CREATING GREEN INFRASTRUCTURE DESIGN GUIDELINES USING PRE-DESIGN PARAMETER OPTIMIZATION

By

Dustin Krise

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ABSTRACT

Urban areas across the country are facing serious flooding and water quality issues, causing significant environmental, economic, and social effects on communities. As the climate changes, increased precipitation and more frequent heavy rain fall events will exacerbate these problems, further degrading the environment. Green infrastructure can mitigate these issues, resulting in a variety of benefits, and has been actively implemented since the late 1990s. There is a significant amount of literature examining the post-occupancy effects of green infrastructure projects, yet there exists little optimization-based guidance on the best design procedures to maximize and balance its economic and environmental benefits. This research created a set of design guidelines for the design of green infrastructure systems, based on pre-design parametric (or sensitivity) analysis. Three models retrieved from the Landscape Performance Series from the Landscape Architecture Foundation were examined and analyzed, creating a hierarchy of the most important types of green infrastructure facilities involved in the design process. The created guidelines were applied to a design of a 659 acre site in Lansing, Michigan, USA, spanning the Grand River's course through Downtown, to confirm their validity, practicability, and functionality. Accordingly, post-design performance was calculated using a series of landscape performance models. The results showed that the most important green infrastructure facilities in reducing runoff while balancing capital and maintenance costs were rain gardens, street planters, infiltration basins, wetlands, and vegetation filter strips. The design framework was used to create a design of the site, leading to a 50% reduction in annual runoff volume, 9 – 16% reductions in water pollution levels, and significant carbon sequestration. The study provides a new way to gain site-specific insights into the design of green infrastructure projects across the nation.

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CHAPTER 1 - INTRODUCTION

As urbanization has progressed in the past few centuries, natural systems have often been displaced in favor of man-made infrastructure systems. One of these systems is the stormwater management system. Conveyance-based gray stormwater systems have been widely implemented in urban areas across the United States and the world (US EPA, 2015). Recent research has shown that these systems are the cause of a large number of urban issues, environmentally, economically, and socially. One example is the severe flooding incident in Midland, Michigan in 2020, which resulted in flash floods and the evacuation of thousands of residents, and caused over $200 million in damages to 2,500 buildings (Beggin, 2020). Additionally, water quality issues have threatened both wildlife and human health, with many rivers becoming contaminated with harmful levels of E.Coli after heavy rainfalls in urban watersheds (Hanshue & Harrington, 2017). Development has also resulted in the loss of access to nature, both as habitats for wildlife and recreational spaces for humans (US EPA, 2015).

As the climate changes going forward, these issues will exacerbate (Zhang et al., 2020). Since 1900, the amount of precipitation in the Great Lakes region has increased by 10%, and precipitation is projected to increase even further in the coming decades. Beyond the amount of precipitation change, its patterns will also change dramatically. Summer and winter precipitation is predicted to fall, leading to higher precipitation in the spring and fall months, concentrated in larger events (*An Assessment of the Impacts of Climate Change on the Great Lakes Region*, 2019). These larger events can be particularly detrimental, overflowing grey infrastructure systems and leading to flooding and water quality issues (Hanshue & Harrington, 2017).

To combat these problems, many projects have been developed to design and implement green infrastructure solutions. These projects prioritize using natural systems to capture, infiltrate, and treat stormwater runoff (Benedict & MacMahon, 2002). As a result, environmental, economic, and social benefits have been realized (Sohn et al., 2014, 2019).To better understand the effects that these projects have on the local environment, economy, and communities, various computer-based models and toolkits have been developed to predict the benefits of these systems. Within the field of landscape architecture, these models have been widely adopted at the post-design phase to predict the benefits of alternative design solutions (Canfield et al., 2018).

Extensive research has been done with these models, predicting the environmental, economic, and social benefits of green infrastructure designs (Canfield et al., 2018). Two studies of design projects in Michigan, USA used landscape performance models as a tool to determine the design impacts (Shevela et al., 2022; S. Yang et al., 2020). However, little research has been conducted on the use of these toolkits in the pre-design phase. The present research focuses on using a set of sensitivity analyses with certain landscape performance models to determine a hierarchy of the most important green infrastructure types in minimizing runoff issues in the pre-design phase. This hierarchy was then applied to the design of a specific site located in downtown Lansing, Michigan, USA. The results of the design were assessed to verify the effectiveness of this pre-design modeling method in providing informed decisions to landscape designers, developers, and contractors, in order to maximize the benefits of applying green infrastructure to the site.

CHAPTER 2 - LITERATURE REVIEW

2.1 Stormwater Management and Green Infrastructure

Many conventional stormwater management systems are based on gray infrastructure, which aims to transport water into the nearest water body as quickly as possible. Gray infrastructure is defined as “human-made structures using hard building materials”, such as sewers, dams, and seawalls (Szönyi & Svensson, 2019). Gray infrastructure systems are primarily designed to protect public health, safety, and property by directing water away from people and infrastructure (Dupont, 2017). However, this conveyance can lead to a range of water quality and flooding issues, which have negative environmental, economic, and social effects on the surrounding regions. With the absence of natural systems, overflows from sanitary and combined sewer systems, industrial pollutants, and non-point pollution sources such as road or lawn chemicals easily contaminate the local watersheds (Hanshue & Harrington, 2017). Climate change will exacerbate these problems. Heavy rain events will increase in frequency and severity over the coming decades, leading to higher amounts of pollutants and contaminants to be swept untreated into the water cycle. Additionally, rising air temperatures will correlate with increased water temperatures, damaging rivers’ natural systems that serve to protect and clean water (Carlson et al., 2020).

2.1.1 Sustainable Stormwater Management

To prevent and mitigate these problems, many municipalities have begun exploring alternative stormwater management options. In the past decades, the concept of “sustainability” has gained widespread popularity. Sustainability focuses not just on human needs, but also on environmental, social, and economic health (UCLA Sustainability, 2023). This trend has emerged in stormwater management practices with a desire to prioritize not only stormwater conveyance but also on other social, economic, and environmental benefits. As a result, a paradigm shift has occurred, with many municipalities having integrated sustainable stormwater management practices in urban design (Darnthamrongkul & Mozingo, 2021).

Sustainable stormwater management aims to treat "stormwater as a resource to be valued, not waste to be managed" (NACTO, 2017). As Liptan (2017) discusses in his book, best management practices incorporate multifaceted principles that prioritize green, biological solutions over traditional gray, mechanical infrastructure. Sustainable systems often involve a combination of green and gray infrastructure, maximizing benefits all around the board. Additionally, other key principles can further enhance the effectiveness of sustainable stormwater management practices. It is important to note that geography plays a large role in the field, and differences in climate and other geographic context can lead to significant variations in best stormwater management practices and how they should be applied. Flexibility is important in stormwater design, focusing on adapting to local characteristics and contexts (Barbosa et al., 2012).

2.1.2 Green Infrastructure

The comprehensive definition of green infrastructure is "an interconnected network of waterways, wetlands, wildlife habitats, and other natural areas; greenways, parks, and other conservation lands; working farms, ranches, and forests; and wilderness and other open spaces that support species, maintain natural ecological processes, sustain air and water resources, and contribute to the health and quality of life for communities and people" (Benedict & MacMahon, 2002, pg. 1). In the context of urban hydrology and landscape site engineering, green infrastructure refers to the use of natural systems to replicate pre-development water cycle and control and treat stormwater runoff on site, as opposed to gray infrastructure or traditional stormwater management techniques. This is accomplished by incorporating green space and vegetation to increase on-site infiltration and evapotranspiration, which results in the reduction of peak flows and the increase of groundwater recharge, while also filtering out pollutants (Liptan, 2017). There are a variety of green infrastructure types, with varying uses and levels of effectiveness, such as constructed wetlands, bioswales, rain gardens, permeable pavements, green roofs, living walls and street planters, among others (Liu et al., 2014).

There is a significant body of literature exploring the impact of green infrastructure on the surrounding environment, and interest in the topic is growing. These benefits extend beyond just environmental benefits, and also encompass economic and social benefits. Studies found that restoring rivers to natural conditions can control flooding and limit water quality issues, by limiting and treating both surface runoff and channel flow (B. Yang & Li, 2013). Additionally, green infrastructure systems introduce habitat zones for birds, insects, amphibians, and other wildlife (P. Li et al., 2020). On the social aspect, green infrastructure provides recreational and educational amenities to surrounding communities (Kim et al., 2014, 2016). Users of these facilities also experience increased social cohesion (Benedict & MacMahon, 2002). Additionally, green infrastructure is also linked with increased physical and mental health, and reduced crime (Parker & Zingoni de Baro, 2019). These interrelated environmental and social benefits can have a positive impact on the local economy. Green infrastructure systems are overall cheaper than competing traditional grey infrastructure systems in both capital and operational costs (Onuma & Tsuge, 2018). Disaster damage and energy use costs can be additionally lowered, while the economic potential of the surrounding communities can be enhanced by the new social opportunities created (Parker & Zingoni de Baro, 2019).

2.2 Landscape Performance

The modern challenges of climate change, economic stability, mental and physical health, and others, have placed an emphasis on the necessity to balance human and natural benefits in the built environment. Landscapes can play a vital role in tackling these issues and providing a variety of benefits. It has become increasingly important to quantify benefits of high-performing landscapes, in order to better understand how landscape designs effectively and sustainably provide services. The Landscape

Architecture Foundation (LAF), a non-profit organization that promotes the long-term value of landscape architecture and supports the conservation and improvement of the natural and built environment, has created the Landscape Performance Series (LPS), a tool to quantify the environmental, social, and economic benefits of built landscape projects in a variety of categories (Canfield et al., 2018).

Within each benefit category, there are several performance metrics that can be used for analysis. Environmentally, the metrics are split into five categories: land, water, habitat, energy, and waste. Potential metrics used to track stormwater management are annual runoff volume retained, runoff detained for a design storm, and reduction in peak discharge rate. Social metrics include recreational value, health, and safety, and economic metrics such as property value and maintenance savings are included. To quantify data using the metrics, a large assortment of data collection methods have been utilized, from survey questionnaires to on-site data collection and computer model simulations (Canfield et al., 2018). The wide variety of metrics, when combined, support a balanced analysis of the overall performance of the landscape (B. Yang, 2020).

It is important to note that the majority use of these performance toolkits is for post-occupancy evaluations, to examine the benefits and effectiveness of the design decisions. Using the developed metrics, the LPS studies focus on built projects and involve collecting and analyzing available data. Through this method, a database of hundreds of case studies has been built up, each utilizing a variety of performance metrics (Canfield et al., 2018). For example, a study comparing three urban landscape architecture projects in Texas found that a “consistent set of performance criteria/indicators, informed by literature, was found to give meaningful results to document performance” (Ozdil et al., 2014). An additional study analyzed a case study of a landscape project, determining and comparing the potential and actual benefits, and found that the potential benefits could accurately predict the actual benefits (M.-H. Li et al., 2013). However, quantifying the economic and social benefits of a landscape project can be more challenging compared to measuring the environmental benefits, which can be easily estimated using computer models and site data (B. Yang, 2020). Yang et. al (2016) found that the provided performance metrics can be used to quantify social benefits. Similarly, the evidence-based research methodology described in the LPS can increase the scientific rigor of landscape research and accurately measure economic benefits (Wang et al., 2016).

Most studies that delve into the topic of landscape performance examine the LPS case studies, evaluating and documenting landscape performance retroactively. The data is collected and analyzed during and after the construction of the project, tracking changes from the pre- to post-development conditions (Canfield et al., 2018). There is a lack of research into how landscape performance metrics can inform design decisions and strategies in the pre-design phase. Yang (2020) extensively studied the LPS, examining hundreds of case studies. He found that documentation of benefits is a strength of performance-based research, but there is vast potential to use performance metrics to shape further research and design decisions (B. Yang, 2020). This research aims to contribute to the existing body of knowledge by exploring the potential use of LPS metrics in shaping design decisions and creating a design guideline for landscape projects.

2.3 Sensitivity Analysis

In the pre-design phase, the LPS method can be utilized to construct a hierarchy of the most important design parameters and thus optimize design selections. This can be achieved through a sensitivity analysis, as known as parametric analysis, which assesses how changes in input variable affect the output results (Ledda & De Montis, 2019). Sensitivity analysis can be used to account for uncertainty in the results of benefit quantification models, which cannot perfectly represent real-world situations. Uncertainty is defined as a lack of confidence in determining exact values due to the presence of random variables (Uusitalo et al., 2015). To effectively rank model parameters, this uncertainty must be tested through various methods, such as model emulation, temporal and spatial variability, and sensitivity analysis.

A sensitivity analysis can be utilized in a wide range of fields, from finance to medicine and design. As a result, there are many different methods to complete a sensitivity analysis, with each method often being tailored to the specific field. This research will utilize decision analysis, which is the form of sensitivity analysis commonly used in similar research topics within the field of landscape architecture. In a 2018 study, Jayasooriya et al. examined the creation of green infrastructure using a multi-tiered approach. A sensitivity analysis was conducted to assess the most optimal performance measures for the design and creation of a green stormwater treatment train. Similarly, a 2021 study used the sensitivity analysis to investigate the effect of green infrastructure locations on flood reduction. By evaluating various green infrastructure types in different locations while holding other variables constant, the researchers found that placing green infrastructure closer to sewer catch-basins resulted in the greatest decrease in flooding (Rodriguez et al., 2021).

As with all design scenarios, there is no perfect solution. With a variety of variables, trade-offs must occur to balance the benefits of various performance metrics. Lanzas et al. (2019) conducted a sensitivity analysis studying ecosystem services provided by networks of green infrastructure. The research explored the potential trade-offs between maximizing the benefits of biodiversity and ecosystem services. The analysis determined that moderate goals of both were reached through the design, but there came a threshold where trade-offs of benefits became unavoidable (Lanzas et al., 2019). Similarly, the present research intends to optimize the design of green infrastructure to achieve the best possible balance between benefits and trade-offs.

Uusitalo et al. (2015) explored the various methods and explained the basics of the decision analysis approach. At the most basic level, model outputs are monitored based upon the changes in each input variable. In the decision analysis conducted by Jayasooriya et al. (2018) while examining a multi-tiered approach to green infrastructure system design, each input value of certain landscape performance models was modified one at a time, based on predetermined weight variation ratios. Ten different green infrastructure treatment train scenarios of various sizes were evaluated, examining their impact on performance measures such as pollutant/sediment removal, runoff reduction, habitat creation, and capital/maintenance costs. This method where each input value is changed one at a time is signified as a local analysis. Global analysis, where each input value is changed in combination with other values, can lead to more comprehensive results (Uusitalo et al., 2015). However, this process requires a large amount of model runs. Therefore, conducting a local analysis is determined to be more feasible and practical for the purposes of this research. In the analysis, the output variables will change in accordance with each input parameter's individual change, one-at-a-time. If the output changes are relatively minimal, it can be interpreted that the output variables are not significantly affected by the input value, and vice versa (Uusitalo et al., 2015).

CHAPTER 3 – METHODS

3.1 Study Area

The study area of this study is the downtown area of Lansing, Michigan, USA. The area was selected because it contains a wide variety of land use and cover types, with varying amounts of urban and suburban commercial and residential areas, industrial areas, and natural areas. It has unique opportunities to study the impact of green infrastructure on the Grand River, a major river system traversing an urban area in Mid-Michigan, also make it an ideal location for this research. Additionally, the author's ease of access to the project site, both physically and through data collection/access, contributed to the site being chosen.

The project boundaries follow the flow of the Grand River through Downtown, Oldtown, and Reo Town in Lansing (see Figure 1). The boundaries were chosen to incorporate the 500-year floodplain along the river, based on the Federal Emergency Management Agency's floodplain data (FEMA, 2020). A buffer zone of several blocks from the river was also incorporated into the site, in order to ensure sufficient space for testing and designing green infrastructure techniques. The site is defined by North Ave to the north, Capitol Ave to the west, the Canadian National Railroad line to the south, and Larch St. to the east. This determines an approximate size of the site being 1.12 square miles.

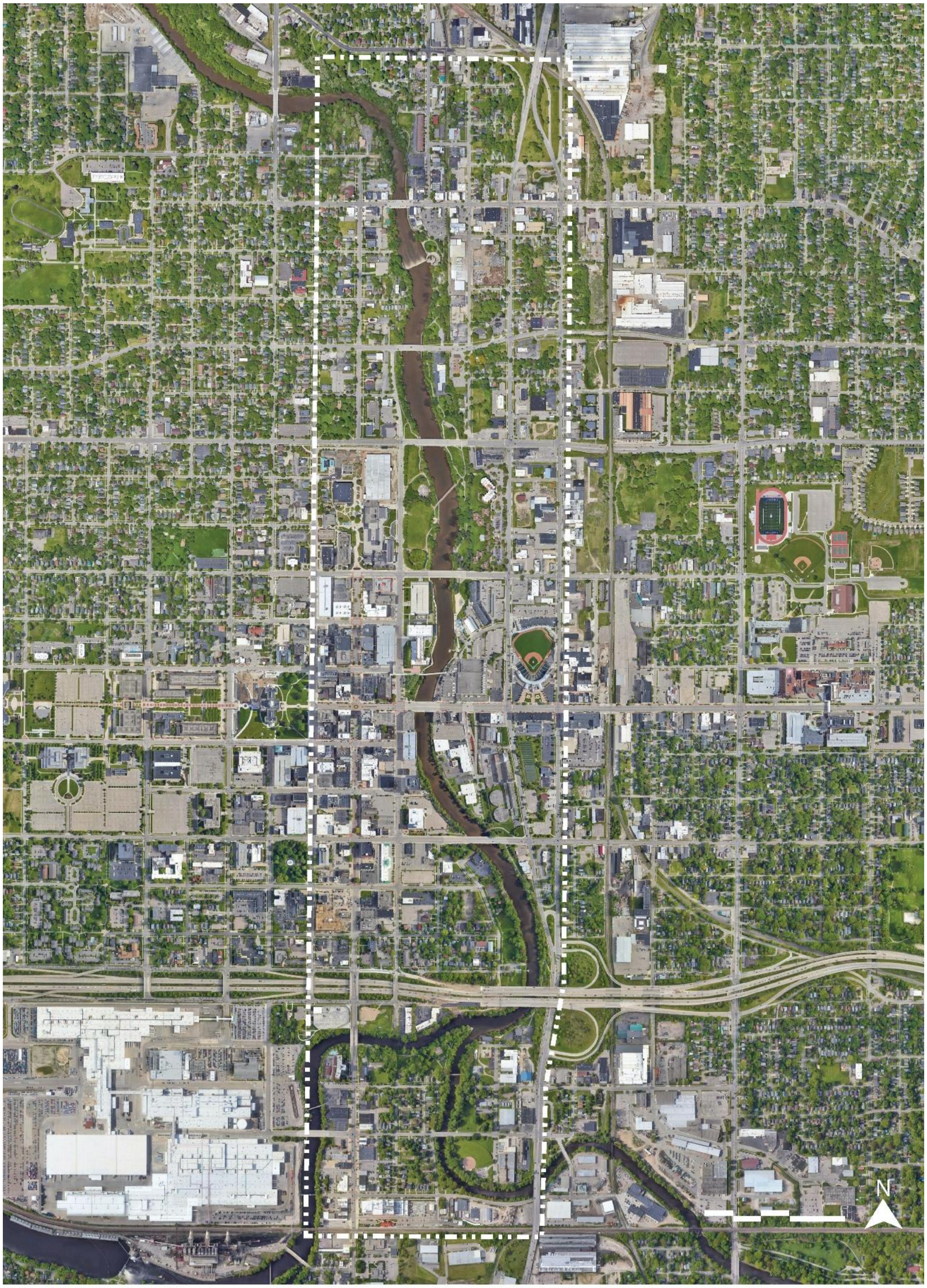


Figure 1. Study Area

The city of Lansing is the home of the Michigan State Capital and state government. The population of Lansing and its metro region is 112,644 and 541,297, respectively (US Census Bureau, 2020). The region is significant for its environmental, economic, and social importance, and the selected site plays an important role within this region (see Figure 2). In Lansing, the vast majority of people use motor vehicles as their primary form of transportation, with 72% driving alone and 12% carpooling (US Census Bureau, 2020). Despite this, the alternative transportation networks that connect the site to the rest of the region are still important and provide a key role in access. The Capital Area Transportation Authority (CATA), runs several bus lines through the region, with the majority of them terminating at the Downtown Transportation Center, located within the site boundaries (CATA, 2023). Additionally, the Lansing River Trail system runs through the site, providing non-motorized access to several key regional destinations. The trail runs along the Grand and Red Cedar Rivers, Sycamore Creek, and along other corridors for a total distance of more than 20 miles. Much of the trail runs separate from motor vehicle traffic, providing non-motorized access from the site to Michigan State University in neighboring East Lansing (Lansing River Trail, 2023).

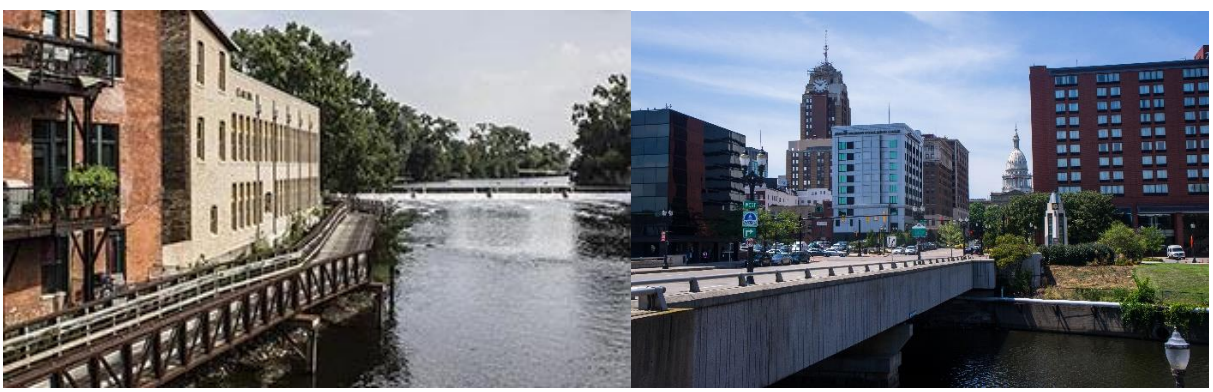


Figure 2. Site Photos of the Study Area

Figure 2 (cont'd)

Environmentally, the region boasts a comprehensive green space network, including parks, natural areas, corridors, and other green spaces. These spaces provide habitats for wildlife and opportunities for human recreation and environmental treatments. However, within the site boundaries, there is a lack of green space, with most of the area being completely developed. Much of the banks of the Grand River have been developed and industrialized, leading to hard edges and a lack of green space (Hanshue & Harrington, 2017). The Grand River, the longest river in Michigan, plays an important role in the health and sustainability of Lake Michigan and the Great Lakes as a whole. Stormwater runoff collected within the site boundaries have the potential to impact not only the site itself, but also the rest of the Grand River and Great Lakes system.

On the site itself, there are several environmental issues. The Grand River has long been plagued by a variety of water quality problems. The stressors from urban and agricultural areas of the watershed have combined to cause severe degradation in the river. Overflows from sanitary and combined sewer systems, industrial pollutants, and non-point pollution sources originating from livestock or agricultural chemicals are just some of the many pollution sources causing harm to the ecosystem (Hanshue & Harrington, 2017). The river is one of the most significant contributors of pollution to Lake Michigan, and E. coli levels regularly degrade to the point of causing harm to humans on partial body contact (Hanshue & Harrington, 2017).

Additionally, the extensive presence of gray infrastructure on the site has caused persistent flooding issues. Large storm events have occurred several times in the past, leading to 100-year storm events, most recently in 2018, 2004, and 1986. The 2018 flood event caused the City of Lansing to declare a state of emergency. Several roads were closed and damaged and numerous residents were forced to evacuate their homes, with hundreds of properties damaged (Ahmad, 2018). As the climate changes, this flooding will continue to become more severe and frequent, threatening to cause devastating damage to the city and region.

3.2 Pre-Design Sensitivity Analysis

To create a system of evaluation criteria for green infrastructure design guidelines, several computer toolkits and models were collected and evaluated for the sensitivity analysis (see Figure 3). The toolkits selected majorly deal with hydrological challenges and benefits, with economic impacts additionally included. There are a lack of models that can predict social outcomes of site design in the conceptual design phase (Canfield et al., 2018). Careful consideration was thus given to the selection of the toolkits, in order to ensure a wide variety of metrics were examined using reliable and valid modeling software.

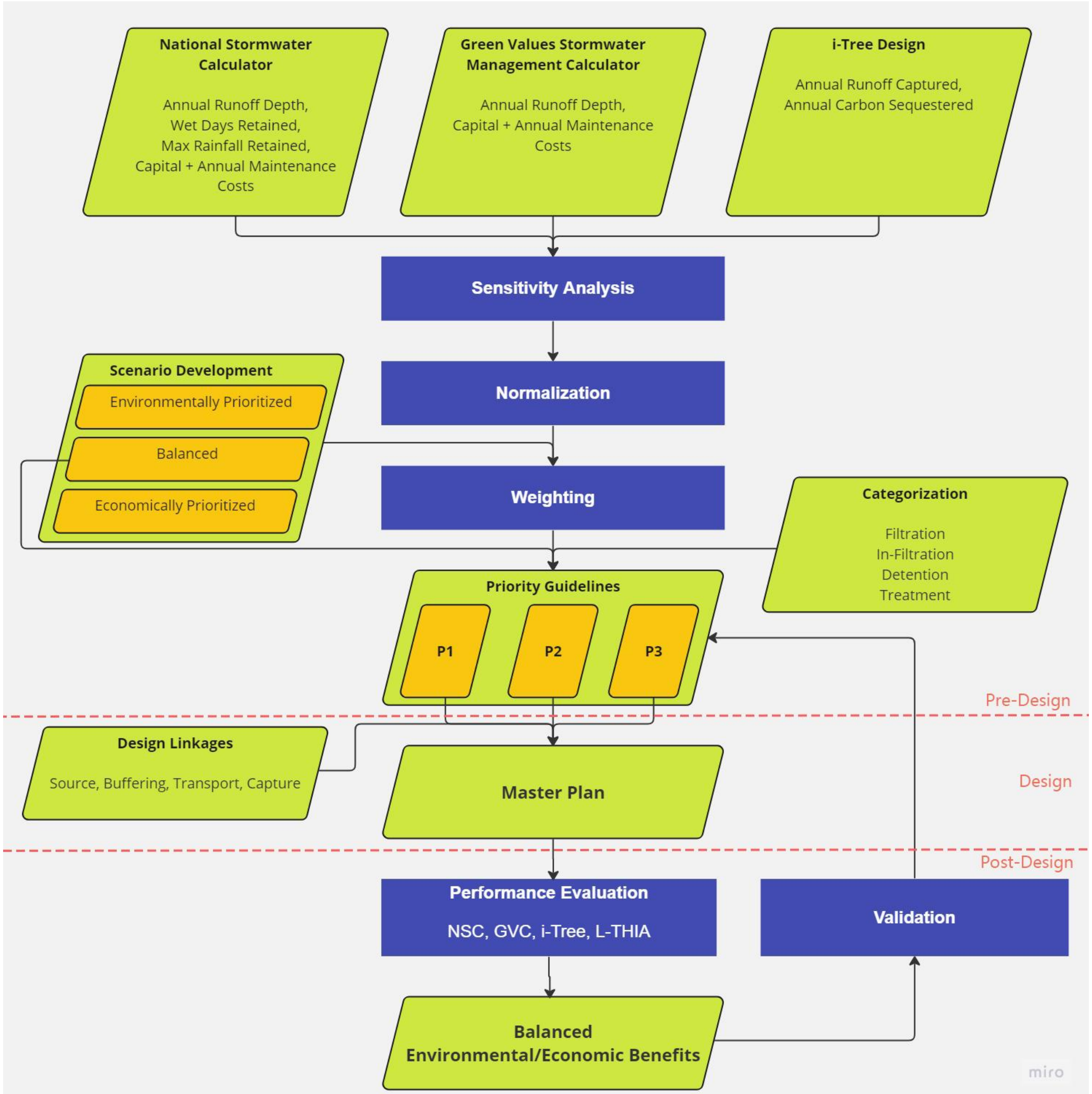


Figure 3. Method Process

The three tools that were finally selected were the National Stormwater Calculator (NSC), Green Values Stormwater Management Calculator (GVC), and i-Tree Design developed by US Environmental Protection Agency, Center for Neighborhood Technology, and US Department of Agriculture, respectively (see Table 1). The NSC and GVC were chosen because of their ability to calculate direct environmental and economic benefits of green infrastructure. i-Tree Design was chosen to evaluate the effectiveness of native tree species in mitigating carbon and runoff.

Table 1. Input, Control, and Output Variables of Selected Models

<table>
<tr><th rowspan="2">Model</th><th colspan="2">Input Variables</th><th rowspan="2">Control Variables</th><th rowspan="2">Output Variables</th></tr>
<tr><th>Category</th><th>Subcategories</th></tr>
<tr><td rowspan="2">National Stormwater Calculator (NSC)</td><td>Land cover (%)</td><td>Permeable area</td><td rowspan="2">Rainfall amount, rainfall intensity, soil type, evaporation, slope, location, project type, site suitability, cost region</td><td rowspan="2">Annual runoff (in), wet days retained (%%), max rainfall retained (in), maintenance and capital costs ($)</td></tr>
<tr><td>Green infrastructure cover (%)</td><td>Disconnection, rain harvesting, rain gardens, green roofs, street planters, infiltration basins, permeable pavement</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Green Values Stormwater Management Calculator (GVC)</td><td>Land cover (%)</td><td>Trees/shrubs, lawn/turf, flower beds, natural open, water, wetlands</td><td rowspan="2">Average rainfall (in), area (acres), location</td><td rowspan="2">Annual runoff volume (gallons), maintenance and capital costs ($)</td></tr>
<tr><td>Green infrastructure cover (%)</td><td>Green roofs, rain gardens, planter boxes, perimeter drains, trees, amended soil, bioswales, urban farming, raised beds, vegetation filter strips, natural vegetation, parking swales, road swales, permeable paving</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 1 (cont'd)

i-Tree Design	Tree species	Betula payrifera, Juglans nigra, Catalpa speciosa, Populus deltoides, Pinus strobus, Acer rubrum, Fagus grandifolia, Quercus rubra, Prunus serotina, Pinus resinosa, Acer saccharum, Acer saccharinum, Quercus alba, Tilia americana, Betula alleghenienis, Abies balsamea, Picea glauca, Larix laricina, Tsuga canadensis	Location, Time	Runoff retained (gallons), carbon sequestered (lbs)
	Tree diameter (in)			
	Tree condition	Excellent, good, fair, poor, dead/dying		
	Tree sunlight exposure	Full sun, part shade, full shade		

A sensitivity analysis was performed for each chosen model. All three models were calibrated to the site. For the NSC and GVC, control parameters were set based on a spatial analysis of the site using the Geographic Information Systems, creating a baseline for the input parameters. For i-Tree Design, the baseline was calculated with no trees.

Many sensitivity analyses adjust each metric proportionally and relative to its current value (Jayasooriya et al., 2018). As many of the baseline values in each model were 0 this would not yield the desired results. Accordingly, the input parameters in the NSC and GVC were changed one at a time, using absolute percentage adjustment levels of 1%, 2%, 5%, and 10% of the total site area. For i-Tree

Design, the input parameters were changed categorically by adjusting the tree species planted. The results of each scenario were recorded and the sensitivity of each parameter was determined by evaluating the effect the input variables had on the output variables. This process helped to identify the most sensitive parameters for each toolkit (Ledda & De Montis, 2019). The parameters were then ranked according to the results of the sensitivity, creating a list of the most important guidelines for designing green infrastructure in Midwest urban watersheds.

3.3 Development of Design Scenarios and Guidelines

Based on the simulation outcomes, various scenarios weighing environmental and economic values differently were developed to allow alternative design options in decision making. To compare and combine results between the NSC and GVC models, and between output parameters with different units, a normalization process was first conducted. In the NSC, the reduction in average annual runoff for each scenario was calculated by subtracting average annual runoff value at the 10% adjustment level from the baseline average annual runoff. This was also completed in the GVC, for the annual average runoff and runoff volume per event parameters. Then, these values and the other environmental output parameters were normalized into a scale ranging from 0 to 1, using a traditional min/max normalization system, which sets the minimum output at 0 and the maximum output at 1 (Gupta, 2021).

For the economic output values in the GVC, the combined capital and maintenance costs over a 20-year period was automatically calculated into the output parameter value. Thus, in the NSC, the capital costs and annual maintenance costs were calculated and combined by adding the capital costs to the maintenance costs over a 20-year period in each scenario, to achieve balanced comparable results between the two models. Both of these values were then normalized using a reversed min/max normalization system, setting the minimum output at 1 and maximum output at 0 (Gupta, 2021). This was done because lower costs are a positive feature, and as a result should have a higher weight. In i-

Tree Design, the normalization system was used to categorize the results of the runoff retained and carbon sequestered for each species of tree.

Within the NSC and GVC, the results of the metrics were then combined to develop design scenarios with varying environmental and economic weights (see Table 2). I-Tree Design was divided into three scenarios taking into account runoff retained and carbon sequestered (see Table 3). This was completed to balance the output variables of each model. To achieve this, for each metric, the normalized metric value (at the 10% adjustment level) was multiplied by the environmental weight of the calculated metrics, and the normalized economic output was multiplied by the economic weight of the calculated metrics. The final result was the combination of these values.

Table 2. Green Infrastructure Scenarios for the NSC and GVC

Green Infrastructure Scenarios			
	Scenario 1	**Scenario 2**	**Scenario 3**
Environmental Weight	75%	50%	25%
Economic Weight	25%	50%	75%

Table 3. Scenarios for i-Tree Design

i-Tree Design Scenarios			
	Scenario 1	**Scenario 2**	**Scenario 3**
Runoff Weight	75%	50%	25%
Carbon Weight	25%	50%	75%

Within each model, the output parameters were then ranked in descending order and classified into three different priority groups using pre-determined criteria (Tables 4-6). The priorities were created to divide the parameters in a way that would be simple and clear to use in the design phase of the project. This process split the output parameters into approximately equal-sized groups. Then, in the NSC and GVC, the criteria for each equivalent scenario were combined to create three main scenarios within each model. Using these scenarios, an overall design framework was created. The priority list for each main scenario was merged with its counterpart from the other model, combining the results of both models.

Table 4. Priority Criteria for the National Stormwater Calculator

National Stormwater Calculator			
Priority	**Scenario 1**	**Scenario 2**	**Scenario 3**
1	>0.7 Average Annual Runoff Reduced >0.7 Wet Days Retained >0.5 Max Rainfall Retained >0.7 Runoff Coefficient >0.6 Construction /Maintenance Costs	>0.8 Average Annual Runoff Reduced >0.7 Wet Days Retained >0.5 Max Rainfall Retained >0.8 Runoff Coefficient >0.7 Construction /Maintenance Costs	>0.8 Average Annual Runoff Reduced >0.7 Wet Days Retained >0.6 Max Rainfall Retained >0.8 Runoff Coefficient >0.7 Construction /Maintenance Costs
2	>0.4 Average Annual Runoff Reduced >0.5 Wet Days Retained >0.2 Max Rainfall Retained >0.3 Runoff Coefficient >0.4 Construction /Maintenance Costs	>0.4 Average Annual Runoff Reduced >0.4 Wet Days Retained >0.2 Max Rainfall Retained >0.4 Runoff Coefficient >0.5 Construction /Maintenance Costs	>0.3 Runoff Coeff >0.3 Wet Days Retained >0.2 Max Rainfall Retained >0.4 Runoff Coefficient >0.5 Construction /Maintenance Costs
3	<0.4 Average Annual Runoff Reduced <0.5 Wet Days Retained <0.2 Max Rainfall Retained <0.3 Runoff Coefficient <0.4 Construction /Maintenance Costs	<0.4 Average Annual Runoff Reduced <0.4 Wet Days Retained <0.2 Max Rainfall Retained <0.4 Runoff Coefficient <0.5 Construction /Maintenance Costs	<0.3 Runoff Coeff <0.3 Wet Days Retained <0.2 Max Rainfall Retained <0.4 Runoff Coefficient <0.5 Construction /Maintenance Costs

Table 5. Priority Criteria for the Green Values Stormwater Management Calculator

Green Values Stormwater Management Calculator			
Priority	**Scenario 1**	**Scenario 2**	**Scenario 3**
1	>0.4 Annual Runoff Volume >0.3 Volume Per Event >0.4 Runoff Coefficient >0.6 Economic Costs	>0.5 Annual Runoff Volume >0.4 Volume Per Event >0.5 Runoff Coefficient >0.7 Economic Costs	>0.6 Annual Runoff Volume >0.5 Volume Per Event >0.5 Runoff Coefficient >0.7 Economic Costs
2	>0.2 Annual Runoff Volume >0.2 Volume Per Event >0.2 Runoff Coefficient >0.3 Economic Costs	>0.25 Annual Runoff Volume >0.25 Volume Per Event >0.2 Runoff Coefficient >0.4 Economic Costs	>0.3 Annual Runoff Volume >0.25 Volume Per Event >0.3 Runoff Coefficient >0.4 Economic Costs
3	<0.2 Annual Runoff Volume <0.2 Volume Per Event >0.2 Runoff Coefficient >0.3 Economic Costs	<0.25 Annual Runoff Volume <0.25 Volume Per Event <0.2 Runoff Coefficient <0.4 Economic Costs	<0.3 Annual Runoff Volume <0.25 Volume Per Event <0.3 Runoff Coefficient <0.4 Economic Costs

Table 6. Priority Criteria for i-Tree Design

	i-Tree Design		
Priority	**Scenario 1**	**Scenario 2**	**Scenario 3**
1	>0.75 Runoff Coefficient >0.5 Carbon Coefficient	>0.6 Runoff Coefficient >0.6 Carbon Coefficient	>0.5 Runoff Coefficient >0.75 Carbon Coefficient
2	>0.4 Runoff Coefficient >0.3 Carbon Coefficient	>0.35 Runoff Coefficient >0.4 Carbon Coefficient	>0.3 Runoff Coefficient >0.5 Carbon Coefficient
3	<0.4 Runoff Coefficient <0.3 Carbon Coefficient	<0.35 Runoff Coefficient <0.4 Carbon Coefficient	<0.3 Runoff Coefficient <0.5 Carbon Coefficient

3.4 Design

Using the developed green infrastructure priority framework system, a design scenario of the site was created. A comprehensive site analysis was undertaken, and case studies of various large-scale green infrastructure projects was reviewed to improve knowledge of the design process and structure. The generated priority chart was applied throughout the design process. Green infrastructure types were added to the site with care taken to control the distribution according to the various priority levels. Priority 1 types were heavily prioritized. Priority 2 types were used in limited contexts where the application of Priority 1 types is not feasible, while priority 3 types were minimally used. For example, bioswales, a Priority 2 type, was utilized to transport runoff as there was no conveyance type in Priority 1. As the green infrastructure facilities were applied to the site, the vast majority were applied on public owned land, usually along rights-of-ways or in city-owned parks. Some facilities were applied opportunistically on privately-owned land, usually in vacant lots or parking lots. The various green infrastructure types that were used in the design are pictured below (see Figure 4).

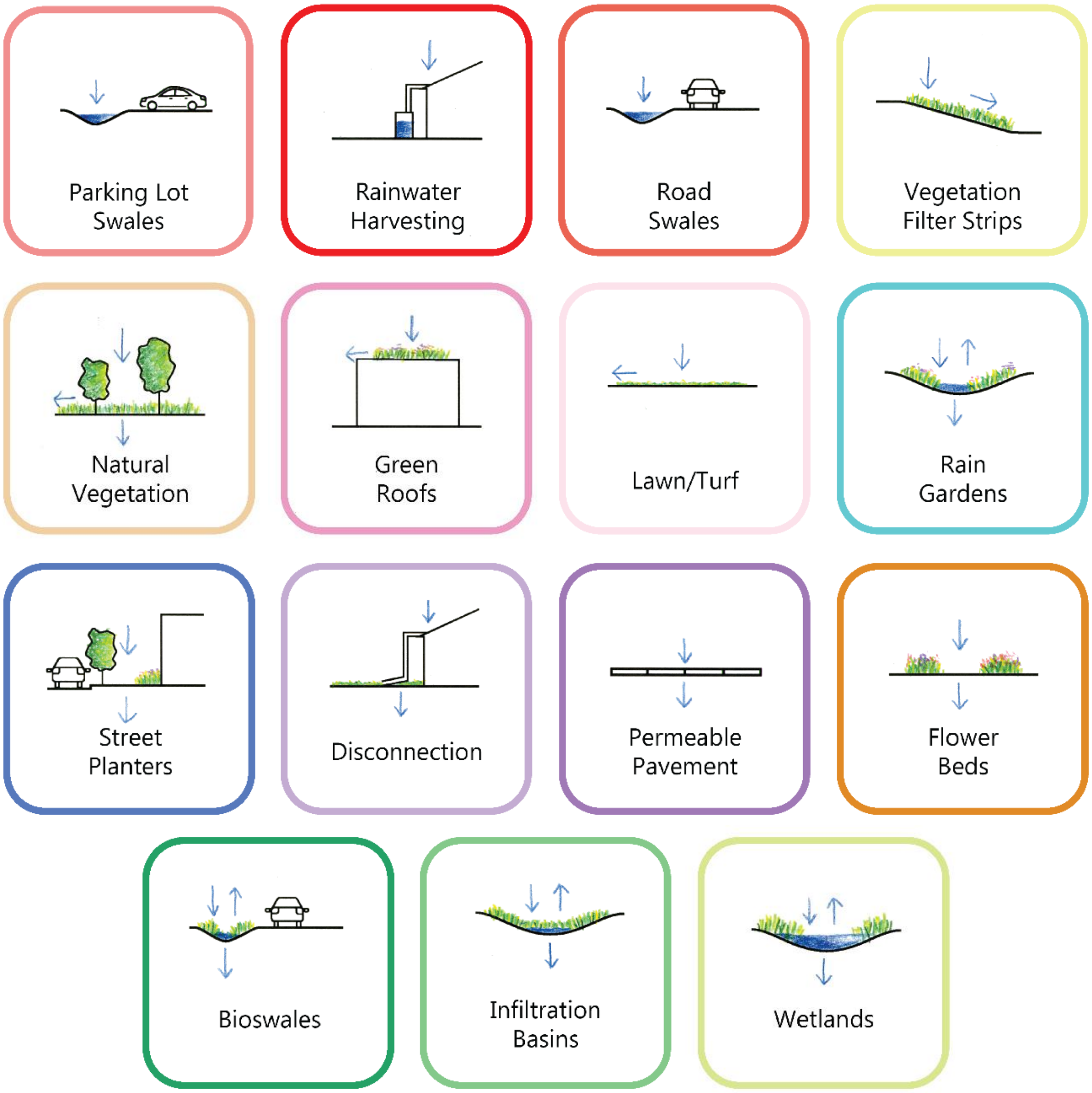


Figure 4. Green Infrastructure Facility Types

3.5 Post-Design Performance Evaluation

To validate the application of priority framework in aiding the design process's effectiveness in increasing environmental and economic benefits for the site, a follow-up post-design performance evaluation was conducted. Each of the three models used in the pre-design sensitivity analysis phase of the project, the GVC, NSC, and i-Tree Design, were utilized. Additionally, the Long-Term Hydrologic Impact Analysis (L-THIA), developed by Purdue University (2016), was used to calculate water quality impacts as well (see Table 7).

Table 7. Input, Control, and Output Variables of L-THIA

Input Variables		Control Variables	Output Variables
Category	**Subcategories**		
Land cover area (acres)	Land cover type (commercial, Industrial, High density residential, low density residential, water/wetlands, grass/pasture, agriculture, and forest)	Rainfall amount, rainfall intensity, evaporation	Runoff volume (in) Runoff depth (in) Nitrogen pollution (lbs) Phosphorous pollution (lbs) Suspended solids (lbs) Lead pollution (lbs) Zinc pollution (lbs) Copper pollution (lbs) Cadmium pollution (lbs) Chromium pollution (lbs) Nickel pollution (lbs COD pollution (lbs) BOD pollution (lbs) Oil & Grease pollution (lbs) Fecal coliform (millions) Fecal Strep (millions)
Soil cover area (acres)	Hydrologic Soil Group (A, B, C ,D)		
Lot size (acres)	low density residential: (1/2, 1, 2) high density residential: (1/4, 1/8)		
Impervious area (%)			
Road width (ft)	Road GI (conventional, porous, swales, porous & swales)		
Building Area (sqft)	Building GI (conventional, rain barrels, cisterns, green roof)		
Sidewalk width (ft)	Sidewalk GI (conventional, porous)		
Parking area (sqft)	Parking GI (conventional, pourous low, porous med, porous high)		
Lawn area (sqft)	Lawn quality (good, fair, poor)		

For the NSC, GVC, and L-THIA, the model was run using the baseline scenario and developed design scenario, separately (see Tables 17–20). The results of each run were collected and compared, analyzing the difference between the two. For i-Tree Design, no baseline scenario was calculated, as there was insufficient data for all the trees located within the site boundaries. Instead, a design scenario was developed using all of the trees planted as part of the design and the model was run (see Table 21).

CHAPTER 4 – RESULTS

4.1 Pre-Design Sensitivity Analysis

4.1.1 National Stormwater Management Calculator

In the NSC, four main output metrics were calculated: runoff reduction, number of wet days retained, maximum amount of rainfall retained, and capital and maintenance cost (see Figure 5). The three scenarios presented in Table 2 were applied to each of these metrics to weigh environmental and economic values differently. As shown in Figures 6-8, an output value closer to 1 means that the specific input variable has a greater effect on the output variable, or is more sensitive with respect to changes in output variables.

In the normalized runoff reduction variable, street planters are found to be the most sensitive input variable across all three scenarios (see Figure 6). Rain gardens, infiltration basins, and rain harvesting also had high impacts. Rooftop disconnection and permeable pavement had high impacts in the 75-25 environmentally prioritized scenario, but significantly decreased in effectiveness in the 50-50 balanced and 25-75 economically prioritized scenarios. Green roofs had significantly lower impacts than other types of green infrastructure throughout the scenarios. The normalized wet days retained variable had similar results, with rain harvesting, street planters, rain gardens, and infiltration basins having consistently high impacts (see Figure 7). Permeable pavement, disconnection, and green roofs had medium effectiveness in the 75-25 scenario which again decreased in the 50-50 and 25-75 scenarios.

In the normalized maximum rainfall retained variable, permeable pavement showed the highest effectiveness in the 75-25 scenario, but this decreased significantly in the other scenarios (see Figure 8). Disconnection followed suit, going from a medium to a low value. Rain harvesting, rain gardens, infiltration basins, and street planters began with medium values in the 75-25 scenario which increased in the other scenarios. Green roofs had a significantly low value across all three scenarios.

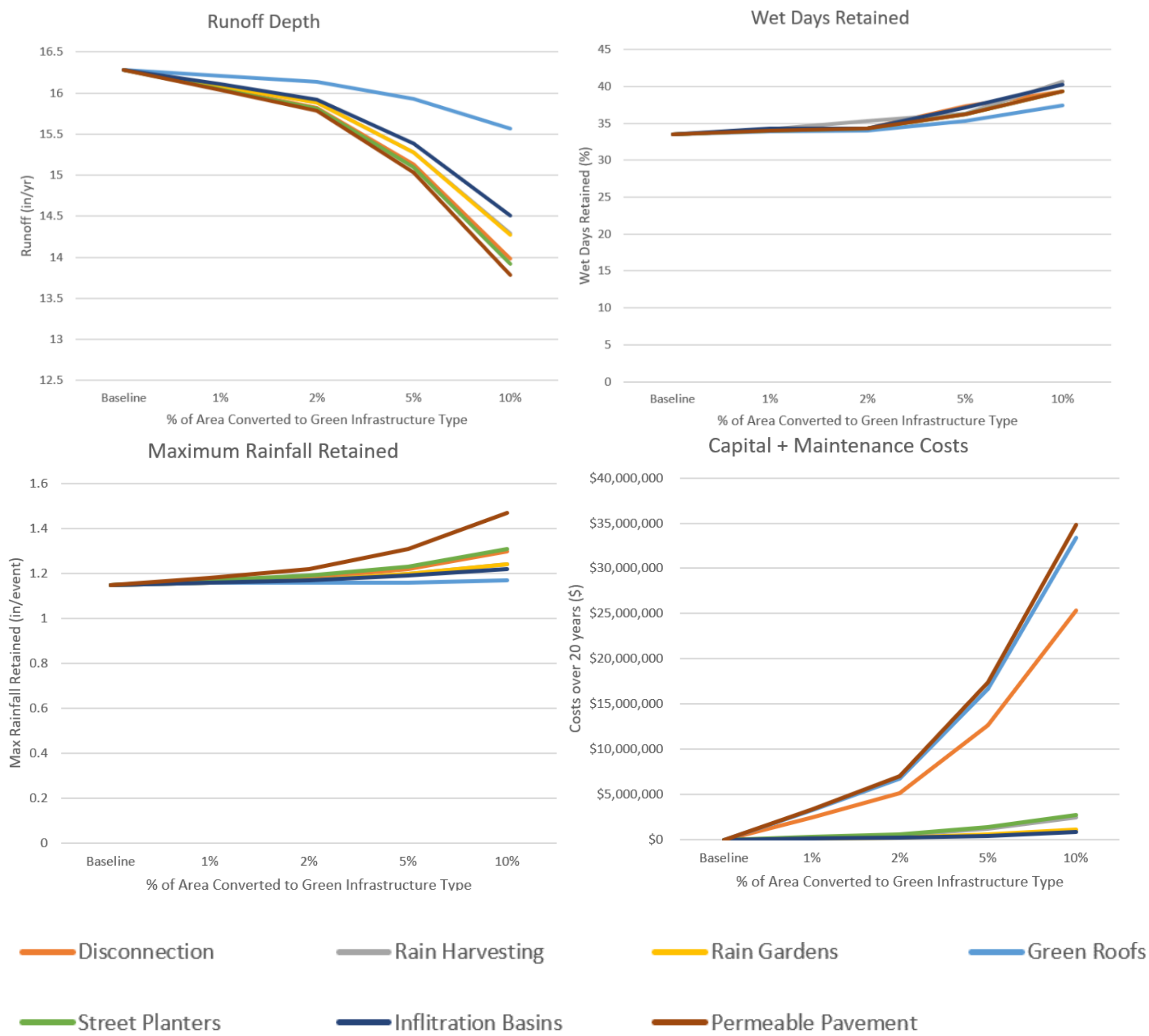


Figure 5. Model Output Values from the National Stormwater Calculator

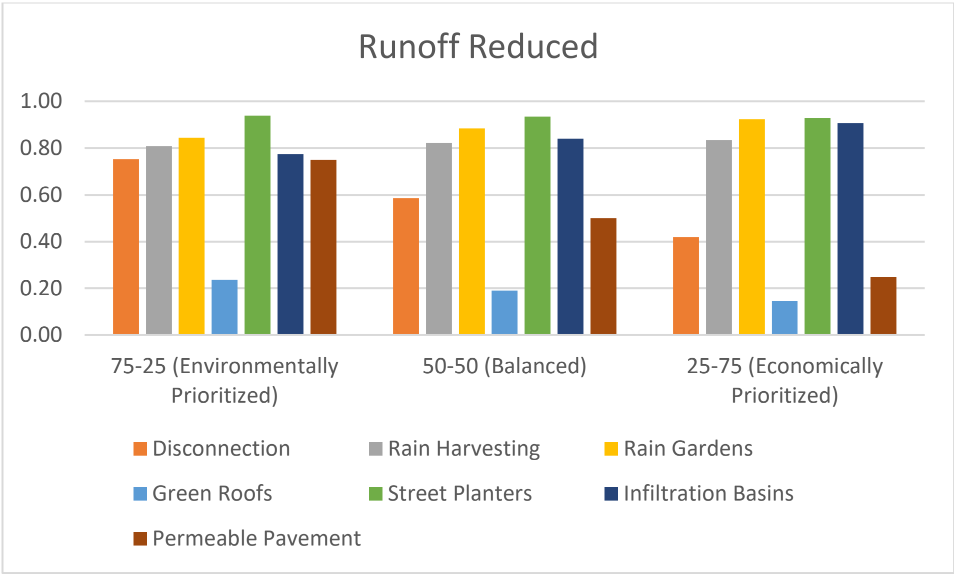


Figure 6. Normalized Runoff Depth Reduction Calculated with the National Stormwater Calculator

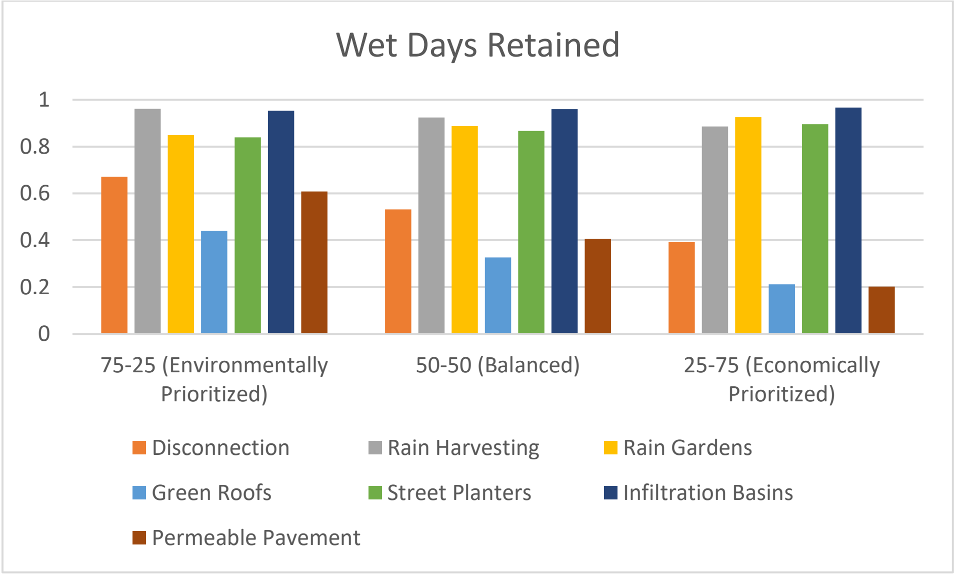


Figure 7. Normalized Number of Wet Days Retained Calculated with the National Stormwater Calculator

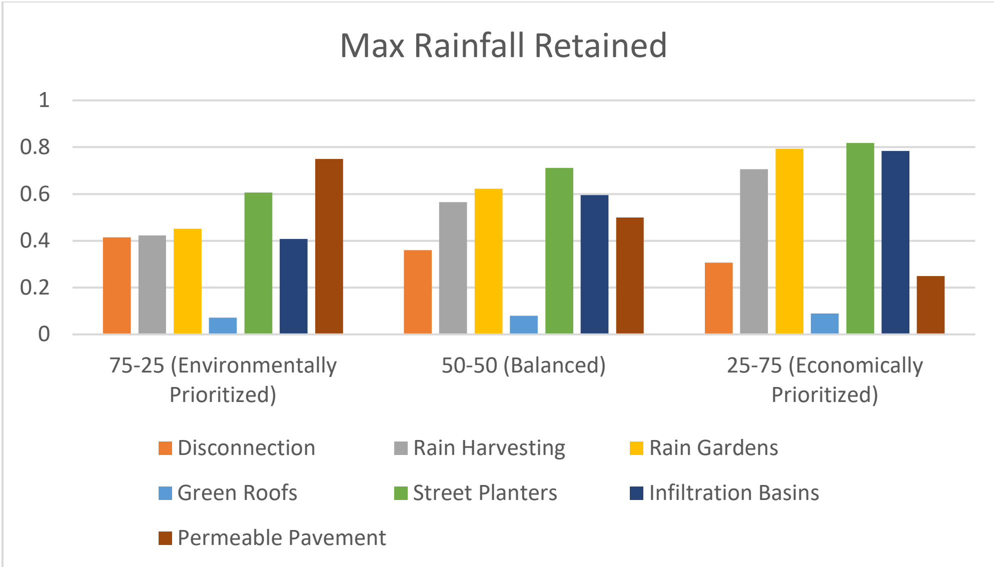


Figure 8. Normalized Maximum Amount of Rainfall Retained Calculated with the National Stormwater Calculator

The results for each scenario were then combined by averaging the results for the three parameters (see Figure 9). Street planters, infiltration basins, rain gardens, and rain harvesting were found to be the most effective methods across the board. The effectiveness of disconnection, green roofs, and permeable pavement all decreased from the 75-25 to the 25-75 scenarios, with disconnection and permeable paving starting at high values, while green roofs maintain relatively low values across all three scenarios.

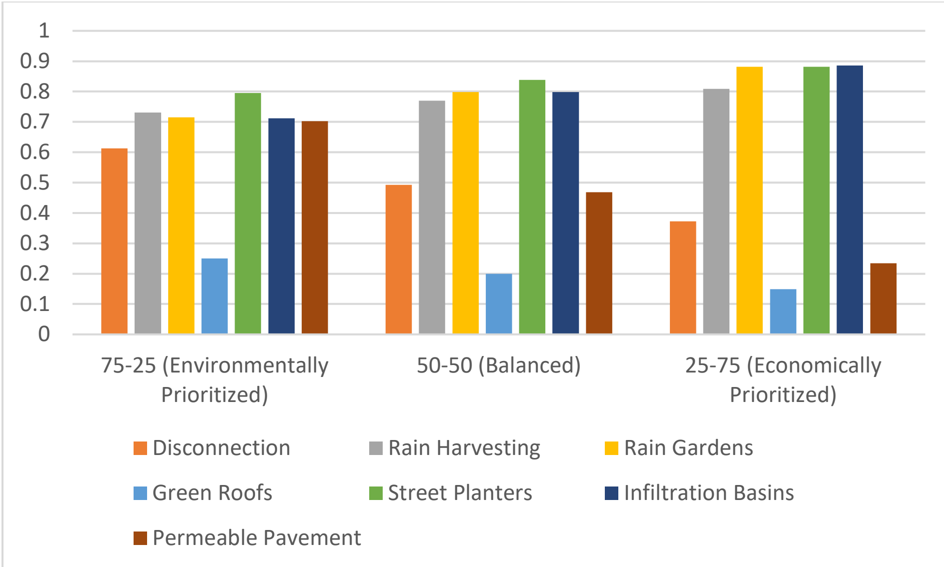


Figure 9. Combined Results of the Sensitivity Analysis Using the National Stormwater Calculator

In this study, the 50-50 balanced scenario was further used to prioritize the types of green infrastructure in the selected study area, aiming to achieve a balance between environmental and economic sustainability (see Table 8). As infiltration basins, rain gardens, street planters, and rain harvesting showed consistently high effectiveness across all three variables and scenarios, they were placed into the highest priority. Permeable pavement and disconnection were placed into priority 2, while green roofs were solely placed into the bottom priority tier.

Table 8. Priorities of Green Infrastructure Types for the Balanced Scenario Based on the Calculations with the National Stormwater Calculator

Priority	**Green Infrastructure Types**	**Combined Criteria**
Priority 1	Infiltration Basins Rain Gardens Street Planters Rain Harvesting	>0.6
Priority 2	Permeable Pavement Disconnection	>0.3
Priority 3	Green Roofs	<0.3

4.1.2 Green Values Stormwater Management Calculator

In the GVC, two main metrics were calculated: annual runoff volume reduction and capital and maintenance cost (see Figure 10). The results were calculated for a range of green infrastructure and land cover types for the three scenarios developed in Table 2. Rain gardens, planter boxes, and vegetation filter strips consistently showed high effectiveness throughout all three scenarios (see Figures 11 and 12). Trees had a high effectiveness value in the 75-25 environmentally prioritized scenario, significantly decreasing in the 25-75 economically prioritized scenario. Most green infrastructure types that had low effectiveness in the 75-25 scenario slightly increased to medium and high effectiveness in the 50-50 balanced and 25-75 economically prioritized scenario. For the land use variables, wetlands had a significant contribution to decreasing runoff volume. Trees/shrubs, natural open space, lawn/turf, and flowers had a minor impact, while water had minimal impact.

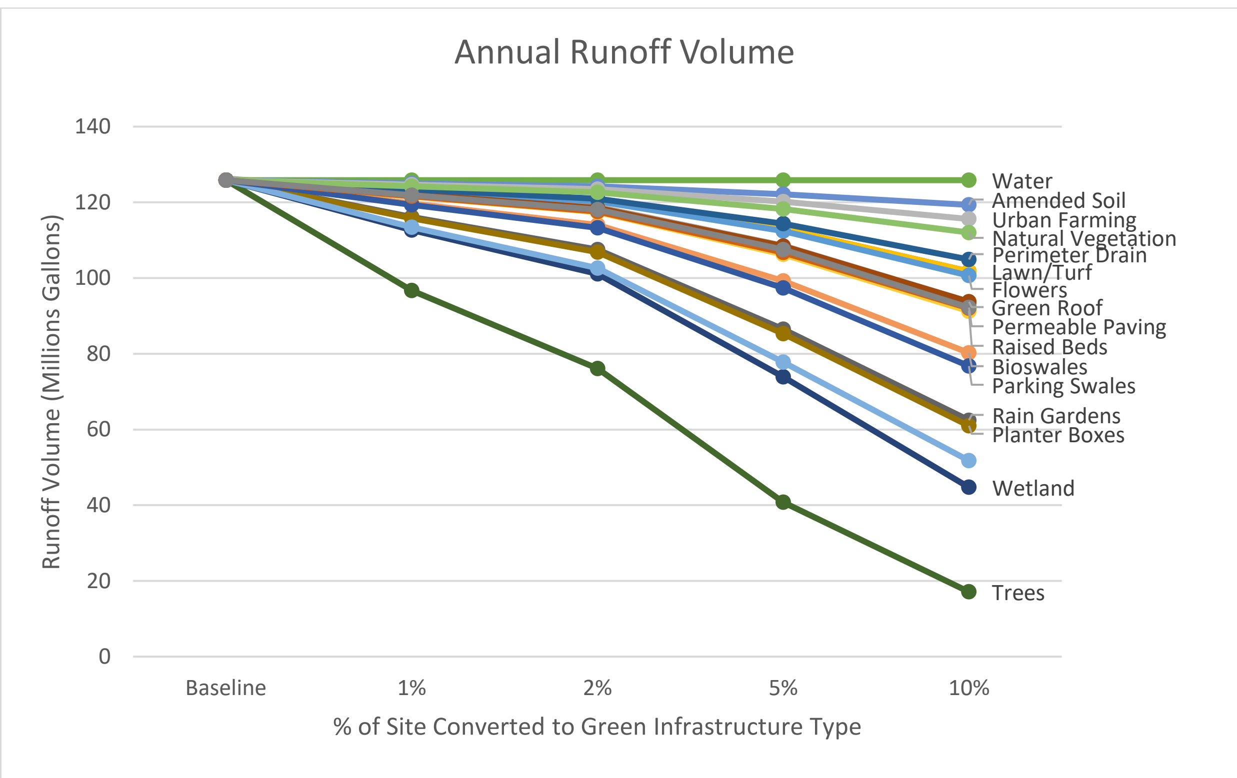
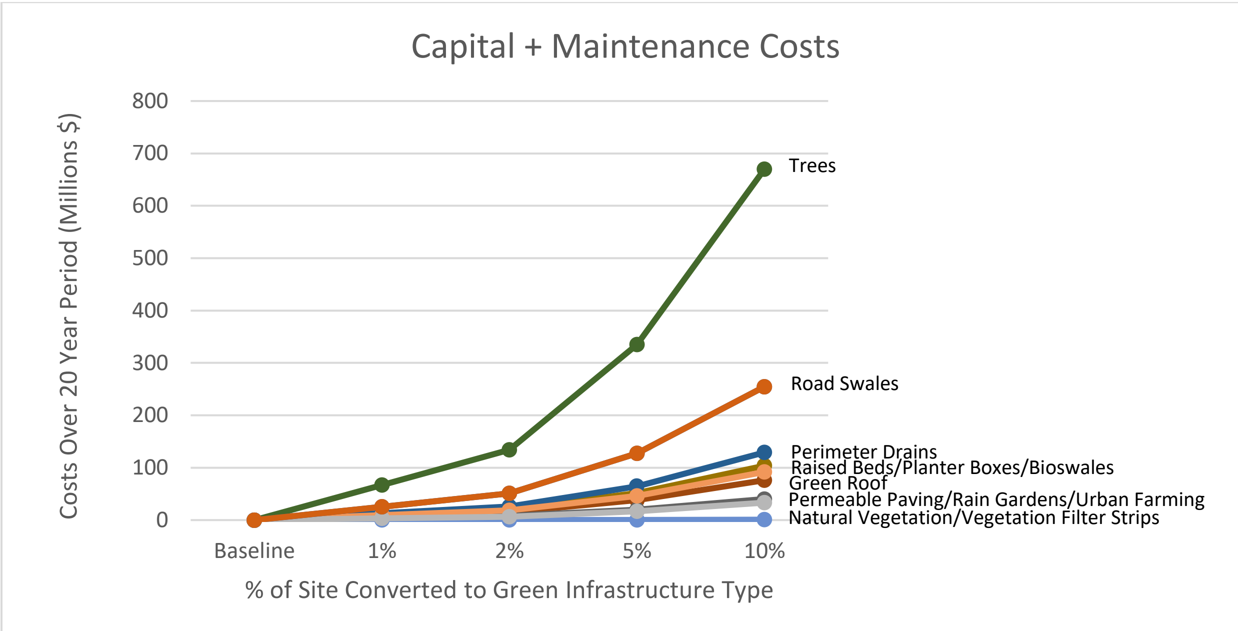


Figure 10. Model Output Values from the Green Values Stormwater Management Calculator

Figure 10 (cont'd)



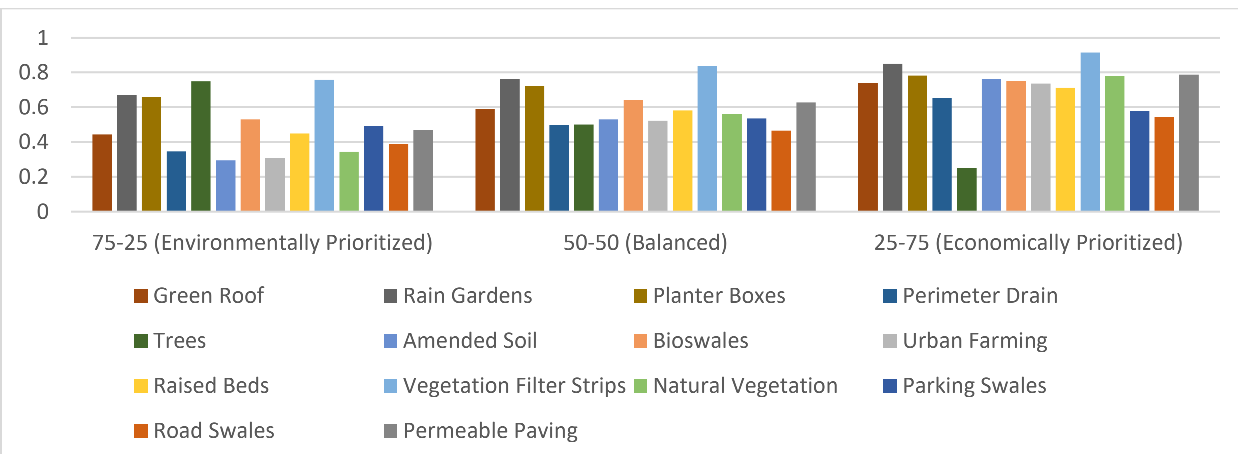


Figure 11. Normalized Annual Runoff Volume Reduction Calculated of Green Infrastructure Types with the Green Values Stormwater Management Calculator

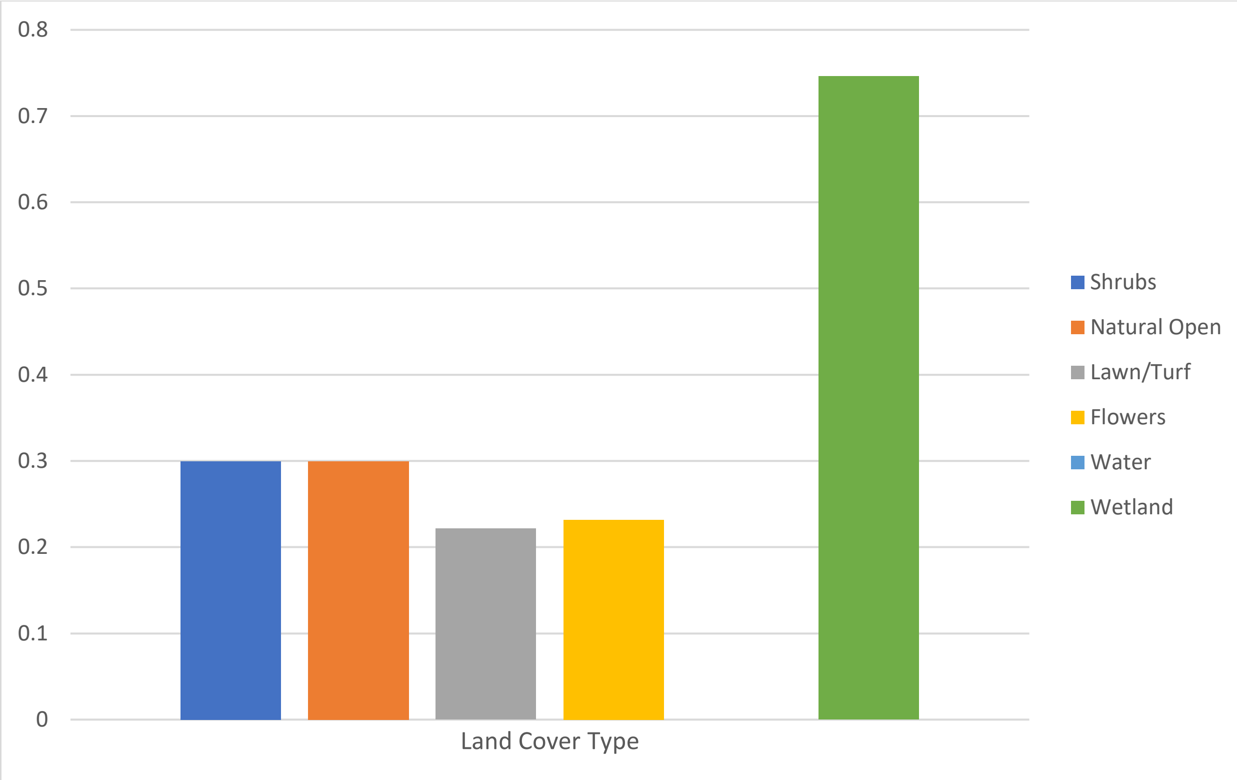


Figure 12. Normalized Annual Runoff Volume Reduction Calculated of Land Cover Types with the Green Values Stormwater Management Calculator

The input parameters were then divided into three priorities. The green infrastructure types were split into three scenarios, but the land cover types did not calculate economic outputs. Therefore, they were assigned a single scenario with no weights applied. Because of this, two separate priority charts were generated (see Tables 9 and 10). In Table 9, vegetation filter strips, rain gardens, and planter boxes were prioritized the highest, while in Table 10, wetlands were the sole parameter in the highest priority.

Table 9. Priorities of Green Infrastructure Types for the Balanced Scenario Based on the Calculations with the Green Values Stormwater Management Calculator

Priority	Green Infrastructure Type	Combined Criteria
1	Vegetation Filter Strips Rain Gardens Planter Boxes	>0.7
2	Bioswales Permeable Paving Green Roofs Raised Beds Natural Vegetation	>0.55
3	Trees Amended Soils Road Swales Parking Swales Perimeter Drains Urban Farming	<0.55

Table 10. Priorities of Land Cover Types Based on the Calculations with the Green Values Stormwater Management Calculator

Priority	Land Cover Type	Criteria
1	Wetland	>0.5 Runoff Coeff
2	Natural Open Trees/Shrubs	>0.25 Runoff Coeff
3	Flowers Lawn/Turf Water	<0.25 Runoff Coeff

4.1.3 i-Tree Design

In i-Tree Design two output values were calculated: runoff retained per year and carbon sequestered per year for each tree species (see Table 11). The most effective trees for limiting runoff were found to be Catalpa speciosa, Betula papyrifera, and Celtis occidentalis, while the least effective were Tsuga canadensis, Abies balsamea, and Picea glauca. The most effective trees for sequestering carbon were Betula papyrifera, Prunus serotina, and Acer rubrum, while the least effective were Tsuga canadensis, Abies balsamea, and Celtis occidentalis.

Table 11. Sensitivity Analysis of i-Tree Design

Tree Species	Runoff Retained Per Year (gallons)					Carbon Sequestered Per Year (lbs)				
	1	**5**	**10**	**15**	**20**	**1**	**5**	**10**	**15**	**20**
Acer saccharum	173	192	213	235	258	15	22	30	39	48
Acer saccharinum	117	152	190	234	281	31	54	77	102	126
Acer rubrum	125	161	200	244	291	25	50	79	112	149
Quercus alba	170	212	257	308	363	11	18	25	32	41
Fagus grandifolia	270	324	375	425	474	16	23	32	41	51
Quercus rubra	196	267	349	442	547	17	30	45	63	81
Tilia americana	160	207	259	319	385	11	19	28	38	48
Betula alleghaniensis	219	263	314	372	436	13	20	27	34	42
Betula papyrifera	239	330	444	580	737	22	48	81	120	164
Juglans nigra	152	246	363	503	665	13	27	43	62	82
Catalpa speciosa	208	315	443	593	765	13	25	38	52	66
Prunus serotina	209	253	301	353	409	24	50	82	117	157
Populus deltoides	116	198	308	442	603	19	41	66	96	129
Celtis occidentalis	197	282	391	521	672	8	11	15	17	20
Pinus strobus	105	180	295	449	644	11	22	36	52	68
Pinus resinosa	125	170	226	295	374	19	35	54	74	96
Abies balsamea	74	99	127	158	192	10	13	17	21	25
Picea glauca	113	134	159	187	219	11	15	20	26	32
Larix laricina	116	158	214	281	359	17	33	52	72	95
Tsuga canadensis	90	97	110	127	148	7	11	15	19	24

The results for each output value were then combined in three scenarios (see Figure 13). Betula payrifera had the highest values across all three scenarios, followed by Prunus serotina and Populus deltoides. Several species dramatically increased from the 75-25 (Runoff Prioritized) scenario to the 25-75 (Carbon Prioritized) scenario, such as Acer rubrum and saccharum, while other trees such as Pinus strobus and Celtis occidentalis dramatically decreased. Abies balsams, Picea glauca, and Tsuga canadensis had the consistently lowest values across all three scenarios.

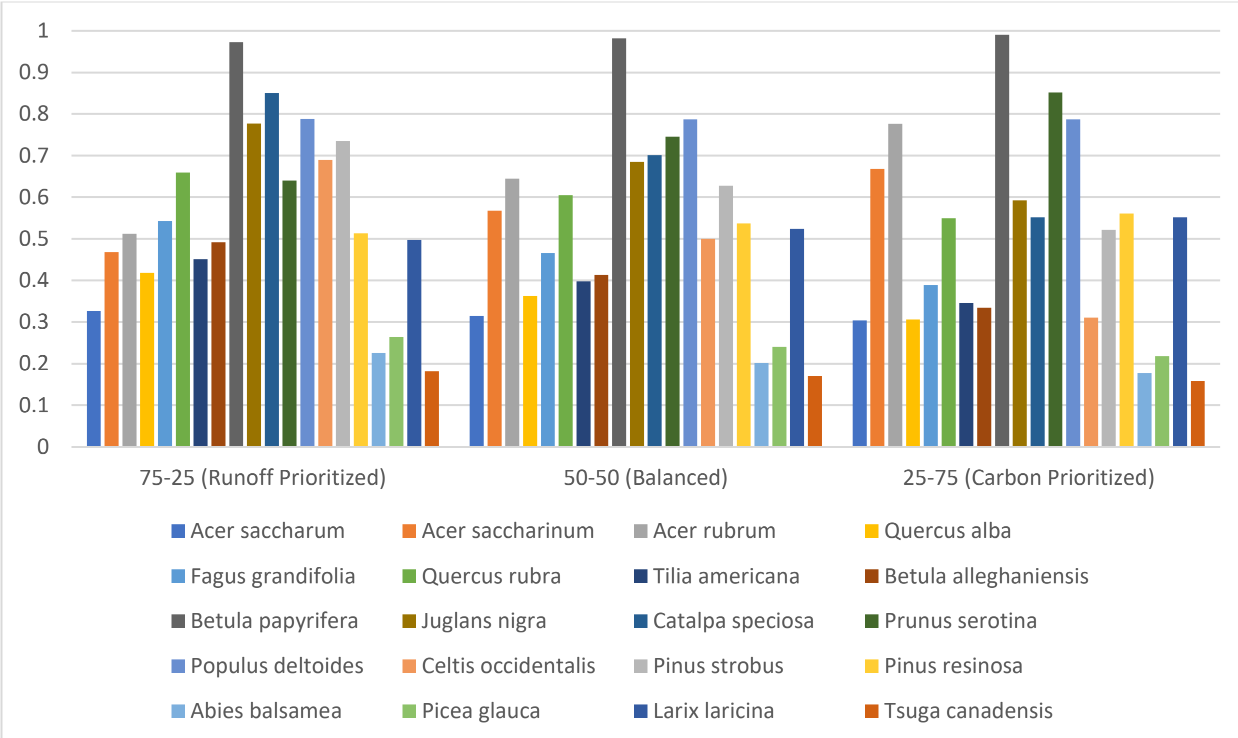


Figure 13. Combined Results of the Sensitivity Analysis Using i-Tree Design

In this study the 50-50 (Balanced) scenario was further used to prioritize the tree species used in the design of the selected study area, aiming to achieve a balance between runoff retention and carbon sequestration (see Table 12).

Table 12. Priorities of Tree Species for the Balanced Scenario Based on the Calculations with i-Tree Design

Priority	Tree Type	Combined Criteria
1	Betula payrifera Prunus serotina Catalpa speciosa Populus deltoides	>0.7
2	Acer rubrum Larix laricina Quercus rubra Acer saccharinum Pinus resinosa Juglans nigra Pinus strobus Celtis occidentalis	>0.5
3	Acer saccharum Quercus alba Tilia americana Betula allegheniensis Abies balsamea Picea glauca Tsuga canadensis Fagus grandifolia	<0.5

4.1.4 Combined Priorities

The results of the three models were then incorporated into site design to create a master priority of green infrastructure and land cover types for balanced stormwater management. Specific green infrastructure types, including trees, raised beds, amended soils, urban farming, and perimeter drains, were removed from the list or combined with similar counterparts to eliminate redundancy. Each green infrastructure type was categorized as a detention, filtration, infiltration, or treatment system based on its hydrological function in stormwater management. Detention systems focus on initial capture of rainwater, while filtration systems have a heavy emphasis on filtering and slowing the runoff rate. Infiltration systems are similar, filtering and slowing runoff while allowing it to infiltration into the soil in large amounts. Treatment systems accomplish filtration and infiltration, while additionally contributing to pollution removal and water quality improvement. The most important (priority 1) types selected were wetlands, infiltration basins, street planters, rain gardens, and vegetation filter strips (see Figure 14).

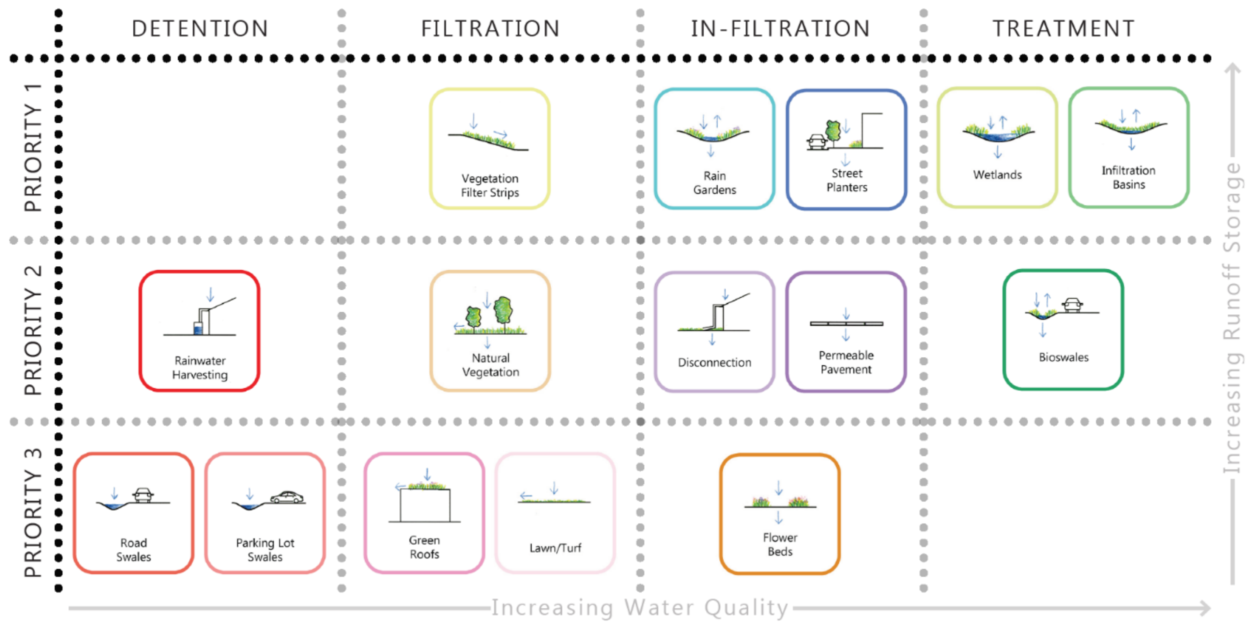


Figure 14. Combined Priorities of Green Infrastructure and Land Cover Types for Balanced Stormwater Management

4.2 Design Proposal

When types of green infrastructure are connected together in a networked system, the environmental and economic benefits can be greatly increased (University of Arkansas, 2010). This system was thereby used throughout the design process to aid the creation of comprehensive green stormwater management systems. The various green infrastructure types were organized into a system of linkages, from source capture to buffering to transportation to treatment. In Figure 15 this system is shown, with the green infrastructure types sorted between the overlapping categories (University of Arkansas, 2010). Source capture facilities, such as green roofs, primarily capture water at the place that it falls. Vegetation filter strips and other buffering facilities filter runoff as it travels away from its source. Transport facilities, such as bioswales, are mainly utilized to deliver water from one green infrastructure facility to another. The final facility type, capture, such as wetlands, aim to infiltrate as much water into the soil as possible.

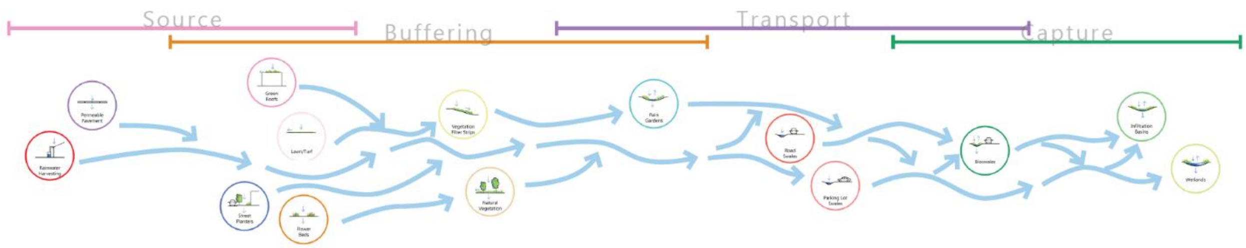


Figure 15. Linkages of Green Infrastructure: Source – Buffering – Transport – Capture

Using these factors, a comprehensive master plan was developed. The master plan features many new components to improve the site environmentally, socially, and economically (see Figure 16). The master plan was split into two sections, with one focusing on the environment with new green infrastructure improvements placed onto the site and the other focusing on the built infrastructure that enhances the social capacity of the community. The types of green infrastructure were designed based off of the priority system created through the sensitivity analysis and the design linkage explored earlier in the design phase, while considering existing site conditions and constraints. As a result, much of the existing traditional grey stormwater infrastructure system was replaced with green infrastructure. The area that each green infrastructure type takes up on the site plan is displayed in Table 13. The most utilized green infrastructure types were vegetation filter strips, followed by natural vegetation, bioswales, and rain gardens. Lawn/turf space was the only type that had less area in the plan than the baseline scenario, as a result of the design replacing the space with more effective green infrastructure types.

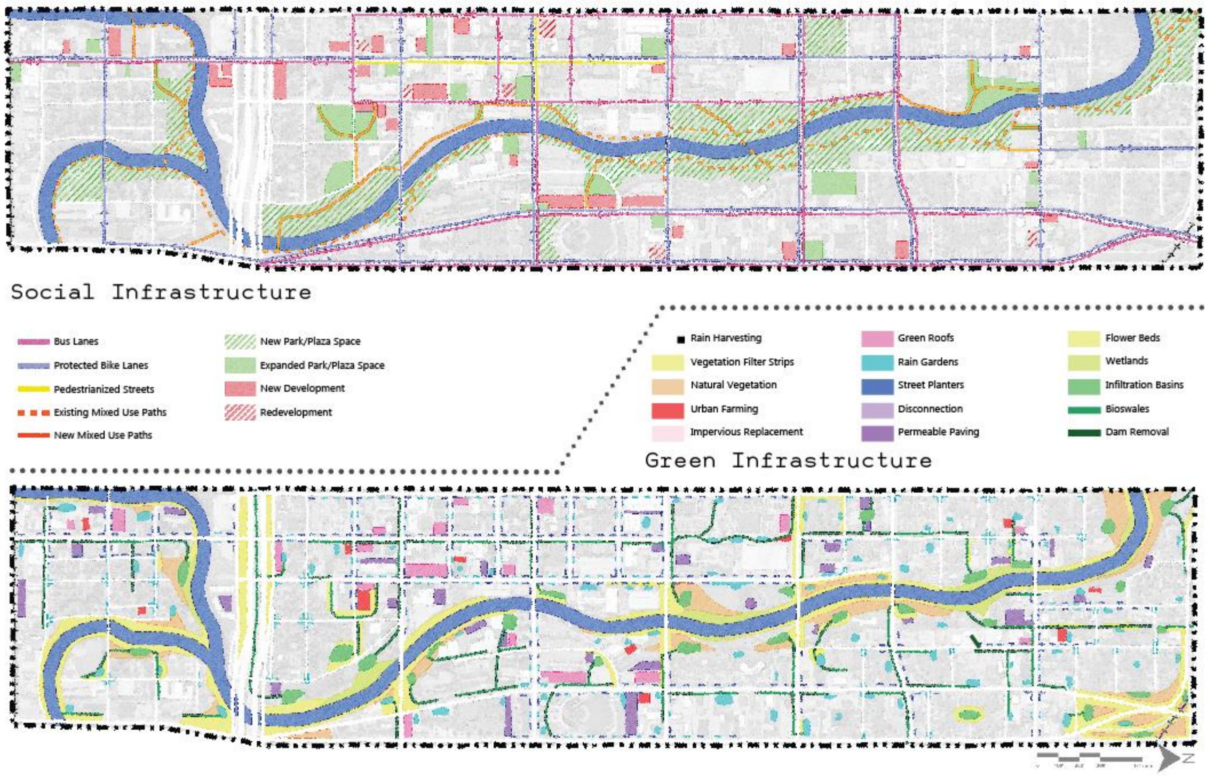


Figure 16. Environmentally and Socially Balanced Master Plan

Table 13. Area of Green Infrastructure Types Across Baseline and Design Scenarios.

Green Infrastructure Type	Baseline Acres	Design Acres	Acres Difference
Rain Gardens	0	14.1	14.1
Street Planters	0	7.32	7.32
Vegetation Filter Strips	0	26.53	26.53
Wetlands	0	8.55	8.55
Infiltration Basins	0	9.52	9.52
Natural Vegetation	0	19.72	19.72
Bioswales	0	17.18	17.18
Permeable Pavement	0	4.04	4.04
Disconnection	0	2.45	2.45
Rainwater Harvesting	0	1.63	1.63
Green Roofs	0	3.16	3.16
Urban Farming	0	3.14	3.14
Lawn/Turf	159.4	130.14	-29.26
Swales	0	1.36	1.36
Flower Beds	6	7.14	1.14

4.3 Post-Design Performance Evaluation

The results of assessing post-design performance using the NSC demonstrated that annual runoff was reduced by 4.17 inches per year, a 26% reduction from the baseline to design scenarios (see Table 14). Days per year without runoff and the percentage of wet days retained increased by a similar metric. On the economic side, estimated capital costs of installing the green infrastructure of the design scenario were between $3.3 and $4.3 million.

Table 14. Post-Design Model Results of the NSC.

Metric	Baseline	Design	Change	Percent Change
Annual runoff (in)	16.25	12.08	-4.17	-26%
Days per year with runoff	43.57	36.08	-7.49	-17%
Percent wet days retained	36.63%	47.53%	10.90%	30%
Smallest rainfall w/ runoff (in)	0.1	0.13	0.03	30%
Largest rainfall w/o runoff (in)	0.25	0.32	0.07	28%
Max rainfall retained (in)	1.16	1.6	0.44	38%
Capital costs low	$0	$3,373,420	$3,373,420	
Capital costs high	$0	$4,245,977	$4,245,977	
Maintenance costs low	$0	$24,459	$24,459	
Maintenance costs high	$0	$202,997	$202,997	

In the GVC, various environmental and economic metrics were calculated (see Table 15). Annual runoff decreased from 5.54” in the baseline scenario to 2.64” in the design scenario, a 52% reduction. Average storm runoff similarly decreased by 0.43”, a 34% reduction. Economically, capital costs and maintenance costs would increase, while additional benefits, such as reduced electricity energy use from green roofs and groundwater replenishment, would provide relief.

Table 15. Post-Design Model Results of the GVC.

Metric	Baseline	Design	Change	Percent Change
Annual Runoff (in)	5.54	2.64	-2.91	-52%
Annual Runoff Volume (Gallons)	99,189,360	47,154,343	-52,035,017	-52%
Average Storm Runoff (in)	1.25	0.83	-0.43	-34%
Average Storm Runoff Volume (Gallons)	22,411,539	14,802,377	-7,609,162	-34%
Initial Abstractions (in)	0.27	0.47	0.20	74%

Table 15 (cont'd)

Initial Abstractions Volume (Gallons)	4,778,401	8,352,252	-3,573,851	74%
Cumulative Abstractions (in)	1.34	2.33	0.99	74%
Cumulative Abstractions Volume (Gallons)	23,892,005	41,761,259	-17,869,253	74%
Curve Number	88.2	81.1	-7.1	-8%
Initial Costs ($ Total)	$64,779,683	$87,104,178	$22,324,496	-34%
Maintenance Costs ($ Annual)	$5,395,584	$5,865,012	$469,429	-9%
Reduced Energy Use ($ Annual)	$0	$24,776.93	$24,776.93	
Groundwater Replenishment ($ Annual)	$0	$13,803.53	$13,803.53	
Reduced Treatment ($ Annual)	$0	$4,782.20	$4,782.20	

L-THIA calculated additional environmental metrics based on land use and green infrastructure data (see Table 16). In this model, annual runoff depth decreased by 0.72", a reduction of 12%. Several water quality and pollution metrics were also calculated, with 9% to 15% reductions of each pollutant from the baseline to design scenarios. Chromium and oil/grease pollution, along with biological oxygen demand, were reduced the most from pre-development levels, while copper pollution levels reduced the least.

Table 16. Post-Design Model Results of the L-THIA.

Metric	Baseline	Design	Change	Percent Change
Annual Volume (acre-ft)	322.73	283.19	-39.54	-12%
Runoff Depth (in)	5.87	5.15	-0.72	-12%
Nitrogen (lbs)	1203	1058	-145	-12%
Phosphorus (lbs)	295.17	259.17	-36	-12%
Suspended Solids (lbs)	46,958	41,018	-5940	-13%
Lead (lbs)	9.96	8.931	-1.03	-10%
Copper (lbs)	11.05	10.02	-1.03	-9%
Zinc (lbs)	150.10	130.10	-20	-13%
Cadmium (lbs)	0.93	0.82	-0.10	-11%
Chromium (lbs)	7.05	6.02	-1.02	-15%
Nickel (lbs)	8.82	7.77	-1.05	-12%
Bio Oxygen Demand (lbs)	19,161	16,695	-2466	-13%
Chem Oxygen Demand (lbs)	86,330	74,222	-12,108	-14%

Table 16 (cont'd)

Oil & Grease (lbs)	6433	5503	-930	-14%
Fecal Coliform (millions)	34,156	30,542	-3614	-11%
Fecal Strep (millions)	81,864	72,562	-9302	-11%

The amount of runoff reduced and carbon sequestered on the site was calculated for each tree species using the i-Tree Design model (see Table 17). Catalpa speciosa had the highest amount of reduced runoff, with Betula papyrifera following close behind. Betula papyrifera additionally sequestered the most carbon on the site. On a site-specific scale, 26.5 million gallons of runoff were reduced annually and 5 million pounds of carbon were sequestered as a result of newly planted trees in the design.

Table 17. Post-Design Model Results of i-Tree Design

Tree Species	# of Trees	Annual Reduced Runoff (gallons)	Annual Carbon Sequestered (lbs)
Acer saccharum	1,200	309,600	57,600
Acer saccharinum	2,200	618,200	277,200
Acer rubrum	3,200	931,200	476,800
Quercus alba	1,500	544,500	61,500
Fagus grandifolia	1,300	616,200	66,300
Quercus rubra	3,700	2,023,900	299,700
Tilia americana	1,900	731,500	91,200
Betula alleghaniensis	800	348,800	33,600
Betula papyrifera	4,800	3,537,600	787,200
Juglans nigra	3,500	2,327,500	287,000
Catalpa speciosa	4,700	3,595,500	310,200
Prunus serotina	4,500	1,840,500	706,500
Populus deltoides	4,200	2,532,600	541,800
Celtis occidentalis	3,000	2,016,000	60,000
Pinus strobus	3,300	2,125,200	224,400
Pinus resinosa	2,900	1,084,600	278,400
Abies balsamea	700	134,400	17,500
Picea glauca	1,100	240,900	35,200
Larix laricina	2,700	969,300	256,500
Tsuga canadensis	1,200	177,600	28,800
TOTAL	52,400	26,705,600	4,897,400

CHAPTER 5 – DISCUSSIONS AND CONCLUSIONS

5.1 Need of Pre-Design Optimization of Green Infrastructure Types

Flooding and water quality issues negatively affect the environment, economy, and social opportunities of cities across the country, and these problems will continue to become more drastic in the future as a result of climate change (Szönyi & Svensson, 2019). Green infrastructure has the potential to mitigate these problems and instead provide benefits to the surrounding communities. The purpose of this study was to use pre-design optimization as a strategy to understand and balance the environmental and economic benefits of green infrastructure facilities, informing design decisions when attempting to reverse these negative effects.

Across the nation, municipalities have begun implementing green infrastructure to reverse these negative effects. The major driving force behind this implementation is the National Pollutant Discharge Elimination System (NPDES), implemented by the Clean Water Act in 1972, which requires permits for stormwater discharges from select categories that contribute to significant water quality problems, including municipal stormwater sewers (Odefey, 2013). Each state has the power to enact the permits, and many states have incorporated green infrastructure requirements into the permitting system, including Michigan (City of Lansing Department of Public Works, 2016). To aid this process, municipalities have begun actively implementing green infrastructure guidelines (Dupont, 2017). These guidelines and manuals often focus on the technical aspects of implementing individual green infrastructure facilities and techniques, lacking information about the potential environmental and economic effects of the facilities.

The City of Lansing's NPDES permit lists several ordinances as a compliance measure, including storm sewer discharge prohibitions, and post-construction stormwater control as part of the zoning code (City of Lansing Department of Public Works, 2016). The post-construction ordinance requires stormwater facilities to be designed to minimize flooding and pollution, by using detention, retention, transport, and drainage facilities to enhance the natural stormwater system. To accomplish this, the City's Stormwater Management Plan has multiple sections dedicated to the construction and maintenance of specific grey and green infrastructure management facilities (City of Lansing Department of Public Works, 2016). However, the plan contains very little information about the effectiveness and design of these facilities. Scenario building, like used in the pre-design phase of this study, could be used to aid the design process and help projects in Lansing and across the nation meet NPDES permit requirements and the Clean Water Act. A sensitivity analysis could be completed on a site-calibrated scale with results judged through various scenarios and split into priority guidelines. This would allow these designs to achieve informed and balanced effects.

This pre-design optimization was completed using a sensitivity analysis of three landscape performance toolkits, the NSC, GVC, and i-Tree Design. The NSC and GVC are similar models, using land cover and green infrastructure input parameters to calculate runoff, capital and maintenance costs, and other environmental and economic metrics. The sensitivity analysis of each of these models determined the effectiveness of various green infrastructure types in reducing varying economic and environmental impacts across three scenarios. In an effort to balance environmental and economic concerns, a master plan was further developed with the balanced scenario. The results of the normalized sensitivity analysis between each model were found to be comparable. Thus, the results of the NSC and GVC were combined, showing a master priority guideline. For i-Tree Design, a priority guideline of the most important trees at sequestering carbon and reducing runoff was created.

With the combined priority guideline, the results clearly showed the green infrastructure types with the most effectiveness to use in the design of the site. The top priority facilities were found to be vegetation filter strips, wetlands, rain gardens, street planters, and infiltration basins. The sensitivity analysis process was simple and provided key location-specific green infrastructure information for the design phase of the project. There is existing research on the effectiveness of various green infrastructure types, but they are lacking in specificity and provide only general information (Li et al., 2013). In this study, the information derived from the sensitivity analysis was used extensively in the design phase, placing green infrastructure onto the site according to the calculated priorities, and by creating a guideline for the linkage of green infrastructure types. Additional research was conducted in green infrastructure design, confirming and shaping the design of the site. The master green infrastructure guideline generated in this study demonstrated its potential for the use not only as the source of information, but also as a supplement that provides additional information to ensure greater accuracy in balancing environmental and economic benefits. This system is scalable and can be used as a simple way to gain insights into the design of green infrastructure systems across the country. The system has the potential to respond to situational factors based on the actual site location, providing information unavailable through traditional green infrastructure design manuals.

5.2 Need of Post-Design Performance Evaluation

Calculating the potential landscape performance of a site design after the design is completed has gained popularity in the field of landscape architecture (Canfield et al., 2018). Landscape performance measures typically use models and other toolkits to calculate the environmental, economic, and social benefits that the design will bring to the site. In this study, the post-design performance evaluation phase was completed to measure the potential site benefits, while additionally evaluating the efficacy of the pre-design sensitivity analysis and created design guidelines.

The three models that were used as a part of the sensitivity analysis, the NSC, GVC, and i-Tree Design were repeatedly used in the post-design evaluation. The use of these models ensured that the actual potential site performance and the effectiveness of the created site guidelines could be evaluated for their validity. The NSC and GVC were analyzed in detail because of their use in creating the green infrastructure priority guidelines that were heavily used during the design phase. Additionally, L-THIA, a model that was not used in the pre-design sensitivity analysis, was utilized to independently evaluate the effects of the design and round-out the post-performance evaluation.

The significant findings of the site design performance evaluation include the reduction of runoff across all the models utilized. Reduction estimates range from 12% as shown by the L-THIA model, to 26% in the NSC, to 52% in the GVC. Water quality would be significantly improved with new treatment systems removing pollutants from runoff. Additionally, runoff would be considerably slowed and the capture of water from large storm events would be improved. Economically, most models showed that there would be considerable capital costs with installing the project, but only minor increases in annual maintenance costs. Additionally, the reduced damages from the mitigated environmental concerns could offset the additional spending. This showed not only that the design could drastically improve the environmental and economic benefits of the region, but also that the design guidelines created by the sensitivity analysis played a significant role in the design process. The addition of the pre-design parameter optimization phase led to a balanced site with a multitude of benefits.

5.3 Limitations and Strengths

One limitation of the study was the potential shortcomings of the models used, especially in the pre-design phase of the project. Each model relies on approximations and calculations using simple control and input parameters, which can result in varied outcomes depending on the data used. This is visualized with the difference in annual runoff amounts calculated between the models, with each model calculating different runoff values and differences between the baseline and design scenarios. Nevertheless, the differences between the model formulas and data helps strengthen the research. By combining the information and analysis from each model, the generated priority guidelines have more involved data and a wider reach. The post-design performance evaluation phase showed that under all the models the site significantly improved both environmentally and economically, just by varying amounts.

The developed design itself has the opportunity to influence the implementation of green infrastructure in the site and the City of Lansing, Michigan. The design has the potential to transform the site, providing a multitude of environmental, social, and economic benefits. Even a small partial implementation of the design could bring significant results to the city and act a model for future designs throughout the region and country.

The significant contribution this study creates is the use of a new pre-design optimization phase in the design process of green infrastructure projects. Many projects use these models to calculate the potential design benefits after that design has been completed, but the present study demonstrates a novel way to use these models and inform best design decisions. In this study, the sensitivity analysis of various landscape performance models/toolkits led to the creation of a priority framework of different types of green infrastructure, which was used extensively in the design of the site. This study acts as a framework that can be replicated for other green infrastructure research and design projects. Future research should aim to expand the depth and breadth of model usage in multiple geographic locations and under various climate conditions, to enable scalable decision-making in sustainable stormwater management.

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APPENDIX A: BASELINE AND DESIGN PARAMETER SETTINGS

Table A-1. Baseline and Design Scenario Settings for the NSC

Parameter Category	Parameter Subcategory	Baseline Setting	Design Setting
Location	Location	Lansing, MI	Lansing, MI
	Area	659 acres	660 acres
Soil Type	Soil Type	C	C
Soil Drainage	Soil Drainage	0.4 in/hr	0.4 in/hr
Topography	Topography	Moderately Steep (5%)	Moderately Steep (5%)
Precipitation	Precipitation	LANSING CAPITAL CITY A (31.03"/yr)	LANSING CAPITAL CITY A (31.03"/yr)
Evaporation	Evaporation	LANSING CAPITAL CITY A (0.15 in/day)	LANSING CAPITAL CITY A (0.15 in/day)
Climate Change	Scenario	No change	No change
	Time Period	Near term	Near term
Land Cover	% Forest	5%	11%
	% Meadow	5%	11%
	% Lawn	25%	25%
	% Desert	0%	0%
	% Impervious	65%	53%
Green Infrastructure	Disconnection	0%	0.70%
	Rain Harvesting	0%	0.47%
	Rain Gardens	0%	4.04%
	Green Roofs	0%	0.90%
	Street Planters	0%	2.10%
	Infiltration Basins	0%	2.73%
	Permeable Pavement	0%	1.16%
Cost-Estimation	Project Type	Re-Development	Re-Development
	Site Suitability	Poor	Poor
	Cost Region	Detroit	Detroit

Table A-2. Baseline and Design Scenario Settings for the GVC

Parameter Category	Parameter Subcategory	Baseline Setting	Design Setting
Area	Area	659 acres	659 acres
Impervious Area	Flat Roof	54 acres	52.59 acres
	Pitched Roof	54 acres	52.59 acres
	Parking Surface	109 acres	77.18 acres
	Sidewalk	55 acres	43.57 acres
	Street	102 acres	72.35 acres
	Patio, Pool Deck, etc.	0 acres	0 acres
	Driveway	0 acres	0 acres
	Water Features	0 acres	0 acres

Table A-2 (cont'd)

Landscape Area	**Lawn/Turf**	**159 acres**	**130.14 acres**
	Flower Beds/Garden	6 acres	7.14 acres
	Natural Open Area	41 acres	41 acres
	Shrubs and Bushes	30 acres	30 acres
	Natural Water	49 acres	49 acres
	Vegetable Garden	0 acres	0 acres
	Raised Deck	0 acres	0 acres
	Natural Wetlands	0 acres	8.55 acres
Location	Location	Lansing, MI	Lansing, MI
Roof Water Capture	Green Roof	0 ft^2	137650 ft^2
	Rain Barrel	0 barrels	0 barrels
	Cistern	0 cisterns	0 cisterns
	Drywell	0 drywells	0 drywells
Roof Water Redirection	Rain Garden	0 ft^2	614196 ft2
	Planter Boxes	0 ft^2	318859 ft2
	Foundation/Perimeter Drain	0 ft	0 ft2
Landscaping	Trees	0 trees	0 trees
	Amended Soil	0 ft^2	0 ft2
	Bio-Swales	0 ft^2	748361 ft2
	Urban Farming/Gardening	0 ft^2	136778 ft2
	Raised Bed	0 ft^2	0 ft2
	Vegetation Filter Strip	0 ft^2	1155647 ft2
	Native Vegetation	0 ft^2	859003 ft2
Directing Runoff	Parking Lot Swales	0 ft	29621 ft2
	Roadside Swales	0 ft	29621 ft2
Permeable Paving	Permeable Patio	0 ft^2	0 ft2
	Permeable Parking	0 ft^2	175982 ft2
	Permeable Sidewalks	0 ft^2	0 ft2
	Permeable Driveway	0 ft^2	0 ft2
	Permeable Streets	0 ft^2	0 ft2

Table A-3. Baseline Scenario Settings for L-THIA

Land Use	**Soil**	**Area (acre)**	**Lot Size (acre)**
Forest	A	30	
Water/Wetlands	B	49	
Grass/Pasture	B	206	
Commercial	D	230	
Industrial	D	46	
High Density Residential	D	30	1/8
Low Density Residential	C	68	1/2

Table A-4. Design Scenario Settings for L-THIA

Land Use	Soil	Area (acre)	Lot Size (acre)	With GI%	Impervious %
Forest	A	45			
Water/Wetlands	B	60			
Grass/Pasture	B	206			
Commercial	D	204		20	70
Industrial	D	46		10	60
High Density Residential	D	30	1/8	15	45
Low Density Residential	C	68	1/2	5	20

Table A-5. Design Scenario Settings for i-Tree Design

Tree Species	# of Trees
Acer saccharum	1000
Acer saccharinum	3000
Acer rubrum	3000
Quercus alba	1000
Fagus grandifolia	1000
Quercus rubra	3000
Tilia americana	1000
Betula alleghaniensis	1000
Betula papyrifera	5000
Juglans nigra	3000
Catalpa speciosa	5000
Prunus serotina	5000
Populus deltoides	5000
Celtis occidentalis	3000
Pinus strobus	3000
Pinus resinosa	3000
Abies balsamea	1000
Picea glauca	1000
Larix laricina	3000
Tsuga canadensis	1000
TOTAL	52000

APPENDIX B: SENSITIVITY ANALYSIS

Table B-1. Sensitivity Analysis of the NSC

Metric	Baseline measurement (existing condition)	Adjustment Percentage	Adjustment Value	Average Annual Runoff (in)	Wet Days Retained (%)	Max Rainfall Retained (in)	Capital Costs ($)	Maintenance Costs ($)
Permeable Area	**35.0%**	**0%**	**35%**	**16.28**	**33.51**	**1.15**		
		1%	36.0%	16.03	33.97	1.19		
		2%	37.0%	15.78	34.27	1.22		
		5%	40.0%	15.04	36.25	1.31		
		10%	45.0%	13.79	39.38	1.47		
Disconnection	**0**	**0%**	**0%**	**16.28**	**33.51**	**1.15**		
		1%	1.5%	16.06	33.97	1.17	$2,472,224.00	$21,530.00
		2%	3.1%	15.82	34.27	1.18	$5,101,154.00	$44,494.00
		5%	7.7%	15.13	37.28	1.22	$12,659,306.00	$110,518.00
		10%	15.4%	13.98	39.3	1.3	$25,310,988.00	$221,036.00
Rain Harvesting	**0**	**0%**	**0%**	**16.28**	**33.51**	**1.15**	$0.00	$0.00
		1%	1.5%	16.09	34.17	1.16	$251,294.00	$17,276.00
		2%	3.1%	15.88	35.33	1.17	$510,062.00	$35,702.00
		5%	7.7%	15.28	36.27	1.2	$1,254,020.00	$88,680.00
		10%	15.4%	14.29	40.65	1.24	$2,499,340.00	$177,360.00
Rain Gardens	**0**	**0%**	**0%**	**16.28**	**33.51**	**1.15**	$0.00	$0.00
		1%	1.5%	16.08	33.97	1.16	$171,396.00	$1,454.00
		2%	3.1%	15.88	34.27	1.17	$243,058.00	$3,004.00
		5%	7.7%	15.28	36.25	1.2	$573,898.00	$7,460.00
		10%	15.4%	14.27	39.3	1.24	$1,127,694.00	$14,920.00
Green Roofs	**0**	**0%**	**0%**	**16.28**	**33.51**	**1.15**	$0	$0.00
		1%	1.5%	16.21	33.89	1.16	$3,288,340.00	$12,100.00
		2%	3.1%	16.14	34.04	1.16	$6,751,492.00	$25,006.00
		5%	7.7%	15.93	35.34	1.16	$16,708,028.00	$62,112.00
		10%	15.4%	15.57	37.47	1.17	$33,374,394.00	$124,222.00
Street Planters	**0**	**0%**	**0%**	**16.28**	**33.51**	**1.15**	$0	$0.00
		1%	1.5%	16.05	33.97	1.17	$295,910	$1,162.00
		2%	3.1%	15.81	34.27	1.19	$581,328	$2,402.00
		5%	7.7%	15.1	36.25	1.23	$1,401,928	$5,968.00
		10%	15.4%	13.92	39.3	1.31	$2,775,458	$11,936.00
Infiltrations Basins	**0**	**0%**	**0%**	**16.28**	**33.51**	**1.15**	$0	$0.00
		1%	1.5%	16.11	34.27	1.16	$106,904	$1,048.00
		2%	3.1%	15.92	34.27	1.17	$193,090	$2,166.00
		5%	7.7%	15.39	37.09	1.19	$440,886	$5,382.00

Table B-1 (cont'd)

		10%	**15.4%**	**14.51**	**40.27**	**1.22**	**$855,670**	**$10,764.00**
Permeable Pavement	**0**	**0%**	**0%**	**16.28**	**33.51**	**1.15**	0	$0.00
		1%	1.5%	16.04	33.97	1.18	$3,395,984	$24,242.00
		2%	3.1%	15.78	34.27	1.22	$7,010,384	$50,100.00
		5%	7.7%	15.03	36.25	1.31	$17,401,754	$124,444.00
		10%	15.4%	13.78	39.3	1.47	$34,795,992	$248,888.00

Table B-2. Sensitivity Analysis of the GVC

Metric	Baseline measurement (existing condition)	Adjustment Percentage	Adjustment Value	Annual runoff volume (gallons)	Runoff volume per event (gallons)	Maintenance + Capital Costs ($)
Roof	**0**	**0%**	**0**	**125861048.9**	**25176633**	
		1%	287060.4	123156809	24919762	
		2%	574120.8	120523791.3	24665042	
		5%	1435302	113031354.1	23913579	
		10%	2870604	101756382.5	22702173	
Shrubs	**0**	**0%**	**0**	**125861048.9**	**25176633**	
		1%	287060.4	122039611.4	24812251	
		2%	574120.8	118360268.2	24452195	
		5%	1435302	$108,109,303	23397370	
		10%	2870604	93286248	21720221	
Natural Open	**0**	**0%**	**0**	**125861048.9**	**25176633**	
		1%	287060.4	122039611.4	24812251	
		2%	574120.8	118360268.2	24452195	
		5%	1435302	$108,109,303	23397370	
		10%	2870604	93286248	21720221	
Lawn/Turf	**0**	**0%**	**0**	**125861048.9**	**25176633**	
		1%	287060.4	123156809	24919762	
		2%	574120.8	120523791.3	24665042	
		5%	1435302	113031354.1	23913579	
		10%	2870604	101756382.5	22702173	
Flowers	**0**	**0%**	**0**	**125861048.9**	**25176633**	
		1%	287060.4	123016471.9	24906302	
		2%	574120.8	120250691.8	24638354	
		5%	1435302	112401581.3	23848556	
		10%	2870604	100649456.1	22577556	
Water	**0**	**0%**	**0**	**125861048.9**	**25176633**	
		1%	287060.4	125861048.9	25176633	
		2%	574120.8	125861048.9	25176633	

Table B-2 (cont'd)

		5%	**1435302**	**125861048.9**	**25176633**	
		10%	2870604	125861048.9	25176633	
Wetland	**0**	**0%**	**0**	**125861048.9**	**25176633**	
		1%	287060.4	112653001.2	23874550	
		2%	574120.8	101090514.7	22627337	
		5%	1435302	73881278.6	19188054	
		10%	2870604	44716350.3	14329905	
	0	**0%**	**0**	**125861048.9**	**25176633**	**$0**
Green Roof		1%	287060.4	122118999.4	24819918	$7,604,837
		2%	574120.8	118511184.3	24467148	$15,209,675
		5%	1435302	108429005.4	23431471	$38,024,187
		10%	2870604	93741499.1	21774728	$76,048,375
Rain Gardens	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	116148294.2	24231142	$4,019,790
		2%	574120.8	107491180.7	23331205	$8,039,580
		5%	1435302	86449637.6	20876654	$20,098,950
		10%	2870604	62447609.3	17466320	$40,197,901
Planter Boxes	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	115800875.3	24196098	$10,377,485
		2%	574120.8	106868593.4	23264249	$20,755,874
		5%	1435302	85304411.2	20730457	$51,889,233
		10%	2870604	60972396.6	17229076	$103,778,466
Perimeter Drain	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	123371849.5	24940361	$12,917,718
		2%	574120.8	120980065	24709517	$25,835,436
		5%	1435302	114351511.3	24048940	$64,588,590
		10%	2870604	104909675.7	23051482	$129,177,180
Trees	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	96687597.4	22122599	$66,972,100
		2%	574120.8	76118476.7	19502924	$133,947,933
		5%	1435302	40802715.2	13538168	$334,864,233
		10%	2870604	17111389.4	7467899.2	$669,732,200
Amended Soil	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	125044222.6	25099538	$83,248
		2%	574120.8	124263794.9	25025482	$166,495
		5%	1435302	122140349.7	24821979	$416,238
		10%	2870604	119331724	24548171	$832,475
Bioswales	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	119725418.4	24586878	$9,190,586
		2%	574120.8	114034857.8	24016588	$18,381,171
		5%	1435302	99216505.5	22414643	$45,952,928

Table B-2 (cont'd)

		10%	**2870604**	**80244272.4**	**20066867**	**$91,905,857**
Urban Farming	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	124636817	25060928	$3,329,900
		2%	574120.8	123458081.5	24948613	$6,659,800
		5%	1435302	120188446.4	24632264	$16,649,520
		10%	2870604	115598127.9	24175606	$33,299,000
Raised Beds	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	121500636.9	24760086	$10,377,861
		2%	574120.8	117379622.1	24354631	$20,755,722
		5%	1435302	106289313.3	23201664	$51,889,305
		10%	2870604	91255091.5	21474585	$103,778,611
Vegetation Filter Strips	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	113394995.6	23950991	$454,724
		2%	574120.8	102629623.4	22799744	$909,448
		5%	1435302	77797436.4	19734993	$2,273,620
		10%	2870604	51771089.8	15657840	$4,547,240
Natural Vegetation	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	124231299.9	25022390	$332,265
		2%	574120.8	122659797.4	24872035	$664,530
		5%	1435302	118280905	24444325	$1,661,325
		10%	2870604	112028749.8	23809924	$3,322,651
Parking Swales	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	119344907.2	24549469	$25,462,751
		2%	574120.8	113279920.6	23939163	$50,925,501
		5%	1435302	97377922.7	22202906	$127,313,753
		10%	2870604	76747153.4	19590235	$254,627,506
Road Swales	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	121612695.3	24770948	$25,462,751
		2%	574120.8	117593060.2	24375925	$50,925,501
		5%	1435302	106753974.2	23251887	$127,313,753
		10%	2870604	92009219.3	21566257	$254,627,506
Permeable Paving	**0**	**0%**	**0**	**125861048.9**	**25176633**	**$0**
		1%	287060.4	121893697	24798148	$3,597,563
		2%	574120.8	118080077.4	24424389	$7,195,126
		5%	1435302	107481979	23330218	$17,987,816
		10%	2870604	92203202.4	21589747	$35,975,633

Table B-3. Sensitivity Analysis of i-Tree Design

Metric	Baseline measurement (existing condition)	Adjustment (years)	Tree Size (Diameter in)	Runoff Retained (Gallons)	Carbon Sequestered (Pounds)
Acer saccharum	**1**	**1**	**3**	**173**	**15**
		5	4.1	192	22
		10	5.3	213	30
		15	6.4	235	39
		20	7.5	258	48
Acer saccharinum	**1**	**1**	**3**	**117**	**31**
		5	5.1	152	54
		10	7.2	190	77
		15	9.3	234	102
		20	11.4	281	126
Acer rubrum	**1**	**1**	**3**	**125**	**25**
		5	5.1	161	50
		10	7.2	200	79
		15	9.3	244	112
		20	11.4	291	149
Quercus alba	**1**	**1**	**3**	**170**	**11**
		5	4.1	212	18
		10	5.3	257	25
		15	6.4	308	32
		20	7.5	363	41
Fagus grandifolia	**1**	**1**	**3**	**270**	**16**
		5	4.1	324	23
		10	5.3	375	32
		15	6.4	425	41
		20	7.5	474	51
Quercus rubra	**1**	**1**	**3**	**196**	**17**
		5	4.6	267	30
		10	6.2	349	45
		15	7.9	442	63
		20	9.5	547	81
Tilia americana	**1**	**1**	**3**	**160**	**11**
		5	4.6	207	19
		10	6.2	259	28
		15	7.9	319	38

Table B-3 (cont'd)

		20	**9.5**	**385**	**48**
Betula alleghaniensis	**1**	**1**	**3**	**219**	**13**
		5	4.1	263	20
		10	5.3	314	27
		15	6.4	372	34
		20	7.5	436	42
Betula papyrifera	**1**	**1**	**3**	**239**	**22**
		5	5.1	330	48
		10	7.2	444	81
		15	9.3	580	120
		20	11.4	737	164
Juglans nigra	**1**	**1**	**3**	**152**	**13**
		5	5.1	246	27
		10	7.2	363	43
		15	9.3	503	62
		20	11.4	665	82
Catalpa speciosa	**1**	**1**	**3**	**208**	**13**
		5	5.1	315	25
		10	7.2	443	38
		15	9.3	593	52
		20	11.4	765	66
Prunus serotina	**1**	**1**	**3**	**209**	**24**
		5	5.1	253	50
		10	7.2	301	82
		15	9.3	353	117
		20	11.4	409	157
Populus deltoides	**1**	**1**	**3**	**116**	**19**
		5	5.1	198	41
		10	7.2	308	66
		15	9.3	442	96
		20	11.4	603	129
Celtis occidentalis	**1**	**1**	**3**	**197**	**8**
		5	5.1	282	11
		10	7.2	391	15
		15	9.3	521	17
		20	11.4	672	20
Pinus strobus	**1**	**1**	**3**	**105**	**11**
		5	5.1	180	22
		10	7.2	295	36

Table B-3 (cont'd)

		15	**9.3**	**449**	**52**
		20	11.4	644	68
Pinus resinosa	**1**	**1**	**3**	**125**	**19**
		5	5.1	170	35
		10	7.2	226	54
		15	9.3	295	74
		20	11.4	374	96
Abies balsamea	**1**	**1**	**3**	**74**	**10**
		5	4.1	99	13
		10	5.3	127	17
		15	6.4	158	21
		20	7.5	192	25
Picea glauca	**1**	**1**	**3**	**113**	**11**
		5	4.1	134	15
		10	5.3	159	20
		15	6.4	187	26
		20	7.5	219	32
Larix laricina	**1**	**1**	**3**	**116**	**17**
		5	5.1	158	33
		10	7.2	214	52
		15	9.3	281	72
		20	11.4	359	95
Tsuga canadensis	**1**	**1**	**3**	**90**	**7**
		5	4.1	97	11
		10	5.3	110	15
		15	6.4	127	19
		20	7.5	148	24