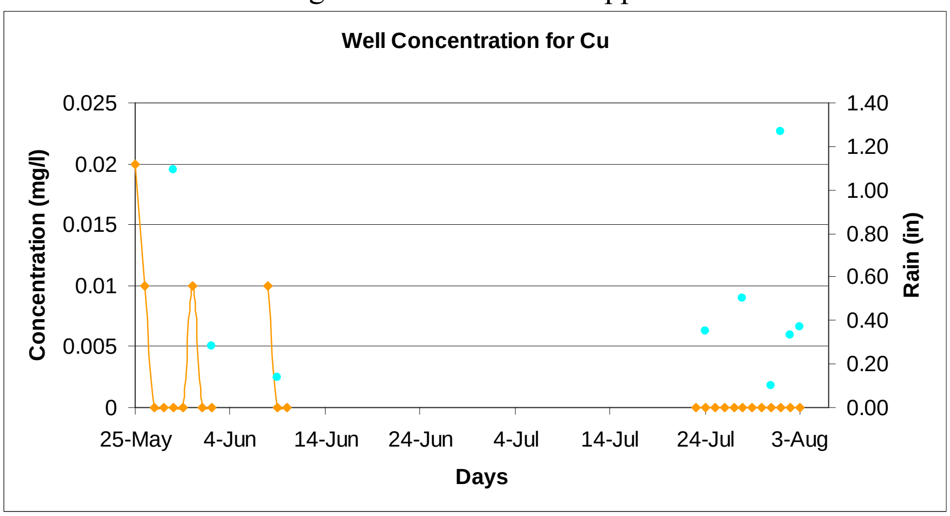


Figure WELL DATA Copper.



The primary reason for the lower chamber within the bioretention cell was for the removal of nitrates. The figure WELL DATA Nitrate demonstrated that following a rain event, nitrate levels increased in the lower region of the bioretention cell. As time increases after such rain events, a decrease in nitrates was observed except for June 9th to 10th. This finding is consistent with the trend found in the laboratory analysis of nitrate removal, but not at the rate at which the removal process occurred. Similar results can be seen in Figures WELL DATA phosphate and zinc. During rain events, an increase in concentration was observed in the well followed by a decrease over time. Very low copper concentrations are observed within this lower region. This finding is consistent with the observation that very little copper entered the bioretention cell from the runoff.

As a note, the outflow concentrations of the August 2, 2004 data are very similar to the well concentrations on that day. The outflow concentrations for nitrate, phosphate, zinc, and copper were 1.0, 0.113, 0.001, and 0.001 respectively while the well concentrations were 1.0, 0.1, 0, and 0 respectively.

DISCUSSION

Based on data collected on the bioretention cell, all runoff as the result of 0.20 inches of rain or less went to infiltration. The prediction equations that were developed show that for a 1-inch rain 50 percent of the runoff will go to infiltration and will not be discharged downstream. It will take a 1.2-inch rainfall amount to have overflow occur from the cell. A 1-inch of runoff from the shipping/receiving lot, the bioretention cell will infiltrate between 36-38% of the runoff. Only six percent of the runoff will be discharge by means of overflow downstream, thus the remaining 56-58% will filter through the layers in the cell and be discharges as drain flow. Twenty-three percent of the runoff from a 2-inch rain will be infiltrated and not discharged.

Table RUNOFF shows a comparison between common concentrations of pollutants found in urban runoff (Davis, 2001a) as compared to runoff from the DANA Corp. shipping/receiving lot. The Orangeburg runoff contains significantly lower concentrations than that of typical runoff concentrations. A possible explanation for this finding may be due to the decreased amount of traffic around the DANA facility. From casual observations of the shipping/receiving lot, few trucks enter and leave on a daily basis. Only a few workers park in this back lot. A limited amount of green space drains directly onto the parking lot. This area is sparse in grass cover and does not appear to be fertilized on a regular basis, if at all.

Table RUNOFF. Pollutant concentrations in typical and Orangeburg runoff

Pollutant	Pollutant Concentrations in Typical Runoff (Davis et al, 2001a)	Pollutant Concentrations in Orangeburg Runoff
Nitrate (mg/l)	2	0.688
Phosphorus (mg/l)	0.6	0.093
Copper (mg/l)	0.08	0.006
Zinc (mg/l)	0.6	0.075

Table Studies of Removal of Pollutants by Bioretention Cells shows various removal rate studies conducted on bioretention areas across the country, with results for selected pollutants. In comparing the August 2nd data with that of these studies, results are inconclusive. The Orangeburg study does appear to outperform the other studies when looking at nitrate alone. Phosphorus removal seems to be in line with these studies. Zinc and copper are significantly lower with the Orangeburg study than those in Table Bioretention Removal Studies except for that of the Landover Study. The original goal of this study was to determine whether the level of nitrates could be reduced using a bioretention cell with this underlying layer.

Table Studies of Removal of Pollutants by Bioretention Cells

	Davis, 1998		Davis, 2001	
	Lab Test	Field Test	Greenbelt Study	Landover Study
Pollutant	Removal Rate (%)	Removal Rate (%)	Removal Rate (%)	Removal Rate (%)
Total Phosphorus	81	65	65+/-8	87+/-2
Nitrate Nitrogen	23	16	15+/-12	16+/-6
Copper	93	97	97+/-2	43+/-11
Zinc	96	<95	>95	64+/-42

Based on the August 2nd data for nitrate removal, the bioretention cell appears to outperform sand filters as shown in Tables TEXAS and SAND TEST, and compost filters as shown in Table COMPOST. More data on these type bioretention cells are needed for conclusive results as to whether they actually perform better in the removal of nitrates. The removal of phosphorus and copper both appear to be inline with if not better than the practices of sand and compost filters. Zinc had mixed results when comparing to these other two types of filters.

Table TEXAS. Removal Efficiencies for sand filters (City of Austin Texas, 1990).

Pollutant	Removal Rate (%)
Nitrate	-79 to 23
Total Phosphorus	19 to 80
Copper	33 to 87
Zinc	49 to 81

Table SAND TEST. Analysis of the removal rates of common pollutants with two sand filters

	Virginia Study[c] (Bell et al, 1995)	Washington Study[d] (Horner and Horner, 1995)
	Removal (%)	Removal (%)
Total Phosphorus	63[a]	20 to 41[b]
Nitrate Nitrogen	-53[a]	Not measured
Zinc	91[a]	33 to 69[b]
Copper	25[b]	22 to 31[b]

[a]Percentage of mass removed from system.
[b]Mean removal percentage from system.
[c]The Virginia study was a sand filter constructed near a new parking lot whereby the inflow and outflow pollution levels were monitored.
[d]The Washington study consisted of two sand filters located by a new loading facility.

Table COMPOST. Removal Efficiencies for compost filters (Stewart, 1992).

Pollutant	Removal Rate (%)
Nitrate	-34
Total Phosphorus	41
Copper	67
Zinc	88

CONCLUSIONS

In general, the bioretention cell was advantageous at reducing runoff discharge. For all rain events 0.20 inches or less, all runoff went to infiltration while for an 1-inch rain 50 percent of the runoff went to infiltration and for storms with rainfall totals less than 1.2 inches, all runoff was filtered through the cell with no direct discharge downstream. The bioretention cell enables infiltration of 36-38% of the runoff from the 'first flush'. Only six percent of the runoff will be discharged without treatment downstream. Thus, the remaining 56-58% will filter through the layers in the cell and be discharges as drain flow.

The bioretention cell performed adequately in the removal of zinc and copper, based on limited observations. In terms of the removal of phosphorus and nitrates, the results were mixed for both nutrients, based on limited observations. However, the concentrations of all potential pollutants in the discharge were well below the thresholds for water quality.

Based on these research findings, several recommendations are offered to improve future research with bioretention cells. In obtaining water samples, the rate at which the drain pipe is sampled should be lengthened to capture more of the runoff event. This increase will provide for obtaining the end of the infiltrate rather than just the first flush through the system. This data may provide for lesser outflow concentrations and thus result in greater removal efficiencies. Another suggestion is made to disregard samples in which there is no outflow. This modification will reduce sample costs and allow for more accurate comparison.

Using a weir that is not submerged may also produce more accurate analysis and results. However, if elevation constraints mandate that the weir be submerged, the weir should be calibrated at the beginning of the study and periodically throughout data collection. Flow data for this study was obtained on a ten minute interval and then averaged between readings. A more accurate measure might be obtained with a lower sample rate of 5-minutes. This change could help minimize the chances of missing the peak flow event as well as make data averaging more accurate. During construction of the bioretention cell, a six to eight inch monitoring well should be installed in addition to the sample well. Such a change would allow water depth in the bottom of the cell to be monitored.

Due to the limits of the prediction equations that were developed for the Orangeburg bioretention cell, a new infiltration/runoff model should be developed based on the data from this study as a means of validating the model. The model should be based on continuity of mass and take into consideration a range of rainfall amounts. A proper model would allow for more accurate bioretention cells to be designed as a means of handling excess flow created due to development.

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Appendix F:

An Economic Analysis of Costs of Bioretention Cells and Stormwater Ponds

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(This paper is a preliminary version of a part of Ms. Sharma's doctoral dissertation. Hence, results are preliminary. A version of this paper will be presented by Mr. Sharma at the 85th Annual Meeting of the Southwestern Economics Association in New Orleans LA on March 23-26, 2005.

An Economic Analysis of Costs of Bioretention Cells and Stormwater Ponds

Introduction

Urban stormwater is one of the leading contributors to the water quality damage in estuaries, lakes, rivers, and bays. Urban runoff and storm sewers pollute 13% of the impaired rivers and stream miles and about 18% of the impaired lake acres (EPA, 2002). The most common pollutant found in stormwater discharges includes heavy metals, such as copper, zinc, and lead. These have been shown to cause health and reproductive problems in pregnant women and children. Other pollutants like phosphorus, nitrogen, and bacteria, can choke the life out of aquatic life in streams, rivers, ponds, and lakes (NRDC).

In December 1999 EPA promulgated regulations for Phase II of the National Pollutant Discharge Elimination System (NPDES) Stormwater Program. One of the purposes of this rule is to reduce pollutants in post-construction runoff (EPA, 2003). It requires an operator of a regulated small municipal separate storm sewer system, MS4, to enforce a program for reducing the pollutants in the post construction runoff from new development and redevelopment projects that result in the land disturbance of greater than 1 acre (EPA, 2000b). The MS4 operator is supposed to reduce the discharge of pollutants to the maximum extent possible in order to protect the water quality and satisfy the appropriate requirements of the Clean Water Act (WSDE). The federal government has given state the responsibility to administer NPDES permit applications and certain federal water quality programs (EPA, 1999a).

Apart from these federal rules and regulations, the state of South Carolina (SC) has its own set of regulations governing stormwater runoff. The Department of Health and Environmental Control (DHEC) is the state agency responsible for environmental matters. The SC Pollution Control Act requires that a permit be issued by DHEC before any waste is discharged to the environment (SCDHEC, 2003a). The stormwater management program of DHEC specifies the "pre- and post-development velocities, peak rates of discharge, and inflow and outflow hydrographs of stormwater runoff at all existing and proposed points of discharge from the site" (SCDHEC, 2003b). The Stormwater Management and Sediment Reduction Act of 1991 aims to reduce the adverse effects of stormwater runoff in the state by requiring the post-development peak discharge rates to be less than the pre-developed ones for the 2- and 10-year frequency 24-hour-duration storm event (SCDHEC, 2003b). Any individual violating any provision of this law would be required to pay a penalty of $1000 daily for each day of violation (SCLO). 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 (EPA, 2000b). Structural BMPs are designed facilities or modified natural environments which help clean the stormwater quality. These include bioretention cells, grass strips, sand and organic filters, wetlands, dry extended detention ponds, and wet ponds. (See SMRC for detailed description of the various BMPs). In this paper we focus on two structural BMPs: bioretention cells and stormwater ponds.

Bioretention cells are most commonly found in parking lots or residential streets in cities or towns (SMRC). Cells are usually built into landscapes that serve other economic uses, rather than take up land area that preclude those uses, as ponds do. Stormwater ponds, on the other hand, are designed to detain the stormwater runoff for some minimum duration and allow sediments and associated particles to settle out. Unlike bioretention cells, ponds require surface area. In addition to saving space, widespread use of bioretention cells might reduce the wildfire hazards because processed forest biomass could be the source of organic material for the cells.

To decide which BMP is most suitable in a given area, one must carefully 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 pollutants and the associated cost. They analyzed construction and annual maintenance costs of various BMPs.

The contributions of this paper to the literature on BMPs for stormwater management are three-fold. First, in this paper costs of bioretention cells and stormwater ponds 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 all previous studies, water-quantity or water-quality volume was the only determinant of construction costs of BMPs. Third, comparisons of the costs of the two BMPs are made. In particular, water-quality volumes over which a bioretention cell is cheaper than a stormwater pond to remove pollutants are estimated.

Data Description

The dataset includes data that were used for two previous studies: 1) Brown and Schueler at the Center for Watershed Protection (CWP) and 2) Wossink and Hunt at 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 department (Brown and

Schueler). In the report by Wossink and Hunt, the cost information about different BMPs was collected through phone surveys and site contacts with designers and property owners in 1999-2001. The data collected were either the bid price or the known amount spent by the granting agencies (Wossink and Hunt).

Construction, engineering and landscape wages were collected from the Bureau of Labor Statistics. The construction wage (CONWAGE) corresponds to the hourly earnings of those who work in construction industries that belong to Standard Industrial Code (SIC) 162. SIC includes heavy construction, construction of water and sewer mains, pipelines, power lines and construction of heavy projects which were not specified elsewhere. The engineering wages (ENGWAGE) reflected data from SIC 8711, 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. Landscape wage (LANDWAGE) data, got from the SIC code 078, which covers landscape counseling and planning, lawn and garden services, and ornamental shrub and tree services. These three wages were adjusted to correspond to Baltimore Maryland in 2003.

Data on the value of the land (LANDVAL) was collected from the Tax Assessors Database (Pulawski). This database contains links to county assessors' databases for each state. The use of the land on which a stormwater pond was located was classified as residential or commercial. Ten random real-estate values for each use of land were collected for the particular county in which the stormwater pond was located. The average of these values was adjusted to correspond to Baltimore Maryland in 2003 with historical cost indices (Murphy). The land cost constituted, on average, 49 percent of the total adjusted cost of a stormwater pond.

The water-quantity volume (QUANVOL) for the stormwater ponds of the CWP data is the volume of the runoff from the drainage area for a ten year storm event. The water-quality volume (QUALVOL) is the responses given in the survey. In the data from Wossink and Hunt, QUANVOL is 0.5 inch times and QUALVOL is 0.24 inch times the drainage area of the ponds. QUALVOL is 0.5 inch times the drainage area of the bioretention cell.

The data points were also classified into major land resource areas according to there 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.

The estimated total cost (ESTTOTCST) consisted of design and engineering and construction cost. Construction costs consisted of excavation and grading cost, cost of materials, cost of the control structures, e.g. risers, barrels etc., cost of the sediment controls put in place during construction of the practice, landscaping cost including labor directly related to BMP, and the appurtenance cost which covers expenses of 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 were 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 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 were collected from the National Best Management Practice Database (EPA, 1999a). For bioretention cells, these data were collected from a study done at Monticello High School (Yu et al.) in VA, the Inglewood Demonstration Project (EPA, 2000a), the Greenbelt and Landover field study in Maryland (Davis), and results stated in Table 14 of the Report No. 344 (Wossink and Hunt).

Methodology

The majority of the research work presented in the literature investigates the relationship between the cost of a BMP and its storage volume. In addition to the emphasis on the cost-volume relationship, this paper establishes other factors that can have a significant influence on the estimated cost. As mentioned in the earlier section, land needs to be reserved for a stormwater pond thus is unavailable for any other economic purpose. On the other hand, land for a bioretention cell is fit for another economic use. Therefore, the opportunity cost of land for the stormwater pond is likely to be significant as compared to that of the bioretention cell. Furthermore three additional factors, namely, engineering, construction, and landscape wages are studied in connection with the costs of the two BMPs.

A salient feature of the methodology proposed in this paper includes cost adjustments with respect to time and geographical locations in order to convert the nominal values into real values. Data from two different sources are combined in this study. Following the same pattern as that followed by CWP, the adjusted cost is regressed on the water quality-quantity volume. Along the lines of the study of Wossink and Hunt, one cost curve is specified here as follows:

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

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

$$LESTTOTCST = Intercept + bLWQV.$$

Simple regression based on the above equation is performed for bioretention cell (using QUALVOL) and the stormwater ponds (using both QUANVOL and QUALVOL). The estimate of the coefficient 'b' is then checked for its effect on the proportional change in the total cost.

The adjusted opportunity cost of land is then added to ESTTOTCST, to give the total adjusted cost for the stormwater ponds (ESTTOTCSTLND). The effect of the type of soil and climate on cost was estimated by inclusion of coastal and Sandhill region dummies for bioretention cells and a coastal dummy for stormwater ponds. The Piedmont region is the base. The dummies were interacted with the water-quality volume in the bioretention-cell model and water-quantity volume in the stormwater-pond model. The logarithmic equations become

$$LESTTOTCSTLND = a + bLQUANVOL + cLCOASTQNV + dLQUALVOL + eLCOASTQLV + fLLANDVAL$$

(stormwater ponds)

$$LESTTOTCST = a + dLQUALVOL + eLCOASTQLV + gLSANDHILLQLV$$

(bioretention cell)

Engineering, construction and landscape wages were then integrated into the total adjusted cost model to obtain the following equations for the two BMPs:

$$LESTTOTCSTLND = a + bLQUANVOL + cLCOASTQNV + dLQUALVOL + eLCOASTQLV + fLLANDVAL + hLENGWAGE + iLCONSWAGE + jLLANDWAGE$$

(stormwater ponds)

$$LESTTOTCST = a + dLQUALVOL + eLCOASTQLV + gLSANDHILLQLV + hLENGWAGE + iLCONSWAGE + jLLANDWAGE$$

(bioretention cells)

In the final specifications, QUALVOL was added to the stormwater-pond model and QUANVOL was added to the bioretention-cell model.

Results and Interpretations

Analysis of the Costs of a Bioretention Cell

The results of the regression analysis for the various models of the bioretention cells are shown in table 3. Model 1 shows the results of regression of the total adjusted costs on the QUALVOL of the cell. In model 2, the effect of the type of soil on total adjusted costs is studied. Model 3 is an extended version of model 2 where the input costs are incorporated. Model 4 studies the effect of the including the QUANVOL in model 3.

In Model 1, the total adjusted costs increase by 0.66 percent for each one percent increase in water-quality volume. 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. These explain costs variability due to the various types of soil on which the cell is located. Sand is one of the materials required for the construction of a bioretention cell. Hence, location of a cell in the Sandhill region can be expected to achieve low transportation cost of sand when compared to the Piedmont region. This hypothesis is supported, since the effect of the water-quality volume on the cost is less by about 0.25 percent (Model 2, Table 3) when the cell is located in the Sandhill region. The inclusion of a variable for type of soil and climate improves the adjusted R-square value by 18 percent (for bioretention cells). The type of soil and climate where a cell is located affects total adjusted costs.

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, construction workers, and landscape workers in or closest to the urban area where the cell is located. The effects of incorporating the different wages are studied in Model 3. The engineering wage is a significant determinant of the total adjusted costs of a bioretention cell. The wages of construction workers and landscape workers are statistically insignificant, even though construction-related costs constitute approximately 90% of the total adjusted costs.

In Model 3 (Table 3) a one percent increase in the engineering wage results in a 7.83 percent increase in the total cost. A highly paid engineer might be more likely to employ more costly materials, technologies, or contractors. In the same model, for every one percent increase in the QUALVOL of the cell, the total costs of the cell increase by an estimated 0.86 percent in the coastal region of the mid-Atlantic states, 0.68 percent in the Piedmont region of these states and 0.51 percent in the Sandhill region.

In Model 4 both the QUANVOL and QUALVOL are significant determinants of the total adjusted costs of a cell. The QUANVOL used here is however, assumed to be equal to the QUALVOL for 23 of the 26 data points used in the regression. QUALVOL is part of the QUANVOL of a bioretention cell. Hence, for every one percent increase in the volume of water that a cell treats for pollutants i.e. QUALVOL, the total adjusted costs increases by 0.76 percent in the coastal areas of mid-Atlantic states, 0.73 percent in the Piedmont region of these states, and by 0.63 percent in the Sandhill region.

Analysis of the Costs of a Stormwater Pond

For the stormwater pond we have models similar to that of the bioretention cell. The results of the regression analysis are shown in Table 4. Model 1 studies the effect of the QUANVOL on the total adjusted costs of a pond. Model 2 includes the input costs as additional explanatory variables and incorporates the estimated land cost in the total adjusted costs, to account for the opportunity cost of land. Model 3, an extension of model 2, studies the effect of QUALVOL in the regression analysis.

In model 1 one percent increase in the QUANVOL 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 67 percent.

Land value and the three types of wages mentioned earlier are used as the explanatory variables in model 2 along with the QUANVOL. The engineering wage is insignificant. Design and engineering costs are approximately 3 percent of the total costs of a stormwater pond.

The construction wage is however an important factor determining the variability of the total costs for the stormwater pond. Total costs increase 4.82 percent for each one percent increase in the wage of construction workers. Excavation and grading constitutes, on average, 38 percent of the total costs for a stormwater pond but only 22 percent of the total costs of a bioretention cell.

The highly negative and significant estimate of the landscape wage indicates that the costs of the stormwater pond are expected to decrease as the landscape wage increase. There does not seem to be any plausible explanation for this result.

The land value, as expected, is highly significant. If the land is used as a stormwater pond it usually cannot be utilized for any other purpose. Thus there is an opportunity cost of land which is a significant factor in determining the costs of constructing a stormwater pond. If the opportunity cost of land increase by one percent the total costs of the stormwater pond is expected to be higher by 0.43 percent. Thus the total costs increase by about almost half the increase in the cost of land.

The QUALVOL in Model 3 is not significant. The insignificance means that storage volume is a more important determinant of costs of a stormwater pond than the treatment volume is. The effects of input prices on the total adjusted costs are similar to those in Model 2.

Comparisons of Costs of Bioretention Cells and Stormwater Ponds

Estimated fixed costs are higher for stormwater ponds than bioretention cells in all model specifications (Tables 3 and 4). The costs per unit of water-quantity volume of stormwater ponds decrease more in absolute value than the costs per unit of water-quality volume of bioretention cells decrease, according to estimates from two specifications of cost models that lack any input price (Models 1 and 2, Table 3 and Model 1, Table 4). In the model of bioretention-cell costs with wages of engineers, construction workers, and landscape workers (Model 3, Table 3) and the model of stormwater-pond costs with these three wages and land prices (Model 2, Table 4) this relationship still holds in the coastal region. However, in the Sandhill and Piedmont regions, the costs per unit of water-quality volume of bioretention cells decrease more in absolute value than the costs per unit of water-quantity volume of stormwater ponds decrease.

Meaningful comparisons of costs of bioretention cells and stormwater ponds that account for both water-quality and water-quantity volumes are difficult, if not impossible, to make. 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-quantity information exists for only three of the twenty six cells in our sample because the Orangeburg cell was also designed to reduce stormwater runoff and the other two might have been so designed.

According to the estimates from two simple models in which costs depend exclusively on water-quality volume (Table 5), a bioretention cell is a cheaper method than a stormwater pond to remove pollutants in volumes of stormwater below 112,536 ft^3, regardless of the region According to the estimates from two models in which costs also depend on mean input prices and regions, in addition to water-quality volume (Table 5), a bioretention cell is a more expensive method of removing pollutants from any volume of water than a stormwater pond in mid-Atlantic coastal areas. However, according to the same two models (Table 5), a bioretention cell is a cheaper management practice than a stormwater pond in the Piedmont region for volumes of stormwater less than 359,017 ft^3, at the sample means of input prices

These estimated volumes illustrate but do not unambiguously define turning points of cost effectiveness of the two BMPs. Although 112,536 ft^3 and 359,017 ft^3 are within one half of a standard deviation from 301,338 ft^3, the mean water-quality volume of stormwater ponds, these turning points substantially exceed 19,874 ft^3, the largest observed water-quality volume of a bioretention cell. Moreover, the drainage areas of a South Carolina industrial park or site that would generate 112,536 ft^3 and 359,017 ft^3 of runoff from the first flush of a rain event are 65.6 and 209.3 acres, which are 13 and 42 times larger than 5 acres, the maximum recommended drainage area for typical bioretention cells (EPA 2004). Furthermore, the two sets of models on which these turning points are based ignore water-quantity volume as a determinant of costs.

Models of costs of bioretention cells and stormwater ponds that depend on water-quality and water-quantity volumes, in addition to input prices and regions, were estimated (Model 4, Table 3 and Model 3, Table 4). However, water-quantity volumes were assumed, not measured, equal to water-quality volumes for 23 of the 26 bioretention cells in our database. Even if measurements existed, these 23 bioretention cells were not designed to reduce stormwater runoff. Hence, even if a bioretention cell and a stormwater pond have the same water-quantity volume, these two BMPs do not necessarily reduce equal amounts of runoff. Similarly, even if a bioretention cell and a stormwater pond have the same water-quality volume, they do not necessarily have the same pollutant trapping efficiencies.

Some evidence indicates that removal efficiencies of bioretention cells are usually higher than the removal efficiencies of stormwater ponds. In Table 6, the percentages of copper, lead, zinc, phosphorus, and nitrogen removed are larger for a bioretention cell than a stormwater pond. If these differences in removal efficiencies could be incorporated in our models, the turning point at which a bioretention cell becomes more costly might be larger.

Conclusions

Bioretention cells and stormwater ponds exhibit economies of water-quality size. Stormwater ponds also exhibit economies of water-quantity size. Predicted costs of bioretention cells are lower in the Sandhills of North Carolina than other regions of mid-Atlantic states. Land prices are a significant determinant of the costs of stormwater ponds. In theory and in our models, other input prices also affect BMP costs. Construction wages positively affect costs of stormwater ponds and engineering wages positively affect costs of bioretention cells. The magnitudes of these positive effects, however, do not yet make sense.

Estimation of cost functions for these two stormwater best management practices will require better and more comprehensive data than are currently available. The effects of rental rates for track hoes and other machinery were not estimated for lack of data. The possibility that unmeasured determinants of costs of a bioretention cell or stormwater pond are correlated with unmeasured determinants of another cell or pond in the same area, i.e., the possibility of spatial autocorrelation of random errors, was not investigated. Maintenance costs of these two BMPs were ignored for lack of usable data. Determination of the precise ranges of water-quality and water-quantity volumes over which, given local input prices and land resource areas, a bioretention cell is a cheaper method than a stormwater pond to meet regulatory standards for stormwater runoff remains an important research endeavor.

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Table 1: Descriptive Statistics for Bioretention Cells (n=26)

Variable	Mean	Standard Deviation	Minimum	Maximum
ESTTOTCST (2003 $s in Baltimore)	27,266	38,439	1,236	190,554
QUALVOL (cubic-feet)	3,590	4,941	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=41)

Variable	Mean	Standard Deviation	Minimum	Maximum
ESTTOTCST (2003 $s in Baltimore)	214,645	371,610	6,881	1,975,191
ESTTOTCSTLND (2003 $s in Baltimore)	890,430	2,062,583	12,741	11,782,125
QUANVOL (cubic-feet)	301,338	785,500	671	4,126,003
QUALVOL (cubic-feet)	205,833	811,502	322	5062108
LANDVAL (2003 $s in Baltimore/acre)	531,801	493,324	28,700	2,638,187
ENGWAGE (2003 $s in Baltimore/hour)	31	4	19	41
CONSWAGE (2003 $s in Baltimore /hour)	19	3	13	22
LANDWAGE (2003 $s in Baltimore /hour)	14	1	10	16

Table 3: Factors that Affect the Costs* of a Bioretention Cell

	Estimate, (Standard Error), and *p-value*			
Variable Name	Model 1	Model 2	Model 3	Model 4
Intercept	4.51590 (1.49760) *0.0060*	3.08633 (1.38036) *0.0358*	-25.21755 (8.83889) *0.0102*	-22.50173 (6.53315) *0.0029*
LQUALVOL	0.66365 (0.19549) *0.0024*	0.86650 (0.18056) *<.0001*	0.67746 (0.17087) *0.0008*	-0.76805 (0.37115) *0.0532*
LCOASTQLV		0.01663 (0.04908) *0.7380*	0.18800 (0.06661) *0.0109*	0.14083 (0.05030) *0.0118*
LSANDQLV		-0.24653 (0.08226) *0.0066*	-0.16375 (0.07626) *0.0449*	-0.16775 (0.05609) *0.0078*
LQUANVOL				1.56436 (0.37759) *0.0006*
LENGWAGE			7.83318 (2.88016) *0.0136*	6.68941 (2.13602) *0.0058*
LCONSWAGE			1.92759 (1.33287) *0.1644*	0.88943 (1.01178) *0.3909*
LLANDWAGE			0.132330 (1.24950) *0.3029*	-0.04984 (0.96902) *0.9595*
Adj. R-Square	0.2963	0.4745	0.6241	0.7967

* Land costs are not included.

Table 4: Factors that Affect the Costs of a Stormwater Pond

	Estimate, (Standard Error), and *p-value*		
Variable Name	Model 1	Model 2 with land costs	Model 3 with land costs
Intercept	4.58477 (0.74761) *<.0001*	12.29770 (2.37017) *<.0001*	12.30732 (2.35827) *<.0001*
LQUANVOL	0.61599 (0.06757) *<.0001*	0.85422 (0.04176) *<.0001*	0.96943 (0.10736) *<.0001*
LQUALVOL			-0.12786 (0.10986) *0.2526*
LLANDVAL		0.42686 (0.10686) *0.0003*	0.42574 (0.10632) *0.0003*
LENGWAGE		-0.07086 (0.67681) *0.9172*	-0.10542 (0.67406) *0.8766*
LCONSWAGE		4.82696 (1.26533) *0.0005*	5.09831 (1.28038) *0.0003*
LLANWAGE		-10.85598 (2.03830) *<.0001*	-11.10347 (2.03918) *<.0001*
Adj. R-Square	0.6725	0.9294	0.9301

Table 5: Two Sets of Comparable Models of Costs of Both BMPs

	Estimate, (Standard Error), and *p-value*			
	Models without Input Prices		Models with Input Prices	
Variable Name	Bioretention Cell	Stormwater Pond	Bioretention Cell	Stormwater Pond
Intercept	4.51590 (1.49760) *0.0060*	5.68633 (0.83482) *<.0001*	-25.21755 (8.83889) *0.0102*	12.79207 (4.28354) *0.0051*
LQUALVOL	0.66365 (0.19549) *0.0024*	0.56302 (0.08231) *<.0001*	0.67746 (0.17087) *0.0008*	0.78688 (0.07725) *<.0001*
LCOASTQLV			0.18800 (0.06661) *0.0109*	
LSANDQLV			-0.16375 (0.07626) *0.0449*	
LLANDVAL				0.51828 (0.19228) *0.0107*
LENGWAGE			7.83318 (2.88016) *0.0136*	-0.09699 (1.22468) *0.9373*
LCONSWAGE			1.92759 (1.33287) *0.1644*	3.74026 (2.31016) *0.1144*
LLANDWAGE			0.132330 (1.24950) *0.3029*	-9.68926 (3.69395) *0.0128*
Adj. R-Square	0.2963	0.5337	0.6241	0.7693

Table 6: Previous Research on Pollutant Removal Effectiveness

Type of pollutant	Average Percentage of Pollutant Removed (Stormwater Ponds)	Average Percentage of Pollutant Removed (Bioretention Cells)
Copper	30%	61%
Lead	61%	78%
Zinc	73%	78%
Phosphorus	49%	80%
Nitrates and Nitrites	57%	16%
Nitrogen	14%	56%
Total Suspended Solids	89%	86%

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

Sources for bioretention cells: Field test of ultra urban BMPs (Yu et al.), Inglewood demonstration project (EPA, 2000a), Maryland's Greenbelt and Landover field study (Davis), and Table 14 (Wossink and Hunt)