8-1-2022

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Recommended Citation

Abera, Liya, "Determining Implementation Barriers for Green Stormwater Infrastructure (GSI) Practices for Urban Flood Control" (2022). *Electronic Theses and Dissertations*. 2343.
https://egrove.olemiss.edu/etd/2343

DETERMINING IMPLEMENTATION BARRIERS FOR GREEN STORMWATER INFRASTRUCTURE (GSI) PRACTICES FOR URBAN FLOOD CONTROL

A dissertation
Presented in partial fulfillment of requirements
for the degree of Doctor of Philosophy
in Civil Engineering

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August 2022

ABSTRACT

An increase in impervious land covers, such as asphalt and buildings from new construction and land development projects, results in cities experiencing flooding events. In 2021, the US was impacted by significant weather and climate disasters, including two flooding events and 11 severe storms. In addition to flooding events, excess runoff carries pollutants to receiving waters causing low water quality and habitat loss. To minimize flooding events and maintain the quality of receiving water bodies, stormwater runoff should be handled near its source. The installation of green stormwater infrastructure (GSI) is one sustainable method of addressing stormwater runoff problems. GSI reduces the volume of runoff, which also prevents downstream flooding and environmental damage. GSI also has environmental and social benefits, such as providing a natural green environment, reducing exposure to toxic substances, improving air quality, and improving human well-being.

Despite its environmental and health benefits, there are barriers that prevent developers and engineers from installing these practices. These barriers usually fall into three main categories: technical, financial, and regulatory. The fact that the benefits of these practices are not widely understood and not adequately quantified is considered a technical barrier. This lack of track record limits developers and engineers from including GSI practices in their design. Financial barriers stem from the high cost of retrofitting and construction of GSI, which does not attract developers. City regulations that lack requirements for implementing GSI are considered a regulatory barrier.

Many studies have been conducted to analyze the effectiveness and cost of GSI. However, the past research studies tend to focus on a watershed and citywide scale implementation of GSI. Although it is valuable to know how GSI can prevent flooding in large development projects, existing research fail to assess that smaller communities do not have the space or the money to implement wholescale GSI projects on a watershed scale. Therefore, this study mainly focused on a small-scale implementation of GSI while analyzing the implementation barriers. Hydrologic performance analysis of GSI on three small sites is presented. This study provided a spreadsheet that combines life-cycle cost analysis (LCCA) and benefit-cost analysis (BCA). Also, city ordinances of six cities were reviewed, and modifications are recommended.

DEDICATION

This work is dedicated to my husband, Leti T. Wodajo, my son Naod L. Teklu, and my daughter Monet L. Teklu, who have been a constant source of energy and encouragement during my study. Also, to my mom Abaynesh Libase and my dad Eshetu Abera for raising me to be a better person and teaching me to dream big. My little sisters, Meski and Tsihoye, thank you for the love and encouragement.

LIST OF ABBREVIATIONS

ADS	Advanced Drainage System
BMPs	Best Management Practices
BCA	Benefit-Cost Analysis
BCR	Benefit-Cost Ratio
CN	Curve number
CNT	Center for Neighborhood Technology
GSI	Green stormwater infrastructure
EPA	Environmental Protection Agency
IRR	Internal Rate of Return
LCCA	Life-cycle Cost Analysis
LID	Low Impact Development
NPB	Net Present Benefit
NPC	Net Present Cost
NPV	Net Present Value
NRCS	Natural Resource Conservation Service
O&M	Operation and Maintenance

PM	particulate matter
PV	Present Value
PVB	Present Value Benefits
PVC	Present Value Costs
SUSTAIN	Urban Stormwater Treatment and Analysis Integration
SWMM	Stormwater Management Modeling
TC	Time of Concentration
US	United States
USEPA	United States Environmental Protection Agency
WERF	Water Environment Research Foundation

ACKNOWLEDGEMENTS

All glory and honor to God, my creator, He the Alpha and Omega.

My sincere gratitude goes to my advisor, Dr. Cris Surbeck, professor and chair of the Civil Engineering Department. I am blessed to have her as my academic advisor and grateful for her constant support and guidance throughout this study. She has been patient and supportive during my bad days and had been a source of encouragement. She is amazingly generous with her time, always available to listen to me, give me academic and career advice. I have learned a lot from her.

I would also like to thank Kristina Alexander for her guidance and advice throughout my study, especially for her valuable insight on the regulatory analysis part of this research. She is such a charming person who makes me enjoy working with her.

I am also thankful to my dissertation committee members, Dr. Yavuz Ozeren, Dr. Mohannad Al-Hamdan, and Dr. Andrew O’Reilly, for their time, guidance, and engagement. This dissertation is better as a result of their comments and suggestions.

I appreciate the City of Oxford Special Projects Engineer, Steve Brunton, for his guidance with the HydroCAD software and for connecting me with the local contractors to get cost data. I would also like to acknowledge Joey Moore, Williams Engineering Consultants, Inc, and Ross Barkley, Eley Barkley Dale Architects, for providing me with cost data.

Thanks to Kit Alexander, the City of Orange Beach Engineer, for her feedback. Rick Stickler and Kristina Greger of the City of Biloxi for their insights.

I would like to thank the U.S. Department of Commerce’s National Oceanic and Atmospheric Administration and the Mississippi-Alabama Sea Grant Consortium for supporting this research.

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CHAPTER 1

1 INTRODUCTION

1.1 MOTIVATION OF RESEARCH

Cities suffer from flooding due to land cover changes resulting from developments and urbanization. Flooding in development sites, on the streets, or in small towns is not considered a big problem, and these incidences might not be studied. However, these small floods add up to a disaster-level flood. One of the solutions to control flooding is the application of green stormwater infrastructure (GSI) practices. Green infrastructure practices have been implemented in large cities as a form of retrofitting and new designs. Case studies GSI reported in government literature tend to focus on large cities and large construction projects (EPA, 2013 and EPA, 2016). Philadelphia and New York cities are mentioned as model cities that have implemented GSI. These cities spend billions of dollars to design a citywide green infrastructure. However, these practices do not apply to small to medium-sized cities with insufficient budgets and resources to implement GSI on a city or watershed scale. More typically, smaller communities consider employing GSI on small sites on a site-by-site basis.

In addition to the lack of attention and research on site-level GSI implementation, multiple barriers prevent the implementation of these practices. In 2011, the Clean Water America Alliance identified four categories of barriers that often prevent the adoption of green infrastructure: technical and physical, legal and regulatory, financial, and communities and institutional (Abhold, 2011). Analyzing these barriers and identifying the points at which the GSI becomes impractical would lead to a solution. Therefore, in this research, GSI implementation barriers were analyzed, and a tipping point of stormwater expenses that discourage developers from implementing GSI on development sites will be assessed.

Studying the applicability and effectiveness of GSI practices in small but growing cities, which are not commonly found in the research literature, would advance the knowledge on the topic of GSI. Furthermore, it will help city engineers, local developers, and regulation makers see the options beyond the barriers through their decision-making process.

1.2 RESEARCH OBJECTIVES

The overall goal of this research was to determine implementation barriers for GSI practices in small urban communities and to show the possible options to overcome these barriers. This study started with the hypothesis that three main barriers prevent the installation of GSI: technical, financial, and regulatory; and focused on a site-scale analysis using three hypothetical development sites to analyze the three barriers. The three sites have unique designs that can characterize different development types. Two of the sites are proposed development sites, and the remaining one is an already developed site. These sites were used as hypothetical sites built in different cities to analyze the implementation barriers.

In order to meet the research objectives, hydrologic performance analyses, life-cycle cost analyses (LCCA), and review of city ordinances are performed. The hydrologic performance analyses are performed to analyze the technical barriers by determining the effectiveness of GSIs on runoff reduction based on different site characteristics. The LCCA derived from benefit-cost analyses are used to determine the costs related to the implementation of GSI practices. The regulatory analyses are used to identify lacking or restricting regulations for implementing GSI in the cities' ordinances.

Based on the hydrologic performance analysis and the LCCA results, a spreadsheet for determining the profitability of implementing GSI was developed. A financial internal rate of return (IRR) and a benefit-cost ratio (BCR) calculations are included in the spreadsheet. Based on the ordinance analysis, modifications to the current city regulations were proposed and hydrologic performance analyses of GSI were conducted based on the modifications.

In summary, this research addressed the following three objectives:

1. Analyze the hydrologic performance of GSI by estimating the change in the stormwater runoff peak and volume based on different stormwater management structures. This objective was accomplished by performing a rainfall-runoff analysis using three hypothetical site plans and four hydrologic soils.
2. Determine the cost-effectiveness of GSI by estimating the short and long-term costs of stormwater management structures, including GSI. In addition, estimate the benefits of GSI and determine at what point the cost and benefit of GSI are balanced.
3. Analyze how municipal ordinances may help or limit the implementation of GSI and suggest sample regulations encouraging GSI implementation that will further reduce runoff.

1.3 WORK SCOPE

This research is composed of five chapters. The scope of each chapter is explained below:

Chapter1 presents an introduction to the motivation of the research, the main research objective, and the scope of the research.

Chapter 2 presents a literature review of previous work on GSI performance, cost, and benefit analyses.

Chapter 3 is titled “Hydrologic Performance of Green Stormwater Infrastructure, Based on Various Urban Site Designs and Soil Types” and has been submitted to the *Journal of Sustainable Water in the Built Environment* and is currently under review.

Chapter 4 is titled “Life-cycle Cost and Benefit-cost Analysis for Site-Scale Implementation of Green Stormwater Infrastructure (GSI)” and is in the form of a final draft of a manuscript for submission to a journal on life-cycle cost and benefit-cost analyses for site-scale implementation of GSI.

Chapter 5 is titled "Evaluating the Effect of City Ordinances on the Implementation of Green Stormwater Infrastructure (GSI)” and has been published in the *Journal of Environmental Challenges.*

Chapter 6 presents the conclusion and contribution of this research and recommendations for future studies.

1.4 OVERVIEW OF FINDINGS

Figure 1.1 shows the overall work scope of the dissertation.

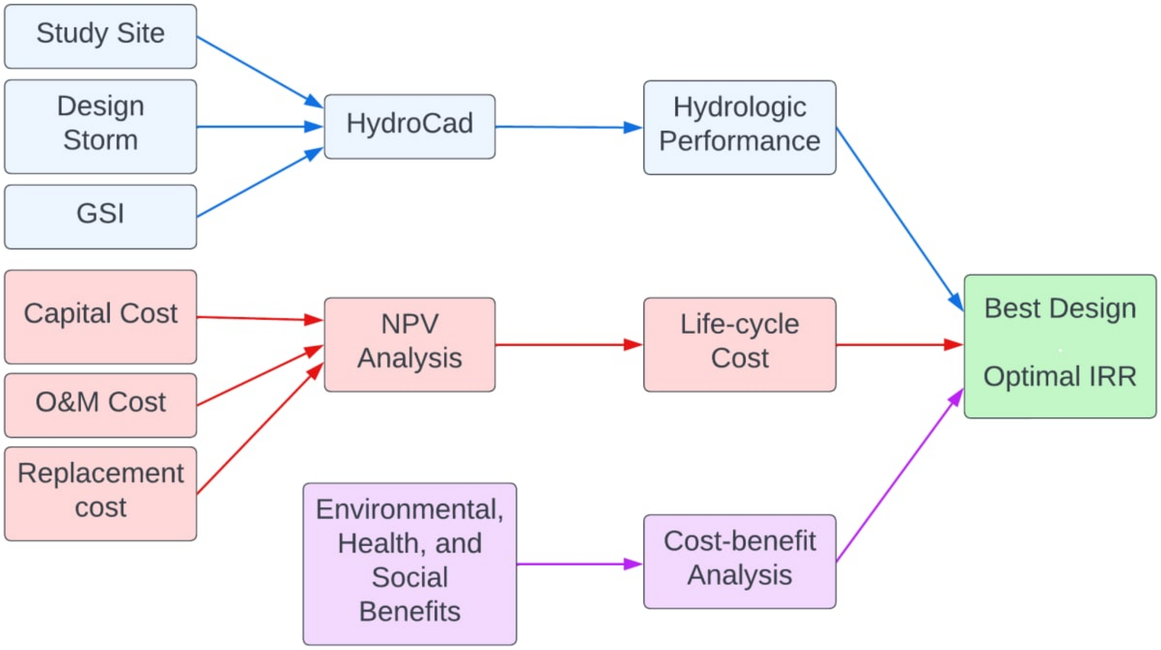

Figure 1.1. Overall flow of the research

CHAPTER 2

2 LITERATURE REVIEW

Various stormwater management practices have been implemented to reduce the effect of urban runoff. Traditional stormwater management infrastructures have been implemented to address stormwater quantity and quality problems for years. The traditional stormwater infrastructure uses combined sewage systems to collect stormwater and domestic waste in a single system. This system usually leads to overflow that results in polluting water bodies (Aspacher and Alam 2020). Green stormwater infrastructure (GSI) has recently gained popularity in managing stormwater runoff. GSI is a favorable alternative to traditional stormwater management infrastructures. GSI is also sometimes called low impact development (LID) controls. GSI is a term for a range of stormwater management systems that use natural processes to capture, slow down, and filter stormwater runoff. It mimics the natural hydrological cycle that improves infiltration and evaporation. Bio-retention cells, green roofs, vegetated swales, rain barrels, and permeable pavements are some of the types of GSI practices. GSI reduces the volume and peak flow, thereby preventing downstream flooding and environmental damage. GSIs showed wide variability in their stormwater runoff reduction effectiveness (Dhakal and Chevalier 2017; Qin et al. 2013; Sparkman et al. 2017). If properly designed and maintained, green infrastructure is at least as adequate as traditional stormwater infrastructure to reduce stormwater runoff volume and peak flow (Jaffe 2010).

2.1 GSI PERFORMANCE ANALYSIS

Several studies have been conducted on the hydrologic performance of GSI. In most cases, studies investigate the performance of GSI in controlling stormwater runoff quantity or improving quality issues. For instance, Damodaram et al. (2010) applied a hydrological model to a watershed located on the campus of Texas A&M University in College Station, Texas, to predict the stormwater reductions resulting from retrofitting existing infrastructure with LID technologies. The results demonstrate that these LID practices yield significant stormwater control for small events and less for flood events. Similarly, Li et al. (2020) assessed the hydrological performance of LIDs at a city level. The study found that LID performed well on urban storm mitigation at a watershed scale under different rainfall scenarios.

Determining the hydrological performance of GSI usually involves the use of hydrologic computer modeling. Modeling software such as the EPA Stormwater Management Modeling (SWMM) and Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN), and The Center for Neighborhood Technology (CNT) Green Values National Stormwater Management Calculator have been commonly used for GSI stormwater quality and quantity analysis. (Jayasooriya and Ng 2014; Rossman 2010; Shoemaker et al. 2013)

HydroCAD has been used in previous studies to model hydrological responses to environmental and land cover changes (Chen 2016; Mt and Eer 2015) and to design low-impact developments (LIDs) (Lu and Yuan 2011). Compared to other rainfall-runoff modeling software, HydroCAD has been used in fewer studies to perform GSI hydrological analysis. Although researchers have not commonly used HydroCAD, it has been used by civil engineers and developers widely since 1986 (Chen et al. 2016; HydroCAD 2019). HydroCAD allows the simulation of rainfall-runoff using different storms (design storms, local rainfall data, or rainfall data in its library) (Obropta and Del Monaco 2018). It also provides several storage design options, essential in modeling detention or retention stormwater facilities to manage the post-development runoff. These make it preferable by engineers and developers rather than researchers. Since this research focused on site-level analysis, where city engineers and developers are involved, HydroCAD was used.

Past research studies on GSI tend to focus on computer modeling of GSI effectiveness on watershed and citywide scales of entire floodplains (Damodaram et al. 2010; Kousky et al. 2013). Evaluating the effectiveness of GSI at site scales has been understudied. Therefore, this dissertation mainly focused on implementing GSI on small site scale analysis.

2.2 GSI COSTS AND BENEFITS ANALYSIS

Limited research has been conducted on GSI cost analysis compared to hydrologic analysis. Previous studies analyzed the costs related to implementing GSI separately or in combination with hydrologic analysis (MacMullan and Reich 2007; Olson et al. 2009; Sample et al. 2003; Vineyard et al. 2015; Wainger et al. 2018). Li et al. (2020) assessed the hydrological performance and life cycle cost (LCC) of GSI practice at a watershed level that covers 5.629 acres (22.78 km^2). The study prioritized three GSI practices (grass swale, bio-retention, and permeable pavement) based on cost-effectiveness. The research result reported that grass swale was more cost-effective than permeable pavement.

Most previous studies have used life-cycle cost analyses (LCCA) to estimate the cost related to implementing GSI (MacMullan and Reich 2007). Life cycle cost (LCC) is the sum of the costs (initial, O&M, and discarding) throughout the whole life cycle of a project. Including the long-term costs of GSI is a crucial part of assessing its cost. Olson et al. (2009) explained how it is essential to include maintenance costs in evaluating the cost-effectiveness of GSI. Because considering the capital costs alone will result in underestimating the costs and misleading decisions.

Previous studies support the idea that green infrastructure is economically beneficial. However, most previous studies looked at a large-scale implementation of GSI (Kousky et al., 2013; Li et al., 2020; Sun et al., 2016. None of the studies have looked at the specific costs for implementing GSI of a small parcel less than approximately 1-acre area (i.e., a commercial establishment or small apartment complex or housing development) in small cities. Although it is valuable to know how green infrastructures can prevent flooding in large development projects, existing research fails to assess that smaller communities do not have the space or the money to implement wholescale GSI projects on a watershed scale. For example, the city of Philadelphia, PA, started implementing a citywide stormwater infrastructure plan that will cost over $2 billion (Philadelphia Water Department, 2011). While it is true that converting many acres of a city (thousands of acres in the case of Philadelphia) to a series of rain gardens and retention basins will limit flooding, it is not a practical practice for small cities.

GSI practices are usually applied to maintain hydrologic balances; however, they positively impact ecosystems and human health in addition to balancing the hydrologic cycle. These added benefits include improving air quality, reducing urban heat islands, saving energy, and creating a green, healthy environment. For example, Demuzere et al. (2014) analyzed the relevance of the benefits of green urban infrastructures on three spatial scales (i.e. city, neighborhood, and site-specific scales). The study discussed how benefits provided by green urban infrastructure could help adapt to and mitigate climate change (Demuzere et al. 2014). Other GSI benefits that are mentioned in several studies are thermal comfort and reduced energy use (Akbari et al. 2001; Choi et al. 2021; Nordman et al. 2018).

GSIs are effective as a climate change adaptation tool (Choi et al. 2021; Demuzere et al. 2014). Urban watersheds are more vulnerable to climate change due to the population size and the infrastructure requirement. Implementing GSI practices such as planting trees can reduce the effect of climate change by reducing the urban heat island effect and lowering building energy demands by reducing indoor temperatures (EPA 2016, Giese et al. 2019). These benefits can be considered as savings from a project cost. Therefore, a benefit-cost analysis would be necessary to complete the LCCA (CNT 2009). There is a growing research area on stormwater costs, but many focus only on the construction and maintenance and do not include the benefit in the analysis.

Previous studies conducted on ecosystem service economics discuss how to evaluate and measure environmental benefits. For instance, Farber et al. (2002) researched economic and ecological concepts for valuing ecosystem services and discussed how to capture social values when market values do not adequately. This research proposed six techniques to measure ecosystem service values: avoiding cost, replacement cost, factor income, travel cost, hedonic pricing, and contingent valuation. Even though each technique has an appropriate set of valuation techniques, an appropriate valuation method should be selected for different services (Farber et al. 2002; Nordman et al. 2018).

From Farber et al. (2002) proposed techniques, a hedonic pricing method is an appropriate approach to estimating the value of environmental benefits from GSI. The hedonic pricing method estimates economic values for ecosystems or environmental services directly affecting market prices. It is most commonly applied to variations in housing prices that reflect the value of local environmental attributes. This approach can estimate economic benefits or costs associated with environmental quality, including air and water pollution. In addition to hedonic pricing, a benefit transfer approach will also help estimate the environmental benefits of GSI. Benefit transfer applies nonmarket values obtained from primary studies of resource or environmental changes undertaken elsewhere to evaluate a proposed or observed change that is of interest (Ecosystem Valuation 2000; Freeman 2003).

Giving a monetary value to the environmental and health benefits of GSIs is challenging. However, in sustainability research and practice, benefits should include outcomes that are both monetary and non-monetary. Some outcomes can be converted to dollars, but other important social or environmental outcomes are not easily monetized (ARB 2018). Therefore, every possible effort and analysis was made to conduct benefit-cost analysis in this research. For most of the benefits, monetizing them requires some sort of method or technique. Some methods are established; however, most are provided as guidelines and summaries (Hamann et al. 2020; Netusil et al. 2022)

For example, the Center for Neighborhood Technology (CNT) Green Values National Stormwater Management Calculator list some of the environmental, social, and health benefits of GSI and a guideline on converting the benefits into monetary value (CNT 2009). CNT developed a guide, The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental, and Socia Benefits, to evaluate the monetary and non-monetary values of GSI benefits (CNT 2011). It includes detailed example calculations and summaries to estimate GSI benefit values.

Elmqvist et al. (2015) analyzed to what extent investments in green infrastructure in urban landscapes can bring monetary and non-monetary benefits to society and human well-being. Monetary benefits from urban ecosystem services were estimated based on data from 25 urban areas in the USA, Canada, and China. Some of the benefits included in this research are pollution removal, carbon sequestration and storage, regulation of water flows, and recreation. The study concludes that ecological infrastructures in cities are beneficial for the environment and economically advantageous.

Furthermore, the US Environmental Protection Agency's Region 9 (EPA Region 9) Environmental Finance Center (EFC) at Sacramento State created a guide as part of a project to provide improved resources for determining benefits and costs of urban stormwater operations. The guide included methods for benefit-cost analysis (BCA). BCA is the process of estimating a project's value based on products and costs. Also, the guide summarized the process of assessing the benefits of GSI by providing a decision tree chart. Figure 2.1 is taken from this report and shows a decision tree for applying methods to assess benefits in benefit-cost analysis (Environmental Finance Center 2019).

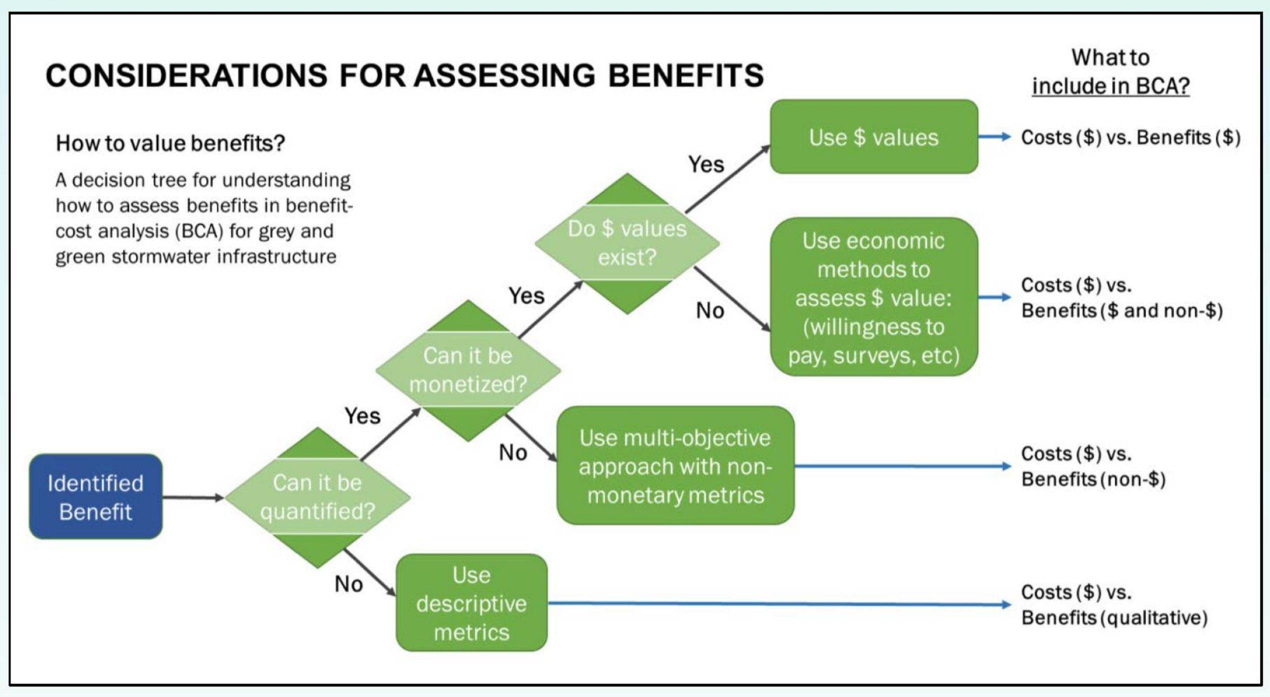

Figure 2.1. Process of assessing benefits in benefit-cost analysis (Environmental Finance Center 2019).

2.3 SUMMARY

In previous studies, GSI hydrologic and cost analyses have been conducted mainly on large scales (watershed or city levels). Although studying the performance of GSI on a large scale is essential, previous studies undermine the importance of studying the performance of GSI in site-scale projects. Most previous studies on the cost-effectiveness of GSI considered only the costs and did not include the benefit in the analyses. The main objective of this research is to add to the body of knowledge on the topic of GSI by analyzing the performance and cost-benefits of GSI on site-scale projects and finding a balance between the technical and financial barriers focusing on small cities. This study also analyzed the regulatory berries to GSI implementations and propose modifications to cities' stormwater ordinances to include requirements for implementing GSI on their development sites. A spreadsheet with cost and benefit analyses that would be used to estimate the BCR and IRR of GSI practices was developed.

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CHAPTER 3 [1]

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[1] This chapter has been submitted to the *Journal of Sustainable Water in the Built Environment* and is currently under review.

3 HYDROLOGIC PERFORMANCE OF GREEN STORMWATER INFRASTRUCTURE (GSI), BASED ON VARIOUS URBAN SITE DESIGNS AND SOIL TYPES

ABSTRACT

The present work used HydroCAD software to evaluate the impact of site design and soil type on the performance of green stormwater infrastructure (GSI, such as permeable pavements, rain gardens, and grassy ditches) using three site designs (mixed-use, commercial, and housing) based on a Natural Resources Conservation Service type II design storm of 222 mm and four hydrologic soil groups. In terms of reducing the runoff peak flow and volume, the rain gardens generally outperformed the permeable pavement and grassy ditches, regardless of the study site. The percent reduction post-development with GSI (compared with post-development, no-GSI) was higher for soil type A than soil type D because of soil type A's greater infiltration capacity. Thus, sites that have substantial land cover with impermeable surfaces, or are built on permeable soil, might require additional post-development GSI to minimize peak flow and volume of runoff. A sensitivity analysis indicates that changing a site's post-development land cover by implementing GSI could reduce the peak flow by up to 87% and the volume by up to 80%, compared with a lack of GSI. The present work will help developers and city planners implement best practices that meet regulations for stormwater management.

3.1 INTRODUCTION

Land cover changes that are associated with urbanization, such as replacing grassy areas with rooftops and cutting trees, diminish natural permeable land cover. Such changes affect the hydrology of urban areas and result in increased runoff volume and runoff peak, which lead to more flooding events. Urbanization also affects the quality of stormwater runoff. Development should be hydrologically sustainable and maintain pre-development conditions (Damodaram et al. 2010).

Recently, the implementation of green stormwater infrastructure (GSI) has been used to reduce the magnitude and improve the quality of stormwater runoff, which helps to maintain pre-development conditions. GSI minimizes urbanization and development impacts and maintains natural water flow in a site or watershed (Sparkman et al. 2017; Wang et al. 2010). Furthermore, the approach is sustainable and environmentally friendly (Aspacher and Alam 2020; EPA 2018; Quan et al. 2020). GSI includes but is not limited to grass swales, green roofs, infiltration trenches, rain gardens, rain barrels, and permeable pavements. These practices reduce runoff volume through infiltration and storage, and lower the peak flow through infiltration and flow retardance caused by increased channel roughness (Davis et al. 2012; Lu and Yuan 2011; Xie et al. 2017). Several studies have reported that the performance of GSI varies with rainfall intensity and duration (Li et al. 2020; Qin et al. 2013). GSI more substantially reduces the stormwater volume and flow rate for small rainfall events than for large storm events (Abera et al. 2021; Damodaram et al. 2010; Davis et al. 2012).

In addition to storm intensity, the soil infiltration capacity also affects the performance of the GSI (Hossain Anni et al. 2020). This paper presents findings from an investigation of the use of GSI on various hydrologic soil groups and urban site designs that will guide developers and city planners to implement optimal stormwater practices that meet their design and soil type. The investigation was done by implementing GSI on three sample urban development sites based on the Natural Resources Conservation Service (NRCS) four hydrologic soil groups: sand (Group A), loamy sand or sandy loam (Group B), silty loam or silty clay loam (Group C), and clay (Group D) (USDA 2009). Group A soils commonly have <10% clay and >90% sand or gravel, or gravel or sand texture. Group B soils commonly have 10% to 20% clay and 50% to 90% sand. Group C soils commonly have 20% to 40% clay and <50% sand. Group D soils typically have >40% clay and <50% sand.

This paper analyzes the effects of urban site designs and soil types on the implementation and performance of GSI. The analysis was conducted by performing rainfall-runoff simulations of three development sites. The rainfall-runoff analyses were performed by computer simulations, considering three development conditions: pre-development, post-development, and post-development with GSI. The simulations were performed in accordance with the four hydrologic soil groups (A–D). HydroCAD, a stormwater analysis software, was used to perform the simulations. The peak and volume of runoff generated from the scenarios were compared based on the results of the simulations.

3.2 STUDY SITES

Three site developments were used as case studies to analyze the implementation and performance differences of GSI: mixed-use, commercial, and housing developments. Each site had unique properties regarding land cover, size, and space availability. The site designs were used to define the development's land cover, and hydrologic inputs, such as time of concentration and design storm, were based on a city ordinance in the southeast United States (Oxford, Mississippi).

3.2.1 Site 1: Mixed-use

Site 1 includes constructing two 3-story, mixed-use buildings; the associated parking lots; and the landscaping. Areas are as follows: buildings, 4,230 m^2; parking lots, 8,201 m^2; and landscaping, 2,539 m^2. Total area: 14,970 m^2.

3.2.2 Site 2: Commercial

Site 2 is a hotel development. Areas are as follows: building, 1,994 m^2; paved parking and an access area, 3,369 m^2; swimming pool, 68 m^2; and landscape area, 2,211 m^2. Total area: 7,642 m^2.

3.2.3 Site 3: Housing

Site 3 is a housing development. Areas are as follows: 14 houses with parking garages underneath the houses, 1,382 m^2; paved surfaces, 2,145 m^2; pool, 72 m^2; and landscape area, 3,226 m^2. Total area: 6,827 m^2.

For consistency, all three sites were assumed to have the same land cover in the pre-development condition: woods/grass combination in good condition. The post-development land cover was defined based on the proposed site design. Table 1 shows the landcover properties of the study sites.

Table 3.1. Land cover properties of the study sites

Post-Development Land Cover	Site 1		Site 2		Site 3	
	Area (m^2)	%	Area (m^2)	%	Area (m^2)	%
Roof top	4,230	28%	1,994	26%	1,384	20%
Paved surface	8,201	55%	3,369	44%	255	4%
Gravel surface	–	–	–	–	1,890	28%
Landscaping	2,539	17%	2,211	29%	3,226	47%
Water surface	–	–	68	1%	72	1%
Total Area (m^2)	**14,970**		**7,642**		**6,827**	
Permeable area (%)	17		29		47	
Impermeable area (%)	83		71		53	

3.3 MATERIALS AND METHODS

The hydrologic performance analysis was conducted with HydroCAD 10.10-7 stormwater management modeling software (US EPA, Washington, DC). This software was selected because it is commonly used for property-scale projects analyzed by city engineers and developers. The three sites were analyzed based on an NRCS type II design storm of 222 mm and four hydrologic soil types.

The hydrologic analyses were conducted based on the study sites' pre- and post-development conditions and three GSIs. Because of the difference in space availability, the sizes of the GSI considered for the sites were different. Permeable pavements, rain gardens, and grassy ditches were the GSI practices considered in this analysis. The peak flow and volume of runoff from the sites were simulated.

3.3.1 Pre- and Post-Development Modeling

The pre- and post-development simulations of the sites were performed based on conditions before and after construction of the developments. The pre-development land cover was assumed as woods/grass combination in good condition for all sites. Therefore, the same curve number (CN) was assigned to a soil group for all of the sites. CNs of 32, 58, 72, and 79 were used for soil groups A–D, respectively. The CN is an empirical parameter for characterizing the runoff potential for a particular soil group and land cover (ASCE 1996; USDA 1982). The land covers for the post-development conditions were defined based on the proposed development design (refer to the Results section).

3.3.2 GSI Modeling

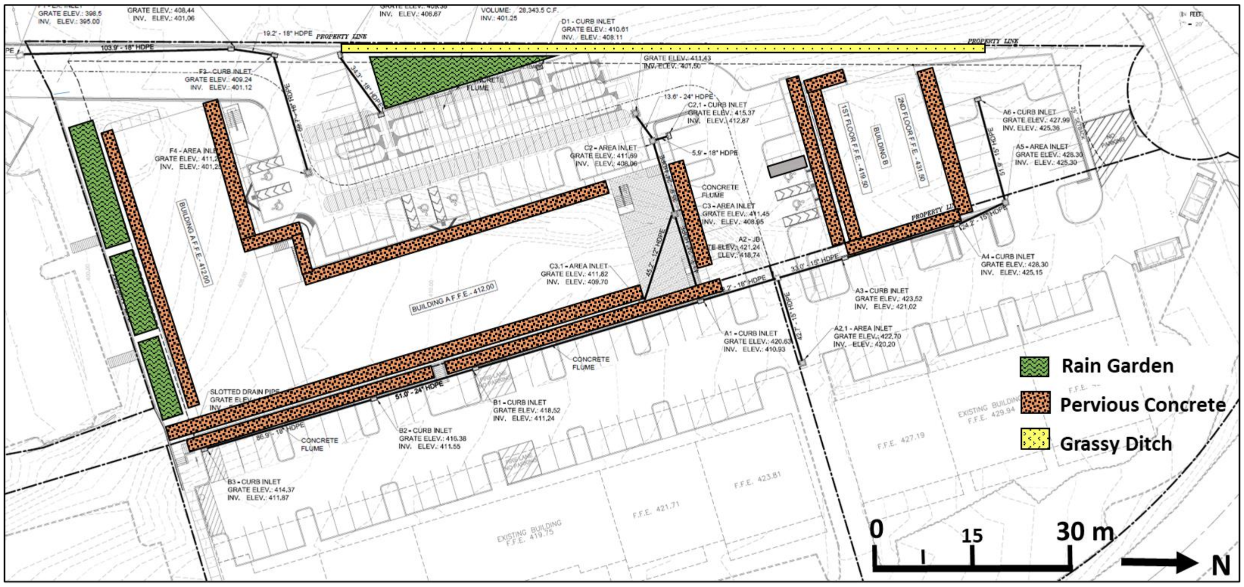
The GSI scenarios were simulated based on implementing three practices: permeable pavements, rain gardens, and grassy ditches. Therefore, three scenarios were considered with different GSI options.

Scenario 1: Permeable pavements in the sidewalks/parking

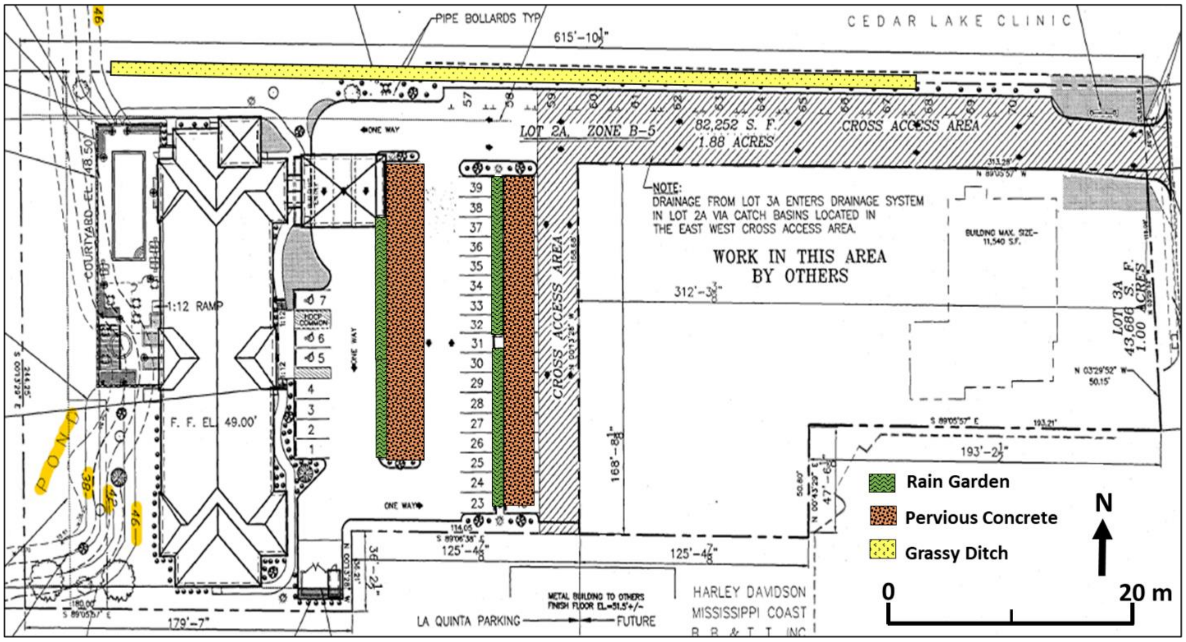
Scenario 2: Rain gardens in the landscaping areas

Scenario 3: Grassy ditches in the landscaping areas

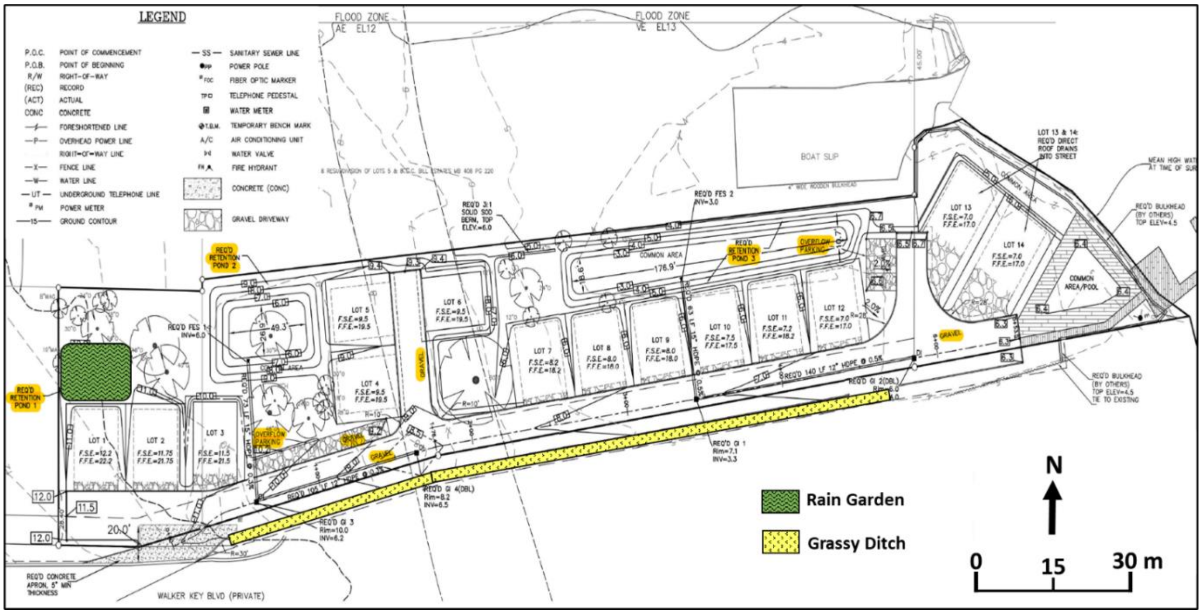
In HydroCAD, the permeable pavement was defined by using adjusted CN values. The rain garden was simulated using a pond node to define each layer, and the inputs were defined in the node. The grassy ditch was defined as a reach node that carries the runoff in an open channel, and the travel time was defined in the time of concentration calculations by the software. Figure 3.1 shows the site plans and proposed GSIs for each site.



(a) Site plan and proposed GSI for Site 1



(b) Site plan and proposed GSI for Site 2



(c) Site plan and proposed GSI for Site 3

Figure 3.1. Green stormwater infrastructure (GSI) scenarios for the three study sites.

3.3.2.1 Modeling Permeable Pavement

Modeling permeable pavement on HydroCAD requires an evaluation of the role of the pavement. There are three setups to consider before modeling the pavement.

(1) No Surface Runoff. This setup considers the ideal condition of permeable pavement, in which all of the rainwater that falls on the pavement infiltrates into the base layers. There is no runoff from the permeable surface.

(2) Complete Surface Runoff. This setup considers the worst condition in that the pavement is clogged and does not achieve its purpose of infiltrating water. In this case, the surface is impermeable, and modeling is done with a standard CN of 98.

(3) Partial Runoff. For this case, an appropriate CN value must be used to estimate the correct surface runoff (HydroCAD 2019). In this study, the partial runoff setup was used for modeling the proposed permeable pavement.

Modeling runoff from permeable pavements requires determining a practical CN value for the surface (Schwartz 2010). The appropriate CN for the permeable pavement was calculated based on the sub-base layers' potential maximum retention, using the NRCS equation for the potential maximum retention (Equation 1), and based on the CN of the underlying soil. Figure 2 shows the layers and thicknesses of the permeable concrete pavement considered in this study. CNs of 64, 69, 71, and 73 were used for soil groups A–D, respectively

$$S = \left(\frac{25{,}400}{CN}\right) - 254 \tag{1}$$

where:

S = potential maximum retention after runoff begins (mm), and CN = runoff curve number.

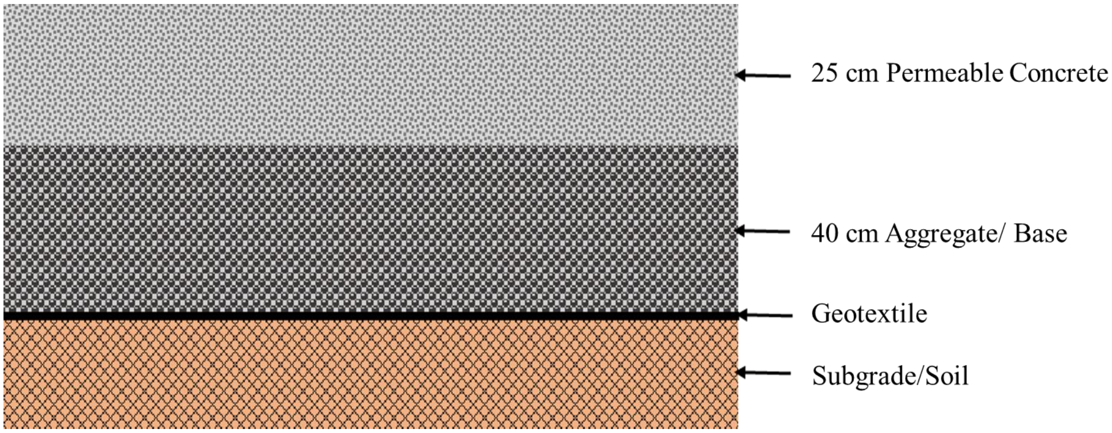


Figure 3.2. Permeable concrete pavement layers.

3.3.2.2 Modeling Rain Gardens

The rainfall-runoff modeling for the rain garden was performed by defining the rain garden using a pond node in HydroCAD with appropriate storage and outlet structures. The pond node enables the delineation of multiple storage layers. Then the layers were arranged on top of one another to model the composite shape. The rain gardens proposed for the study sites consist of ponding, mulch, amended soil, and gravel layers; defined as prismatic shapes. Except for the mulch layer (7.6 cm thick), the depth of the layers was 30.5 cm. Rain gardens are designed to infiltrate and store runoff. When there is a rainfall event beyond the capacity of the rain gardens, the runoff will leave through the overflow outlet structure. Outflow from the rain garden was defined as exfiltration and overflow.

3.3.2.3 Modeling Grassy Ditches

The grassy ditch proposed for the sites is a shallow, grass-lined ditch that mainly slows down the runoff before combining with the outflow. The grassy ditch was included in the study because it is preferable by property owners due to convenient long-term maintenance. The open and shallow nature of the channel design facilitates maintenance. The design has an average depth of 40 cm (Figure 3.3). In HydroCAD, the ditch was defined by a reach node with a trapezoidal shape. A reach performs a runoff routing through an open channel based on normal Manning flow. The cross-sections (width, depth, slope, and roughness coefficient) and profile of the grassy ditch are some input parameters defined for a reach node. The flow and infiltration characteristics of the ditch were defined by the Manning roughness coefficient (n) and the CN. The ditch area and ditch travel time were defined under a sub-catchment node. The travel time was defined under the time of concentration tab and calculated by the velocity method. Except for the length, this exact design was implemented for all of the sites. The length of the ditch varied based on the availability of the area and the topography of the sites. These differences also affect the drainage area that drains into the ditch. A longer ditch can manage a larger drainage area.

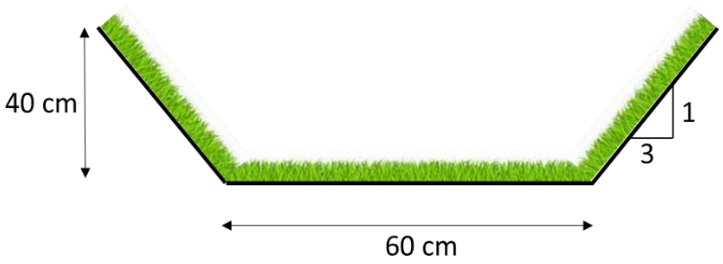


Figure 3.3. Geometry of a grassy ditch considered for the sites

3.3.3 CN Sensitivity Analysis

In this study, land cover change due to development or implementation of GSI was defined by CN. Model sensitivity was tested with HydroCAD to evaluate the implication of the CN change on the resulting runoff. In this study, the smallest CN used for the hydrologic analysis was 32, assigned for woods/grass combination land cover. The largest CN was 98, used for roofs and paved parking. Therefore, the sensitivity analysis was performed by setting the midpoint CN, 65, as a baseline. Then the sensitivity was tested by altering the CN in increments of 10% above and below the baseline.

3.4 RESULTS AND DISCUSSION

Because the post-development land cover of the sites was not uniform, HydroCAD uses the weighted CN to estimate the runoff. Table 3.2 shows the weighted CN for each site.

Table 3.2. Pre- and post-development weighted curve number (CN) of the study sites

Scenario		Soil Group A	B	C	D
Pre-Development		32	58	72	79
Post-Development	**Site 1**	88	92	94	95
	Site 2	81	87	91	93
	Site 3	69	79	86	93

3.4.1 Pre- and Post-Development

The simulations indicate that the peak flow and volume of runoff from each site were higher for the post-development condition due to the proposed impermeable surfaces, as expected.

However, the magnitudes were different for each site and each soil group. The differences in the simulated runoff were compared.

Figure 3.4 shows the pre- and post-development peak flows from each site based on the four hydrologic soil groups. There was a relatively large difference in the pre-development peak flows based on the soil groups. Sites with soil group A resulted in the least runoff, and sites with soil group D resulted in the highest runoff. However, the differences in peak flow between the soil groups were less post-development. For example, for Site 1, the pre-development peak flows were 0.047, 0.47, 0.69, and 0.79 m^3/s for soil groups A–D, respectively. For post-development, the peak flows were 1.16, 1.25, 1.30, and 1.32 m^3/s. Therefore, the pre- and post-development differences were higher for soil group A and lower for soil group D. For Site 1, the peak flow increased by 2388% for soil group A and only 67% for soil group D.

Comparing the sites, on average, Site 2 had the highest percent runoff increase, whereas Site 3 had the least. This increase in runoff is mainly because Site 2 had a large area of impermeable surfaces. In addition, the flow length also affected the velocity of the runoff to the outlet. For instance, the post-development impermeable land cover for Site 1 was 83% and for Site 2, it was 71%. Even though the impermeable land cover of Site 2 was smaller, the peak flow was higher. This is because Site 2 had a shorter flow length than Site 1, which resulted in the runoff quickly leaving the site.

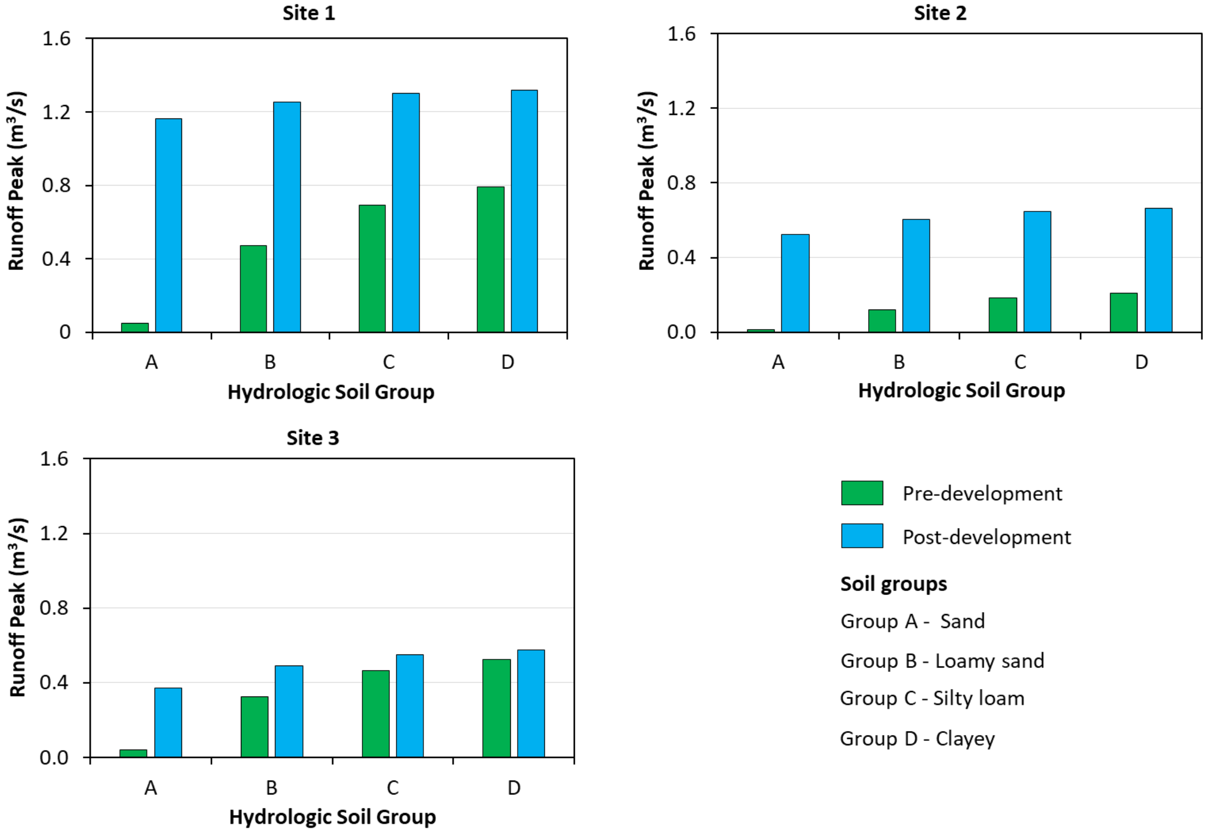


Figure 3.4. Pre- and Post-development runoff peak based on different soil types

Similarly to the peak flows, the runoff volumes from the developments were higher than in the pre-development conditions. Site 2 had the highest volume difference as well. Soil group A had the highest percent increase, and soil group D had the least percent increase. Figure 5 shows the resulting runoff peak and volume of the pre- and post-development conditions of the sites based on the soil groups.

The volumes of runoff from the post-development conditions depended on the site design and soil type. Thus, the quantity of runoff that developers must consider during stormwater management design will depend on the property size, land cover, and soil type. Sections 4.2 and 4.3 present a detailed discussion on the effect of site design and soil type on the generated runoff.

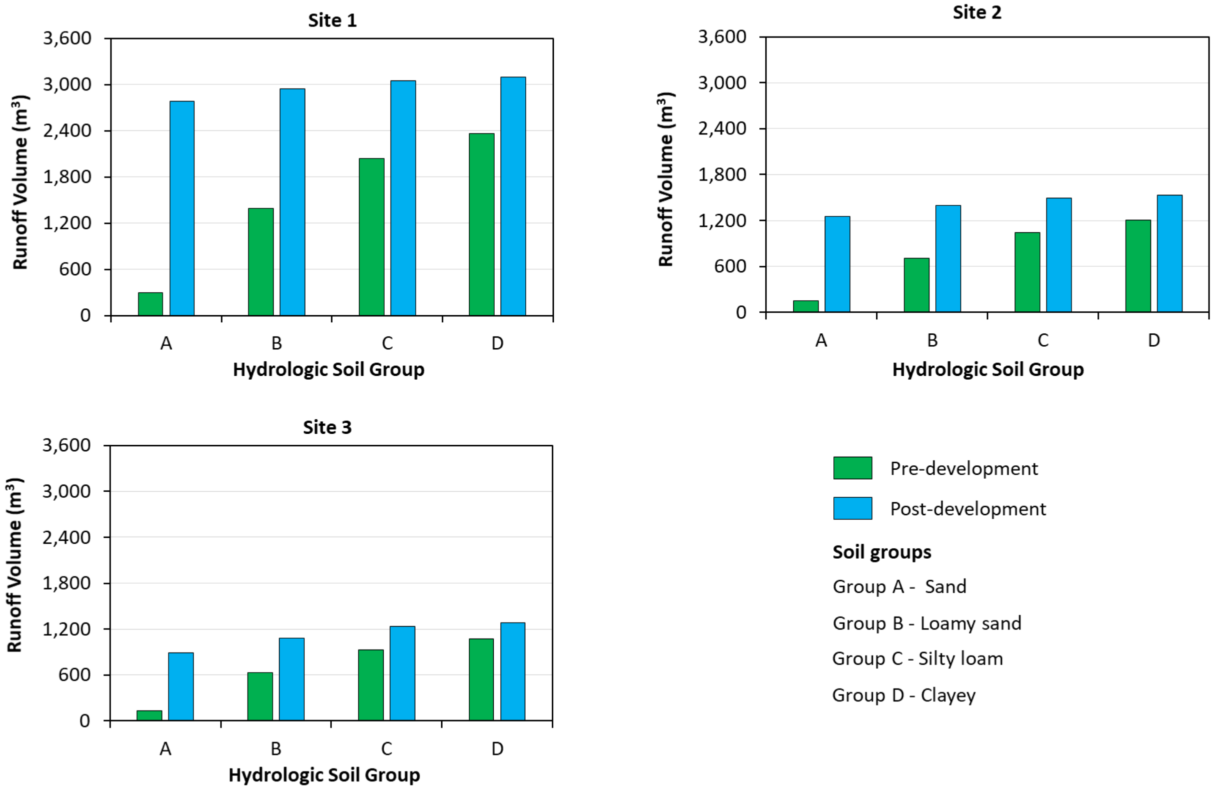


Figure 3.5. Runoff volume from the pre- and post-development condition of the sites

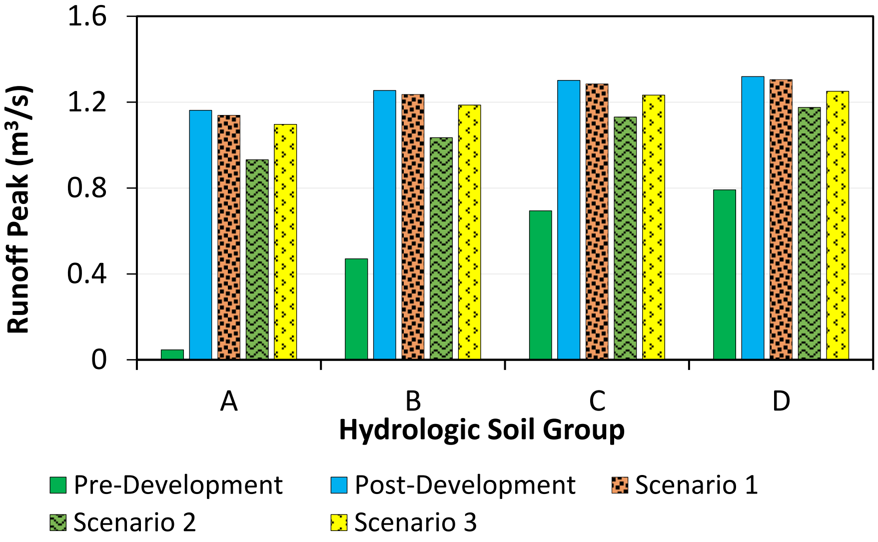
3.4.2 Performance of GSI Based on Site Designs

3.4.2.1 Site 1: Mixed-use design

For Site 1, Scenario 1, a 699 m^2 permeable pavement was implemented on the sidewalks. The resulting peak and runoff volume were reduced compared with the post-development, no-GSI condition. On average, the peak was reduced by 1.47% and the volume by 2.1%. The reductions varied based on the soil groups.

For Scenario 2, a 379 m^2 rain garden was implemented on the site. The rain garden received runoff from the buildings (rooftops) for all of the soil groups. Compared with the post-development, no-GSI condition, the runoff reduction was higher for the rain garden than in the permeable pavement scenario. The average peak flow reduction was 15.3%, and the volume reduction was 12.5%, depending on the soil type.

For Scenario 3, a grassy ditch with a total surface area of 153 m^2 was considered for the site. Similarly, to the other scenarios, Scenario 3 also had reductions in the peak flow. On average, the peak was reduced by 5.4%. However, the runoff volume was the same as in the post-development, no-GSI condition. The volume did not change because a grassy ditch was used to replace the landscaped land cover at approximately the same infiltration capacity. The only difference is that the ditch had depth, which slowed down the flow. Figure 3.6 shows the peak flow for the scenarios.



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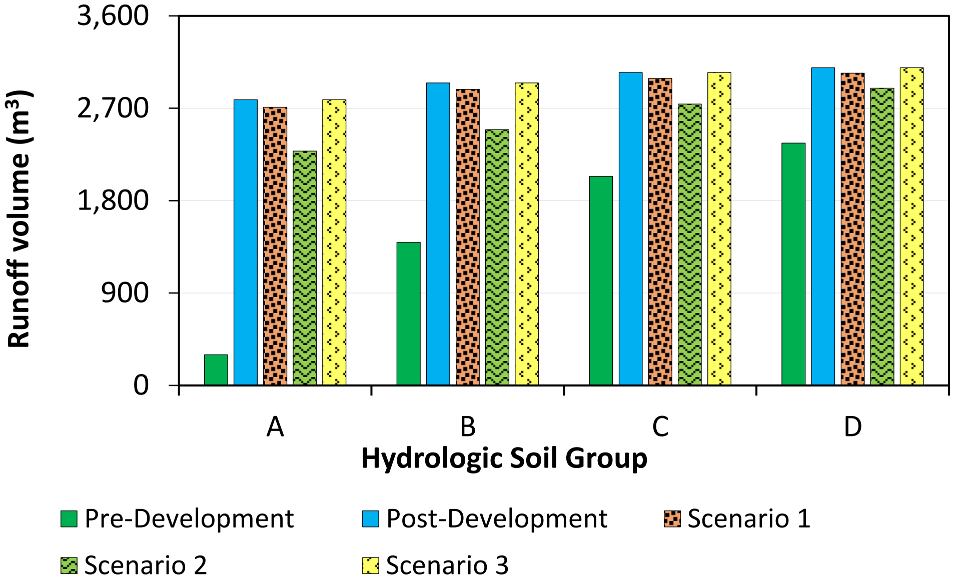


(b)

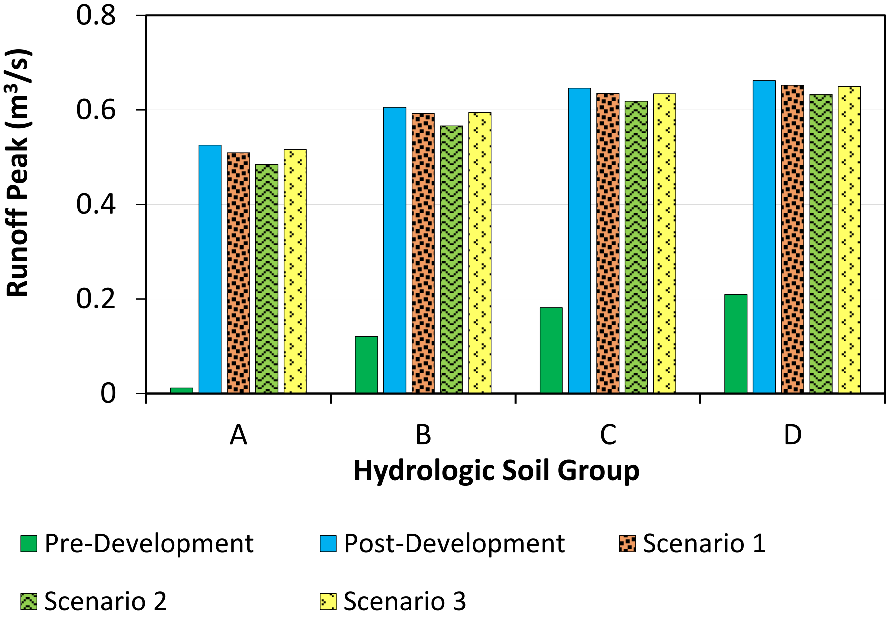
Figure 3.6. Site 1: Runoff peak flow (a) and volume (b) for the GSIs based on the soil types.

3.4.2.2 Site 2: Commercial

For Site 2, Scenario 1, a 482 m^2 permeable pavement was implemented on the sidewalks. On average, the peak flow was reduced by 2.1% and the volume by 3.1% compared with the post-development, no-GSI condition.

For Scenario 2, three small rain gardens with a total area of 113 m^2 were installed on the parking islands. These rain gardens received runoff from the adjacent impermeable parking areas. Similar to Site 1, the runoff reduction was higher than in the permeable pavement scenario. Based on the soil groups, the average peak flow reduction was 5.8%, and the volume reduction was 11.4%.

For Scenario 3, installing a 58 m^2 grassy ditch on the site caused a 1.8% reduction in the runoff peak flow compared with the post-development condition. Similarly to Site 1, the volume was not reduced; the volume was the same as in the post-development, no-GSI condition. Figure 3.7 shows the peak flow and volume of runoff for Site 3 based on the scenarios.



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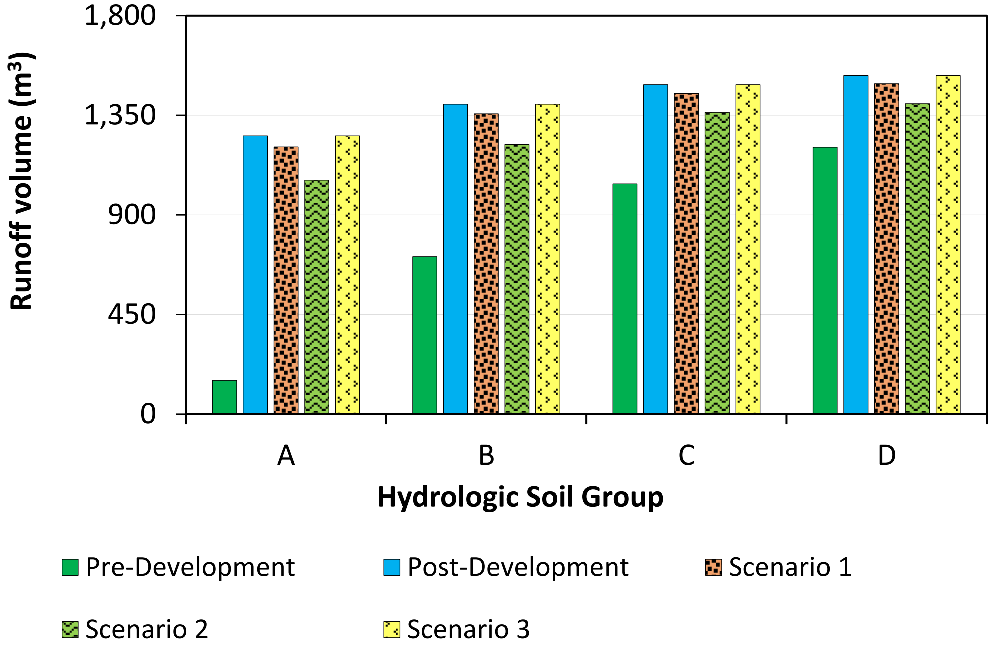


(b)

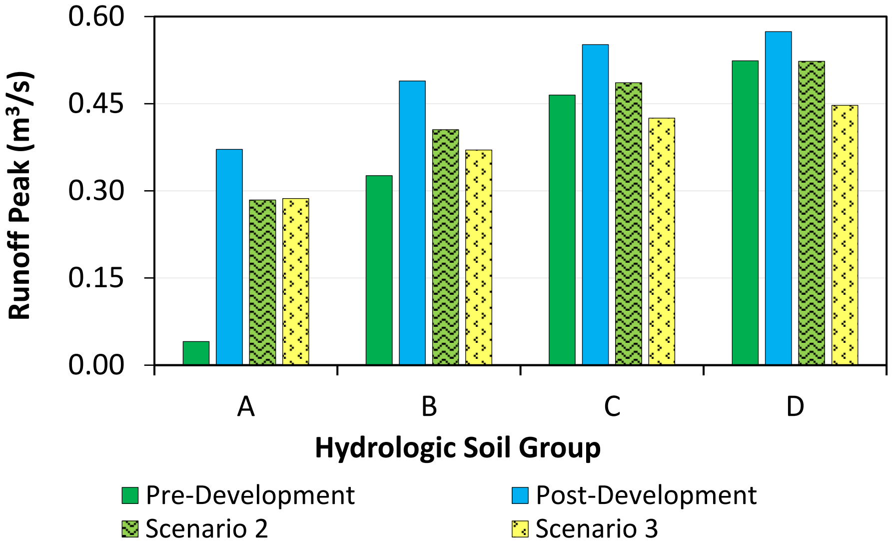
Figure 3.7. Site 2: Runoff peak flow (a) and volume (b) for the GSIs based on the soil types.

3.4.2.3 Site 3: Housing

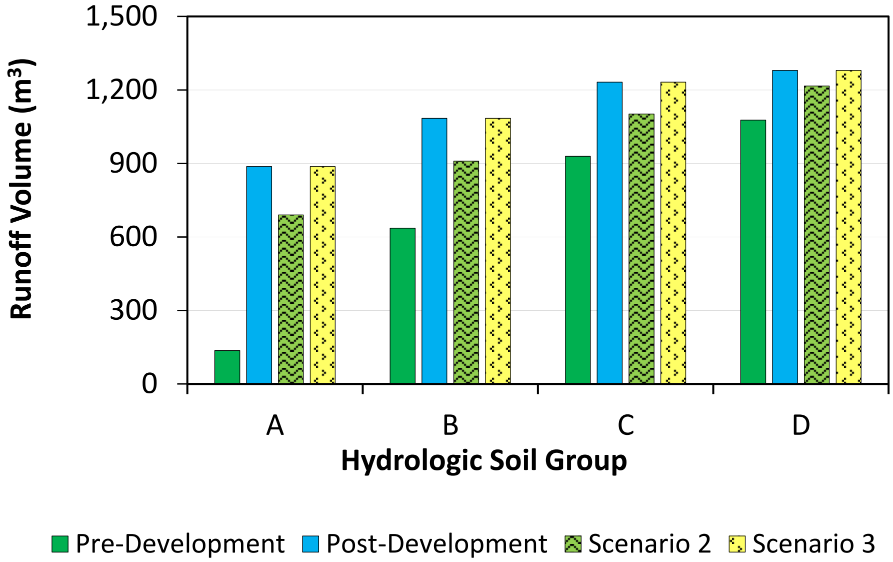
The parking area for Site 3 was designed to be constructed under the houses. Because of this design, there were no areas to implement the first GSI scenario (Scenario 1, permeable pavements). Therefore, only two scenarios were simulated for this site.

For Scenario 2, two rain gardens with a 113 m^2 area were considered for the landscaping. These rain gardens received runoff from the adjacent rooftops. The peak flow was reduced by 15%, and the volume by 13.5%, compared with the post-development, no-GSI condition based on the soil types.

For Scenario 3, the site was simulated for a 246 m^2 area of a grassy ditch. The peak flow was reduced from the post-development, no-GSI condition by 27%. However, the volume that left the site was the same as in the post-development, no-GSI condition, similar to the other sites. Figure 3.8 shows the peak flow and volume of runoff for Site 3 based on the scenarios.



(a)



(b)

Figure 3.8. Site 3: Runoff peak flow (a) and volume (b) for the GSIs based on the soil types.

Scenario 1, permeable pavement, had somewhat a higher performance for Site 2 than in the other sites. This performance increase might be because the permeable pavement was implemented on a slightly larger area on Site 2, considering the site's total area. For Site 1, the permeable pavement covered 4.7% of the site, and for Site 2, 6.3%. Increasing the surface area of a permeable pavement would result in a higher runoff reduction, especially for high-intensity storm events (Abera et al. 2018).

The rain garden scenario (Scenario 2) had a higher reduction for all of the sites. The rain garden area for Site 1 was larger than the other two sites. However, the performance of the rain garden in terms of runoff reduction was similar for Sites 1 and 3. The rain gardens in all of the sites managed a portion of the runoff from the rooftops. Because Site 3 had a design with more permeable surfaces than the other sites, when the rain garden managed the runoff from the rooftop, the overall permeability of the site increased. Therefore, there was a higher runoff reduction. For

Site 2, unlike the other sites, three small rain gardens were assumed because of the absence of a large open area to install a sizable rain garden. Each rain garden received a certain quantity of runoff from the impermeable surfaces, then drained separately into the outlet. Because the three rain gardens sizes were smaller than rain gardens on the other sites, the aforementioned smaller rain gardens might fill quickly.

The grassy ditch was designed to slow down the runoff water and thus maintain a lower peak flow. When the runoff flowed through the ditch, the travel time increased, such that the runoff from the site did not reach the outlet simultaneously. The quantity of peak flow that was reduced by the ditch depended on its size (length). The lengths of the ditches were 100, 38, and 115 m for Sites 1–3, respectively. Site 3 had a substantially higher reduction than the other sites. This is because the ditch considered for this site was longer than in the other sites. The site design facilitated the installation of a long ditch.

In general, the rain garden scenario had the best performance in terms of runoff reduction for all of the sites. For Site 1, even though the area covered by the grassy ditch was smaller than the area covered by the permeable pavement, it had a better runoff reduction than the permeable pavement. However, the grassy ditch scenario on Site 2 did not perform as well as in the other sites. A possible reason is the length of the ditches; Site 2 had the shortest ditch because the site design did not enable adding a long ditch.

3.4.3 Performance of GSI based on soil type

The runoff generated after the implementation of GSI was less than in the post-development, no-GSI condition for all of the soil groups. However, this change was not uniform for all of the soil groups. The change was less for soil group A and higher for soil group D. This variation is due to the infiltration capacity difference between the soil groups. Soil group A has a higher infiltration capacity than soil group D. For instance, in the case of Scenario 2, one of the inputs for the rain garden was the conductivity of the underlying soil. This value varied for the soil groups. 144 and 3.56 mm/h were assigned for soil groups A and D. Therefore, even though most of the other parameters had the same value, the quantity of water that left the rain garden through exfiltration differed.

Similarly, for Scenario 3, the CN of each soil group was different. Therefore, even though the size of the grassy ditch was the same, the quantity of runoff varied. Furthermore, the difference in the runoff reduction between the two soil groups varied by site.

3.4.3.1 Peak flow reduction based on soil group.

Based on the simulation results, the quantity of runoff from the sites differed for each soil group. From the four soil groups, the two extremes (soil groups A and D) were compared. A comparison was made for each study site and GSI scenario. Table 3.3 shows the peak flow reduction compared with the post-development condition.

Table 3.3. Simulation results: peak flow reduction from the post-development condition

Site	Soil group	Peak flow reduction from the post-development condition (m3/s)		
		Scenario 1	**Scenario 2**	**Scenario 3**
Site 1 Mixed-use development	**A**	0.024 (2.02%)	0.230 (19.8%)	0.066 (5.7%)
	B	0.018 (1.5%)	0.219 (17.5%)	0.067 (5.4%)
	C	0.016 (1.26%)	0.170 (13.1%)	0.069 (5.3%)
	D	0.015 (1.1%)	0.144 (10.9%)	0.069 (5.2%)
Site 2 Commercial development	**A**	0.016 (3.1%)	0.041 (7.8%)	0.009 (1.7%)
	B	0.013 (2.1%)	0.039 (6.5%)	0.011 (1.8%)
	C	0.011 (1.8%)	0.028 (4.3%)	0.012 (1.8%)
	D	0.010 (1.5%)	0.029 (4.4%)	0.012 (1.9%)
Site 3 Housing development	**A**	–	0.087 (23.5%)	0.085 (22.8%)
	B	–	0.084 (17.1%)	0.119 (24.3%)
	C	–	0.065 (11.9%)	0.126 (22.9%)
	D	–	0.051 (8.9%)	0.127 (22.1%)

Except for Site 2, Scenario 3, all of the other scenarios had a higher peak flow reduction for soil group A than D. In contrast, Site 2, Scenario 3, had a higher peak flow reduction for soil group D than A. For Site 2, overall, the peak reduction was lower than in the other sites. For Site 3, implementing permeable pavement (Scenario 1) was not practical because the parking areas were under the building. Therefore, the analysis was done only for Scenarios 2 and 3.

These results indicate that in most cases, the GSI scenarios performed better in terms of peak flow reduction for soil group A than D. Because the infiltration capacity of soil group A is higher, the runoff created from these soils was lower than from the other soil groups. The results were consistent when moving from soil group A to D. These results also imply that GSI performs well in terms of runoff reduction for a site with soil group A, especially if the practice has an infiltration component.

3.4.3.2 Runoff Volume Reduction Based on Soil Group

The runoff volume that was generated from the sites varied based on the soil group, similarly to the peak flow. Table 3.4 shows the peak flow reduction from the post-development condition.

Table 3.4. Simulation results: runoff volume reduction from the post-development condition

Site	Soil group	Volume reduction from the post-development condition (m^3)		
		Scenario 1	Scenario 2	Scenario 3
Site 1 Mixed-use development	**A**	73 (2.6%)	500 (18%)	0
	B	62 (2.1%)	455 (15.4%)	0
	C	58 (1.9%)	307 (10.1%)	0
	D	54 (1.7%)	200 (6.5%)	0
Site 2 Commercial development	**A**	50 (4.0%)	201 (16%)	0
	B	43 (3.1%)	182 (13%)	0
	C	40 (2.7%)	125 (8.4%)	0
	D	37 (2.4%)	127 (8.3%)	0
Site 3 Housing development	**A**	–	197 (22.2%)	0
	B	–	175 (16.1%)	0
	C	–	130 (10.6%)	0
	D	–	64 (5.0%)	0

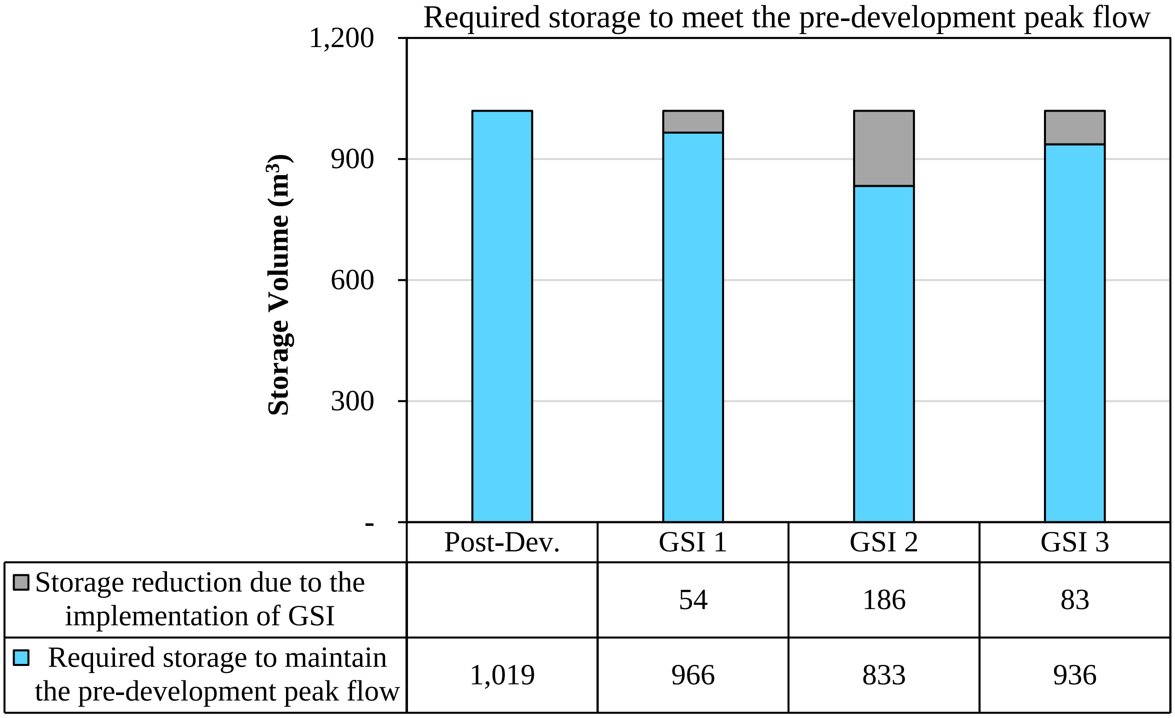
The results presented in Table 4 indicate that the rain garden and permeable pavement reduced the runoff volume from the post-development condition. The rain garden scenario had a substantial reduction over the permeable pavement scenario. Similar to the peak flow, the volume reduction for soil group A was higher than for soil group D.

However, the grassy ditch scenario did not have a volume reduction from the post-development condition. This result is due to the implementation of the grassy ditch in a landscaping area. Because the ditch will have the same land cover (grass) as landscaping, the land cover or the permeability is not changed. Therefore, the CN would be the same. However, the travel time and the peak flow were reduced by the channel.

Even though adding GSI on the sites reduced the runoff from the post-development condition, in all cases, the peak flow after adding GSI nevertheless exceeded the pre-development peak flow. Most cities' requirements for post-development stormwater management structures are to maintain the pre-development peak flow from a site. Therefore, GSI should be combined with detention/retention facilities to prevent flooding. However, the size of the required detention/retention facilities would be much smaller when combined with GSI.

Usually, cities require new developments to maintain the pre-development peak flow. Since the GSI scenarios alone did not meet this requirement, they should be combined with the traditional detention/retention facilities. However, the GSI scenarios reduced the peak flow from the post-development scenario. Therefore, the required storage size is smaller than the GSI scenarios. Figure 3.9 shows the storage reductions due to the implementation of GSI.

Figure 3.9 shows an example reduction in required storage due to the implementation of GSI on Site 1 soil group B. In this scenario, the runoff peak flow was reduced from the post-development scenario by 1.5%, 17.5%, and 5.4% due to the implementation of GSI 1,2, and 3, respectively (See Figure 3.6(a) and Table 3.3). As a result of this reduction in peak flow, the detention/retention storage required to maintain the pre-development peak flow was also reduced. For GSI 1, the reduction in the required detention/retention storage was 54 m^3, which is a 5.3% reduction. The reductions in detention/retention storage for GSI 2 and 3 were 186 m^3 (18%) and 83 m^3 (8.1%). Similar to the peak flow reduction, the GSI 2 showed a higher reduction in the required storage. This change will also reduce the cost related to the construction of detention/retention facilities.



	Post-Dev.	GSI 1	GSI 2	GSI 3
▨ Storage reduction due to the implementation of GSI		54	186	83
☐ Required storage to maintain the pre-development peak flow	1,019	966	833	936

Figure 3.9. Required storage volume for Site 1, soil group B, to maintain the pre-development peak flow. The gray bars show the storage volume met by GSI. The blue bars show the storage volume necessary using detention/retention facilities.

3.4.4 Sensitivity Analysis

CN sensitivity analysis was performed by altering the CN by ±10%, using 65 as a baseline. The lower boundary was CN 33, representing soil group A with a land cover of a woods/grass combination and good hydrologic condition. The upper boundary was CN 98, representing soil group A with paved land cover. The percentage change in the peak and runoff volume was determined based on the simulation results. Simulations were run for the three study sites. Varying the CN affected the resulting runoff peak and volume. Percent change in the peak and runoff volume were equal for all study sites. Varying the CN by 10% changed the peak flow by 5% to 20% and the volume by 13% to 19%.

Figure 3.9 shows the sensitivity analysis results. The peak flow was reduced by 87% from the baseline on the lower boundary (CN 33). On the upper boundary (CN 98), the peak flow increased by 55% from the baseline. The increment rate of the peak flow decreased when the CN approached the upper boundary. The reductions were relatively the same for the runoff volume in both directions from the baseline. The volume was reduced by up to 80% on the lower boundary and was increased by 89% on the upper boundary.

As shown in Figure 3.10, the peak flow and the volume curves diverge. When the CN increased by more than 30% (CN 85), the runoff volume increased at a higher rate than the peak flow. This change is because the surface is getting smoother for the runoff to flow faster, but there is still infiltration. For instance, if we compare the increases in 40% (CN 91) and 50% (CN 98), the peak flows were 1.31 and 1.35 m^3/s; and the volumes were 2,915 and 3,236 m^3. There is not much difference between the peak flow because the surface is smooth in both cases. However, CN 91 has a higher infiltration capacity than CN 98; therefore, the difference in the runoff volume was higher.

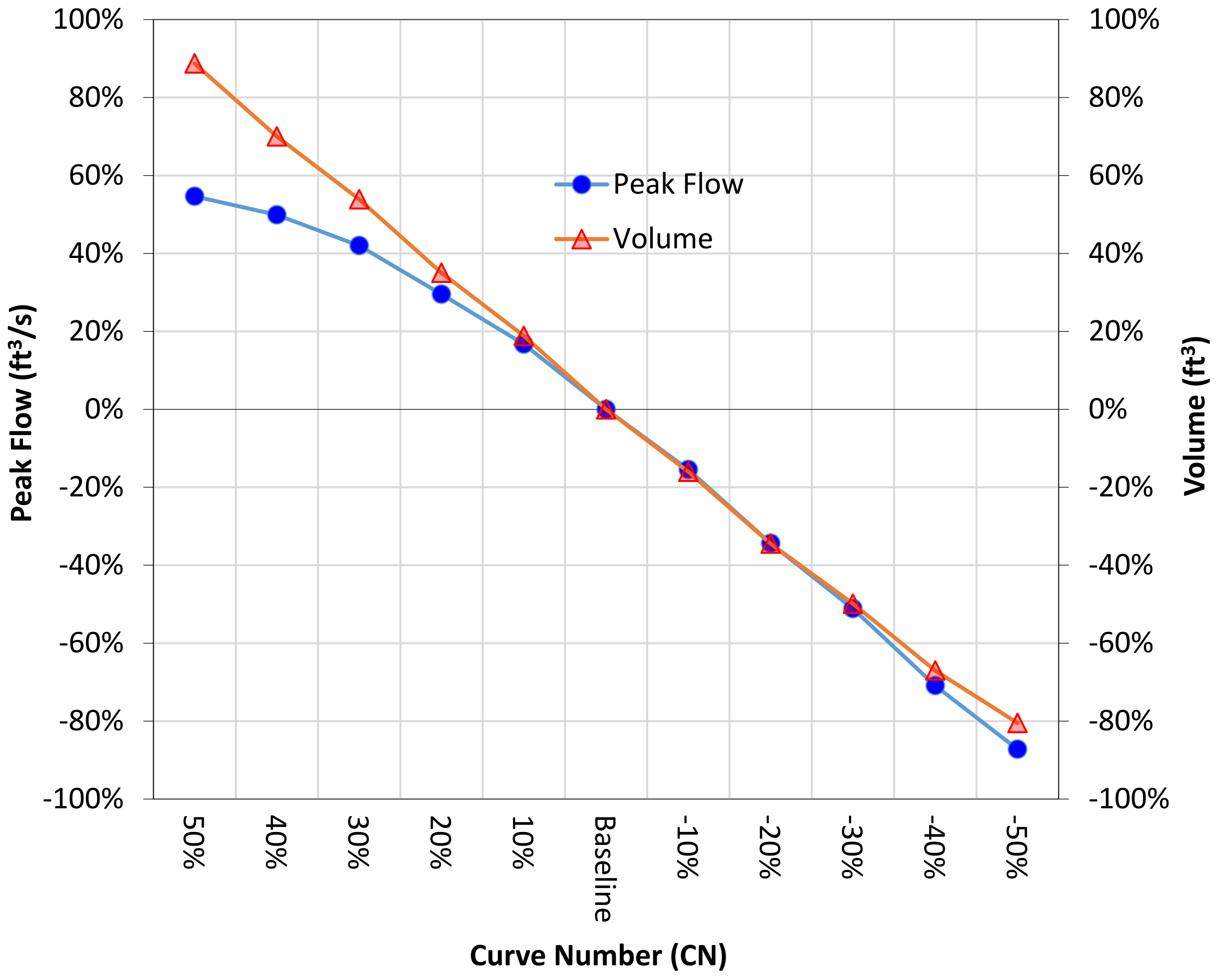


Figure 3.10. CN sensitivity analysis results

3.5 CONCLUSIONS

A stormwater management analysis was performed based on various site plans and soil groups. The optimal implementation of GSI depended on the development site designs. When the site had more landscaping in the post-development condition, only a small GSI was necessary to reduce the peak flow and runoff volume. When the post-development site design covered a large area with impermeable surfaces such as roofs and asphalt, a larger-scale GSI was required to reduce the runoff to the same extent. When the site was located on soil group A, a GSI with infiltration performed 5% to 8% better in reducing peak flow than in soil group D. This is due to the infiltration capacity difference between the soil groups.

Furthermore, because soil group A has a higher infiltration capacity, the pre-development runoff from this soil was relatively small. The post-development runoff was high when the post-development condition covered the area with substantial impermeable surfaces. Therefore, the difference between the pre- and post-development was much higher. In this case, GSI with an infiltration component performed well in a manner that best approximated the pre-development condition.

When a site was located on soil group D and was also crowded with impermeable surface land cover, the site produced the highest runoff compared with the other soil groups. However, when the site was located on soil group A and had substantial permeable land cover, the site produced the smallest runoff compared with the other soil groups.

An ideal site with minimal runoff is one with soil group A and substantial permeable land cover. A site with maximal runoff is one with soil group D and substantial impermeable area. Based on the sensitivity analysis, changes in a site's land cover can reduce the peak flow by up to 87% and the volume by up to 80%.

Overall, the efficacy of incorporating green stormwater infrastructure in urban developments depends on the choice of infrastructure and the underlying soil type. The present finding may help developers and city planners implement best practices that meet stormwater management regulations and suit their development site design and soil conditions.

This study has potential limitations that need to be considered when interpreting the findings. The hydrologic modeling was done with only one software. The results might vary if other modeling software or methods are used. Estimating the peak and volume of runoff from the proposed GSI scenarios based on another rainfall-runoff analysis software is recommended for further comparison. The other possible limitation is with the CN calculation for permeable pavement. This study used the partial runoff setup from the three approaches for modeling permeable pavement (discussed under section 3.2.1). The results might be different if the other approaches are used.

3.6 ACKNOWLEDGEMENT

The authors thank the University of Mississippi, Office of Research & Sponsored Programs, for funding the purchase of the full version of HydroCAD software through the Graduate School Research Grant Program. The research reported in this manuscript was partly funded through the US Department of Commerce National Oceanic and Atmospheric Administration under NOAA Award NA18OAR4170080 and the Mississippi–Alabama Sea Grant Consortium. We thank Dr. Mohammad Al-Hamdan for his suggestions on this manuscript.

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CHAPTER 4

4 LIFE-CYCLE AND BENEFIT-COST ANALYSIS FOR SITE-SCALE IMPLEMENTATION OF GREEN STORMWATER INFRASTRUCTURE (GSI)

ABSTRACT

Green stormwater infrastructure (GSI) has been implemented to reduce flooding events caused by excess stormwater runoff. Large cities implement GSI on large scales by spending billions of dollars. These large-scale practices are not practical for small- to medium-sized cities with limited resources. More typically, smaller cities consider implementing GI on a site-by-site basis. This study investigated the cost-effectiveness of site-scaled GI by performing a whole life-cycle cost analysis (LCCA) and benefit-cost analysis (BCA) on small sites. A small site development design was used as example developments for the conduct the LCC and BC analyses. The study was conducted by implementing three GSIs (pervious pavement, rain garden, and grass swale) on the example developments. The capital, operation and maintenance (O&M) costs were considered in the cost analysis. Benefits gained from the implementation of GI were also included for a complete whole life-cycle benefit-cost analysis. The present value (PV) approach was used to add and compare costs and benefits incurred at different times during the life cycle of the developments. Results from the cost analysis showed that using GI in the example developments increased the overall cost of the stormwater infrastructure by 45% on average, depending on the size and type of GSI. However, the benefits outweigh the costs by up to 35% rate of return.

4.1 INTRODUCTION

The installation of green stormwater infrastructure (GSI) in cities is a sustainable method of addressing stormwater runoff problems (Giese et al. 2019; Kousky et al. 2013). GSI reduces the runoff volume by promoting stormwater infiltration into the ground, which prevents downstream flooding, erosion, and environmental damage. However, barriers prevent the implementation of these practices on development sites. One of the barriers is financial, which includes high capital, retrofit, and operation and maintenance costs of GSI.

This study analyzes a hypothesis that the costs related to implementing GSI practices on development sites should not be an implementation barrier. The analysis was performed by conducting a life-cycle cost analysis (LCCA) of different GSI scenarios and the traditional detention/retention facilities. The goal of LCCA for any project or product is to provide a framework for finding the total cost of design or development, production, use, and disposal of the product to reduce the total cost (Durairaj et al. 2002; Naumann et al. 2011). Costs commonly considered in LCCA include initial, operational, and residual costs. Initial costs refer to the capital investment costs for land purchase, construction, renovation, labor, and equipment needed. Operational costs include operational, maintenance, and replacement costs required to keep the project operational. Residual cost is the remaining salvage value at the end of the study period or when the structure is replaced (WBDG 2016).

In addition to the costs, the benefits gained from different scenarios need to be included when evaluating alternatives. GSI treats polluted stormwater runoff, which improves the quality of receiving water bodies (CWAA 2016; Pennino et al. 2016). Also, it has environmental, social, and health benefits, such as providing a natural green environment, reducing exposure to toxic substances, improving air quality, and improving human well-being (CNT 2011; Elmqvist et al. 2015; EPA 2017; Nordman et al. 2018; Suppakittpaisarn et al. 2017). GSI practices also improve urban air quality by absorbing air pollutants, such as particulate matter (Demuzere et al. 2014; World Bank and IHME 2016). Jayasooriya (2017) assessed different GSI practices and identified that tree-based GSI significantly improves air quality by taking up harmful air pollutants while providing several other ecosystem services.

GSI is also known for energy savings, specifically for industrial areas where energy consumption can be particularly high (CNT 2011; Jayasooriya et al. 2017). For example, permeable pavement reduces energy use by lowering the surrounding air temperatures. This reduction in energy results in a reduction in demand for cooling systems within buildings. Thermal comfort is also another benefit. By providing shading and enhancing evapotranspiration, GSI reduces surface temperature, which leads to improved thermal comfort (Choi et al. 2021). Similarly, rain gardens reduce the energy needed to treat polluted runoff (CNT 2011).

Several studies have been conducted to analyze the cost related to implementing GSI. Even though cost determination provides a valuable explanation for the benefit of GSI, they do not capture the benefits fully. The lack of data/methods for valuation and the wide range of benefits of implementing GSIs in urban development make the benefit analysis complex (Elmqvist et al. 2015; Nordman et al. 2018; Nowak and Dwyer 2000). In this study, an effort has been made to quantify the benefits and give them monetary values. Due to the lack of available data, some benefits are presented qualitatively. The analyses were performed by comparing the costs and benefits analysis of different GSI alternatives for a sample development site (Figure 4.1). The capital, operation and maintenance (O&M), and replacement costs are considered in the cost analysis. The present value (PV) approach was used to add and compare costs incurred at different times during the life cycle of the development. A similar approach was used to quantify the benefits gained from implementing GI. Then, the costs and benefits of the different scenarios were compared using benefit-cost analyses.

A spreadsheet was developed based on the Center for Neighborhood Technology (CNT) guideline to recognize the value of green infrastructure (CNT 2011) and the Water Environment Research Foundation (WERF) Low Impact Development (LID) cost analysis tools. CNT has a web-based tool, Green Value Stormwater Toolbox Calculator from the CNT, that can be used to benefit and cost stormwater GI. However, the calculator was designed based on the hydrology of the Great Lakes region so that the results would be different for other regions. The other limitation is that the user cannot input custom values for the cost and benefits (CNT 2009). The WERF was developed to address the cost associated with GSI. The tool has the ability to conduct GSI cost estimates for capital costs and operation and maintenance costs. However, the tool does not include benefit analysis. It has only the LCCA. The spreadsheet developed in this study has both the cost and benefit analysis, and the inputs can be customized.

The study objectives are to analyze how costs impact the implementation of GSI, select the types of GSI with the lowest life-cycle costs with more benefits, and identify financially and environmentally best GSI options. The analyses were performed by estimating the lifetime costs of alternative stormwater management infrastructures, including traditional detention/retention facilities and several GSI practices. Also, by conducting benefit-cost analysis using two possible approaches; benefit-cost ratio (BCR) and internal rate of return analysis (IRR).

4.2 STUDY SITE

The analysis was conducted using a proposed mixed-use development site as an example development. Figure 4.1 shows the plan view of the development site, with a total area of 161,136 ft^2 (14,970 m^2), including 45,526 ft^2 (4,230 m^2) of rooftops, 88,280 ft^2 (8,201 m^2) of sidewalks and parking lots, and 27,330 ft^2 (2,539 m^2) of landscaping. This development includes constructing two three-story mixed-use buildings and the associated parking lots. Both buildings are designed to have commercial use space on the first floor and residential use space on the second and third floors.

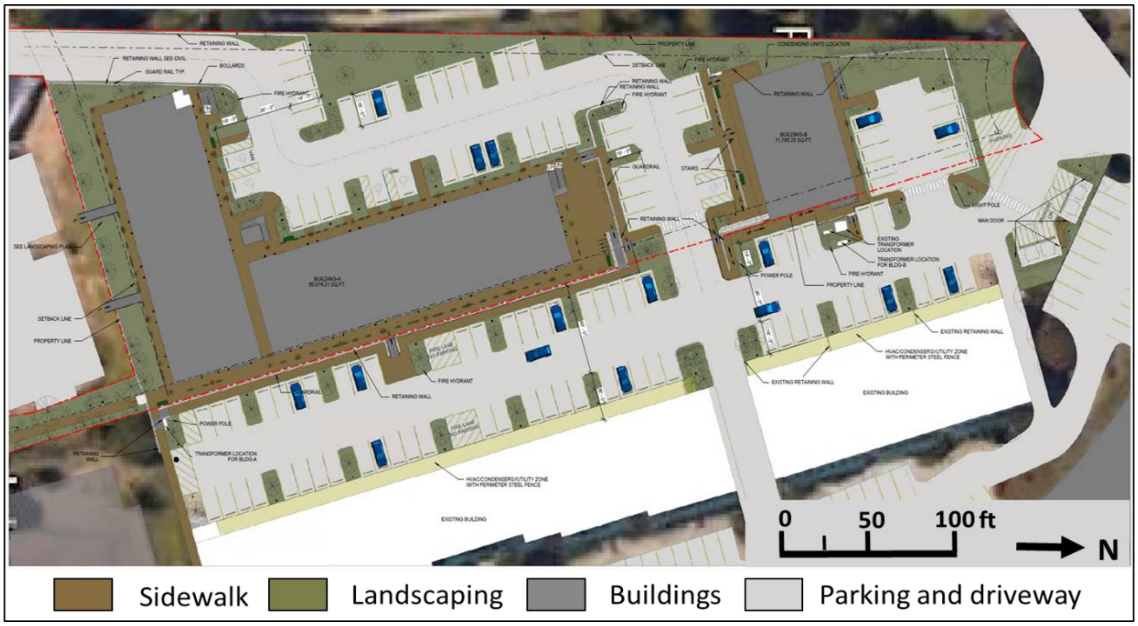


Figure 4.1. Plan view of the sample development site

4.3 MATERIALS AND METHODS

The cost and benefit analyses were performed based on simulating implementing three GSI scenarios and the traditional detention/retention facilities.

Scenario 0 - Baseline scenario with traditional underground storage considering the use of Advanced Drainage System (ADS) MC-4500 Chamber and no GSI, as shown in Figure 4.2.

Scenario 1 - Permeable concrete pavement on the sidewalks

Scenario 2 - Rain gardens on the part of the landscaped areas

Scenario 3 – Grassy ditch at the west side of the site

In simulation Scenario1, permeable pavement was implemented on the sidewalks of the site, which covers an area of 7,525 ft^2. Simulation scenario 2 considered installation of rain gardens on the landscaping. The total areas of the rain gardens were 4,080 ft^2. In Scnario3, 2,310 ft^2 of grassy ditch was implemented on the western side of the site.

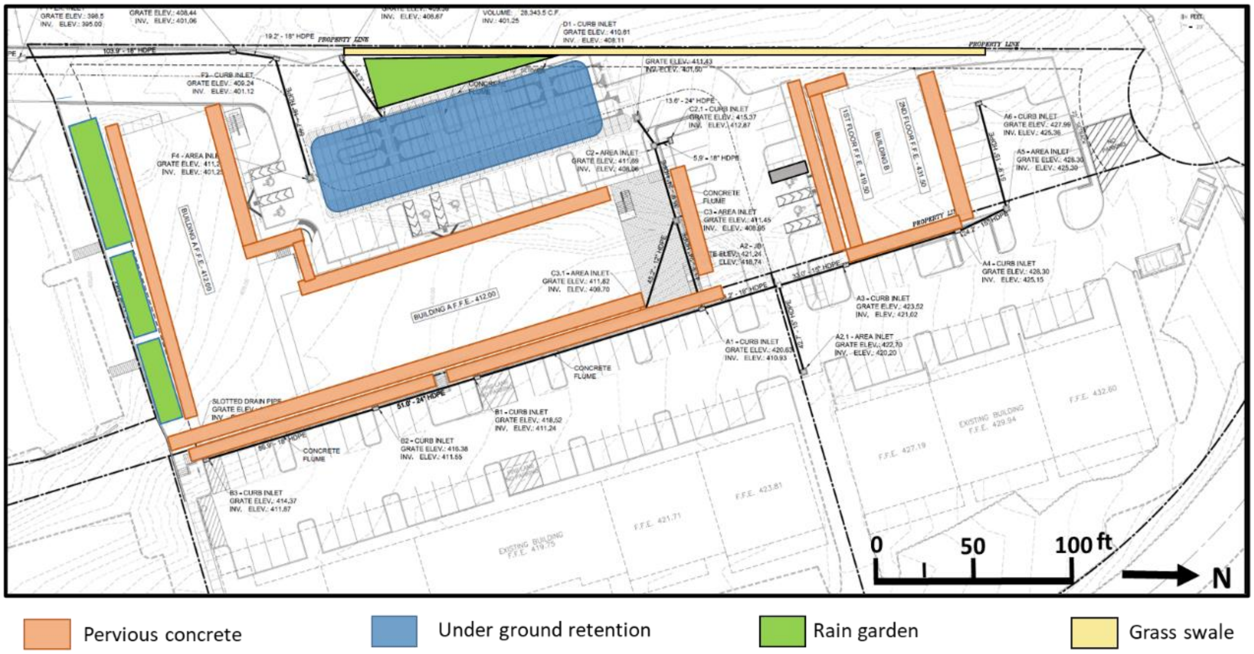


Figure 4.2. The proposed GSI scenarios for the study site

4.3.1 Cost analysis

To analyze the costs related to the simulation of GSI, LCCA was performed for the study site based on different GSI scenarios. Life cycle cost (LCC) is the sum of the costs (initial, O&M, and discarding) throughout the whole life cycle of the practice. The initial and O&M costs happen at different times of the lifetime period. To add and compare these costs incurred during a project's life cycle, they must be made time-equivalent. Similarly, the benefits from the GSIs have to be expressed in terms of equivalent money value. The benefits happen throughout the practice's lifetime as long as the practice functions. Therefore, similar to the costs, the benefits also are made time-equivalent. The present value (PV) approach was used to bring the costs and benefits as a value amount in today's dollars.

The Water Environment Research Foundation (WERF) Low Impact Development (LID) cost analysis tools were used as a base tool to conduct the LCCA. The tool has cost details obtained from US literature, interviews, and expert judgments (WERF, 2009). However, the default cost data need to be updated with site-specific data. Also, the current costs impact the final result of the estimated costs. Therefore, the default values are being adjusted with site-specific cost data. One of the challenges during the cost analysis was finding appropriate cost information. Since costs are different from place to place and there are no local cost guides or databases, the unit cost data for each construction and O&M activity were found from different sources. Most of these data were collected from local developers using an itemized spreadsheet of the proposed GSIs. This spreadsheet is provided in the supplementary document. Data from the RSMeans Site Work and Landscape Costs book were also used to assign unit prices to some items (RSMeans, 2019).

Literature and web pages were also used as a source of cost data for some items (Derviş, 2013; Fu & Liu, 2018; Home Guide, n.d.; Homewyse, n.d.).

Since the costs found in the literature are for different cities and from different times, location and time adjustments were made. The location adjustments were made using the RSMeans city cost indexes (CCI) to estimate the expected cost. The CCIs are provided in the RSMeans database book. Then, the adjustments were made following the guideline provided in the book and using Equation 4.1.

$$\text{Cost in City A } = \frac{Index\ for\ City\ A}{Index\ for\ City\ B} * Cost\ in\ City\ B \qquad \text{Equation 4.1}$$

For costs estimated based on the national average cost, the adjustments were made using Equation 4.2.

$$\text{Cost in City A } = \frac{Index\ for\ City\ A}{100} * National\ average\ cost \qquad \text{Equation 4.2}$$

In addition to the location, the time when the literature studies were conducted differs. Therefore, similar adjustments were made for the time. Equation 3 was used to make time adjustments national historical cost index.

$$\text{Cost in year A } = \frac{Index\ for\ year\ A}{Index\ for\ year\ B} * Cost\ in\ year\ B \qquad \text{Equation 4.3}$$

The cost analysis compared the initial (capital) and long-term O&M costs of stormwater management facilities, including GSI, and identified the least-cost alternative for a 30-year lifetime. The present value of costs (PVC) was computed using a discount rate of 5.5%. The initial and annualized costs were converted to a PVC using Equation 4. Costs of all scenarios were estimated using the same approach.

$$\mathrm{PVC} = \mathrm{C_0} + \sum_{\mathrm{y}=1}^{\mathrm{n}} \mathrm{C_y} \frac{1}{(1+\mathrm{i})^{\mathrm{y}}} \qquad \text{Equation 4.4}$$

where:

$\frac{\mathbf{1}}{(\mathbf{1}+\mathbf{i})^{\mathrm{y}}}$ = discount factor

C_o = initial cost (capital cost)

C_y = O&M cost in year y

i = discount rate, 0.055 (5.5%)

n = life-cycle period, 30 y

y = years 1 to n

4.3.1.1 Capital Costs

The capital cost is the initial cost that happens at the beginning of the project's lifetime. Mainly it is the construction and labor expense. These costs were estimated for simulated scenarios without and with GSI implementations on the study site. Several GSI scenarios were proposed for the study site. The cost estimates were done by considering only the areas considered to implement GSI. This consideration was made because the remaining structure will be the same for both scenarios; it will not affect the estimated cost. For instance, if a scenario proposes to change concrete sidewalks to permeable surfaces, the only cost difference will be the sidewalks' cost. Therefore, the comparison will be between concrete and permeable sidewalk costs.

The capital cost for permeable pavement was estimated based on constructing a 9-inch permeable concrete layer and a 12-inch gavel sub-layer. The average construction cost of permeable concrete pavement per unit square foot was estimated to be between $7 and $23, based on local contractors' quotes and literature reviews (Derviş, 2013; Fu & Liu, 2018). Because the permeable pavement replaced the sidewalks' concrete pavement, the construction cost of the concrete was included for comparison purposes. An average of $6.5 per square foot was estimated to construct Portland cement concrete pavement (Fu and Liu 2018, Homewyse, n.d.).

The construction cost of the rain garden was estimated for a 24-inch deep rain garden. This depth includes the storage (ponding), mulch, and amended planting soil layers. The cost for the construction of rain gardens per unit ft^3 ranges from $6 to $11 (Vineyard et al., 2015). The rain gardens were proposed to be placed on the landscaping. Therefore, the cost of landscaping was included to make the comparison. $4 was estimated for the construction cost of a cubic foot of landscaping. The construction activities for a grassy ditch are the same as the landscaping, except that it has excavation for the ditch. $1 per ft^2 was added to the unit cost per ft^2 of the grassy ditch, assuming the additional excavation and site cleaning. Table 1 shows the adjusted unit price ranges and average prices for the construction/installation of the GSI practices.

Table 4.1. Unit price ranges for the capital costs

		Unit Price			
Item	**Unit**	**Minimum**	**Maximum**	**Average**	**References**
Underground storage	ft^3	$7.50	$8.50	$8.00	According to the StormTech local sales representative's estimate
Concrete pavement	ft^2	$5.00	$8.00	$6.50	(Fu and Liu 2018)
Permeable concrete pavement	ft^2	$7.00	$23.00	$15.00	Local developers' estimates, the WERF tool, Rutgers University, 2018, and (Homewyse, n.d.)
Landscaping	ft^2	$3.00	$5.00	$4.00	Local planters and (Home Guide, n.d.)
Rain garden	ft^3	$6.00	$11.00	$8.50	(Derviş, 2013); Rutgers University, (2018); Vineyard et al., (2015).

4.3.1.2 Operation and Maintenance (O&M) costs

Each GSI requires different types of maintenance activities. The types and frequencies of the maintenance activities were defined, then the O&M costs were estimated. The WERF tool recommends three maintenance activities: inspection, litter removal, and sweeping for permeable pavement. The inspection of the pavement was assumed to be done every three years. Litter removal and pavement sweeping were assumed to be done every year. The costs were estimated to be $320 and $188 per service for inspection and litter removal of 7,525 ft^2 of permeable pavement. On average, $0.04 and $0.025 per ft^2, respectively. Maintaining the average infiltration rate of permeable pavement is critical for the pavement to perform as intended. Therefore, the surface should be vacuumed at least once a year to clean clogged voids. The cost of sweeping and vacuuming the surface was estimated to be \$0.15 per ft^2 (Fu & Liu, 2018).

For the rain garden, two types of maintenance, (a) regular maintenance and (b) corrective and infrequent maintenance, were considered. The regular maintenance contains vegetation management, and the corrective maintenance includes replacing mulch and tilling the soil. Assumptions were made that a two-labor crew would be required to perform the maintenance activities. The crew would perform regular maintenance once every year for two days. For the corrective maintenance, replacing mulch would be done every three years and tilling every five years. The one-time average O&M costs for the size of the proposed rain garden were estimated to be \$2,040 for vegetation management, \$5,916 for mulch replacement, and \$2,713 for tilling. Maintenance activities for a rain garden were also assumed for grassy ditch and landscaping. After the O&M costs were estimated, the costs were brought to the current today's money value, and the present value of costs (PVC) of a 30-year lifetime were estimated for all scenarios.

Table 4.2. Unit price ranges for maintenance activities

Maintenance Activities	Frequency	Unit	Price per Unit ($)		
			Minimum	Maximum	Average
Permeable concrete					
Inspection	3 years	ft^2	0.0325	0.0525	$0.043
Litter removal	yearly	ft^2	0.015	0.035	0.025
Sweeping/Vacuuming	yearly	ft^2	0.12	0.18	0.150
Rain garden					
Vegetation management	yearly	ft^2	0.45	0.55	0.50
Replace mulch	3 years	ft^2	1.20	1.70	1.45
Till the soil	5 years	ft^2	0.58	0.75	0.67
Grassy ditch					
Mowing	yearly	ft^2	0.40	0.5	0.45
Ditch cleaning	yearly	ft^2	0.45	0.70	0.58
Landscaping					
Mowing	yearly	ft^2	0.15	0.45	0.30
Vegetation/grass management	yearly	ft^2	0.40	0.48	0.44
Concrete pavement					
Inspection	3 years	ft^2	0.0325	0.0525	$0.043
Seal the joints	8 years	ft^2	0.15	0.3	0.225

4.3.2 Benefit Analysis

Annual benefits were estimated for the GSI scenarios and converted into the present value of benefits (PVB) using Equation 5.

$$\mathrm{PVB} = \mathrm{B}_0 + \sum_{y=1}^{n} \mathrm{B}_y \frac{1}{(1+i)^y} \qquad \text{Equation 4.5}$$

The values of benefits were assessed for six benefit categories water, energy, climate change, air quality, health, and community. The benefit analysis considered the direct and indirect benefits of the GSI scenarios. The purpose was to compare the results with the scenarios' life-cycle costs. The benefit analysis was performed for the three proposed GSIs. The post-development condition with no GSI was set as a baseline. Since putting a monetary value to all benefits is not possible, some of the benefits are measured by qualitative measures.

One of the benefits under the water category is reduced storage need. This benefit was directly measured from the hydrologic computer simulation of the site and defined as a percentage. Based on the design storms, the required storage sizes for the post-development condition and the three GSI scenarios were determined. Then, the capital cost for the reduced storage size (avoided storage) was included as an initial benefit in the benefits analysis, which is an avoided cost. Also, the annual maintenance cost related to the reduced storage was added as an annual benefit.

Energy use was the other benefit category. The benefit was estimated based on GSI's lowering surrounding air temperature, which reduces demand for cooling buildings. Rain gardens and grassy ditches release water into the atmosphere, resulting in cooler air temperatures and reduced building energy consumption. The benefit was estimated based on the saved kWh per area of GSI, and the monetary value was calculated by multiplying this amount by the cost of energy per kWh. Another benefit under this category is saving energy by reducing water treatment. This benefit does not apply to the study site and therefore is not included in the analysis.

Climate change was another benefit category considered in this study and recommended by the CNT guideline. Reduction in atmospheric CO_2, one of the greenhouse gases contributing to climate change, was considered under this benefit category because it is the greenhouse gas most directly affected by green infrastructure (CNT, 2011). Also, the benefit of the avoided CO_2 emissions from energy-saving was added to this category; this is avoided cost analysis method.

The fourth category was air quality. The benefits were estimated based on pollutant uptake by or deposit to the GSI. Air pollutants considered in this benefit category are nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), and particulate matter (PM). The monetary values of pollution removal by the GSI were estimated based on costs for emission control, which is the replacement cost method. Then, the costs were multiplied by the mass of pollutants the GSI could remove.

Reducing air pollution by implementing GSI has health benefits, too. These benefits include reducing asthma attacks, bronchitis, emphysema, and other respiratory diseases due to the removal of Pollutants (City of Portland, 2010). Matthews and Lave (2000) assessed the economic values associated with PM reduction at $1.89 per pound in terms of avoided health care costs.

The last category considered in this analysis was community-based benefits such as increased recreational opportunity, property values, and improved habitat. GSI increased recreational opportunities by providing a green environment. Vegetated GSI features can improve habitat for various native species. The increase in property value due to the installation of GSI on the site was estimated based on the median housing price of the area.

Previous studies and guidelines determined the benefits amount and the economic values (American Rivers, the Water Environment Federation, 2011; City of Portland, 2010; Cordier et al., 2014; Elmqvist et al., 2015; Jaffe, 2010; Rai et al., 2019). Several valuation approaches were used to quantify the benefits and give monetary value to the benefit. One of the approaches that was used in this research is a benefit transfer. This approach uses the results of other benefit studies to estimate benefits that might accrue from similar installations undertaken elsewhere (Freeman, 2003). This study used the benefit transfer approach to estimate benefits under energy, climate change, and air quality categories. The other approach is the hedonic pricing method, which estimates economic values for ecosystems or environmental services directly affecting market prices. In this study, the hedonic pricing method was used to estimate increased housing prices due to having GSI on the site and reduce medical cost as a result if improved air quality.

Several assumptions have been made while valuing the benefits and their monetary values. These assumptions were set based on previous studies and the CNT guideline. Also, the benefit analysis structure provided in the supplementary document is based on a guideline provided by CNT to recognize the value of green infrastructure (CNT, 2011).

Assumptions:

- Studies used as references in the benefits analysis were conducted in different years. Adjustments were made to standardize the prices from these different years by considering the inflation rate.

- Most benefit analysis studies have been conducted on urban street trees and green roofs (City of Portland, 2010; McPherson et al., 2005). However, these GSI are not considered in this study. Therefore, for the rain garden scenario, an assumption was made that benefits that can be gained per tree are equal to benefits from 1,500 ft^2 of a rain garden (McPherson et al., 2005). This assumption was made by equivalent analysis of the leaf area of a medium tree area (Goude et al., 2019; McDowell et al., 2002; McPherson et al., 2005; Peper & McPherson, 2003)

- The unit amount and economic value of each benefit were gathered from several studies based on the number of GSIs. (American Rivers, the Water Environment Federation, 2011; City of Portland, 2010; CNT, 2011; Nordhaus, 2017; Zhou et al., 2018). Then, Ranges are set based on these data. In most cases, the average values were used to estimate the benefits. However, the lowest values were used for permeable pavement in some cases. For instance, rain gardens absorb more air pollutants than permeable pavements. Therefore, the lower boundary was set for the permeable pavement.

- GSI would increase property values by 2 to 10% (Jaffe, 2010). An assumption was made that the median home value for the city of Oxford is $300,000. 5% property value increase was assumed for the rain garden scenario, 3% for the grassy ditch, and 1% for permeable pavement. The percentages were assigned based on the GSIs' benefits and attraction.

- Benefits from permeable concrete were assumed to be the same as benefits that could be gained from interlock permeable pavement (Antunes et al., 2020; Zhou et al., 2018). Overall, there are few studies on the environmental benefit of permeable pavement, especially in the air quality category.

Table 4.3. List of possible benefits from the proposed GSIs for the study site

<table>
<tr><th colspan="2">Benefit</th><th>Pervious Pavements</th><th>Rain Garden</th><th>Grass Swale</th><th>Applicable for the Study Site?</th></tr>
<tr><td rowspan="4">Reduce Stormwater Runoff</td><td>Reduces water treatment needs</td><td>√</td><td>√</td><td>√</td><td>No</td></tr>
<tr><td>Improve water quality</td><td>√</td><td>√</td><td>√</td><td>Yes</td></tr>
<tr><td>Reduces storage needs</td><td>√</td><td>√</td><td>√</td><td>Yes</td></tr>
<tr><td>Reduces flooding and erosion</td><td>√</td><td>√</td><td>√</td><td>Yes</td></tr>
<tr><td colspan="2">Improve air quality</td><td>×</td><td>√</td><td>√</td><td>No</td></tr>
<tr><td colspan="2">Reduce atmospheric CO_2</td><td>√</td><td>√</td><td>√</td><td>Yes</td></tr>
<tr><td colspan="2">Reduce urban heat island</td><td>√</td><td>√</td><td>√</td><td>Yes</td></tr>
<tr><td rowspan="4">Improves Community Livability</td><td>Reduce noise pollution</td><td>√</td><td>×</td><td>×</td><td>Yes</td></tr>
<tr><td>Increase property values</td><td>√</td><td>√</td><td>√</td><td>Yes</td></tr>
<tr><td>Increases Recreational Opportunity</td><td>×</td><td>√</td><td>×</td><td>Yes</td></tr>
<tr><td>Improve habitat</td><td>×</td><td>√</td><td>√</td><td>Yes</td></tr>
</table>

4.3.3 Benefit-cost Analysis

The benefit-cost analysis was conducted to analyze the cost-effectiveness of the GSI alternatives. A cost-effective alternative is an alternative that gives benefits equal to other alternatives with lower LCC. This analysis was conducted using two approaches, BCR and IRR. The benefit-cost analysis estimates the total equivalent money value of the benefits and costs to identify whether a project is worthy. The project is worthwhile if the benefits' present value exceeds the cost's present value. In other words, the ratio of the benefits to the costs must be greater than one; see Equation 6.

$$\mathrm{BCR} = \frac{\mathrm{B}_0 + \sum_{y=1}^{n} B_y \frac{1}{(1+i)^y}}{C_0 + \sum_{y=1}^{n} C_y \frac{1}{(1+i)^y}} = \frac{\mathrm{PVB}}{\mathrm{PVC}} \qquad \text{Equation 4.6}$$

The other benefit-cost analysis approach is determining the IRR. A rate of return is the net gain or loss of an investment over a specified period, expressed as a percentage of its initial cost, see Figure 4.3. IRR is the discount rate for which the net present value (NPV) of all cash flows equals zero, which means the point at which the costs and the benefits become equal. It represents the return on the capital invested in the project.

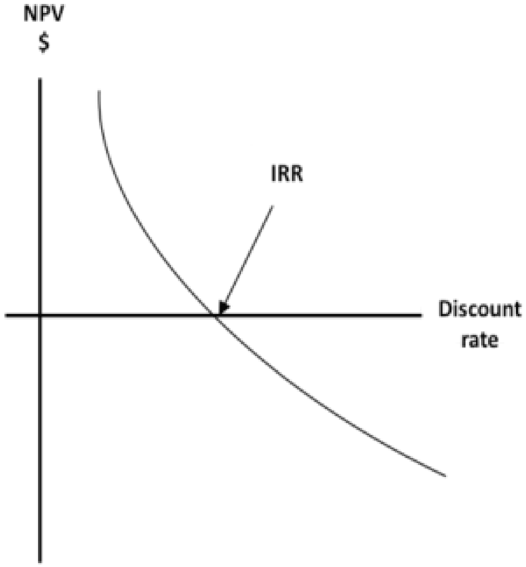


Figure 4.3. NPV cure and IRR (ACCA, n.d.)

A spreadsheet was developed based on the CNT guideline and the WERF tool. The spreadsheet contains both the cost and the benefit analysis. It provides a price range for the costs and benefits of the three GSI scenarios: Permeable pavement, rain garden, and grassy ditch. Also, the IRR calculation is provided. Since this spreadsheet has both the cost and benefit analysis together, it would be more convenient and straightforward for a quick benefit-cost analysis.

4.4 RESULTS AND DISCUSSIONS

4.4.1 Cost Analysis

Based on the LCCA, the capital costs for the simulated GSI scenarios were higher than for the baseline scenario, which is only traditional stormwater retention. Adding permeable concrete sidewalks on the site increased the capital cost by $63,963, 86% higher than the baseline cost. The rain garden scenario increased the capital cost by 48% and the grassy ditch by only 4%. Because the grassy ditch replaced the landscaping area, all the installation activities are similar to landscaping except for excavating the ditch.

Similar to the capital costs, the PVC of O&M costs were higher for the GSI scenarios than for the baseline scenario. Comparing its size and capital cost, the rain garden scenario (GSI 2) had relatively higher O&M costs than the other GSI scenarios. This increase is because the rain garden needs more maintenance activities than the landscaping, such as replacing mulch and tilling the soil. On the other hand, the cost for the grassy ditch scenario (GSI 3) was smaller because most of the maintenance activities are similar to the landscaping. Figure 4.3 shows the capital and O&M costs of all scenarios.

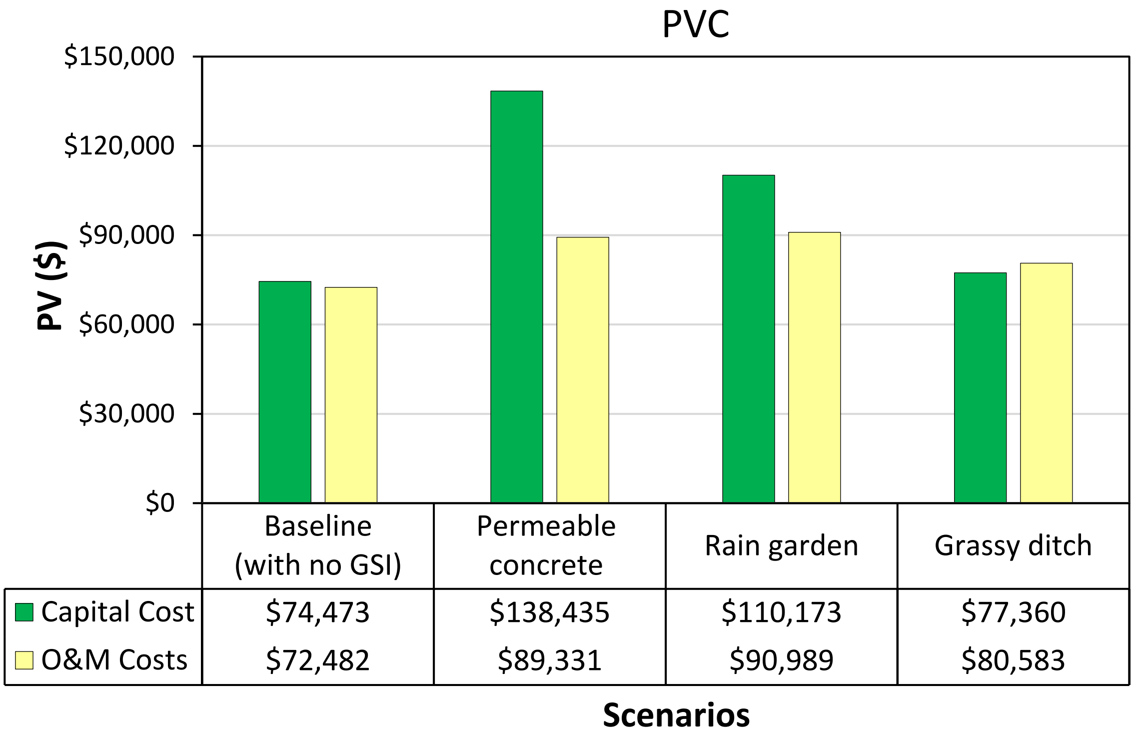


Figure 4.4. Present value of costs (PVC) of the GSI scenarios

Furthermore, the capital and O&M costs are covered by different parties. Usually, the capital costs are the developer's responsibility, and the O&M costs are the property owners' responsibility. In this study, comparisons of the overall costs were conducted. However, different comparison approaches should be followed based on the scope and purpose of the project. For instance, if a developer would like to include GSI in the design, only comparing capital costs would be sufficient.

Comparing only the capital and O&M costs might lead to the wrong conclusion that implementing GSI is not cost-efficient than traditional stormwater management. However, implementing GSI has other cost co-benefits, such as reducing the potential of flooding, which is not accounted for in the direct costs used in the LCCA. Reducing flooding would save money for property owners and the city. It also reduces the required storage to handle the excess stormwater runoff. These benefit analyses are presented in Section 4.4.2.

After the capital and O&M costs were estimated, the PVCs were calculated. The PVCs for implementing only traditional stormwater retention and both traditional and GSI scenarios were estimated. Table 4.4 summarizes the PVC of all simulated scenarios based on the PV calculations using Equation 4.4. Adding GSI on the site increased the PV of life-cycle costs for all GSI scenarios (Table 4.4). The costs differed based on the type and size of the GSI. The PVC for the pervious concrete pavement was higher than for the other scenarios, and the grassy ditch scenario resulted in a smaller PVC. It is because the capital cost for the permeable pavement is much higher than the capital cost of the grassy ditch.

Table 4.4. Present value costs (PVC) for different scenarios

Stormwater Infrastructure	**Baseline Scenario**	**GSI Scenarios**		
		Scenario 1	**Scenario 2**	**Scenario 3**
Concrete Pavement	$52,670	-	$51,203	$51,203
Landscape	$94,284	$94,284	$34,084	$60,200
Pervious Pavement	-	$133,481	-	-
Rain Garden	-	-	$115,875	-
Grassy Ditch	-	-	-	$46,540
Total Cost	**$146,954**	**$227,766**	**201,162**	**$157,943**
Difference (with - without GSI)	-	**$80,811**	**$54,207**	**$10,989**

4.4.2 Benefit Analysis

The benefit analysis was based on six categories: water, energy, climate, air quality, health, and community livability.

The first category was water; the economic value of avoided storage and flood reduction benefits were estimated under this category. Average unit prices were assigned for all of GSIs based on literature reviews. However, the quantity of the benefit was different for each GSI scenario. For instance, the required storage size reduction due to implementing GSI 1 was 1,903 ft^3 (5% reduction from the baseline), and for GSI 2, it was 6,572 ft^3 (18% reduction from the baseline). However, the unit price for storage installation was the same for both scenarios, \$8 per ft^2. The estimated economic value of GSI 1 under the water benefit category was \$9,085 for GSI 1, \$28,306 for GSI 2, and \$9,227 for the grassy GSI 3. In addition to the monetary value of the benefits, improving water quality was included as a non-monetary benefit. Reductions in total suspended solids (TSS)and dissolved Cu were estimated for GSI 1 and 2. GSI 1 reduced 563 g of TSS and 2.8 mg of dissolved Cu; GSI 2 reduced 2,672 g of TSS and 3.2 mg of dissolved Cu annually. Under the water benefit category, GSI 2 showed the highest economic value of \$ 28,306.

Under the energy category, GSI 1 showed a higher benefit than the other scenarios by reducing the energy use by 1,348 kWh/ft^2/year. GSI 2 and 3's benefits were 1,096 and 413 kWh/ft^2/year, respectively.

The climate benefit category primarily considered the benefits of atmospheric CO_2 reduction. The amount of direct carbon sequestration in CO_2 equivalent per area of GSI was defined then its economic value was estimated. Based on literature, ranges of unit costs per lb CO_2

were set (American Rivers, the Water Environment Federation, 2011; ARB, 2018; Elmqvist et al., 2015). For GSI 2 (rain garden), the average stored/absorbed CO_2 was 4,894 lbs per year. For GSI 3, the average stored/absorbed CO_2 was 143 lbs. The rain garden showed the highest CO_2 absorption because of its direct sequestration of CO_2 through its vegetated cover. This absorption contributes to reducing climate change, as CO_2 is the most common greenhouse gas. Similarly, the total avoided CO_2 emission from electricity saving was estimated in lbs of CO_2/kWh. For GSI 1, the total avoided CO_2 was 2,036; for GSI 2 and 3, it was 1,656 lbs and 625 lbs, respectively. The total estimated economic value of climate change benefits for the GSI scenarios 1, 2, and 3 were \$150, \$482, and \$ 48, respectively. Under this benefit category, GSI 2 (the rain garden scenario) showed the highest benefit.

Under the air quality benefit category, the benefits were estimated by estimating the amount of pollutant mass that can be up-taken by the GSI. The pollutants considered in the analysis were NO_2, SO_2, and PM. On average, GSI filters approximately 0.00114 to 0.004 lbs. of PM, 0.003 to 0.0048 of NO_2, and 0.0059 to 0.0061 lbs. of SO_2 per ft^2 (CNT, 2011; McPherson et al., 2005; Zhou et al., 2018). Based on these ranges, the annual monetary values of benefits from GSI 2 and 3 were estimated to be \$219 and \$105. The air quality benefit considered in this study is based on reducing pollutants through pollutant uptake/deposit. Since permeable pavement does provide these benefits, the monetary value was estimated only for the rain garden and grassy ditch.

The economic value of health benefits related to reducing exposure to PM was estimated based on avoiding health care expenses related to respiratory disease. Matthews and Lave (2000) assessed the economic values associated with PM reduction at \$1.89 per pound in terms of avoided health care costs. A cost of \$3.20 was estimated considering inflation and used for today's cost.

This benefit was estimated based on the PM reduced by the GSI but not included in the benefits analysis because the frequency of the benefit is not precise in the reference study.

Under the community livability benefit, the increase in property value was estimated. The average house value in the study area is estimated to be $300,000. If GSIs are implemented on-site, housing prices could increase by $3,000 to $15,000 based on the type of GSI.

Table 4.4. Economic values of GSI benefits

Benefit Category	**Economic valuation of benefits**		
	GSI Scenarios		
	GSI 1	**GSI 2**	**GSI 3**
Water	$9,085	$28,306	$9,227
Energy	$492	$400	$151
Air Quality	_	$219	$105
Climate Change	$150	$483	$48
Health	_	$52	$19
Community	$3,000	$15,000	$9,000
Total Benefit	**$9,727**	**$29,408**	**$9,531**

Similar to the PVC analysis, the PVB was estimated based on a 30-year design period using Equation 5. The PVB for the permeable pavement scenario (GSI 1) was $8,476, $26,557 for the rain garden scenario (GSI 2), and $9,041 for the grassy ditch scenario (GSI 3).

4.4.3 Benefit-cost Analysis

After the PVB and PVC were estimated, the BCR was calculated for each GSI scenario. Table 5 shows the benefit-cost ratio (BCR) for the three GSI scenarios. Based on the BCR calculation, the rain garden (GSI2) and grassy ditch (GSI3) resulted in a BCR greater than 1, which means the PVB of these scenarios exceeded their PVC. The BCR for GSI 2 was 1.25, which is higher than the other scenarios. Therefore, installing a rain garden is more worthwhile for this specific site than the other scenarios.

The IRR, the discount rate at which the cost and benefit balance (NPV, becomes zero), was estimated. The IRR for GSI 2 (rain garden) was 21.3%, and for GSI 3 (grassy ditch), it was 3.2%. Due to the negative net cashflow values for the GSI 1 (permeable pavement), the IRR was not valued for this value.

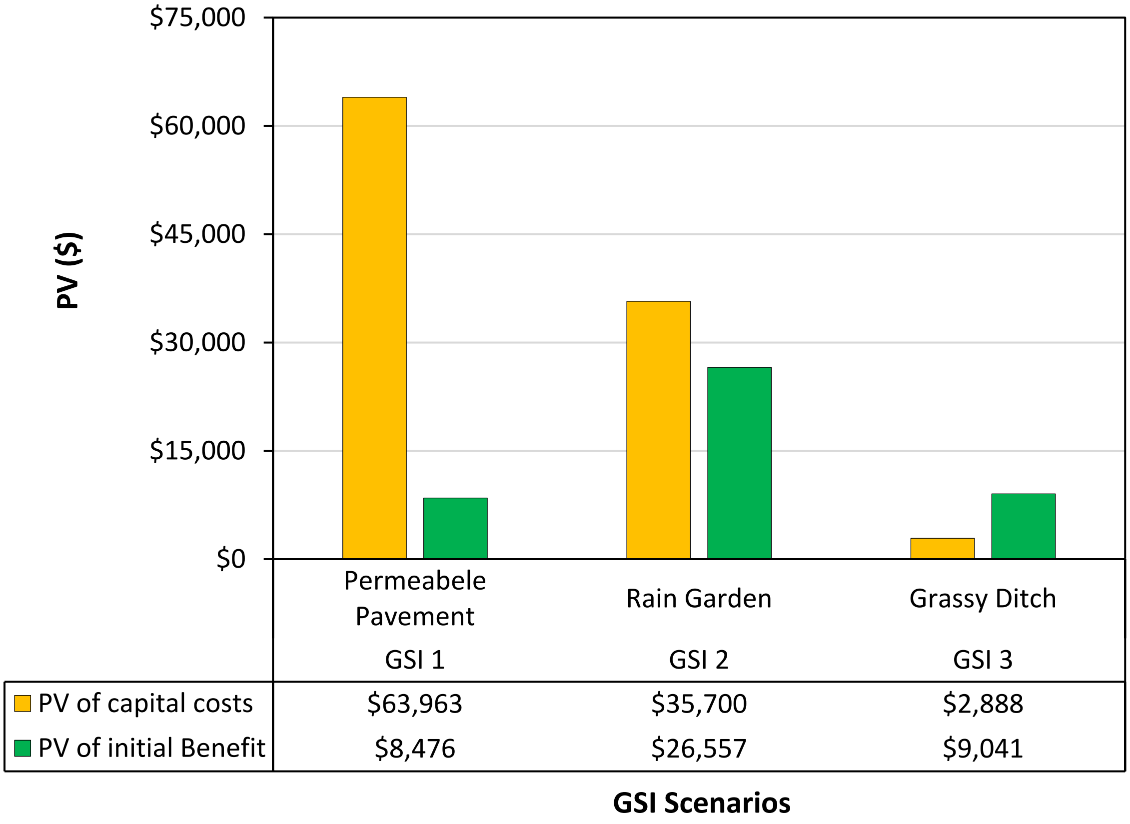
Table 4.5. Benefit-cost ratio (BCR) of the Economic value of GSI benefits

GSI Scenarios	Present Value of Benefits PVB	Present Value of Costs PVC	Benefit-cost Ratio BCR
GSI 1	$26,664	$80,278	0.33
GSI 2	$67,994	$54,207	1.25
GSI 3	$12,452	$10,989	1.13

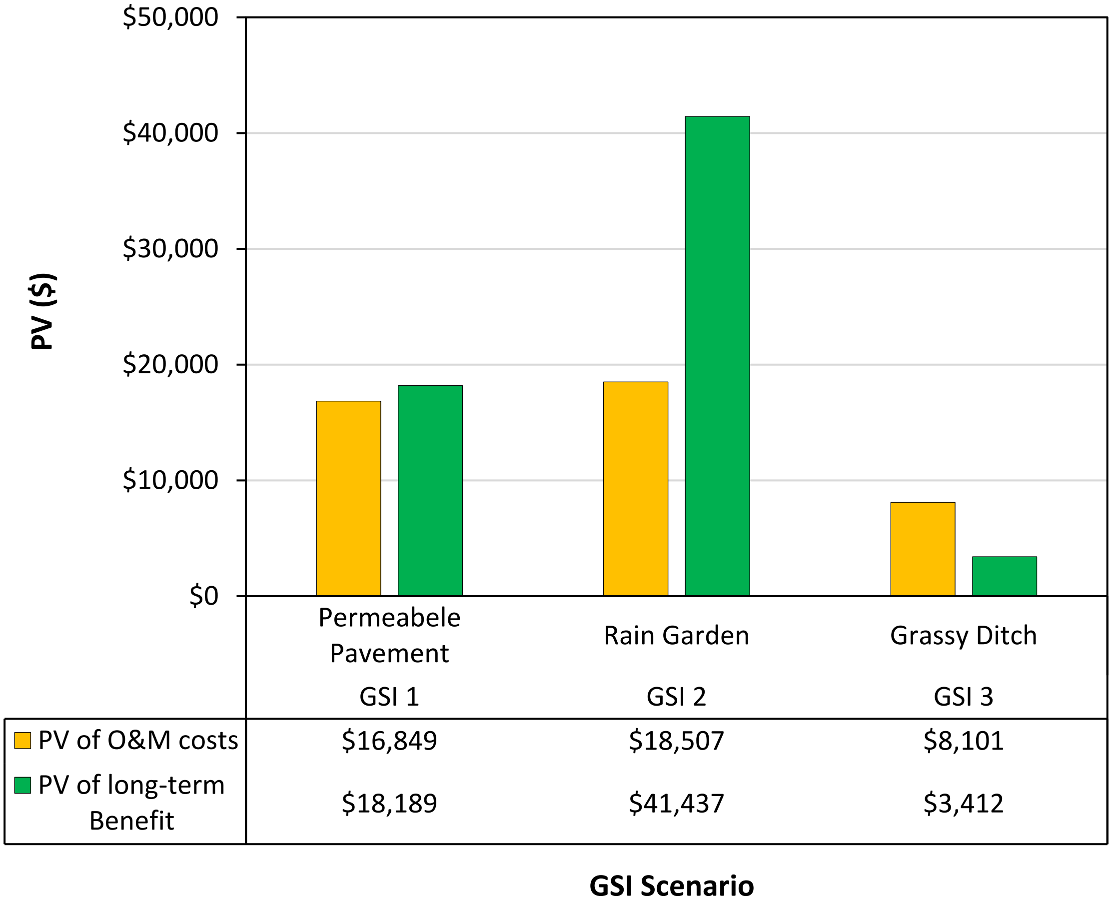
Since the capital and O&M costs are covered by different parties, comparing the initial and the long-term costs and benefits separately gives a better understanding. Figure 4.5(a) shows the

PV of initial costs (capital costs) versus initial benefits. Figure 4.5(b) shows the long-term costs versus long-term benefits.

As shown in Figure 4.5 (a), for GSIs 1 and 2, the capital costs were higher than the initial benefits. For GSI 3, the capital cost was lower than the initial benefit. The capital cost for GSI 1 was relatively higher than the other scenarios. Figure 4.5 (b) shows the long-term costs and benefits of the GSI scenarios. For GSI 1, the long-term O&M costs and the long-term monetary value of benefits are almost the same. For GSI 2, the long-term benefit is higher than the O&M costs, which makes it more economical. For GSI 3, the O&M costs are higher than the long-term benefits.



(a)



	Permeabele Pavement GSI 1	Rain Garden GSI 2	Grassy Ditch GSI 3
🟨 PV of O&M costs	$16,849	$18,507	$8,101
🟩 PV of long-term Benefit	$18,189	$41,437	$3,412

(b)

Figure 4.5. Present value of costs and benefits (a) initial (b) long-term

4.5 CONCLUSIONS

In this study, LCCA and BCA of GSI were conducted based on implementing three GSI practices on a small development site. In this study, LCCA and BCA of GSI were conducted by implementing three GSI practices on a small development site. Based on the analysis result, the costs of GSI are higher than for traditional stormwater infrastructure. However, in most cases, the long-term benefits outweigh the costs.

The LCCA results showed that GSI with traditional stormwater infrastructure would cost more than traditional stormwater infrastructure alone. Based on the simulated scenarios, the 30-year LCCs are higher by 45% on average, depending on the size and type of GSI. The capital costs for permeable concrete pavement are higher than for the other GSI scenarios. On the other hand, the O&M costs for the rain garden scenario are higher than for pervious concrete pavement relative to their capital costs. However, most of the maintenance for both the grassy ditch and rain gardens can be accomplished as part of routine landscape maintenance and does not require specialized equipment.

Based on the quantified benefits, the rain garden has the highest benefit in most categories than the other GSIs, making the rain garden the most cost-efficient scenario than permeable pavement and grassy ditch, with a BCR of 1.25 and 21.3% IRR. The costs of implementing permeable pavement are higher than the benefits, with a BCR of 0.33.

The capital costs of GSI are higher than the initial benefits. However, the long-term benefits of GSI are higher than the long-term O&M costs in most cases. Therefore, implementing GSI on urban development sites is advisable.

This study relied on simulations, assumptions, and available data. Because cost and benefit data are available in non-standardized sources, several data sources were used, and several assumptions and modifications were made in the cost and benefit analyses. This variation in cost estimate makes it challenging to standardize the cost and also affects the BCR analysis. In both benefit-cost analysis approaches (BCR and IRR), some benefits are not included due to the lack of quantitative methodologies. However, since the same assumptions have been taken for all scenarios, this should not affect the comparison. The cost and benefit estimates presented here are only accurate for the study location but can serve as a template for application at different sites. Most of the values are location and site-specific. The spreadsheet accompanying this study can be used at other sites by adjusting the cost and benefit inputs.

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CHAPTER 5 [2]

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[2] Published: Abera, L. E., Surbeck, C. Q., & Alexander, K. (2021). Evaluating the effect of city ordinances on the implementation and performance of green stormwater infrastructure (GSI). *Environmental Challenges*, *4*(June), 100183. https://doi.org/10.1016/j.envc.2021.100183

5 EVALUATING THE EFFECT OF MUNICIPALITY ORDINANCES ON THE IMPLEMENTATION OF GREEN STORMWATER INFRASTRUCTURE (GSI)

ABSTRACT

The replacement of natural pervious surfaces with impervious surfaces due to urbanization, construction, and development causes excess stormwater runoff and results in cities experiencing localized flooding events. The installation of green stormwater infrastructure (GSI) is one way of reducing flooding events and preventing downstream erosion and damage. In this study, computer rainfall-runoff simulations were performed to analyze GSI's effectiveness in mitigating stormwater runoff when applied to sites with different soil types and for which different design storms were established by regulation. A mixed-use development site was used as a hypothetical site on which to perform the analysis. The study applied the same design to six small- to medium-sized cities in the southeastern United States with different design storm magnitudes. The cities' ordinances were reviewed, and none required GSI. Therefore, this study revised some of the stormwater management requirements to stress GSI implementation, and then stormwater modeling was conducted to see how regulatory changes would affect runoff. The HydroCAD stormwater modeling tool was used to perform hydrologic simulations for the hypothetical building site in each of the six cities using the design storms and small storms of the cities. Even though GSI has been commonly implemented in large cities, small and medium-sized cities can also prevent excess stormwater by incorporating GSI in their ordinances for new developments and site retrofits. Based on the hydrologic simulation results, municipalities with lower magnitude

design storms and low infiltration soils have the most to benefit from GSI and could benefit from ordinances requiring GSI. For smaller, more frequent storms, GSI alone can meet the pre-development peak flow requirements.

5.1 INTRODUCTION

Green stormwater infrastructure (GSI) provides environmental benefits, but the costs and burdens on development as well as regulatory limitations may restrict its use in many cities. The installation of GSI in cities is a sustainable method of addressing stormwater runoff problems (Giese et al., 2019; Kousky et al., 2013; Li et al., 2020). GSI reduces the runoff volume and velocity by promoting stormwater infiltration into the ground, which prevents downstream flooding, erosion, and environmental damage. GSI may also serves as a treatment for polluted stormwater runoff, which improves the quality of receiving water bodies (CWAA 2016; Pennino et al. 2016). In addition to managing stormwater quantity and quality, GSI has environmental and social benefits, such as providing a natural green environment, reducing exposure to toxic substances, improving air quality, and improving human well-being (EPA 2017; Gallet 2012). GSI also improves urban air quality by taking up harmful air pollutants while providing several other ecosystem services (Jayasooriya et al. 2017).

In order to meet the benefits described, GSI should be used together with, or to replace when feasible, gray stormwater infrastructure. Gray stormwater infrastructure consists of street gutters, storm drains, pipes, and underground storage structures. Gray infrastructure is designed for the important function of quickly moving stormwater away from homes, businesses, and flood-prone areas. However, gray infrastructure does not promote infiltration, evapotranspiration, and temporary storage as GSI does. GSI is different from gray infrastructure because it mimics the natural hydrologic cycle by simulating pre-development or pre-construction conditions that have more permeable surfaces.

Even though GSI has many environmental and health benefits, there are barriers that prevent cities, developers, construction contractors, and engineers from installing these practices (CWAA, 2016; Dhakal and Chevalier, 2017). These barriers usually fall into three main categories: technical, financial, and regulatory. Variability in hydrologic performance and uncertainty of the state-of-the-practice are considered technical barriers. Also, the effectiveness of GSI is very site-specific, particularly in regards to soils and climate (EPA, 2020). Financial barriers include high capital, retrofit, and operation and maintenance costs of GSI. The regulatory barrier often consists of city ordinances that may restrict GSI and promote gray infrastructure (Braden and Ando, 2011; Derviş, 2013; Liberalesso et al., 2020). Mindset, unawareness, fear, attitudes, and perceptions are also other factors that discourage landowners, water resource managers, and policy-makers from using GSI (Dhakal and Chevalier, 2017; Ureta et al., 2021).

Some studies have described barriers that often limit the implementation of GSI. Derviş (2013) categorized three types of uncertainty for the implementation of GSI: variability in cost, hydrological performance, and adaptation. Braden and Ando (2021) discussed three other GSI implementation barriers. The first is that many cities have zoning ordinances and building codes that create barriers to GSI design. The second is the division of responsibility. The responsibility for initial stormwater management is on the builders, whereas ongoing stormwater management is on the property owners. Property owners might be reluctant to accept the responsibility for something they do not understand. The third barrier in the Braden and Ando study is that adopting

GSI requires stakeholders to obtain new knowledge. Similarly, the Clean Water America Alliance identified four categories of barriers that often prevent the adoption of GSI: technical and physical, legal and regulatory, financial, and communities and institutional (CWAA 2016).

This paper specifically analyzes GSI barriers due to local regulations. The analysis was performed by identifying regulatory barriers and incentives in existing municipal ordinances of six southeastern United States cities with populations ranging between 6,200 and 46,000. Six cities, Biloxi, MS, Calhoun, GA, Sevierville, TN, Oxford, MS, Orange Beach, AL, and Ruston, LA, were selected for this analysis. Small to medium-sized cities from similar climate regions were chosen because they experience stormwater effects but are often under-resourced compared to major cities with already well-established stormwater departments, ordinances, and staff. The design storm magnitudes of the selected cities range from 4.66 (118.36 mm) to 14.5 inches (368.3 mm) in 24 hours (NOAA Hydrolometeorological Design Studies Center, 2020). The cities of Biloxi and Orange Beach represent coastal cities on the Gulf of Mexico, an area often affected by extreme storms. Consideration was taken to address the cities' zoning, flooding, and stormwater management requirements.

This paper addresses four objectives. The first objective is to identify existing municipal ordinances of those cities that referenced GSI implementation either specifically, by requiring GSI, or impliedly, by suggesting green alternatives to gray infrastructure. The second objective is to quantify the runoff due to design storms cited in city ordinances. This objective was met by conducting rainfall-runoff analyses using the HydroCAD stormwater analysis software. Third, to suggest practical sample regulations encouraging GSI implementation to reduce runoff. The last objective is to quantify the runoff reduction based on the sample regulations.

5.2 CITIES AND HYPOTHETICAL SITE

This section describes the cities and the study site that was modeled in each city. Table 1 shows general information about each city. These cities represent small to medium-sized growing cities with similar (but not identical) climatic conditions, though different soil groups, and that may have fewer financial resources than larger cities.

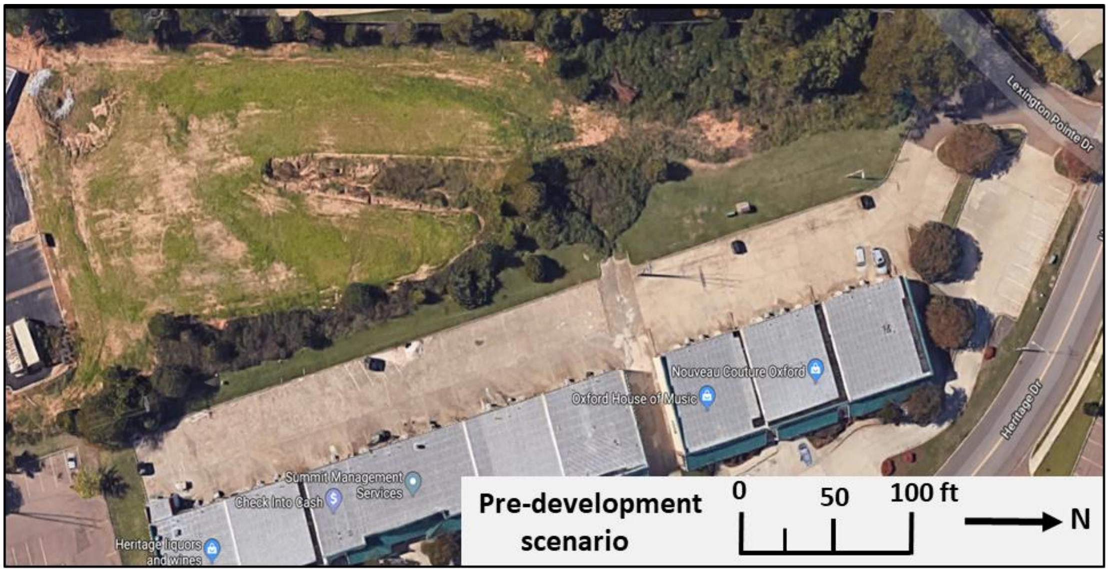
Table 5.1. General information on the six cities selected for this study (Census 2020).

City		**Biloxi, MS**	**Calhoun, GA**	**Orange Beach, AL**	**Oxford, MS**	**Ruston, LA**	**Sevierville, TN**
Area, mi^2 (km^2)	**Total**	67.83 (175.7)	15.00 (38.85)	15.95 (41.31)	16.5 (42.73)	20.98 (54.34)	24.27 (62.86)
	Land	38.22 (98.99)	14.93 (38.67)	14.70 (38.08)	15.83 (40.99)	20.85 (54.00)	24.14 (62.52)
	Water	29.61 (76.71)	0.07 (0.18)	1.25 (3.24)	0.67 (1.74)	0.13 (0.34)	0.13 (0.34)
Population		46,212	17,271	6,235	28,122	21,859	17,117
Density per mi^2 (per km^2)		1153 (398)	1048 (361)	370 (128)	1195 (412)	1049 (362)	614 (212)
Median household income, U.S. dollars		$44,972	$35,890	$81,506	$39,886	$30,119	$40,780

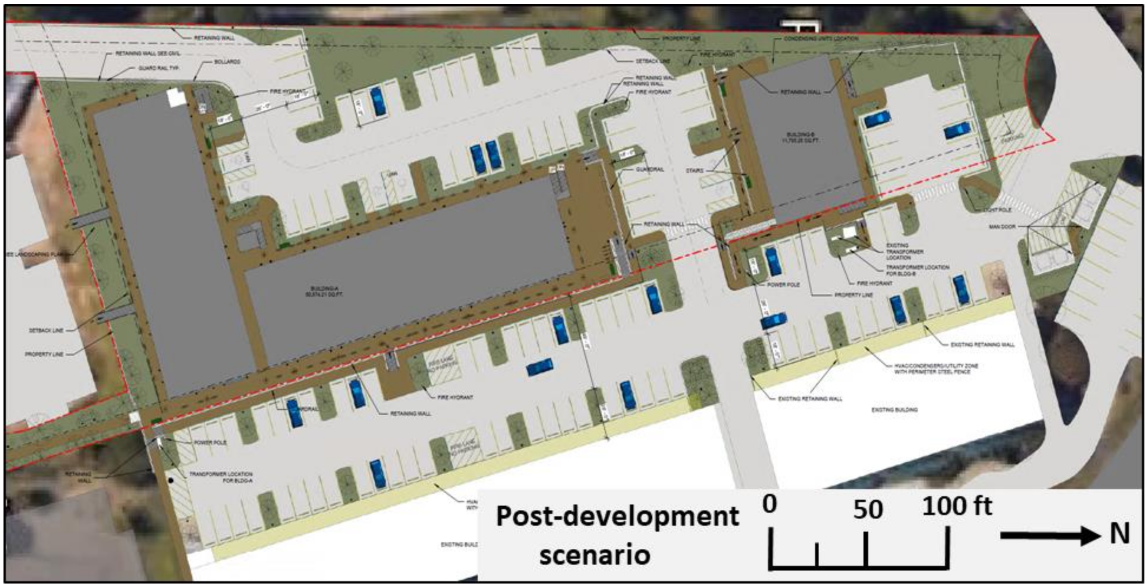
The study was conducted by assuming a mixed-use development with the same buildings, parking lots, and landscaping built in each city, using applicable zoning requirements from each city. Figure 5.1 shows the pre-development and post-development scenarios of the study site. The pre-development is the condition of the study site before the project is built. The post-development scenario is the study site with the proposed mixed-use development completed. Figure 5.1(b) shows the plan view of the proposed development, with a total area of 161,136 ft^2 (14,970 m^2), including 45,526 ft^2 (4,230 m^2) of rooftops, 88,280 ft^2 (8,201 m^2) of parking lots, and 27,330 ft^2

(2,539 m^2) of landscape. The post-development includes the construction of two three-story mixed-use buildings and the associated parking lots. Both buildings are designed to have commercial space on the first floor and residential space on the second and third floors.

Computer simulations for the rainfall-runoff analysis of the site were run for pre- and post-development conditions, with post-development simulations including scenarios of no stormwater control and some implementing GSI. The same pre-development land cover was assumed for all cities. The post-development land cover was simulated based on the cities' design requirements defined in their ordinances consistent with the proposed site plan.



(a)



(b)

Figure 5.1. Pre-development and post-development plan views of the study site. 100 ft = 30.48 m

5.3 MATERIAL AND METHODS

5.3.1 Ordinance Review

Each municipality's zoning and stormwater management ordinances were obtained from the Municode Library (Municode 2020). The requirements were analyzed for issues related to GSI, such as permeable surfaces, green area coverage, landscape or open space, and stormwater management incentives. Only practices that could be applied to the study site were considered for the analysis. Provisions that related to GSI were found, and then revised versions were written with stricter requirements. The revised version was crafted to be practicable for small and mid-sized cities to adopt and use on new construction sites of five acres or less in non-residential areas.

All six cities require stormwater management facilities to reduce the post-development peak flow rate from a storm to less than or equal to the pre-development peak flow rate. However, none of the cities do this by requiring GSI. Of the six cities considered in this study, two of them, Biloxi and Oxford, require a drainage/storage system to be designed for a maximum 100-year 24-hr storm. The remaining four cities require design for a maximum 25-year 24-hr storm. A summary of the design storms and ordinances related to GSI (focusing on, but not limited to, permeable surfaces and rain gardens) is presented in Table 2**.**

The ordinances were reviewed to find GSI requirements for new developments in similarly zoned areas. The regulations in the second column of Table 2 are the text passages taken from the ordinances. No city required GSI. However, all had some non-enforceable advisory provisions that emphasized green space over gray infrastructure.

GSI practices were chosen to be applicable to the hypothetical site's limited size and zoning. The GSI focuses on stormwater runoff quantity management. Stormwater quality management is outside the scope of this study.

Table 5.2. Summary of design storms and the stormwater-related GSI language in the ordinance for each municipality.

City	Stormwater-related GSI Language as stated in Ordinances	Stormwater Design Requirements
Biloxi, MS	If 20% of the total vehicular area is covered by **permeable pavement**, the size requirement for canopy and understory trees can be reduced by 5% (Article 23-6-3(D)(4)).	100-year 24-hour design storm magnitude = 14.5 in (368 mm)
	If **permeable surfacing***[3] materials are used for some or all of the parking area surfaces, points that lead towards the Leadership in Energy and Environmental Design (LEED) certification will be earned. If a minimum 25% of the area is covered, 2 points will be earned. If a minimum 59% of the area is covered, 4 points will be earned (Table 23-6-12(B)).	
	If **permeable surfacing** materials are used for all sidewalks, 2 LEED points can be achieved (Table 23-6-12(B)).	
	If a development includes **rain gardens** where each has an area of at least 100 ft^2 (9.29 m^2), and is sized to hold stormwater runoff from between 5 and 10 percent of the impermeable area draining into it, 1 LEED point can be earned per rain garden (Table 23-6-12(B)).	
	30% of the total required parking is subjected to a shared parking agreement.	
Calhoun, GA	For apartment buildings, a permit may not be issued if the **impermeable cover** is more than 30% of the total area (Sec. 11.3.1(a)(3)).	

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[3] * Words in bold indicate GSI.

City	Stormwater-related GSI Language as stated in Ordinances	Stormwater Design Requirements
	The purposes of the stormwater management ordinances include **encouraging** the use of nonstructural stormwater management and **stormwater better site design practices**, such as the **preservation of green space and other conservation areas**, to the maximum extent practicable (Sec. 46-300(5)).	25-year 24-hour design storm magnitude = 6.18 in (157 mm)
	Use of **stormwater better site design practices**, including nonstructural stormwater measures, allow the applicant to reduce the water quality volume requirement (Sec. 46-336).	
Orange Beach, AL	Vehicle use areas must be constructed of concrete, asphalt, brick, cement pavers, or similar material installed and maintained per industry standard. **Alternative** all-weather surfaces such as **gravel, shell, permeable concrete, and reinforced turf** may be approved by the Planning Commission in consideration of site conditions, traffic intensity and land use (Sec. 8.0107404).	25-year 24-hour design storm magnitude = 11.8 in (300 mm)
	Runoff should be designed and maintained using retention/detention or **exfiltration/infiltration** (Sec. 42-272(a)).	
	Other stormwater control systems can be considered to manage runoff exceeding the detailed volume, such as **exfiltration/infiltration ponds, grass swales, and vegetated buffer strips** (Sec. 42-272(c)).	
Oxford, MS	Parking lots must be surfaced with asphalt or similar material. However, **permeable solid surfaces** may be allowed on areas of limited use at the approval of the city. (Sec 5.3.3.1)	For detention: 100-year 24-hr design storm magnitude = 8.75 in (222 mm) Multi-stage outlet structures ranging from the 2- to 100-year storms.
	At least 75% of parking island landscape areas should be covered with **grass** or another surface approved by the city (Sec 5.3.3.6(b)).	
	Parking lot landscaping requirements may be altered if **low impact design (LID)** stormwater management elements are approved (Sec 5.3.3.7(a)).	

City	Stormwater-related GSI Language as stated in Ordinances	Stormwater Design Requirements
	Permeable pavers may replace up to 25% of landscaping requirements for the permeable surface of the lot, approvable at the discretion of the planning director (Sec 5.7.3.5).	
	A minimum of 15% of the pervious surface of the parking lot should be **landscaped** with trees and shrubs (Sec 5.7.3.1).	
Ruston, LA	Where possible, a portion of the drainage from parking areas should be drained through swales that include deep rooted perennial ornamental grasses (Sec. 5.5.3.H.5).	25-year 24-hr design storm magnitude = 7.83 in (199 mm)
Sevierville, TN	Stormwater designs should seek to utilize **permeable** areas for stormwater treatment and to **infiltrate** stormwater runoff from impermeable surfaces and landscaped areas to protect water quality and quantity (Sec. 18-404(6)).	For detention: 25-year 24-hr design storm magnitude = 4.66 in (118 mm) Multi-stage outlet structures ranging from the 1- to 25-year storms.
	[In areas zoned Town Center Commercial] Wherever practical, low impact development techniques shall be used and maintained (Sec. 4.13.4).	

5.3.2 Rainfall-runoff Modeling

The study site's hydrologic processes were simulated using HydroCAD 10.10-4, a stormwater modeling software. This software was selected because it is commonly used among city engineers and developers. HydroCAD uses the Natural Resources Conservation Service (NRCS) Technical Release 20 (TR-20) runoff method procedure to determine the runoff's peak flow rate and volume. The Curve Number (CN) value is a primary input parameter for the TR-20 method used by HydroCAD. The CN is an empirical parameter used to characterize the runoff potential for a particular soil group and land cover (ASCE, 1996; USDA, 1982). The CN values were determined using the CN table provided in HydroCAD. This table of CN values is based on the NRCS TR-55 reference table (USDA, 1986). Table 3 shows the CNs used in this study.

In this study, we simulated the peak flow rates of runoff leaving the site at each city by employing HydroCAD. The 24-hr rainfall distribution was used in all of the simulations. Based on the NRCS designation of rainfall regions in the United States, the cities are in locations with different storm types. Calhoun, Oxford, and Sevierville are located in the region of Type II rainfall distribution. Biloxi, Orange Beach, and Ruston are located in the region of Type III rainfall distribution. These storm types are developed by the NRCS as dimensionless synthetic rainfall distributions to characterize the rainfall patterns in the United States. The Type II storm represents most of the country. Type III represents the Gulf of Mexico and the Atlantic coastal area (Mays, 2010; USDA, 1986). The storm magnitudes used were those required by the city ordinances and shown in Table 2.

We used the same pre-development land cover for all cities. This set the same baseline scenario. It also enabled us to study only the effect of each municipality's predominant soil group, design storms, and regulations related to GSI implementation and potential flood reduction. The pre-development land cover of the site was grass, woods-grass, paved area, and buildings. Even though the site's land cover was assumed to be the same for all cities, different CNs (see Table 3) were assigned based on each municipality's soil group. The soil groups affect how much rainwater infiltrates the ground, changing the amount of runoff that will be generated. Hydrologic soil groups were determined using the NRCS table and the EPA Stormwater Calculator soil maps (EPA, 2019; USDA, 2009). Since each city has several hydrologic soil groups, one representative soil group was selected for each.

Two post-development models were simulated for each city. The first model considered the cities' design storm requirements, keeping the same post-development land cover (post-development without GSI) (Figure 5.1(b)) for all cities.

The second model simulated the application of proposed sample regulations requiring GSI. The changes in the amount of runoff generated from these two sets of models were analyzed by comparing the simulation results. The comparisons were made between post development without stormwater control and post-development with GSI following the sample GSI regulations. The results of these analyses explain the effect on runoff when GSI regulations are implemented.

It is assumed that the full designs in all of these cities would incorporate proper piping and other conveyance structures, and water storage to account for runoff not handled by GSI.

When modeling runoff based on the proposed sample regulations, we introduced to the post-development site GSI such as permeable pavement and rain gardens. Modeling runoff from permeable pavements requires determining an effective CN value for the pavement (Schwartz, 2010). Although several types of permeable pavements are available, permeable concrete pavement was selected for this study site. The effective CN was estimated based on the permeable concrete area, the thickness and porosity of the permeable concrete and the sub-base layers, and the underlying soil's infiltration rate. The effective CN values (see Table 5.3) were estimated using the NRCS potential maximum retention equation; the values are presented in Table 3 for each soil group. The depth of the permeable concrete pavement layers, including ponding, amended soil, and gravel layers, were accounted for storage. Exfiltration through the underlying soil and overflow from the ponding layer were defined as outlets for the system.

The rainfall-runoff modeling for the rain garden was performed by defining the rain garden using a pond node in HydroCAD with the appropriate storage and outlet structures. The pond node allows the definition of multiple storage layers. Then, the layers were arranged on top of one another to model the composite shape. The rain gardens proposed for the study site consists of ponding, mulch, amended soil, and gravel layers, and they were defined as prismatic shapes. Except for the mulch layer, the depth of the layers is 12 inches (30.5 cm). The mulch layer is 3 inches (7.6 cm) thick. Outflow from the rain garden was defined as exfiltration and overflow.

The rainfall-runoff simulation results, the ordinance review, and the sample regulations are discussed in the Results and Discussion section.

Table 5.3. CNs of different scenarios and effective CNs used for permeable concrete.

City	Rainfall Distribution Types	Hydrologic Soil Group	Curve number (CN)		Effective CN for Permeable Concrete	Curve number (CN)	
			Pre-Dev.	Post Dev.		Sample Regulation 1	Sample Regulation 3
Biloxi, MS	III	B	72	92	69	90	88
Calhoun, GA	II	B	72	92	69	90	88
Orange Beach, AL	III	A	55	88	64	86	83
Oxford, MS	II	B	72	92	69	90	88
Ruston, LA	III	C	81	94	71	93	90
Sevierville, TN	II	D	86	95	73	94	92

5.3.3 Determination of Sample Ordinances

From the ordinance review and the baseline hydrologic analysis, it was observed that to benefit from implementing GSI, municipalities need to include these practices as requirements in their ordinances. If they are stated as recommendations, the implementation will depend on the developer's interest. Therefore, to show the effect of city regulations, we proposed modified sample regulations that emphasize the implementation of GSI. Table 5.4 shows the list of modified and proposed GSI requirements, citing similar existing ordinances that simply recommend GSI.

Table 5.4. Sample GSI regulations with recommended modifications.

Issue	Current Language in City Ordinances	Reference	Sample Regulation with GSI
Change sidewalk requirements	Sidewalks shall be concrete or another approved surface.	City of Oxford (Sec 5.3.3.1); City of Sevierville (Sec. 4.7.1.5)	Sample Regulation 1: All sidewalks shall be covered by permeable surfacing.
	If permeable surfacing materials are used for all sidewalks, 2 LEED* points can be achieved.	City of Biloxi (Table 23-6-12(B))	
	Sidewalks shall have a concrete depth of a minimum of four inches.	City of Ruston (Sec. 24-50(a)); City of Calhoun (Sec. 82-50(b))	
Include rain garden design as a part of landscaping	If a development includes rain gardens where each has an area of at least 100 square feet, 1 LEED* point can be earned per rain garden.	City of Biloxi, Table 23-6-12(B)	Sample Regulation 2: 15% of the landscape area should be designated for a rain garden that receives water from impermeable surfaces.
Change parking spaces coverage with permeable surface	Parking lots must be surfaced with asphalt. However, permeable solid surfaces may be allowed at the approval of the city.	City of Biloxi, Table 23-6-12(B)	Sample Regulation 3: Permeable surfacing materials shall be used to cover a minimum of 25% area of parking area.
	Vehicle use areas must be constructed of concrete, asphalt, brick, cement pavers, or similar material installed.	City of Orange Beach (Sec. 8.010405)	
	All parking lots (except per Sec. 4.6.2.10 - sidewalks) shall be paved with asphalt or cementious concrete	City of Sevierville (Sec. 4.6.3.2)	

Issue	Current Language in City Ordinances	Reference	Sample Regulation with GSI
Change parking island requirements	Parking aisles and interior dividers shall be terminated with terminal islands not less than five (5) feet in width constructed with raised curbs.	City of Sevierville (Sec. 4.6.3.10)	Sample Regulation 4: Parking islands shall be designed for rain garden to receive stormwater runoff from impervious parking surfaces.
	Where parking facilities or any other vehicular use areas are provided, they shall have concrete curbs to prevent vehicles from overhanging adjacent property or landscaped areas	City of Ruston (Sec. 5.5.3.G)	

Sample Regulation 1 proposes permeable pavement sidewalks (Table 5.4, Figure 5.2). Permeable pavement is one type of GSI, an alternative for paved surfaces, such as sidewalks and parking lots. There are several types of permeable pavement alternatives for sidewalk use. For this study, permeable concrete pavement was considered. The pavement's effective CN was estimated based on its layers' potential maximum water storage (Table 5.3). Therefore, simulations under Sample Regulation 1 were performed by assigning the effective CN of permeable concrete to the corresponding area of the sidewalks. The resulting runoff peak flows for the site at each city are shown in Figure 5.3.

Because Sample Regulation 1 did not result in significant decreases in peak flows, another approach was considered. This approach designated a portion of the landscape for a rain garden, per Sample Regulation 2 (Table 5.4). Because the rain garden's size is fixed in this regulation to 15% of the landscape (in the case of the hypothetical site, 2.5% of the total area) the runoff amount that the rain garden can handle depends on the magnitude of the design storm. When the storm magnitude is low, the rain garden would receive and store runoff from a larger impermeable area. In contrast, when the storm magnitude is high, the rain garden would handle runoff from a smaller impermeable area.

The third sample regulation proposed to cover 25% of the paved area with permeable pavement (Table 5.4). Covering 25% of the parking area, which is 17,657 ft^2 (1,640 m^2, Figure 5.2), with permeable concrete was assumed for this analysis.

A fourth sample regulation was recommended, proposing the use of small rain gardens as parking islands that receive stormwater runoff from the surrounding impermeable parking surfaces, eliminating curbs (Table 5.4). Based on their locations, ten parking islands were selected for installation of the rain gardens (Figure 5.2).

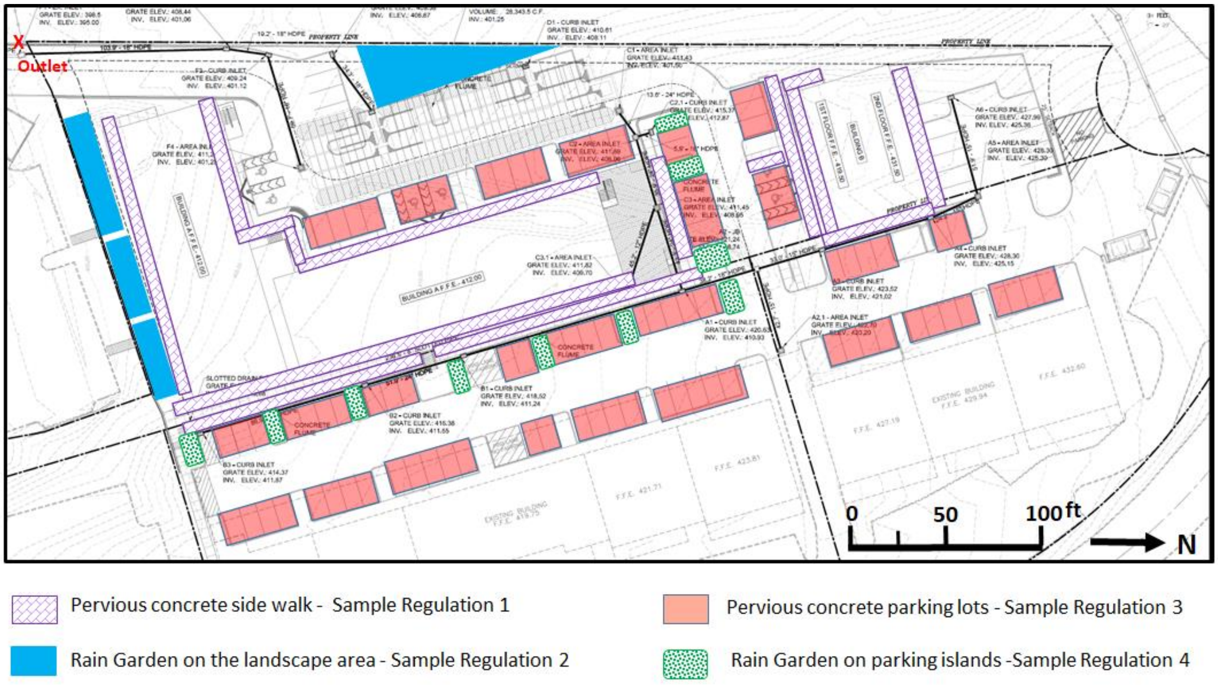

Figure 5.2. Plan view of the study site with possible locations for the implementation of the GSI required by the sample regulations. The site outlet is in the southwest corner, shown by the red X. This figure also shows the potential gray infrastructure collection and detention systems.

5.4 RESULTS

5.4.1 Ordinance Review

The ordinance review revealed the differences among stormwater management requirements for the municipalities. Those requirements are presented in this section.

Biloxi's ordinance promotes stormwater best management practices (BMPs) that emphasize infiltration and storage. The city puts a greater emphasis on GSI than the other cities by providing permeable pavement alternatives. Biloxi also provides detailed standards and requirements with tables and figures, which are easy to understand and interpret. For example, dimensional standards for parking spaces with different orientations are provided with a table and figure (Article 23-6-3 (D) Table 23-6-2(G) (1)). Also, several incentives and sustainable development options for earning points towards LEED certification are offered in the ordinance, as shown in Table 2. These sustainable development designs include parking area reduction, vehicular use area landscaping, permeable surfacing material, rain gardens, and site configuration (Table 23-6-12(B)) (City of Biloxi, 2021).

Oxford provides detailed design requirements for stormwater management facilities (detention, retention, underground basins, and outlet control structures). These requirements include the magnitude of design storms, time of concentration, and method for runoff analysis, which the other cities do not specify. Few GSI options are provided in the ordinance as a form of alternative to gray infrastructure. For instance, the city recommends a GSI alternative of replacing up to 15% of landscaping requirements with permeable surfaces on areas of limited use such as parking spaces and sidewalks (Sec. 5.7.3.5)(City of Oxford, 2021). Also, the term low impact design (LID) is used, which is a similar term to GSI. However, the ordinance doesn't set these alternatives as a mandatory implementation.

Calhoun's Zoning Ord. Sec. 11.3.1(a)(3), requires the impermeable area of a site to be less than 30 percent of the total area to obtain a building permit for any residential lot or apartment complex (City of Calhoun, 2011). Calhoun encourages “better site design practices” to preserve green space. Orange Beach’s ordinances do not call specifically for use of GSI but state that exfiltration/infiltration systems may be used, upon approval, for containing stormwater, including for volumes exceeding the design retention capacity. In addition, Orange Beach provides an alternative for the vehicle use area requirement. The regulation requires vehicle use areas to be constructed of impermeable materials, such as concrete, asphalt, brick, and cement pavers, allowing alternatives, such as gravel, crushed shells, or turf, based on traffic intensity and use (City of Orange Beach, 2020). Sevierville’s ordinances also do not call specifically for the use of GSI but state that structural stormwater control measures can include pervious areas for infiltration. Sevierville’s ordinances have a high focus on water quality in addition to quantity (City of Sevierville, 2013). For the city of Ruston, our research did not find regulations that apply to the study site, although the city’s ordinances suggest swales with native grasses for parking lot runoff (City of Ruston, 2020).

Overall, the ordinance review showed that only two municipalities (Biloxi and Oxford) mention GSI as alternatives, and none of the studied cities had GSI requirements. The language used in the municipal ordinances plays a vital role in the implementation of GSI.

5.4.2 Baseline Hydrologic Analysis

The baseline scenario analysis was performed by simulating the pre-development and post-development conditions of the study site. The pre-development simulation, which is before the construction of the project, was simulated using the land cover shown in Figure 5.1(a) and the predominant soil group in that city. The post-development simulation was done by implementing the proposed development design shown in Figure 5.1(b), at first using a scenario without any stormwater management infrastructure. Since all municipalities require reducing the post-development peak flow rate to less than or equal to the pre-development peak flow rate, evaluating the results of these two simulations will convey to a designer the amount of water that has to be controlled after development. The simulation results showed that the post-development peak flows were higher by 55 to 131% from the pre-development, depending on the city (see blue and gray bars in Figure 5.3). This increase in peak flows was a result of the land cover change from the natural permeable surface to impermeable surfaces. The CNs increased as shown on Table 3, columns 4 and 5. The difference in the range of increased peak flows is due to the cities' different prevalent soil groups and design storm magnitudes.

To show the effect of proposed municipal regulations on the implementation of GSI and peak runoff reduction, additional analyses were performed by incorporating sample GSI regulations into the hydrologic model. The sample regulation analysis and results are discussed in the following sub-section.

5.4.3 Hydrologic Analysis Incorporating Sample Ordinances

The rainfall-runoff simulation results due to the sample regulations are presented in this section. The simulations were performed by implementing the GSI required by the sample regulations in each city. A total of twenty-four simulations were run for four sample regulations and six cities.

5.4.3.1 Sample Regulation 1: All sidewalks should be covered by permeable surfacing.

Based on Sample Regulation 1 simulation results, the peak runoff was reduced by an average of 1.3% from the post-development scenario (compare gray and yellow bars in Figure 5.3). The peak flows resulting from this regulation, however, did not meet the pre-development peak flow requirement. All of the peak flows for post-development with permeable sidewalks were higher than the pre-development peak flows. Therefore, permeable pavement alone would not meet the cities' current ordinance requirements for the post-development peak flow to be below the pre-development peak flow.

Each city performed differently for this sample regulation. For instance, even though the CN of Sevierville was higher than the other municipalities' (Table 5.3), this site had the second largest percent reduction in peak flow (1.5%), with Calhoun showing the largest percent reduction (2.4%). Ruston showed the least percent reduction (0.62%). This variation is a result of the different design storm magnitudes and soil groups among the cities (Table 5.2).

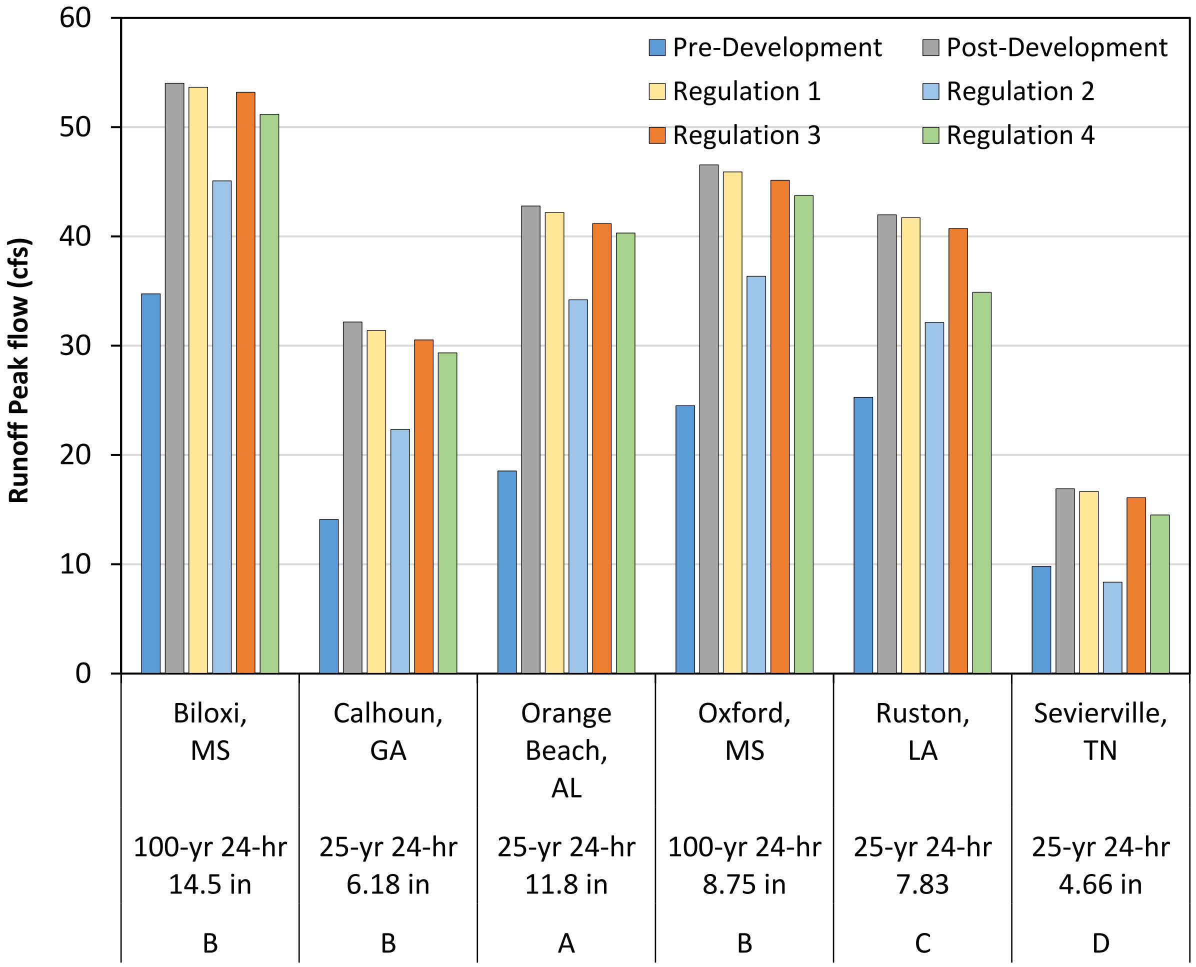

Figure 5.3. Simulation results of pre- and post-development (no stormwater control) and the application of Sample Regulations 1 through 4. The horizontal axis shows the cities, their design storms, and their predominant soil group. (10 cfs = 0.28 m^3/s)

5.4.3.2 Sample Regulation 2: 15% of the landscape area should be designated for a rain garden that receives water from impermeable surfaces.

Using the model with the rain gardens, the rainfall-runoff simulation results showed that the runoff peaks were reduced from the post-development peaks by 27% on average, as shown by the gray and light blue bars in Figure 5.3. Except for Sevierville, the cities' peak flows still were higher than the pre-development peak flow. Sevierville showed a peak flow 15% lower than the pre-development. As mentioned earlier, the municipalities require the stormwater detention/retention facilities to be designed to maintain the pre-development peak flow. In the case of Sevierville, rain gardens alone would reduce the flow to below the pre-development peak flow, rendering other gray infrastructure, such as detention and retention facilities, necessary only for storm magnitudes higher than the 25-year 24-hr storm.

5.4.3.3 Sample Regulation 3: Permeable surfacing materials should be used to cover a minimum of 25% of the paved area. If more than 25% of the area is covered, a permit fee waiver will be granted.

For Sample Regulation 3, 25% of the parking area was assumed to be covered by permeable concrete. After covering the parking spaces with permeable concrete in the model, the peak flow was reduced on average by 3.5% from the post-development peak flow (compare gray and orange bars in Figure 5.3). Even though the peak is lower than the post-development scenario, it did not reach below the pre-development peak flow. On average, the resulting peak flow was 84% higher than the pre-development scenario. This result tells us that the site still needs a detention or retention structure to handle the remaining flow to meet the pre-development peak flow requirement.

5.4.3.4 Sample Regulation 4: Parking islands must be designed for rain gardens to receive stormwater runoff from impermeable parking surfaces.

After applying Sample Regulation 4 to the model of the study site, the peak flow was reduced by 9.5% (compare gray and green bars in Figure 5.3). The simulation results for this sample regulation showed that all of the cities' peak flows were higher than the pre-development. However, this regulation showed the second-highest reduction compared to the other regulations.

The rainfall-runoff analysis results showed that when municipalities incorporate GSI in their ordinances, the study site's runoff peak flows decrease. The peak flow reductions ranged from 1.3 to 27%, depending on the regulations modeled. Sample Regulations 2 and 4 showed relatively higher reductions. Both regulations are based on the implementation of rain gardens on the study site. The other two regulations considered the installation of permeable concrete pavement on paved areas. Adding rain gardens on the study site showed a greater peak flow reduction than adding permeable concrete. Rain gardens, while not occupying a large area, are deeper than permeable pavement and can store more stormwater underground.

5.4.3.5 Effects of Sample Regulations on Smaller, Frequent Storms

All of the previous analyses were performed based on the large design storms of the cities (25- or 100-year storms shown in Table 2). For example, the design storm magnitude for Biloxi is 14.5 in, which is a 100-year 24-hour storm. However, by definition, cities mostly experience smaller, more frequent storm events known as 1-year and 2-year storms, or even smaller storms. For example, for Biloxi, the 1-year and 2-year 24-hr storms are 4.93 in (122 mm) and 5.84 in (148 mm), respectively. Therefore, additional simulations were performed to analyze how the sample regulation would perform for 1- and 2-year 24-hr storm events. This analysis was conducted based on the implementation of Sample Regulation 2. This regulation was selected because of its high performance on the design storm analysis. Since the area of the rain garden was fixed in the proposed regulation, the impermeable area that drains into the rain garden was adjusted based on the magnitude of the 1- and 2-year storms applicable to each city. This adjustment was made in HydroCAD to use the available storage of the rain garden effectively for different storm magnitudes.

For 1- and 2-year storms, the simulation results showed that the percent reductions in the peak flows were greater than the reductions from the design storm scenarios (Table 5). For the 1-year storm, the highest peak flow reduction from the post-development scenario was 98%, and the lowest was 50%. The peaks were, on average, 69% higher than the pre-development peak. For the 2-year storm, the peak was less than the post-development peak by 51% on average, and it was higher than the pre-development by 67%. Just as occurred for the design storm analyses, Sevierville showed the highest reduction for both storm events, and the peak flows were less than the pre-development. Since every city had the same size rain garden for the simulation, the variation of the peak flows results from the difference in the magnitude of the storms and the soil groups.

5.5 DISCUSSION

Cities with lower magnitude design storms and low permeability soils benefitted more from GSI. And rain gardens were more efficient than permeable pavement for reducing runoff.

Based on the results of the rainfall-runoff analysis for the sample regulations, cities benefited from GSI at different levels. For example, Sevierville and Calhoun had the greatest peak flow reductions in most cases, and Biloxi showed the least reductions. There was a 1% to 35% difference between the greatest and the least reductions, depending on the four sample regulations. Considering the different input variables, these differences result from the design storm magnitude and the hydrologic soil group variability. The hydrologic soil group of Sevierville is Group D, which has high runoff potential and relatively low infiltration rate and consists of clay soils. Even though soil Group D has high runoff potential, the runoff from Sevierville was the lowest for most of the scenarios. That is because the city has a less intense design storm, 4.66 in/hr (118.4 mm/hr). Calhoun and Biloxi's hydrologic soil group is Group B, which has a moderate infiltration rate and runoff potential. The only difference between these two cities was the design storm magnitude. Accordingly, similar to Sevierville, Calhoun showed a higher reduction in peak flow due to the city's less intense design storm magnitude compared with Biloxi. Therefore, based on this analysis, we can conclude that municipalities with lower magnitude design storms and low infiltration soils have the most to benefit from GSI and could benefit from ordinances requiring GSI.

Rain gardens were more effective at decreasing runoff than permeable pavements. Comparing the HydroCAD modeling results by sample regulations based on their average peak flow reduction, the highest reductions were shown with Sample Regulations 2 and 4 (both call for rain gardens), and the lowest with Sample Regulations 1 and 3. In general, installing a rain garden showed a greater reduction in peak flow than using permeable concrete over a greater area. For instance, for Sample Regulation 1, permeable concrete was used on an area of 7,525 ft^2 (699 m^2), and for Sample Regulation 2, the rain garden was 4,080 ft^2 (379 m^2). Despite the permeable concrete being applied to a larger area than for the rain garden, the runoff reduction from the rain garden was greater. Therefore, for this analysis, rain gardens are more effective at reducing post-development runoff than permeable pavement, even when applied to a smaller area.

Permeable concrete pavements showed a greater peak flow reduction when they covered a larger area. For instance, Sample Regulations 1 and 3 proposed implementing permeable pavements for sidewalks and parking areas. Permeable concrete pavement of 7,525 ft^2 (699 m^2) and 22,070 ft^2 (2050 m^2) was used to implement Sample Regulations 1 and 3, respectively. The peak reductions under Sample Regulation 3 were higher than Sample Regulation 1 for all of the cities. But the reduction was not uniform due to the different storm magnitudes of each municipality. To reduce the same runoff volume, a larger surface area of permeable concrete is required for a high-intensity storm compared to a low-intensity storm. The most effective permeable pavement coverage design should be based on a range of storms that a particular city experiences (Abera et al., 2018). Therefore, municipalities should take their storm magnitude and the soil group into consideration to select and incorporate the more effective type of GSI in their ordinances.

The results of the HydroCAD modeling of the 1- and 2-year storms show that rain gardens per Sample Regulation 2 alone can infiltrate stormwater runoff from those storms without the need of other gray stormwater infrastructure. Table 5 shows these results for the cities' design storm and 1- and 2-year storms. Focusing first on the cities of Biloxi, Calhoun, Orange Beach, and Ruston, we see that the Sample Regulation 2 peak flows for the smaller storms are well below the pre-development peak flow for the design storms (which for Biloxi, for example, are 8.51 and 12.04 cfs for the 1- and 2-year storms, respectively, compared to 34.75 cfs for the design storm). Additionally, Sample Regulation 2 succeeds in Sevierville, which requires a stormwater outlet structure to control a 1-year storm, in addition to the design storm; Sample Regulation 2 peak flows for 1- and 2-year storms (0.17 and 1.42 cfs) are within the 1-year pre-development requirement of 3.39 cfs. However, Sample Regulation 2 does not meet Oxford's requirements to control a 2-year storm, in addition to the design storm; Sample Regulation 2 peak flows for the 1- and 2-year storms in Oxford_(10.35 and 13.17 cfs, respectively) exceed that city's 2-year pre-development limit of 7.36 cfs. These results show that while GSI might not alone meet runoff requirements for the extreme design storms, GSI can comfortably meet the runoff requirements for 1- and 2-year storms for most cities.

GSI is just one element of controlling stormwater flow. Even though Sample Regulation 2 showed the highest peak flow reduction, the resulting peak flow for the design storm was higher than the pre-development for all of the cities, except Sevierville. This result shows that GSI must be combined with other stormwater gray infrastructure, such as detention/retention facilities, to meet the pre-development peak flow requirement. Using GSI will allow smaller detention facilities to be employed than without GSI. This will reduce the construction and installation costs, wear and tear, and maintenance on those gray stormwater structures, as well as offering the ecological benefits of mimicking the natural hydrologic cycle.

Table 5.4. Sample Regulation 2 peak flow results for the smaller, more frequent storm events.

City	**Design Storm**				**1-Year Storm**				**2-Year storm**			
	Magnitude (in)	**Peak flow (cfs)**			**Magnitude (in)**	**Peak flow (cfs)**			**Magnitude (in)**	**Peak flow (cfs)**		
		Pre-dev.	**Post-dev.**	**Sample Reg. 2**		**Pre-dev.**	**Post-dev.**	**Sample Reg. 2**		**Pre-dev.**	**Post-dev.**	**Sample Reg. 2**
Biloxi, MS	14.5	**34.75 *[4]**	54.02	45.08	4.93	7.00	17.17	**8.51**	5.84	9.44	20.73	**12.04**
Calhoun, GA	6.18	**14.10**	32.17	22.35	3.29	4.16	15.73	**5.83**	3.78	5.67	18.55	**8.62**
Orange Beach, AL	11.8	**18.54**	42.78	34.21	5.01	2.58	16.15	**7.76**	5.92	4.26	19.77	**11.20**
Oxford, MS	8.75	24.52	46.55	36.36	3.72	5.61	18.20	**10.35**	4.25	**7.36**	21.23	**13.17**
Ruston, LA	7.83	**25.27**	41.98	32.13	3.90	9.41	20.02	**10.33**	4.41	11.41	22.90	**13.07**
Sevierville, TN	4.66	9.81	16.92	8.36	2.31	**3.39**	7.73	**0.17**	2.75	4.54	9.47	**1.42**

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[4] Numbers in bold are used for comparison.

5.6 CONCLUSIONS AND RECOMMENDATIONS

This paper addressed four objectives. It first examined how municipal ordinances may help or hinder the implementation of GSI. A review of the ordinances from six cities found that they do not require, though some encourage, GSI. The second objective was to quantify the runoff due to design storms set by city ordinances. The third objective was to suggest regulations encouraging GSI implementation to reduce runoff. This objective was achieved by developing four sample regulations. The fourth objective was to quantify the runoff reduction based on the sample regulations. This objective was met by conducting rainfall-runoff, implementing the sample regulations on the study site, and then comparing them.

Overall, based on the simulation results for different scenarios, it can be understood that requiring GSI in municipal ordinances can reduce peak runoff from a development site. For both the design storm and more frequent storm analyses, the runoff peaks were reduced after implementing the GSI on the proposed study site in the different cities. Even though the reductions varied from city to city due to the magnitude differences of the storms (design, 1-year, and 2-year) and the soil groups, the HydroCAD modeling for all of the municipalities showed a reduction in the runoff peak flow when GSI was applied.

General conclusions include: (1) municipalities with lower magnitude design storms and low infiltration soils have the most to benefit from GSI and could benefit from ordinances requiring GSI; (2) rain gardens were more effective at decreasing runoff than permeable pavements; (3) for 1- and 2-year storms, GSI alone can meet the pre-development design storm peak flow requirements in many cases; and (4) GSI must be complemented by gray infrastructure to control storms of higher magnitudes.

Based on these conclusions, we offer the following recommendations:

- Most of the GSI-like terms found in the municipal ordinances are recommendations rather than requirements. Therefore, implementing GSI is at the developer's discretion. Likely the recommendations will be implemented only if the developer wants to benefit from some of the incentives, for instance, to gain some points for LEED certification, or have a reduced permit fee. Therefore, municipalities should require GSI regulations to maximize runoff reduction while gaining environmental benefits.

- Municipalities should consider the hydrologic soil group of the site and the design storm magnitude when deciding on the size and type of the GSI. Our study showed the same site plan and regulations will yield different results due to soil types.

- When applied to the same area, rain gardens offer a greater runoff reduction than permeable pavements, making them useful when size is limited on a site.

- Overall, incorporating GSI in municipalities' regulations showed a reduction in peak flow of runoff. Therefore, municipalities have the potential to reduce local flooding by designing GSI in their new developments or retrofits.

5.7 ACKNOWLEDGMENTS

The authors thank Steve Brunton of the City of Oxford, Mississippi, USA, for assistance with the modeling. We thank Kit Alexander of the City of Orange Beach, Alabama, and Kristin Greger and Rick Stickler of the City of Biloxi, Mississippi for their perspectives on city ordinances and challenges. The research reported in this manuscript has been partly funded through the U.S. Department of Commerce's National Oceanic and Atmospheric Administration under NOAA Award NA18OAR4170080 and the Mississippi-Alabama Sea Grant Consortium. The authors thank four anonymous reviewers who provided detailed comments to the earlier version of this article.

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CHAPTER 6

6 CONCLUSION

6.1 OVERVIEW OF FINDINGS

This research aimed to analyze implementation barriers of GSI, specifically focusing on site-scale developments. Three implementation barriers: technical, financial, and regulatory, were analyzed at the site scale level, considering different site designs.

Hydrologic performance analyses of three GSIs were conducted using a computer simulation to analyze the technical barriers. The analysis was performed for three development sites; mixed-use, commercial, and housing, based on the four hydrologic soil groups (A, B, C, and D). From this analysis, runoff peak and volume were estimated. Since the soil groups are defined by curve number (CN), model sensitivity was tested to evaluate the implication of the CN change on the resulting runoff.

The hydrologic performance of GSI varied for each soil group and site design. Implementing GSI on a site located on soil group A reduced the runoff higher than in the other soil groups. A site design with a large impermeable land cover requires a larger-scale GSI to reduce the stormwater runoff. Even though the magnitude is different, all GSIs showed peak flow and runoff reduction. Rain gardens, in particular, showed the highest reduction than permeable concrete and grassy ditch. The efficacy of incorporating green stormwater infrastructure in urban developments depends on the choice of infrastructure and the underlying soil type.

Financial barriers were analyzed by conducting LCCA and BCA of GSI. For this analysis, the mixed-use development site was used. The LCCA included the capital and maintenance costs related to the implementation of GSI. After the whole LCCs of the three GSI were estimated, the PVCs of each scenario were estimated considering a design period of 30 years. The BCA was conducted based on six benefit categories water, energy, climate change, air quality, health, and community. These categories were selected based on the CNT guideline to recognize the value of green infrastructure. Of the six benefits, the water category has the highest benefit due to the runoff reduction of the GSI.

Two approaches, internal rate of return (IRR) and benefit-cost ratio (BCR) were used to identify the most cost-efficient GSI alternative. Like the hydrologic performance, the rain garden has the highest benefit of the other GSI scenarios with the highest IRR and BCR. Rain garden is an optimal design that balanced the benefits and costs.

The third GSI implementation barrier analyzed in this research was regulatory. The analysis was performed by identifying barriers and incentives in the existing municipality ordinances. In this analysis, ordinances of six southeastern United States cities were compared, and modifications were suggested. Based on the modification, rainfall-runoff simulations were performed using the cities’ design storm, ranging from 4.66 to 14.5 inches in magnitude.

Municipalities with lower intensity design storms and low infiltration soils benefit most from GSI and could benefit from ordinances requiring GSI. Incorporating GSI practice in municipalities' regulations showed reduced stormwater runoff, potentially reducing local flooding. Even though GSI has been commonly implemented in large cities, small and medium-sized cities can also prevent excess stormwater by incorporating GSI in their ordinances for new developments and site retrofits.

6.2 CONTRIBUTIONS

GSIs are commonly applied on city or watershed scales. GSIs are not commonly implemented on site-scale developments due to economic, financial, and regulatory barriers. A thorough literature search showed a lack of research on analyzing the feasibility of GSIs' on-site scale developments. One of the main contributions of this study is analyzing the implementation barriers for GSI based on simulations of small development sites. The analyses were conducted based on implementing three GSIs on three site designs. Based on the analysis, cities can overcome GSI implementation barriers by selecting the type of GSI based on site-specific conditions.

Another contribution of this study is the site scale benefit-cost analysis, which is not commonly found in the literature. A spreadsheet that combined LCCA and BCA and included ranges of unit benefits and costs of GSI was provided. Developers can use this spreadsheet as a template to investigate the benefit-cost of their GSI options.

In addition, cities' ordinances were thoroughly reviewed, modifications were proposed, and these modifications were assessed by performing hydrologic analysis. This review is the first time such a study has been conducted. It is concluded that city regulators should include GSI as a requirement in their stormwater ordinances instead of a recommendation to encourage the application of GSIs on small-scale developments.

This research's findings are being shared with the public. Reports were submitted to partner cities and posted on the Mississippi-Alabama Sea Grant Legal Program website to outreach and educate the public. Chapter 5, the regulatory analysis, is published in the *Journal of Environmental*

Challenges. Chapter 3, the hydrologic performance of GSI, is submitted for publication. Chapter 4, the LCCA of GSI, is also in a final draft to submit for publication.

6.3 RECOMMENDATIONS FOR FUTURE STUDIES

The following suggestions are made based on the overall findings of this study.

- The hydrologic performance analysis of GSI was done with the HydroCAD rainfall-runoff simulation software. Which mainly depends on the CN of the site. The result might vary if other modeling software or methods are used. For comparison purposes, another rainfall-runoff analysis software is recommended for running the proposed GSI scenarios.
- The hydrologic performance analysis was based on implementing three GSIs (permeable pavement, rain garden, and grassy ditch). Analysis of implementing other GSI practices could provide additional information.
- The data used for the LCCA and BCA were found from different sources, mainly from peer-reviewed articles. To develop cost databases for site-scale implementation of GSI, researchers should collaborate with developers and track costs. In this study, due to limited data being available, only some of the possible benefits were estimated under each benefit category. Conducting research in collaboration with ecologists and economists would help to recognize more environmental benefits of GSI and develop a new approach to economic valuation.
- Most of the terms in the municipal ordinances recommend using GSI instead of requiring it. Therefore, implementing these alternatives depends on the developer's choice. Wording GSIs as requirements in ordinances will further promote their implementation at

a development site. Therefore, municipalities should revise the language used in their GSI regulations.

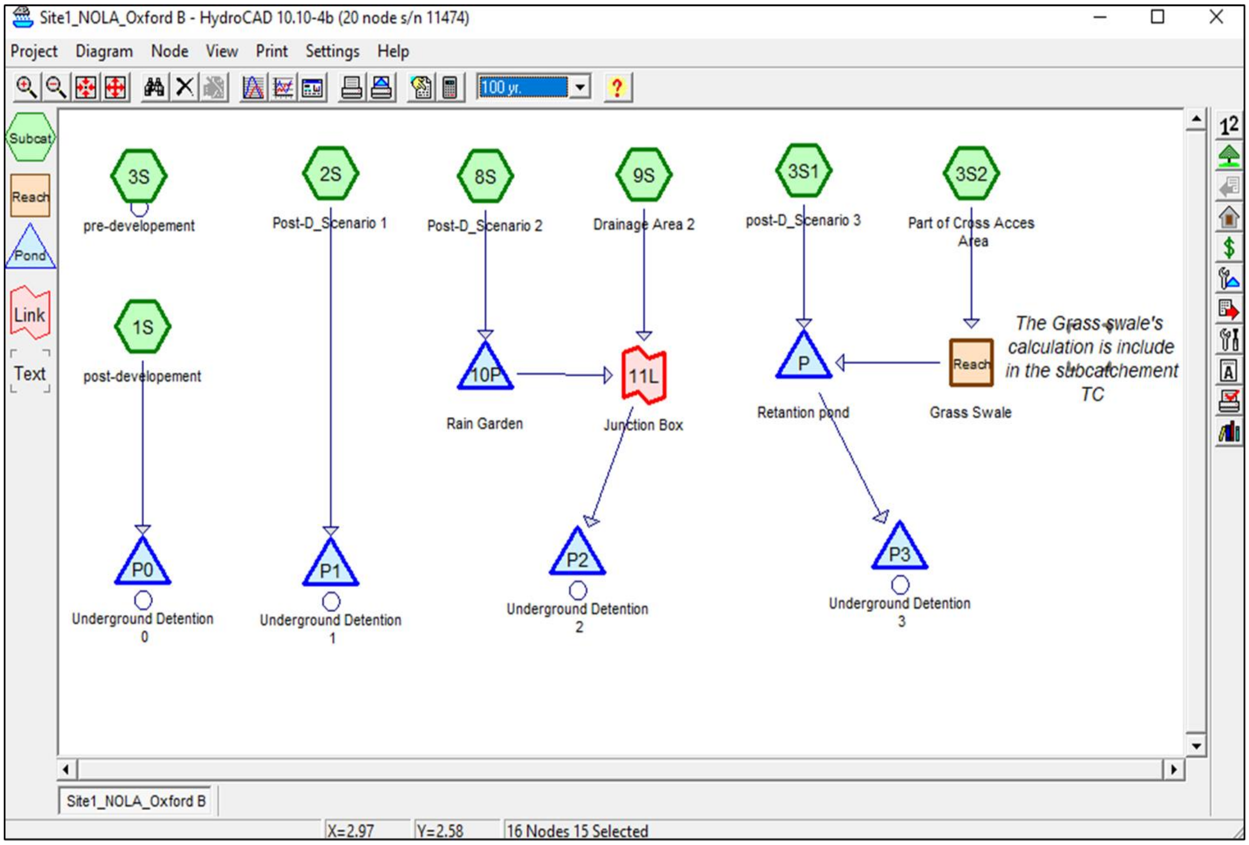
- Educating the public about the values of GSI on new developments or retrofitting sites would encourage and promote the implementation of GSI. The education can be done in collaboration with all responsible parties, such as educational institutions, developers, engineers, and the local community.
- Because GSI involves more vegetation, a recommended area for further research is GSI's potential benefits in curbing climate change by sequestering CO_2.

APPENDIXES

APPENDIX A: HYDROLOGIC PERFORMANCE ANALYSIS

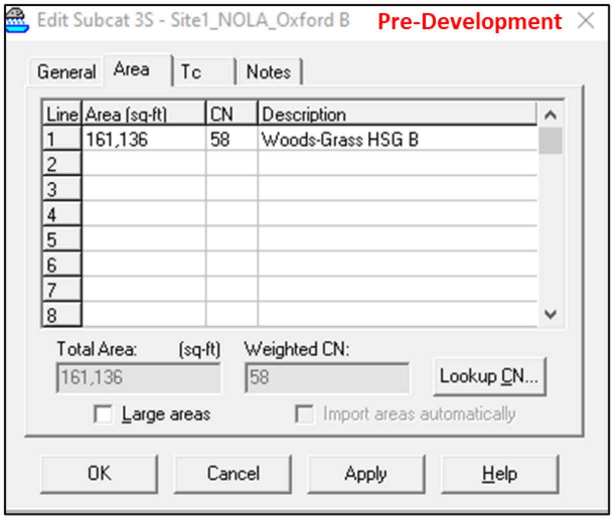
1. Site 1 Mixed- Development - Rainfall Runoff Simulations

- Simulation Layout on HydroCAD main window



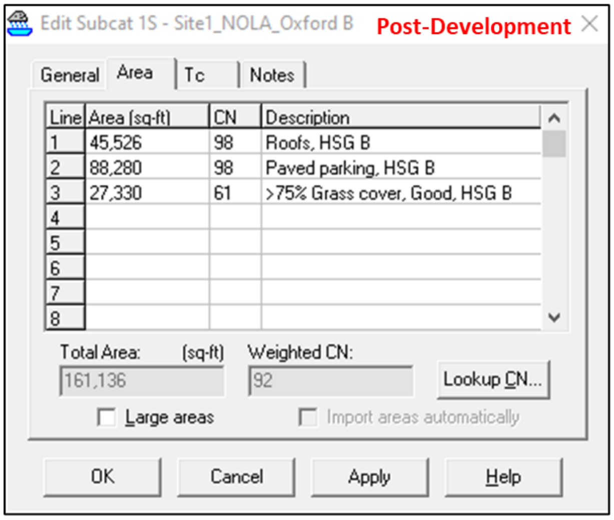
The Grass swale's calculation is include in the subcatchment TC

- Different landcover area and CNs, based on soil group B.



Line	Area (sq-ft)	CN	Description
1	161,136	58	Woods-Grass HSG B
2			
3			
4			
5			
6			
7			
8			

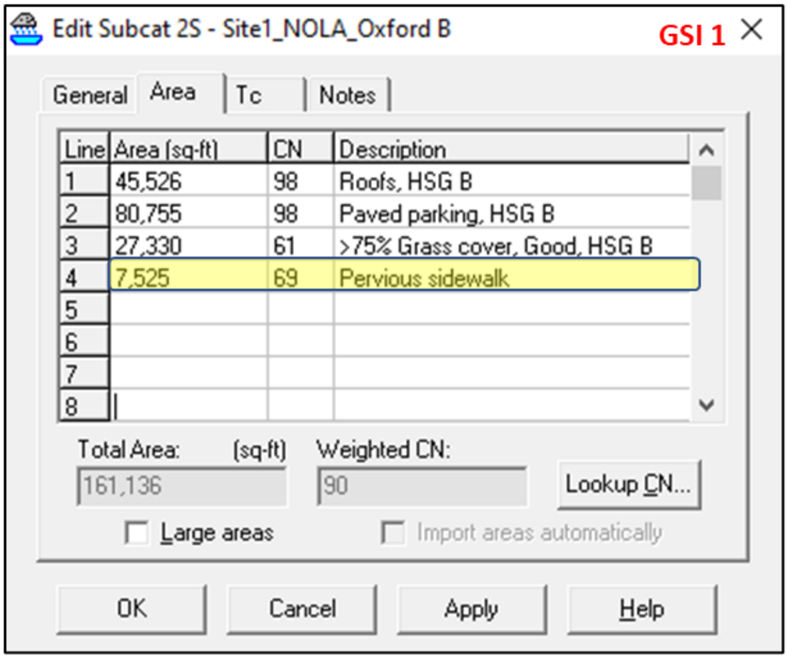
Total Area: (sq-ft) 161,136
Weighted CN: 58
☐ Large areas
☐ Import areas automatically



Line	Area (sq-ft)	CN	Description
1	45,526	98	Roofs, HSG B
2	88,280	98	Paved parking, HSG B
3	27,330	61	>75% Grass cover, Good, HSG B
4			
5			
6			
7			
8			

Total Area: (sq-ft) 161,136
Weighted CN: 92
☐ Large areas
☐ Import areas automatically

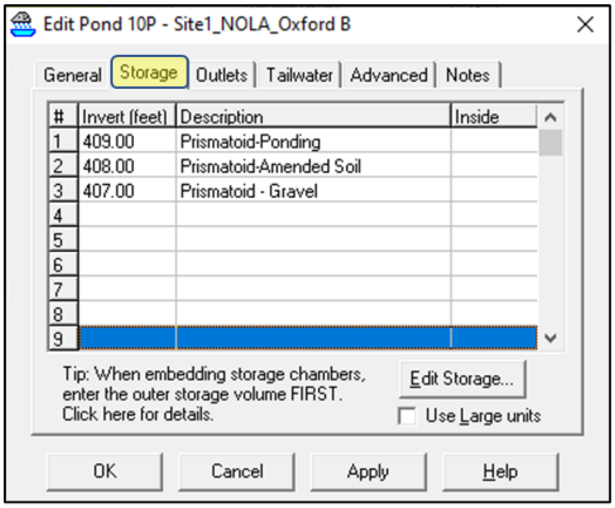
- The permeable pavement was defined on HydoCAD by changing the CN value.



Line	Area (sq-ft)	CN	Description
1	45,526	98	Roofs, HSG B
2	80,755	98	Paved parking, HSG B
3	27,330	61	>75% Grass cover, Good, HSG B
4	7,525	69	Pervious sidewalk
5			
6			
7			
8			

Total Area: (sq-ft) 161,136
Weighted CN: 90
☐ Large areas
☐ Import areas automatically

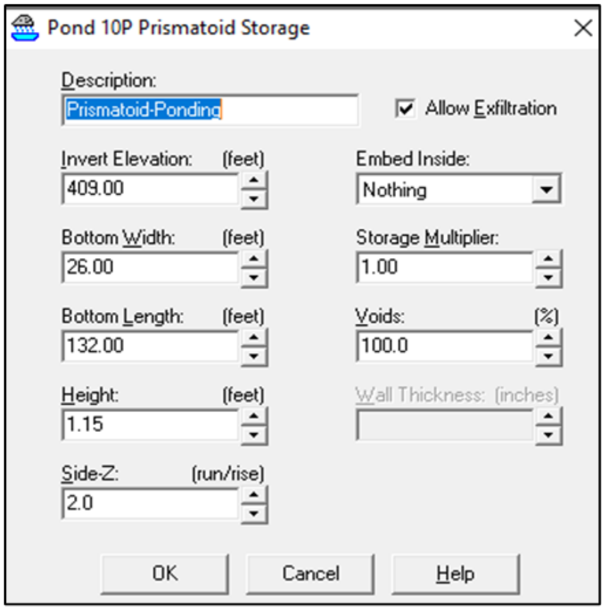
- Defining rain garden on HydroCAD - The storages were defined using a pond node.



#	Invert (feet)	Description	Inside
1	409.00	Prismatoid-Ponding	
2	408.00	Prismatoid-Amended Soil	
3	407.00	Prismatoid - Gravel	
4			
5			
6			
7			
8			
9			

Tip: When embedding storage chambers, enter the outer storage volume FIRST. Click here for details.

☐ Use Large units



Description: Prismatoid-Ponding

☑ Allow Exfiltration

Invert Elevation: (feet) 409.00

Embed Inside: Nothing

Bottom Width: (feet) 26.00

Storage Multiplier: 1.00

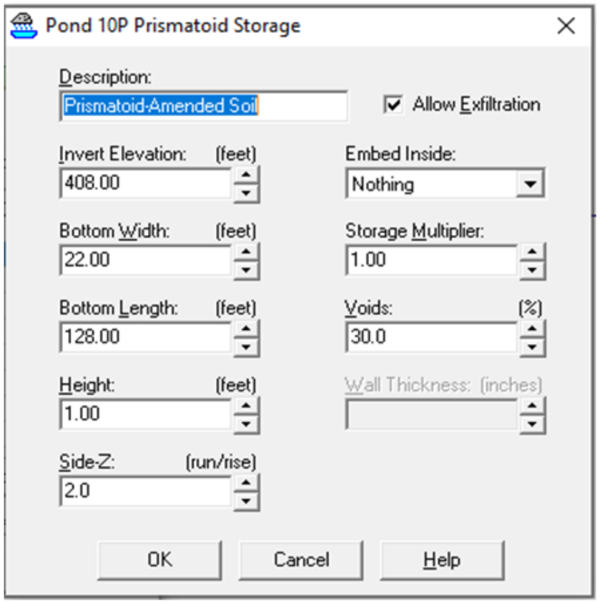
Bottom Length: (feet) 132.00

Voids: (%) 100.0

Height: (feet) 1.15

Wall Thickness: (inches)

Side-Z: (run/rise) 2.0



Description: Prismatoid-Amended Soil

☑ Allow Exfiltration

Invert Elevation: (feet) 408.00

Embed Inside: Nothing

Bottom Width: (feet) 22.00

Storage Multiplier: 1.00

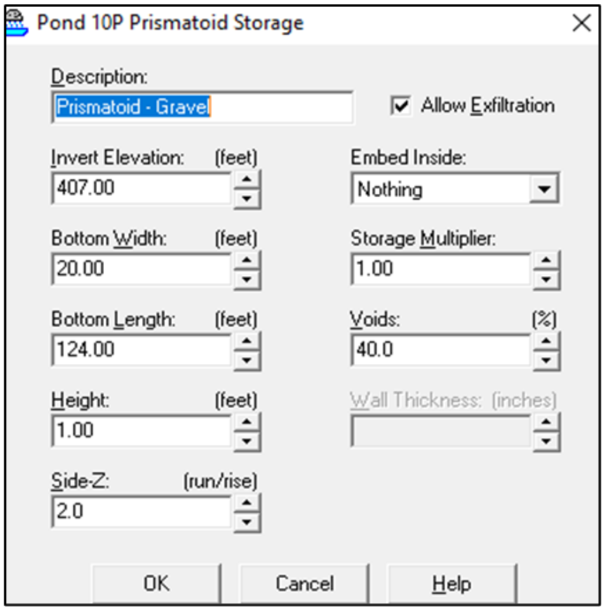
Bottom Length: (feet) 128.00

Voids: (%) 30.0

Height: (feet) 1.00

Wall Thickness: (inches)

Side-Z: (run/rise) 2.0



Description: Prismatoid - Gravel

☑ Allow Exfiltration

Invert Elevation: (feet) 407.00

Embed Inside: Nothing

Bottom Width: (feet) 20.00

Storage Multiplier: 1.00

Bottom Length: (feet) 124.00

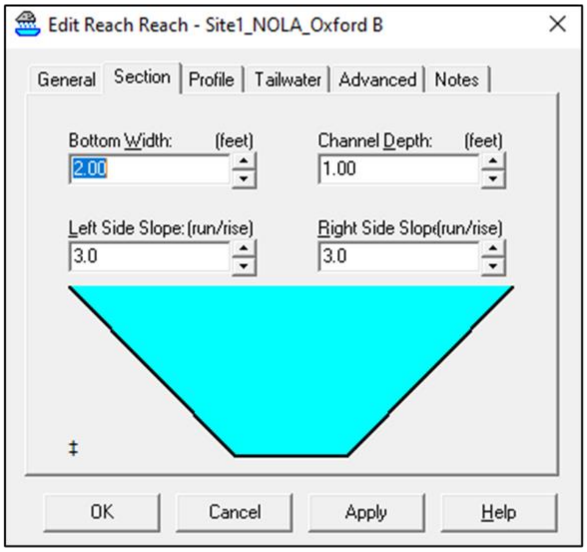
Voids: (%) 40.0

Height: (feet) 1.00

Wall Thickness: (inches)

Side-Z: (run/rise) 2.0

- Defining grassy ditch on HydroCAD - The grassy ditch was defined by using a reach node.



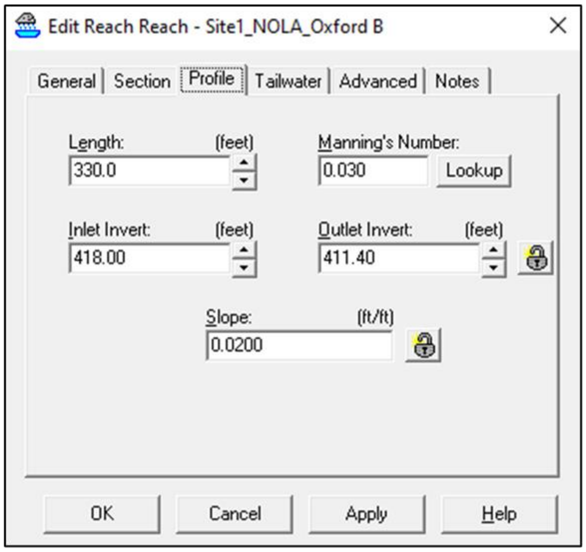
Edit Reach Reach - Site1_NOLA_Oxford B

Bottom Width: (feet) 2.00

Channel Depth: (feet) 1.00

Left Side Slope: (run/rise) 3.0

Right Side Slop(run/rise) 3.0



Edit Reach Reach - Site1_NOLA_Oxford B

Length: (feet) 330.0

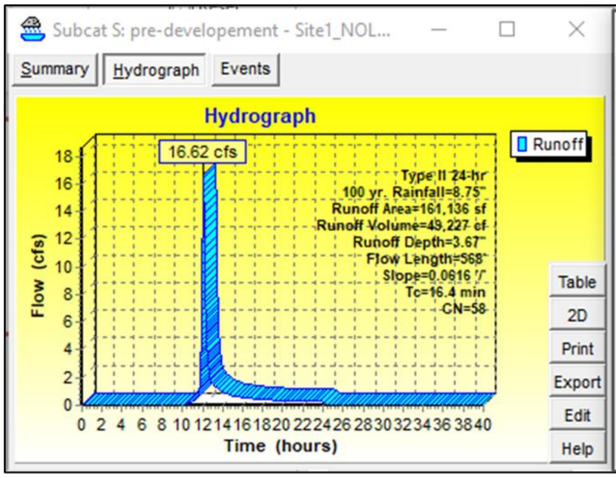
Manning's Number: 0.030

Inlet Invert: (feet) 418.00

Outlet Invert: (feet) 411.40

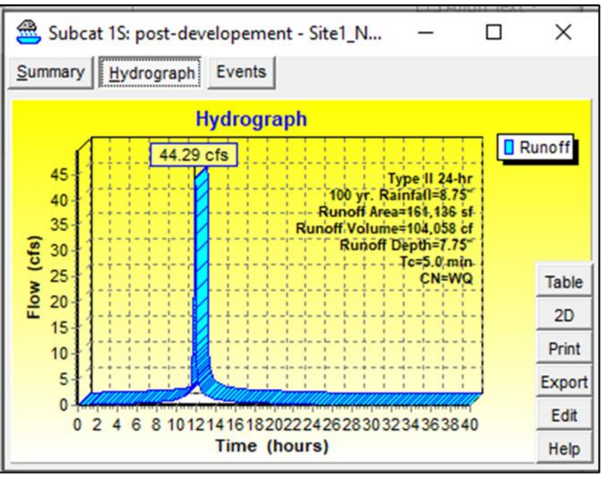
Slope: (ft/ft) 0.0200

- Pre- and Post-development Scenarios Hydrographs



Subcat S: pre-developement - Site1_NOL...

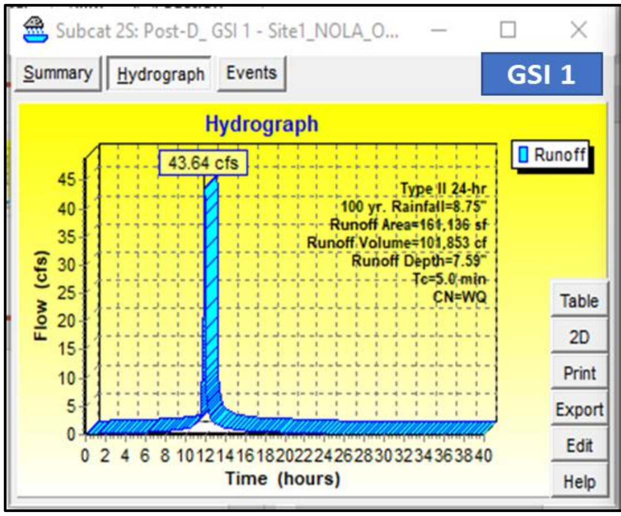
Type II 24-hr
100 yr. Rainfall=8.75"
Runoff Area=161,136 sf
Runoff Volume=49,227 cf
Runoff Depth=3.67"
Flow Length=568'
Slope=0.0616 '/'
Tc=16.4 min
CN=58



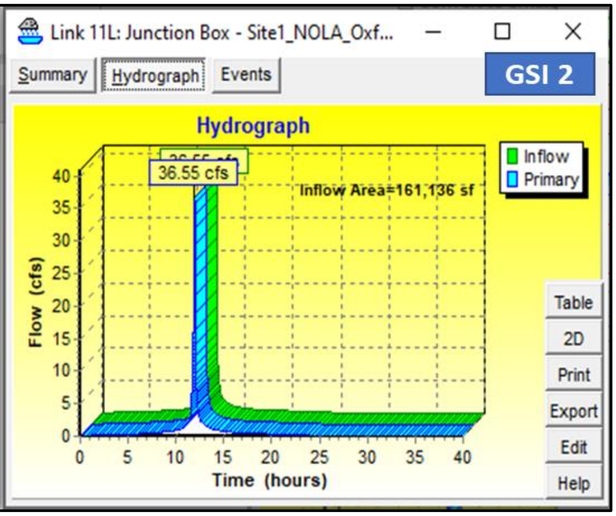
Subcat 1S: post-developement - Site1_N...

Type II 24-hr
100 yr. Rainfall=8.75"
Runoff Area=161,136 sf
Runoff Volume=104,058 cf
Runoff Depth=7.75"
Tc=5.0 min
CN=WQ

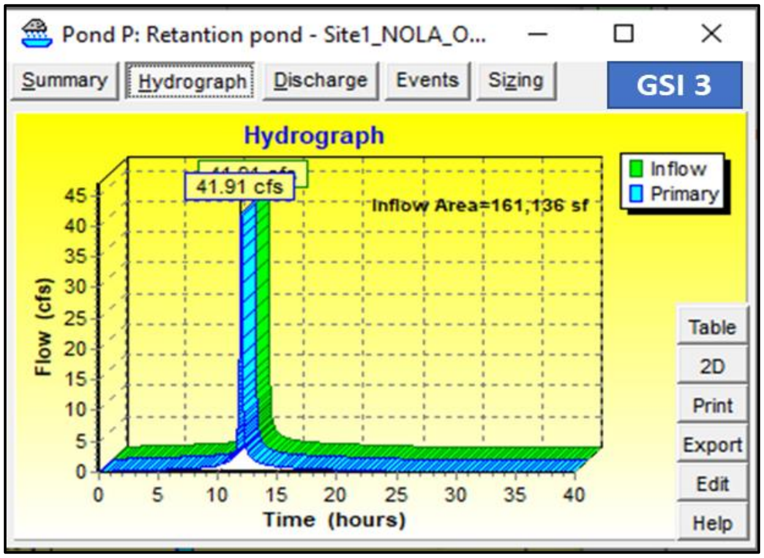
- GSI Scenarios Hydrographs



Type II 24-hr
100 yr. Rainfall=8.75"
Runoff Area=161,136 sf
Runoff Volume=101,853 cf
Runoff Depth=7.59"
Tc=5.0 min
CN=WQ



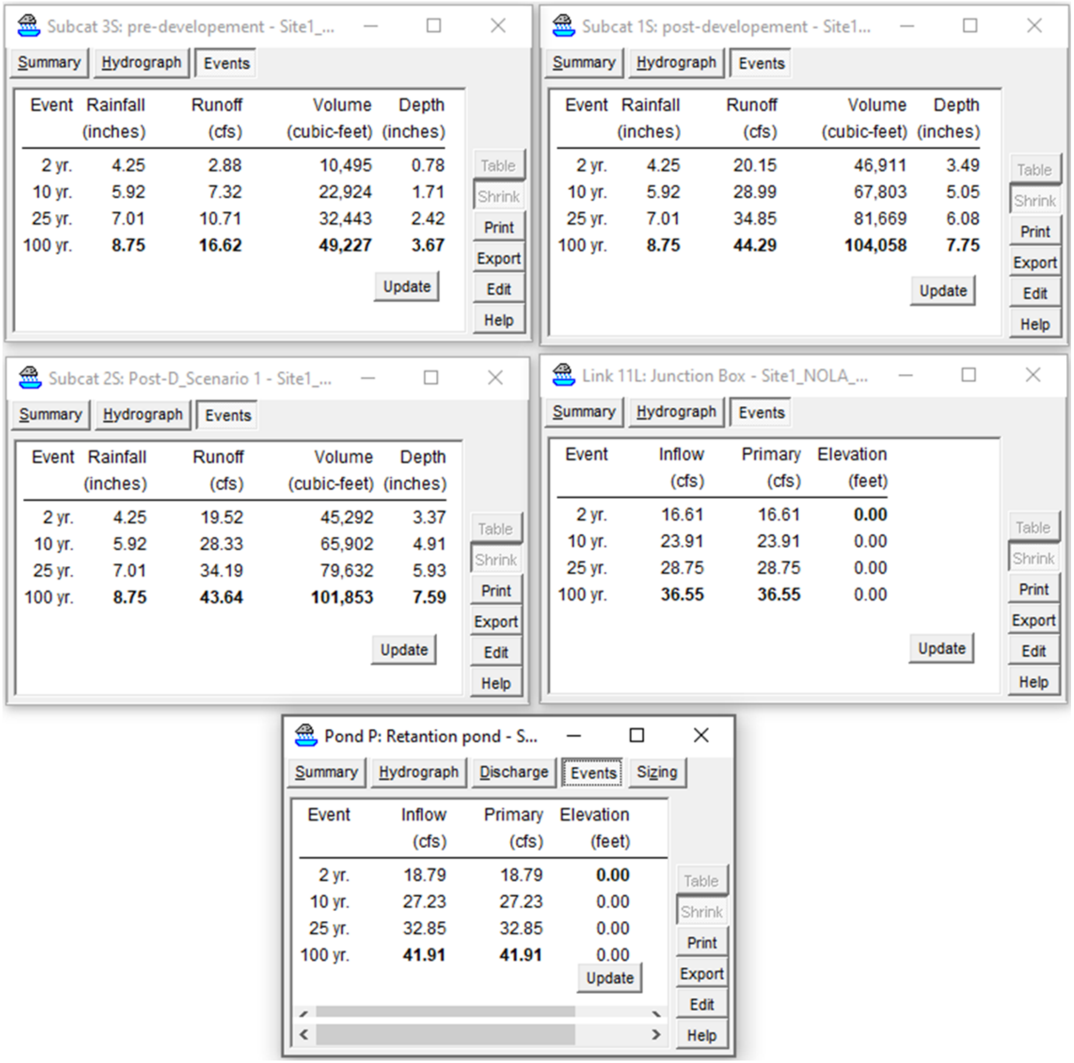
Inflow Area=161,136 sf



Inflow Area=161,136 sf

2. Simulation result summaries

- Simulation results for Site 1, Mixed-use development, based on Soil Group B. Below is screenshots from HydroCAD and a summary Table.



Subcat 3S: pre-developement - Site1_...

Event	Rainfall (inches)	Runoff (cfs)	Volume (cubic-feet)	Depth (inches)
2 yr.	4.25	2.88	10,495	0.78
10 yr.	5.92	7.32	22,924	1.71
25 yr.	7.01	10.71	32,443	2.42
100 yr.	**8.75**	**16.62**	**49,227**	**3.67**

Subcat 1S: post-developement - Site1...

Event	Rainfall (inches)	Runoff (cfs)	Volume (cubic-feet)	Depth (inches)
2 yr.	4.25	20.15	46,911	3.49
10 yr.	5.92	28.99	67,803	5.05
25 yr.	7.01	34.85	81,669	6.08
100 yr.	**8.75**	**44.29**	**104,058**	**7.75**

Subcat 2S: Post-D_Scenario 1 - Site1_...

Event	Rainfall (inches)	Runoff (cfs)	Volume (cubic-feet)	Depth (inches)
2 yr.	4.25	19.52	45,292	3.37
10 yr.	5.92	28.33	65,902	4.91
25 yr.	7.01	34.19	79,632	5.93
100 yr.	**8.75**	**43.64**	**101,853**	**7.59**

Link 11L: Junction Box - Site1_NOLA_...

Event	Inflow (cfs)	Primary (cfs)	Elevation (feet)
2 yr.	16.61	16.61	**0.00**
10 yr.	23.91	23.91	0.00
25 yr.	28.75	28.75	0.00
100 yr.	**36.55**	**36.55**	0.00

Pond P: Retantion pond - S...

Event	Inflow (cfs)	Primary (cfs)	Elevation (feet)
2 yr.	18.79	18.79	**0.00**
10 yr.	27.23	27.23	0.00
25 yr.	32.85	32.85	0.00
100 yr.	**41.91**	**41.91**	0.00

- Runoff Peak flows(ft^3/s)

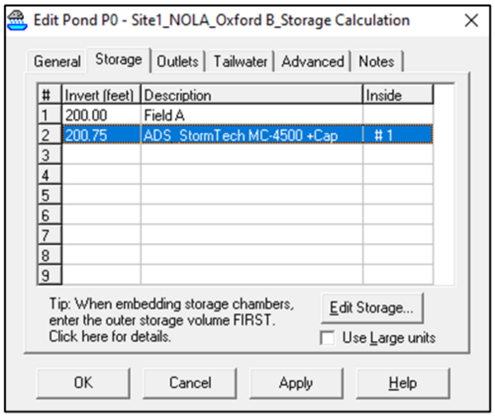
Site		**Site 1 (NOLA)**				**Site 2 (La Quinta)**				**Site 3 (Robinson)**			
Soil group		**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Runoff Peak (ft3/s)	**Pre-Development**	1.65	16.62	24.52	27.96	0.41	4.26	6.42	7.39	1.44	11.52	16.42	18.50
	Post-Development	41.05	44.29	45.95	46.60	18.56	21.38	22.82	23.38	13.12	17.27	19.48	20.27
	Scenario 1	40.22	43.64	45.37	46.08	17.99	20.93	22.42	23.03	–	–	–	–
	Scenario 2	32.91	36.55	39.93	41.51	17.11	19.99	21.84	22.35	10.04	14.31	17.17	18.47
	Scenario 3	38.71	41.91	43.53	44.17	18.24	21.00	22.40	22.94	10.13	13.08	15.02	15.79

- Runoff Volume (ft^3)

Site		**Site 1: Mixed-use Design**				**Site 2: Hotel Site**				**Site 3: Housing Development**			
Soil group		**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Runoff Volume (ft^3)	**Pre-Dev.**	10,560	49,227	71,952	83,385	5,390	25,128	36,728	42,564	4,816	22,450	32,814	38,028
	Post-Dev.	98,273	104,058	107,646	109,308	44,397	49,435	52,560	54,008	31,334	38,290	43,509	45,193
	GSI 1	95,689	101,853	105,593	107,408	42,617	47,916	51,146	52,699	–	–	–	–
	GSI 2	80,617	88,000	96,795	102,243	37,311	42,999	48,142	49,515	24,371	32,118	38,908	42,935
	GSI 3	98,273	104,058	107,646	109,308	44,397	49,435	52,560	54,008	31,334	38,290	43,508	45,193

3. Storage calculation on HydroCAD

- Advanced Drainage System (ADS)

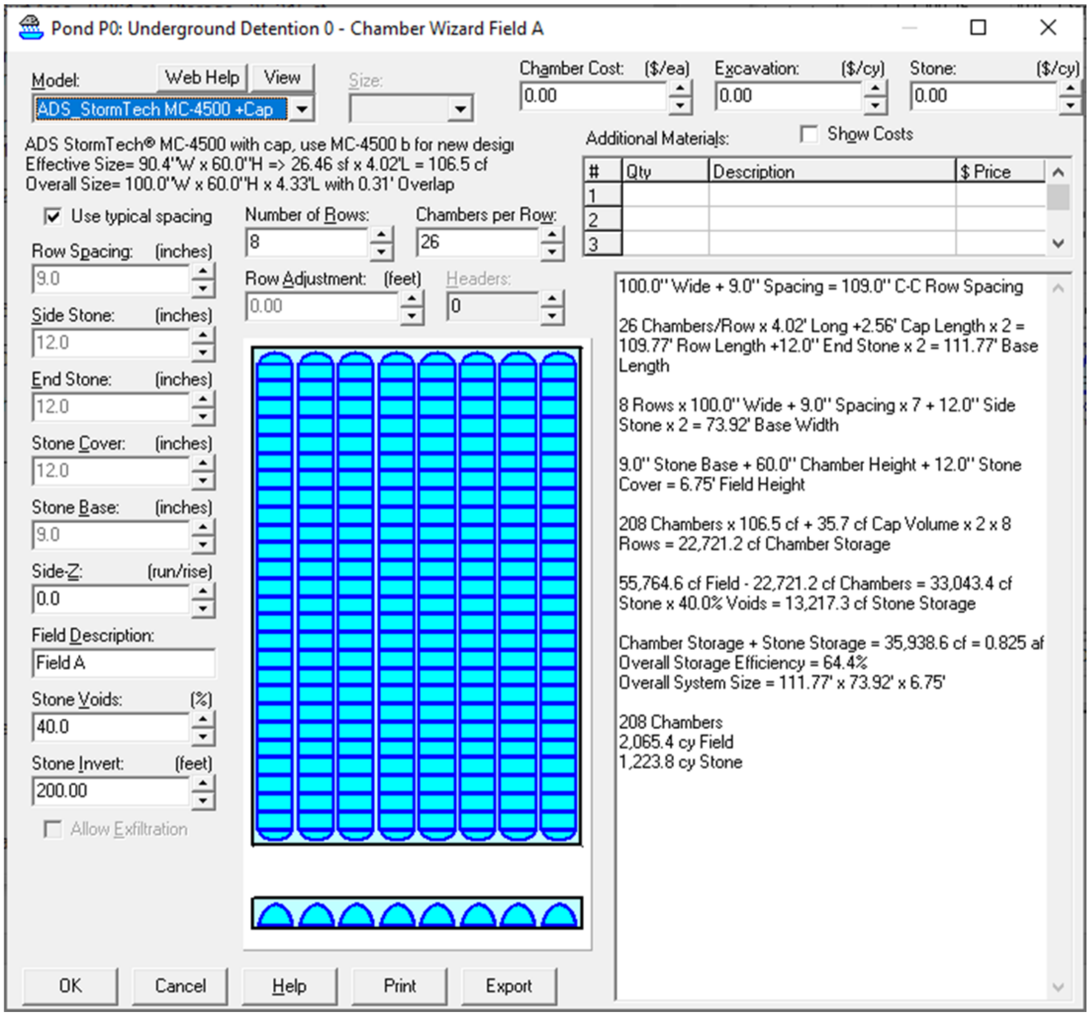


Edit Pond P0 - Site1_NOLA_Oxford B_Storage Calculation

#	Invert (feet)	Description	Inside
1	200.00	Field A	
2	200.75	ADS_StormTech MC-4500 +Cap	#1
3			
4			
5			
6			
7			
8			
9			

Tip: When embedding storage chambers, enter the outer storage volume FIRST. Click here for details.

☐ Use Large units



Pond P0: Underground Detention 0 - Chamber Wizard Field A

Model: ADS_StormTech MC-4500 +Cap

Size:

Chamber Cost: ($/ea) 0.00

Excavation: ($/cy) 0.00

Stone: ($/cy) 0.00

ADS StormTech® MC-4500 with cap, use MC-4500 b for new desig
Effective Size= 90.4"W x 60.0"H => 26.46 sf x 4.02'L = 106.5 cf
Overall Size= 100.0"W x 60.0"H x 4.33'L with 0.31' Overlap

Additional Materials: ☐ Show Costs

#	Qty	Description	$ Price
1			
2			
3			

☑ Use typical spacing

Row Spacing: (inches) 9.0

Side Stone: (inches) 12.0

End Stone: (inches) 12.0

Stone Cover: (inches) 12.0

Stone Base: (inches) 9.0

Side-Z: (run/rise) 0.0

Field Description: Field A

Stone Voids: (%) 40.0

Stone Invert: (feet) 200.00

☐ Allow Exfiltration

Number of Rows: 8

Chambers per Row: 26

Row Adjustment: (feet) 0.00

Headers: 0

100.0" Wide + 9.0" Spacing = 109.0" C-C Row Spacing

26 Chambers/Row x 4.02' Long +2.56' Cap Length x 2 = 109.77' Row Length +12.0" End Stone x 2 = 111.77' Base Length

8 Rows x 100.0" Wide + 9.0" Spacing x 7 + 12.0" Side Stone x 2 = 73.92' Base Width

9.0" Stone Base + 60.0" Chamber Height + 12.0" Stone Cover = 6.75' Field Height

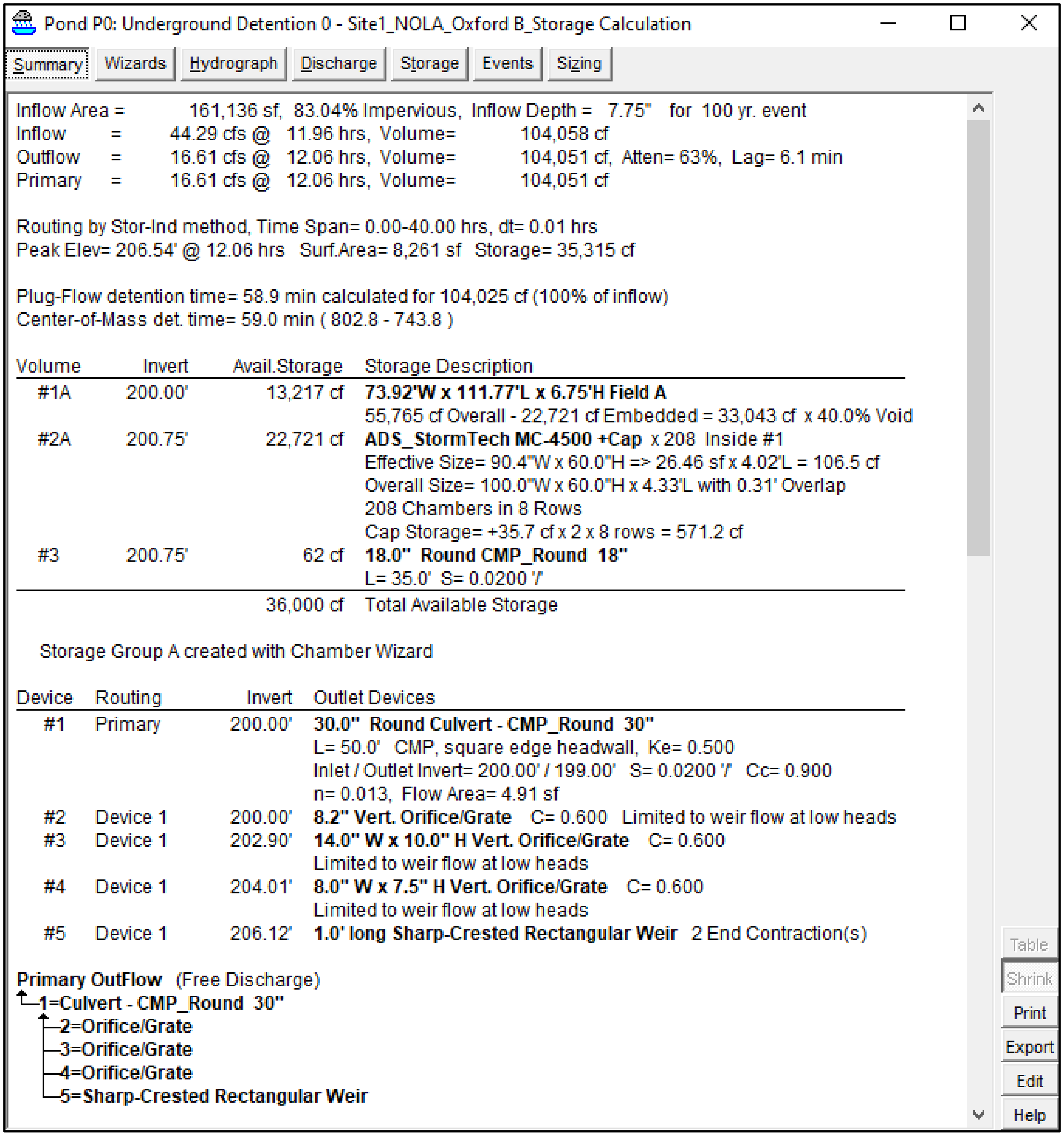
208 Chambers x 106.5 cf + 35.7 cf Cap Volume x 2 x 8 Rows = 22,721.2 cf Chamber Storage

55,764.6 cf Field - 22,721.2 cf Chambers = 33,043.4 cf Stone x 40.0% Voids = 13,217.3 cf Stone Storage

Chamber Storage + Stone Storage = 35,938.6 cf = 0.825 af
Overall Storage Efficiency = 64.4%
Overall System Size = 111.77' x 73.92' x 6.75'

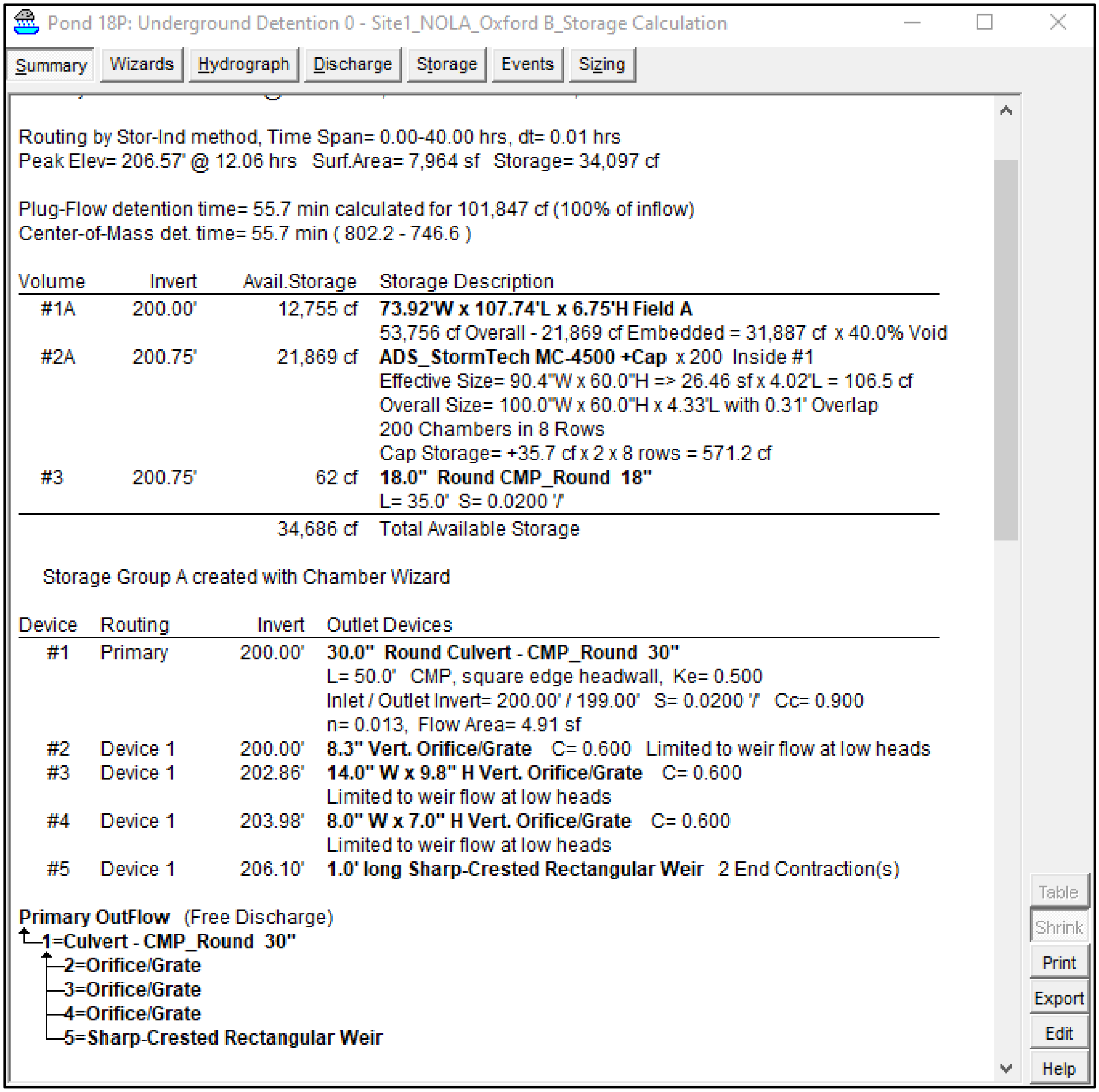
208 Chambers
2,065.4 cy Field
1,223.8 cy Stone

- Storage Summary Report – Site 1 - Post-development



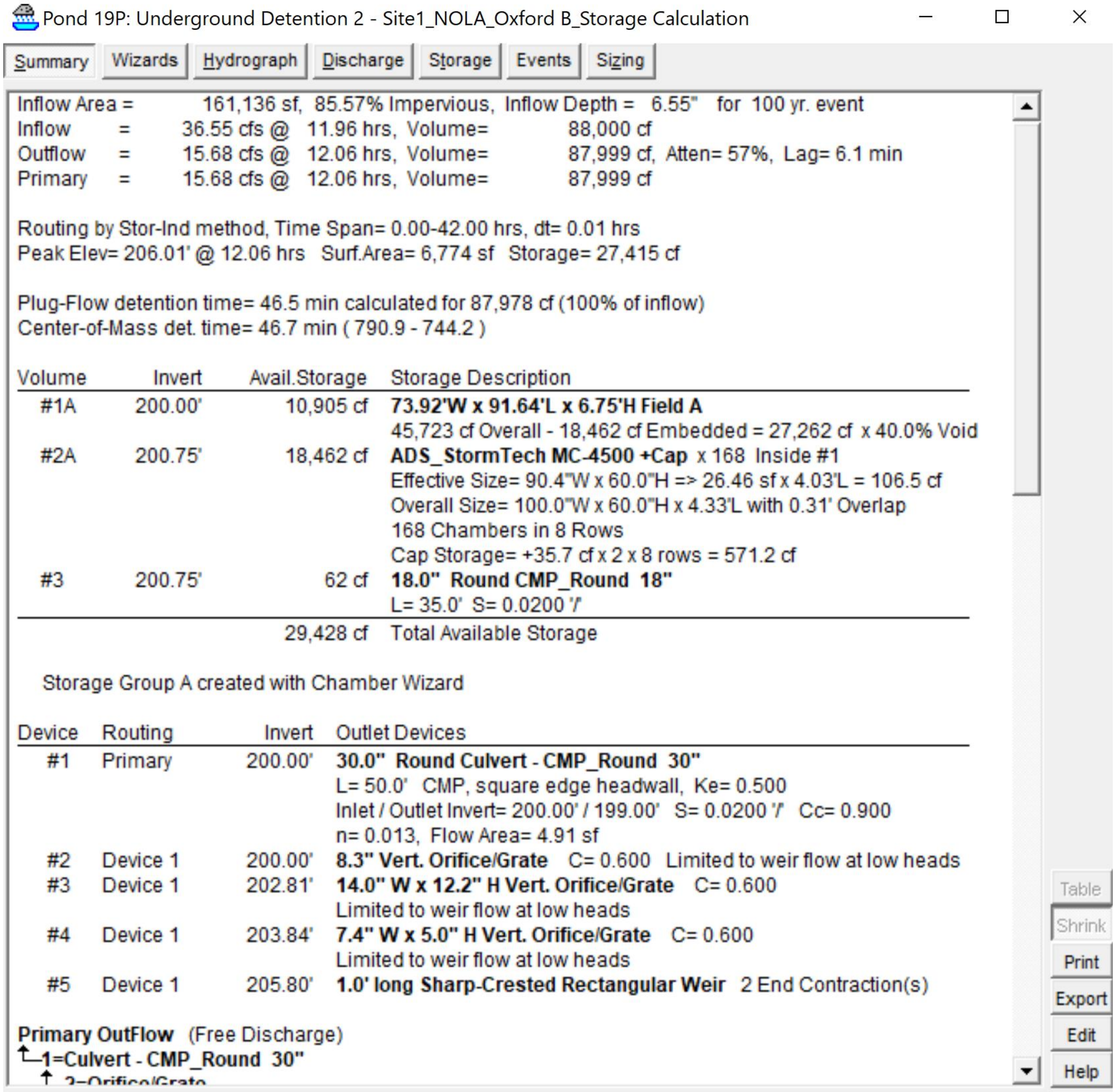
```
Inflow Area =      161,136 sf,  83.04% Impervious,  Inflow Depth =  7.75"   for  100 yr. event
Inflow      =     44.29 cfs @  11.96 hrs,  Volume=          104,058 cf
Outflow     =     16.61 cfs @  12.06 hrs,  Volume=          104,051 cf,  Atten= 63%,  Lag= 6.1 min
Primary     =     16.61 cfs @  12.06 hrs,  Volume=          104,051 cf

Routing by Stor-Ind method, Time Span= 0.00-40.00 hrs, dt= 0.01 hrs
Peak Elev= 206.54' @ 12.06 hrs   Surf.Area= 8,261 sf   Storage= 35,315 cf

Plug-Flow detention time= 58.9 min calculated for 104,025 cf (100% of inflow)
Center-of-Mass det. time= 59.0 min ( 802.8 - 743.8 )

Volume        Invert     Avail.Storage   Storage Description
   #1A        200.00'         13,217 cf  73.92'W x 111.77'L x 6.75'H Field A
                                          55,765 cf Overall - 22,721 cf Embedded = 33,043 cf  x 40.0% Void
   #2A        200.75'         22,721 cf  ADS_StormTech MC-4500 +Cap  x 208  Inside #1
                                          Effective Size= 90.4"W x 60.0"H => 26.46 sf x 4.02'L = 106.5 cf
                                          Overall Size= 100.0"W x 60.0"H x 4.33'L with 0.31' Overlap
                                          208 Chambers in 8 Rows
                                          Cap Storage= +35.7 cf x 2 x 8 rows = 571.2 cf
   #3         200.75'             62 cf  18.0"  Round CMP_Round  18"
                                          L= 35.0'  S= 0.0200 '/'
                              36,000 cf  Total Available Storage

   Storage Group A created with Chamber Wizard

Device   Routing        Invert   Outlet Devices
   #1    Primary        200.00'  30.0"  Round Culvert - CMP_Round  30"
                                 L= 50.0'   CMP, square edge headwall,  Ke= 0.500
                                 Inlet / Outlet Invert= 200.00' / 199.00'   S= 0.0200 '/'   Cc= 0.900
                                 n= 0.013,  Flow Area= 4.91 sf
   #2    Device 1       200.00'  8.2" Vert. Orifice/Grate    C= 0.600   Limited to weir flow at low heads
   #3    Device 1       202.90'  14.0" W x 10.0" H Vert. Orifice/Grate    C= 0.600
                                 Limited to weir flow at low heads
   #4    Device 1       204.01'  8.0" W x 7.5" H Vert. Orifice/Grate    C= 0.600
                                 Limited to weir flow at low heads
   #5    Device 1       206.12'  1.0' long Sharp-Crested Rectangular Weir   2 End Contraction(s)

Primary OutFlow   (Free Discharge)
└1=Culvert - CMP_Round  30"
   ├2=Orifice/Grate
   ├3=Orifice/Grate
   ├4=Orifice/Grate
   └5=Sharp-Crested Rectangular Weir
```

- Storage Summary Report – Site 2- GSI 1



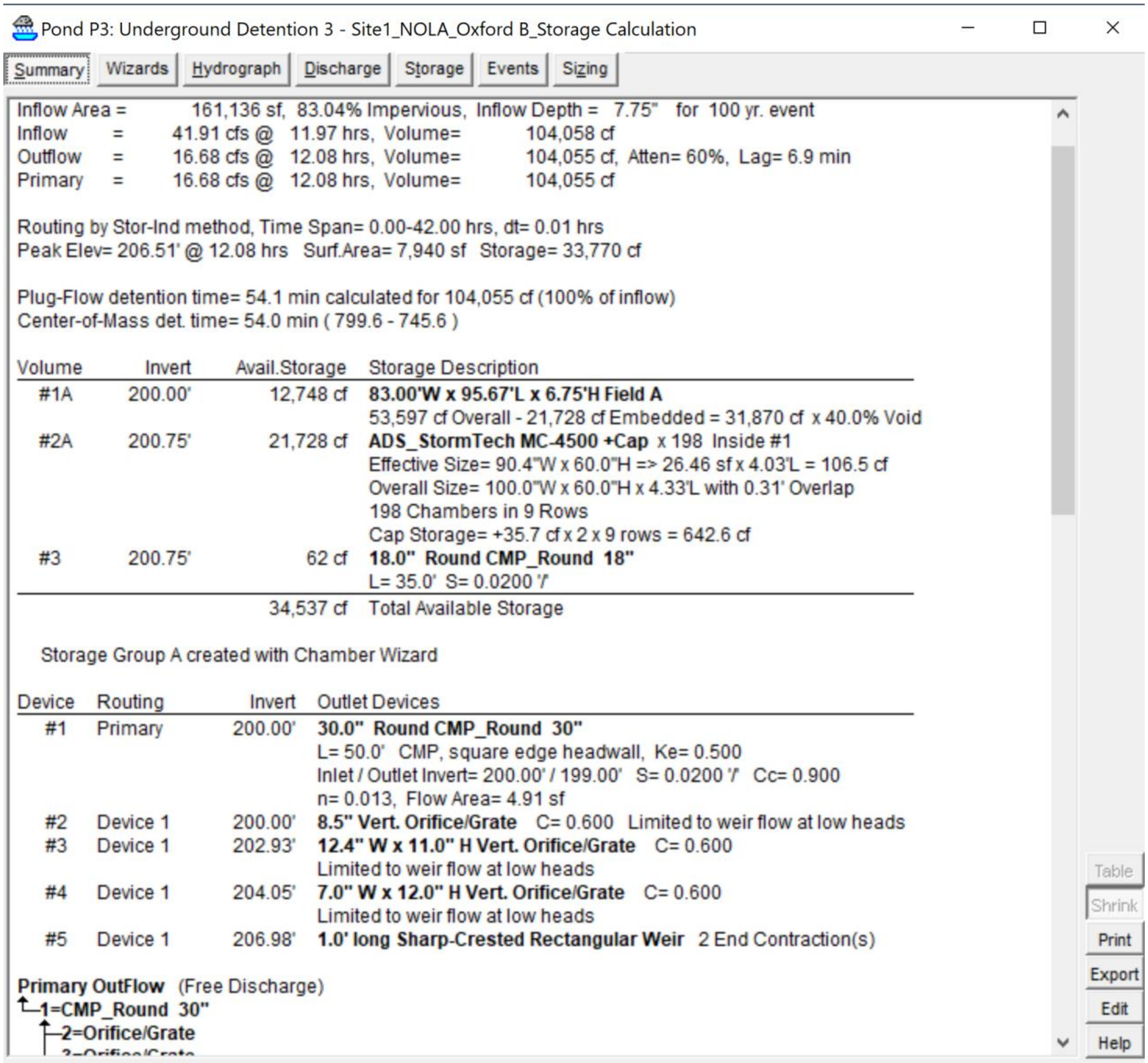
```
Routing by Stor-Ind method, Time Span= 0.00-40.00 hrs, dt= 0.01 hrs
Peak Elev= 206.57' @ 12.06 hrs   Surf.Area= 7,964 sf   Storage= 34,097 cf

Plug-Flow detention time= 55.7 min calculated for 101,847 cf (100% of inflow)
Center-of-Mass det. time= 55.7 min ( 802.2 - 746.6 )

Volume     Invert    Avail.Storage  Storage Description
  #1A      200.00'       12,755 cf  73.92'W x 107.74'L x 6.75'H Field A
                                    53,756 cf Overall - 21,869 cf Embedded = 31,887 cf  x 40.0% Void
  #2A      200.75'       21,869 cf  ADS_StormTech MC-4500 +Cap  x 200  Inside #1
                                    Effective Size= 90.4"W x 60.0"H => 26.46 sf x 4.02'L = 106.5 cf
                                    Overall Size= 100.0"W x 60.0"H x 4.33'L with 0.31' Overlap
                                    200 Chambers in 8 Rows
                                    Cap Storage= +35.7 cf x 2 x 8 rows = 571.2 cf
  #3       200.75'           62 cf  18.0"  Round CMP_Round  18"
                                    L= 35.0'  S= 0.0200 '/'
                         34,686 cf  Total Available Storage

   Storage Group A created with Chamber Wizard

Device  Routing      Invert   Outlet Devices
  #1    Primary      200.00'  30.0"  Round Culvert - CMP_Round  30"
                              L= 50.0'   CMP, square edge headwall,  Ke= 0.500
                              Inlet / Outlet Invert= 200.00' / 199.00'   S= 0.0200 '/'   Cc= 0.900
                              n= 0.013,  Flow Area= 4.91 sf
  #2    Device 1     200.00'  8.3" Vert. Orifice/Grate    C= 0.600   Limited to weir flow at low heads
  #3    Device 1     202.86'  14.0" W x 9.8" H Vert. Orifice/Grate    C= 0.600
                              Limited to weir flow at low heads
  #4    Device 1     203.98'  8.0" W x 7.0" H Vert. Orifice/Grate    C= 0.600
                              Limited to weir flow at low heads
  #5    Device 1     206.10'  1.0' long Sharp-Crested Rectangular Weir   2 End Contraction(s)

Primary OutFlow  (Free Discharge)
└1=Culvert - CMP_Round  30"
  ├2=Orifice/Grate
  ├3=Orifice/Grate
  ├4=Orifice/Grate
  └5=Sharp-Crested Rectangular Weir
```

- Storage Summary Report – Site 1- GSI 2



```
Inflow Area =        161,136 sf,  85.57% Impervious,  Inflow Depth =   6.55"    for  100 yr. event
Inflow      =       36.55 cfs @   11.96 hrs,  Volume=           88,000 cf
Outflow     =       15.68 cfs @   12.06 hrs,  Volume=           87,999 cf,  Atten= 57%,  Lag= 6.1 min
Primary     =       15.68 cfs @   12.06 hrs,  Volume=           87,999 cf

Routing by Stor-Ind method, Time Span= 0.00-42.00 hrs, dt= 0.01 hrs
Peak Elev= 206.01' @ 12.06 hrs   Surf.Area= 6,774 sf   Storage= 27,415 cf

Plug-Flow detention time= 46.5 min calculated for 87,978 cf (100% of inflow)
Center-of-Mass det. time= 46.7 min ( 790.9 - 744.2 )

Volume        Invert    Avail.Storage   Storage Description
  #1A        200.00'        10,905 cf   73.92'W x 91.64'L x 6.75'H Field A
                                        45,723 cf Overall - 18,462 cf Embedded = 27,262 cf  x 40.0% Void
  #2A        200.75'        18,462 cf   ADS_StormTech MC-4500 +Cap  x 168  Inside #1
                                        Effective Size= 90.4"W x 60.0"H => 26.46 sf x 4.03'L = 106.5 cf
                                        Overall Size= 100.0"W x 60.0"H x 4.33'L with 0.31' Overlap
                                        168 Chambers in 8 Rows
                                        Cap Storage= +35.7 cf x 2 x 8 rows = 571.2 cf
  #3         200.75'            62 cf   18.0"  Round CMP_Round  18"
                                        L= 35.0'  S= 0.0200 '/'
                            29,428 cf   Total Available Storage

  Storage Group A created with Chamber Wizard

Device   Routing          Invert   Outlet Devices
   #1    Primary         200.00'   30.0"  Round Culvert - CMP_Round  30"
                                   L= 50.0'   CMP, square edge headwall,  Ke= 0.500
                                   Inlet / Outlet Invert= 200.00' / 199.00'   S= 0.0200 '/'   Cc= 0.900
                                   n= 0.013,  Flow Area= 4.91 sf
   #2    Device 1        200.00'   8.3" Vert. Orifice/Grate    C= 0.600   Limited to weir flow at low heads
   #3    Device 1        202.81'   14.0" W x 12.2" H Vert. Orifice/Grate    C= 0.600
                                   Limited to weir flow at low heads
   #4    Device 1        203.84'   7.4" W x 5.0" H Vert. Orifice/Grate    C= 0.600
                                   Limited to weir flow at low heads
   #5    Device 1        205.80'   1.0' long Sharp-Crested Rectangular Weir   2 End Contraction(s)

Primary OutFlow   (Free Discharge)
↑—1=Culvert - CMP_Round  30"
   ↑ 2=Orifice/Grate
```

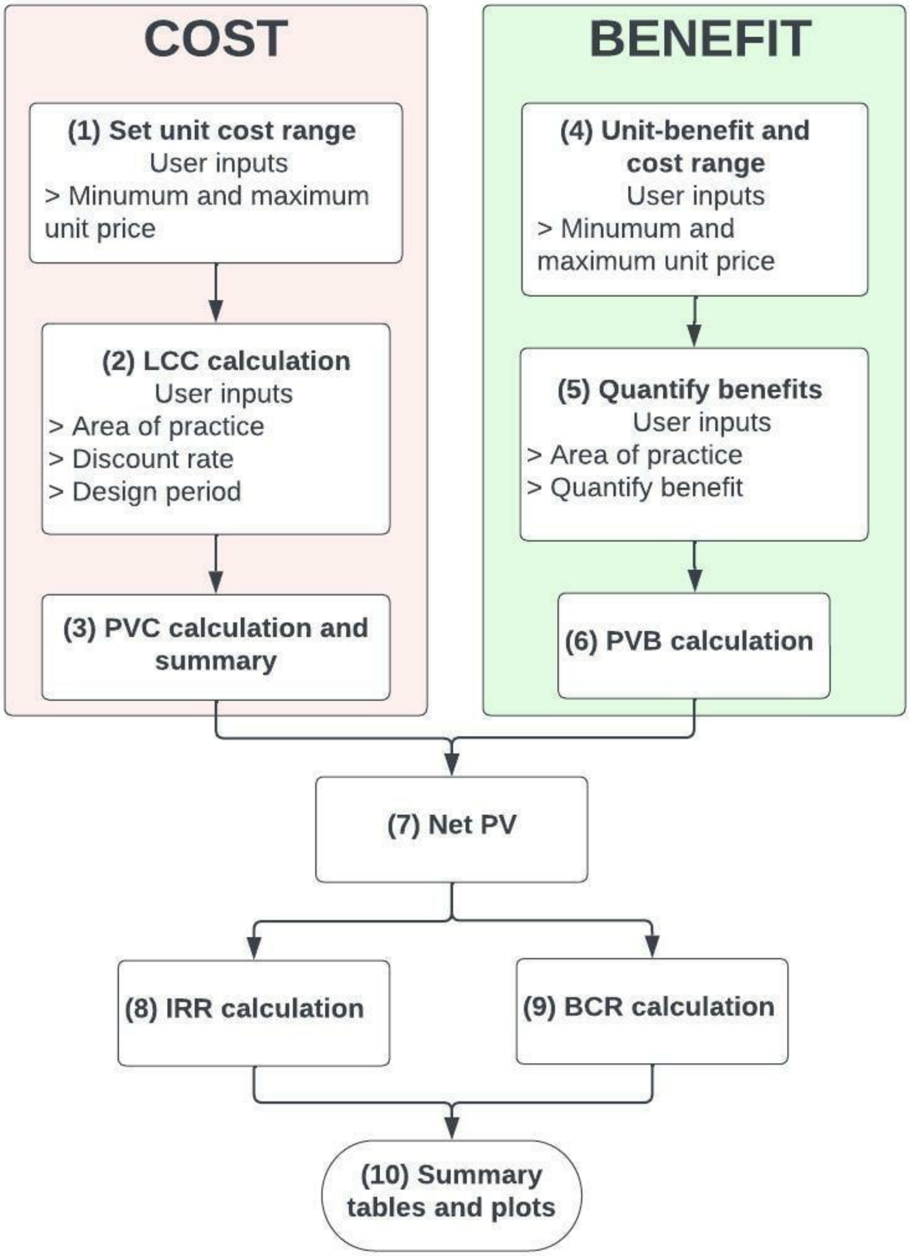
- Storage Summary Report – Site 1- GSI 3



```
Inflow Area =        161,136 sf,  83.04% Impervious,  Inflow Depth =   7.75"   for  100 yr. event
Inflow      =      41.91 cfs @   11.97 hrs,  Volume=          104,058 cf
Outflow     =      16.68 cfs @   12.08 hrs,  Volume=          104,055 cf,  Atten= 60%,  Lag= 6.9 min
Primary     =      16.68 cfs @   12.08 hrs,  Volume=          104,055 cf

Routing by Stor-Ind method, Time Span= 0.00-42.00 hrs, dt= 0.01 hrs
Peak Elev= 206.51' @ 12.08 hrs   Surf.Area= 7,940 sf   Storage= 33,770 cf

Plug-Flow detention time= 54.1 min calculated for 104,055 cf (100% of inflow)
Center-of-Mass det. time= 54.0 min ( 799.6 - 745.6 )

Volume       Invert     Avail.Storage   Storage Description
  #1A        200.00'        12,748 cf   83.00'W x 95.67'L x 6.75'H Field A
                                        53,597 cf Overall - 21,728 cf Embedded = 31,870 cf  x 40.0% Void
  #2A        200.75'        21,728 cf   ADS_StormTech MC-4500 +Cap  x 198  Inside #1
                                        Effective Size= 90.4"W x 60.0"H => 26.46 sf x 4.03'L = 106.5 cf
                                        Overall Size= 100.0"W x 60.0"H x 4.33'L with 0.31' Overlap
                                        198 Chambers in 9 Rows
                                        Cap Storage= +35.7 cf x 2 x 9 rows = 642.6 cf
  #3         200.75'            62 cf   18.0"  Round CMP_Round  18"
                                        L= 35.0'  S= 0.0200 '/'
                            34,537 cf   Total Available Storage

  Storage Group A created with Chamber Wizard

Device   Routing          Invert   Outlet Devices
  #1     Primary          200.00'  30.0"  Round CMP_Round  30"
                                   L= 50.0'   CMP, square edge headwall,  Ke= 0.500
                                   Inlet / Outlet Invert= 200.00' / 199.00'   S= 0.0200 '/'   Cc= 0.900
                                   n= 0.013,  Flow Area= 4.91 sf
  #2     Device 1         200.00'  8.5" Vert. Orifice/Grate    C= 0.600   Limited to weir flow at low heads
  #3     Device 1         202.93'  12.4" W x 11.0" H Vert. Orifice/Grate    C= 0.600
                                   Limited to weir flow at low heads
  #4     Device 1         204.05'  7.0" W x 12.0" H Vert. Orifice/Grate    C= 0.600
                                   Limited to weir flow at low heads
  #5     Device 1         206.98'  1.0' long Sharp-Crested Rectangular Weir   2 End Contraction(s)

Primary OutFlow  (Free Discharge)
└─1=CMP_Round  30"
   ├─2=Orifice/Grate
   ├─3=Orifice/Grate
```

APPENDIX B: LIFE-CYCLE COST AND BENEFIT-COST ANALYSES

1. LCCA and BCA flow chart



2. Life-cycle Cost Analysis

- **Cost estimate using specification and bill of quantities**

Site: The NOLA Mixed-Development

Location: Oxford, MS

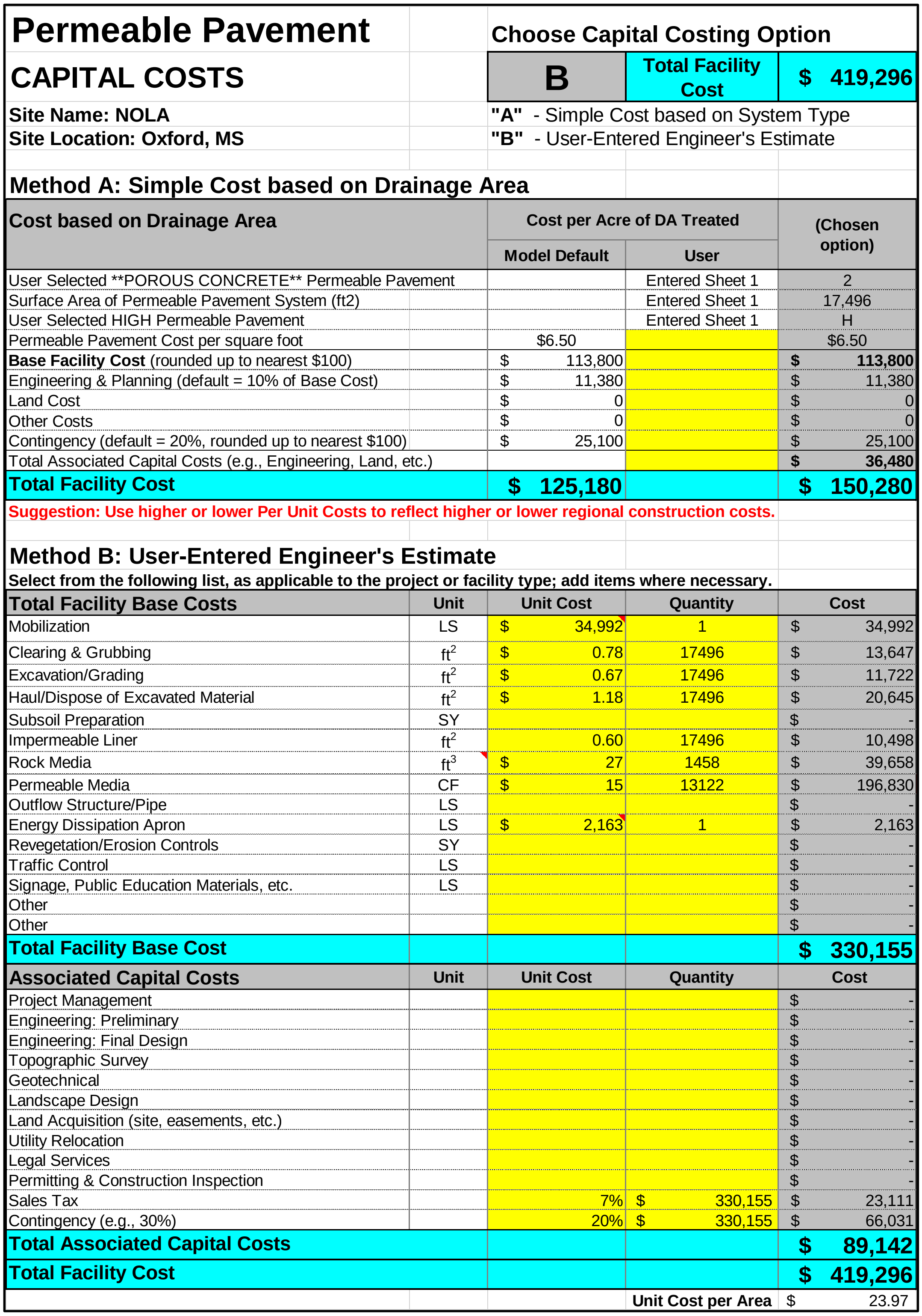
Total Area of pervious pavement on the parking area = 17,496 ft^2

Specification and Pice estimate for construction of pervious concrete

	Items/Description	Unit	Quantity	Unit Price (USD)	Total Price (USD)	Remark
A	CONSTRUCTION COST					
1	**Mobilization**					
	Mobilization of equipment, manpower, and material.	LS	1	15,000.00	**15,000.00**	
	Sub Total				**15,000.00**	
2	**Cleaning and Grubbing**					
2.1	Clear the site to remove and dispose all top vegetative, trees, stumps, roots, grass, weeds, and other litter from the site, except those designated by the Engineer to be saved	Acer	0.4	40,075.20	16,030.08	
	Sub Total				**16,030.08**	
3	**Earth work**					
3.1	Excavation and grading of the site to place the subbase and pervious pavement layers, with an average depth of 24" .	CY	1188	4.75	5,643.00	Considering 12" of sub base and 10" of pervious concrete layer
3.2	Removal and disposal of excavated material from the site.	CY	1188	1.00	1,188.00	
3.3	Place fabric impermeable liner under the subbase	SF	17496	1.00	17,496.00	
3.4	Take soil sample to test the porosity and permeability rate of the underlying soil. Also to classify the soil type using the NRCS soil texture classification. (before the subbase placed).	EA	3	400.00	1,200.00	Assuming to have at least 3 soil samples
	Sub Total				**25,527.00**	
4	**Stone work**					
4.1	Place subbase layer of a clean, open graded, washed core aggregate with a porosity of 40% under the pervious concrete layer with an average thickness of 10" depth. * The subbase layer should be deeper in clay soils.	TONs	980	38.00	37,240.00	Assuming 1" (1ft) Sub layer = 17,496 CF volume
	Sub Total				**37,240.00**	
5	**Formwork**					
5.1	Cut and fix in position the formwork. The formwork should be steel, wood or other material that are sufficiently rigid to maintain specific tolerances and capable of supporting the pervious concrete and concrete placing equipment. the formwork should have a minimum thickness equivalent to the thickness of the pervious concrete layer	SF	5000	1.25	6,250.00	
	Sub Total				**6,250.00**	

6	**Concrete work**					
6.1	Placing a sand layer under the subbase.	CF	270	1.00	270.00	Assuming 4" depth
6.2	Mix the pervious concrete comply with ASTM C94 and ACI 522.1-13. Wet the subbase with water before placing the concrete. Deposit the pervious concrete mix onto the subbase to approximately uniform height. Spread the concrete using mechanized equipment or hand tools, with out segregation.	CF	540	15.00	8,100.00	
6.3	with ASTM D994 or D1752 and ACI 522.1-13 to the specified depth and width in fresh concrete immediately after the concrete is placed.	LS	1	200.00	200.00	
6.4	Cover the pavement surface and all exposed edges with a polyethylene curing sheet comply with ASTM C171. Cure the pavement for a minimum of 7 days.	SF	17496	0.75	13,122.00	
6.5	Construct energy dissipation structure with the form of Erosion control stone-lined channels at the outlet.	TONS	18.5	50.00	925.00	
	Sub Total				**22,617.00**	
7	**Pipe**					
7.1	Installation of a minimum of 3" diameter perforated or slotted HDPE pipe, including all required fittings, in the top of the subbase layer, to control over flow.	F	100	8.00	800.00	
7.2	Installation of a minimum of 4" diameter sloped to outlet perforated or slotted HDPE pipe, including all required fittings, in the top of the subbase layer, to control over flow.	F	100	8.00	800.00	
	Sub Total				**1,600.00**	
8	**Traffic control**					
8.1	Provide physical barriers to minimize vehicular traffic during construction	LS	1	500.00	500.00	
	Sub Total				**500.00**	
Total Construction Cost					**124,764.08**	7.13
Landscape Design (3%)					**3,742.92**	
Tax (7%)					**8,733.49**	
Contingency (20%)					**24,952.82**	
Total					**162,193.30**	

- **Cost estimate using the WERF Tool – Capital Costs**



Permeable Pavement	**Choose Capital Costing Option**
CAPITAL COSTS	**B** | **Total Facility Cost** | **$ 419,296**
Site Name: NOLA	**"A"** - Simple Cost based on System Type
Site Location: Oxford, MS	**"B"** - User-Entered Engineer's Estimate

Method A: Simple Cost based on Drainage Area

Cost based on Drainage Area	**Cost per Acre of DA Treated**		**(Chosen option)**
	Model Default	**User**	
User Selected **POROUS CONCRETE** Permeable Pavement		Entered Sheet 1	2
Surface Area of Permeable Pavement System (ft2)		Entered Sheet 1	17,496
User Selected HIGH Permeable Pavement		Entered Sheet 1	H
Permeable Pavement Cost per square foot	$6.50		$6.50
Base Facility Cost (rounded up to nearest $100)	$ 113,800		**$ 113,800**
Engineering & Planning (default = 10% of Base Cost)	$ 11,380		$ 11,380
Land Cost	$ 0		$ 0
Other Costs	$ 0		$ 0
Contingency (default = 20%, rounded up to nearest $100)	$ 25,100		$ 25,100
Total Associated Capital Costs (e.g., Engineering, Land, etc.)			**$ 36,480**
Total Facility Cost	**$ 125,180**		**$ 150,280**

Suggestion: Use higher or lower Per Unit Costs to reflect higher or lower regional construction costs.

Method B: User-Entered Engineer's Estimate

Select from the following list, as applicable to the project or facility type; add items where necessary.

Total Facility Base Costs	**Unit**	**Unit Cost**	**Quantity**	**Cost**
Mobilization	LS	$ 34,992	1	$ 34,992
Clearing & Grubbing	ft^2	$ 0.78	17496	$ 13,647
Excavation/Grading	ft^2	$ 0.67	17496	$ 11,722
Haul/Dispose of Excavated Material	ft^2	$ 1.18	17496	$ 20,645
Subsoil Preparation	SY			$ -
Impermeable Liner	ft^2	0.60	17496	$ 10,498
Rock Media	ft^3	$ 27	1458	$ 39,658
Permeable Media	CF	$ 15	13122	$ 196,830
Outflow Structure/Pipe	LS			$ -
Energy Dissipation Apron	LS	$ 2,163	1	$ 2,163
Revegetation/Erosion Controls	SY			$ -
Traffic Control	LS			$ -
Signage, Public Education Materials, etc.	LS			$ -
Other				$ -
Other				$ -
Total Facility Base Cost				**$ 330,155**

Associated Capital Costs	**Unit**	**Unit Cost**	**Quantity**	**Cost**
Project Management				$ -
Engineering: Preliminary				$ -
Engineering: Final Design				$ -
Topographic Survey				$ -
Geotechnical				$ -
Landscape Design				$ -
Land Acquisition (site, easements, etc.)				$ -
Utility Relocation				$ -
Legal Services				$ -
Permitting & Construction Inspection				$ -
Sales Tax		7%	$ 330,155	$ 23,111
Contingency (e.g., 30%)		20%	$ 330,155	$ 66,031
Total Associated Capital Costs				**$ 89,142**
Total Facility Cost				**$ 419,296**
			Unit Cost per Area	$ 23.97

- **Cost estimate using the WERF Tool - Maintenance Costs**

REGULAR MAINTENANCE ACTIVITIES	**Included in WLC Calculation**			**Years between Events**	**Cost per Event**	**Total Cost per Year**
	Model	**User**	**Chosen option**			
Inspection, Reporting & Information Management	Y		Y	3	$320	$107
Litter & Minor Debris Removal	Y		Y	1	$180	$180
Permeable pavement sweeping	Y		Y	1	$1,129	$1,129
Additional activities	Y		Y	0	$0	$0
Additional activities	Y		Y	0	$0	$0
Totals, Regular Maintenance Activities						**$1,416**

CORRECTIVE AND INFREQUENT MAINTENANCE ACTIVITIES (Unplanned and/or >3yrs. betw. events)	**Included in WLC**			**Years between Events**	**Cost per Event**	**Total Cost per Year**
	Model	**User**	**Chosen option**			
Intermittent facility maintenance	Y		Y	0	$0	$0
Remove existing pavement & aggregate; wash and/or replace & reinstall*	Y		Y	35	$0	$0
Additional activities	Y		Y	0	$0	$0
Additional activities	Y		Y	0	$0	$0
Totals, Corrective & Infrequent Maintenance Activities						**$0**

- **Unit price/costs assigned for construction and maintenance activities**

Unit Cost Ranges for the Capital and Operation and Maintenances of Stormwater Management Facilities Including GSI and the Traditional Underground Storage

Items	Frequency	Unit	Price per Unit			References
			Minimum ($)	Maximum ($)	Average ($)	
1. Permeable concrete						Local developers' estimates, the WERF tool, Rutgers University, 2018, and (Homewyse, n.d.)
Capital	Initial	ft^2	**7**	**23**	15	
Regular maintenance						WERF (2009); Fu and Liu (2018)
Inspection	3 years	ft^2	**0.0325**	**0.0525**	0.0425	
Litter removal	yearly	ft^2	**0.015**	**0.035**	0.025	
Sweeping/Vacuuming	yearly	ft^2	**0.12**	**0.18**	0.150	
2. Rain garden						Minimum based on literature (Derviş, 2013). Maximum based on contractor's estimate and WERF tool. Another reference (Rutgers University, 2018; Vineyard et al., 2015).
Capital	Initial/one time	ft^3	**6**	**11**	8.5	
Maintenance						WERF (2009); Rutgers University, 2018
Vegetation management	yearly	ft^2	**0.45**	**0.55**	0.500	
Replace mulch	3 years	ft^2	**1.20**	**1.70**	1.45	
Till the soil	5 years	ft^2	**0.58**	**0.75**	0.67	
3. Grassy ditch						Local planters and (Home Guide, n.d.)
Capital	initial	ft^2	**5**	**5.5**	5.25	
Regular maintenance						
Mowing/grass management	yearly	ft^2	**0.4**	**0.5**	0.45	
Ditch cleaning	yearly	ft^2	**0.45**	**0.7**	0.58	
4. Landscaping						Local planters and (Home Guide, n.d.)
Capital	initial	ft^2	**3**	**5**	4	
Regular maintenance						
Mowing	yearly	ft^2	**0.15**	**0.45**	0.30	
Vegetation/grass management	yearly	ft^2	**0.40**	**0.48**	0.440	
5. Concrete pavement						Fu and Liu 2018, Homewyse, n.d.
Capital	Initial	ft^2	**5**	**8**	6.50	
Corrective maintenances						
Inspection	3 years	ft^2	**0.0325**	**0.0525**	0.0425	
Seal the joints	8 years	ft^2	**0.15**	**0.3**	0.225	
7. Underground storage						StormTech local sales representative's estimate. Local developers.
Using ADS						
Capital	initial	ft^2	**7.5**	**8.5**	8	
Regular maintenance						
Ditch cleaning	yearly	ft^3	**0.14**	**0.19**	0.165	

- **Present Value of Costs (PVC) Calculations**

Scenario	Baseline Scenario					
Item		Concrete Sidewalks			Landscaping	
Area (ft^2)		7,525			6,390	
Volume (ft^3)		–			–	
Capital Cost ($)		$48,913			$25,560	
			Frequency			Frequency
Operation and Maintenance cost ($)	Inspection	$320	3-year	Vegetation Management	$2,812	yearly
	Seal the joints	$1,693	8-year	Mowing	$1,917	yearly
Discount Rate (%)		5.5			5.5	
Design period (Years)		30			30	

Year	Discount Factor	Capital Costs	O&M Costs	Present Value	Capital Costs	O&M Costs	Present Value
Cash Sum ($)			$8,278	$52,670		$141,858	$ 94,284
0	1.000	48,912.50	$0	48,912.50	25,560.00	$0	25,560.00
1	0.948	$0	$0	0.00	$0	4,728.60	4,482.09
2	0.898	$0	$0	0.00	$0	4,728.60	4,248.42
3	0.852	$0	$320	272.36	$0	4,728.60	4,026.94
4	0.807	$0	$0	0.00	$0	4,728.60	3,817.01
5	0.765	$0	$0	0.00	$0	4,728.60	3,618.01
6	0.725	$0	$320	231.94	$0	4,728.60	3,429.40
7	0.687	$0	$0	0.00	$0	4,728.60	3,250.61
8	0.652	$0	1,693.13	1,103.24	$0	4,728.60	3,081.15
9	0.618	$0	$320	197.53	$0	4,728.60	2,920.52
10	0.585	$0	$0	0.00	$0	4,728.60	2,768.27
11	0.555	$0	$0	0.00	$0	4,728.60	2,623.95
12	0.526	$0	$320	168.22	$0	4,728.60	2,487.16
13	0.499	$0	$0	0.00	$0	4,728.60	2,357.49
14	0.473	$0	$0	0.00	$0	4,728.60	2,234.59
15	0.448	$0	$320	143.25	$0	4,728.60	2,118.10
16	0.425	$0	1,693.13	718.87	$0	4,728.60	2,007.67
17	0.402	$0	$0	0.00	$0	4,728.60	1,903.01
18	0.381	$0	$320	122.00	$0	4,728.60	1,803.80
19	0.362	$0	$0	0.00	$0	4,728.60	1,709.76
20	0.343	$0	$0	0.00	$0	4,728.60	1,620.63
21	0.325	$0	$320	103.89	$0	4,728.60	1,536.14
22	0.308	$0	$0	0.00	$0	4,728.60	1,456.06
23	0.292	$0	$0	0.00	$0	4,728.60	1,380.15
24	0.277	$0	2,012.94	556.89	$0	4,728.60	1,308.20
25	0.262	$0	$0	0.00	$0	4,728.60	1,240.00
26	0.249	$0	$0	0.00	$0	4,728.60	1,175.35
27	0.236	$0	$320	75.35	$0	4,728.60	1,114.08
28	0.223	$0	$0	0.00	$0	4,728.60	1,056.00
29	0.212	$0	$0	0.00	$0	4,728.60	1,000.95
30	0.201	$0	$320	64.17	$0	4,728.60	948.77

GSI 1- Permeable Pavement

	Permeable Pavement Substituting the concrete sidewalks	Frequency		Landscaping	Frequency
	7,525			6,390	
	–			–	
	$112,875			$25,560	
Inspection	$320	3-year	Vegetation Management	$2,812	yearly
Litter removal	$188	yearly	Mowing	$1,917	yearly
Vacuuming	$1,129	yearly			
	5.5			5.5	
	30			30	

Capital Costs	O&M Costs	Present Value	Capital Costs	O&M Costs	Present Value	Net Cash Flow [GSI 1 - Baseline]
	$42,704	$ 133,481		$141,858	$ 94,284	
112,875.00	$0	112,875.00	**25,560.00**	$0	25,560.00	63,962.50
$0	1,316.88	1,248.22	$0	4,728.60	4,482.09	1,316.88
$0	1,316.88	1,183.15	$0	4,728.60	4,248.42	1,316.88
$0	1,636.69	1,393.83	$0	4,728.60	4,026.94	1,316.88
$0	1,316.88	1,063.00	$0	4,728.60	3,817.01	1,316.88
$0	1,316.88	1,007.59	$0	4,728.60	3,618.01	1,316.88
$0	1,636.69	1,187.00	$0	4,728.60	3,429.40	1,316.88
$0	1,316.88	905.27	$0	4,728.60	3,250.61	1,316.88
$0	1,316.88	858.07	$0	4,728.60	3,081.15	-376.25
$0	1,636.69	1,010.87	$0	4,728.60	2,920.52	1,316.88
$0	1,316.88	770.94	$0	4,728.60	2,768.27	1,316.88
$0	1,316.88	730.75	$0	4,728.60	2,623.95	1,316.88
$0	1,636.69	860.87	$0	4,728.60	2,487.16	1,316.88
$0	1,316.88	656.54	$0	4,728.60	2,357.49	1,316.88
$0	1,316.88	622.31	$0	4,728.60	2,234.59	1,316.88
$0	1,636.69	733.13	$0	4,728.60	2,118.10	1,316.88
$0	1,316.88	559.12	$0	4,728.60	2,007.67	-376.25
$0	1,316.88	529.97	$0	4,728.60	1,903.01	1,316.88
$0	1,636.69	624.34	$0	4,728.60	1,803.80	1,316.88
$0	1,316.88	476.15	$0	4,728.60	1,709.76	1,316.88
$0	1,316.88	451.33	$0	4,728.60	1,620.63	1,316.88
$0	1,636.69	531.70	$0	4,728.60	1,536.14	1,316.88
$0	1,316.88	405.50	$0	4,728.60	1,456.06	1,316.88
$0	1,316.88	384.36	$0	4,728.60	1,380.15	1,316.88
$0	1,636.69	452.80	$0	4,728.60	1,308.20	-376.25
$0	1,316.88	345.33	$0	4,728.60	1,240.00	1,316.88
$0	1,316.88	327.33	$0	4,728.60	1,175.35	1,316.88
$0	1,636.69	385.61	$0	4,728.60	1,114.08	1,316.88
$0	1,316.88	294.09	$0	4,728.60	1,056.00	1,316.88
$0	1,316.88	278.76	$0	4,728.60	1,000.95	1,316.88
$0	1,636.69	328.39	$0	4,728.60	948.77	1,316.88

GSI 2 - Rain Garden

Rain garden replacing some of the landscaping			**Concrete Sidewalks**			**Remaining landscaping area after the implementation of the rain garden**			**Net Cash Flow [GSI 2 - Baseline]**
	4,080			7,525			2,310		
	6,120			–			–		
	$52,020			$48,913			$9,240		
		Frequency			**Frequency**			**Frequency**	
Vegetation Management	$2,040	yearly	**Seal the joints**	$1,693	8-year	**Vegetation Management**	$1,016	yearly	
Replace mulch	$5,916	3-year				**Mowing**	$693	yearly	
Till the soil	$2,713	5-year							
	5.5			**5.5**			**5.5**		
	30			**30**			**30**		
Capital Costs	**O&M Costs**	**Present Value**	**Capital Costs**	**O&M Costs**	**Present Value**	**Capital Costs**	**O&M Costs**	**Present Value**	
	$136,639	**$ 115,875**		**$5,079**	**$51,203**		**$51,282**	**$ 34,084**	
52,020.00	$0	52,020.00	**48,912.50**	$0	48,912.50	**9,240.00**	$0	9,240.00	35,700.00
$0	2,040.00	1,933.65	$0	$0	0.00	$0	1,709.40	1,620.28	-979.20
$0	2,040.00	1,832.84	$0	$0	0.00	$0	1,709.40	1,535.81	-979.20
$0	7,956.00	6,775.44	$0	$0	0.00	$0	1,709.40	1,455.75	4,616.99
$0	2,040.00	1,646.72	$0	$0	0.00	$0	1,709.40	1,379.86	-979.20
$0	4,753.20	3,636.84	$0	$0	0.00	$0	1,709.40	1,307.92	1,734.00
$0	7,956.00	5,770.06	$0	$0	0.00	$0	1,709.40	1,239.74	4,616.99
$0	2,040.00	1,402.37	$0	$0	0.00	$0	1,709.40	1,175.10	-979.20
$0	2,040.00	1,329.26	$0	1,693.13	1,103.24	$0	1,709.40	1,113.84	-979.20
$0	7,956.00	4,913.86	$0	$0	0.00	$0	1,709.40	1,055.78	4,616.99
$0	4,753.20	2,782.67	$0	$0	0.00	$0	1,709.40	1,000.74	1,734.00
$0	2,040.00	1,132.02	$0	$0	0.00	$0	1,709.40	948.56	-979.20
$0	7,956.00	4,184.71	$0	$0	0.00	$0	1,709.40	899.11	4,616.99
$0	2,040.00	1,017.06	$0	$0	0.00	$0	1,709.40	852.24	-979.20
$0	2,040.00	964.04	$0	$0	0.00	$0	1,709.40	807.81	-979.20
$0	10,669.20	4,779.09	$0	$0	0.00	$0	1,709.40	765.70	7,330.19
$0	2,040.00	866.15	$0	1,693.13	718.87	$0	1,709.40	725.78	-979.20
$0	2,040.00	820.99	$0	$0	0.00	$0	1,709.40	687.94	-979.20
$0	7,956.00	3,034.94	$0	$0	0.00	$0	1,709.40	652.08	4,616.99
$0	2,040.00	737.62	$0	$0	0.00	$0	1,709.40	618.08	-979.20
$0	4,753.20	1,629.06	$0	$0	0.00	$0	1,709.40	585.86	1,734.00
$0	7,956.00	2,584.60	$0	$0	0.00	$0	1,709.40	555.32	4,616.99
$0	2,040.00	628.17	$0	$0	0.00	$0	1,709.40	526.37	-979.20
$0	2,040.00	595.42	$0	$0	0.00	$0	1,709.40	498.93	-979.20
$0	7,956.00	2,201.08	$0	1,693.13	468.41	$0	1,709.40	472.92	4,616.99
$0	4,753.20	1,246.45	$0	$0	0.00	$0	1,709.40	448.26	1,734.00
$0	2,040.00	507.07	$0	$0	0.00	$0	1,709.40	424.89	-979.20
$0	7,956.00	1,874.47	$0	$0	0.00	$0	1,709.40	402.74	4,616.99
$0	2,040.00	455.58	$0	$0	0.00	$0	1,709.40	381.75	-979.20
$0	2,040.00	431.83	$0	$0	0.00	$0	1,709.40	361.84	-979.20
$0	10,669.20	2,140.71	$0	$0	0.00	$0	1,709.40	342.98	7,330.19

Grassy Ditch

Grassy ditch replacing some of the landscaping			Concrete Sidewalks			Landscaping			Net Cash Flow [GSI 3 - Baseline]
	2,310			7,525			4,080		
	–			–			–		
	$12,128			$48,913			$16,320		
		Frequency			Frequency			Frequency	
Mowing	$1,040	yearly	Seal the joints	$1,693	8-year	Vegetation Management	$1,795	yearly	
Ditch cleaning	$1,328	year				Mowing	$1,224	yearly	
	5.5			5.5			5.5		
	30			30			30		
Capital Costs	O&M Costs	Present Value	Capital Costs	O&M Costs	Present Value	Capital Costs	O&M Costs	Present Value	
	$71,033	$ 46,540		$5,079	$51,203		$90,576	$ 60,200	
12,127.50	$0	12,127.50	**48,912.50**	$0	48,912.50	**16,320.00**	$0	16,320.00	2,887.50
$0	2,367.75	2,244.31	$0	$0	0.00	$0	3,019.20	2,861.80	658.35
$0	2,367.75	2,127.31	$0	$0	0.00	$0	3,019.20	2,712.61	658.35
$0	2,367.75	2,016.41	$0	$0	0.00	$0	3,019.20	2,571.19	338.54
$0	2,367.75	1,911.29	$0	$0	0.00	$0	3,019.20	2,437.15	658.35
$0	2,367.75	1,811.65	$0	$0	0.00	$0	3,019.20	2,310.09	658.35
$0	2,367.75	1,717.20	$0	$0	0.00	$0	3,019.20	2,189.66	338.54
$0	2,367.75	1,627.68	$0	$0	0.00	$0	3,019.20	2,075.51	658.35
$0	2,367.75	1,542.82	$0	1,693.13	1,103.24	$0	3,019.20	1,967.31	658.35
$0	2,367.75	1,462.39	$0	$0	0.00	$0	3,019.20	1,864.75	338.54
$0	2,367.75	1,386.15	$0	$0	0.00	$0	3,019.20	1,767.53	658.35
$0	2,367.75	1,313.89	$0	$0	0.00	$0	3,019.20	1,675.39	658.35
$0	2,367.75	1,245.39	$0	$0	0.00	$0	3,019.20	1,588.04	338.54
$0	2,367.75	1,180.47	$0	$0	0.00	$0	3,019.20	1,505.25	658.35
$0	2,367.75	1,118.93	$0	$0	0.00	$0	3,019.20	1,426.78	658.35
$0	2,367.75	1,060.59	$0	$0	0.00	$0	3,019.20	1,352.40	338.54
$0	2,367.75	1,005.30	$0	1,693.13	718.87	$0	3,019.20	1,281.90	658.35
$0	2,367.75	952.89	$0	$0	0.00	$0	3,019.20	1,215.07	658.35
$0	2,367.75	903.22	$0	$0	0.00	$0	3,019.20	1,151.72	338.54
$0	2,367.75	856.13	$0	$0	0.00	$0	3,019.20	1,091.68	658.35
$0	2,367.75	811.50	$0	$0	0.00	$0	3,019.20	1,034.77	658.35
$0	2,367.75	769.19	$0	$0	0.00	$0	3,019.20	980.82	338.54
$0	2,367.75	729.09	$0	$0	0.00	$0	3,019.20	929.69	658.35
$0	2,367.75	691.08	$0	$0	0.00	$0	3,019.20	881.22	658.35
$0	2,367.75	655.05	$0	1,693.13	468.41	$0	3,019.20	835.28	338.54
$0	2,367.75	620.90	$0	$0	0.00	$0	3,019.20	791.74	658.35
$0	2,367.75	588.53	$0	$0	0.00	$0	3,019.20	750.46	658.35
$0	2,367.75	557.85	$0	$0	0.00	$0	3,019.20	711.34	338.54
$0	2,367.75	528.77	$0	$0	0.00	$0	3,019.20	674.25	658.35
$0	2,367.75	501.20	$0	$0	0.00	$0	3,019.20	639.10	658.35
$0	2,367.75	475.07	$0	$0	0.00	$0	3,019.20	605.78	338.54

PRESENT VALUE OF COSTS (PVC) OF GSI SCENARIOS

		GSI 1		GSI 2		GSI 3	
		Permeable Pavement		Rain Garden		Grassy Ditch	
		Expected Cost		Expected Cost		Expected Cost	
Discount Factor	5.5	Cash flow ($)	Present Value ($)	Cash flow ($)	Present Value ($)	Cash flow ($)	Present Value ($)
Year	Discount Factor		**80,811**		**54,207**		**10,989**
0	1.000	63,962.50	63,962.50	35,700.00	35,700.00	2,887.50	2,887.50
1	0.948	1,316.88	1,248.22	-979.20	-928.15	658.35	624.03
2	0.898	1,316.88	1,183.15	-979.20	-879.76	658.35	591.50
3	0.852	1,316.88	1,121.47	4,616.99	3,931.89	338.54	288.30
4	0.807	1,316.88	1,063.00	-979.20	-790.43	658.35	531.43
5	0.765	1,316.88	1,007.59	1,734.00	1,326.74	658.35	503.73
6	0.725	1,316.88	955.06	4,616.99	3,348.45	338.54	245.52
7	0.687	1,316.88	905.27	-979.20	-673.14	658.35	452.57
8	0.652	-376.25	-245.16	-979.20	-638.05	658.35	428.98
9	0.618	1,316.88	813.34	4,616.99	2,851.59	338.54	209.09
10	0.585	1,316.88	770.94	1,734.00	1,015.14	658.35	385.42
11	0.555	1,316.88	730.75	-979.20	-543.37	658.35	365.33
12	0.526	1,316.88	692.65	4,616.99	2,428.45	338.54	178.06
13	0.499	1,316.88	656.54	-979.20	-488.19	658.35	328.23
14	0.473	1,316.88	622.31	-979.20	-462.74	658.35	311.12
15	0.448	1,316.88	589.87	7,330.19	3,283.43	338.54	151.64
16	0.425	-376.25	-159.75	-979.20	-415.75	658.35	279.52
17	0.402	1,316.88	529.97	-979.20	-394.08	658.35	264.95
18	0.381	1,316.88	502.34	4,616.99	1,761.22	338.54	129.14
19	0.362	1,316.88	476.15	-979.20	-354.06	658.35	238.05
20	0.343	1,316.88	451.33	1,734.00	594.29	658.35	225.64
21	0.325	1,316.88	427.80	4,616.99	1,499.88	338.54	109.98
22	0.308	1,316.88	405.50	-979.20	-301.52	658.35	202.72
23	0.292	1,316.88	384.36	-979.20	-285.80	658.35	192.15
24	0.277	-376.25	-104.09	4,616.99	1,277.32	338.54	93.66
25	0.262	1,316.88	345.33	1,734.00	454.71	658.35	172.64
26	0.249	1,316.88	327.33	-979.20	-243.39	658.35	163.64
27	0.236	1,316.88	310.26	4,616.99	1,087.78	338.54	79.76
28	0.223	1,316.88	294.09	-979.20	-218.68	658.35	147.02
29	0.212	1,316.88	278.76	-979.20	-207.28	658.35	139.36
30	0.201	1,316.88	264.22	7,330.19	1,470.76	338.54	67.93

3. Benefit-Cost Analysis

• Benefits per unit and monetary value of the benefits per unit

ECONOMIC VALUATION OF BENEFIT
Benefit Ranges per Unit and Unit Cost of Benefit Ranges

		Benefit per Unit					Cost per Unit				
Category	**Frequency**	**Unit**	**Minimum ($)**	**Maximum ($)**	**Average ($)**	**Notes/References**	**Unit**	**Minimum ($)**	**Maximum ($)**	**Average ($)**	**References**
1. Water											
Reduce storage needs											
Permeable Pavement	Storage size	%	3%	3%	3%	The percent reduction varies per GSI. This values are based on rainfall-runoff analysis of the site on. These value depends on the storm magnitude, soil type, and size of the GSI. Therefore, the inputs are site specific. Post-development storage need should be calculated first to include this benefit	ft^3	7.5	8.5	$8.00	Based on the type of the storage facility. This estimate is based on the installation of 4500 ADS
Rain Garden		%	9%	9%	9%						
Grassy Ditch		%	3.2%	3.2%	3.2%						
Reduces flooding and erosion											
Permeable Pavement	Rain event	%	3%	3%	3%	To convert this into a yearly benefit an annual rainfall magnitude is required. It is one of the inputs in the next Tab (The value here is for this study's specific site)	ft^3	0.051	0.051	0.051	
Rain Garden		%	15.3%	15.3%	15.3%						
Grassy Ditch		%	0.0%	0.0%	0.0%						
Improve water quality											
TSS and Metals Removal											
TSS	one time	mg/L	30.01	17.5	23.755			–	–	–	These benefits are reported qualitatively (non-monetary value)
Dissolved Cu	one time	µg/L	0.51	1.25	0.88	Nowal et al (2012),		–	–	–	
2. Energy											
Reduce energy use	yearly	kWh/ft^2	0.18	0.269	0.224	CNT (2011), and Mullaney et al., (2001).	kWh	0.10	0.63	0.365	City of Portland (2010), CNT (2011), and Mullaney et al., (2001), Elmqvist et al., (2015)
3. Air Quality											
Improve air quality						The economic value is related to the removal of the pollutants (cost per lb of pollutant removal)					The economic value is related to the removal of the pollutants (cost per lb of pollutant removal)
NO_2	yearly	lbs/ft^2	0.003000	0.00477	0.003885	Zhou et al. (2018), McPherson et al. (2005) CNT (2012), American Rivers, the Water Environment Federation (2011)	lbs	3.34	5.73	4.535	Zhou et al. (2018), McPherson et al. (2005) CNT (2012)
SO_2	yearly	lbs/ft^2	0.00588	0.00606	0.00597		lbs	2.06	4.78	3.42	
PM	yearly	lbs/ft^2	0.00114	0.004	0.00257		lbs	2.84	2.84	2.84	
4. Climate change											
Reduce atmospheric CO2	yearly	lbs CO_2/ft^2	0.267	2.132	1.1995	For permeable pavement- Zhou et al. (2018), Nordman et al. (2018)	lbs CO_2	0.05535	0.092	0.074	Elmqvist et al.,(2015), American Rivers, the Water Environment Federation (2011)
Direct Carbon Sequestration	yearly	lbs CO_2/ft^2	0.062	0.123	0.0925						
From saved electricity	yearly	lbs CO_2/kWh	1.51	1.51	1.51	CNT (2011)- Table 4.2					
5. Health											
Health Benefit due to removal of PM	yearly	lb of PM/ft^2	0.00114	0.004	0.00257	Zhou et al. (2018), McPherson et al. (2005) CNT (2012)	lb of PM/ft^2	1.89	3.20	2.545	City of Portland (2010), American Rivers, the Water Environment Federation, (2011)
6. Community											
Increase property values		%	2	10	6		%	2	10	6	The economic value depends on the areas mean house price

- ## Estimate of Economic Benefit of GSIs

Monetary Value of Benefit Calculation

Permeable Pavement

Area of Practice (ft^2) 7,525
Annual Rainfall (in) 60.52
post-dev. Storage need (ft^3) 35,315

BENEFIT			Benefits		Economic Values		Data Sources
			Resource Unit	Possible Annual Benefit	Price/ Resource Unit ($)	Annual Benefit Valuation ($)	
1. Water	Reduce Stormwater Runoff	Reduce storage needs	Avoided storage Construction (initial benefit)	ft^3 1059.45	8	$8,475.60	Hydrologic modeling
			Maintenance	1059.45	0.165	$174.81	Local Contractors, Environmental Finance Center, 2019
		Reduces flooding and erosion	Annual reduced amount of runoff	Gallon 8,519	0.051	$434.46	
		Improve water quality TSS	mg/L TSS 17.5	mg 563,517	NA	NA	
		Dissolved Cu	µg/L Cu 1.25	µg 2,817			
		Sub-Total				$9,084.87	
2. ENERGY		Reduce energy use	kWh/ft^2 0.18	kWh 1348.48	0.365	$492.20	CNT, 2011, Mullaney et al., 2015
		Sub-Total				$492.20	
3. CLIMATE CHANGE		Reduce atmospheric CO_2	Direct Carbon Sequestration in CO_2 Equivalent (lbs CO_2/ft^2) NA	lbs C NA	NA		CNT (2011), Nowak et al.(2012), Mullaney et al.,(2015), Nordhaus, (2017) McPherson et al. (2005), Zhou et al. (2018)*
		Reduced Energy use	Benefit from kWh of Electricity saveing (lbs CO_2/kWh) 1.51	lbs CO_2 avoided 2036.205	0.074	$150.02	
		Sub-Total				$150.02	
4. AIR QUALITY		Improve air quality	Pollutant uptake/deposit (lbs/ft^2)	lbs			The cost is related to the removal of the pollutants Environmental Services City of Portland, 2010, Elmqvist et al., 2015
			NO_2 NA	#VALUE!		#VALUE!	
			SO_2 NA	#VALUE!		#VALUE!	
			PM NA	#VALUE!		#VALUE!	
		Sub-Total					
5. Health			Health Benefit due to removal of PM PM NA	lbs PM NA			(city of Portland (2010))
			Pollutants can trigger asthma attacks as well as worsen bronchitis, emphysema, and other respiratory diseases. GSI improves the air qualt, provides health environment, and protects public health.				
		Sub-Total				NA	
6. COMMUNITY		Increase property values	Increase property value by (%) 1	Median property value in the area ($) 300000	0.01	3,000.00	(Jaffe, 2010)
		Improve habitat	Provide habitat and increase biodiversity.				
		Sub-Total				NA	
		Initial Benefits				$8,475.60	
		Annual Benefits				$1,251.48	
		Total Benefits				$9,727.08	

Rain Garden

Area of Practice (ft^2) 4,080
Annual Rainfall (in) 60.52

BENEFIT			Benefits		Economic Values		Data Sources
			Resource Unit	Possible Annual Benefit	Price/ Resource Unit ($)	Annual Benefit Valuation ($)	
1. Water	Reduce Stormwater Runoff	Reduce storage needs	Avoided storage Construction (initial benefit)	ft^3 3319.61	8	$26,556.88	Hydrologic modeling
			Maintenance	3,320	0.165	$547.74	Local Contractors, Environmental Finance Center, 2019
		Reduces flooding and erosion	Annual reduced amount of runoff	Gallon 23,556	0.051	$1,201.35	
		Improve water quality TSS	mg/L TSS 30.01	mg 2,672,137			
		Dissolved Cu	µg/L Cu 0.51	µg 3,178			
		Sub-Total				$28,305.97	
2. ENERGY		Reduce energy use	kWh/ft^2 0.2688	kWh 1096.704	0.365	$400.30	CNT, 2011, Mullaney et al., 2015
		Sub-Total				$400.30	
3. CLIMATE CHANGE		Reduce atmospheric CO_2	Direct Carbon Sequestration in CO_2 Equivalent (lbs CO_2/ft^2) 1.1995	lbs C 4893.96	$0.0737	$360.56	CNT, 2011, Nowak et al., 2012, Mullaney et al., 2015, Nordhaus, 2017
		Reduced Energy use	Benefit from kWh of Electricity saveing (lbs CO_2/kWh) 1.51	lbs CO_2 avoided 1656.02	$0.0737	$122	
		Sub-Total				$482.57	
4. AIR QUALITY		Improve air quality	Pollutant uptake/deposit (lbs/ft^2)	lbs			Environmental Services City of Portland, 2010, Elmqvist et al., 2015
			NO_2 0.00477	19.4616	$4.54	$88.26	
			SO_2 0.00606	24.7248	$3.42	$84.56	
			PM 0.004	16.32	$2.84	$46.35	
		Sub-Total				$219.17	
5. Health			Health Benefit due to removal of PM PM 0.004	lbs PM 16.320	3.20	52.22	
			Pollutants can trigger asthma attacks as well as worsen bronchitis, emphysema, and other respiratory diseases. GSI improves the air qualt, provides health environment, and protects public health.				
		Sub-Total				NA	
6. COMMUNITY		Increase property values	Increase property value by (%) 5	Average property value in the area ($) 300000	0.05	15,000.00	(Jaffe, 2010)
		Improve habitat	Provide habitat and increase biodiversity.				
		Sub-Total				NA	
		Initial Benefits				$26,556.88	
		Annual Benefits				$2,851.12	
		Total Benefits				$29,408.00	

Grassy Ditch

Area of Practice (ft^2) 2,310
Annual Rainfall (in) 60.52

BENEFIT			Benefits		Economic Values		Data Sources
			Resource Unit	Possible Annual Benefit	Price/ Resource Unit ($)	Annual Benefit Valuation ($)	
1. Water	Reduce Stormwater Runoff	Reduce storage needs	Avoided storage Construction (initial benefit)	ft^3 1130	8	$9,040.64	Hydrologic modeling
			Maintenance	1130	0.165	$186.46	Local Contractors, Environmental Finance Center, 2019
		Reduces flooding and erosion	Annual reduced amount of runoff	Gallon 0	0.051	$0.00	
		Improve water quality TSS	mg/L TSS 30.01	mg 0			
		Dissolved Cu	µg/L Cu 0.51	µg 0			
		Sub-Total				$9,227.10	
2. ENERGY		Reduce energy use	kWh/ft^2 0.18	kWh 413.952	0.365	$151.09	CNT, 2011, Mullaney et al., 2015
		Sub-Total				$151.09	
3. CLIMATE CHANGE		Reduce atmospheric CO_2	Direct Carbon Sequestration in CO_2 Equivalent (lbs CO_2/ft^2) 0.062	lbs C 143.22	$0.01550	$2.22	CNT, 2011, Nowak et al., 2012, Mullaney et al., 2015, Nordhaus, 2017
		Reduced Energy use	Benefit from kWh of Electricity saveing (lbs CO_2/kWh) 1.51	lbs CO_2 avoided 625.07	$0.074	$46.1	
		Sub-Total				$48.27	
4. AIR QUALITY		Improve air quality	Pollutant uptake/deposit (lbs/ft^2)	lbs			Environmental Services City of Portland, 2010, Elmqvist et al., 2015
			NO_2 0.0039	8.97435	$4.54	$40.70	
			SO_2 0.0060	13.7907	$3.42	$47.16	
			PM 0.0026	5.9367	$2.84	$16.86	
		Sub-Total				$104.72	
5. Health			Health Benefit due to removal of PM PM 0.00	lbs PM 5.9367	3.20	19.00	
			Pollutants can trigger asthma attacks as well as worsen bronchitis, emphysema, and other respiratory diseases. GSI improves the air qualt, provides health environment, and protects public health.				
		Sub-Total				NA	
6. COMMUNITY		Increase property values	Increase property value by (%) 3	Average property value in the area ($) 300000	0.03	9,000.00	(Jaffe, 2010)
		Improve habitat	Provide habitat and increase biodiversity.				
		Sub-Total				NA	
		Initial Benefits				$9,040.64	
		Annual Benefits				$234.73	
		Total Benefits				$9,275.37	

- **Present Value of Benefits (PVB)**

Whole Life-cycle Benefit and Present Value of Benefits (PVB) of GSI Scenarios

	GSI 1	GSI 2	GSI 3
	Permeable Pavement	Rain Garden	Grassy Ditch
Initial Benefit ($)	$8,476	$26,557	$9,041
Yearly Benefit ($)	$1,251	$2,851	$235
Discount Rate (%)	5.5	5.5	5.5
Design period (Years)	30	30	30

Year	Discount Factor	GSI 1 Initial Benefit	GSI 1 Yearly Benefit	GSI 1 Present Value	GSI 2 Initial Benefit	GSI 2 Yearly Benefit	GSI 2 Present Value	GSI 3 Initial Benefit	GSI 3 Yearly Benefit	GSI 3 Present Value
Cash Sum ($)		$8,476	$37,544	$26,664	$26,557	$85,534	$67,994	$9,041	$7,042	$12,452
0	1.000	8,475.60	0.00	8,475.60	26,556.88	0.00	26,556.88	9,040.64	0.00	9,040.64
1	0.948	$0	1,251.48	1,186.24	$0	2,851.12	2,702.49	$0	234.73	222.50
2	0.898	$0	1,251.48	1,124.39	$0	2,851.12	2,561.60	$0	234.73	210.90
3	0.852	$0	1,251.48	1,065.78	$0	2,851.12	2,428.06	$0	234.73	199.90
4	0.807	$0	1,251.48	1,010.22	$0	2,851.12	2,301.47	$0	234.73	189.48
5	0.765	$0	1,251.48	957.55	$0	2,851.12	2,181.49	$0	234.73	179.60
6	0.725	$0	1,251.48	907.63	$0	2,851.12	2,067.76	$0	234.73	170.24
7	0.687	$0	1,251.48	860.31	$0	2,851.12	1,959.97	$0	234.73	161.37
8	0.652	$0	1,251.48	815.46	$0	2,851.12	1,857.79	$0	234.73	152.95
9	0.618	$0	1,251.48	772.95	$0	2,851.12	1,760.94	$0	234.73	144.98
10	0.585	$0	1,251.48	732.65	$0	2,851.12	1,669.13	$0	234.73	137.42
11	0.555	$0	1,251.48	694.46	$0	2,851.12	1,582.12	$0	234.73	130.26
12	0.526	$0	1,251.48	658.25	$0	2,851.12	1,499.64	$0	234.73	123.47
13	0.499	$0	1,251.48	623.94	$0	2,851.12	1,421.46	$0	234.73	117.03
14	0.473	$0	1,251.48	591.41	$0	2,851.12	1,347.35	$0	234.73	110.93
15	0.448	$0	1,251.48	560.58	$0	2,851.12	1,277.11	$0	234.73	105.15
16	0.425	$0	1,251.48	531.35	$0	2,851.12	1,210.53	$0	234.73	99.66
17	0.402	$0	1,251.48	503.65	$0	2,851.12	1,147.42	$0	234.73	94.47
18	0.381	$0	1,251.48	477.40	$0	2,851.12	1,087.61	$0	234.73	89.54
19	0.362	$0	1,251.48	452.51	$0	2,851.12	1,030.91	$0	234.73	84.88
20	0.343	$0	1,251.48	428.92	$0	2,851.12	977.16	$0	234.73	80.45
21	0.325	$0	1,251.48	406.56	$0	2,851.12	926.22	$0	234.73	76.26
22	0.308	$0	1,251.48	385.36	$0	2,851.12	877.93	$0	234.73	72.28
23	0.292	$0	1,251.48	365.27	$0	2,851.12	832.16	$0	234.73	68.51
24	0.277	$0	1,251.48	346.23	$0	2,851.12	788.78	$0	234.73	64.94
25	0.262	$0	1,251.48	328.18	$0	2,851.12	747.66	$0	234.73	61.56
26	0.249	$0	1,251.48	311.07	$0	2,851.12	708.68	$0	234.73	58.35
27	0.236	$0	1,251.48	294.85	$0	2,851.12	671.74	$0	234.73	55.30
28	0.223	$0	1,251.48	279.48	$0	2,851.12	636.72	$0	234.73	52.42
29	0.212	$0	1,251.48	264.91	$0	2,851.12	603.52	$0	234.73	49.69
30	0.201	$0	1,251.48	251.10	$0	2,851.12	572.06	$0	234.73	47.10

- **Net Present Value (NPV) Calculation. NPV = PVB – PVC**

Net Present Value (NPV) Calculation

Discount Factor 5.5

GSI type		GSI 1 Permeable Pavement						GSI 2 Rain Garden						GSI 3 Grassy Ditch					
		Expected Benefit		Expected Cost		Net (Benefit-Cost)		Benefit		Cost		Net (Benefit-Cost)		Benefit		Cost		Net (Benefit-Cost)	
Year	Discount Factor	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)	Cash flow ($)	Present value ($)
					80,811		**-54,147**		**67,994**		**54,207**		**13,787**		**12,452**		**10,989**		**1,464**
0	1.000	8,475.60	8,475.60	63,962.50	63,962.50	-55,486.90	-55,486.90	26,556.88	26,556.88	35,700.00	35,700.00	-9,143.12	-9,143.12	9,040.64	9,040.64	2,887.50	2,887.50	6,153.14	6,153.14
1	0.948	1,251.48	1,186.24	1,316.88	1,248.22	-65.40	-61.99	2,851.12	2,702.49	-979.20	-928.15	3,830.32	3,630.64	234.73	222.50	658.35	624.03	-423.62	-401.53
2	0.898	1,251.48	1,124.39	1,316.88	1,183.15	-65.40	-58.75	2,851.12	2,561.60	-979.20	-879.76	3,830.32	3,441.36	234.73	210.90	658.35	591.50	-423.62	-380.60
3	0.852	1,251.48	1,065.78	1,316.88	1,121.47	-65.40	-55.69	2,851.12	2,428.06	4,616.99	3,931.89	-1,765.86	-1,503.83	234.73	199.90	338.54	288.30	-103.80	-88.40
4	0.807	1,251.48	1,010.22	1,316.88	1,063.00	-65.40	-52.79	2,851.12	2,301.47	-979.20	-790.43	3,830.32	3,091.90	234.73	189.48	658.35	531.43	-423.62	-341.95
5	0.765	1,251.48	957.55	1,316.88	1,007.59	-65.40	-50.04	2,851.12	2,181.49	1,734.00	1,326.74	1,117.12	854.75	234.73	179.60	658.35	503.73	-423.62	-324.12
6	0.725	1,251.48	907.63	1,316.88	955.06	-65.40	-47.43	2,851.12	2,067.76	4,616.99	3,348.45	-1,765.86	-1,280.69	234.73	170.24	338.54	245.52	-103.80	-75.28
7	0.687	1,251.48	860.31	1,316.88	905.27	-65.40	-44.96	2,851.12	1,959.97	-979.20	-673.14	3,830.32	2,633.10	234.73	161.37	658.35	452.57	-423.62	-291.21
8	0.652	1,251.48	815.46	-376.25	-245.16	1,627.73	1,060.63	2,851.12	1,857.79	-979.20	-638.05	3,830.32	2,495.83	234.73	152.95	658.35	428.98	-423.62	-276.03
9	0.618	1,251.48	772.95	1,316.88	813.34	-65.40	-40.39	2,851.12	1,760.94	4,616.99	2,851.59	-1,765.86	-1,090.65	234.73	144.98	338.54	209.09	-103.80	-64.11
10	0.585	1,251.48	732.65	1,316.88	770.94	-65.40	-38.28	2,851.12	1,669.13	1,734.00	1,015.14	1,117.12	654.00	234.73	137.42	658.35	385.42	-423.62	-248.00
11	0.555	1,251.48	694.46	1,316.88	730.75	-65.40	-36.29	2,851.12	1,582.12	-979.20	-543.37	3,830.32	2,125.49	234.73	130.26	658.35	365.33	-423.62	-235.07
12	0.526	1,251.48	658.25	1,316.88	692.65	-65.40	-34.40	2,851.12	1,499.64	4,616.99	2,428.45	-1,765.86	-928.81	234.73	123.47	338.54	178.06	-103.80	-54.60
13	0.499	1,251.48	623.94	1,316.88	656.54	-65.40	-32.60	2,851.12	1,421.46	-979.20	-488.19	3,830.32	1,909.65	234.73	117.03	658.35	328.23	-423.62	-211.20
14	0.473	1,251.48	591.41	1,316.88	622.31	-65.40	-30.90	2,851.12	1,347.35	-979.20	-462.74	3,830.32	1,810.09	234.73	110.93	658.35	311.12	-423.62	-200.19
15	0.448	1,251.48	560.58	1,316.88	589.87	-65.40	-29.29	2,851.12	1,277.11	7,330.19	3,283.43	-4,479.06	-2,006.32	234.73	105.15	338.54	151.64	-103.80	-46.50
16	0.425	1,251.48	531.35	-376.25	-159.75	1,627.73	691.10	2,851.12	1,210.53	-979.20	-415.75	3,830.32	1,626.28	234.73	99.66	658.35	279.52	-423.62	-179.86
17	0.402	1,251.48	503.65	1,316.88	529.97	-65.40	-26.32	2,851.12	1,147.42	-979.20	-394.08	3,830.32	1,541.50	234.73	94.47	658.35	264.95	-423.62	-170.48
18	0.381	1,251.48	477.40	1,316.88	502.34	-65.40	-24.95	2,851.12	1,087.61	4,616.99	1,761.22	-1,765.86	-673.62	234.73	89.54	338.54	129.14	-103.80	-39.60
19	0.362	1,251.48	452.51	1,316.88	476.15	-65.40	-23.65	2,851.12	1,030.91	-979.20	-354.06	3,830.32	1,384.96	234.73	84.88	658.35	238.05	-423.62	-153.17
20	0.343	1,251.48	428.92	1,316.88	451.33	-65.40	-22.41	2,851.12	977.16	1,734.00	594.29	1,117.12	382.87	234.73	80.45	658.35	225.64	-423.62	-145.19
21	0.325	1,251.48	406.56	1,316.88	427.80	-65.40	-21.24	2,851.12	926.22	4,616.99	1,499.88	-1,765.86	-573.66	234.73	76.26	338.54	109.98	-103.80	-33.72
22	0.308	1,251.48	385.36	1,316.88	405.50	-65.40	-20.14	2,851.12	877.93	-979.20	-301.52	3,830.32	1,179.45	234.73	72.28	658.35	202.72	-423.62	-130.44
23	0.292	1,251.48	365.27	1,316.88	384.36	-65.40	-19.09	2,851.12	832.16	-979.20	-285.80	3,830.32	1,117.97	234.73	68.51	658.35	192.15	-423.62	-123.64
24	0.277	1,251.48	346.23	-376.25	-104.09	1,627.73	450.32	2,851.12	788.78	4,616.99	1,277.32	-1,765.86	-488.54	234.73	64.94	338.54	93.66	-103.80	-28.72
25	0.262	1,251.48	328.18	1,316.88	345.33	-65.40	-17.15	2,851.12	747.66	1,734.00	454.71	1,117.12	292.95	234.73	61.56	658.35	172.64	-423.62	-111.09
26	0.249	1,251.48	311.07	1,316.88	327.33	-65.40	-16.25	2,851.12	708.68	-979.20	-243.39	3,830.32	952.08	234.73	58.35	658.35	163.64	-423.62	-105.29
27	0.236	1,251.48	294.85	1,316.88	310.26	-65.40	-15.41	2,851.12	671.74	4,616.99	1,087.78	-1,765.86	-416.05	234.73	55.30	338.54	79.76	-103.80	-24.46
28	0.223	1,251.48	279.48	1,316.88	294.09	-65.40	-14.60	2,851.12	636.72	-979.20	-218.68	3,830.32	855.39	234.73	52.42	658.35	147.02	-423.62	-94.60
29	0.212	1,251.48	264.91	1,316.88	278.76	-65.40	-13.84	2,851.12	603.52	-979.20	-207.28	3,830.32	810.80	234.73	49.69	658.35	139.36	-423.62	-89.67
30	0.201	1,251.48	251.10	1,316.88	264.22	-65.40	-13.12	2,851.12	572.06	7,330.19	1,470.76	-4,479.06	-898.70	234.73	47.10	338.54	67.93	-103.80	-20.83

- **Internal Rate of Return Calculation**

Internal Rate of Return (IRR) Calculation

$$IRR \Rightarrow \text{NPV} = \sum_{y=0}^{n} C_y \frac{1}{(1+IRR)^y} = 0$$

IRR		
-15.0%	21.3%	3.2%

GSI 1

Permeable Pavement

Expected Benefit	Expected Cost	Net
Cash flow ($)	Cash flow ($)	Cash flow ($)
8,475.60	63,962.50	-55,486.90
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	-376.25	1,627.73
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	-376.25	1,627.73
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	-376.25	1,627.73
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40
1,251.48	1,316.88	-65.40

GSI 2

Rain Garden

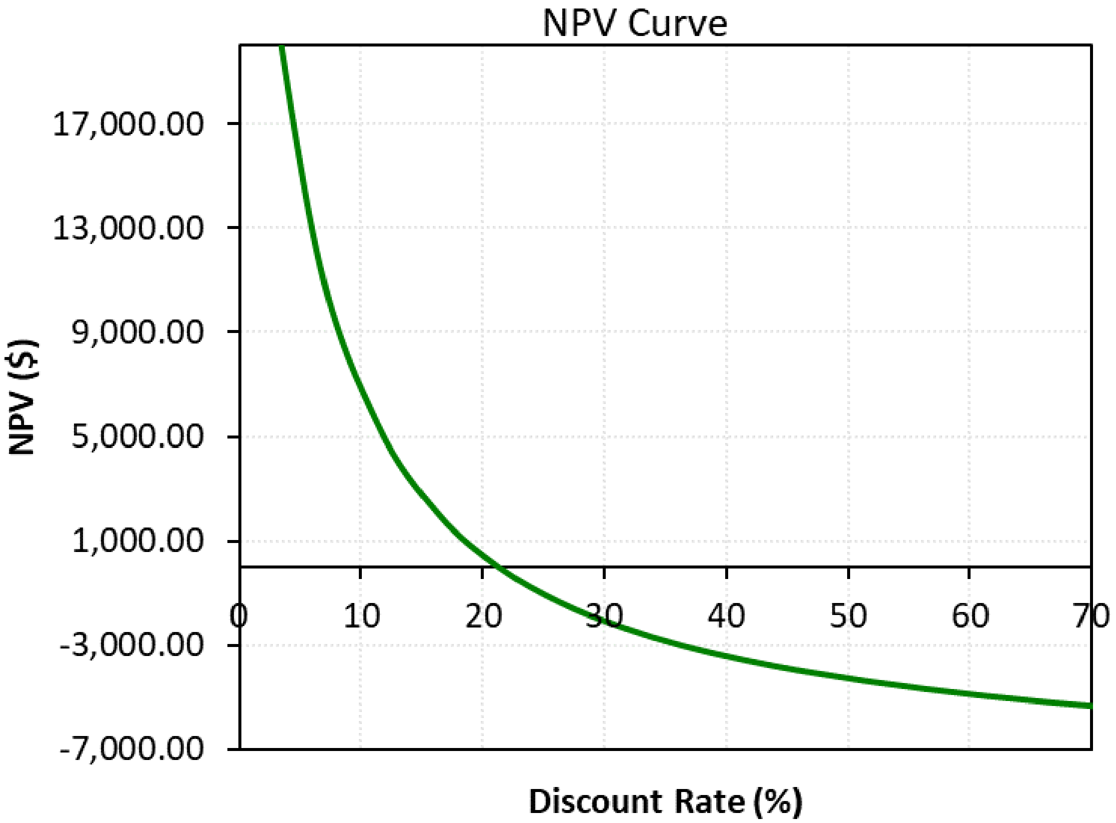
Expected Benefit	Expected Cost	Net
Cash flow ($)	Cash flow ($)	Cash flow ($)
26,556.88	35,700.00	-9,143.12
2,851.12	-979.20	3,830.32
2,851.12	-979.20	3,830.32
2,851.12	4,616.99	-1,765.86
2,851.12	-979.20	3,830.32
2,851.12	1,734.00	1,117.12
2,851.12	4,616.99	-1,765.86
2,851.12	-979.20	3,830.32
2,851.12	-979.20	3,830.32
2,851.12	4,616.99	-1,765.86
2,851.12	1,734.00	1,117.12
2,851.12	-979.20	3,830.32
2,851.12	4,616.99	-1,765.86
2,851.12	-979.20	3,830.32
2,851.12	-979.20	3,830.32
2,851.12	7,330.19	-4,479.06
2,851.12	-979.20	3,830.32
2,851.12	-979.20	3,830.32
2,851.12	4,616.99	-1,765.86
2,851.12	-979.20	3,830.32
2,851.12	1,734.00	1,117.12
2,851.12	4,616.99	-1,765.86
2,851.12	-979.20	3,830.32
2,851.12	-979.20	3,830.32
2,851.12	4,616.99	-1,765.86
2,851.12	1,734.00	1,117.12
2,851.12	-979.20	3,830.32
2,851.12	4,616.99	-1,765.86
2,851.12	-979.20	3,830.32
2,851.12	-979.20	3,830.32
2,851.12	7,330.19	-4,479.06

GSI 3

Grassy Ditch

Expected Benefit	Expected Cost	Net
Cash flow ($)	Cash flow ($)	Cash flow ($)
9,040.64	2,887.50	6,153.14
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80
234.73	658.35	-423.62
234.73	658.35	-423.62
234.73	338.54	-103.80

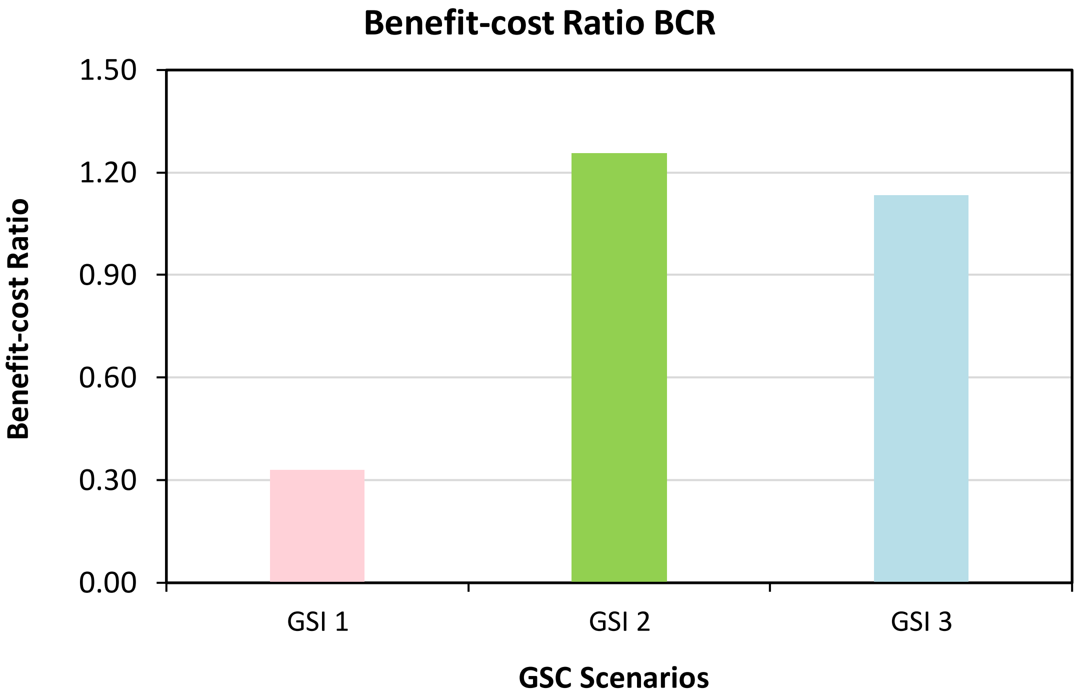
- **NPV Curve for the rain garden scenario**



- **Benefit-cost Ratio Calculation**

Benefit-cost Ratio of GSI Scenarios

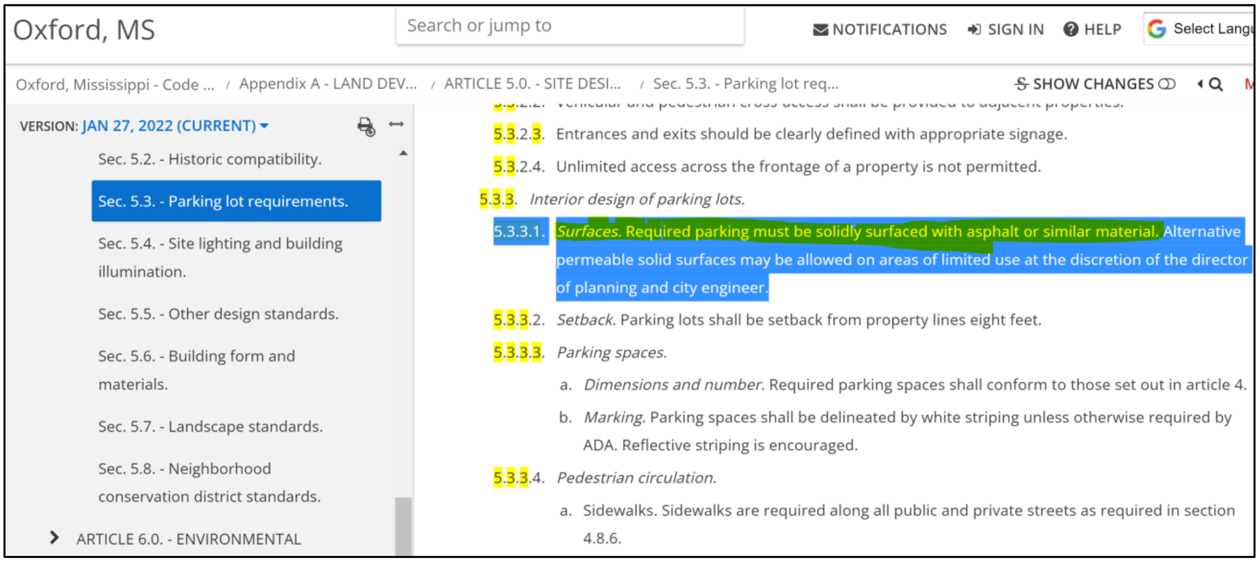
GSI Scenarios	Present Value of Benefits PVB	Present Value of Costs PVC	Benefit-cost Ratio BCR
GSI 1	$26,664	$80,811	0.33
GSI 2	$67,994	$54,207	1.25
GSI 3	$12,452	$10,989	1.13



APPENDIX C: REGULATORY ANALYSIS

- **City Ordinances**

a) Oxford, MS



5.3.2.3. Entrances and exits should be clearly defined with appropriate signage.

5.3.2.4. Unlimited access across the frontage of a property is not permitted.

5.3.3. *Interior design of parking lots.*

5.3.3.1. *Surfaces.* Required parking must be solidly surfaced with asphalt or similar material. Alternative permeable solid surfaces may be allowed on areas of limited use at the discretion of the director of planning and city engineer.

5.3.3.2. *Setback.* Parking lots shall be setback from property lines eight feet.

5.3.3.3. *Parking spaces.*

a. *Dimensions and number.* Required parking spaces shall conform to those set out in article 4.

b. *Marking.* Parking spaces shall be delineated by white striping unless otherwise required by ADA. Reflective striping is encouraged.

5.3.3.4. *Pedestrian circulation.*

a. Sidewalks. Sidewalks are required along all public and private streets as required in section 4.8.6.

b) Biloxi, MS

(Ord. No. 2192, Art. 26, 11-29-11)

Sec. 16.5-27. - Design storm frequency.

(a) The minimum design frequency for drainage facilities and structures shall be a 100-year, 24-hour storm occurrence. Drainage calculations shall be submitted to the engineering division evaluating stormwater runoff pre- and post- development. Post-development peak stormwater runoff from a 100-year, 24-hour storm event shall not exceed the same storm event pre-construction. At a minimum the first one-inch of runoff from the 100-year, 24-hour storm event shall be detained onsite for water quality. Residential single family homes are exempt from this requirement.

(b) Upon recommendation by the city engineer and the director of community development to the mayor, the mayor may approve a lesser storm water requirement for a specific development upon a fact-based recommendation from a civil engineer licensed in Mississippi that a lesser requirement for that development will not adversely impact the public's interest in stormwater control within the drainage basin in which the development is located and will not adversely impact the public interest in stormwater control within the specific development site requesting the lesser requirement.

(Ord. No. 2215, § 1, 10-16-12; Ord. No. 2290 , § 1, 12-29-2015)

c) Orange Beach, AL

(Ord. No. 2003-741, § 2.4, 4-1-2003)

Secs. 42-250—42-270. - Reserved.

DIVISION 3. - RETENTION/DETENTION PLANNING FOR PROPOSED STORMWATER DISCHARGES

Sec. 42-271. - Goals.

As part of the city's effort to minimize water quality problems in its adjacent and internal water bodies, the primary goal of its retention/detention planning is to eliminate any direct discharges to the Gulf of Mexico, Gulf beaches, coastal dunes, the Intercoastal Waterway and any contiguous surface waters thereof, or wetlands. In addition, no direct discharges originating from storms less than or equal to a 25-year, 24-hour event will be made to the Intercoastal Waterway or Wolf Bay. To achieve these goals, the city encourages the use of retention/detention areas in future developments. However, other acceptable engineering methods, such as exfiltration/infiltration devices, may be approved.

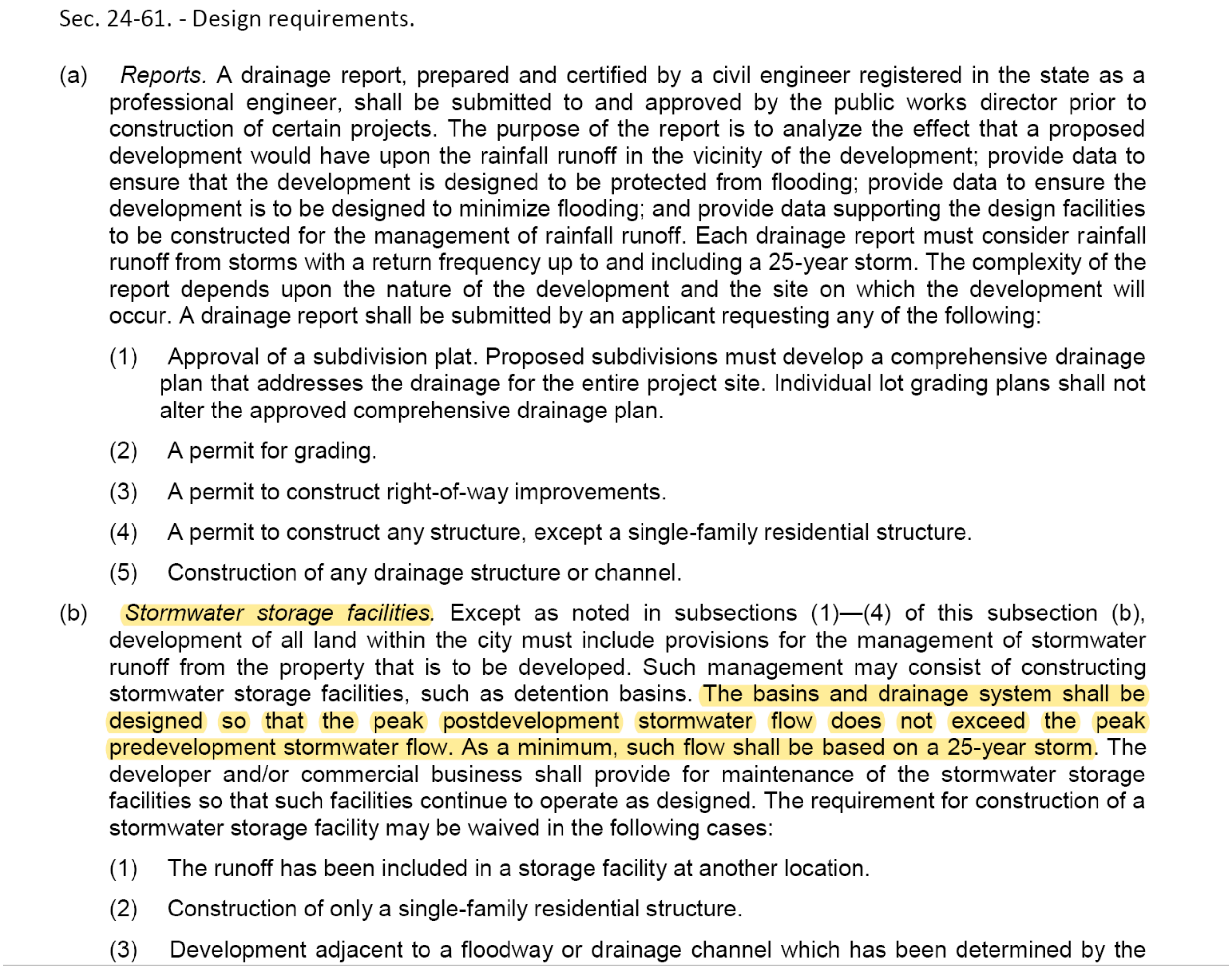
(Ord. No. 2003-741, § 3.1, 4-1-2003)

Sec. 42-272. - Methods of discharge disposal.

(a) Runoff and other associated discharges resulting from a 25-year, 24-hour storm event (or less) should be handled through the design and maintenance of retention/detention areas or exfiltration/infiltration systems where approved. For those storm events greater than this magnitude, other options should be considered to detain runoff so no direct discharge to the aforementioned areas occurs.

(b) Localized depressions should be evaluated to capture the direct runoff generated by storm events larger than the 25-year, 24-hour rainfall. These depressions, human-made or natural, could be localized wetland areas, but would not possess the characteristics (e.g. hydrologic, ecological, etc.) representative of state jurisdictional wetlands, as determined by ADEM, or federal jurisdictional wetlands, as determined by the USACOE. Thus, they must be non-contiguous with other water bodies. The plants, microorganisms, and soils found in these non-contiguous wetlands help cleanse some of the water quality contaminants associated with urban stormwater runoff.

d) Ruston, LA



Sec. 24-61. - Design requirements.

(a) *Reports.* A drainage report, prepared and certified by a civil engineer registered in the state as a professional engineer, shall be submitted to and approved by the public works director prior to construction of certain projects. The purpose of the report is to analyze the effect that a proposed development would have upon the rainfall runoff in the vicinity of the development; provide data to ensure that the development is designed to be protected from flooding; provide data to ensure the development is to be designed to minimize flooding; and provide data supporting the design facilities to be constructed for the management of rainfall runoff. Each drainage report must consider rainfall runoff from storms with a return frequency up to and including a 25-year storm. The complexity of the report depends upon the nature of the development and the site on which the development will occur. A drainage report shall be submitted by an applicant requesting any of the following:

(1) Approval of a subdivision plat. Proposed subdivisions must develop a comprehensive drainage plan that addresses the drainage for the entire project site. Individual lot grading plans shall not alter the approved comprehensive drainage plan.

(2) A permit for grading.

(3) A permit to construct right-of-way improvements.

(4) A permit to construct any structure, except a single-family residential structure.

(5) Construction of any drainage structure or channel.

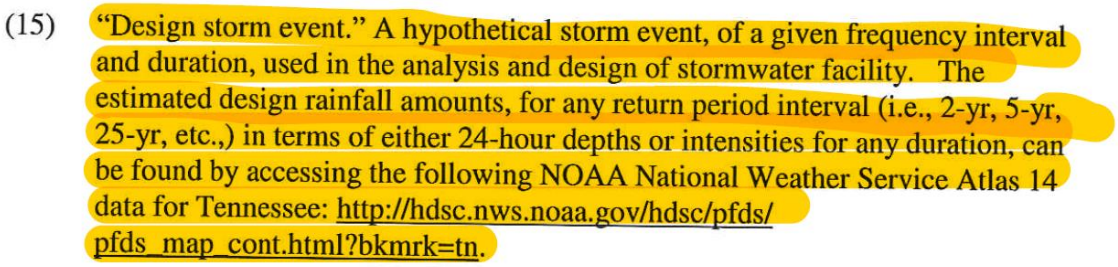
(b) *Stormwater storage facilities*. Except as noted in subsections (1)—(4) of this subsection (b), development of all land within the city must include provisions for the management of stormwater runoff from the property that is to be developed. Such management may consist of constructing stormwater storage facilities, such as detention basins. The basins and drainage system shall be designed so that the peak postdevelopment stormwater flow does not exceed the peak predevelopment stormwater flow. As a minimum, such flow shall be based on a 25-year storm. The developer and/or commercial business shall provide for maintenance of the stormwater storage facilities so that such facilities continue to operate as designed. The requirement for construction of a stormwater storage facility may be waived in the following cases:

(1) The runoff has been included in a storage facility at another location.

(2) Construction of only a single-family residential structure.

(3) Development adjacent to a floodway or drainage channel which has been determined by the

e) Sevierville, TN



(15) "Design storm event." A hypothetical storm event, of a given frequency interval and duration, used in the analysis and design of stormwater facility. The estimated design rainfall amounts, for any return period interval (i.e., 2-yr, 5-yr, 25-yr, etc.,) in terms of either 24-hour depths or intensities for any duration, can be found by accessing the following NOAA National Weather Service Atlas 14 data for Tennessee: http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=tn.

VITA

Education

2022	Ph.D. in Engineering Science University of Mississippi
2015	M. Sc. in Civil Engineering University of Mississippi
2008	B. Sc. in Civil Engineering Jimma University

Professional Experience

August 2013 - May 2015 and August 2018 – Present	Teaching Assistant University of Mississippi
September 2015 – September 2016	Associate Research and Development Engineer University of Mississippi National Center for Physical Acoustics
January 2009 - July 2012	Infrastructure Engineer World Vision Ethiopia

Awards and Grants

- Graduate Student Council Research Symposium Podium Presentation 2nd Place winner at the University of Mississippi (2022).
- Society of Women Engineers (SWE) Bertha-Lamme Memorial Scholarship Award (2021).
- 3MT overall winner of the University of Mississippi competition and Conference of Southern Graduate Schools (CSGS) final competitor (2021).
- Alabama/Mississippi Section of the American Water Works Association Scholarship Award (2020).
- Graduate Student Council Research Grant from the University of Mississippi Office of Research and Sponsored Programs and the Graduate School at the University of Mississippi (2020). https://egrove.olemiss.edu/gsc_researchgrants/1
- Outstanding Teaching Assistant Award from the University of Mississippi Department of Civil Engineering (2019).
- Certificate of Excellence for Final Year Project from Jimma University Faculty of Technology (2008).
- Certificate of Appreciation for Senior Thesis from Jimma University Civil Engineering Department (2008).

Publications and Presentations

- Liya E. Abera, Cristiane Q. Surbeck, and Kristina L. Alexander. “Site-scale Whole Life-cycle Cost-benefit Analysis of Green Stormwater Infrastructure.” Presented at the ASCE World Environmental &Water Resources Congress, June 2022.

- Liya E. Abera, Cristiane Q. Surbeck, and Kristina Alexander (2021) “Evaluating the effect of city ordinance on the implementation and performance of green stormwater infrastructure (GSI).” ELSEVIER Journal of Environmental Challenges.

- Liya E. Abera, Cristiane Q. Surbeck, and Kristina L. Alexander. “Effect of City Regulations on the Implementation of Green Stormwater Infrastructure.” Presented at the ASCE World Environmental &Water Resources Congress, June 2021.

- Liya E. Abera, Cristiane Q. Surbeck, and Kristina L. Alexander. “Determining Implementation Barriers for Green infrastructure for Coastal Flood Control. “ Presented at the 2020 Bays and Bayous Symposium, December 2020.

- Abera L. E., Surbeck C. Q., and O'Reilly A. M. (2018) “Simulated Performance of In-Place Pervious Concrete under Varying Storms, Surface Areas, and Infiltration Rates.” ASCE Journal of Sustainable Water in the Built Environment.

- Liya E. Abera and Cristiane Q. Surbeck. “Analysis of Pervious Concrete as a Stormwater Management Tool Using Stormwater Management Modeling (SWMM).” Presented at the Mississippi Water Resources Conference (MWRC), April 2015.