DETERMINING COST AND TREATMENT EFFECTIVE SOIL AND PLANT COMBINATIONS IN BIORETENTION CELLS FOR STORM WATER MANAGEMENT IN THE PIEDMONT REGION OF GEORGIA

by

HILLARY SMITH TANNER

(Under the direction of Jeffrey Mullen)

ABSTRACT

Six bioretention cells at the Rockdale Career Academy in Conyers, GA were studied in order to determine which set of cells, the control (40% topsoil, 40% engineered soil amendments, 20% sand) or the experimental (40% topsoil, 20% engineered soil amendments, and 40% sand), were more cost and treatment effective. Water quality analysis found that experimental cells reduced pollutants (metals, solids, and nutrients) in storm water runoff just as effectively as the control cells. The cost analysis showed that combinations of experimental bioretention cells provided the least cost solutions to meet water quality criteria and runoff volume requirements. The experimental bioretention cells were also found to be more cost effective at treating water quality, per cubic foot of runoff treated. It was concluded that the experimental bioretention cells were likely to be more cost and treatment effective than the control cells.

INDEX WORDS: Bioretention Cells, Cost Effective, Water Quality, Pollution Reduction, Storm Water Management

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HILLARY SMITH TANNER

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HILLARY SMITH TANNER

Major Professor: Jeffrey Mullen

Committee: David Gattie
Jack Houston
Jimmy Bramblett

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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DEDICATION

To my husband, Matthew

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CHAPTER 1

INTRODUCTION

Storm water is the runoff from land and impervious surfaces, such as pavement and rooftops, during rainfall events. It often contains pollutants from human activities, such as nutrients, metals, sediment and bacteria, especially in the first few inches of runoff, which may adversely affect water quality in streams, lakes, and rivers. Local, State, and Federal governments have been working to implement storm water management programs since 1987 when the U.S. Congress amended the Federal Clean Water Act (CWA) to require the U.S. Environmental Protection Agency (EPA) to establish regulations for storm water discharges. These regulations fall under the CWA's National Pollutant Discharge Elimination System permitting system for point source discharges (GAEPD Storm Water Fact Sheet, 2003).

In 1990, Georgia's Environmental Protection Division (GAEPD) changed the Georgia Rules and Regulations for Water Quality Control to adopt the Federal regulations at the State level (GAEPD Storm Water Fact Sheet, 2003). Georgia has implemented the NPDES Storm Water Program in stages. Phase I began in 1990 and applied to the sources of storm water with the greatest potential for negative impact, including large municipal storm sewer systems, large construction sites, and industries. Phase II began in 1999 and includes cities with small municipal separate storm sewer systems (MS4s) and small construction sites (Risse, et.al., 2004).

1.1. Purpose of Research

The actual permitting process for the NPDES Storm Water Program Phase II cities in Georgia began in May 2003. There are nearly 60 cities and counties that meet criteria to be considered part of Phase II. Part of the requirements for Georgia's NPDES Storm Water Program Phase II Storm Water Management Plans include the implementation of structural best management practices (BMPs) to help improve the quality of storm water before it reaches water bodies (Risse, et.al., 2004). Cities and counties that meet Phase II criteria often develop ordinances dealing with storm water management. These ordinances generally include pre-construction, during construction, and post-construction requirements for handling runoff volume, sediment, and other pollutants as well as requirements for amount of pervious area and tree protection. The ordinances dealing with storm water management typically have two components, structural and non-structural BMPs. This project will focus primarily on structural BMPs.

There are scores of structural BMPs for improving storm water quality that are acceptable for use in the State of Georgia, including bioretention cells, sand filters, storm water wetlands, and porous pavements (Georgia Stormwater Management Manual, Technical Handbook, 2001). These options not only treat storm water, but they also encourage environmentally based design. While the treatment capabilities of these BMPs have been researched extensively throughout the United States, there are few local studies available that focus on their treatment of storm water and their economic feasibility. Knowledge of water quality benefits and costs associated with pollutant removal is crucial to making informed storm water management decisions.

The study site for this project, the Rockdale Career Academy (RCA) is located in an NPDES Storm Water Program Phase II city, Conyers, GA (in the Georgia Piedmont Region). In addition to Phase II regulations, the Rockdale Career Academy is located in a watershed that contributes to an impaired stream, Almand Branch, which is included on the 303(d)/305(b) List of Impaired Waters. Therefore, it was imperative that the storm water design for the RCA not only meet Phase II regulations, but not contribute to existing water quality problems in its receiving stream. Many bioretention cells were incorporated into the storm water management site plan because they are multipurpose storm water controls that are capable of holding limited amounts of runoff and reducing pollutants in runoff, while providing aesthetic appeal with plants, grasses, and trees.

1.2. Objectives

1. Determine the water quality treatment capacity of the soil and plant combinations in control bioretention cells at the Rockdale Career Academy and compare this capacity to experimental bioretention cells.
2. Determine the most cost efficient combination of soils and plants for treating pollution to a desired water quality target by studying the control and experimental bioretention cells at the Rockdale Career Academy.
3. Make recommendations for plant and soil combinations for treating parking lot and road runoff in the Piedmont Region of Georgia and for educational/research opportunities for students and faculty at the Rockdale Career Academy.

Objective 1 will be met by conducting water quality sampling at the study site to determine actual outlet concentrations and by using a water quality model to predict pollutant removal for each bioretention cell. Objective 2 will be met by minimizing costs subject to pollutant reduction and volume of runoff treated, while Objective 3 will be met by reviewing results from the water quality and cost analyses.

1.3. Hypothesis

All bioretention cells incorporated in the Rockdale Career Academy site design will reduce pollutants in storm water runoff from the surrounding parking lots. While the cells with a higher percentage of engineered soils may have a higher treatment capacity, those cells with more sand and less engineered soil will adequately treat the runoff, and be more cost efficient.

1.4. Benefits

The benefits of this research are two-fold. Water quality test results and cost analysis will help determine more cost efficient options for soil and plant combinations for bioretention cells in the Piedmont Region of Georgia. This benefits engineers and planners as they will be able to make better decisions on bioretention fill materials. The Rockdale Career Academy will also benefit by gaining valuable baseline information on the treatment capacity of their bioretention cells. The Rockdale Career Academy offers emphasis areas in Engineering and Agricultural Sciences/Horticulture (Rockdale County BOE, 2006) that would particularly benefit from hands-on research related to the bioretention cells.

1.5. Overview of Thesis

This thesis is comprised of six chapters: introduction, literature review, case study description, methodology, results and discussion, and conclusions and recommendations. The literature review's primary focus will be on describing bioretention and swale systems; how they work, the costs and benefits associated with their use as storm water management BMP’s, and studies that focus on water quality treatment and economic impacts. It will also include discussions on the impacts of storm water runoff, benefits (physical and economic) of treating storm water, storm water policy as well as various storm water best management practices (including bioretention cells), their water quality treatment capacity, economic analyses, and related research. The case study description chapter will give in-depth information pertaining to the case study site, including a description of the area surrounding the site, engineering design specifications for the bioretention cells, and costs associated with the their construction. This section will also discuss goals that Rockdale County and Breedlove Land Planning (the designer) wish to meet with this study. The methodology section will include methods for water quality sampling and analysis, modeling, and economic analysis. The results and discussion chapter will include results of water quality analysis and modeling, in addition to economic analysis, statistical analysis and discussion of these results. The conclusions and recommendations chapter will summarize the findings of this study and give recommendations for future research on this topic, for choosing the most economically efficient combinations of soils and plants for bioretention cells and for educational opportunities that Rockdale Career Academy may take advantage of in the future.

CHAPTER 2

LITERATURE REVIEW

2.1. Storm Water Background and Issues

Storm water issues are a product of the advancement of our society through growth and development. Clearing land (removal of vegetation and topsoil) and grading (flattening natural features of land) remove natural measures for slowing and treating runoff, while the addition of impervious surfaces further increases the rate at which potentially polluted storm water flows over the land to streams, rivers, lakes and other water bodies. Storm water adversely affects watersheds in several ways, including changes in stream flow, stream morphology, biological communities, and water quality. (Georgia Storm Water Management Manual, Policy Guidebook, 2001).

2.1.1. Changes in Stream Flow

Alteration of natural environments associated with development effects the flow of streams in several ways. Replacing topsoil and vegetation with impervious surfaces causes the entire hydrology of watersheds to change. Impervious surfaces provide ideal situations to increase runoff volume, peak discharge, and velocity. Impervious surfaces also greatly reduce infiltration, which leads to flooding in wet events and lower base flows during dry conditions (Georgia Storm Water Management Manual, Policy Guidebook, 2001). The following figure shows a graphical representation of the effects of urbanization (increased impervious surfaces) on stream flows.

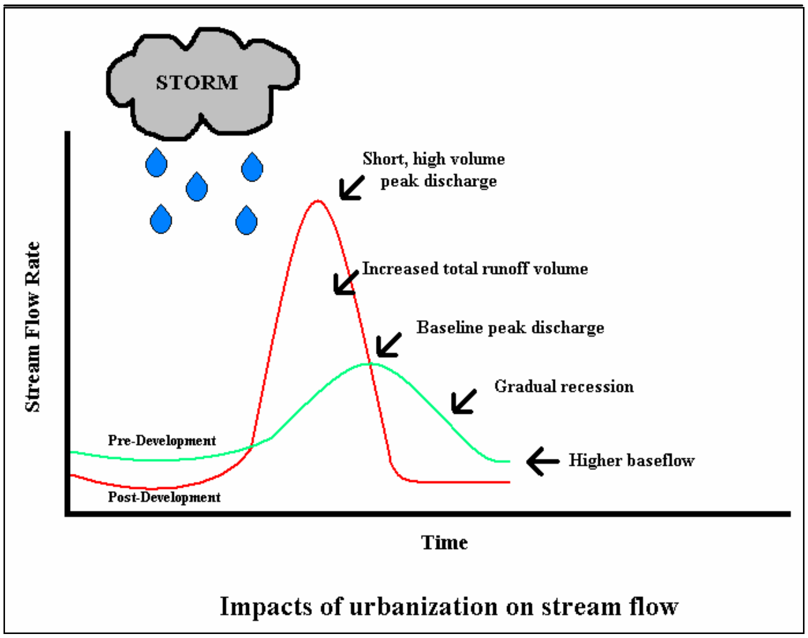


Figure 2.1. Impacts of Urbanization on Stream Flow

From: UGA Watershed Group, 1999.

2.1.2. Changes in Stream Morphology

Urbanization also changes the morphology of streams by increasing velocities and volumes of runoff; stream beds erode and widen, banks become undercut, riparian vegetation is affected, sediments are deposited and floodplains become wider (Georgia Storm Water Management Manual, Policy Guidebook, 2001). Figure 2.2 shows some of the changes of a stream's morphology due to increased storm flows.

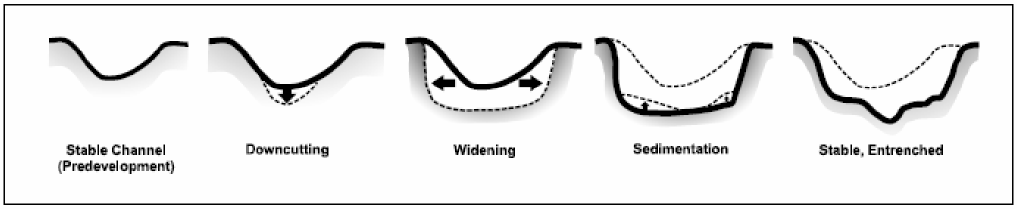


Figure 2.2. Effects of Storm Flow on Stream Morphology

From: Georgia Storm Water Management Manual (§1.1.1.3)

2.1.3. Impact on Biological Health of Streams

High flows, erosion, and sedimentation associated with storm water runoff are detrimental to the habitat of streams. High flows cause habitat for insects and fish to wash away, while sediment deposits choke out habitat, making streams all but unlivable. Lack of infiltration due to increased impervious surface causes baseflows to be lower and consequently, the temperature of streams increase. Biological communities, especially fish, are very sensitive to temperature changes (Georgia Storm Water Management Manual, Policy Guidebook, 2001).

A preliminary study conducted by the University of Georgia's Watershed Group focusing on the effects of urbanization on stream dwelling insects found there was a clear relationship between biological response and urban land use in the 0% to 5% range. These findings indicated that the most damage to the stream environment was done in the first stages of development, from non-urban land use to urban land use. As land is developed further (higher % urban landuse), biological scores level off slightly, but still continue to fall, emphasizing that while initial development causes the most damage to benthic macroinvertebrate communities, urbanization decreases biological health of streams at all levels (Gattie, et. al. 2003).

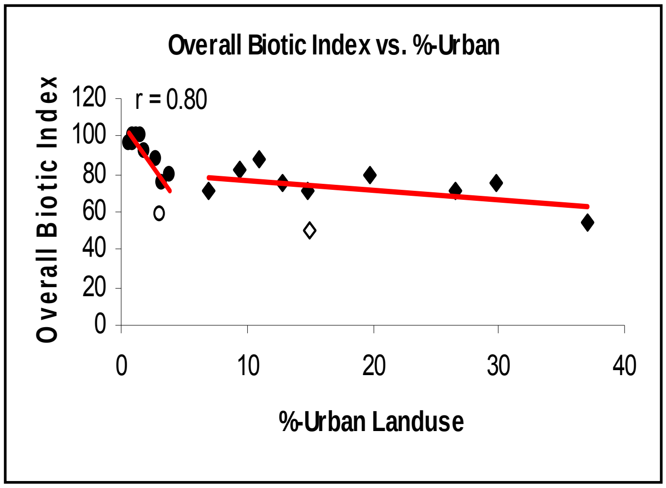


Figure 2.3. Impact of Urbanization on Biological Communities

From Gattie et. al., 2003

While the Gattie study did not focus on effects of storm water in particular, urbanization typically involves replacing undeveloped areas with impervious surfaces, which as discussed previously, increases storm flow.

2.1.4. Effects on Water Quality

As storm water runoff flows over impervious surfaces (rooftops, parking lots, etc) and lawns, it picks up pollutants such as nitrogen and phosphorus (used in fertilizers), sediment, oil, grease, diesel and gasoline, bacteria, and other pollutants. Typical concentrations of pollutants in runoff from heavy transportation applications (highways, etc) include suspended solids (up to 800 mg/L), phosphorus (up to 1 mg/L), nitrogen (up to 2 mg/L), metals (up to 7 mg/L), pathogens (up to 600 CFU/100mL), and petroleum products (U.S. DOT, FHA). According to the U.S. DOT, these pollutants come from a variety of different sources such as atmospheric deposition and fertilizers (nutrients), auto exhaust (lead), tire wear (lead, zinc), motor oil and grease (zinc), moving engine parts, brake wear and bearing and bushing wear (copper). Once these pollutants reach streams, they can seriously affect the quality of the stream water. Organics, that reach streams attached to sediments, consume oxygen as they decay and therefore reduce the amount of oxygen in the water. Fish, insects and aquatic plants depend on oxygen for survival, so reduced oxygen levels contribute to the reduction of these important biological communities. Nutrients such as nitrogen and phosphorus encourage growth of algae, which block sunlight from under water plants and other organisms, and contribute to the reduction of oxygen levels. If these nutrients, especially nitrogen, reach ground water they can contaminate drinking water wells. Bacteria are also carried in sediments deposited in streams by storm water runoff. According to the Georgia Storm Water Management Manual, bacteria levels in storm water runoff often exceed public health standards for water contact recreation (swimming and wading). Bacteria are also a concern for drinking water sources.

2.2. Economic Impacts of Storm Water Runoff

As can be seen from the previous discussion, when storm water runoff reaches streams at a greater rate than natural conditions water quantity and water quality problems arise. Once these problems are created, it is difficult to return to pre-development conditions. Methods such as replanting riparian areas to reduce flow and restoring stream beds and banks are often prohibitively expensive and treating water contaminated with heavy metals, hydrocarbons, bacteria, nutrients and sediments to recreational and drinking water standards can also be extremely expensive.

Instead of looking to short term solutions, maintaining “natural” conditions by reducing runoff volumes and treating storm water before it reaches streams, lakes and rivers will provide a long term solution to many water quantity and water quality problems. While many policies implemented by federal, state, and local governments often focus on restoration activities, such as remediating streams already affected by storm water runoff, a study by Novotny, et. al. (2000) suggests that the general public may be becoming more proactive instead of reactive to environmental issues. Novotney's study focused on watersheds in Wisconsin and determined, through willingness to pay (WTP) surveys, that nearly 80% of respondents were willing to pay more in taxes or fees to improve urban streams for "the sake of nature itself" than actual remediation activities would cost.

2.2.1. Hydrologic Benefits

Hydrologic benefits of structural BMPs deal primarily with managing runoff, from the time it reaches the ground to when it reaches a receiving stream. All storm water management BMPs, discussed in this review, manage runoff in some way. Because most BMPs are designed to hold or slowly release runoff, they help to restore predevelopment flows in receiving streams, by mimicking a more natural rainfall to runoff ratios (Low Impact Development Center, Inc.). Managing the amount of runoff reaching streams may be the most important function of structural BMPs because if volumes are not handled property, habitat benefits, health benefits, and water quality benefits may not be realized.

2.2.2. Habitat Benefits

Habitat benefits of implementing BMPs are difficult to quantify. Aquatic insects and fish are extremely sensitive to changes in stream morphology, water quantity, and water quality and often suffer with even small changes in either. In situations where land is going from a “natural” state to a more developed state, BMPs have not been shown to be particularly effective at maintaining biological quality when compared to a reference “natural” site (Jones, et.al., 1996). Implementing flow regulating BMPs in situations where biological communities are already compromised will, at the very least, help to stabilize stream conditions as opposed to a do nothing scenario.

2.2.3. Human Health and Recreational Benefits

Human health can be negatively impacted by pollutants carried in storm water, either by direct contact (recreation) or through contaminated seafood. Implementing best management practices that are effective at removing bacteria, metals, and nutrients from storm water runoff will create better surface water quality for human use. This is beneficial because recreational waters will have less bacteria and algal growth (from nutrients) that come in contact with humans, levels of metals (such as mercury) in fish will decrease, and raw water will be cleaner at the inlets of water treatment plants, and therefore, would require less treatment. A specific example of human health benefits of implementing BMPs is reduced medical expenses from consuming contaminated seafood. An EPA study conducted in 1997 found that by installing Phase II BMPs to improve water quality (indirectly improving shellfish quality) medical costs for shellfish related illnesses could be expected to decrease between $73,000 and $300,000 annually (Strassler, et.al., 1999).

Recreational benefits to treating storm water are closely tied to health benefits. Activities such as fishing, swimming, wading, and boating, are highly valued activities that bring people in contact with water. Bergstrom, et. al. (2000) conducted a study, in part, to determine the value of ecosystem services in the Little Tennessee River

Watershed. A majority of survey respondents from the study area were involved in some sort of recreational use of the Little Tennessee River and its contributing watershed. The respondents also thought, with a mean ranking of 5.6 (with 7 being very important), that habitat for fish and wildlife other indicators of healthy river systems should be protected.

The study also looked at the survey willingness to pay (WTP) for restoring a portion of the Little Tennessee River and found that survey respondents were willing to pay an average of $37 for restoration efforts in order to be able to continue recreational activities in a natural setting. Respondents also indicated they were willing to pay an average of $37 to protect tributaries to the Little Tennessee River (Bergstrom, et. al., 2000).

2.2.4. Increased Property Value

Storm water BMPs provide benefits not directly associated with environmental quality. They can increase property value (both residential and commercial) by providing landscaped areas (bioretention) and water features (retention ponds, wetlands, etc) that support birds, animals, and fish, which people value quite highly. A literature review of property value case studies conducted by the EPA in 1995 (EPA 841-S-95-002) add support to the argument. Survey results from residents in Columbia, Maryland indicated that 75% of homeowners surveyed felt permanent bodies of water (such as wet ponds and wetlands) added to real estate value and 73% of homeowners said they would pay more for property where storm water controls provided habitat for fish and wildlife. Residents in a Boulder, Colorado neighborhood paid up to a 30% premium for lots adjacent to a constructed wetland, while condominium owners in

Alexandria, Virginia spent an average of $7,500 more per unit for a view of a storm water wet pond. These case studies and others discussed in the EPA literature review show just how much people value “natural settings”. One could expect that as more development occurs, property adjoining natural areas will be at even more of a premium.

2.3. Storm Water Policy

Environmental policies can be broken into two main groups, policies without fixed reduction targets and those with fixed reduction targets. Policies with no fixed pollution reduction targets focus on non-structural solutions such as fees, fines, reporting requirements and educational programs. Policies with fixed pollution reduction targets generally include structural components that are designed specifically to reduce pollutants to the target level (U.S. Congress, 1995). The storm water policies discussed in detail below, and particularly the Phase I and II regulations, combine these two types of environmental policies. The following sections discuss storm water policy on the federal, state and local levels. It also discusses how federal and state storm water policies have affected local storm water policies.

2.3.1. Federal and State Policy

As mentioned in Chapter 1, the Federal Clean Water Act drives storm water management policy at the national level. 1987 Amendments to the Clean Water Act stipulated that storm water management would be implemented in two stages. Phase I applies to sources of pollution that have the greatest potential for negative impact. These sources include construction and industrial activities and municipalities with large storm sewer systems and large expanses of impervious surfaces. Phase II applies to small municipalities with storm sewer systems and small construction sites. Since the case study site is in a Phase II city, Conyers, GA, the focus of this section will be Phase II policies in the State of Georgia.

The process to obtain Phase II permits includes several components. The first is the submittal of a storm water management plan to the Georgia Environmental Protection Division (GAEPD). The goals of storm water management plans are to reduce pollutants discharged in storm water, protect water quality, reduce volume of storm water, and satisfy water quality requirement of the Clean Water Act. Storm water management plans must include goals for the development of public education and involvement programs; maps, best management practices (BMPs), and goals for detecting and eliminating illicit discharges; erosion and sedimentation control measures, site inspection and enforcement procedures, and BMPs and goals for managing runoff from construction sites; implementation strategies for BMPs, operation and maintenance, ordinances, and goals for post-construction runoff control; and pollution prevention attributes to reduce runoff to storm sewers, employee training, and BMPs.

In order to be in complete compliance with the GAEPD's Phase II permitting, efforts to manage storm water are to be reported annually for the first term of the permit (usually 5 years) and then every two years for subsequent permit terms. These reports should include status of compliance with program goals, results of monitoring, and any changes that may be made to goals (Risse, et.al., 2004). The Phase II permitting process, dictated by the federal and state governments, is the key driver for storm water policy at the local level. Section 2.3.2 discusses specific policies for Rockdale County and the City of Conyers.

2.3.2. City of Conyers and Rockdale County, GA Storm Water Policy

Since Rockdale County and the City of Conyers are Phase II municipalities, they must follow state requirements for managing storm water. To meet many of the goals outlined in Phase II requirements, the City of Conyers and Rockdale County government enforce ordinances dealing with managing storm water. The ordinances that apply to this study focus on post-construction storm water management, storm water utilities, and tree protection. The discussion of ordinances will center on City of Conyers ordinances, since the Rockdale Career Academy is located in the city limits.

The Post-Development Storm Water Ordinance for the City of Conyers (Code of the City of Conyers, Title 12) discusses the requirements of storm water management. The post-development ordinance suggests using management practices included in the Georgia Storm Water Management Manual to meet performance criteria. These criteria include water quality, stream channel protection (water quantity), and flood protection. A discussion of how the Rockdale Career Academy addresses this ordinance is included in Chapter 3.

The Storm Water Utility and Enterprise Fund is discussed in Title 8, Chapter 12 of the Code of the City of Conyers, GA. This storm water utility was set up to allow the City of Conyers “to provide storm water management services, systems and facilities”, to contribute to the protection and preservation of public health, safety, and natural resources (Code of the City of Conyers, § 8-11-1). Under this ordinance, property owners within the City of Conyers limits pay a fee to maintain storm water management systems. The fee assessed is based on type of property (commercial, residential, industrial, etc) and acreage of the property. There are special exemptions for city or county owned properties and institutional properties, as well as a credit system that allow land owners a reduced fee by treating storm water on-site. Since the Rockdale Career Academy is part of the Rockdale County School System, it is exempt from the storm water utility fee (§ 8-11-9). Chapter 3 will discuss how bioretention on the Rockdale Career Academy could reduce storm water fees if it were subject to the utility.

The main objective of the Tree Preservation and Landscape Ordinance (Code of the City of Conyers, GA, Chapter 10) is to help ensure the city realizes the benefits of trees in the urban landscape. While this ordinance does not directly deal with storm water management, it does require certain percentages of parking lots and other impervious areas be set aside for planting beds that can support trees, which do provide some storm water management as they reduce runoff. Since tree protection areas are required by code, opportunity costs associated with lost parking spaces are reduced, but not eliminated because planting beds for tree preservation are typically smaller than bioretention cells. Chapter 3 contains a full description of how this ordinance is applied in the case of Rockdale Career Academy.

2.3.3. NPDES Phase II Economic Analysis

As the NPDES Phase II regulations were being implemented, the United States Environmental Protection Agency found it necessary to conduct economic analysis of the program to address issues about costs and benefits of the program that were raised through public comments. The study was done in 1997, so all costs in tables were converted to 2007 dollars using the Consumer Price Index.

2.3.3.1. Costs

Strassler, et. al.(1999), in a study for the EPA looking at urban BMPs, estimated nation wide costs for municipal compliance (record keeping, reporting, permits, etc.) and construction. Using census data, the Strassler, et. al. determined the number of Phase II communities and the total number of households to estimate compliance costs. Construction costs were determined based on model sites of 1, 3, and 5 acres. In addition to acreage, soil erodibility (low, medium, and high) and slopes (3, 7, and 12 %) were also taken into account. After determining costs for compliance and construction, total per site costs for implementing Phase II requirements were determined. Table 2.1 shows the costs broken down into 1, 3, and 5 acre sites and an average annual nation-wide cost for compliance. 1997 dollars were converted to 2007 dollars using the Consumer Price Index.

Table 2.1. Estimated Phase II Compliance Costs

Site Size	Estimated Compliance Costs	
(acres)	1997 dollars	2007 dollars
1	2,535	3,246
3	5,937	7,602
5	10,038	12,852
Average Annual Cost for Compliance Nation-wide		
		1997 dollars
		512,000,000

Adapted from EPA-821-R-99-012 § 6.4.1

2.3.3.2. Benefits

The Urban BMP study also looked at benefits of municipal measures and construction site controls using a benefits transfer approach (applying benefits of one site to other similar sites). To determine the benefits of municipal measures, analysts at the EPA applied willingness to pay for improvements in water quality to water impaired by storm water runoff to estimate the value of improving water quality through Phase II activities. Assuming that municipal measures will be at least 80% effective, the EPA estimated annual benefits (nation-wide) to be between $67.2 and $241.2 million (2007 dollars). This calculation does not take health factors or improvements to marine waters into account (Strassler, et. al., 1999, §6.4.2.1).

To determine benefits of actual structural controls on construction sites, the Strassler, et. al. again used willingness to pay (WTP) data, this time from erosion and sedimentation control. These data were applied to estimated Phase II construction starts to determine a WTP for Phase II structural controls, which may be as high as $624.2 million per year, nationally (§6.4.2.2).

2.4. Bioretention Systems

The following discussion will describe the various types of bioretention systems, their water quality and quantity improvement performance, and costs associated with construction, operation, and maintenance of the systems.

2.4.1. Bioretention Design

Bioretention cells are known by several names including, rain gardens and bioretention areas, although the ideas behind their designs are fairly similar. Bioretention cells are structural storm water controls that capture and temporarily store runoff, while reducing pollutants using soils and vegetation. They are used in urban as well as suburban settings and are often used in parking lots and along roadways to help slow runoff and provide aesthetic appeal to the landscape.

The typical path runoff takes through a bioretention cell begins on a hard surface. Runoff sheet-flows over grassed buffer strips, enters the landscaped ponding area, is taken up by plants or filters through the soil. The runoff that filters through the soil ends up in an underdrain conveyance or infilterates to the surrounding soil.

Bioretention cells consist of several layers of materials that are chosen to maximize water quality treatment, soil moisture for plants, and infiltration. The layers begin with the ponding area, which is designed to contain a specific volume from a design storm. The ponding area is planted with plants that are aesthetically pleasing, can handle periods of extreme wet (even minimal ponding), can handle periods of extreme dry, and can uptake pollutants from runoff. The plants are typically surrounded with a layer of mulch that helps hold in moisture during dry periods and filters large debris from runoff. The next layer is the planting soil, which is usually a mixture of soil from the construction site and engineered soils, is capable of retaining enough moisture to keep the plants alive, and porous enough to infiltrate runoff.

Bioretention cells often have a layer of filter fabric beneath the soil to keep it from migrating into the multipurpose gravel bed layer. If the bioretention cell has an underdrain, the gravel helps filter the runoff before it enters the drain. The gravel bed also provides some detention volume whether the runoff goes to an underdrain or infiltrates into the surrounding soil. Finally, another layer of filter fabric is often included to keep soil below the bioretention cell from migrating into, and potentially clogging, the gravel bed (Georgia Stormwater Management Manual, Technical Handbook, 2001; EPA Bioretention Fact Sheet, 1999; and Low Impact Development Center, Inc.) Figures 2.4 and 2.5 show typical plan and cross-sectional views of bioretention cells.

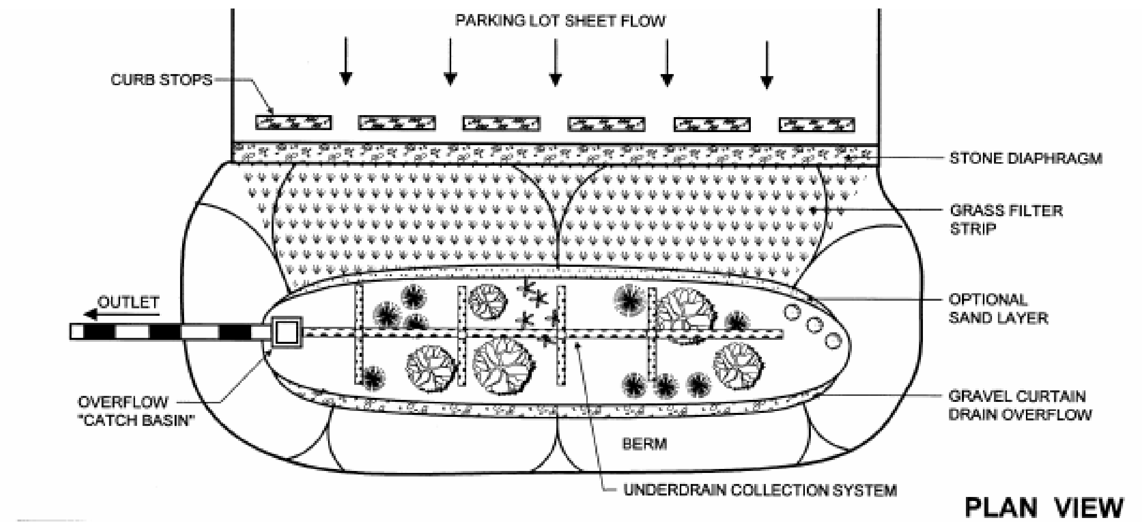


Figure 2.4 – Typical bioretention cell plan view.
Georgia Stormwater Management Manual

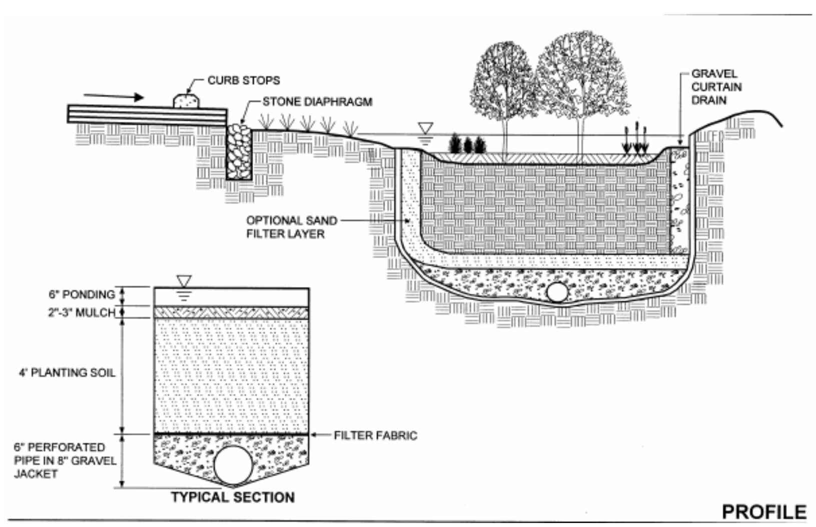


Figure 2.5 – Typical bioretention profile and cross section.
Georgia Stormwater Management Manual

2.4.2. Water Quality Treatment

Bioretention cells are excellent at reducing pollutants from parking lot and roadway storm water runoff, where pollutants can occur in high concentrations. Pollutants that do enter a bioretention system can be removed by several mechanisms. Grassed filter strips help to filter particulates from runoff, the mulch layer further filters runoff, and provides a medium for microorganisms to grow and degrade pollutants, the planting soil acts as another filter, and soil amendments such as clay provide adsorption of pollutants, vegetation planted in the ponding area uptake pollutants and help stabilize the surrounding soil, and the sand or gravel bed surrounding the underdrain provides yet another filter and provides positive drainage in the system (to avoid anaerobic conditions). (Georgia Storm Water Management Manual, Technical Handbook, 2001)

Studies that have measured the water quality treatment capacity of bioretention cells, with varying mixes of soils and plants found that bioretention cells are capable of removing up to 90% of suspended solids, 80% of phosphorus, 80% of nitrogen, 99% of metals, and 90% of oils and grease from parking lot and roadway runoff. They also help reduce temperature of runoff as it infiltrates through a bioretention cell. Studies have shown the temperature can drop up to 12 C from inlet to outlet. (Low Impact Development Center, Inc.; Georgia Stormwater Management Manual, Technical Handbook, 2001, EPA Bioretention Fact Sheet, 1999).

2.4.3. Runoff Reduction

Bioretention cells serve many purposes when installed to manage storm water. They serve as landscaped areas for aesthetic purposes, they improve water quality of runoff, and they also reduce runoff volume. Bioretention cells reduce runoff in several ways, some of which were discussed in Section 2.4.1. The ponding area functions as a shallow detention pond, holding runoff until it infiltrates through the cell. The soil itself holds small amounts of water, depending on the media used (many engineered soils are specifically designed to hold moisture). Finally, the gravel or sand layer and the underdrain provide some temporary storage for runoff. While bioretention cells do not hold a significant amount of runoff, they are effective at reducing the "immediate volume load to the storm drain and reduce the peak discharge rate" (Low Impact Development Center, Inc.).

2.4.4. Limitations

Bioretention cells are fairly flexible designs and, with the exception of contributing area and slope, have few limitations. Bioretention cells are not recommended for use for large drainage areas. While a single bioretenion cell could handle up to a 5 acre site, smaller sites lead to better function. However, if bioretention is desired on larger sites, cells in series could be effective. Bioretention cells also take up more space than other BMPs. Typically, they require 5% of the contributing impervious area to handle runoff volumes. While this may be a problem in ultra urban areas, most cities and counties require landscaped areas in addition to storm water management (Low Impact Development Center, Inc.; Georgia Stormwater Management Manual, Technical Handbook, 2001, EPA Bioretention Fact Sheet, 1999). Bioretention cells are also not recommended for areas with steep slopes (more than 6% slope) because function is compromised in steep slope situations (Georgia Stormwater

Management Manual, 2001). Finally, bioretention cells require regular maintenance to function properly, but the maintenance schedule is similar to that of other landscaped areas.

2.4.5. Maintenance

The Georgia Storm Water Management Manual and the Low Impact Development Center suggest similar maintenance practices for bioretention cells. These include pruning and weeding, replacing mulch, and removing trash as needed; inspecting inflow and outflow points for sediment, inspecting filter strips for erosion, reseeding filter strips (if necessary), and evaluating the health of plants in the bioretention cell semi-annually; and testing the pH of the soil (and adjusting if needed) annually. Larger maintenance tasks such as aerating soil to improve filtration, replacing gravel beds, replacing plants or trees and completely replacing mulch may need to be done every 2-3 years.

2.4.6. Costs

Costs for bioretention cells can vary, depending on location of the cell, and what kind of pollutants are expected to filter through. The following discussions break bioretention costs into construction (including design and permitting) and operation and maintenance.

2.4.6.1. Construction

Construction costs for bioretention cells vary with application. The EPA Bioretention Fact Sheet (1999), quoting Brown and Schueler, 1997, suggests a general cost equation for bioretention areas.

$$C = 7.30V^{0.99}$$

where:

C = construction, design, and permitting ($) and

V = volume of water treated by the facility (ft^3)

It may be helpful to also look at different cases in which bioretention may be applied instead of using a general equation because costs can vary with application. The Low Impact Development Center, Inc.suggests a range of costs for different applications because cells in residential areas are typically smaller and require less infrastructure than those in commercial or industrial areas. In general, bioretention areas in residential applications cost between $3 and $4 per square foot to construct. This range takes planning, design, and construction costs into account, as well as costs of plants and soil amendments. Larger scale bioretention projects for commercial, industrial, and institutional applications can cost between $10 and $40 per square foot. This cost reflects a more complex design with control structures, curbing, and under drains, as well as costs for permitting, planning, design, construction, and closeout inspections.

2.4.6.2. Operation and Maintenance

Operation and maintenance costs are typically estimated to be some percentage of base capital costs. Bioretention cells require regular maintenance, as discussed in

Section 2.4.5. Strassler, et. al. (1999) estimates maintenance costs for bioretention cells to range from 5 to 7% of construction costs.

2.5. Other Storm Water Best Management Practices

In addition to bioretention, there are many other structural best management practices (BMPs) for managing storm water quality and quantity. They range from very simple grassed swales to complex constructed wetlands. The most common storm water BMPs, their treatment capacity, and associated costs will be discussed in this section. References used for this section include a combination of Strassler, et. al. (1999), Low Impact Development Center, Inc., and the Georgia Stormwater Management Manual, Technical Handbook (2001) unless otherwise cited.

2.5.1. Retention Basins

Retention basins are designed to retain runoff by catching storm water runoff and holding it until it is displaced by runoff from another storm event. Retention basins typically have permanent pools of water between storm events which allows pollutants, such as sediments and metals, settle out between rain events.

Retention basins are quite effective at treating water quality (see Table 2.2), although there are some limitations to retention systems. During large rain events, the retention time decreases so pollutants are not allowed to settle before the water is released. Large rain events can also re-suspend solids and metals that have settled out in the pond. The most significant problem with retention systems is water temperature. Since retention ponds often have large surface areas, the temperature of the water, particularly during summer months, can increase so significantly that it affects biological communities in receiving waters.

2.5.2. Detention Basins

Detention basins are designed detain runoff. They catch storm water runoff, hold it for a short period of time, and slowly release the runoff. Because they are designed to release runoff, detention basins rarely have permanent pools of water between storm events. Detention basins treat storm water by slowing runoff enough for some settling of pollutant laden solids to occur. Limitations of detention systems are similar to retention systems.

2.5.3. Constructed Wetlands

Constructed wetlands are designed to capture runoff and then filter it through pools containing wetland vegetation. They are similar to detention systems as they usually release runoff, but they are also similar to retention systems in that they have permanent vegetated pools between storm events. Pollutants are removed by settling as runoff slowly flows through the wetland and by uptake by the wetland plants.

Table 2.2 shows that constructed wetlands are also good at treating runoff (with the possible exception of phosphorus). Since wetland plants provide a majority of water quality treatment, it is important to keep the vegetation healthy. Wetland plants need continuous baseflow to function properly, so constructed wetlands may not be applicable in areas with extended dry seasons. Sediment also affects the function of wetland plants, so proper maintenance to keep sediment levels low is often necessary.

2.5.4. Porous Pavement

Porous pavement is a type of infiltration system that utilizes pavement areas for infiltration. Porous pavement includes grassed pavers or, porous concrete and porous asphalt, which are conventional concrete or asphalt mixed a particular way to create voids. Storm water is treated as it filters through porous pavement media and by subsequent layers of coarse gravel and filter fabric. Porous pavement systems will work with or without an underdrain system, but in order for infiltration to occur, the pavement must rest on porous soils.

As with any infiltration system, porous pavements are excellent at treating water quality, but do have limitations. The most common issue with porous pavements is clogging. If porous pavements become clogged, they function more like impervious surfaces. Unclogging porous pavement can be labor intensive and expensive, because it involves vacuuming or surface replacement (Low Impact Development Center, Inc.l)

2.5.5. Grassed Swales and Filter Strips

Grassed swales and filter strips are also often called biofilters. They can infiltrate runoff from small rain events if base soils are porous, but typically filter runoff through shallow grassed basins (swales) or over grassed strips (filter strips). Biofilters are usually used along with other BMPs since they are not particularly good at treating quality or quantity as a stand alone BMP.

2.5.6. Sand Filters

Sand filters are systems that filter runoff through sand to remove pollutants through settling and filtering. They also provide some detention time as the runoff filters through the media. Sand filters usually have under drains that convey runoff to other BMPs in a system or to receiving waters. Sand filters have similar limitations as porous pavement systems.

2.5.7. Water Quality Treatment of Other Storm Water BMPs

There are many studies that have tested the efficiency of storm water BMPs at removing pollutants from storm water. The EPA's study of urban storm water BMPs summarized those studies in the following table.

Table 2.2. Typical BMP Pollutant Removal Capacity

BMP Type	Typical Pollutant Removal (%)				
	Suspended Solids	Nitrogen	Phosphorus	Pathogens	Metals
Detention Basin	30-65	15-45	15-45	<30	15-45
Retention Basin	50-80	30-65	30-65	<30	50-80
Constructed Wetland	50-80	<30	15-45	<30	50-80
Porous Pavement	65-100	65-100	30-65	65-100	65-100
Grassed Swales	30-65	15-45	15-45	<30	15-45
Filter Strips	50-80	50-80	50-80	<30	30-65
Sand Filters	50-80	<30	50-80	<30	50-80

Adapted from EPA-821-R-99-012, Table 5-7.

Bioretention, with the exception of porous pavement, out performs all of the BMPs discussed above for all of the discussed water quality parameters.

2.5.8. Costs of Other Storm Water BMPs

The costs associated with storm water BMPs vary greatly depending on the application and where the BMP will be installed. The table below summarizes base capital costs for installing the BMPs discussed above. The EPA study cited below was done in 1997, so all costs in tables were converted to 2007 dollars using the Consumer Price Index.

Table 2.3. Typical BMP Costs

BMP Type	Typical Cost (1997)		Typical Cost (2007)	
	($/cubic foot)		($/cubic foot)	
	low	high	low	high
Retention/Detention System	0.50	1.00	0.64	1.28
Constructed Wetland	0.60	1.25	0.77	1.60
Grassed Swales	0.50	0.50	0.64	0.64
Filter Strips	0.00	1.30	0.00	1.66
Sand Filters	3.00	6.00	3.84	7.68
	Typical Cost (2001)		Typical Cost (2007)	
	($/square foot)		($/square foot)	
Porous Pavement				
Asphalt	0.50	1.00	0.64	1.28
Concrete	2.00	6.50	2.56	8.32
Grassed Pavers	1.50	5.75	1.92	7.36

Adapted from EPA-821-R-99-012, Table 6-1 and LID Permeable Paver Costs

While bioretention cells may be slightly more expensive than porous pavement systems (the most expensive BMP discussed above) per square foot, porous pavement systems usually cover larger areas, which makes the prices comparable. Other costs associated with BMP design include design costs, and operation and maintenance costs. In general, design, and other related costs range from 25 to 32% of base construction costs. The table below summarizes maintenance costs for the BMPs discussed in this section.

Table 2.4. Estimated BMP Maintenance Costs

BMP Type	Est. Annual Maintenance Cost % of construction cost
Detention Basin	3%-6%
Retention Basin	<1%
Constructed Wetland	3%-6%
Porous Pavement	no data
Grassed Swales	5%-7%
Filter Strips	$320/acre
Sand Filters	11%-13%

Adapted from EPA-821-R-99-012, Table 6-10

Bioretention operation and maintenance costs similar to several of the other discussed BMPs.

2.6. Cost Minimization as an Environmental Policy Tool

Cost minimization (static efficiency, cost efficiency), according to Bohm and Russell (1985), can help determine management practices that achieve a goal at the least cost. They further define cost minimization analysis as one that assumes the environmental goal is static and the technology to reduce pollution and location of the technology remain fixed. Since this project focuses on structural storm water management tools (bioretention cells) specifically designed to improve water quality to a target level, cost minimization is a natural choice for analyzing the efficiency of the bioretention cells.

Most references describe the cost minimization model with the classic example of two firms discharging a residual to the environment (Bohm and Russell, 1985 and Sterner, 2003). The marginal costs of pollution control for both firms are considered in the equation, as is a clean-up target. The following is the general cost minimizing equation suggested in the above two references.

$$\min \sum_{i=1}^{n} C_i(x_i) \qquad s.t. \sum_{i=1}^{n} x_i \le X_i$$

where,

C_i = marginal cost of clean-up for each firm

x_i = amount each firm must reduce pollution to meet the target

X_i = the target pollution level

The “marginal clean up cost” is minimized subject to the target by using a Lagrange multiplier and setting up a Lagrangian (a method often used for minimizing or maximizing an outcome with many variables).

$$\min L = \min \sum_{i=1}^{n} Ci(x_i) + \lambda(X_i - \sum_{i=1}^{n} x_i)$$

The first derivative (or first order conditions) of the cost equation with respect to both firm’s marginal costs and the Lagrange multiplier are then determined.

$$\frac{\delta L}{\delta x_i} = C_i' - \lambda = 0 \Rightarrow C_i' = \lambda \quad \text{and}$$

$$\frac{\delta L}{\delta \lambda} = X_i - \sum_{i=1}^{n} x_i = 0 \Rightarrow X_i = \sum_{i=1}^{n} x_i$$

Since derivative of the costs of both firms are equal at the cost minimizing point (in this case, zero) , they are set equal to each other to solve for the marginal cost of reducing pollution by each firm (Bohm and Russell, 1985; Sterner, 2003; Keeler, 2002). Chapter 4 will discuss the cost minimizing process as it pertains to this study.

2.7. P8 Model Information

The Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds (P8) Urban Catchment Model Version 3.1 was chosen to simulate the treatment capacity of the study bioretention cells at the Rockdale Career Academy in Conyers, GA. The P8 model was developed in 1990 for the US Environmental Protection Agency and the Wisconsin Department of Natural Resources. It has been updated over the years and was converted to a Windows operating system in 2006 (Walker, 2007).

The P8 was included in an EPA study conducted by researchers at Oregon State University that looked at alternatives for BMP modeling. The study found that P8 was capable of simulating bioretention area performance in urban settings. While other models were capable of simulating bioretention areas, the P8 model was chosen because it can be applied to evaluate site plans for compliance and to evaluate BMP design to achieve treatment objectives (Huber, et. al., 2006) based on relative predictions in terms of percent removal (Walker, 2007) . Both of these functions are primary goals of this project. Since existing studies conducted for bioretention cells express efficiency rates as percent removal, comparisons between results from this study and other studies should be straightforward.

2.7.1. Inputs and Outputs

There are a variety of inputs required for the P8 model to simulate BMP function. They are grouped into five categories, treatment device, watershed parameters, particle parameters, water quality parameters, and climate data (Shoemaker, et. al., 1997). The treatment device inputs include type of device (structural control), dimensions, outlet configuration, infiltration rates, and slopes/roughness (for overland flow areas). Watershed parameters cover both impervious and pervious areas and include total area, impervious fraction, depression storage, runoff coefficient for impervious portion, street sweeping frequency, and runoff curve number for pervious portion. Both the device parameters and the watershed parameters must be input by the user. Particle parameters include accumulation/washoff parameters, runoff concentrations, street sweeper efficiency, settling velocities, decay rates, and filtration efficiencies. There are default values for particle parameters (since they are difficult to estimate in site specific cases) that were calibrated to "typical urban runoff" measured under the Nationwide Urban Runoff Program (NURP). Water quality parameters include weight distribution for several particle classes (0,10th, 30th, 50th and 80th percentiles), and up to three treatment objectives for water quality. Default values for water quality particle classes are included in the model, again calibrated to NURP values. The default water quality parameters are total suspended solids, total Phosphorus, Total Kjeldahl Nitrogen, Lead, Copper, and Zinc. The user can specify water quality objectives or can use default values. Finally, climate data, hourly precipitation and daily temperatures can be input by the user or can come from default files provided in the model (Walker, 2007). Chapter 4 will discuss the specific inputs to the P8 model for this study.

Model outputs include water and mass balances, pollutant removal efficiency, mean concentrations at inflow/outflow, and various statistical analyses by device (Shoemaker, et. al., 1997). Outputs will be discussed further in Chapter 5 (Results and Discussion).

2.7.2. Limitations

As with any predictive model, the P8 model has limitations, which Walker (2007) broke down into three categories; general limitations, watershed simulations, and device simulations. In general, the P8 model is more accurate for comparative analysis of BMPs (percent removal) than it is for more concrete predictions, such as concentrations of pollutants at outlets. It is fairly accurate at determining predictions of concentrations using NURP data, but only for worst case and typical scenarios. Simulation accuracy would be much more rigorous with site specific monitoring and weather data. P8 does not take effects of variations in vegetative cover into account when simulating evapotranspiration from a watershed, and does not simulate erosion, so it is not recommended for agricultural watersheds (Walker, 2007 and Shoemaker, et. al., 1997). P8 device limitations include not taking backflow effects (effects of flow from a downstream device) into account and it excludes precipitation that falls directly onto the device from simulations (unless the device is included in the watershed area). The P8 model also assumes that runoff to the devices is mixed (no plug flow simulated) and does not simulate particles being resuspended (Walker, 2007).

CHAPTER 3

CASE STUDY DESCRIPTION

In 2002, the Rockdale County, GA Board of Education approved the development of the county's fourth high school, a charter school with a focus on technological education. With their charter school status, and central location off Parker Road in Conyers, GA, (See Figure 3.1) Rockdale Career Academy (RCA) will serve students from Rockdale County's other high schools as well as non-traditional students interested in technology. The RCA will offer courses in business information and management, health and human services, technology and engineering (See Appendix A for more information on the Rockdale Career Academy and its curriculum).

The storm water management design, developed by Breedlove Land Planning, Inc. (BLP), the consulting firm in charge of site design, incorporated a bioretention cell/grassed swale system to provide an aesthetically pleasing landscape as well as a way to treat storm water run-off. Construction of the bioretention cells and swales began in spring 2006, and was completed in fall 2006. At the suggestion of BLP, the Rockdale County Board of Education approved turning six (6) bioretention cells and two (2) grassed swales in the student/faculty/staff parking lot into a research project that can transition to a teaching and research tool for students and faculty at RCA. See Figure 3.1 for the layout of the RCA.

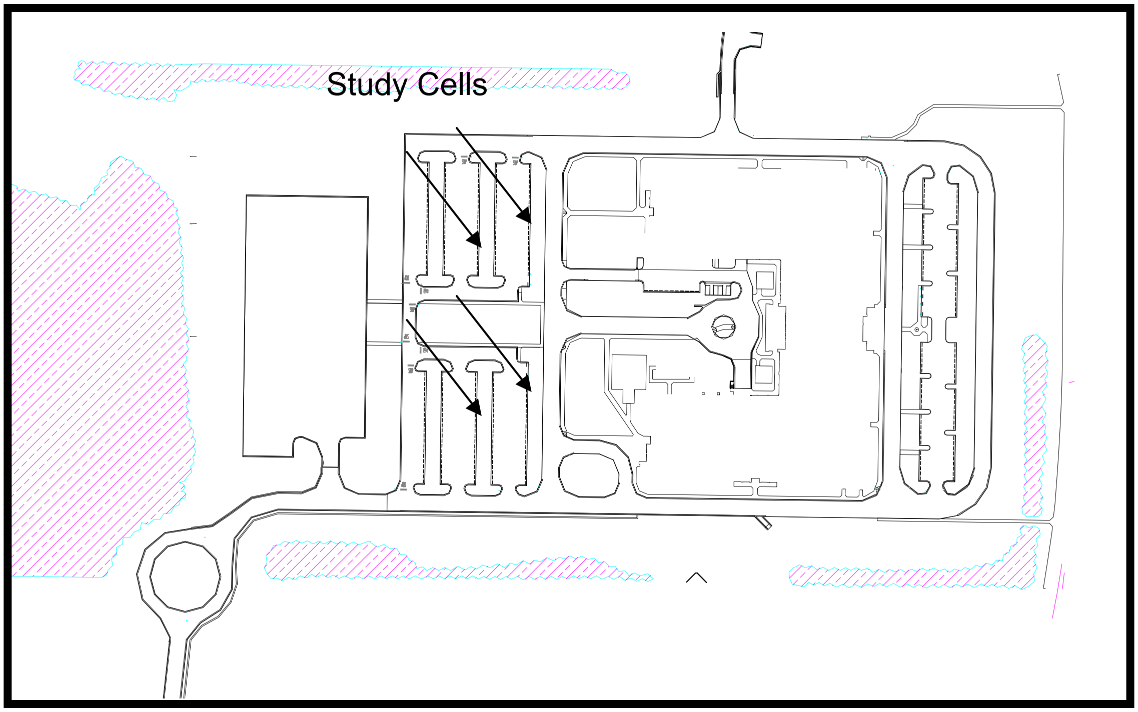


Figure 3.1. Rockdale Career Academy Site Layout

From: BLP Design

The Rockdale Career Academy is located on a 42 acre site in the southern part of Conyers, GA near Interstate 20. It is included in the Almand Branch watershed that drains the southwest portion of Conyers. Almand Branch, from Tanyard Branch to Snapping Shoals (just south of the RCA), is included on the 303(d)/305(b) List of Impaired Waters because it does not meet its designated use of fishing. It violates fecal coliform and pH criteria, likely due to urban influences (GAEPD 305(b)/303(d) List, 2006). Figure 3.2 shows the City of Conyers, the location of the RCA, the Upper Almand Branch watershed, and the impaired section of Almand Branch.

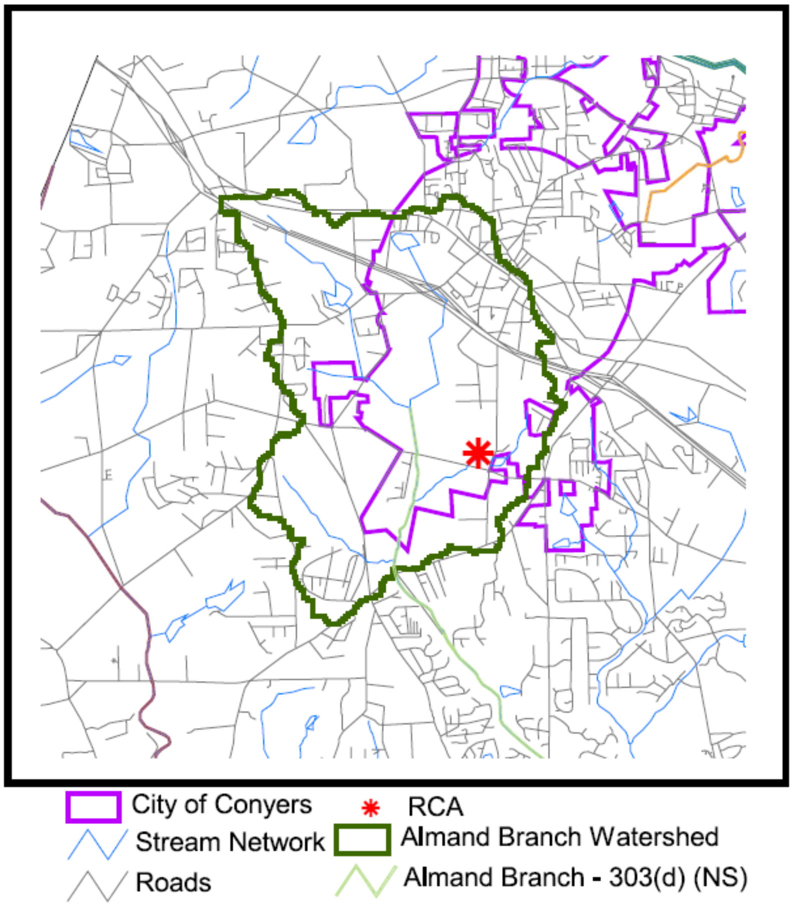


Figure 3.2. Upper Almand Branch Watershed

3.1. Project Description

As mentioned previously, six bioretention cells and two grassed swales on the Rockdale Career Academy campus were designed for research. The goal of the research was to provide valuable information as to cost and treatment (water quality) effective combinations of soil and planting material to help project managers choose appropriate alternatives of future bioretention projects. All six of the bioretention cells were studied, two were "control" cells with a standard mix of soils and four (in two larger cells) were "experimental" cells with reduced amounts of engineered soil amendments. Because the grassed swales were not constructed to design specifications, they will not be studied for this project. The impervious areas contributing to the bioretention cells are all student/faculty/staff parking and range in size from 0.17 acres to 0.52 acres.

3.2. Bioretention Design

BLP was responsible for all site design work for the Rockdale Career Academy. BLP's landscape architects and engineers designed the parking lots that drain to the bioretention cells and swales as well as the cells and swales themselves. They designed the bioretention cells handle the first 1.2 inches runoff coming from the surrounding parking areas, as required by the Georgia Stormwater Management Manual and the City of Conyers, GA.

The parking areas draining to bioretention cells have no curbs and are graded so rainfall can sheet-flow into the bioretention cells, which helps slow the flow. Runoff first filters through grassed strips that encircle the bioretention cells. The grassed strips reduce flow and start treating runoff by removing some pollutants. The runoff then enters the bioretention area. The bioretention area consists of several "layers". The first consists of planted material. There are some trees planted around the perimeter of the cells, but for the most part, the plant materials for this project are the specified wildflower mixes. The plant layer provides aesthetic appeal, uptakes nutrients and other pollutants, and helps reduce water volume by evapotranspiration and by creating infiltration pathways along roots (Georgia Stormwater Management Manual, Technical Handbook, 2001). The next layer consists of planting soil. For this project, two soil mixes were used and are discussed in the following section. The planting soil provides water and nutrients to the plants as well as providing media for microbes to break down organic compounds and nutrients that can be used by plants (Georgia Stormwater

Management Manual, Technical Handbook, 2001). In order to keep valuable soil from migrating into the gravel layer and the underdrain, a layer of filter fabric lines the area to the sides and below the soil. The next layer consists of filter stone, which a moderately coarse gravel, that further filters the runoff before it reaches the underdrain. The next layer is consists of two underdrains (per cell). The underdrains are slightly sloped toward the overflow structure at one end of each bioretention cell. The underdrains help ensure proper drainage for plants and infiltration (Georgia Stormwater Management Manual, Technical Handbook, 2001). They are wrapped in filter fabric to prevent clogging. The underdrains empty into the overflow wells through a cap with a hole in it. The final layer is again, filter fabric, which prevents on-site soil below the cells from migratomg into the gravel bed. The overflow structure mentioned above is important in case of large storm events that may overwhelm the infiltration capacity of the bioretention cells or if the soil or underdrain become clogged. Figure 3.3 shows a cross-section of a typical bioretention cell at the RCA site.

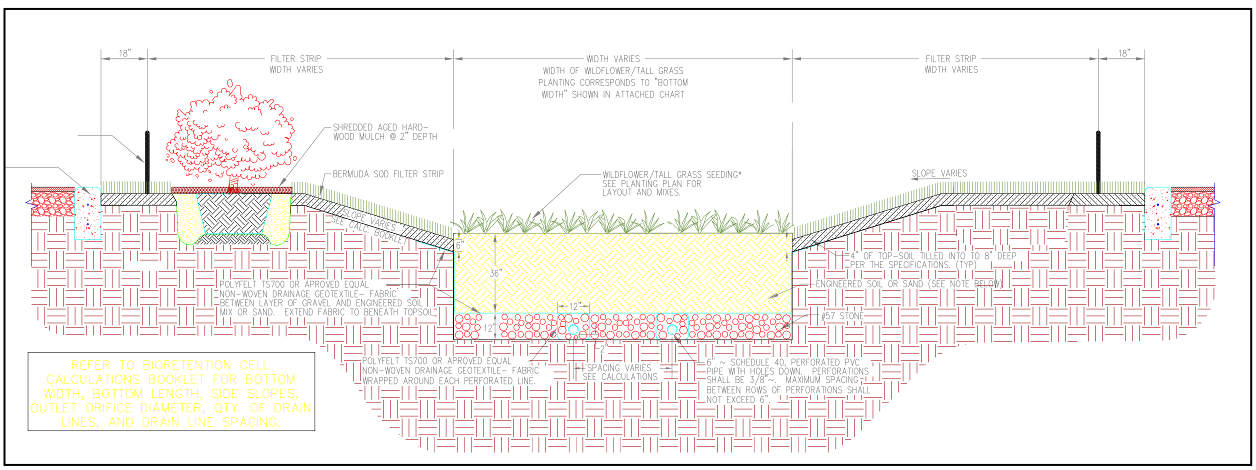


Figure 3.3 – Bioretention Cell Cross Section (BLP Design Documents)

Appendix A contains design information, including water quality calculations, discharge orifice calculations, water quality basin sizing, and basin design dimensions that were provided by BLP.

3.3. Bioretention Soils and Plants

There are two soils and two plant combinations that will be studied for this project. Soil A, the control soil mixture for bioretention, contains 40% topsoil (from the site), 20% organic, composted soil conditioner (ERTH Food ® specified), 20% expanded clay (HydRocks ™ specified), and 20% river sand. Soil B, the experimental soil mixture for bioretention, contains 40% topsoil (from the site), 10% organic, composted soil conditioner (ERTH Food ® specified), 10% expanded clay (HydRocks ™ specified), and 40% river sand. The two plant combinations, Plants A (short prairie mix) and B (wildlife prairie mix), are two commercially available wildflower mixes that will be paired with Soils A and B. See Appendix A for more details on ERTH Food ®, HydRocks ™ and the specified wildflower mixes. It should be noted that the use of ERTH Food ®, HydRocks™, and the commercially available wildflower mixes in this project is not an endorsement by the author or The University of Georgia. Figure 3.4 shows the bioretention cells while Table 3.1 lists soil and plant types in each cell as well as the contributing area and the impervious area percentage.

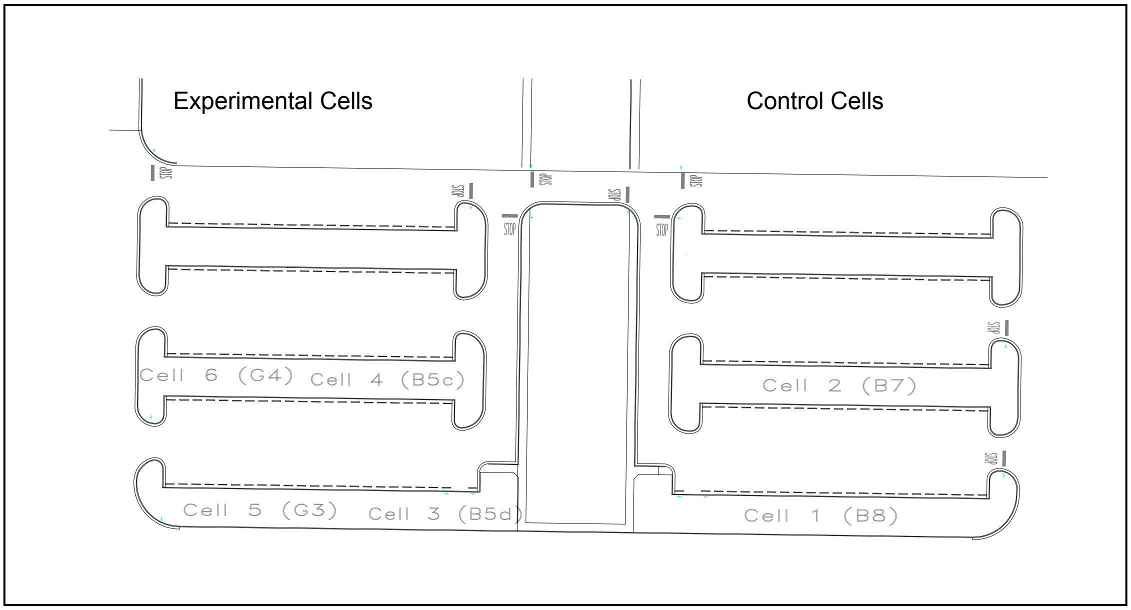


Figure 3.4. Study Bioretention Cells (Soil and Plant Mixtures)

Table 3.1 – Soil, Plants and Contributing Areas for Bioretention Cells

Cell #	Soil	Plant	Developed Area (ac)	Impervious Area (ac)
Cell 1 (B8)	A	B	0.73	0.52
Cell 2 (B7)	A	A	0.60	0.42
Cell 3 (B5d)	B	B	0.28	0.28
Cell 4 (B5c)	B	A	0.37	0.17
Cell 5 (G3)	B	B	0.48	0.37
Cell 6 (G4)	B	A	0.31	0.22

3.4. Bioretention Cell Costs

The actual costs for the bioretention cells came from cost estimates provided by BLP for the RCA project. Costs considered in this study included gravel, ERTHFood ®, onsite topsoil, HydRocks™, river sand, geotextile (filter) fabric, and construction related labor. The material costs were determined using design specifications such as cell volume and soil mix percentages coupled with standard rates for each material. Labor costs were also determined based on cell volume. The overall material costs reported were calculated by multiplying the cost per cubic foot treated by the design volume of water treated. A similar calculation was done, taking labor into account, to determine the overall cost for each cell. Appendix A has the complete cost breakdown and Table 3.2 shows the overall costs for the study bioretention cells at the RCA.

Table 3.2 – Study Bioretention Cell Costs

Cell ID	Total Cost of Soil & Gravel & Fabric	Cost Per C.Y of Material.	Labor Cost ($20/yd)	Total Cost of Cell	Volume Treated (c.f.)	Material Cost Per Cubic Foot Treated	Total Cost Per Cubic Foot Treated
Cell B8	$15,783.30	$23.08	$13,680.00	$29,463.30	2275	$ 6.94	$ 12.95
Cell B7	$15,468.80	$23.08	$13,407.41	$28,876.20	2229	$ 6.94	$ 12.95
Cell B5d	$4,779.05	$19.93	$4,797.04	$9,576.09	778	$ 6.14	$ 12.31
Cell B5c	$8,147.11	$19.93	$8,177.78	$16,324.89	1300	$ 6.27	$ 12.56
Cell G3	$8,941.16	$19.93	$8,974.81	$17,915.97	1591	$ 5.62	$ 11.26
Cell G4	$6,343.53	$19.93	$6,367.41	$12,710.94	996	$ 6.37	$ 12.76
Cell B5d/G3	$13,720.21	$39.85	$13,771.85	$27,492.06	2369	$ 5.88	$ 11.78
Cell B5c/G4	$14,490.64	$39.85	$14,545.19	$29,035.83	2296	$ 6.32	$ 12.66

The values reported in Table 3.2 do not include costs for items considered to be constant across all cells, including overflow structures, underdrains, plantings, and design work.

3.5. Requirements Met with Bioretention Cells

The bioretention cells installed at the RCA help to meet structural storm water management requirements of the Phase II General NPDES Storm Water Permit that was issued in 2002 (GAEPD 305(b)/303(d) List, 2006). As mentioned in Chapter 2, Phase II Storm Water Regulations drive construction requirements for most cities and counties in Georgia. The goals of Phase II are to incorporate public education and outreach with BMPs to improve water quality while reducing runoff. The bioretention cells at RCA help meet all of these requirements by slowing runoff, improving water quality, and providing educational opportunities for students and faculty at RCA. Section 3.5.2 will discuss how the RCA bioretention cells meet specific ordinances, while Section 3.6 will discuss the educational component of the project. Since Conyers is a Phase II community, its storm water related ordinances are designed to meet Phase II criteria.

3.5.1. City of Conyers Ordinances

Since the site plan for Rockdale Career Academy was approved by the City of Conyers' planners, it can be inferred that it met all requirements for tree protection and post development storm water management. This section will give details on how city ordinances were met.

The tree protection ordinance gives minimum design criteria for landscape parking lot median islands, which is one of the functions of the bioretention cells. The ordinance requires that median islands be at least 8 feet wide from curb to curb, end islands at least 10 feet wide, and trees placed every 10 to 30 feet depending on species. The RCA bioretention cells are approximately 25 feet wide with end islands that are 20 feet wide. The trees planted along the cells are spaced between 20 and 30 feet apart. The design exceeds minimum requirements of the tree protection ordinance.

While the entire RCA site meets the post-development requirements laid out in Title 12 of the Code of the City of Conyers, the bioretention cells were designed specifically to meet water quality requirements. The water quality volume required to capture and treat the first 1.2 inches of rainfall was exceeded in the design. The cells also provide storage in the ponding area, soil, gravel bed, and under drain, which does contribute to downstream channel protection, although the storage capacity of the cells was not considered in the overall design hydrology study.

3.5.2. Storm Water Utility

The City of Conyers implemented a storm water utility to help maintain storm water conveyances and improve storm water quality. All business, industries, and residences are subject to fees under the utility. While some institutional owners are subject to storm water fees, the Rockdale Career Academy is exempt. Had it not been exempt, the RCA's design would have likely allowed for storm water credit, up to 50% fee reduction using any combination of water quality features, reduced imperviousness, and downspout disconnection. In order to receive storm water credit, it must be shown that features on the site exceed City development requirements.

Water quality features on the RCA site may qualify for storm water credits. The water quality features must exceed Georgia Stormwater Management Manual requirements by 25% to receive credits. All of the study bioretention cells were designed to handle larger than required water quality volume. The cells also, according to water quality results, exceed the only required water quality measurement, 80% removal rates for solids. While the removal rate is not exceeded by 25% for solids, the high removal rates for metals and fair removal rates for nutrients contribute to water quality improvement at the outlet.

The study bioretention cells also reduce imperviousness by providing between 3500 and 4000 extra square feet (between 0.08 and 0.09 acres) of pervious and landscaped area per cell than required by tree ordinance. The site design also handles roof runoff using bioretention cells (not included in this study) so it may qualify for credits pertaining to downspout disconnection.

3.6. Educational Component of Bioretention Cells

In addition to determining efficient combinations of soils and plants for bioretention, a goal of all involved parties was to develop recommendations for educational programs for students attending Rockdale Career Academy. The recommendations discussed in Chapter 7 focus on three career tracks at RCA that are the most applicable to the research conducted, Engineering Drawing and Design, Horticulture/Agri-Science, and Manufacturing and Engineering Technology.

CHAPTER 4

METHODOLOGY

4.1. Water Quality Sampling Methodology

The methodology used for water quality sampling for the bioretention cells at the Rockdale Career Academy was developed by the author. The University of Georgia's Agricultural Services Laboratories, the Soil, Plant, and Water Laboratory and the Feed and Environmental Water Laboratory provided support services for water quality testing.

Ideally, each storm event should be separated by at least 72 hours of dry weather (as suggested by the Environmental Protection Division). Results of the sampling should be reported only when rainfall was greater than 0.5 inches over a 24-hour period (this interval was chosen instead of the standard 0.2 inches of rain so there will be sufficient sample available at the sampling ports). Since the State of Georgia was in moderate to severe drought during the time of sampling, and storm events were few and far between, the outfall of each cell was checked after every rain event to see if any runoff had infiltrated. There was only one rain event that afforded enough water from each outfall to run water quality analysis. Water quality grab samples were taken from six sampling ports (Figure 4.1) following one storm event in May 2007 at the Rockdale Career Academy project site.

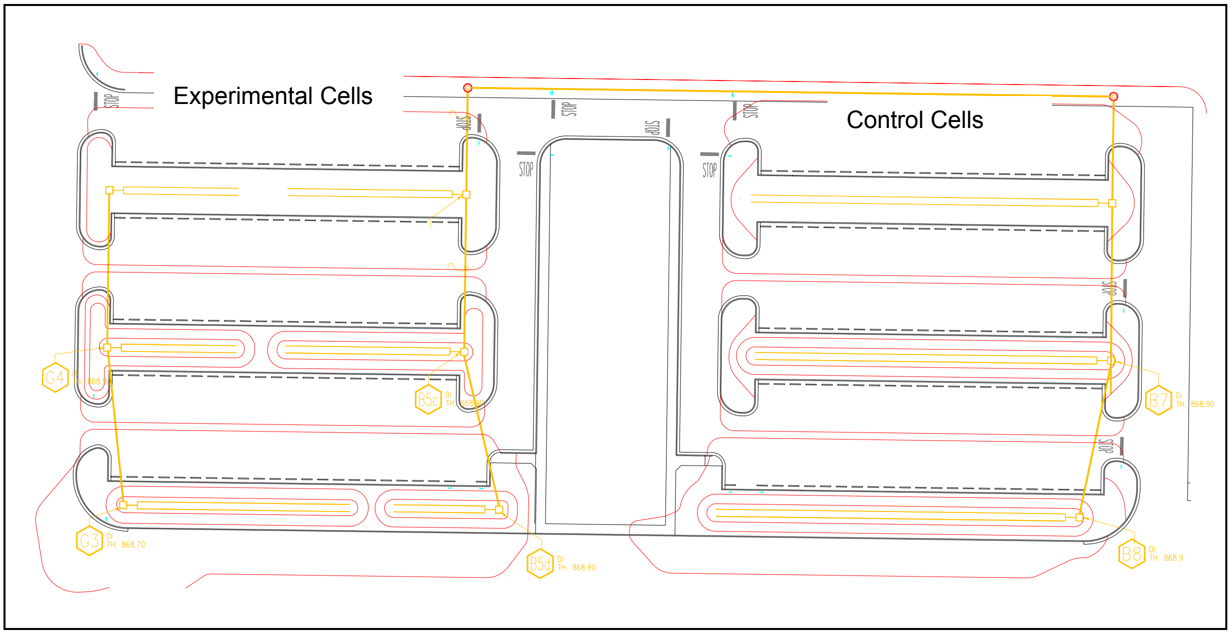


Figure 4.1. Water Quality Sampling Ports

The samples were taken and temporarily stored in pre-cleaned high-density polyethylene sampling containers that were properly labeled. Samples were collected by University of Georgia (UGA) and Breedlove Land Planning, Inc. employees and taken to the Agricultural Services Laboratories at UGA for analysis. Water samples taken from the Rockdale Career Academy site were analyzed for several parameters commonly present in storm water runoff. These parameters include metals (Lead, Copper, Iron, and Zinc), suspended solids, Nitrate/Nitrite-N (form of Nitrogen most used by aquatic plants), and total Phosphorus. A total of 1250 mL of sample was required for the analysis conducted, with 125 mL for metals and other elements, 125 mL for nutrients, and 1000 mL for solids. Samples were preserved by transporting and storing them in ice to keep the temperature at 4˚C and by preserving the nutrient samples with ph<2 sulfuric acid, which was done by Agricultural Services Laboratory personnel upon receipt of the samples.

4.2. Water Quality Analysis Methodology

As mentioned above, UGA's Agricultural Services Laboratories provided support services for water quality testing. Total suspended solids were analyzed by the Feeds and Environmental Water Lab, while metals and nutrient analyses were conducted by the Soil, Plant, and Water Analysis Laboratory. Appendix B contains water quality analyses methods and protocols.

4.3. Modeling Methodology

4.3.1. Simulations

The Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds (P8) model uses several procedures to conduct simulations. The following section will discuss the procedures used to model the treatment capacity of the six bioretention cells at the Rockdale Career Academy in Conyers, GA. All information in this section comes from the help file (manual) accompanying the P8 model, unless otherwise cited.

4.3.1.1. Watershed Runoff

The P8 model estimates runoff based on rainfall and snowmelt data in precipitation files that are either available with the model or are user defined. Runoff for the pervious portions of the watersheds was simulated using the SCS (Soil Conservation Service) curve number method that was suggested by the USDA in 1964, while runoff from impervious portions of watersheds simulation began after rainfall and snowmelt exceed the depression storage (a value specified by the user that will be discussed later). Background soil moisture content or antecedent moisture condition (AMC) can be adjusted based on rainfall and snowmelt data as well. Percolation is not considered unless runoff is routed to an aquifer and evapotranspiration is calculated using air temperature, day length and month. See Appendix B for calculations from the P8 Manual that were used to determine snowmelt runoff, runoff from frozen soils, runoff from impervious areas, and how curve numbers can be adjusted based on the AMC.

4.3.1.2. Watershed Pollutant Loadings

In addition to the storm water runoff component, P8 simulates pollutant loadings from watersheds. Pollutant loadings from the pervious portions of watersheds are determined by applying a fixed concentration to the runoff volume for each particle class (particle classes will be discussed in a later section). Pollutant loads from impervious surfaces are calculated by applying a fixed concentration to the runoff volume and by simulating particle buildup and washoff processes. The pollutant loads are then summed for each watershed and multiplied by the “pollutant load factor”, which can be adjusted to model more loading or less loading, due to land use or other factors, if data are available. See Appendix B for equations used by P8 to calculate particle buildup and washoff.

4.3.1.3. Storm Water Best Management Practices

P8 also simulates water quality flows through and treatment capacity of storm water best management practices (BMPs). Flow through devices is simulated using inputs such as device volume, inflows, number and type of outlets. Then the model uses flow and the other inputs, along with inflow pollutant loads, particle settling velocities, and device surface area to determine concentration of water quality parameters at the outlet.

4.3.2. Model Inputs

The P8 model has several input interfaces where the user can either enter site-specific data or use data sets provided with the program. The following sections will discuss the inputs used for simulating the study watersheds and why they were chosen.

4.3.2.1. General

The "general" interface screen allows the model user to specify general information about the case to be modeled. The hourly precipitation file was obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center. The weather station at Hartsfield-Jackson International Airport was the closest station to the Rockdale Career Academy that had hourly data available. One year of precipitation information (June 2006 – May 2007) was converted to a .pcp file (a type of text file) so the P8 model could read the data. Since the airport is about 40 miles away from the study site, the precipitation data may not be truly representative of the conditions at the RCA. The "general" interface also allows the user to change the number of times the simulation runs through the storm file (to simulate more events), the precipitation scale factor (to increase storm events in the precipitation file), and change the number of time steps per hour. These inputs, with the exception of time steps per hour (set at 60) were kept at the default value, one (1), for the initial model run.

4.3.2.2. Devices

The "devices" interface for each case is set up as a system of best management practices (BMPs) and the watersheds that contribute runoff to them. There are seven (7) devices to choose from in the P8 model device interface, including detention ponds, swales, and pipes. The device chosen for this project was the infiltration basin because it most closely resembled the function of a bioretention cell. Once the device type was chosen, design parameters were entered into the model. Since overflow and infiltrated runoff leave the system through the drop inlet overflow structure and the underdrain, respectively, they are considered by the model to leave the system. The particle removal scale factor changes particle removal rates. According to the P8 Manual, this factor could increase if plants were incorporated into the design to stabilize sediments and provide pollutant uptake. Since plants are an important part of bioretention function, the removal scale factor for this study was increased to 3, which is an average for removal efficiency for plants in a storm water structure.

Parameters specific to the physical aspects of the bioretention cells were entered. These include the bottom elevation (ft), the bottom area (ac), storage pool area (ac), storage pool volume (ac-ft), void volume (%), and infiltration rate (in/hr). The void volume and infiltration rate were the two parameters that differed between the control and experimental cells. Void volumes were estimated to be 30% for control cells and 40% for experimental cells, while infiltration rates ranged from 24 inches/hour for control and 32 inches/hour for experimental bioretention cells. These parameters came directly from the Breedlove Land Planning design parameters for the RCA bioretention cells. Appendix B contains a table with the actual inputs for each bioretention cell.

4.3.2.3. Watersheds

Each watershed entered into the P8 model is linked to a downstream device, so once each watershed was named, its outflow device (or BMP) was chosen. There should be little if any percolation to groundwater, because underdrains and overflows should catch any water that infiltrates through the cell and overflow. For this reason no values were entered pertaining to percolation. The total area of each watershed was entered according to data from BLP's design documents. The pervious area curve number was determined using a table that lists curve numbers for various land use and hydrologic conditions from P8 Manual (Georgia Stormwater Management Manual, Technical Handbook, 2001).

After researching the hydrologic soil groups, it was determined that the soils in the pervious areas of the watersheds (the bioretention cell surfaces) were grassed areas with good vegetative cover and underlying soils most closely described by Hydrologic Soil Group B (Georgia Stormwater Management Manual, Technical Handbook, 2001). The curve number used for all watersheds was 61, which was listed in the P8 Manual as the value for Group B soils with good vegetative cover. The scale factor for particle loads was left as the default, one (1), as recommended by the P8 Manual.

The model can simulate both "swept" and "not swept" portions of watersheds. Since the RCA site is not swept, all of the swept inputs are zero. Data for the impervious fraction of the watershed and the impervious runoff coefficient came directly from the BLP design, while the depression storage (runoff storage of the impervious portion of the watershed) was calculated using information from the BLP design and the equation provided by the P8 Manual. Appendix B contains a table with the actual inputs for each bioretention cell.

4.3.2.4. Particles

Default particle files, provided with the model, were used to simulate particle movement through the bioretention cell system. The default particle file used in this simulation is based on Nationwide Urban Runoff Program (NURP, 1987) data for particulates in runoff and contains information for five particle classes, which are used to simulate settling of particulates in storm water. The first class (P0%) corresponds to the amount of dissolved water quality parameters that may be present. The remaining classes, 10^{th} percentile, 30^{th} percentile, 50^{th} percentile, and 80^{th} percentile were determined based on calibrating the model to NURP data using settling velocities of particulates. While site-specific particle data would be ideal in this situation, it was unavailable for this study.

4.3.2.5. Water Quality

The water quality interface in P8 allows the user to input particle composition information for up to 10 water quality parameters and up to three water quality criteria (target water quality levels) for each parameter. The default water quality parameters are total suspended solids (TSS), total phosphorus (TP), total kjeldahl nitrogen (TKN), total copper (Cu), total lead (Pb), total zinc (Zn), and hydrocarbons (this study will not consider hydrocarbons). The particle composition table uses particle classes from the particle file and is "used to translate particle concentrations into water quality parameter concentrations" (P8 Manual). The particle composition concentrations (mg/kg) were also calibrated to correspond to median values determined by the NURP study. Default values for particle compositions were used for this study due to lack of site specific data. P8 uses the particle concentrations, along with filtering efficiencies (the amount of each particle class is reduced by infiltration) to predict concentrations from device discharges. P8 also uses target levels of water quality to determine if violations of the criteria occur during the model run. The model compares the target criteria with mean concentrations for each device and lists the percent of events where the target level was exceeded. The default criteria were not used, as more site-specific values were available. Table 4.1 lists the targets for the water quality parameters considered in this study. These targets will also be used for the cost analysis, discussed later in this document.

Table 4.1. Water Quality Targets

TSS (mg/L)	TP (mg/L)	TKN (mg/L)	NO3/NO2-N (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
20	0.10	10	5	0.007	0.03	0.065
Michigan Dept of Env. Quality considered to be “clear”	USGS suggested level not to exceed to prevent eutrophication	USGS suggested drinking water level	North Carolina State University suggested not to exceed for fish health	GAEPD acute criteria for flowing waters	GAPED acute criteria for flowing waters	GAEPD acute criteria for flowing waters

4.3.2.6. Evapotranspiration and Snowmelt

The P8 Model also has an interface for snowmelt, pervious area runoff, and evapotranspiration parameters. Snowmelt will likely have little effect on the simulation for the RCA bioretention cells, so no values were entered for the snowmelt coefficient and critical temperatures. The pervious area runoff parameters include growing season and antecedent moisture condition, ACM, (the five-day antecedent rainfall) for both growing and non growing seasons. The Georgia State Climatology Office website provided the growing season for Georgia, while the ACM came from the lower end of the range for normal and saturated soils as described by the Soil Conservation Service and referenced in the P8 Manual. The vegetated cover values were left at the default value, while average monthly air temperature values came from the Georgia State Climatology Office and day length hours (first of each month, June 2006-May 2007) came from The Georgia Automated Environmental Monitoring Network. Appendix B contains a table with the actual inputs for each parameter mentioned above.

4.4. Cost Minimization Methodology

Cost minimization was chosen to analyze the cost efficiency of the study bioretention cells at treating water quality parameters. To begin the analysis, costs were determined for each bioretention cell. Estimated construction costs (converted to 2007 dollars) were determined using the equation from Brown and Schueler discussed in Chapter 2 and “actual” construction costs came from Breedlove Land Planning, Inc. design documents. Since all six cells are on the same site, designed by the same company, and were constructed at nearly the same time, some of the actual costs were assumed to be constant across all cells, including design and maintenance. While the plants are different mixes, they were similar enough to assume comparable costs across cells as well. The main cost differential between the control cells and the experimental cells came from the soil mix.

Opportunity costs will not be considered in the calculation of costs because they are reduced significantly (if not completely) by exceeding local ordinances. As discussed in Chapter 3, landscaped areas with trees are required for all parking lot construction. The bioretention cells at the RCA are larger than the required area for tree protection, but they provide more pervious area to the campus and exceed requirements for storm water management controls, which would reduce costs, if the RCA were subject to the storm water utility fees.

4.4.1. Cost Minimization – The Ideal Solution

Ideally, costs as a function of materials would be minimized subject to water quality treatment, as a function of materials used, and volume of runoff treated in an analysis such as:

Min $C = C(m)$

st. $x_i = f_i(m) \geq$ *or* $\leq X_i$ *(depending on if % reduction or concentration is used, and*

$v \geq V$

where: m is a vector of materials,
x is pollutant reduction or concentration of i pollutant,
X is the target pollutant reduction level or concentration for i pollutant,
v is the design runoff volume and,
V is the required runoff volume

Solving the above equation would result in design criteria for the ideal bioretention cell that treats water quality to target levels and handles the required amount of runoff at the least cost. Determining water quality treatment as a function of materials was not within the scope of this project as it would require extensive soil and plant testing, but expected results of such a study are discussed in Chapter 5. Instead of designing an ideal bioretention cell, the bioretention cells already in place at the Rockdale Career Academy will be analyzed to determine the least cost set of bioretention cells (to reach desired targets) and the most cost effective (per volume of runoff treated) cell for treating each pollutant.

4.4.2. Cost Minimization

A cost minimization analysis was conducted to determine the least cost combination of existing bioretention cells that will meet water quality criteria and runoff volume requirements. The mathematical model for this analysis is:

$$\min C = \sum_{j=1}^{6} C_j u_j$$

$$st. \sum_{j=1}^{6} v_j u_j \geq V \quad \textit{and} \quad st \frac{\sum_{j=1}^{6} x_{i,j} u_j}{\sum_{j=1}^{6} u_j} \leq or \geq X_i \quad \textit{and} \quad st \sum_{j=1}^{6} u_j = or \leq or \geq U$$

where C_j *= Cost of each bioretention cell*
u_j *= optimal units of j bioretention cell*
v_j *= volume of runoff treated by j bioretention cell*
V *= volume of runoff treated required*
$x_{i,j}$ *= water quality % reduction or concentration for i pollutant in j bioretention cell*
X_i *= target water quality for i pollutant*
U *= target number of units*

Because there are multiple targets, one for volume, one for each water quality parameter, and one for the number of units, the solution Lagrangian will be set up with multiple constraints, in order to minimize the cost for each bioretention cell. The general solution equation is:

$$\min L = \min \sum_{j=1}^{6} C_j(u_j) - \lambda_1 (V - \sum_{j=1}^{6} v_j u_j) - \lambda_2 (X_i - \frac{\sum_{j=1}^{6} x_{i,j} u_j}{\sum_{j=1}^{6} u_j}) - \lambda_3 (U - \sum_{j=1}^{6} u_j)$$

Taking the partial derivative of the general Lagrangian with respect to u_j, and λ_1, λ_2, and λ_3 and setting each derivative equal to zero will set up equations that can be solved to find the optimal values of u_j (existing bioretention cells) to minimize the overall cost.

Excel Solver will be used to solve these equations to find the optimal number of bioretention cells that meet water quality criteria and volume requirements at the least cost. A spreadsheet with input values from BLP design documents, water quality sampling, and predictive modeling was set up along with constraints for water quality (Table 4.1) and volume (Appendix A, BLP design documents). See Appendix B for the inputs used in the Excel Solver.

4.4.3. Cost Efficiency

An analysis will also be conducted to determine how cost efficient each bioretention cell is at reducing the various pollutants (lead, copper, zinc, total suspended solids, and total phosphorus) per volume of runoff handled. The general equation used to rank the bioretention cells according to their cost efficiency for treating individual parameters is:

$$E_i = \frac{C_j}{V_j \times T_i}$$

where: E = Bioretention Cell Efficiency per pollutant i
C = cost of bioretention cell ($) j
V = design volume (ft^3) j
T = % reduction of pollutant i

Once the cost efficiency per pollutant for each bioretention cell is established, each cell will be analyzed to determine which cells perform more efficiently if one or more water quality parameter is given more weight (importance) than others. To do this, a weighted average will be calculated (using MS Excel) for each cell taking into account each water quality parameter at a specified weight and then the weighted averages will be ranked to determine which bioretention cell performs the most efficiently.

This analysis will focus on increasing importance of treating total suspended solids (TSS) because current storm water policy focuses on TSS levels at site outfalls to determine if the site is in compliance with NPDES Phase II requirements. There will be eight scenarios investigated for this analysis; each pollutant weighted equally, TSS weighted 50% and others weighted 12.5%, TSS weighted 75% and others weighted 6.25%, and TSS weighted 100%, for both predicted and actual pollutant removal percentages. The results will show which cells are more efficient at treating TSS at varying levels of importance.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter will present the results of water quality sampling, water quality modeling, and cost minimization analysis for the six study bioretention cells at the Rockdale Career Academy (RCA) in Conyers, GA.

5.1. Water Quality Sampling Results and Discussion

As discussed in Chapter 4, the State of Georgia was in a moderate to severe drought in May and June 2007, so a limited amount of water quality data were actually collected. Only one set of samples was analyzed from the outlets of the bioretention cells at the RCA. While there were not enough samples available to draw any conclusions about the treatment capacity of the bioretention cells, the analysis did provide valuable information. Lead concentrations were all less than 0.002 mg/L, while copper concentrations ranged from less than 0.005 mg/L to 0.0141 mg/L (Cell G4). Zinc concentrations ranged from 0.018 mg/L (Cell B8) to 0.304 mg/L (Cell G4). Suspended solids ranged from less than 1 mg/L (Cell B7) to 10 mg/L (Cell B5d). Nitrate-Nitrite concentrations ranged from 1.17mg/L (Cell B5d) to 3.19 mg/L (Cell G4), and Phosphorus ranged from 0.14 mg/L (Cell B7) to 0.64 (Cell G4). All of the cells had pollutant concentrations well below the Georgia Environmental Protection Division's standards (for metals), and suggested levels of solids and nitrate/nitrite to maintain fish habitat. Phosphorus levels were slightly higher than the suggested level of 0.1mg/L to prevent eutrophication in lakes. Table 5.1 shows the outlet pollutant concentrations for all water quality parameters for all six cells.

Table 5.1 – Outlet Pollutant Concentrations for Bioretention Cells at the RCA

	Cell B8	Cell B7	Cell B5d	Cell G3	Cell B5d/G3*	Cell B5c	Cell G4	Cell B5c/G4*
Lead (mg/L)	0.0019	0.0019	0.0019	0.0019	0.0019	no sample	0.0019	0.0019
Copper (mg/L)	0.0049	0.0049	0.0049	0.0049	0.0049	no sample	0.0141	0.0141
Zinc (mg/L)	0.018	0.0207	0.0235	0.0194	0.02145	no sample	0.0304	0.0304
TSS (mg/L)	4	0.9	10	2	6	no sample	8	8
NO2/NO3-N (mg/L)	2.69	3.13	1.17	1.26	1.215	no sample	3.19	3.19
TP(mg/L)	0.23	0.14	0.05	0.21	0.13	no sample	0.64	0.64
*values are average across both cells								

The water quality data were used to determine “actual” pollutant reduction, using average national values from the National Stormwater Quality Database (2004) for pollutant concentration entering the bioretention cell and observed values for output. Cells B5d and G3 and Cells B5c and G4 were grouped together to make comparisons between the experimental and control cells straightforward, and because they are already spatially grouped on the site (but because of site considerations could not drain to the same outlet). Reduction percentages for the grouped cells were averaged before they were used in any analysis. Table 5.2 shows the pollutant reduction percentage for all water quality parameters for all six cells.

Table 5.2 – Pollutant Reduction for Bioretention Cells at the RCA

WQ Parameter	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Lead (% Reduction)	88.82	88.82	88.82	88.82	88.82	ns	88.82	88.82
Copper (% Reduction)	71.18	71.18	71.18	71.18	71.18	ns	17.06	17.06
Zinc (% Reduction)	86.67	84.67	82.59	85.63	84.11	ns	77.48	77.48
Suspended Solids (% Reduction)	92.59	98.33	81.48	96.30	88.89	ns	85.19	85.19
TKN (% Reduction)								
Nitrate/Nitrite (% Reduction)	*	*	*	*	*	ns	*	*
Total Phosphorus (% Reduction)	11.54	46.15	*	19.23	*	ns	*	*

As can be seen from the results presented in Tables 5.1 and 5.2, the bioretention cells at RCA appear to be quite efficient at reducing metals (lead, copper, and zinc) as well as suspended solids. Some of the cells were fairly efficient at removing Phosphorus, and none were effective at removing Nitrate/Nitrite. The problems with Phosphorus and Nitrate/Nitrite arose because the input pollutant levels were lower than the output value. The high output value may be due to fairly high background levels of nutrients in the engineered soil amendments (U.S. Composting Council, 2006) that are necessary to promote plant growth. At the time of sampling the plants in the bioretention cells were not functioning as desired (due to improper maintenance – see Appendix C for pictures) and were likely not taking up many nutrients, however, levels of nitrogen compounds and some of the phosphorus levels were below suggested levels to maintain fish populations.

Water quality sampling results were also used in the cost analysis. The concentrations of the various water quality parameters and the pollutant reduction results shown above were used to determine the bioretention cell at the RCA that meets water quality criteria and volume requirements at the least cost and to determine which bioretention cell treats individual water quality parameters most efficiently per volume of runoff treated.

5.2. P8 Model Results and Discussion

The P8 Model was also used to determine water quality treatment capacity of the bioretention cells at the RCA. Model outputs were not calibrated to existing data for this study because only one rain event was sampled for the project. The first model run used inputs discussed in Chapter 4 and Appendix B. As discussed in section 5.1, the average percent reduction for Cell B5d and Cell G3 was calculated, as was the average percent reduction for Cell B5c and G4. Table 5.3 shows the results.

Table 5.3 – P8 Model Results

Variable	CELL_B8	CELL_B7	CELL_B5D	CELL_G3	CELL_B5D/G3	CELL_B5C	CELL_G4	CELL_B5c/G4
PB	58.9	63.5	64	62.2	63.1	67	66.3	66.65
CU	58.2	62.9	63.6	61.4	62.5	66.3	65.7	66
ZN	35	41.1	44.2	39.7	41.95	46.2	46.1	46.15
TSS	59.2	63.7	64.1	62.6	63.35	67.3	66.6	66.95
TKN	38.7	44.8	46.3	43.9	45.1	50.3	49.4	49.85
NO3/NO2	*	*	*	*	*	*	*	*
TP	38.9	45	46.4	44.2	45.3	50.5	49.6	50.05

Sensitivity analysis was conducted, using a utility built into the P8 model, to determine how sensitive the output was to changing device parameters. The analysis was run for 10% and 25% change in inputs associated with the devices, since some of the device inputs, such as void volume and infiltration rate, vary between control and experimental cells, and may vary between storm events. Both scenarios returned similar results for all cells across all water quality parameters. The model output (% pollutant reduction) was the most sensitive to the flood pool area and somewhat sensitive to infiltration rate. Nutrient removal rates were more sensitive to changes in inputs than other parameters. Appendix C contains the results of the sensitivity analysis for all water quality parameters at 10% and 25% increases in device input values.

The P8 model also has a statistical analysis utility. The analysis returned statistics pertaining to outflow pollutant concentrations including how many events were modeled, the average concentration of each water quality parameter for each cell, the minimum value, the maximum value, and how often the outflow of each cell exceeded the target water quality value. The average concentrations of pollutants in the model output were significantly higher than the water quality targets. Appendix C contains the statistical information for the model results.

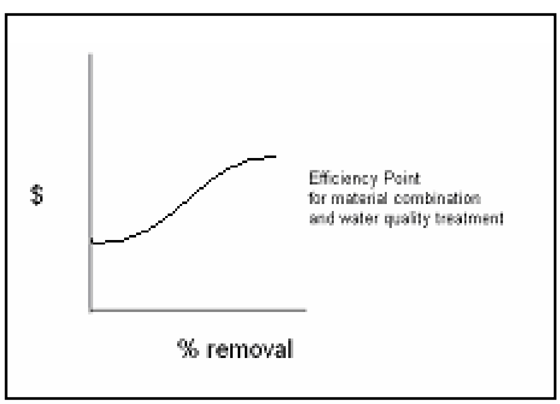
The P8 model results for pollutant removal were somewhat conservative, but showed trends similar to estimated removal. When compared to estimated pollutant reduction (from literature review), the model predicted the bioretention cells pollutant removal to be about 20% less for Lead, Copper and suspended solids, about 45% less for Zinc, and about 25% less for Phosphorus. Predicted results were also lower than actual results in most cases, although the lack of actual data made comparisons inconclusive. Appendix C contains tables and charts that show the complete comparison of the estimated, predicted and actual pollutant removal efficiency of all the bioretention cells.

5.3. Cost Analysis Results and Discussion

5.3.1. Cost Minimization – The Ideal Solution

The ideal cost minimization analysis, as discussed in Chapter 4 would be one that minimizes costs (as a function of materials) with water quality treatment (also as a function of materials) and volume of runoff treated to determine design criteria for an ideal bioretention cell. An analysis such as this is outside the scope of this project, but predictions can be made as to the outcomes. One would expect that as materials costs go up, indicating more expensive materials (such as engineered soils and plants), that water quality at the outlet of the cell will improve. However, a balance of materials (soil combinations and plants) must be achieved in order for water quality to improve. Unbalanced combinations of materials, such as too much nitrogen rich compost or not enough plants for nutrient uptake may actually decrease water quality at the outlet so there is definitely a point of pollutant removal efficiency with respect to materials. After that point, pollution reductions will likely decrease with increasing materials costs. Figure 5.1 shows what the cost curve may look like for the analysis discussed above.

Figure 5.1 – Possible Cost Curve for "Ideal" Bioretention Cell



5.3.2. Cost Minimization

The cost minimization analysis for this study determined the least cost combination of existing bioretention cells at the RCA that meets water quality criteria and runoff volume requirements. Six scenarios were run (in Excel Solver), with three different unit targets using actual and predicted water quality data to minimize the cost of implementation. Since there are actually six bioretention cells at the RCA, the analysis began by constraining the number of units to six. Subsequent analyses reduced the number of cells from five to four. Appendix C contains the tables used by Excel Solver for each scenario. The results of each scenario, including the cost of implementation and the number of each bioretention cell required to meet the targets, are summarized in Table 5.4.

Table 5.4 – Cost Minimization Analysis Results

Predicted WQ data			
	6 cells*	5 cells *	4 cells*
Cost	$48,690.80	$53,598.96	$61,875.19
B8	0	0	0
B7	0	2	4
B5d	1	1	0
G3	4	2	0
B5c	1	0	0
G4	0	0	0
* analysis run without Zinc or Phosphorus			
Actual WQ data			
	6 cells*	5 cells*	4 cells*
Cost	$49,484.85	$51,233.44	$56,291.06
B8	0	0	3
B7	0	1	0
B5d	1	4	0
G3	5	0	1
B5c	**	**	**
G4	0	0	0
* analysis run without Phosphorus			
**no sample taken at B5c			

The first three scenarios used the pollutant removal percentage from the P8 model results (Table 5.3). While all of the cells analyzed met volume requirements, none of the cells met Zinc or Total Phosphorus criteria so the scenarios did not take those two water quality parameters into account.

As can be seen in Table 5.4, when more cells are allowed, the smaller, lower cost experimental cells (B5d, G3, B5c, and G4) met the water quality and volume requirements. As the number of bioretention cells was reduced, the higher cost control cells (B8 and B7) became better options although they had lower pollutant removal percentages than the experimental cells. This occurred primarily because the control cells are larger, can handle the runoff volume needed, and still treat water quality to the desired target. Meeting the volume requirements caused the total cost of the scenarios to increase as the number of cells decreased.

The second three scenarios used actual water quality concentrations from the bioretention cells' outlets. All of the cells sampled met volume requirements and all water quality parameters, except Total Phosphorus. Cell B5d was the only cell that met the all water quality criteria so when the analysis was run using fewer than six cells, Phosphorus had to be eliminated from the analysis. Phosphorus was eventually eliminated from the analysis using actual data so the scenarios could be compared to each other. Cell B5c did not have enough sample for testing for the one storm event sampled, so it was also left out the Excel Solver analysis.

The results using actual water quality data are similar to those using predicted data. The smaller, less expensive experimental cells minimize the cost when a larger number of bioretention cells were specified, but the larger, more expensive control cells had to be considered when the number of cells was lower to meet volume requirements. Again, the total cost of the scenarios increased as the number of cells decreased in order to meet volume requirements.

5.3.3. Cost Efficiency

The analysis to determine which bioretention cell was most efficient at reducing pollutants per runoff volume handled also used both actual and predicted pollutant reduction values. An example calculation, for cell B8 using the actual pollutant removal for TSS was:

$$E_{B8} = \frac{\$15,783.30}{2275\ ft^3 \times 80\%\ removal} = 0.162$$

A similar calculation was done for each bioretention cell and each pollutant removal rate (both predicted and actual) and the resulting table can be found in Appendix C. Once the cost efficiency for each pollutant in each bioretention cell was determined, the rates were ranked, highest cost efficiency (highest removal rates) to lowest cost efficiency (lowest removal rate). Table 5.5 shows which bioretention cells are most efficient at reducing individual pollutants.

Table 5.5 – Pollutant Reduction Efficiency

Predicted % Removal					
Rank	Lead	Copper	Zinc	TSS	TP
1	G3	G3	B5c	G3	B5c
2	B5c	B5c	G3	B5c	G3
3	B5d	B5d	G4	G4	G4
4	G4	G4	B5d	B5d	B5d
5	B7	B7	B7	B7	B7
6	B8	B8	B8	B8	B8
Actual % Removal					
Rank	Lead	Copper	Zinc	TSS	TP
1	G3	G3	G3	G3	B5d
2	B5d	B5d	B8	B7	*
3	G4	B8	B7	B8	*
4	B8	B7	B5d	G4	*
5	B7	*	G4	B5d	*
6	*	*	*	*	*

* values either no sample was taken or % removal calculation returned a negative % removal and were not taken into account for this calculation.

Table 5.5 indicates that experimental cells G3 and B5c are the most cost efficient cells (using predicted % removal) at treating all water quality parameters. They are followed by the other two experimental cells, G4 and B5c. Overall, the experimental cells were more cost efficient (ranked 1-4) at reducing pollutants, using predicted removal rates. The rankings using actual removal rates tell a slightly different story. Experimental cell G3 was the most cost efficient at reducing all parameters except Phosphorus. Experimental cell B5d the most efficient at treating Phosphorus and was ranked second for reducing Lead and Copper. Control cells B7 and B8 both ranked second for one parameter. So the actual data suggests that the experimental cells are more cost efficient than the control cells, but not as significantly as the predicted data suggest. There were a few problems with the actual data that may have skewed the data slightly. There was no sample available for cell B5c sample so it was not considered in the rankings and only cell B5d was able to treat Phosphorus to the target level.

The cost efficiencies in Table 5.5 were also used to determine each bioretention cell's cost efficiency for treating water quality parameters that are given different weights, or levels of importance. The idea behind this calculation was to apply levels of importance to one or more of the water quality parameters for cases where treating one (or more) parameter may be of more importance than others. TSS reduction is the most important parameter when making decisions for storm water management, so increasing rates were applied to TSS efficiencies (holding all other parameters equal) for all bioretention cells, again using actual and predicted removal percentages. The bioretention cells were then ranked according to overall efficiency. Table 5.6 shows these rankings.

Table 5.6 - Overall Efficiency with TSS Weighted

Predicted % Removal				
Rank	TSS 20%	TSS 50%	TSS 75%	TSS 100%
1	G3	B5c	B5c	B5c
2	B5c	G4	G4	G4
3	G4	B5d	B5d	B5d
4	B5d	G3	G3	G3
5	B7	B7	B7	B7
6	B8	B8	B8	B8
Actual % Removal				
Rank	TSS 20%	TSS 50%	TSS 75%	TSS 100%
1	G3	G3	B7	B7
2	B7	B7	G3	G3
3	B8	B8	B8	B8
4	B5d	B5d	B5d	B5d
5	*	*	*	*
6	*	*	*	*
* values either no sample was taken or % removal calculation returned a negative % removal and were not taken into account for this calculation.				

The first column of Table 5.6 ranks the bioretention cells where each pollutant was weighted equally (20%), while the following three columns increase the weight placed on TSS from 50% to 75% to 100%. Examining the results using predicted reduction percentages, the experimental cells performed better at reducing TSS at increasing weights than the control cells. The experimental cells G3 and B5c performed the best followed by the other two experimental cells. Examining the results using actual reduction percentages, showed the experimental cells performed better at lower TSS weights, while the control cells improved as the weight given TSS increased.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The focus area for this study is located on the campus of the Rockdale Career Academy (RCA) in Conyers, GA. Many bioretention cells were incorporated into the storm water management site plan because they are multipurpose storm water controls that are capable of holding limited amounts of runoff and reducing pollutants in runoff, while providing aesthetic appeal with plants, grasses, and trees. Six of the 42 bioretention cells on the site were designed for research by specifying two soil mixes coupled with two plant mixes in “control” and “experimental” cells. The bioretention cells were researched to determine cost efficient and treatment effective combinations of soils and plants for bioretention cells in the Piedmont Region of Georgia.

The objectives of the research were: 1. Determine water quality treatment capacity of control and experimental bioretention cells; 2. Determine cost efficiency of the control and experimental cells, based on water quality treatment and volume of runoff treated; and 3. Make recommendations for treatment and cost effective combinations of soils and plants to aide planners in choosing the most efficient materials for bioretention cells and for continued research and educational opportunities at the RCA.

6.1. Conclusions

6.1.1. Water Quality

One of the main objectives of this study was to determine the treatment capacity of the bioretention cells at the Rockdale Career Academy. The initial hypothesis regarding water quality treatment was that the experimental bioretention cells would provide water quality treatment similar to the control bioretention cells. To begin the water quality analysis, existing bioretention cell literature was reviewed to find estimates of water quality treatment capacity of bioretention cells and other storm water management structures. These data provided a general idea of how structures should perform and allowed for conclusions to be drawn on how bioretention cells compare to other storm water treatment methods. The bioretention cells at the RCA, according to the literature review, were expected to provide excellent water quality treatment at relatively low costs, compared to other storm water management structures.

A preliminary goal of this study was to collect and analyze a sample from each bioretention cell after six storm events in order to compare the water quality treatment for the control and experimental bioretention cells. Only one storm event was sampled due to drought conditions and time constraints. The resulting data analysis indicated that the experimental cells may be slightly better at reducing pollutants than the control cells, but it is difficult to make definitive conclusions based on only one storm event.

The collected concentrations of pollutants were then used to calculate the pollutant reduction percentage of each bioretention cell. While this calculation provided meaningful information for metals and solids, nutrients proved a problem. The input values for nitrogen and phosphorus compounds in storm water runoff were lower than the output values found by analysis, which returned negative pollutant removal percentages. The pollutant removal percentages for metals and solids were similar to expected removal rates from other studies.

Although the limited amount of water quality data collected from the bioretention cells were not used for the cost analysis, the data did provide some insight into the actual treatment capacity of the RCA's bioretention cells. The preliminary collected data showed that the study bioretention cells at the Rockdale Career Academy are capable of reducing concentrations of pollutants in runoff to levels consistent with water quality standards and suggested levels to maintain aquatic organisms in streams. Future water quality data is expected to be similar to what was reported in this study, although nutrient removal will likely depend upon the condition of plant life in the bioretention cells.

Because there was so little water quality data available, it was necessary to use a model to predict pollutant reduction. The study bioretention cells were simulated using the P8 model. Specifications from the bioretention cell design and site specific weather data were coupled with runoff water quality data from the Nationwide Urban Runoff Program (NURP) study to predict how well each cell would perform. The model results were conservative when compared to estimated data from the literature review and the water quality analysis, but the results were expected because default values, built into the model and based on conservative assumptions, were used for many inputs.

The sensitivity analysis of the model results showed that treatment capacity was quite sensitive to changes in infiltration rate; higher infiltration rates returned higher pollution reduction rates. The model results were not particularly sensitive to any other device specific parameters, such as the presence of plants and soil void volume. This insensitivity may have contributed to the conservative results because plants and void volume in the soil were expected to have more of an impact on the results. The water quality data available for this study lead to the conclusion that both the control and experimental bioretention cells at the RCA are likely to provide similar water quality treatment.

6.1.2. Cost Analysis

6.1.2.1. Cost Minimization

The cost minimization analysis resulted in six least cost solutions for implementing bioretention cells that will meet water quality and runoff volume requirements. The number of bioretention cells per solution varied between 4 and 6 (the actual number of cells on the RCA site). Since the experimental cells had similar water quality to the control cells, meeting the volume requirement became the deciding factor in the analysis. Although the analyses using predicted and actual data returned different optimal solution combinations, they both followed the same trend; when the number of cells implemented was higher, the experimental cells, with lower costs (less volume), were the optimal solution. As the number of cells decreased, the more expensive cells control cells, that treated more volume, were included in the optimal solution.

The overall costs determined for each scenario increased as the number of cells chosen decreased. This was also a function of how much runoff volume the cells could handle. The scenarios using predicted water quality data had higher overall costs than those using actual water quality data. This was likely due to the conservative nature of predictive modeling. Overall, the results of the cost analysis showed that the least cost solutions were those that combined low cost experimental cells to meet runoff volume requirements. These results lead to the conclusion that implementing multiple cells similar to the experimental cells for this study would minimize the cost of implementation.

6.1.2.2. Cost Efficiency

Ranking the cost efficiency of each bioretention cell found that using predicted water quality data, the experimental cells should all be more cost efficient than the control cells. Using actual water quality data showed that the experimental cells were more cost efficient at reducing pollutants. The rankings of control cells improved using actual data but were still not as efficient as the experimental cells. One can conclude from this analysis that for most pollutants, the experimental bioretention cells will be more cost efficient than the control cells.

Placing more emphasis on total suspended solids (TSS) than on other water quality parameters returned similar results for predicted water quality data, the experimental cells were more cost efficient as TSS was given more importance in the analysis. The actual data indicated that experimental cells will be more efficient when TSS is closer to the weights of other parameters and the control cells would be more efficient when TSS was weighted significantly more than the other parameters.

6.2. Recommendations

6.2.1. Study Improvements

The conclusions reached in the previous sections although useful, may not adequately describe the function of the bioretention cells at the Rockdale Career Academy because they are based on predicted data from a model that returned conservative pollutant reduction. There are several recommendations that will improve the robustness of future studies. First and foremost, more water quality data must be collected, because it is the basis for all other analyses. As discussed in Chapter 5, the pollutant levels in runoff water quality from the NURP study were, in some cases, lower than the levels at the outlet. This, coupled with only one set of samples, made it difficult to make any concrete conclusion about actual pollutant reduction. A better estimate of runoff water quality at the study site would provide a more accurate picture of pollutant removal, as runoff filters through the many layers of the bioretention cells. Second, the P8 model should be calibrated to site-specific water quality data instead of the default data from the NURP study. This will improve the accuracy the model predictions for pollutant removal. Finally, the improved pollutant removal estimates from both the actual and predicted water quality analyses, should be used to determine the least cost bioretention cell for pollutant removal in the cost minimization analysis and the most cost efficient cell at treating the various pollutants. A statistical analysis using ANOVA (analysis of variance) can be done to compare the control and experimental bioretention cells for pollutant removal and costs to treat runoff per volume treated, once a more robust set of data is available. These recommendations would provide a much clearer picture of cost and treatment effectiveness for the bioretention cells at the Rockdale Career Academy.

6.2.2. Recommendations for Educational Opportunities

The final objective of this study was to recommend educational programs for the RCA and to provide information for planners regarding the treatment capacity and costs of bioretention cells. Although the third objective is not specifically addressed in this study, the RCA will receive assistance in developing research projects after a full set of water quality data is available.

The bioretention cells at the RCA provide many educational opportunities for students and faculty in the Rockdale County school system and for planners designing storm water management plans. It is important to have good initial data to base educational experiences upon. In order to provide the RCA students and faculty with a good set of baseline data, samples will be taken following five additional storm events, after classes begin at the RCA in Fall 2007. Once the data initial data are collected, it is recommended that students and faculty at the RCA continue to monitor the bioretention cells. Educational research projects can be formulated to study effects of plants on pollutant reduction, long-term function of the bioretention cells, and effects of drought and extended wet periods on function. It is recommended that the bioretention cells plant matter be better maintained so the cells can continue to remove the pollutants discussed in this project and improve their treatment of nutrients before future studies are conducted. Continued study of the bioretention cells provide educational benefits for RCA students and faculty through research projects, and will provide valuable information for site planners as to the long-term function of bioretention cells.

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APPENDICES

APPENDIX A. Project Description

APPENDIX A.1. Rockdale Career Academy Information

In August 2002, the Board of Education approved the framework for the development of a fourth high school in Rockdale County , which incorporated the Planning Committee's recommendations. Although more components could come out of committee work, specific components currently include:

- share facilities/equipment/materials (including maintaining and updating) with business and industry, as well as colleges and technical colleges
- dual/joint enrollment/postsecondary credit can be earned
- students can earn a high school diploma, a technical college degree/diploma/certificate, and a college degree
- include teaching staff from industry and technical colleges, as well as from traditional certified teacher pool
- available to full-time and part-time students in grades 9-12 (attendance zone would be entire county) with full-time status initially limited to juniors and seniors
- grant diplomas
- develop an application process that includes an interview
- publicize program and begin recruitment in middle school
- offer all courses needed for Career/Technology seal on the diploma
- provide on-line learning opportunities for both secondary and postsecondary courses
- offer Advanced Placement courses
- include a School-to-Work component (internships, job shadowing, apprenticeships, etc.)
- include strong counseling/advisement/career support components

Subsequently, in September 2002, the Board agreed that the school should make application for charter school status. This would provide for the waiver of specifically identified state and local rules, regulations, policies, procedures, and portions of state law. Flexibility would be available in employing teaching staff with business experience, in rewriting some curriculum to better meet the needs of students, and in addressing the size of classrooms.

Board Names Career / Technology High School

The Board of Education recently voted to name the new career/technology high School Rockdale Career Academy. Becoming Rockdale County's fourth high school, this new facility will be a non-traditional high school building and will be built on a 48+ acre site recently purchased by the Board of Education on the west side of Parker Road. This site is centrally located within the county as it will be drawing its student base from throughout the county.

Mission Statement

The mission of Rockdale Career Academy, an award winning technologically innovative learning community, is to ensure students achieve academic, social, and career success by providing a supportive environment that identifies, encourages, and develops each student's interests and abilities to prepare tomorrow's workforce today for a fulfilling, productive career by:

- Offering programs of study designed by experts in business, industry, and education
- Providing customized work-based learning experiences
- Involving family and community stakeholders
- Offering industry certification in appropriate programs
- Teaching a rigorous and relevant academic and career curricula
- Cultivating a clear awareness of their rights, responsibilities, and obligations to be ethical, community oriented citizens and productive members of the workforce and the global community
- Fostering a sense of responsibility and ability to plan their own personal and professional growth beyond high school
- Building a community of hope

APPENDIX A.2. Breedlove Land Planning, Inc. Design Documents

Project Name	**Rockdale Career Academy**
Area Name	**SP-1**
Structure Number	**G3**

WATER QUALITY CALCULATIONS

TOTAL DEVELOPED AREA (ACRE)	=	0.48
TOTAL IMPERVIOUS AREA (ACRE)	=	0.37
PERCENT IMPERVIOUS (%)	=	77.08

WATER QUALITY VOULUME:

WQr = 1.2 * (RV)
RV = 0.05 + I * 0.009
WQv = (WQr/12) * A

WHERE:
WQr = WATER QUALITY RUNNOFF
Rv = WEIGHTED VOLUMETRIC RUN OFF COEFICIENT
I = PERCENT IMPERVIOUS
A = ONSITE AREA

WQr = 1.2 * (0.05+(I *0.009))	=	0.89
WQv = WQr/12 *43560*1.90 [CUFT]	=	1555

DISCHARGE ORIFICE CALCULATIONS

H (FT) =	=	3.00
A = WQv/t / [0.60*(64.4*(H/2))^.5]	=	0.0031

WHERE:
t = 24 HOURS (86,400 SEC)
A= AREA OF ORICIFE (SQFT)
H = HIEGHT ABOVE CENTROID OF ORIFICE (FT)
WQv = WATER QUAL. VOULUME (CUFT)

RADIUS OF ORIFICE (FT)	=	0.03
RADIUS OF ORIFICE (IN.)	=	0.37
DIAMETER (IN)	=	***0.75***

WATER QUALITY BASIN SIZE

(Volume calculated with average ends method)

Bio-retention Cell is **9**" deep	Elevation (ft)	Area (ft^2)	Volume Provided (ft^3)	Volume Required (ft^3)	Is Volume Provided Greater than Volume Required
Bottom of Bio-retention Cell =	868.05	1213	1591	1555	Yes
Top of Bio-retention Cell =	868.8	3029			

BASIN DESIGN DIMENSIONS

Side slopes (H:V)	6.67:1
Bottom Width (ft.)	15.75
Bottom Length (ft.)	473
Number of Drain Lines	2
Length of each drain line (ft.)	451.5
Spacing between drain lines (ft.)	4

Project Name	**Rockdale Career Academy**
Area Name	**SP-2**
Structure Number	**G4**

WATER QUALITY CALCULATIONS

TOTAL DEVELOPED AREA (ACRE)	=	0.31
TOTAL IMPERVIOUS AREA (ACRE)	=	0.22
PERCENT IMPERVIOUS (%)	=	70.97

WATER QUALITY VOULUME:

WQr = 1.2 * (RV)
RV = 0.05 + I * 0.009
WQv = (WQr/12) * A

WHERE:
WQr = WATER QUALITY RUNNOFF
Rv = WEIGHTED VOLUMETRIC RUN OFF COEFICIENT
I = PERCENT IMPERVIOUS
A = ONSITE AREA

WQr = 1.2 * (0.05+(I *0.009))	=	0.83
WQv = WQr/12 *43560*1.90 [CUFT]	=	930

DISCHARGE ORIFICE CALCULATIONS

H (FT) =	=	3.00
A = WQv/t / [0.60*(64.4*(H/2))^.5]	=	0.0018

WHERE:
t = 24 HOURS (86,400 SEC)
A= AREA OF ORICIFE (SQFT)
H = HIEGHT ABOVE CENTROID OF ORIFICE (FT)
WQv = WATER QUAL. VOULUME (CUFT)

RADIUS OF ORIFICE (FT)	=	0.02
RADIUS OF ORIFICE (IN.)	=	0.29
DIAMETER (IN)	=	***0.58***

WATER QUALITY BASIN SIZE

(Volume calculated with average ends method)

Bio-retention Cell is **8**" deep	Elevation (ft)	Area (ft^2)	Volume Provided (ft^3)	Volume Required (ft^3)	Is Volume Provided Greater than Volume Required
Bottom of Bio-retention Cell =	868.27	825	996	930	Yes
Top of Bio-retention Cell =	868.90	2149			

BASIN DESIGN DIMENSIONS

Side slopes (H:V)	6.67:1
Bottom Width (ft.)	15.75
Bottom Length (ft.)	473
Number of Drain Lines	2
Length of each drain line (ft.)	451.5
Spacing between drain lines (ft.)	4

Project Name	**Rockdale Career Academy**
Area Name	**SP-4**
Structure Number	**B5d**

WATER QUALITY CALCULATIONS

TOTAL DEVELOPED AREA (ACRE)	=	0.28
TOTAL IMPERVIOUS AREA (ACRE)	=	0.17
PERCENT IMPERVIOUS (%)	=	60.71

WATER QUALITY VOULUME:

WQr = 1.2 * (RV)
RV = 0.05 + I * 0.009
WQv = (WQr/12) * A

WHERE:
WQr = WATER QUALITY RUNNOFF
Rv = WEIGHTED VOLUMETRIC RUN OFF COEFICIENT
I = PERCENT IMPERVIOUS
A = ONSITE AREA

WQr = 1.2 * (0.05+(I *0.009))	=	0.72
WQv = WQr/12 *43560*1.90 [CUFT]	=	727

DISCHARGE ORIFICE CALCULATIONS

H (FT) =	=	3.00
A = WQv/t / [0.60*(64.4*(H/2))^.5]	=	0.0014

WHERE:
t = 24 HOURS (86,400 SEC)
A= AREA OF ORICIFE (SQFT)
H = HIEGHT ABOVE CENTROID OF ORIFICE (FT)
WQv = WATER QUAL. VOULUME (CUFT)

RADIUS OF ORIFICE (FT)	=	0.02
RADIUS OF ORIFICE (IN.)	=	0.26
DIAMETER (IN)	=	***0.51***

WATER QUALITY BASIN SIZE

(Volume calculated with average ends method)

Bio-retention Cell is **8"** deep	Elevation (ft)	Area (ft^2)	Volume Provided (ft^3)	Volume Required (ft^3)	Is Volume Provided Greater than Volume Required
Bottom of Bio-retention Cell =	868.23	704	778	727	Yes
Top of Bio-retention Cell =	868.90	1619			

BASIN DESIGN DIMENSIONS

Side slopes (H:V)	6.67:1
Bottom Width (ft.)	15.75
Bottom Length (ft.)	473
Number of Drain Lines	2
Length of each drain line (ft.)	451.5
Spacing between drain lines (ft.)	4

Project Name	**Rockdale Career Academy**
Area Name	**SP-5**
Structure Number	**B5c**

WATER QUALITY CALCULATIONS

TOTAL DEVELOPED AREA (ACRE)	=	0.37
TOTAL IMPERVIOUS AREA (ACRE)	=	0.28
PERCENT IMPERVIOUS (%)	=	75.68

WATER QUALITY VOULUME:

WQr = 1.2 * (RV)
RV = 0.05 + I * 0.009
WQv = (WQr/12) * A

WHERE:
WQr = WATER QUALITY RUNNOFF
Rv = WEIGHTED VOLUMETRIC RUN OFF COEFICIENT
I = PERCENT IMPERVIOUS
A = ONSITE AREA

WQr = 1.2 * (0.05+(I *0.009))	=	0.88
WQv = WQr/12 *43560*1.90 [CUFT]	=	1178

DISCHARGE ORIFICE CALCULATIONS

H (FT) =	=	3.00
A = WQv/t / [0.60*(64.4*(H/2))^.5]	=	0.0023

WHERE:
t = 24 HOURS (86,400 SEC)
A= AREA OF ORICIFE (SQFT)
H = HIEGHT ABOVE CENTROID OF ORIFICE (FT)
WQv = WATER QUAL. VOULUME (CUFT)

RADIUS OF ORIFICE (FT)	=	0.03
RADIUS OF ORIFICE (IN.)	=	0.33
DIAMETER (IN)	=	***0.65***

WATER QUALITY BASIN SIZE

(Volume calculated with average ends method)

Bio-retention Cell is **8**" deep	Elevation (ft)	Area (ft^2)	Volume Provided (ft^3)	Volume Required (ft^3)	Is Volume Provided Greater than Volume Required
Bottom of Bio-retention Cell =	868.23	1120	1300	1178	Yes
Top of Bio-retention Cell =	868.90	2760			

BASIN DESIGN DIMENSIONS

Side slopes (H:V)	6.67:1
Bottom Width (ft.)	15.75
Bottom Length (ft.)	473
Number of Drain Lines	2
Length of each drain line (ft.)	451.5
Spacing between drain lines (ft.)	4

Project Name	**Rockdale Career Academy**
Area Name	**SP-7**
Structure Number	**B8**

WATER QUALITY CALCULATIONS

TOTAL DEVELOPED AREA (ACRE)	=	0.73
TOTAL IMPERVIOUS AREA (ACRE)	=	0.52
PERCENT IMPERVIOUS (%)	=	71.23

WATER QUALITY VOULUME:

WQr = 1.2 * (RV)
RV = 0.05 + I * 0.009
WQv = (WQr/12) * A

WHERE:
WQr = WATER QUALITY RUNNOFF
Rv = WEIGHTED VOLUMETRIC RUN OFF COEFICIENT
I = PERCENT IMPERVIOUS
A = ONSITE AREA

WQr = 1.2 * (0.05+(I *0.009))	=	0.83
WQv = WQr/12 *43560*1.90 [CUFT]	=	2198

DISCHARGE ORIFICE CALCULATIONS

H (FT) =	=	3.00
A = WQv/t / [0.60*(64.4*(H/2))^.5]	=	0.0043

WHERE:
t = 24 HOURS (86,400 SEC)
A= AREA OF ORICIFE (SQFT)
H = HIEGHT ABOVE CENTROID OF ORIFICE (FT)
WQv = WATER QUAL. VOULUME (CUFT)

RADIUS OF ORIFICE (FT)	=	0.04
RADIUS OF ORIFICE (IN.)	=	0.44
DIAMETER (IN)	=	***0.89***

WATER QUALITY BASIN SIZE

(Volume calculated with average ends method)

Bio-retention Cell is **8**" deep	Elevation (ft)	Area (ft^2)	Volume Provided (ft^3)	Volume Required (ft^3)	Is Volume Provided Greater than Volume Required
Bottom of Bio-retention Cell =	868.23	2174	2275	2198	Yes
Top of Bio-retention Cell =	868.90	4617			

BASIN DESIGN DIMENSIONS

Side slopes (H:V)	6.67:1
Bottom Width (ft.)	15.75
Bottom Length (ft.)	473
Number of Drain Lines	2
Length of each drain line (ft.)	451.5
Spacing between drain lines (ft.)	4

Project Name	**Rockdale Career Academy**
Area Name	**SP-8**
Structure Number	**B7**

WATER QUALITY CALCULATIONS

TOTAL DEVELOPED AREA (ACRE)	=	0.60
TOTAL IMPERVIOUS AREA (ACRE)	=	0.42
PERCENT IMPERVIOUS (%)	=	70.00

WATER QUALITY VOULUME:

WQr = 1.2 * (RV)

RV = 0.05 + I * 0.009

WQv = (WQr/12) * A

WHERE:

WQr = WATER QUALITY RUNNOFF

Rv = WEIGHTED VOLUMETRIC RUN OFF COEFICIENT

I = PERCENT IMPERVIOUS

A = ONSITE AREA

WQr = 1.2 * (0.05+(I *0.009))	=	0.82
WQv = WQr/12 *43560*1.90 [CUFT]	=	1777

DISCHARGE ORIFICE CALCULATIONS

H (FT) =	=	3.00
A = WQv/t / [0.60*(64.4*(H/2))^.5]	=	0.0035

WHERE:

t = 24 HOURS (86,400 SEC)

A= AREA OF ORICIFE (SQFT)

H = HIEGHT ABOVE CENTROID OF ORIFICE (FT)

WQv = WATER QUAL. VOULUME (CUFT)

RADIUS OF ORIFICE (FT)	=	0.03
RADIUS OF ORIFICE (IN.)	=	0.40
DIAMETER (IN)	=	***0.80***

WATER QUALITY BASIN SIZE

(Volume calculated with average ends method)

Bio-retention Cell is **8**" deep	Elevation (ft)	Area (ft^2)	Volume Provided (ft^3)	Volume Required (ft^3)	Is Volume Provided Greater than Volume Required
Bottom of Bio-retention Cell =	868.23	2129	2229	1777	Yes
Top of Bio-retention Cell =	868.90	4525			

BASIN DESIGN DIMENSIONS

Side slopes (H:V)	6.67:1
Bottom Width (ft.)	15.75
Bottom Length (ft.)	473
Number of Drain Lines	2
Length of each drain line (ft.)	451.5
Spacing between drain lines (ft.)	4

APPENDIX A.3. RCA Bioretention Cell Pictures

November 2005

April 2006

May 2006

August 2006

November 2006

May 2007

APPENDIX A.4. ERTHFood ® Specifications and Information

ERTH Food® is an all-natural, organic, composted fertilizer that provides soil-conditioning organic matter and nutrients. ERTH Food®, unlike other soil amendments and synthetic fertilizers, is rich in organic matter and nutrients and contains microorganisms. ERTH Food® contains more than just Nitrogen (N), Phosphorus (P), and Potassium (K); it also contains the other micro and macro nutrients essential for plant growth, such as Magnesium, Calcium, Iron, Manganese, Copper, Boron, Sulfur, and Sodium. ERTH Food® compost helps preserve, purify, and restore soil and water resources. Because organic matter enhances water and nutrient-holding capacity and improves soil structure, the use of ERTH Food® can enhance productivity and environmental quality and can reduce the severity and costs of natural phenomena such as drought, flood, and disease.

From: www.erthproducts.com

APPENDIX A.5. HydRocks ™ Specifications and Information

HydRocks™ is an inorganic expanded clay soil amendment (clay that is calcined or heated to a temperature just below its melting point to remove moisture). It is used for a variety of applications, but most commonly to help maintain porosity and aeration in soils (since it will not compress or decompose). HydRocks™ also can absorb up to 30% of its weight in water and water borne nutrients, helping to maintain soil moisture in dry conditions.

From: www.hydrocks.com

APPENDIX A.6. Wildflower Mix Specifications

Mix A – For Clay Soils	**Flowers:** Smooth Aster, New England Aster, Canada Milk Vetch, Blue False Indigo, White False Indigo, Wild Senna, Purple Prairie Clover, Canada Tick Trefoil, Illinois Tick Trefoil, Pale Purple Coneflower, Purple Coneflower, Rattlesnake Master, Showy Sunflower, Ox Eye Sunflower, Roundhead Bushclover, Bergamot, Wild Quinine, Smooth Penstemon, Yellow Coneflower, Black Eyed Susan, Sweet Black Eyed Susan, Brown Eyed Susan, Rosinweed, Compassplant, Cupplant, Prairie Dock, Stiff Goldenrod **Grasses:** Big Bluestem, Sideoats Grama, Canada Wild Rye, Switchgrass, Indiangrass
Mix B	**Flowers:** Lavender Hyssop, Nodding Pink Onion, Butterflyweed for Clay, Sky Blue Aster, Smooth Aster, Canada Milk Vetch, Lanceleaf Coreopsis, White Prairie Clover, Purple Prairie Clover, Shootingstar, Pale Purple Coneflower, Purple Coneflower, Rattlesnake Master, Roundhead Bushclover, Rough Blazingstar, Meadow Blazingstar, Prairie Blazingstar, Wild Quinine, Smooth Penstemon, Great Solomon's Seal, Black Eyed Susan, Brown Eyed Susan, Stiff Goldenrod, Ohio Spiderwort **Grasses:** Sideoats Grama, Little Bluestem, Prairie Dropseed

APPENDIX A.7. RCA Bioretention Cell Initial Construction Costs

Cell ID	Surface Area of Cell Floor (s.f.)	Total Volume of Soil Mix (c.f.) Based on 3' Depth	Total Volume of Soil Mix (c.y.) Based on 3' Depth	Volume of Gravel (c.f.) Based on 1' Depth	Volume of Gravel (c.y.)	Cost of Gravel ($20/yd)	Onsite Top Soil Percentage of Mix (%)	Volume of Onsite Top Soil (c.f.)	Volume of Onsite Top Soil (c.y.)	Cost of Onsite Top Soil ($3/yd)	ERTH Food Percentage of Mix (%)
Cell B8	4,617	13,851	513	4,617	171	$ 3,420.00	40%	5,540	205	$ 615.60	20%
Cell B7	4,525	13,575	503	4,525	168	$ 3,351.85	40%	5,430	201	$ 603.33	20%
Cell B5d	1,619	4,857	180	1,619	60	$ 1,199.26	40%	1,943	72	$ 215.87	10%
Cell B5c	2,760	8,280	307	2,760	102	$ 2,044.44	40%	3,312	123	$ 368.00	10%
Cell G3	3,029	9,087	337	3,029	112	$ 2,243.70	40%	3,635	135	$ 403.87	10%
Cell G4	2,149	6,447	239	2,149	80	$ 1,591.85	40%	2,579	96	$ 286.53	10%
Cell B5d/G3	4,648	13,944	516	4,648	172	$ 3,442.96	40%	5,578	207	$ 619.73	10%
Cell B5c/G4	4,909	14,727	545	4,909	182	$ 3,636.30	40%	5,891	218	$ 654.53	10%

Cell ID	Volume of ERTH Food (c.f.)	Volume of ERTH Food (c.y.)	Cost of ERTH Food ($22/yd)	River Sand Percentage of Mix (%)	Volume of River Sand (c.f.)	Volume of River Sand (c.y.)	Cost of River Sand ($20/yd)	Hydrocks Percentage of Mix (%)	Volume of Hydrocks (c.f.)	Volume of Hydrocks (c.y.)	Cost of Hydrocks ($55/yd)
Cell B8	2,770	103	$ 2,257.20	20%	2,770	103	$ 2,052.00	20%	2,770	103	$ 6,156.00
Cell B7	2,715	101	$ 2,212.22	20%	2,715	101	$ 2,011.11	20%	2,715	101	$ 6,033.33
Cell B5d	486	18	$ 395.76	40%	1,943	72	$ 1,439.11	10%	486	18	$ 1,079.33
Cell B5c	828	31	$ 674.67	40%	3,312	123	$ 2,453.33	10%	828	31	$ 1,840.00
Cell G3	909	34	$ 740.42	40%	3,635	135	$ 2,692.44	10%	909	34	$ 2,019.33
Cell G4	645	24	$ 525.31	40%	2,579	96	$ 1,910.22	10%	645	24	$ 1,432.67
Cell B5d/G3	1,394	52	$ 1,136.18	40%	5,578	207	$4,131.56	10%	1,394	52	$3,098.67
Cell B5c/G4	1,473	55	$ 1,199.98	40%	5,891	218	$4,363.56	10%	1,473	55	$3,272.67

Cell ID	Area of 8 oz Non-woven Geotextile Fabric (s.y.)	Cost of Fabric ($1/s.y)	Total Cost of Soil & Gravel & Fabric	Cost Per C.Y of Material.	Labor Cost ($20/yd)	Total Cost of Cell	Volume Treated (c.f.)	Material Cost Per Cubic Foot Treated	Total Cost Per Cubic Foot Treated
Cell B8	1,283	$ 1,282.50	$ 15,783.30	$ 23.08	$ 13,680.00	$ 29,463.30	2,275	$ 6.94	$ 12.95
Cell B7	1,257	$ 1,256.94	$ 15,468.80	$ 23.08	$ 3,407.41	$ 28,876.20	2,229	$ 6.94	$ 12.95
Cell B5d	450	$ 449.72	$ 4,779.05	$ 19.93	$ 4,797.04	$ 9,576.09	778	$ 6.14	$ 12.31
Cell B5c	767	$ 766.67	$ 8,147.11	$ 19.93	$ 8,177.78	$ 16,324.89	1,300	$ 6.27	$ 12.56
Cell G3	841	$ 841.39	$ 8,941.16	$ 19.93	$ 8,974.81	$ 17,915.97	1,591	$ 5.62	$ 11.26
Cell G4	597	$ 596.94	$ 6,343.53	$ 19.93	$ 6,367.41	$ 12,710.94	996	$ 6.37	$ 12.76
Cell B5d/G3	1,291	$ 1,291.11	$ 13,720.21	$ 39.85	$ 3,771.85	$ 27,492.06	2,369	$ 5.88	$ 11.78
Cell B5c/G4	1,364	$ 1,363.61	$ 14,490.64	$ 39.85	$ 14,545.19	$ 29,035.83	2,296	$ 6.32	$ 12.66

APPENDIX B. Methodology

APPENDIX B.1. Water Quality Analysis Methods and Protocols

THE UNIVERSITY OF GEORGIA
COOPERATIVE EXTENSION
Colleges of Agricultural and Environmental Sciences & Family and Consumer Sciences

SOIL, PLANT, AND WATER LABORATORY
Agricultural and Environmental Services Lab
University of Georgia

PARAMETER	METHOD	INSTRUMENT USED
P, K, Ca, Mn, Cu, Cd, Fe, Ni, Mg, B, Mo, Si, Al, Cr, Zn, Na	Inductively coupled plasma spectrography	Thermo Jarrell-Ash model 61E ICP Thermo Elemental 27 Forge Parkway Franklin, MA 02038
NO_3-N	Cadmium Reduction Column, Colorimetric-Autoanalyzer Method	Perstorp EnviroFlow 3000 AutoAnalyzer Perstop Analytical, Inc. 9445 SW Ridder Road Wilsonville, OR 97070
NO_2-N	Colorimetric-Autoanalyzer Method (Cadmium Reduction Column Removed)	Perstorp EnviroFlow 3000 AutoAnalyzer Perstop Analytical, Inc. 9445 SW Ridder Road Wilsonville, OR 97070
Lead	AA Graphite Furnace Method	Perkin-Elmer Model 4100 ZL Atomic Absorption Spectrophotometer Perkin-Elmer Norwalk, CT
Total P	Persulfate Digestion – Colorimetric Method	Perstorp EnviroFlow 3000 AutoAnalyzer Perstop Analytical, Inc. 9445 SW Ridder Road Wilsonville, OR 97070
Total Suspended Solids	Filtering, Drying, Weighing	Standard Methods for the Examination of Water and Wastewater, 20th Edition, 1998. Method 2540 D, p. 2-57-2-58.

APPENDIXB.2. P8 Equations and Simulation Information

Simulation Methods

Simulations are performed using the algorithms summarized below. Additional detail is provided in the Version 1 model development report and version 2 update report (see References).

Watershed Runoff

Runoff is driven by rainfall & snowmelt. Runoff from pervious areas is simulated using version of SCS curve number method (USDA,1964), as invoked in GWLF model (Haith et al., 1992). Antecedent moisture condition (AMC) is adjusted based upon 5-day antecedent rainfall + snowmelt.

Percolation from pervious areas is estimated by difference (rainfall -runoff). Percolation is not considered unless explicity routed to an aquifer (device type = 7). Evapotranspiration is computed from air temp, day length, & month using method described by Haith & Shoemaker (1987).

Runoff from the impervious watershed starts after the cumulative event rainfall + snowmelt exceeds the specified depression storage.

All runoff is routed directly to downstream devices (without lag). This assumes that the time of concentration is small in relation to the precip. time step (1 hr). For large watersheds, predicted watershed response will be overestimated. To retard watershed response, direct runoff to a "pipe" device with a positive time-of-concentration.

SnowFall / SnowMelt Simulation

The snow simulation is essentially a water balance with melting governed by SCS degree-day equation.

Tair = mean daily air temperature (deg-F)
S(t) = snowpack at end of hour t (inches, water equivalent)
M(t) = snowmelt occuring in hour t (inches)
P(t) = total precipitation in hour t (inches)
R(t) = rainfall occuring in hour t (inches)
X(t) = snowfall occuring in hour t (inches)
Tsnow = air temperature generating snowfall (deg-F)
Tmelt = minimum air temperature for snowmelt (deg-F)
SMCoef = snowmelt coefficient (inches/degreeF-day)

```
If Tair <= Tsnow then

    X(t) = P(t)

    R(t) = 0

else

    X(t) = 0

    R(t) = P(t)

endif

S(t) = S(t-1) + X(t) - M(t)

M(t) = MIN [ MAX [ 0 , SMCoef ( Tair - Tmelt )/24 ] , S(t-1) + X(t) ]
```

Ths sum of M(t) + R(t) drives runoff simulation from pervious & impervious areas.

Runoff from Frozen Soils

The Frozen Soil (Tfreeze, 'Edit ET/Snowmelt' screen) can be adjusted to control the rate of runoff from pervious areas when the soil is likely to be frozen.

At the start of each event, P8 computes the 5-day-average antecedent air temperature (TAir). If TAir < TFreeze, the following adjustments are made to the runoff simulation for the duration of the event:

-> Antecedent Moisture Condition = 3

-> Maximum Abstraction computed from Curve Number is multiplied by the Scale Factor for maximum abstraction specified on the 'Edit ET/Snowmelt' screen. The scale factor would range from 0-1. If = 0, the soil will be treated as completely impervious. If = 1, the effect of soil freezing on max abstraction would be ignored.

This capability has been included to permit dsimulation of conditions in northern climates (e.g., long cold spell followed by rainfall). To turn this option off, set Tfreeze to a very low number (e.g.,-50).

Impervious Area Runoff Simulation

Runoff from impervious areas is governed by the following equations:

Cum rain+melt: $Y(t) = Y(t-1) + dY(t)$

Excess rain+melt: $Et = MAX [(Y(t)-Si) , 0]$

Runoff: $ri(t) = Fi (E(t) - E(t-1))$

Infiltration: $qi(t) = (1 - Fi) (E(t) - E(t-1))$

where,

Y(t) = cumulative rainfall + snowmelt at end of hour t in current event (in)
dY(t) = incremental rainfall + snowmelt occuring in hour t (in)
Si = impervious depression storage for watershed i (inches)
Fi = runoff coefficient for impervious areas in watershed i (dimensionless)
E(t) = cumulative excess rainfall + snowmelt at end of hour t (inches)

ri(t) = impervious runoff rate in hour t (inches/hr)
qi(t) = infiltration rate from impervious area in hour t (inches/hr) ???

Particle washoff is governed by sum of ri(t) & qi(t).

Curve Number Adjustment based on Antecedent Moisture Condition

Reference: GWLF Model (Haith et al, 1992)

P5 = 5-day antecedent rainfall + snowmelt (prior to start of event)
T5 = 5-day antecedent average air temperature at start of event (deg-F)
RAMC2, RAMC3 = P5 value corresponding to AMC 2 & 3 (inches)
CN1,CN2,CN3 = curve numbers for amc 1, 2, & 3 for current event
TFREEZE = T5 value forcing AMC 3 (deg-F)
RAMC2 & RAMC3 defined separately for growing & non-growing seasons.

$$CN1 = CN2 / (2.334 - .01334\ CN2)$$

$$CN3 = CN2 / (0.04036 + .0059\ CN2)$$

```
IF (T5 < TFREEZE) or (Snowmelt Event) or (P5 >= RAMC3), then

        CN = CN3

 Else If P5 <= RAMC2  then

        CN = CN1 + (CN2 - CN1)*P5/RAMC2

 Else

        CN = CN2 + (CN3 - CN2)*(P5 - RAMC2)/(RAMC3 - RAMC2)
 Endif
```

Watershed Loadings

Loadings from pervious areas are computed by applying a fixed concentration to the computed runoff volume for each particle class. If percolation is routed to an aquifer, the concentration in percolating flow is reduced by the filtration efficiency defined for each particle class.

Loadings from impervious areas are computed using two techniques:

- applying a fixed concentration to computed runoff volume; and/or
- simulating particle buildup & washoff processes

Loads resulting from these mechanisms are totaled.

For each watershed, computed loadings are multiplied by a constant factor 'Pollutant Load Factor'. This factor (normally = 1) can be used to adjust for differences in loading intensity due to land use, for example, if sufficient data are available.

Particle Buildup & Washoff

The differential equation describing buildup & washoff is:

$$\frac{dB}{dt} = L - k B - f s B - a B r^{c}$$

where, in consistent units:

B = buildup or accumulation on impervious surface
L = rate of deposition
k = rate of decay due to non-runoff processes
s = rate of street sweeping
f = efficiency of street sweeping (fraction removed per pass)
a = washoff coefficient = SWMM "RCOEFX" (Huber & Dikinson, 1988)
c = washoff exponent = SWMM "WASHPO" (Huber & Dikinson, 1988)
r = runoff intensity from impervious surfaces

Values are updated using the analytical solution of this equation for each time step. At the start of the simulation, B values are set equal to one day's worth of deposition.

Device Flows

Flow routing is performed in downstream order using a modified second-order Runge- Kutta technique (Bedient & Huber, 1986). For each device, outlet, & timestep the relationship between volume & outflow is represented by:

$$Q = d0 + d1\ V$$

where, in consistent units,

Q = outflow
V = current device volume
d0, d1 = intercept & slope of outflow vs. storage relationship
d0 & d1 values are updated at each time step, based upon the elevation/area/volume/outflow table for the device.< BR >

Linearization of the storage/outflow relationship permits analytical solution of the device flow balance at each time step:

$$\frac{d\,V}{d\,t} = Qin - SUM\ [\ Qout\ ],\ Qout \ =\sim\ d0 + d1\ V$$

Analytical solution for volume increase, not shown here for lack of space:

$$V2 - V1 = F(V,t)$$

where, in consistent units:

V = device volume, V1 at start, V2 at end of time step
Qout = outflow for given device & outlet
Qin = total inflows (from watersheds & upstream devices)
SUM = sum over device outlets (exfiltration, normal, spillway)
d0,d1 = intercept & slope of Qout vs. V relationship

Because d0 & d1 may vary with V, a two-stage procedure is used to estimate volume derivative:

$$Vm = V1 + .5\ F(V1,t)$$

$$V2 = V1 + F(Vm,t)$$

Device Mass Balances

Each device is assumed to be completely mixed for the purposes of computing particle masses & concentrations, using the following equations:

$$B = Q/V + K1 + K2\ Cm + U\ A/V$$

$$\frac{d\,M}{d\,t} = W - B\,M$$

Analytical Solution:

If B>0Then

$$M2 = W/B + (M1 - W/B)\exp(-Bt)$$

else

$$M2 = M1 + W\,t\ ,\ \text{if } B=0$$

endif

where, in consistent units:

B = sum of first-order loss terms Cm = average concentration during step
V = avg. device volume in step M = particle mass in device t = time
W = total inflow load to device (from watersheds & upstream devices)
Q = average outflow from device (from flow balance)
U = particle settling veloc A = average device surface area
K1,K2 = first & second order decay coefficients

Average values of V, W, Q, & A are used in each time step. Technique is similar to that used in the SWMM Transport Block (Huber & Dikinson, 1988), except based upon mass rather than concentration.

Concentrations are solved as follows:

$$C2 = M2/V2$$

$$Cm = [\ W + (M1 - M2)/t\ ]\ V / B \text{ (from mass balance)}$$

where,

C2, V2 = concentration & volume at end of time step

Cm = average concentration during time step (used for downstream routing)

If a nonzero 2nd-order decay rate is specified, 3 iterations are performed, updating the first-order loss term (B) each time based upon the average concentration (CM) computed in the previous iteration.

APPENDIX B.3. P8 Model Inputs

Devices

Input	Control		Experimental				Source
Device Name	CELL_B8	CELL_B7	CELL_B5D	CELL_B5C	CELL_G3	CELL_G4	
Type	INF_BASIN	INF_BASIN	INF_BASIN	INF_BASIN	INF_BASIN	INF_BASIN	
Outflow Device							
Overflow	OUT	OUT	OUT	OUT	OUT	OUT	
Infiltration	OUT	OUT	OUT	OUT	OUT	OUT	
Particle Removal Scale Factor	3	3	3	3	3	3	
Infiltration Basin Parameters							
Bottom Elev (ft)	868.23	868.23	868.23	868.23	868.05	868.27	BLP Design Docs
Bottom Area (ac)	0.0499	0.0489	0.0162	0.0257	0.0278	0.0189	BLP Design Docs
Storage Pool Area (ac)	0.10599	0.1039	0.0372	0.0634	0.0695	0.0493	BLP Design Docs
Storage Pool Volume (ac-ft)	0.0522	0.0512	0.0179	0.0298	0.0365	0.0229	BLP Design Docs
Void Volume (%)	30	30	40	40	40	40	Estimated by BLP
Infiltration Rate (in/hr)	24	24	32	32	32	32	Personal Communication with Wayne King (ERTHFood)

Watersheds

Input	Control		Experimental				Equation/Source
Watershed Name	W_B8	W_B7	W_B5D	W_B5C	W_G3	W_G4	
Outflow Device for Surface Runoff	CELL_B8	CELL_B7	CELL_B5D	CELL_B5C	CELL_G3	CELL_G4	
Outflow Device for Percolation	None	None	None	None	None	None	
Total Area (ac)	0.73	0.6	0.28	0.37	0.4799	0.31	BLP Design Docs
Pervious Area Curve Number	61	61	61	61	61	61	BLP Design Docs
Scale Factor for Particle Loads	1	1	1	1	1	1	BLP Design Docs
Impervious Area Type	Not Swept	Not Swept	Not Swept	Not Swept	Not Swept	Not Swept	
Impervious Fraction	0.7123	0.6999	0.6071	0.7569	0.7708	0.7097	BLP Design Docs
Depression Storage	0.01606	0.01606	0.0153	0.01606	0.01606	0.01606	[0.03*Watershed Slope^-0.49]
Impervious Runoff Coefficient	0.6917	0.68	0.5964	0.7338	0.7436	0.6887	BLP Design Docs
Scale Factor for Particle Loads	1	1	1	1	1	1	

Evapotranspiration, Pervious Runoff Parameters, Etc

Input	Value		
Snowmelt Paramters			
Melt Coefficient (in/day-DegF)	NA		
Scale Factor	NA		
Critical Temperature (F)			
SnowFall	NA		
SnowMelt	NA		
SoilFreeze	NA		
Pervious Area Runoff Parameters			
Growing Season (Months)	3 thru 11 (Mar-Nov)		
Antecedent Moisture Condition	AMC II	AMC III	
Growing Season	0.5	1.1	
Non-Growing Season	1.4	2.1	
Evapotranspiration Calibration Factor	1		
Monthly ET Coefficients			
Month	Veg. Cover Factor	Air Temp (F)	Daylength (hrs)
January	0.5	41.2	9.98
February	0.5	45	10.58
March	0.75	53.6	11.47
April	1	61.6	12.55
May	1	69.3	13.05
June	1	76.2	14.22
July	1	78.9	14.33
August	1	78.2	13.78
September	1	72.9	12.87
October	1	62.5	11.85
November	0.75	53.3	10.82
December	0.5	44.8	10.1

APPENDIX B.4. Cost Minimization Raw Data

		actual data					predicted data						
Cell	Cost (as a function of materials)	Lead Concentration	Copper Concentration	Zinc Concentration	TSS Concentration	TP Concentration	Lead Removal	Copper Removal	Zinc Removal	TSS Removal	TP Removal	Volume (Design)	Volume (Required)
B8	$15,783.30	0.0019	0.0049	0.018	4	0.23	58.90	58.20	35.00	59.20	38.90	2275	2198
B7	$15,468.80	0.0019	0.0049	0.0207	0.9	0.14	63.50	62.90	41.10	63.70	45.00	2229	1777
B5d	$4,779.05	0.0019	0.0049	0.0235	10	0.05	64.00	63.60	44.20	64.10	46.40	778	727
G3	$8,941.16	0.0019	0.0049	0.0194	2	0.21	62.50	61.40	39.70	62.60	44.20	1591	1555
B5c	$8,147.11						67.00	66.30	46.20	67.30	49.60	1300	1175
G4	$6,343.53	0.0019	0.0141	0.0304	8	0.64	66.30	65.70	46.10	66.60	50.05	996	930
	target	0.03	0.007	0.065	20	0.1	50*	58.8	51.8	62.96	82.76	9169	8362

*input data level lower than target

APPENDIX B.5. – Cost Minimization (Excel Solver) Inputs

Cell B8	
Cost	$15,783.30
Volume	2275
Lead	58.90
Copper	58.20
Zinc	35.00
TSS	59.20
TP	38.90
Units Needed	
Cell B7	
Cost	$15,468.80
Volume	2229
Lead	63.50
Copper	62.90
Zinc	41.10
TSS	63.70
TP	45.00
Units Needed	
Cell B5d	
Cost	$4,779.05
Volume	778
Lead	64.00
Copper	63.60
Zinc	44.20
TSS	64.10
TP	46.40
Units Needed	

Cell G3	
Cost	$8,941.16
Volume	1591
Lead	62.50
Copper	61.40
Zinc	39.70
TSS	62.60
TP	44.20
Units Needed	
Cell B5c	
Cost	$8,147.11
Volume	1300
Lead	67.00
Copper	66.30
Zinc	46.20
TSS	67.30
TP	49.60
Units Needed	
Cell G4	
Cost	$6,343.53
Volume	996
Lead	66.30
Copper	65.70
Zinc	46.10
TSS	66.60
TP	50.05
Units Needed	

actual cost for each cell
design volume for each cell

pollutant reduction or concentration for each individual cell

Total Cost	$0.00	Total Cost of Optimal Solution

Total Volume	0	
Lead Reduction	0.00	average pollutant reduction or concentration for each parameter across all cells
Copper Reduction	0.00	
Zinc Reduction	0.00	
TSS Reduction	0.00	
TP Reduction	0.00	
Units Built	0	

Constraints

Volume Constraint	>=	8362
Lead Constraint	>=	50
Copper Constraint	>=	58.8
Zinc Constraint	>=	51.8
TSS Constraint	>=	62.96
TP Constraint	>=	82.76
Unit Constraint	=	6

Unit Constraints

Units B8	>=	0	forces unit to be a positive number
Units B7	>=	0	
Units B5d	>=	0	
Units G3	>=	0	
Units B5c	>=	0	
Units G4	>=	0	

Units B8	=	integer	forces unit to be a whole number
Units B7	=	integer	
Units B5d	=	integer	
Units G3	=	integer	
Units B5c	=	integer	
Units G4	=	integer	

APPENDIX C. Results

APPENDIX C.1. Water Quality Analysis Results

Rockdale Career Academy Bioretention
Cells
Water Quality Analysis
Results
Conducted by UGA Agricultural Services Laboratories, Athens, GA

Sample Date: 5/14/2007 (Rain Event 5/12-13 2007)

WQ Parameter	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Lead (mg/L)	0.0019	0.0019	0.0019	0.0019	0.0019	no sample	0.0019	0.0019
Copper (mg/L)	0.0049	0.0049	0.0049	0.0049	0.0049	no sample	0.0141	0.0141
Zinc (mg/L)	0.018	0.0207	0.0235	0.0194	0.02145	no sample	0.0304	0.0304
Suspended Solids (mg/L)	4	0.9	10	2	6	no sample	8	8
Nitrate/Nitrite (mg/L)	2.69	3.13	1.17	1.26	1.215	no sample	3.19	3.19
Total Phosphorus (mg/L)	0.23	0.14	0.5	0.21	0.355	no sample	0.64	0.64

Notes: No sample was collected from B5c. For Lead and Copper, 0.0019 and 0.0049 are the numerical equivalent of <0.002 and <0.005 reported by the lab. For TSS, 0.09 is the numerical equivalent of <1.0 reported by the lab.

APPENDIX C.2. RCA Bioretention Cell Pictures (Choked with grass clippings - Maintenance Issues) – May 2007

APPENDIX C.3. Sensitivity Analysis Results

Lead - 25% change in removal rate / %change in input value

Cell B8								
Input Variable	Removal	Change	Change%	Sensit	OutLoad	Change	Change%	Sensit
Base Result -->	58.93				2.61			
watershed area	53.86	-5.07	-8.6	-0.34	3.67	1.06	40.65	1.63
imperv fraction	58.39	-0.54	-0.92	-0.04	1.03	-1.58	-60.44	-2.42
depression stor	58.94	0	0	0	2.61	0	0	0
curve number	58.29	-0.65	-1.09	-0.04	3.36	0.75	28.71	1.15
Cell B7								
Input Variable	Removal	Change	Change%	Sensit	OutLoad	Change	Change%	Sensit
Base Result -->	63.5				1.98			
watershed area	58.13	-5.37	-8.45	-0.34	2.85	0.87	43.69	1.75
imperv fraction	63.11	-0.39	-0.61	-0.02	0.85	-1.13	-57.06	-2.28
depression stor	63.5	0	0	0	1.98	0	0	0
curve number	62.78	-0.72	-1.14	-0.05	2.57	0.58	29.29	1.17
Cell G3								
Input Variable	Removal	Change	Change%	Sensit	OutLoad	Change	Change%	Sensit
Base Result -->	61.13				1.3			
watershed area	55.61	-5.52	-9.03	-0.36	1.86	0.56	43.11	1.72
imperv fraction	59.41	-1.72	-2.81	-0.11	0.24	-1.06	-81.58	-3.26
depression stor	61.13	0	0	0	1.3	0	0	0
curve number	60.57	-0.56	-0.92	-0.04	1.67	0.37	28.46	1.14
Cell G4								
Input Variable	Removal	Change	Change%	Sensit	OutLoad	Change	Change%	Sensit
Base Result -->	65.1				0.95			
watershed area	59.31	-5.79	-8.9	-0.36	1.38	0.44	46.23	1.85
imperv fraction	64.63	-0.47	-0.73	-0.03	0.38	-0.56	-59.68	-2.39
depression stor	65.1	0	0	0	0.95	0	0	0
curve number	64.35	-0.75	-1.15	-0.05	1.23	0.28	29.55	1.18

Cell B5d								
Input Variable	Removal	Change	Change%	Sensit	OutLoad	Change	Change%	Sensit
Base Result -->	62.82				1.23			
watershed area	57.21	-5.61	-8.93	-0.36	1.77	0.54	44.29	1.77
imperv fraction	63.13	0.31	0.5	0.02	0.75	-0.48	-38.81	-1.55
depression stor	62.82	0	0	0	1.23	0	0	0
curve number	61.77	-1.04	-1.66	-0.07	1.6	0.37	30.52	1.22
Cell B5c								
Input Variable	Removal	Change	Change%	Sensit	OutLoad	Change	Change%	Sensit
Base Result -->	65.75				0.93			
watershed area	59.9	-5.85	-8.9	-0.36	1.37	0.44	46.83	1.87
imperv fraction	64.52	-1.23	-1.87	-0.07	0.23	-0.7	-75.49	-3.02
depression stor	65.75	0	0	0	0.93	0	0	0
curve number	65.13	-0.62	-0.94	-0.04	1.2	0.27	29.01	1.16

APPENDIX C.4. P8 Mass Balances by Device

P8 Urban Catchment Model, Version 3.1 Run Date 06/22/07

Case	HT_Thesis_Trial1.p8c	FirstDate	06/01/06	Precip(in)	261.2
Title	HT Thesis Test 1	LastDate	05/31/07	Rain(in)	261.16
PrecFile	PRECIPTST.pcp	Events	65	Snow(in)	0.00
PartFile	p8_default.p8p	TotalHrs	8740	TotalYrs	1.00

Mass Balances by Device

Device: CELL_B8													
	Flow Loads (lbs)							Concentrations (ppm)					
Mass Balance Term	acre-ft	TSS	TP	TKN	CU	PB	ZN	TSS	TP	TKN	CU	PB	ZN
01 watershed inflows	9.89	35241.24	84.13	333.30	12.35	6.40	51.03	1311.15	3.13	12.40	0.46	0.24	1.90
03 infiltrate	2.91	5362.07	19.39	77.17	1.93	0.98	12.79	677.35	2.45	9.75	0.24	0.12	1.62
04 exfiltrate	2.91	0.00	0.08	0.47	0.01	0.00	0.51		0.01	0.06	0.00	0.00	0.06
05 filtered	0.00	5362.07	19.31	76.70	1.92	0.98	12.28	0.00	0.00	0.00	0.00	0.00	0.00
07 spillway outlet	6.96	14298.07	51.02	202.69	5.12	2.61	32.52	755.64	2.70	10.71	0.27	0.14	1.72
08 sedimen + decay	0.00	15504.12	13.44	52.35	5.27	2.79	5.58	0.00	0.00	0.00	0.00	0.00	0.00
09 total inflow	9.89	35241.24	84.13	333.30	12.35	6.40	51.03	1311.15	3.13	12.40	0.46	0.24	1.90
10 surface outflow	6.96	14298.07	51.02	202.69	5.12	2.61	32.52	755.64	2.70	10.71	0.27	0.14	1.72
11 groundw outflow	2.91	0.00	0.08	0.47	0.01	0.00	0.51		0.01	0.06	0.00	0.00	0.06
12 total outflow	9.87	14298.07	51.10	203.17	5.13	2.61	33.02	532.75	1.90	7.57	0.19	0.10	1.23
13 total trapped	0.00	20866.19	32.75	129.05	7.19	3.77	17.87						
14 storage increase	0.01	59.18	0.21	0.82	0.02	0.01	0.11						
15 mass balance chec	0.00	17.80	0.07	0.27	0.01	0.00	0.03						
Load Reduction (%)	0.00	59.21	38.93	38.72	58.24	58.93	35.01						

Device: CELL_B7													
	Flow Loads (lbs)							Concentrations (ppm)					
Mass Balance Term	acre-ft	TSS	TP	TKN	CU	PB	ZN	TSS	TP	TKN	CU	PB	ZN
01 watershed inflows	7.99	30193.66	71.95	284.77	10.56	5.48	42.88	1390.48	3.31	13.11	0.49	0.25	1.97
03 infiltrate	2.85	5303.13	19.39	77.15	1.91	0.97	12.69	685.01	2.50	9.97	0.25	0.13	1.64
04 exfiltrate	2.85	0.00	0.08	0.46	0.01	0.00	0.50		0.01	0.06	0.00	0.00	0.06
05 filtered	0.00	5303.13	19.32	76.69	1.90	0.97	12.19	0.00	0.00	0.00	0.00	0.00	0.00
07 spillway outlet	5.13	10868.29	39.24	155.73	3.88	1.98	24.64	779.99	2.82	11.18	0.28	0.14	1.77
08 sedimen + decay	0.00	13944.98	13.04	50.79	4.74	2.51	5.42	0.00	0.00	0.00	0.00	0.00	0.00
09 total inflow	7.99	30193.66	71.95	284.77	10.56	5.48	42.88	1390.48	3.31	13.11	0.49	0.25	1.97
10 surface outflow	5.13	10868.29	39.24	155.73	3.88	1.98	24.64	779.99	2.82	11.18	0.28	0.14	1.77
11 groundw outflow	2.85	0.00	0.08	0.46	0.01	0.00	0.50		0.01	0.06	0.00	0.00	0.06
12 total outflow	7.97	10868.29	39.31	156.19	3.90	1.99	25.13	501.41	1.81	7.21	0.18	0.09	1.16
13 total trapped	0.00	19248.11	32.36	127.48	6.64	3.48	17.61						
14 storage increase	0.01	58.67	0.21	0.82	0.02	0.01	0.11						
15 mass balance chec	0.00	18.59	0.07	0.28	0.01	0.00	0.03						
Load Reduction (%)	0.00	63.75	44.97	44.77	62.86	63.50	41.07						

Device: CELL_G3													
	Flow Loads (lbs)							Concentrations (ppm)					
Mass Balance Term	acre-ft	TSS	TP	TKN	CU	PB	ZN	TSS	TP	TKN	CU	PB	ZN
01 watershed inflows	7.07	18499.78	44.67	178.03	6.55	3.37	30.06	962.94	2.33	9.27	0.34	0.18	1.56
03 infiltrate	2.40	3363.58	12.27	49.16	1.23	0.62	9.00	515.36	1.88	7.53	0.19	0.09	1.39
04 exfiltrate	2.40	0.00	0.06	0.39	0.01	0.00	0.42		0.01	0.06	0.00	0.00	0.06
05 filtered	0.00	3363.58	12.20	48.77	1.22	0.62	8.59	0.00	0.00	0.00	0.00	0.00	0.00
07 spillway outlet	4.65	7068.99	25.41	101.62	2.58	1.30	18.12	558.89	2.01	8.03	0.20	0.10	1.43
08 sedimen + decay	0.00	8010.39	6.79	26.44	2.72	1.44	2.82	0.00	0.00	0.00	0.00	0.00	0.00
09 total inflow	7.07	18499.78	44.67	178.03	6.55	3.37	30.06	962.94	2.33	9.27	0.34	0.18	1.56
10 surface outflow	4.65	7068.99	25.41	101.62	2.58	1.30	18.12	558.89	2.01	8.03	0.20	0.10	1.43
11 groundw outflow	2.40	0.00	0.06	0.39	0.01	0.00	0.42		0.01	0.06	0.00	0.00	0.06
12 total outflow	7.05	7068.99	25.47	102.01	2.58	1.30	18.54	368.66	1.33	5.32	0.13	0.07	0.97
13 total trapped	0.00	11373.97	18.99	75.21	3.95	2.06	11.41						
14 storage increase	0.01	42.20	0.15	0.59	0.01	0.01	0.09						
15 mass balance chec	0.00	14.63	0.06	0.22	0.00	0.00	0.02						
Load Reduction (%)	0.00	61.48	42.52	42.25	60.25	61.13	37.95						

Device: CELL_G4													
	Flow Loads (lbs)							Concentrations (ppm)					
Mass Balance Term	acre-ft	TSS	TP	TKN	CU	PB	ZN	TSS	TP	TKN	CU	PB	ZN
01 watershed inflows	4.18	15099.60	36.03	142.72	5.29	2.74	21.77	1327.74	3.17	12.55	0.47	0.24	1.91
03 infiltrate	1.68	3061.38	11.13	44.32	1.10	0.56	7.36	669.52	2.43	9.69	0.24	0.12	1.61
04 exfiltrate	1.68	0.00	0.05	0.27	0.01	0.00	0.29		0.01	0.06	0.00	0.00	0.06
05 filtered	0.00	3061.38	11.09	44.04	1.10	0.56	7.07	0.00	0.00	0.00	0.00	0.00	0.00
07 spillway outlet	2.49	5178.61	18.58	73.78	1.85	0.95	11.77	764.07	2.74	10.89	0.27	0.14	1.74
08 sedimen + decay	0.00	6805.06	6.12	23.85	2.31	1.22	2.54	0.00	0.00	0.00	0.00	0.00	0.00
09 total inflow	4.18	15099.60	36.03	142.72	5.29	2.74	21.77	1327.74	3.17	12.55	0.47	0.24	1.91
10 surface outflow	2.49	5178.61	18.58	73.78	1.85	0.95	11.77	764.07	2.74	10.89	0.27	0.14	1.74
11 groundw outflow	1.68	0.00	0.05	0.27	0.01	0.00	0.29		0.01	0.06	0.00	0.00	0.06
12 total outflow	4.18	5178.61	18.62	74.05	1.86	0.95	12.07	456.26	1.64	6.52	0.16	0.08	1.06
13 total trapped	0.00	9866.44	17.21	67.89	3.41	1.78	9.61						
14 storage increase	0.01	34.22	0.12	0.48	0.01	0.01	0.07						
15 mass balance chec	0.00	20.33	0.08	0.31	0.01	0.00	0.03						
Load Reduction (%)	0.00	65.34	47.76	47.57	64.49	65.10	44.14						

Device: CELL_B5D													
	Flow Loads (lbs)							Concentrations (ppm)					
Mass Balance Term	acre-ft	TSS	TP	TKN	CU	PB	ZN	TSS	TP	TKN	CU	PB	ZN
01 watershed inflows	3.29	18420.64	43.47	171.16	6.38	3.33	23.41	2058.10	4.86	19.12	0.71	0.37	3.62
03 infiltrate	1.27	3487.15	12.43	49.14	1.23	0.63	7.22	1011.99	3.61	14.26	0.36	0.18	2.10
04 exfiltrate	1.27	0.00	0.03	0.21	0.00	0.00	0.22		0.01	0.06	0.00	0.00	0.06
05 filtered	0.00	3487.15	12.40	48.93	1.23	0.63	7.00	0.00	0.00	0.00	0.00	0.00	0.00
07 spillway outlet	2.02	6752.00	23.74	93.59	2.37	1.23	13.14	1230.39	4.33	17.06	0.43	0.22	2.40
08 sedimen + decay	0.00	8111.82	7.04	27.43	2.76	1.46	2.93	0.00	0.00	0.00	0.00	0.00	0.00
09 total inflow	3.29	18420.64	43.47	171.16	6.38	3.33	23.41	2058.10	4.86	19.12	0.71	0.37	2.62
10 surface outflow	2.02	6752.00	23.74	93.59	2.37	1.23	13.14	1230.39	4.33	17.06	0.43	0.22	2.40
11 groundw outflow	1.27	0.00	0.03	0.21	0.00	0.00	0.22		0.01	0.06	0.00	0.00	0.06
12 total outflow	3.29	6752.00	23.77	93.80	2.37	1.23	13.36	755.80	2.66	10.50	0.27	0.14	1.50
13 total trapped	0.00	11598.97	19.44	76.36	3.99	2.09	9.93						
14 storage increase	0.01	39.70	0.14	0.54	0.01	0.01	0.07						
15 mass balance chec	0.00	29.98	0.12	0.45	0.01	0.01	0.05						
Load Reduction (%)	0.00	62.97	44.73	44.62	62.43	62.82	42.42						

Device: CELL_B5C													
	Flow Loads (lbs)							Concentrations (ppm)					
Mass Balance Term	acre-ft	TSS	TP	TKN	CU	PB	ZN	TSS	TP	TKN	CU	PB	ZN
01 watershed inflows	5.36	15122.46	36.40	144.84	5.34	2.75	23.83	1038.74	2.50	9.95	0.37	0.19	1.64
03 infiltrate	2.17	3130.94	11.53	46.13	1.14	0.58	8.32	531.02	1.95	7.82	0.19	0.10	1.41
04 exfiltrate	2.17	0.00	0.06	0.35	0.01	0.00	0.38		0.01	0.06	0.00	0.00	0.06
05 filtered	0.00	3130.94	11.47	45.78	1.14	0.57	7.94	0.00	0.00	0.00	0.00	0.00	0.00
07 spillway outlet	3.18	5080.62	18.45	73.68	1.84	0.93	12.83	588.54	2.14	8.54	0.21	1.11	1.49
08 sedimen + decay	0.00	6859.01	6.24	24.28	2.33	1.23	2.59	0.00	0.00	0.00	0.00	0.00	0.00
09 total inflow	5.36	15122.46	36.40	144.84	5.34	2.75	23.83	1038.74	2.50	9.95	0.37	0.19	1.64
10 surface outflow	3.18	5080.62	18.45	73.68	1.84	0.93	12.83	588.54	2.14	8.54	0.21	0.11	1.49
11 groundw outflow	2.17	0.00	0.06	0.35	0.01	0.00	0.38		0.01	0.06	0.00	0.00	0.06
12 total outflow	5.35	5080.62	18.51	74.03	1.85	0.93	13.21	349.70	1.27	5.10	0.13	0.06	0.91
13 total trapped	0.00	9989.95	17.70	70.06	3.47	1.81	10.53						
14 storage increase	0.01	35.53	0.13	0.50	0.01	0.01	0.07						
15 mass balance chec	0.00	16.37	0.06	0.25	0.01	0.00	0.03						
Load Reduction (%)	0.00	66.06	48.63	48.37	64.96	65.75	44.17						

APPENDIX C.5. P8 Model Results Concentration Statistics

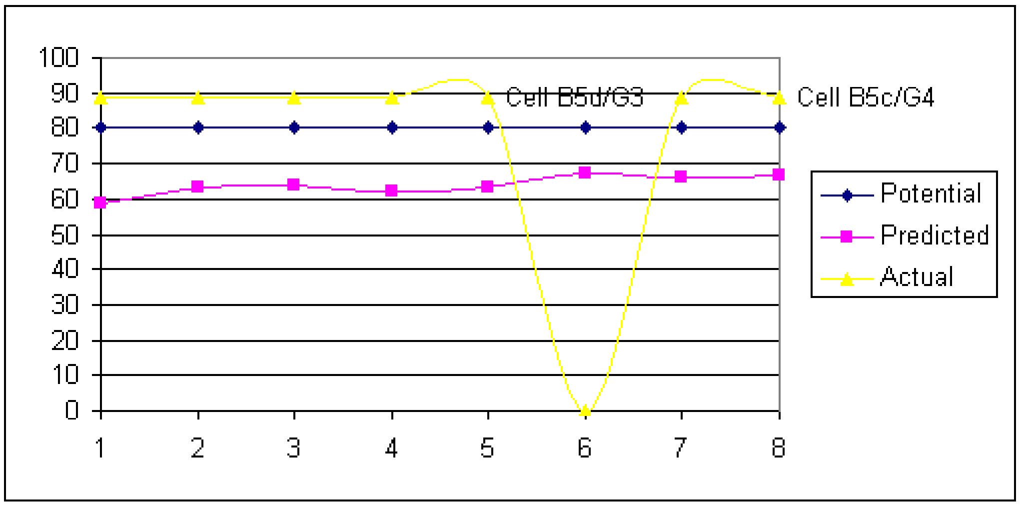
P8 Urban Catchment Model, Version 3.1					Run Date 06/22/07			
Case HT_Thesis_Trial1.p8c			FirstDate 06/01/06		Precip(in) 261.2			
Title HT Thesis Test 1			LastDate 05/31/07		Rain(in) 261.16			
PrecFile PRECIPTST.pcp			Events 65		Snow(in) 0.00			
PartFile p8_default.p8p			TotalHrs 8740		TotalYrs 1.00			
Concentration Statistics Events with Rainfall + Snowmelt > 0.05 inches								
Term: 12 total outflow								
Device	Variable	Count	Mean	CV	Min	Max	Freq>A	A ppm
CELL_B8	TSS	13	532.788	0.009	529.479	543.866	100%	20
CELL_B8	TP	13	1.904	0.009	1.893	1.942	100%	0.1
CELL_B8	TKN	13	7.571	0.009	7.526	7.718	100%	1
CELL_B8	CU	13	0.191	0.009	0.19	0.195	100%	0.007
CELL_B8	PB	13	0.097	0.009	0.097	0.099	100%	0.03
CELL_B8	ZN	13	1.231	0.007	1.225	1.248	100%	0.065
CELL_B7	TSS	13	501.445	0.01	498.136	511.824	100%	20
CELL_B7	TP	13	1.814	0.01	1.802	1.85	100%	0.1
CELL_B7	TKN	13	7.206	0.01	7.161	7.346	100%	1
CELL_B7	CU	13	0.18	0.01	0.179	0.183	100%	0.007
CELL_B7	PB	13	0.092	0.01	0.091	0.093	100%	0.03
CELL_B7	ZN	13	1.16	0.008	1.154	1.18	100%	0.065

CELL_G3	TSS	13	368.694	0.01	366.186	376.461	100%	20
CELL_G3	TP	13	1.329	0.01	1.32	1.355	100%	0.1
CELL_G3	TKN	13	5.321	0.01	5.287	5.423	100%	1
CELL_G3	CU	13	0.135	0.01	0.134	0.137	100%	0.007
CELL_G3	PB	13	0.068	0.01	0.067	0.069	100%	0.03
CELL_G3	ZN	13	0.967	0.008	0.963	0.986	100%	0.065
CELL_G4	TSS	13	456.297	0.01	453.18	465.832	100%	20
CELL_G4	TP	13	1.641	0.01	1.63	1.674	100%	0.1
CELL_G4	TKN	13	6.525	0.01	6.482	6.652	100%	1
CELL_G4	CU	13	0.164	0.01	0.163	0.167	100%	0.007
CELL_G4	PB	13	0.083	0.01	0.083	0.085	100%	0.03
CELL_G4	ZN	13	1.063	0.008	1.058	1.084	100%	0.065
CELL_B5D	TSS	13	755.856	0.01	750.908	770.897	100%	20
CELL_B5D	TP	13	2.661	0.01	2.644	2.713	100%	0.1
CELL_B5D	TKN	13	10.501	0.01	10.434	10.7	100%	1
CELL_B5D	CU	13	0.266	0.01	0.264	0.271	100%	0.007
CELL_B5D	PB	13	0.137	0.01	0.136	0.14	100%	0.03
CELL_B5D	ZN	13	1.496	0.008	1.488	1.524	100%	0.065
CELL_B5C	TSS	13	349.728	0.011	347.286	357.126	100%	20
CELL_B5C	TP	13	1.274	0.01	1.266	1.3	100%	0.1
CELL_B5C	TKN	13	5.096	0.01	5.063	5.199	100%	1
CELL_B5C	CU	13	0.128	0.01	0.127	0.13	100%	0.007
CELL_B5C	PB	13	0.064	0.01	0.064	0.066	100%	0.03
CELL_B5C	ZN	13	0.909	0.008	0.905	0.928	100%	0.065

APPENDIX C.6. Comparison of Pollutant Removal Efficiencies (Estimated, Predicted, and Actual)

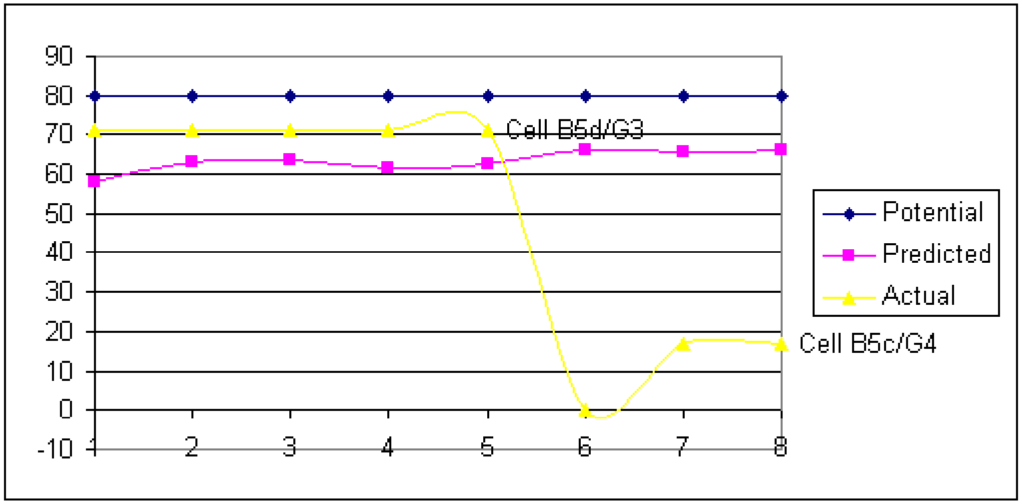
Lead

	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Potential	80	80	80	80	80	80	80	80
Predicted	58.9	63.5	64	62.2	63.1	67	66.3	66.65
Actual	88.823529	88.823529	88.8235294	88.823529	88.8235294	ns	88.823529	88.8235294



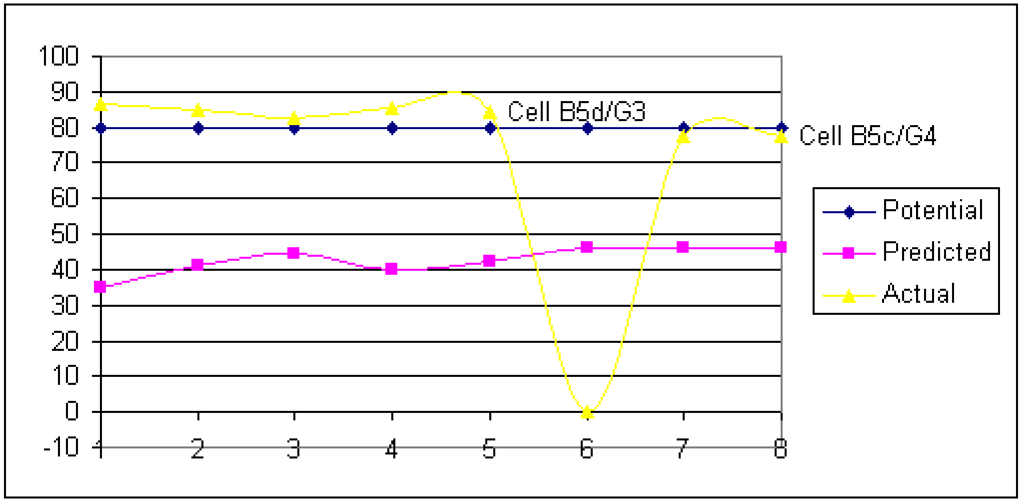
Copper

	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Potential	80	80	80	80	80	80	80	80
Predicted	58.2	62.9	63.6	61.4	62.5	66.3	65.7	66
Actual	71.176471	71.176471	71.1764706	71.176471	71.1764706	ns	17.058824	17.0588235



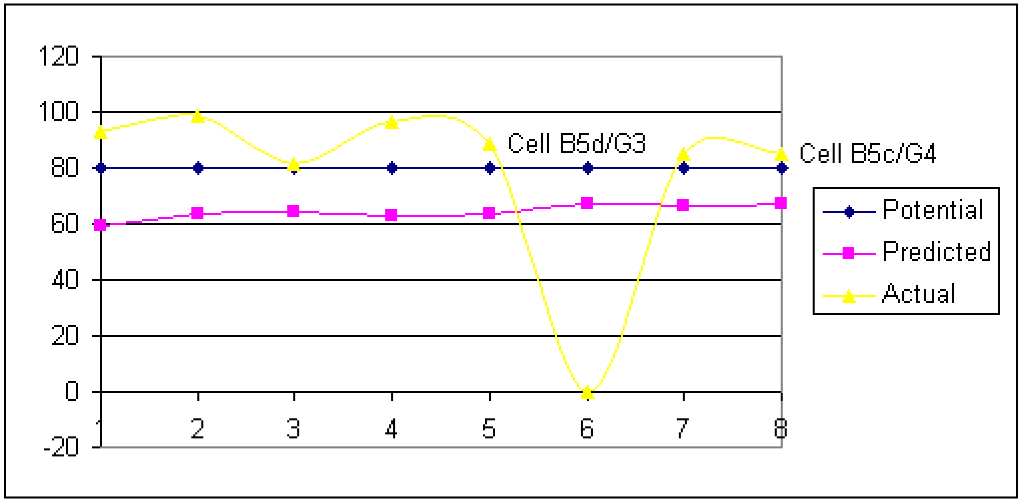
Zinc

	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Potential	80	80	80	80	80	80	80	80
Predicted	35	41.1	44.2	39.7	41.95	46.2	46.1	46.15
Actual	86.666667	84.666667	82.5925926	85.62963	84.1111111	ns	77.481481	77.4814815



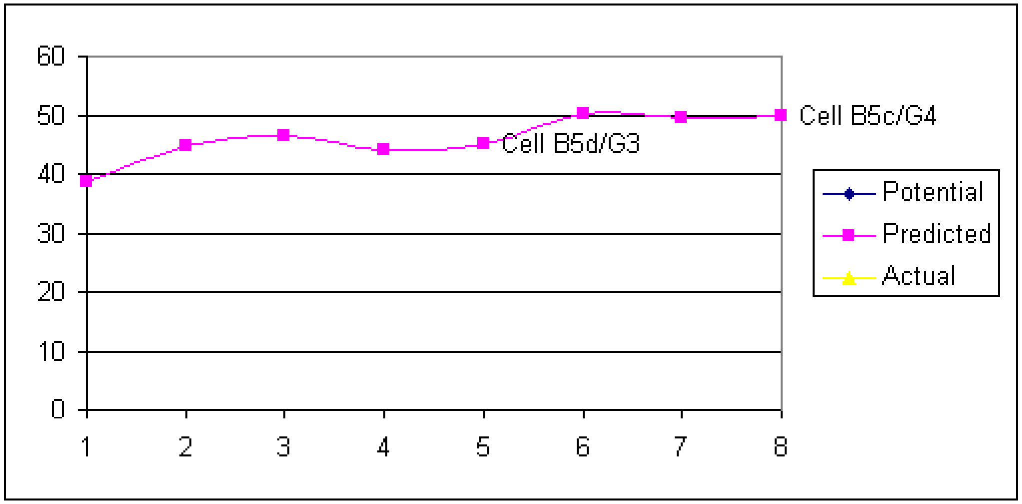
TSS

	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Potential	80	80	80	80	80	80	80	80
Predicted	59.2	63.7	64.1	62.6	63.35	67.3	66.6	66.95
Actual	92.592593	98.333333	81.4814815	96.296296	88.8888889	ns	85.185185	85.1851852



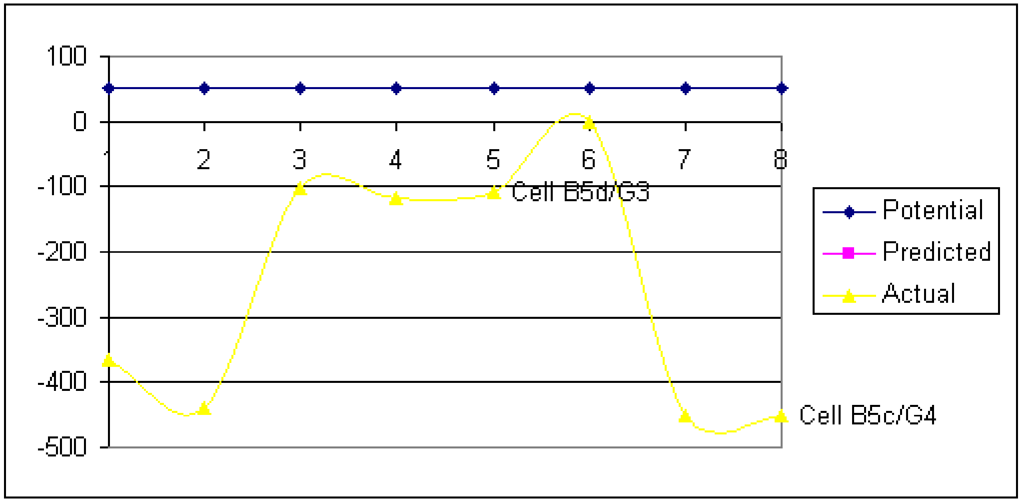
TKN

	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Potential								
Predicted	38.7	44.8	46.3	43.9	45.1	50.3	49.4	49.85
Actual								



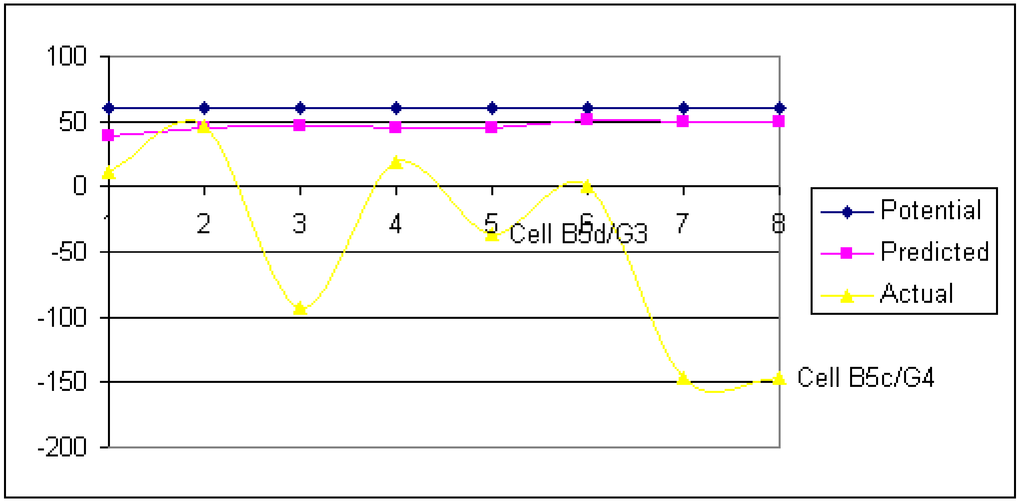
Nitrate/Nitrite-N

	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Potential	50	50	50	50	50	50	50	50
Predicted								
Actual	-363.7931	-439.65517	-101.72414	-117.2414	-109.48276	ns	-450	-450



Total Phosphorus

	Cell B8 (1)	Cell B7 (2)	Cell B5d (3)	Cell G3 (5)	Cell B5d/G3	Cell B5c (4)	Cell G4 (6)	Cell B5c/G4
Potential	60	60	60	60	60	60	60	60
Predicted	38.9	45	46.4	44.2	45.3	50.5	49.6	50.05
Actual	11.538462	46.153846	-92.307692	19.230769	-36.538462	ns	-146.1538	-146.15385
Percent Diff (pot/pre)								



APPENDIX C.7. Cost Minimization Analysis Scenarios

Scenario 1: Predicted Water Quality Data, Six Units

Cell B8		Cell G3		Total Cost	$48,690.80	
Cost	$15,783.30	Cost	$8,941.16			
Volume	2275	Volume	1591	Total Volume	8,442	
Lead	58.90	Lead	62.50			
Copper	58.20	Copper	61.40	Lead Reduction	63.50	
Zinc	35.00	Zinc	39.70	Copper Reduction	62.58	
TSS	59.20	TSS	62.60	Zinc Reduction	41.53	
TP	38.90	TP	44.20	TSS Reduction	63.63	
Units Needed	0	Units Needed	4	TP Reduction	45.47	
				Units Built	6	
Cell B7		Cell B5c				
Cost	$15,468.80	Cost	$8,147.11			
Volume	2229	Volume	1300	Constraints		
Lead	63.50	Lead	67.00			
Copper	62.90	Copper	66.30	Volume Constraint	>=	8362
Zinc	41.10	Zinc	46.20	Lead Constraint	>=	50
TSS	63.70	TSS	67.30	Copper Constraint	>=	58.8
TP	45.00	TP	49.60	Zinc Constraint	>=	51.8
Units Needed	0	Units Needed	1	TSS Constraint	>=	62.96
				TP Constraint	>=	82.76
				Unit Constraint	<=	6
Cell B5d		Cell G4				
Cost	$4,779.05	Cost	$6,343.53			
Volume	778	Volume	996	Unit Constraints		
Lead	64.00	Lead	66.30	Units B8	>=	0
Copper	63.60	Copper	65.70	Units B7	>=	0
Zinc	44.20	Zinc	46.10	Units B5d	>=	0
TSS	64.10	TSS	66.60	Units G3	>=	0
TP	46.40	TP	50.05	Units B5c	>=	0
Units Needed	1	Units Needed	0	Units G4	>=	0

Scenario 2 Predicted Water Quality Data, Five Units

Cell B8		Cell G3		Total Cost	$53,598.96	
Cost	$15,783.30	Cost	$8,941.16			
Volume	2275	Volume	1591	Total Volume	8,418	
Lead	58.90	Lead	62.50			
Copper	58.20	Copper	61.40	Lead Reduction	63.20	
Zinc	35.00	Zinc	39.70	Copper Reduction	62.44	
TSS	59.20	TSS	62.60	Zinc Reduction	41.16	
TP	38.90	TP	44.20	TSS Reduction	63.34	
Units Needed	0	Units Needed	2	TP Reduction	44.96	
				Units Built	5	
Cell B7		Cell B5c				
Cost	$15,468.80	Cost	$8,147.11			
Volume	2229	Volume	1300	Constraints		
Lead	63.50	Lead	67.00			
Copper	62.90	Copper	66.30	Volume Constraint	>=	8362
Zinc	41.10	Zinc	46.20	Lead Constraint	>=	50
TSS	63.70	TSS	67.30	Copper Constraint	>=	58.8
TP	45.00	TP	49.60	Zinc Constraint	>=	51.8
Units Needed	2	Units Needed	0	TSS Constraint	>=	62.96
				TP Constraint	>=	82.76
				Unit Constraint	=	5
Cell B5d		Cell G4				
Cost	$4,779.05	Cost	$6,343.53			
Volume	778	Volume	996	Unit Constraints		
Lead	64.00	Lead	66.30	Units B8	>=	0
Copper	63.60	Copper	65.70	Units B7	>=	0
Zinc	44.20	Zinc	46.10	Units B5d	>=	0
TSS	64.10	TSS	66.60	Units G3	>=	0
TP	46.40	TP	50.05	Units B5c	>=	0
Units Needed	1	Units Needed	0	Units G4	>=	0

Scenario 3 Predicted Water Quality Data, Four Units

Cell B8		Cell G3		Total Cost	$61,875.19	
Cost	$15,783.30	Cost	$8,941.16			
Volume	2275	Volume	1591	Total Volume	8,916	
Lead	58.90	Lead	62.50			
Copper	58.20	Copper	61.40	Lead Reduction	63.50	
Zinc	35.00	Zinc	39.70	Copper Reduction	62.90	
TSS	59.20	TSS	62.60	Zinc Reduction	41.10	
TP	38.90	TP	44.20	TSS Reduction	63.70	
Units Needed	0	Units Needed	0	TP Reduction	45.00	
				Units Built	4	
Cell B7		Cell B5c				
Cost	$15,468.80	Cost	$8,147.11			
Volume	2229	Volume	1300	Constraints		
Lead	63.50	Lead	67.00			
Copper	62.90	Copper	66.30	Volume Constraint	>=	8362
Zinc	41.10	Zinc	46.20	Lead Constraint	>=	50
TSS	63.70	TSS	67.30	Copper Constraint	>=	58.8
TP	45.00	TP	49.60	Zinc Constraint	>=	51.8
Units Needed	4	Units Needed	0	TSS Constraint	>=	62.96
				TP Constraint	>=	82.76
				Unit Constraint	=	4
Cell B5d		Cell G4				
Cost	$4,779.05	Cost	$6,343.53			
Volume	778	Volume	996	Unit Constraints		
Lead	64.00	Lead	66.30	Units B8	>=	0
Copper	63.60	Copper	65.70	Units B7	>=	0
Zinc	44.20	Zinc	46.10	Units B5d	>=	0
TSS	64.10	TSS	66.60	Units G3	>=	0
TP	46.40	TP	50.05	Units B5c	>=	0
Units Needed	0	Units Needed	0	Units G4	>=	0

Scenario 4: Actual Water Quality Data, Six Units

Cell B8		Cell G3		Total Cost	$49,484.85	
Cost	$15,783.30	Cost	$8,941.16			
Volume	2275	Volume	1591	Total Volume	8733	
Lead	0.0019	Lead	0.0019			
Copper	0.0049	Copper	0.0049	Lead Reduction	0.00	
Zinc	0.0180	Zinc	0.0194	Copper Reduction	0.00	
TSS	4.0000	TSS	2	Zinc Reduction	0.02	
TP	0.2300	TP	0.21	TSS Reduction	3.33	
Units Needed	0	Units Needed	5	TP Reduction	0.18	
				Units Built	6	
Cell B7		Cell B5c				
Cost	$15,468.80	Cost	$8,147.11			
Volume	2229	Volume	1300	Constraints		
Lead	0.0019	Lead				
Copper	0.0049	Copper		Volume Constraint	>=	8362
Zinc	0.0207	Zinc		Lead Constraint	<=	0.03
TSS	0.9	TSS		Copper Constraint	<=	0.007
TP	0.14	TP		Zinc Constraint	<=	0.065
Units Needed	0	Units Needed	0	TSS Constraint	<=	20
				TP Constraint	<=	0.1
				Unit Constraint	=	6
Cell B5d		Cell G4				
Cost	$4,779.05	Cost	$6,343.53			
Volume	778	Volume	996	Unit Constraints		
Lead	0.0019	Lead	0.0019	Units B8	>=	0
Copper	0.0049	Copper	0.0141	Units B7	>=	0
Zinc	0.0235	Zinc	0.0304	Units B5d	>=	0
TSS	10	TSS	8	Units G3	>=	0
TP	0.05	TP	0.64	Units B5c	>=	0
Units Needed	1	Units Needed	0	Units G4	>=	0

Scenario 5: Actual Water Quality Data, Five Units

Cell B8		Cell G3		Total Cost	$51,233.44	
Cost	$15,783.30	Cost	$8,941.16			
Volume	2275	Volume	1591	Total Volume	8593	
Lead	0.0019	Lead	0.0019			
Copper	0.0049	Copper	0.0049	Lead Reduction	0.00	
Zinc	0.0180	Zinc	0.0194	Copper Reduction	0.00	
TSS	4.0000	TSS	2	Zinc Reduction	0.02	
TP	0.2300	TP	0.21	TSS Reduction	1.78	
Units Needed	0	Units Needed	4	TP Reduction	0.20	
				Units Built	5	
Cell B7		Cell B5c				
Cost	$15,468.80	Cost	$8,147.11			
Volume	2229	Volume	1300	Constraints		
Lead	0.0019	Lead				
Copper	0.0049	Copper		Volume Constraint	>=	8362
Zinc	0.0207	Zinc		Lead Constraint	<=	0.03
TSS	0.9	TSS		Copper Constraint	<=	0.007
TP	0.14	TP		Zinc Constraint	<=	0.065
Units Needed	1	Units Needed	0	TSS Constraint	<=	20
				TP Constraint	<=	0.1
				Unit Constraint	=	5
Cell B5d		Cell G4				
Cost	$4,779.05	Cost	$6,343.53			
Volume	778	Volume	996	Unit Constraints		
Lead	0.0019	Lead	0.0019	Units B8	>=	0
Copper	0.0049	Copper	0.0141	Units B7	>=	0
Zinc	0.0235	Zinc	0.0304	Units B5d	>=	0
TSS	10	TSS	8	Units G3	>=	0
TP	0.05	TP	0.64	Units B5c	>=	0
Units Needed	0	Units Needed	0	Units G4	>=	0

Scenario 6: Actual Water Quality Data, Four Units

Cell B8		Cell G3		Total Cost	$56,291.06	
Cost	$15,783.30	Cost	$8,941.16			
Volume	2275	Volume	1591	Total Volume	8416	
Lead	0.0019	Lead	0.0019			
Copper	0.0049	Copper	0.0049	Lead Reduction	0.00	
Zinc	0.0180	Zinc	0.0194	Copper Reduction	0.00	
TSS	4.0000	TSS	2	Zinc Reduction	0.02	
TP	0.2300	TP	0.21	TSS Reduction	3.50	
Units Needed	3	Units Needed	1	TP Reduction	0.23	
				Units Built	4	
Cell B7		Cell B5c				
Cost	$15,468.80	Cost	$8,147.11			
Volume	2229	Volume	1300	Constraints		
Lead	0.0019	Lead				
Copper	0.0049	Copper		Volume Constraint	>=	8362
Zinc	0.0207	Zinc		Lead Constraint	<=	0.03
TSS	0.9	TSS		Copper Constraint	<=	0.007
TP	0.14	TP		Zinc Constraint	<=	0.065
Units Needed	0	Units Needed	0	TSS Constraint	<=	20
				TP Constraint	<=	0.1
				Unit Constraint	=	4
Cell B5d		Cell G4				
Cost	$4,779.05	Cost	$6,343.53			
Volume	778	Volume	996	Unit Constraints		
Lead	0.0019	Lead	0.0019	Units B8	>=	0
Copper	0.0049	Copper	0.0141	Units B7	>=	0
Zinc	0.0235	Zinc	0.0304	Units B5d	>=	0
TSS	10	TSS	8	Units G3	>=	0
TP	0.05	TP	0.64	Units B5c	>=	0
Units Needed	0	Units Needed	0	Units G4	>=	0

APPENDIX C.8. Cost Efficiency Values

Predicted % Removal									
Lead		Copper		Zinc		TSS		TP	
B5c	0.168	B5c	0.170	B5c	0.244	B5c	0.167	B5c	0.227
B5d/G3	0.186	B5d/G3	0.189	B5c/G4	0.274	B5d/G3	0.186	B5c/G4	0.254
B5c/G4	0.190	B5c/G4	0.192	G4	0.277	B5c/G4	0.189	G4	0.255
B5d	0.192	B5d	0.194	B5d	0.278	G4	0.192	B5d/G3	0.260
G4	0.192	G4	0.194	B5d/G3	0.281	B5d	0.192	B5d	0.265
G3	0.201	G3	0.205	B7	0.315	G3	0.201	G3	0.284
B7	0.204	B7	0.206	G3	0.316	B7	0.203	B7	0.288
B8	0.220	B8	0.223	B8	0.370	B8	0.219	B8	0.333
Actual % Removal									
Lead		Copper		Zinc		TSS		TP	
B5d/G3	0.126	B5d/G3	0.393	B5d/G3	0.176	B7	0.136	B5d	0.246
B5d	0.131	B5d	0.410	G3	0.179	G3	0.140	B5c	*
G3	0.134	G3	0.419	B8	0.179	B8	0.162	B5c/G4	*
G4	0.136	B8	0.432	B7	0.190	B5d/G3	0.168	B5d/G3	*
B8	0.138	B7	0.432	B5d	0.193	G4	0.213	B7	*
B7	0.138	B5c	*	G4	0.240	B5d	0.246	B8	*
B5c	*	B5c/G4	*	B5c	*	B5c	*	G3	*
B5c/G4	*	G4	*	B5c/G4	*	B5c/G4	*	G4	*

* values either no sample was taken or % removal calculation returned a negative % removal and were not taken into account for this calculation.