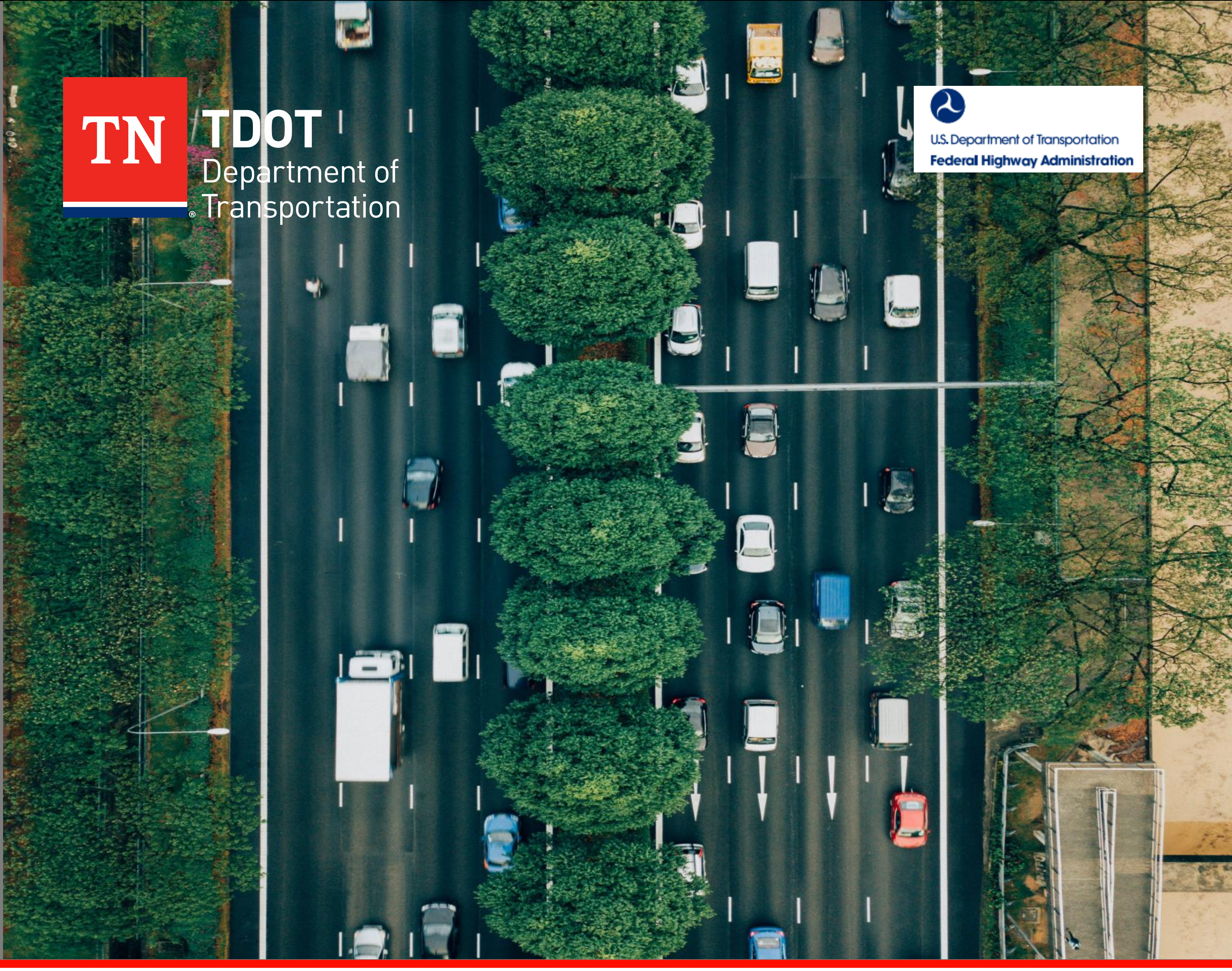

A FRAMEWORK FOR QUANTITATIVE ASSESSMENT OF THE ENVIRONMENTAL, SOCIAL, AND ECONOMIC BENEFITS OF TDOT INFRASTRUCTURE PROJECTS

Research Final Report from The University of Tennessee at Chattanooga | Ignatius Fomunung, Jejal Bathi, Mbaki Onyango, Thomas Wilson, Yu Liang | September 30, 2023

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Traditional infrastructure planning and design has mostly focused on the economic impacts of a project, while under prioritizing the environmental and social impacts. As state departments of transportation begin to integrate Green Infrastructure (GI) and Low Impact Development strategies into transportation infrastructure—to meet sustainability goals, promote economic growth, and enhance public safety and social objectives—there is a need for a standardized framework that quantifies and considers economic, environmental, and social impacts while also taking public opinion and the hierarchy of importance for these benefits into consideration. This study aims to develop a systematic quantification framework that does just that, with the use of spatially specific and temporally dynamic metrics, objective weights, practical quantification methods, and calculations to value tangential benefits. This framework is meant to be used by practitioners to assess the applicability and quantified benefits of GI practices to be used in transportation projects. To do this, the Analytical Hierarchy Process and Monte Carlo Simulation methods, along with results from two surveys, are employed to build the toolbox, complete with a searchable database of applicable GI measures that can be used for specific field conditions of a project. Additionally, a step-by-step user guide has been developed to facilitate practitioner’s use of the toolbox, and a case study was conducted to demonstrate the toolbox‘ capabilities and benefits.</td></tr>
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1. Md Kamrul Hasan Sabbir, Ignatius Fomunung, Casey Langford, Thomas Wilson, Jejal Reddy Bathi, Patrick Garner, Yu Liang, Mbaki Onyango, "Quantification and Integration of Social Benefits of Green Infrastructure in Screening Transportation Project Alternatives", The Transportation Research Board (TRB) 102nd Annual Meeting, Washington, D.C , USA (2022) (Accepted for presentation)
2. Jejal Reddy Bathi, Carmen Harvey, Ignatius Fomunung, Mbakisya Onyango, M.K.H. Sabbir, Yu Liang, Wilson Thomason, "Database of Green Infrastructure in Transportation Projects Planning: Current Guidance and Standards by Transportation Agencies", The Transportation Research Board (TRB) 102nd Annual Meeting, Washington, D.C, USA (2022) (Accepted for presentation)
3. Md Kamrul Hasan Sabbir, "Integrating Social and Environmental Impacts of Green Transportation Infrastructure: A Framework for Effective Decision-Making", MS thesis.

Executive Summary

Green Infrastructure (GI) is a multi-benefit tool that has existed in the municipal "toolbox" for a while. However, the lack of an efficient cost-benefit analysis—one that considers economic as well as environmental and social impacts—leaves it being underutilized, and our community suffers these consequences. The Tennessee Department of Transportation (TDOT) is currently integrating GI components into its infrastructure projects in order to fulfill its sustainability objectives. GI practices reduce *and* treat stormwater runoff, along with improving water and air quality, and climate resiliency, but it also offers valuable benefits to society and our communities. GI elements, which employ Low Impact Development (LID) techniques, aim to replicate natural processes to treat stormwater as close to its source as feasible and in a way that promotes ground infiltration rather than conveying runoff to a treatment facility. In addition to the obvious environmental benefits stemming from the implementation of these techniques, there are also social and indirect economic benefits. Social benefits of GI could be the aesthetic value of rain gardens and green spaces or the improved public safety and sanitation, while economic benefits could be the costs and investments saved from remediating flooding or other wet weather damages. However, conventional approaches typically emphasize the economic effects—primarily the principal costs—of infrastructure development and disregard the environmental and social impacts of GI. As a result, GI is perceived as less desirable than Traditional Infrastructure (TI), also known as gray infrastructure. Furthermore, existing methodologies fail to account for public opinion in the decision-making process.

In order to secure funding and satisfy sustainability objectives, TDOT must present GI implementations as a feasible stormwater management option to stakeholders. Achieving this goal necessitates the development of a comprehensive, integrated framework (i.e. a decision-making algorithm) that considers the relative importance of various GI co-benefits, incorporates public opinion, and integrates spatially specific and temporally dynamic metrics for quantifying and monetizing the diverse benefits of GI. When all the impacts—environmental, social, and economic—of implementing GI are determined and considered, it becomes challenging to see how developers would want to choose gray infrastructure over GI. The benefits of GI surpass economic advantages, which tend to be the main benefit of gray infrastructure.

This study utilizes the Analytical Hierarchy Process (AHP) and Monte-Carlo Simulation (MCS) methods—along with a searchable database of applicable GIs for possible field conditions of transportation projects—to construct this comprehensive framework that integrates the various impacts of transportation infrastructures, and ultimately facilitates the selection of suitable GI for different locations. Initially, a GI database was created to serve as a reference for the framework and eventually the end product of the toolbox, which is a tool that employs the framework to be used by TDOT and other practitioners. This database comprehensively compiled more than 30 different types of GI, including rain harvesting methods like cisterns and rain barrels, permeable pavement, green roofs, bioretention systems, landform grading and level spreaders, amongst others. Within this repository of GI measures, site requirements and specific restrictions were listed for each practice, as well as the quantified impacts and benefits of various GI methods, with many impacts having monetized values. In order to establish a hierarchy of importance, two surveys were conducted: one on a national scale across all State Departments of Transportation (SDOTs) from which 18 SDOTs responded and another at the community level throughout the state of Tennessee from which 98 citizens responded. These surveys revealed that the opinion of administrators and citizens did not significantly differ. Perception of GI is overwhelmingly positive and the benefits of implementing such infrastructure—whether environmental, social or economic—are largely understood and accepted. Integrating the hierarchy of importance into the framework makes it possible to consider the biases of public opinion, while still being able to deliver standard unbiased results.

This toolbox can be employed by TDOT to evaluate the all-inclusive spatially specific and temporally dynamic impacts of distinct infrastructure choices, as well as to facilitate decision-making among various infrastructure options. Accompanying the toolbox, a step-by-step user guide was developed to assist practitioners with the use of the GI toolbox in assessing the total benefits of applicable GI. This guide is embedded into the toolbox itself and offers guidance while the tool is being used. Additionally, a case study using the toolbox is also presented to demonstrate the capabilities of the benefit analysis tool and to assist TDOT personnel in navigating the toolbox.

Key Findings

The key findings of this project are as follows:

- All the state DOTs are implementing GI elements into their infrastructure projects.
- There is a lack of a unified decision-making process regarding the overall use of GI in Tennessee *and* nationally.
- There is a lack of quantitative assessment method for social impacts of GI.
- The Analytical Hierarchy Process offers a robust solution for addressing the Multi-Criteria, Multi-Level complexity inherent in decision-making when selecting the optimal GI choice, effectively managing the associated subjectivity.
- Employing the Monte Carlo Simulation enables the extension of this methodology's applicability to encompass the entire United States.

Key Recommendations

A web-based cost-benefit analysis tool, considering quantified economic, social, and environmental impacts will help SDOTs make the best and most informed decisions about which type of infrastructure to implement in transportation projects. Using the toolbox, environmental and social benefits will no longer be disused, resulting in better choices of infrastructure, and not just from an economic perspective. The community will benefit, and the environment will be impacted less. This toolbox has integrated a hierarchy of importance regarding GI, which allows for unbiased results—no matter the users' opinions—while still considering the biases of public opinion.

- When determining the optimal choice among various Green Infrastructure (GI) options, it is essential to consider the social and environmental impacts associated with each alternative along with the economic impacts.
- The tool can be used to obtain monetary impact from social, environmental and economic aspect of Green Transportation Infrastructure.

- The tool can also be used to obtain quantified environmental and social impacts such as stormwater runoff reduction, air pollutant reduction, energy saved, anticipated green space for recreational use, etc.
- The tool aids in making informed decisions by assisting in the selection of the most optimal infrastructure option from a range of choices.
- The toolbox offers a convenient and easy method for choosing and implementing GI, which undoubtedly will lead to more GI implementation across the state of TN, reducing stormwater hazards and meeting sustainability goals.

With less than a third of SDOTs performing GI analysis regarding economic, environmental, and social impacts, TDOT would be a leader amongst SDOTs to analyze and implement GI based on these impacts.

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Glossary of Key Terms and Acronyms

AHP	Analytical Hierarchy Process
CSO	Combined Sewer Overflow
CSS	Combined Sewer Systems
DA	Drainage Area
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GI	Green Infrastructure
LID	Low Impact Development
MCDM	Multi-Criteria Decision-Making
MCS	Monte-Carlo Simulation
PDF	Probability Distribution Function
SDOT	State Departments of Transportation
TI	Traditional Infrastructure
	Bioretention
	Bioswale
	Criteria Pollutants
	Likert Scale
	Permeable Pavement
	Rain Harvesting
	Urban Heat Island Effect

Chapter 1 Introduction

Green Infrastructure (GI) is a holistic approach that uses natural systems to provide multiple benefits in urban areas. It includes Low Impact Development (LID) techniques, which imitate natural processes to capture and treat stormwater close to its source [1]. When GI techniques are used to manage stormwater, ground infiltration increases and the need for treating stormwater runoff which becomes polluted traveling across impervious surfaces is decreased, or possibly eliminated as GI also treats stormwater through filtration and/or sedimentation processes. GI not only helps to reduce strain on capacity limitations of pipe networks that can lead to flooding, or decrease the urban heat island effect with green over "gray" (i.e. concrete) areas and provides habitats for wildlife but also promotes sustainable transportation options that encourage non-motorized travel and compact communities.

Numerous state and federal authorities across the United States are presently incorporating sustainable practices into their infrastructure management plans and land use development strategies. The objective behind this is to stimulate economic growth while simultaneously creating a healthy environment that enhances the overall quality of life. These sustainable infrastructure practices, collectively known as GI, include an array of techniques such as green sidewalks, permeable pavement, downspout disconnection, rainwater harvesting, bioretention, bioswales, urban tree canopy, and many more. In addition to the obvious environmental benefits, the incorporation of GI practices also provides a range of social and economic benefits. Due to these multifaceted advantages, the integration of GI practices into various infrastructure sectors such as transportation and communication, water resources, sewage management systems, power production, etc., has been on the rise in recent years [2-5]. The conventional approaches to infrastructure planning, design, and implementation typically focus on the economic impacts of a project, while environmental impacts may also be considered but not consistently. Many environmental impacts are straightforward and easy to quantify, such as the amount of runoff reduced, but there are various environmental impacts that are much more challenging to quantify and subsequently monetize. For example, wildlife benefit greatly from more green spaces opposed to concrete areas and in turn the environment benefits, but these impacts are very difficult to monetize. To a greater extent, social impacts too can be challenging to quantify due to their subjective nature and are often overlooked. Social impacts are highly variable in terms of space and time, which makes it difficult to generalize their effects in specific locations and periods. Consequently, by omitting social and environmental impacts the traditional approach to infrastructure planning may seem more cost-effective to policymakers than GI projects. However, by integrating the quantification of social and environmental benefits into the cost-benefit analysis of a project, GI projects could become a much more attractive option than traditional infrastructure (TI) [6-9].

The economic benefit of implementing TI pales in comparison to the breadth and value of the numerous benefits of GI. After conducting a literature review, it was found that there have been some attempts to quantify and monetize the social and environmental benefits of GI in recent years. However, these studies do not consider the potential for randomness in public opinion and acceptance of GI within society, nor do they account for the hierarchy of importance among different social, environmental and economic benefits. To address these limitations, this research employs the Analytical Hierarchy Process (AHP) and Monte Carlo Simulation (MCS) techniques to overcome the subjectivity, as well as spatial and temporal variations inherent in the social and environmental benefits of GI. The proposed framework is intended to be applicable to various regions across the United States [9, 10].

1.1 Problem Statement

The adoption of GI practices by many state departments of transportation (SDOT) in the United States aims to meet sustainability goals, promote economic development, enhance traffic safety, and improve quality of life. GI refers to a living network that integrates landscape areas, natural areas, and waterways, including Low Impact Development (LID) techniques. However, traditional approaches to infrastructure planning (e.g. the use of gray infrastructure) tend to prioritize economic impacts while disregarding environmental and social impacts. While several SDOTs and the Federal Highway Administration (FHWA) have initiatives to quantify the benefits of GI [11-14], there is a need for a unified framework that considers economic, environmental, and social benefits along with public opinion and the comparison of importance of different benefits to aid decision making. In this context, the proposed research aims to develop a systematic quantification framework that captures economic, environmental and social impacts of infrastructure projects, including spatially specific and temporally dynamic metrics, objective weights, practical quantification methods, and calculations to value tangential benefits. The study will propose a framework that can be used by practitioners to promote sustainable infrastructure practices by assessing the applicability and quantified benefits of possible GI for development projects.

1.2 Objectives

The objectives of this study are as following:

1. To explore and examine the multifaceted benefits of GI and LID techniques in promoting sustainable urban development and enhancing the quality of life in urban areas.

2. To generate a database of GI practices with attributes detailing the applicability and benefits of each possible GI, to be used as a reference for the proposed framework (Objective 5).

3. To identify and evaluate the existing approaches to quantify and monetize the social and environmental benefits of GI and LID in infrastructure planning and decision-making processes.

4. To apply the AHP and MCS techniques to capture the randomness and hierarchy of social and environmental benefits in GI and LID projects and develop a practical calculation model.

5. To propose a systematic and comprehensive framework that integrates environmental, social and economic impacts of infrastructure projects, including spatially specific and temporally dynamic metrics, objective weights, and practical quantification methods.

1.3 Report Outline

The subsequent sections of this report are organized as follows: Chapter II presents a review of the pertinent literature, which has been instrumental in informing the author's understanding of the state of the art and shaping the direction of the study. The first segment of Chapter III elucidates the methodology and approach adopted in employing the Analytical Hierarchy Process and Monte Carlo Simulation, while the latter segment outlines the quantification framework developed for evaluating the various impacts of GI. Chapter IV explains the usage of the toolbox through a case study with hypothetical parameters. And finally, the results of the research supplied in the toolbox's fabrication, along with the results of the case study which explicitly show the function and advantage of the toolbox, are described in Chapter V.

Chapter 2 Literature Review

Green infrastructure (GI) has the potential to serve as a cost-effective solution for fulfilling transportation infrastructure requirements while enabling SDOTs to maximize the value of their investments in infrastructure by generating various environmental, economic, and social benefits. The implementation of GI in transportation projects has been successful in addressing stormwater management challenges, and an increasing number of projects are adopting a mix of both green and gray infrastructure to lower the overall costs of compliance with stormwater management regulations. GI projects can significantly enhance the aesthetics of communities, particularly when compared to traditional built environment expansion. Successful GI projects have the potential to enhance public safety, improve the attractiveness of communities, raise property values, and create new job opportunities in the green economy.

Recent studies have highlighted the importance of integrating social and environmental impacts into decision-making processes for transportation infrastructure projects. For example, a study by Strong et al. (2017) found that incorporating environmental and social considerations in transportation infrastructure planning and design can result in significant benefits such as reduced greenhouse gas emissions and improved public health outcomes [15]. Similarly, a study by Ameen et al. (2015) emphasized the need for a comprehensive framework that integrates both environmental and social impacts of green transportation infrastructure, highlighting the role of community engagement and stakeholder involvement in the decision-making process [16]. In addition, recent research has focused on developing more robust and standardized frameworks for evaluating the social and environmental impacts of green transportation infrastructure. For instance, a study by Ramani et al. (2011) proposed a framework for quantifying the social and environmental benefits of green transportation infrastructure based on a set of performance indicators that account for factors such as accessibility, safety, and air quality [17]. Another study by Liang et al. (2020) developed a framework for evaluating the environmental and social impacts of transit-oriented development projects, which can help transportation agencies prioritize projects that maximize benefits for both the environment and communities [18].

Furthermore, recent studies have emphasized the need to address implementation challenges associated with integrating social and environmental impacts into decision-making processes. For example, a study by May (2022) identified institutional and regulatory barriers that can hinder the implementation of sustainable transportation policies, emphasizing the need for a coordinated and collaborative approach across different levels of government [19]. Another study by Romero-Bonsu et al. (2020) highlighted the importance of community involvement and stakeholder engagement in green transportation infrastructure projects, emphasizing the need to address power imbalances and ensure equitable outcomes for all stakeholders [20].

Overall, these recent studies highlight the importance of integrating social and environmental impacts along with economic ones into decision-making processes for transportation infrastructure projects. They also provide insights into the challenges and opportunities associated with developing more robust and standardized frameworks for evaluating these impacts and implementing sustainable transportation policies.

There is currently a lack of standardized and formalized frameworks for evaluating the environmental and social benefits of infrastructure systems. This makes it difficult for transportation departments to optimize their investment strategies. Existing quantification programs also vary significantly in terms of performance metrics, quantification methods, weighting schemes, and integration techniques. Furthermore, these frameworks often prioritize single economic aspects over environmental and social merits [21], resulting in biased decision making. Additionally, individual programs often use subjective and ad-hoc methods for scoping performance metrics and determining their relative importance [22], without considering their effectiveness in benefit characterization or the implications to the corresponding community. While many individual benefit quantification/modeling studies exist, their results have not been efficiently used for quantitative framework development, leading to unstable analysis outcomes due to the strong dependency between explanatory variables. The frameworks often prioritize function [23] and fail to consider the natural variations in stakeholder perspectives and perceptions [24, 25], as well as temporal and spatial factors. Finally, integrating all the benefits into a single measurement tends to be subjective and uncertain, leading to a need for more objective and credible understanding of the mechanism of infrastructure impacts and causes.

The Environmental Protection Agency (EPA) and the Federal Highway Administration's (FHWA) Green Highways Partnership aims to engage public and private entities to enhance the functionality and sustainability of highways through GI practices such as bioretention, planting street trees, landscape improvements, and removal of unnecessary pavement [26]. The partnership assigns a score to projects based on the extent to which they adopt such practices, among others. The FHWA Sustainable Highways Self-Evaluation Tool is a self-assessment tool that incorporates sustainable principles into system planning and processes, project development, and transportation systems management, operations, and maintenance [27]. Greenroads, initiated by the University of Washington and developed jointly with CH2M HILL, is a rating system, similar to LEED, that certifies roads as "green" based on established standards [28]. The University of Wisconsin's BE2ST is a green highway construction rating system based on Life Cycle Assessment/ Life Cycle Cost Analysis [29], while the Sustainable Infrastructure Project Rating System assesses infrastructure based on economic, environmental, and social impacts using the "Triple Bottom Line" approach, which verifies the sustainability of civil engineering projects [30].

A significant gap in the literature mentioned above is the limited consideration of stakeholder perspectives and perceptions [31]. Stakeholders, such as community members and local businesses, have unique perspectives and interests in transportation infrastructure projects. Their input is critical in understanding the local context and can provide valuable insights into the potential impacts of a project. However, the current frameworks often lack a systematic and inclusive approach to engage and incorporate the input from stakeholders. Furthermore, most existing frameworks do not consider temporal and spatial variations in impacts [32]. Impacts of green transportation infrastructure can change over time and differ based on the location of the project. Ignoring such variations can lead to inadequate understanding of the long-term impacts of the infrastructure and can result in poor decision-making. Finally, there is a need for more objective and credible understanding of the mechanisms of infrastructure impacts and causes. Many benefit quantification and modeling studies exist, but their results have not been efficiently used for quantitative framework development, leading to unstable analysis outcomes due to the strong dependency between explanatory variables. Therefore, the development of more robust models and tools to account for these complexities is necessary.

Addressing these gaps in the literature is crucial for developing effective decision-making frameworks that incorporate the social, environmental and economic impacts of green transportation infrastructure. Future research could focus on developing standardized and objective metrics for quantifying the social and environmental benefits of green transportation infrastructure, incorporating stakeholder input systematically, accounting for temporal and spatial variations in impacts, and developing robust models that can account for the complexity of the infrastructure system.

Chapter 3 Methodology

The methodology employed in this study integrates several key components:

1. The Analytical Hierarchy Process

2. Monte-Carlo Simulation

3. Quantification and Monetization frameworks for various impacts of GI

The subsequent sections will delve into each of these subjects, providing a comprehensive overview of their roles and significance in this study.

3.1 The Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) method that was developed by Thomas Saaty in the late 1970s [33]. It is a mathematical model used for complex MCDM problems that require the consideration of multiple criteria and preferences. AHP has been widely applied in various fields, including engineering, economics, management, and environmental science [34]. The method involves a structured process that allows decision-makers to break down complex problems into smaller, more manageable parts, and to prioritize them based on their importance. The AHP method is based on the principle that decisions can be made by comparing the relative importance of different criteria and alternatives. It involves a pairwise comparison of criteria and alternatives, where the decision-maker assigns values to each criterion or alternative in relation to others using a scale from 1 to 9. These values are then used to derive a set of weights that reflect the relative importance of each criterion or alternative. The AHP method also includes a consistency test to ensure that the pairwise comparisons are logical and consistent.

TABLE I

THE FUNDAMENTAL SCALE FOR PAIRWISE COMPARISON

Intensity of importance	*Definition*

1	Equal importance
3	Moderate importance
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Reciprocals Values for inverse comparison

The AHP method has been widely adopted in various fields due to its ability to provide a structured, transparent, and flexible decision-making process. The method has also been extensively studied and validated by researchers, and its effectiveness has been demonstrated in numerous applications.

The AHP method is mathematically represented by a series of equations, which are used to calculate the weights of criteria and alternatives. The most widely used equation for AHP is the eigenvector method, which is based on the principle of maximizing the consistency of the pairwise comparisons. The AHP is deemed particularly appropriate for the current study given its focus on addressing the inherent subjectivity in evaluating the social and environmental impacts of green transportation infrastructure. The use of AHP can effectively transform subjective assessments into objective measures, making it a fitting approach for the current study. Furthermore, AHP was chosen to address the complexities of the decision-making process that involves multiple levels and criteria, which requires a systematic and rigorous analysis to arrive at an optimal decision.

3.2 Monte-Carlo Simulation

Monte Carlo Simulation (MCS) is a powerful computational tool widely used in various fields such as engineering, finance, physics, and environmental sciences. It is a probabilistic method that uses random sampling to simulate different scenarios and estimate the probability distribution of outcomes [35]. MCS has been used in environmental sciences to assess the uncertainty and variability of different parameters and their impacts on the system [36]. It is particularly useful in assessing the uncertainty associated with the implementation of Green Infrastructure (GI) projects, which involves various uncertain factors.

The basic idea behind MCS is to generate a large number of random samples from a probability distribution function (PDF) of the input parameters and propagate them through a mathematical model to obtain the output distribution. The output distribution represents the probability of different outcomes for a given scenario, which can be used to estimate the expected value and variance of the output.

The MCS can be mathematically represented by the following equation:

$$I = \frac{1}{N} \sum_{i=1}^{n} f(x_i)$$

Where,

I = the estimated value of the output

N = the number of samples

x_i = a random sample from the PDF of the input parameters

$f(x_i)$ = the corresponding output of the model for the input sample x_i

The utilization of MCS in this study was motivated by the need to account for the inherent randomness that may stem from public opinion. Given that the community survey was conducted solely within the state of Tennessee, the use of MCS is expected to facilitate the extrapolation of the survey results to a broader scale encompassing the entire United States.

3.3 The Hierarchy Structure

The hierarchy structure for determining the best choice among GI, traditional infrastructure, and combined infrastructure is shown in **Error! Reference source not found.**:

TABLE II

THE HIERARCHY STRUCTURE FOR DETERMINING THE BEST INFRASTRUCTURE CHOICE

Goal	*Level 1*	*Level 2*	*Alternatives*
Likelihood of Selection	*Social*	*Recreational use*	*Green infrastructure (GI)*
		Heat reduction	
		Job creation	*Combination of green and traditional infrastructure (CI)*
		Enhanced property value	
	Environmental	*Reduced stormwater runoff*	
		Reduced air pollutants	
		Reduced energy use	*Traditional infrastructure (TI)*
	Economic	*Initial cost*	
		Maintenance cost	

However, the 'Reduced Energy Use' impact under environmental impact was discarded for two reasons:

1. In the case of transportation infrastructure, the area is typically open and not confined, rendering the shading effect ineffective in providing any cooling benefits.
2. The diminished urban heat island effect resulting from the majority of transportation infrastructures being situated in open areas may yield certain indirect financial advantages through the mitigation of extreme heat events. However, it should be noted that the benefit derived from this impact has already been considered within the 'Heat Reduction' impact discussed in the section on social impacts. Consequently, in order to prevent duplication of calculations, the 'Reduced Energy Use' impact was excluded.

As a result of not considering the 'reduced energy use' impact, the hierarchy structure shown in Error! Reference source not found. takes the form of Error! Reference source not found.**:**

Table III

THE HIERARCHY STRUCTURE FOR DETERMINING THE BEST INFRASTRUCTURE CHOICE

Goal	*Level 1*	*Level 2*	*Alternatives*
Likelihood of Selection	*Social*	*Recreational use*	*Green infrastructure (GI)*
		Heat reduction	
		Job creation	
		Enhanced property value	*Combination of green and traditional infrastructure (CI)*
	Environmental	*Reduced stormwater runoff*	
		Reduced air pollutants	
	Economic	*Initial cost*	*Traditional infrastructure (TI)*
		Maintenance cost	

3.4 Social Impact Quantification Frameworks

In the next step of the AHP, we need to determine entries for four pairwise matrices—one for each social criterion—to compare the efficiency of the three alternatives in contributing to the social aspect in concern.

In order to populate the matrices with appropriate entries, the social impact monetization framework, which has been developed through previous research, will be employed.

Recreational Use

The increase in vegetation due to the newly built GI would allow increased participation of the inhabitants of the areas encapsulated by the GI in activities like walking, biking, jogging on sidewalks, etc. These activities are similar to the ones performed in parks. Therefore, the benefits gained from recreational use resulting from the increase in vegetation can be compared to the benefits from the added area in a park.

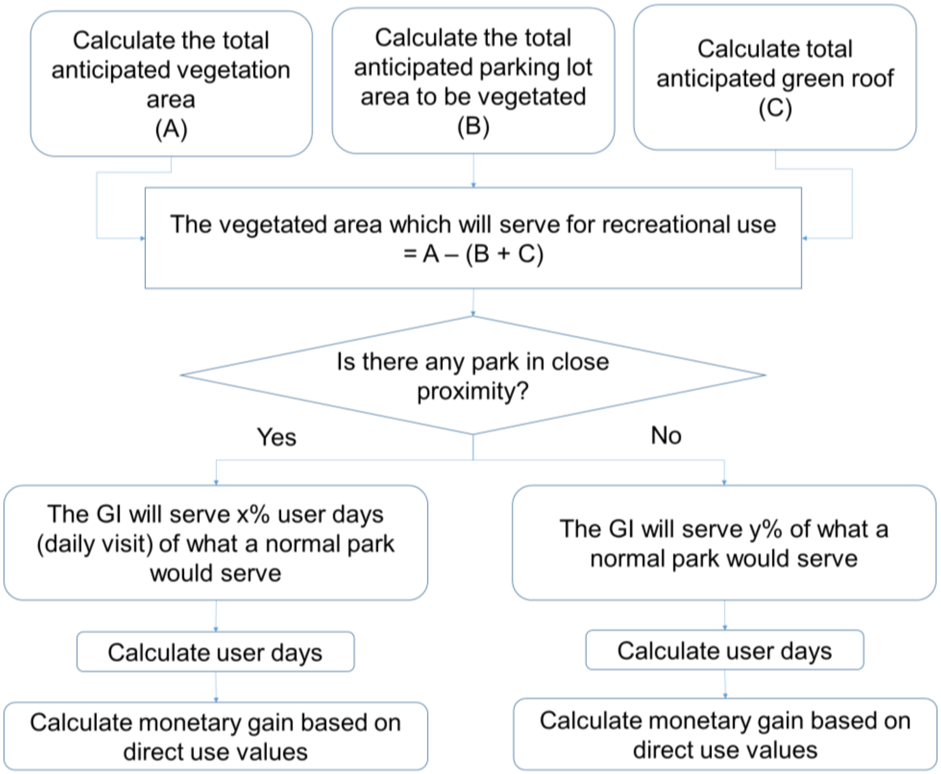


Figure 3-1 Framework for monetizing recreational use

As the first step to quantifying the benefit, the area which will serve for recreation is determined. The total amount of anticipated vegetation less the parking lot vegetation and green roof area will serve for recreation. After identifying the vegetated area, the GI's proximity to the available recreational area is determined. A GI in close proximity to a park may not function as effectively as a GI without such adjacency, in terms of its ability to serve as a park. Therefore, a GI's ability to serve recreational activities depends on its proximity to existing recreational opportunities. A 10-minute walking distance or 0.5 miles radius is selected as the proximity measure.

The methodology relies on a report *How Much Value Does the City of Philadelphia Receive from its Park and Recreation System* [37] prepared by the Trust for Public Land to determine the increase in recreational activities per acre increase in vegetation. The report calculates the increase in the number of daily visits (user days) per acre of the increased area in the park. According to a survey conducted by the National Recreation and Parks Association, residents frequent nearby parks at an average rate of 26.7 visits annually per 1,000 acres of parkland [38]. The increase in the user days is then attributed to a monetary value by the 'Unit Day Value' method [39] as the last step of the methodology.

Heat Reduction

Extreme heat events (EHE) are one of the major reasons for loss of lives [40-42] and increased emergency room use due to morbidity impacts [43, 44] during the summer season. GI reduces the urban heat island effect as trees provide shading and replace dark paved surfaces with green vegetation that absorbs less heat [45-47]. Several heat-related hospitalizations and mortalities can be avoided due to the reduced heat resulting from the impact of GI.

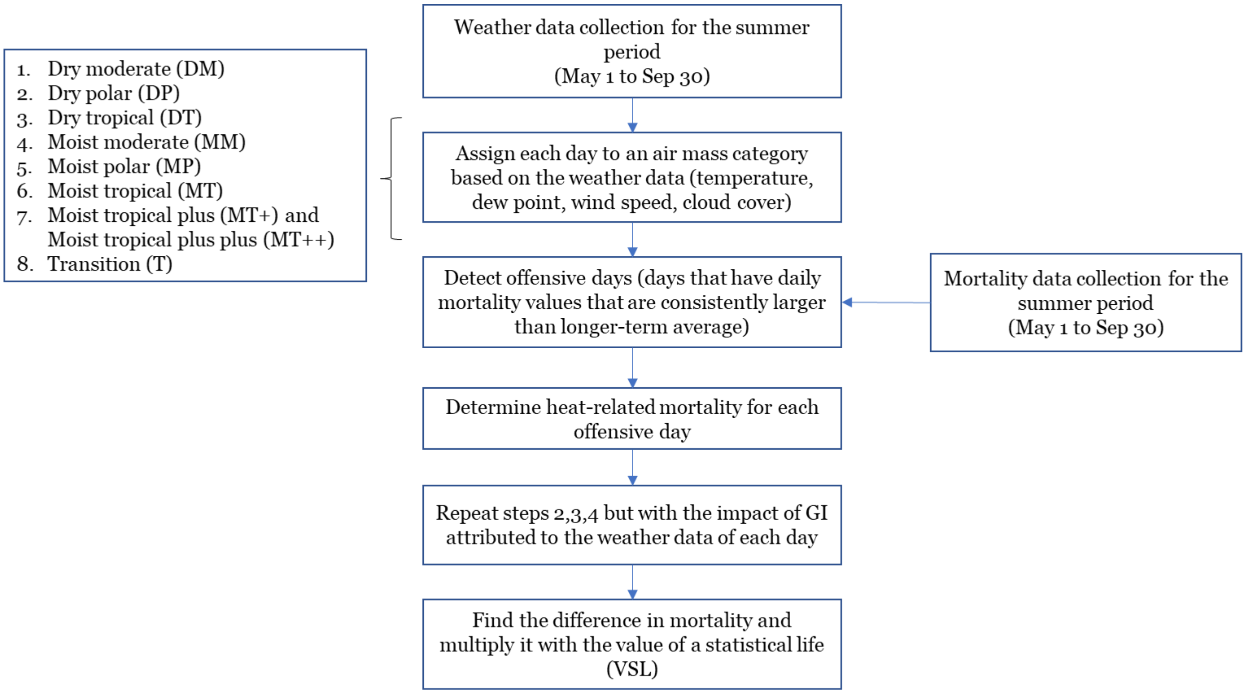


Figure 3-2 Framework for monetizing heat reduction benefit

The weather data for the summer season for the area where the GI is going to be built is collected as the first step of monetizing this benefit. Consequently, based on the weather data (temperature, dew point, wind speed, cloud cover, etc.), each day of summer is assigned to an air mass category [48]. The mortality data for the area of interest is also necessary for this framework. Based on the air mass labels of each day and mortality data for respective days, the 'offensive days' are identified. An 'offensive day' is when daily mortality values are higher than the longer-term average. The next step is to determine the heat-related mortality on each of the offensive days.

The next step repeats steps 2 ,3, and 4 however with the impact of GI attributed to the weather data. The impact of GI is going to be determined by the existing meteorological models [46, 47]. Having the impact of GI attributed to the weather data, we can calculate the difference in the number of fatalities between the two scenarios. Based on the calculated number, we can anticipate the total number of lives saved throughout the project. The last step is to estimate the monetary gain based on the Environmental Protection Agency's (EPA) recommended Value of Statistical Life [49].

Enhanced Property Value

Due to increased aesthetics, vegetation, improved air and water quality, and better living standards in general, properties adjacent to a GI are expected to experience an increase in value. Previous studies have attempted to estimate the enhancement of value, and the value ranges from 1% to 7%. Table 4 shows a literature review of those studies and their estimated percent increase in property values:

Table IV

LITERATURE ON ESTIMATING PROPERTY VALUE ENHANCEMENT

Study	***% increase in value***
The effect of low-impact-development on property values. [50]	*3.5 – 5.0*
How Water Resources Limit and/or Promote Residential Housing Developments in Douglas County. [51]	*1.1 – 2.7*
Piedmont community tree guide: benefits, costs, and strategic planting. [52]	*3.0 – 7.0*
What is a tree worth? Green-city Strategies and Housing Prices. [53]	*2.0*
Influence of trees on residential property values in Athens, Georgia (USA): A survey based on actual sales prices. [54]	*3.5 – 4.5*

As the first step of this methodology, the area where the GI is going to be built has to be identified. After the area is identified, the median value of the properties in that area will be calculated from the house sales data. The property sales data is a prerequisite in this framework.

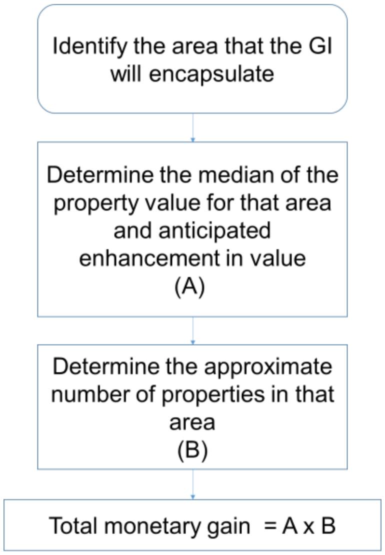


Figure 3-3 Enhanced property value quantification framework.

Having determined that, the enhancement in property value is estimated using the literature listed in the previous section. Consequently, the number of properties in the area of interest is calculated. As the last step of the framework, the total monetary gain is determined using the median value and the anticipated increase in value.

Job Creation Benefit

Traditional infrastructures need skilled workers with esoteric knowledge whereas GI can create job opportunities that can be done by comparatively less-skilled workers. While the skilled workers can afford to manage jobs elsewhere, employing the unskilled people comes with additional social benefits.

The total work hours anticipated in the lifetime of the GI is a data prerequisite for this framework to quantify the benefit. Having collected the data, the framework utilizes existing literature [55-58] to estimate the number of jobs that will allow unskilled workers to be employed throughout the project.

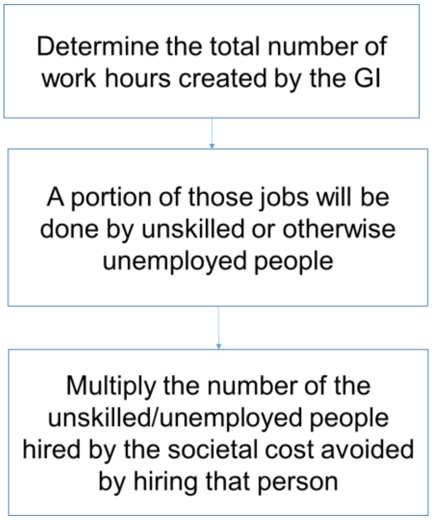


Figure 3-4 Framework for quantifying job creation benefit

The last step of the methodology is to determine the total monetary value of employing unskilled people by multiplying the number of jobs created by the social cost avoided by employing each person [59-61].

3.5 Environmental Impact Quantification Frameworks

Coherent with the procedure for social impacts, quantification methods elucidated below are used to determine the two pairwise matrices for the environmental impacts.

Reduced Stormwater Runoff

Green infrastructure is an approach that incorporates a combination of natural and engineered elements, including vegetation, pipes, soil, and stone, with the purpose of mitigating the speed and volume of stormwater runoff, treating it, and enabling absorption and infiltration into the soil where appropriate [13]. Various components of GI, such as trees, green sidewalks, green medians, permeable pavement, bioretention, and water harvesting, can collectively aid in the reduction of stormwater runoff [62-64], consequently leading to a decrease in the amount of stormwater runoff collected and conveyed to a facility for treatment. The total amount of reduced runoff can be computed by consolidating the different components utilized in a GI project. The calculated figure can subsequently be translated into a monetary equivalent, taking into account the amount of water treatment costs saved as a result of runoff reduction [9].

While green roofs are a widely used feature in GI projects, they are not commonly utilized in green transportation infrastructure. As a result, the contribution of green roofs will not be factored into the benefit transfer framework being employed.

Table V

DATA REQUIREMENT FOR QUANTIFYING REDUCED STORMWATER RUNOFF

GI Element	*Data Requirements*
Tree plantation	1. *Estimated number of trees to be planted* 2. *Annual precipitation*
Bioretention and Infiltration	1. *Annual precipitation* 2. *Area covered by the element* 3. *Contributory drainage area to the element* 4. *Percentage of the rainfall captured*
Permeable Pavement	1. *Annual Precipitation* 2. *Permeable pavement area* 3. *Percentage of precipitation retained*
Water Harvesting	1. *Annual precipitation* 2. *Area covered by the element* 3. *Collection efficiency*

The equation for the total amount of runoff reduced can be expressed as below:

$$Q_T = Q_{TP} + Q_{BI} + Q_{PP} + Q_{WH} \quad (2)$$

Where,

Q_T = Total amount of reduced stormwater runoff

Q_{TP} = Runoff amount reduced by tree plantation

Q_{BI} = Runoff amount reduced by bioretention and infiltration

Q_{PP} = Runoff amount reduced by permeable pavement

Q_{WH} = Runoff amount reduced by water harvesting

The following sections will describe the procedure to calculate each runoff amount in Equation (2).

Stormwater Runoff Reduced by Tree Plantation

Accurate estimation of water interception at the individual tree level is imperative in determining the reduction in stormwater runoff for a given project. This necessitates the knowledge of the size, type, and number of trees being planted. It is worth noting that the extent of rainfall interception varies depending on the leaf surface area of the tree species, where larger leaf surface area results in increased interception. Moreover, the rate of rainfall interception by trees is influenced by the climate zone of the site, precipitation levels, and seasonal variability, which ultimately impacts evapotranspiration rates.

Table VI

Average Runoff Interception Amount by Tree Size and Climate Zone

	40 Year Avg Annual Interception i_t (gallon/year/tree)		
Climate Zones	*Small Tree*	*Medium Tree*	*Large Tree*
Coastal Southern California	*1,583*	*1,396*	*2,120*
Desert Southwest	*570*	*1,818*	*930*
Inland Empire	*107*	*1,925*	*2,238*
Interior West	*281*	*573*	*1,245*
Northern California Coast	*420*	*369*	*673*
Northern Mountain and Prairie	*549*	*948*	*1,209*
San Joaquin Valley	*49*	*350*	*552*
Temperate Interior West	*161*	*893*	*1,111*
Tropical	*605*	*1,237*	*2,108*
Central Florida	*1,573*	*6,191*	*12,641*
Coastal Plain	*723*	*1,962*	*5,699*
Lower Midwest	*1,116*	*1,870*	*4,808*
Midwest	*292*	*1,129*	*2,162*

	40 Year Avg Annual Interception i_t (gallon/year/tree)		
Climate Zones	Small Tree	Medium Tree	Large Tree
Northeast	358	1,156	1,909
Piedmont	1,265	2,566	4,778
Western Washington and Oregon	182	346	549

The US Forest Services' Center for Urban Forest Research has developed a set of Tree Guides, which considers various factors to estimate the level of benefits offered by trees [65]. The above table illustrates the findings in the report and the intercept values to be used in the quantification procedure.

The following figure shows the climate zones *used in the report.*

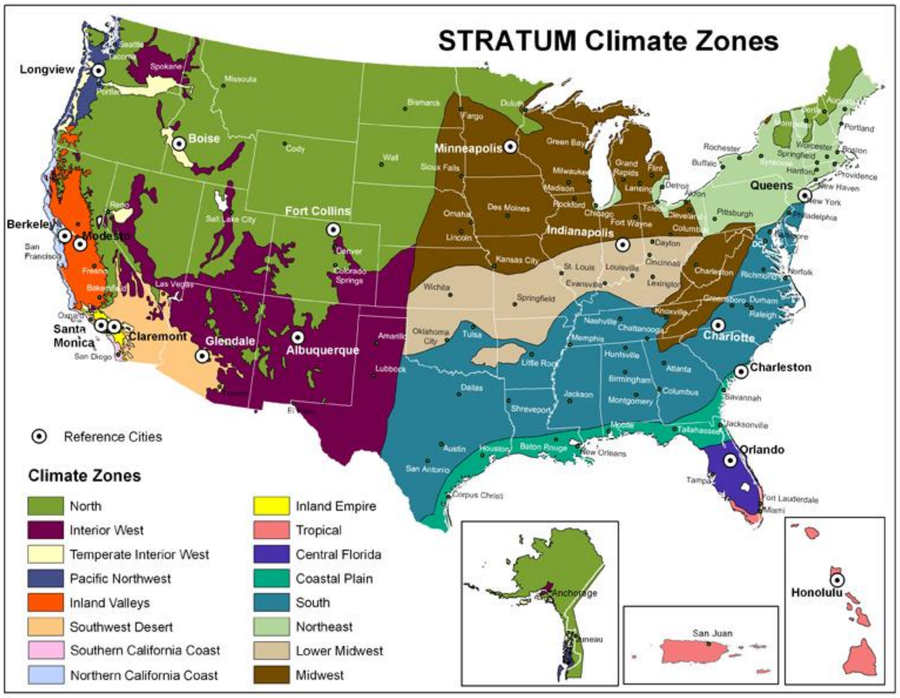


Figure 3-5 The climate zones used to estimate the rainfall interception of trees [65].

Based on the interception value i_t obtained from Table 6, the equation for Q_{TP} is:

$$Q_{TP}\ (\text{gallons}) = Number\ of\ Trees \times i_t$$

Based on the number of trees varied by sizes, the total runoff reduced can be determined by multiplying by the corresponding i_t value.

Stormwater Runoff Reduced by Bioretention and Infiltration

Bioretention and infiltration features that are well-designed are capable of capturing a significant portion, if not all, of the precipitation that falls within their coverage area, including the associated drainage area (DA). However, the ability of these features to accommodate rainfall in urban settings is contingent upon the availability of square footage and the locally prescribed maximum ponding times. To determine a site-specific measure of performance, sophisticated hydrological modeling is required.

$$Q_{BI}\ (\text{gal}) = [Precipitation\ (in) \times \{Element\ Area\ (sq.ft.) + Drainage\ Area\ (sq.ft.)\}] \times\ \%\ Rainfall\ Capture \times 144\ \frac{sq.in.}{sq.ft.} \times 0.00433\ \frac{gal}{in^3}$$

To enable a generalized quantification method across the United States, a straightforward equation will be employed, utilizing a default and conservative value of 80% for rainfall capture ability. Therefore, the equation converts to:

$$Q_{BI}\ (gal) = [Precipitation\ (in) \times \{Element\ Area\ (sq.ft.) + Drainage\ Area\ (sq.ft.)\}] \times 0.80\ \times 144\ \frac{sq.in.}{sq.ft.} \times 0.00433\ \frac{gal}{in^3}$$

Stormwater Runoff Reduced by Permeable Pavement

Research indicates that pervious pavement has the capacity to infiltrate between 80% to 100% of the rainwater that falls on a given site, depending on the precipitation intensity [62, 66, 67]. The following equation provides a means of quantifying the aggregate volume of runoff that a specific permeable pavement installation can mitigate on an annual basis, taking the capacity as 80% for conservative approach.

$$Q_{PP}\ (\text{gal}) = Annual\ Precipitation\ (in) \times Permeable\ Pavement\ Area\ (sq.ft.) \times 0.80 \times 144 \frac{sq.in.}{sq.ft.} \times 0.00433 \frac{gal}{in^3}$$

Stormwater Runoff Reduced by Water Harvesting

The advantages associated with water harvesting are contingent upon the quantity, measured in gallons, of stormwater runoff that is stored at the site. Under optimal conditions, a maximum of 0.62 gallons of runoff per inch of rain can be collected from each square foot of roof collection area. However, the following equation incorporates a conservative efficiency factor of 0.75 from the range of 0.75-0.9 to accommodate water loss resulting from a range of factors, including evaporation and suboptimal gutter systems [68].

$$Q_{WH}\ (\text{gal}) = Annual\ Precipitation\ (in) \times GI\ Element\ Surface\ Area\ (sq.ft.) \times 0.75 \times 144 \frac{sq.in.}{sq.ft.} \times 0.00433 \frac{gal}{in^3}$$

Benefit Monetization

In urban areas where combined sewer systems (CSS) are in place, stormwater runoff mixes with wastewater and proceeds to a treatment facility. To quantify the benefits of reducing stormwater runoff in these cities, an avoided cost method is a viable option. The value of reducing stormwater runoff is deemed equivalent to the expenditure that would be incurred by the local stormwater utility to manage the same. Thus, the valuation formula is straightforward. The cost of treating stormwater has been reported varying from \$0.01 to \$0.03 per gallon of stormwater [69]. Considering the report is from 2009 and the corresponding time value of money, taking the conservative value of \$0.01/gallon to estimate avoided treatment cost, the total monetary gain from the avoided water stormwater treatment is given by the following equation.

$$Monetary\ Gain\ from\ Avoided\ Stormwater\ Treatment\ = Q_T\ (gal) \times 0.01 \times C$$

Where,

Q_T = Total amount of reduced stormwater runoff,

C = Conversion factor to calculate the time value of money from 2009 to current year.

Reduced Air Pollutants

The implementation of GI in communities can aid in the reduction of air pollutants [14]. The utilization of vegetated systems such as green sidewalks and tree barriers can effectively mitigate the adverse impact of urban heat island effects while also improving air quality [70]. This section aims to provide a quantitative analysis of the impact of green infrastructure on air quality, and outlines guidelines for assessing these impacts in monetary terms. Specifically, the pollutants of concern are carbon dioxide (CO_2), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter with an aerodynamic diameter of ten micrometers or less (PM_{10}).

Trees, and bio-infiltration are examples of practices that offer a direct benefit in terms of uptake and deposition. While numerous studies have acknowledged that vegetative infrastructure, such as bioswales, rain gardens, and other bio-infiltration techniques, can offer substantial air quality benefits, there is a current absence of scientific research that measures and quantifies the direct uptake potential of these practices in relation to air pollution. The lack of studies that provide specific uptake values for bio-infiltration practices impedes the ability to comprehensively calculate their direct uptake benefits. Therefore, the data requirement to quantify the total amount of pollutant reduction by the practices are only regarding the tree plantation practice and they are listed below:

Table VII

DATA REQUIREMENTS TO QUANTIFY POLLUTANT REDUCTION

GI Element	*Data Requirements*
Tree plantation	*1. Estimated number of trees to be planted by size* *2. Average annual uptake of pollutant by each tree*

Air Pollutants Reduced by Tree Plantation

The uptake potential of tree planting depends on various factors, such as climate zone, existing air quality and pollutant levels, and the size, age, and type of tree. The Forest Service's *Tree Guides* offer an estimation of air quality benefits from trees based on the climate zone [65]. The appendices in the guides are organized based on the size of the tree (including example tree types) and its location in relation to a surrounding building. By utilizing the "Uptake and Avoided" data available in the Tree Guides' appendices, one can calculate air quality benefits on a per-tree basis. The following table shows a summary of the value to be used in framework for the "Uptake and Avoided" value for trees based on its size and location. The 'Piedmont' region extends from southern New Jersey in a broad band south and west to eastern Texas, and should be the chosen region for TDOT users in Chattanooga, TN. This region is characterized by rolling wooded hills separated by streams and rivers. As for TDOT users in Knoxville and the Eastern part of the state, the 'Midwest' region is the appropriate choice in the tool. The 'Midwest' region extends from North Dakota to northern Kansas, stretching to the southeast into the Appalachian Mountains of West Virginia, Virginia, Kentucky, Tennessee, Georgia, and the Carolinas. It's characterized by wooded states on the eastern side and former prairie lands mostly converted to crop fields on the western side. While TDOT users in Nashville, Memphis, and the western part of the state should choose the 'Lower Midwest' region in the tool, which is characterized by hot, humid summers, and winters that are cold but milder than the areas to the north.

Table VIII

AVERAGE UPTAKE AND AVOIDED AMOUNT OF AIR POLLUTANT BY TREE SIZE AND LOCATION [65]

		40 Year Avg Uptake + Avoided k_{ua} (lbs/year/tree)		
Climate Zones	*Pollutant*	*Small Tree*	*Medium Tree*	*Large Tree*
Coastal Southern California	O_3	0.20	0.48	0.89
	CO_2	14	34	140
	NO_2	0.05	0.12	0.48
	SO_2	0.13	0.21	0.42
	PM_{10}	0.33	0.79	1.49
Desert Southwest	O_3	0.21	0.47	0.21
	CO_2	159	318	267
	NO_2	0.31	0.74	0.42
	SO_2	0.19	0.46	0.28
	PM_{10}	0.25	0.64	0.46
Interior West	O_3	0.26	0.48	0.92
	CO_2	174	363	628

		40 Year Avg Uptake + Avoided k_{ua} (lbs/year/tree)		
Climate Zones	*Pollutant*	*Small Tree*	*Medium Tree*	*Large Tree*
	NO_2	0.46	0.84	1.51
	SO_2	0.37	0.68	1.22
	PM_{10}	0.20	0.43	0.67
Northern California Coast	O_3	0.16	0.16	0.26
	CO_2	82	134	158
	NO_2	0.12	0.12	0.20
	SO_2	0.03	0.03	0.04
	PM_{10}	0.35	0.16	0.36
Northern Mountain and Prairie	O_3	0.32	0.36	0.43
	CO_2	37	85	161
	NO_2	0.19	0.32	0.43
	SO_2	0.20	0.34	0.46
	PM_{10}	0.10	0.13	0.16
San Joaquin Valley	O_3	0.16	1.46	2.71
	CO_2	26.91	107.05	229.79
	NO_2	0.16	0.80	1.56
	SO_2	--	--	--
	PM_{10}	0.14	1.15	2.17
Temperate Interior West	O_3	0.20	0.31	0.70
	CO_2	214	313	358
	NO_2	0.33	0.52	0.69
	SO_2	0.66	1.13	1.39
	PM_{10}	0.17	0.27	0.59
Tropical	O_3	0.16	0.31	0.6
	CO_2	174	188	370
	NO_2	0.45	1.03	1.18
	SO_2	0.39	0.91	1.03
	PM_{10}	0.25	0.51	0.73
Central Florida	O_3	0.39	0.92	1.99
	CO_2	99	187	584
	NO_2	0.18	0.42	0.81

		40 Year Avg Uptake + Avoided k_{ua} (lbs/year/tree)		
Climate Zones	Pollutant	Small Tree	Medium Tree	Large Tree
	SO_2	0.12	0.29	0.55
	PM_{10}	0.17	0.46	0.84
Coastal Plain	O_3	0.17	0.29	0.88
	CO_2	103	149	489
	NO_2	0.22	0.33	0.93
	SO_2	0.63	0.93	2.55
	PM_{10}	0.14	0.31	0.63
Lower Midwest	O_3	0.20	0.32	0.68
	CO_2	91	150	374
	NO_2	0.16	0.27	0.57
	SO_2	0.53	0.89	1.86
	PM_{10}	0.15	0.27	0.45
Midwest	O_3	0.15	0.20	0.28
	CO_2	336	444	734
	NO_2	0.39	0.63	1.11
	SO_2	0.23	0.42	0.69
	PM_{10}	0.17	0.26	0.35
Northeast	O_3	0.14	0.29	0.54
	CO_2	144	250	485
	NO_2	0.18	0.37	0.70
	SO_2	0.15	0.40	0.85
	PM_{10}	0.13	0.33	0.45
Piedmont	O_3	0.14	0.35	0.21
	CO_2	168	128	340
	NO_2	0.22	0.33	0.41
	SO_2	0.42	0.60	0.82
	PM_{10}	0.17	0.56	0.31
Western Washington and Oregon	O_3	0.14	0.27	0.43
	CO_2	15	61	257
	NO_2	0.08	0.17	0.28
	SO_2	0.03	0.07	0.10

		40 Year Avg Uptake + Avoided k_{ua} (lbs/year/tree)		
Climate Zones	Pollutant	Small Tree	Medium Tree	Large Tree
	PM_{10}	0.15	0.29	0.45
Inland Empire	O_3	0.25	0.78	1.36
	NO_2	0.20	0.72	1.08
	CO_2	24	157	275
	SO_2	0.05	0.14	0.19
	PM_{10}	0.16	0.61	0.90

Once the uptake value is determined, the total air pollutant reduction can be determined by the following equation:

$$\text{Total annual air pollutant reduction (lbs)} = no.\ of\ trees\ \times k_{ua}$$

Where,

k_{ua}= average annual uptake and avoided pollutant emissions lbs/ tree obtained from Table 8

This equation can be utilized to obtain the total reduction of each air pollutant (O_3, NO_2, SO_2, PM_{10}).

Benefit Monetization

The benefit transfer equation for the reduced air pollutant is as follows:

$$\textit{Total value of pollutant reduction (\$)} = \ Total\ annual\ criteria\ pollutant\ reduction\ benefit\ (lbs) \times price\ of\ criteria\ pollutant\ (USD/lb)$$

Here,

The ‘price of criteria pollutant’ refers to the avoided cost of treating each pound of air pollutant. The value suggested by The Forest Service are as follows [9, 71-73]:

Table IX

AVOIDED COST OF CRITERIA POLLUTANTS

Pollutant	*Price of criteria pollutant(USD/lb)*
O_3	3.34
NO_2	3.34

Pollutant		Price of criteria pollutant(USD/lb)
SO_2		2.06
PM_{10}		2.84
CO_2	Low	0.023
	High	0.046

However, since these values correspond to the time value of money of 2006, additional conversion is required to convert them to current value.

3.6 Economic Impact Quantification Framework

The economic impact quantification frameworks start with the inherent assumption that the subsequent direct benefits of traditional and green transportation infrastructure are the same. Since this study considers the marginal impact of green transportation infrastructure, the direct benefits are not considered. However, the initial and maintenance cost of infrastructures depending on what GI elements are integrated into the system vary largely. Therefore, the initial and maintenance cost of different GI elements are considered in this study. Due to well-developed research to determine the economic aspects of green infrastructure quantification frameworks rely on previously developed quantification methods with some modification to make them spatially specific and temporally dynamic.

Rainwater harvesting (Cistern/Rain Barrel)

Initial Cost

1. Determine impervious area (user input)
2. Choose rain event.
3. Determine storage = 20-year rainfall event x impervious area
4. Determine Tank cost = Storage x avg cost per gallon

Table X

Rainwater Harvesting Tank Costs

Material	Size range (gallons)	Avg Cost per gallon ($)
Steel	500 – 15,000	2.51
Fiberglass	10,000 – 35,000	1.33
Concrete	2,000 – 35,000	1.66
HDPE	50 – 1,500	1.43

1. Determine installation cost = 60% of tank cost
2. Determine pump cost from
   Horsepower needed:

$$x = Qh_p\gamma = \frac{4\,gallon\ per\ minute\ \times 1\,cfs}{449\,gpm} \times h_p\,ft \ \times 62.4\frac{lb}{ft^3}$$

   a. h_p is user input (take default 15 ft)

$$Pump\ cost\ = -100.71x2 + 1327.7x - 39.38$$

3. Total capital cost = Tank cost + Installation cost + pump cost
4. Repeat capital cost for the project period. Example: If the project period is 100 years, divide it by the GI element lifespan which is 20 years for rainwater harvesting. Therefore, repetition = 100/20 = 5 times

Maintenance Cost

1. Choose maintenance frequency:

Table XI

MAINTENANCE COSTS FOR RAINWATER HARVESTING

Cost Item	*Low*	*Med*	*High*
Inspection, Reporting & Information Management	*135 x 1*	*130 x 2*	*340 x 12*
Roof Washing, Cleaning Inflow Filters	*150 x 1*	*240 x 2*	*540 x 12*
Tank inspection and disinfection	*120 x 0.5*	*240 x 1*	*360 x 2*
Intermittent System Maintenance (System flush, debris/sediment removal from tank)	*270 x 1/3*	*390 x 1/3*	*510 x 1/3*
Total	***435***	***1,110***	***11,450***

2. Determine the maintenance cost and convert to current money value.

Bioretention (Bioswales/Bio slopes/ Bioretention cells/ Basins with or without underdrain/ Rain Garden)

Initial Cost

1. User input: Drainage area (acre)
2. User input: Underdrain? (Yes/No)
3. Underdrain: Base Facility Cost = 0.80 * Drainage Area * $89,028
   No underdrain: Base Facility Cost = 0.80 * Drainage Area * $42,254
4. Engineering & Planning Cost = 25 % of Base facility cost
5. Total initial cost = Base facility cost + Engineering & Planning Cost

6. Repeat for project period.

Maintenance Cost

1. Choose maintenance frequency and convert to current money value.

Table XII

MAINTENANCE COSTS FOR BIORETENTION CELLS, BIOSWALES, AND RAIN GARDENS

Cost Item	*Low*	*Med*	*High*
Inspection, Reporting & Information Management	*60 x 1/3*	*130 x 0.5*	*570 x 1*
Vegetation Management with Trash & Minor Debris Removal	*60 x 1*	*124 x 2*	*270 x 3*
Till Soil	*320 x 0.2*	*448 x 0.25*	*560 x 0.5*
Unclog Drain	*160 x 0.2*	*160 x 0.5*	*190 x 1*
Replace Mulch	*1,935 x 0.25*	*1,999 x 0.5*	*2,145 x 1*
Total	***660***	***1,505***	***3,995***

Basins (Detention/Retention Basins)

Initial Cost

1. Determine Drainage Area (DA) in acres (User Input)
2. Base facility cost level per acre of DA? (User Input)
    a. Very High = $15,000/acre
    b. High = $5,000/acre
    c. Medium = $3,000/acre
    d. Low = $1,000/acre
3. Cost Adjustment Factor:

Table XIII

COST ADJUSTMENT FACTORS FOR DRAINAGE AREA

DA (ac)	*Multiplier*
10	*2.00*
75	*1.35*
75	*1.35*
200	*1.00*
>200	*1.00*

Final base facility cost = base facility cost x adjustment factor

4. Engineering and planning cost = 25% of final Base facility cost

5. Total cost = Final base facility cost + Engineering and planning cost.

Maintenance Cost

1. Choose maintenance frequency and convert to current money value.

Table XIV

MAINTENANCE COSTS FOR BASINS

Cost Item	*Low*	*Med*	*High*
Inspection, Reporting & Information Management	*90 x 1/3*	*140 x 1/3*	*260 x 1*
Vegetation Management with Trash & Minor Debris Removal	*360 x 1/3*	*480 x 1*	*825 x 12*
Vector Control	*200 x 1/6*	*200 x 1/3*	*2,675 x 12*
Intermittent Facility Maintenance (Excluding Sediment Removal)	*250 x 1*	*1,000 x 1*	*2,800 x 1*
Total	***435***	***1,595***	***45,060***

Planter Boxes (Open/Closed)

Initial Cost

1. Determine Drainage Area (DA) (User Input)
2. Determine Impervious area percentage (User Input)
3. Determine total impervious area
4. Determine total number of vaults needed = 1 vault per 0.25 acre of impervious area
5. Select construction type (User input):
    a. In situ
    b. Prefabricated
6. Determine capital cost =
    a. In situ = $38,957 / planter box
    b. Prefabricated = $10000 / planter box

Maintenance Cost

1. Choose maintenance frequency and convert to current money value

Table XV

MAINTENANCE COSTS FOR PLANTER BOXES

Cost Item	*Low*	*Med*	*High*
Inspection, Reporting & Information Management	*20 x 1/3*	*30 x 1*	*45 x 3*

Cost Item	Low	Med	High
Litter & Minor Debris Removal, and Vegetation Management	*45 x 1*	*60 x 2*	*75 x 6*
In-Curb Planter Vault Sweeping	*65 x 1*	*80 x 2*	*95 x 6*
Unclog Drain	*160 x 0.2*	*160 x 0.5*	*190 x 1*
Up-Fill Growth Medium	*125 x 0.2*	*130 x 0.5*	*200 x 1*
Total	***175***	***455***	***1,545***

Permeable Pavement

Initial Cost

1. Select type:

Table XVI

INITIAL COST FOR PERMEABLE PAVERS

Paver System	*Cost Per Sq. Foot (Installed)*	
	Low	*High*
Asphalt	*$0.50*	*$1.00*
Porous Concrete	*$2.00*	*$6.50*
Grass / Gravel Pavers	*$1.50*	*$5.75*
Interlocking Concrete Paving Blocks	*$5.00*	*$10.00**

2. Surface Area of Permeable Pavement System (ft2)
3. Base Facility Cost = Surface are x Unit cost
4. Engineering cost = 10% of Base cost
5. Total capital cost = Base cost + Engineering cost

Maintenance Cost

1. Choose maintenance frequency and convert to current money value.

Table XVII

MAINTENANCE COSTS FOR PERMEABLE PAVEMENT

Cost Item	*Low*	*Med*	*High*
Inspection, Reporting & Information Management	*90 x 1/3*	*140 x 1/3*	*260 x 1*
Litter & Minor Debris Removal	*45 x 1/3*	*120 x 1*	*120 x 12*
Permeable pavement sweeping	*160 x 1/3*	*80 x 1*	*80 x 12*
Total	***99***	***247***	***2,660***

Swales

Initial Cost

1. Drainage Area (acre) – User input
2. Drainage area impervious cover – user input
3. Base cost level – user input

Table XVIII

INITIAL COSTS FOR SWALES

Base Facility Cost guidelines (Year 2005)
Very High = $15,000/acre
High = $5,000/acre
Medium = $3,000/acre
Low = $1,000/acre

4. Cost multiplier y = -0.4x + 3, where x is DA (if x ≥ 5-acre, y = 1)
5. Total base cost = Multiplier x base cost
6. Engineering and planning cost = 25% of base cost
7. Total capital cost = base cost + engineering and planning cost

Maintenance Cost

1. Choose maintenance frequency and convert to current money value

Table XIX

MAINTENANCE COSTS FOR SWALES

Cost Item	*Low*	*Med*	*High*
Inspection, Reporting & Information Management	*90 x 1/3*	*140 x 1/3*	*260 x 1*
Vegetation Management with Trash & Minor Debris Removal	*360 x 1/3*	*480 x 1*	*480 x 12*
Corrective Maintenance	*960 x 0.1*	*1,440 x 0.25*	*1,440 x 0.5*
Total	***246***	***1,967***	***6,740***

Chapter 4 Case Study

A case study, with hypothetical site characteristics and parameters, was performed to demonstrate the utility of the tool. In the study, two scenarios—of the same project site (i.e., identical site parameters)—were compared to illustrate how the tool functions to give results of implementing disparate GI at a potential site. The hypothetical project site is located in a suburban area of East Chattanooga, TN. Scenario 1 analyzed Cistern implementation, while Scenario 2 analyzed bioretention system implementation. To create these two different analytical "Scenarios," a profile was created and saved for each. Within each corresponding profile, values were entered into the toolbox—some the same, for site characteristics and parameters, and some different, for each respective GI. When scenarios of different GI and GI configurations are being analyzed for the same project site, time can be saved by creating the first scenario profile, complete with input values, and then creating the second scenario profile using the first profile as a template. The second scenario profile will then have the same input values as the first profile and any different GI-related values can be changed.

Table XX

INPUT VALUES FOR 'DETERMINING GI'

Category	*Sub-Category*	*Input*	*Reasoning*
Site Requirements	*Site Slope Restrictions*	*Max 0.05*	*Many GI should be constructed on land with less than 5%, but some GI can be accommodated on 5-10% slope.*
	Cross-sectional and side slope restrictions	*Max 0.04*	*Many GI should be constructed on land with less than 5%, but some GI can be accommodated on 5-10% slope.*
	Contributing Drainage Area	*Max 4 acres*	*1-4 acres is an average DA of many infiltration GI.*
		Min 0.10	
Subgrade Requirements	*Soil infiltration rate*	*Min 0.5 in/hr*	*Hydrologic Soil Group B has an infiltration rate of 0.3-0.5 in/hr*
	GI infiltration rate	*Min 6.40 in/hr*	*Amended soils of GI typically have much better infiltration rates than natural soils.*
	Soil Groups	-	
	Distance to high water table	*Min 2 ft*	*Minimum of 2' is required between bottom of infiltration basins and seasonal high groundwater table.*
Setback Requirements	*Set back from buildings*	*Min 10 ft*	
	Distance from drinking wells	-	
Environmental Benefits	*TSS % removal*	*Min 0.90*	*Studies indicate that GI measures, such as bioretention systems, can remove*
	TP % removal	*Min 0.80*	

Category	*Sub-Category*	*Input*	*Reasoning*
	TN % removal	*Min 0.80*	*75-80% phosphorous and nitrogen, 95% of metals, and 90% of total suspended solids and organics/bacteria.*
	Metals % removal	*Min 0.95*	
	Organisms % removal	*Min 0.90*	
Stormwater Improvements	*Flooding Reduction*	*Y*	
	Rainwater Detention	-	
	Groundwater Recharge	-	
	Temperature Reduction	-	
	Peak Rate Reduction	-	
	Runoff Reduction Volume	*Y*	
Cost Considerations	*Installation Cost Range*		
	Low	-	
	High	-	
	Unit	-	
	Maintenance Cost Range		
	Low	-	
	High	-	
	Unit	-	
GI	*Lifespan*	-	
Social Benefits	*Motorists and Commuters*	-	
	Public Safety	-	
	Public Spaces	-	

The values for site requirements (site slope restrictions, soil groups, setback requirements, etc.), desired environmental benefits (percent total suspended solids, phosphorus, nitrogen, metals and organisms removed, stormwater improvements, etc.), and cost considerations (installation cost range, maintenance cost range, and lifespan) that were entered under the 'Determine GI' tab of the tool were the same for both Scenario 1 and Scenario 2. Table XX summarizes these input values and offers reasonings for the parameter choice. The 'Possible GI' offered to the user on the right-hand side of the interface of the toolbox, blocked in red, were the same. These suggested GI practices, dependent on the input values for the site and desired environmental benefits, for the case study were 'Sand Filters,' 'Level Spreaders,' 'Green Streets,' 'Urban Tree Canopy,' and 'Downspout Disconnection.' These 'Possible GI' are merely suggestions based on the given parameters. The user is not limited in their analysis to these 'Possible GI' suggestions. To emphasize this capability, Scenario 1 of the case study analyzed the implementation of Cisterns (i.e., rain harvesting) and Scenario 2 analyzed the implementation of a bioretention system.

The second tab of the tool, 'Economic Impact,' has several header tabs of possible GI to be implemented. It is only necessary for the user to fill-out the input values for the GI element or elements they wish to analyze in the current profile. While the GI repository encompasses more than 30 different GI elements, summarized and suggested on the home tab of the tool, the economic impacts, encompassing both capital and maintenance costs, for all 30+ GI components were not incorporated into the framework. This omission was due to the heterogeneous design details present across various SDOTs, coupled with time constraint for this study. As a result, in the 'Economic impact' tab of the tool only the GI elements for which the cost equations are devised are shown for consideration. Additional research is required to establish standardized metrics for all remaining GI elements.

Scenario 1 analyzed a steel cistern collecting from a drainage area of 2,000 ft^2 for a maximum rainfall event of 6 in. (approximately a 25-year storm), all maintenance costs were categorized as 'Medium.' Scenario 2 analyzed a bioretention system with underdrain and a drainage area of 90,000 ft^2 (approximately 2 acres), maintenance cost to unclog the drain was categorized as 'Medium' and all others were categorized as 'Low.' Table XXI and Table XXII show the input values along with capital and maintenance cost totals (in red) calculated by the tool for Scenario 1 and Scenario 2, respectively.

Table XXI

SCENARIO 1 INPUT VALUES FOR 'ECONOMIC IMPACT'

CISTERN		
Category	*Sub-Category*	*Input/ Output*
Capitol Cost	*Impervious Area*	*2,000 ft^2*
	Max. Design Rainfall Event	*6 in*
	Material	*Steel*
	Total Storage Needed	*7,480 gal*
	Total Capital Cost	*$9,948.40*
Maintenance Cost	*Inspection, reporting and information management*	*Medium*
	Roof washing, cleaning inflow filters	*Medium*
	Tank inspection and disinfection	*Medium*
	Intermittent system maintenance	*Medium*
	Total Maintenance Cost	*$1,110*

Table XXII

SCENARIO 2 INPUT VALUES FOR 'ECONOMIC IMPACT'

BIORETENTION		
Category	*Sub-Category*	*Input/ Output*
Capitol Cost	*Drainage area*	*2 acres*
	Underdrain	*Y*
	Total Capital Cost	*$178,056*
Maintenance Cost	*Inspection, reporting and information management*	*Low*
	Vegetation management with trash and minor debris removal	*Low*
	Till Soil	*Low*
	Unclog Drain	*Medium*
	Replace Mulch	*Low*
	Total Maintenance Cost	*$707.75*

Input values for 'Environmental Impacts' regarding climate zone and number of trees were the same for both Scenario 1 and Scenario 2—like site characteristics and parameters from above—since these "scenarios" were analyzing different GI implemented on the same project site. 'Environmental Impact' inputs for both scenarios are summarized in Table XXIII, along with the total runoff and air pollutant reduction and any monetized value of savings (in green). The climate zone 'Piedmont' is the appropriate choice for Chattanooga, TN and many other Tennessee regions. The 'Reduced Stormwater Runoff' section of the 'Environmental Impact' tab requires the user only enter values in the appropriate and corresponding GI practice to be analyzed (between 'Bioretention and Infiltration,' 'Permeable Pavement,' and 'Water Harvesting'). Although there are only three categories, the majority of possible GI practices will fall under one of these categories. For example, bioswales, green roofs, downspout disconnections and many others function through infiltration, thus values would be entered into the 'Bioretention and Infiltration' category, in order for the reduced runoff amount to be calculated and those benefits be considered in the analysis.

Table XXIII

INPUT VALUES FOR 'ENVIRONMENTAL IMPACT'

Category	*Sub-Category*	*Scenario 1 Input*	*Scenario 2 Input*
Options	*STRATUM Climate Zone*	*Piedmont*	
	Number of Small Trees	*50*	
	Number of Medium Trees	*20*	
	Number of Large Trees	*10*	
Reduced Stormwater Runoff			
Runoff amount reduced by tree plantation		*162,350 gal/yr*	

Category	Sub-Category	Scenario 1 Input	Scenario 2 Input
Bioretention and Infiltration	Annual Precipitation	-	53 in
	Element Area	-	4,000 ft^2
	Drainage Area	-	90,000 ft^2
Runoff amount reduced by bioretention and infiltration		-	2,485,101 gal/yr
Permeable Pavement	Annual Precipitation	-	-
	Permeable Pavement Area	-	-
Runoff amount reduced by permeable pavement		-	-
Water Harvesting	Annual Precipitation	53 in	-
	GI Element Surface Area	36 ft^2	-
Runoff amount reduced by water harvesting		892 gal/yr	-
Total amount of reduced stormwater runoff		163,242 gal/yr	2,647,451 gal/yr
Benefit Monetization	Conversion Factor from 2009 to current USD	1.42	
Monetary Gain from Avoided Stormwater Treatment		\$2,318.04 /yr	\$37,593.81 /yr
Reduced Air Pollutants			
Total annual Air Pollutant Reduction		48.6 lbs	48.6 lbs
Total value of Pollutant Reduction		\$148.43	\$148.43
Reduced Energy Use			
40-Year Average of Energy Saved		65,540 kWh/tree/yr	65,540 kWh/tree/yr
Value of Energy saved		\$7,786.15	\$7,786.15

Reduced stormwater runoff for Scenario 1 (analyzing Cistern) was calculated with values entered into the 'Water Harvesting' category—leaving values for 'Permeable Pavement' and 'Bioretention and Infiltration' blank—while the reduced runoff for Scenario 2 (analyzing Bioretention) was calculated with values entered into the 'Bioretention and Infiltration' category—likewise, leaving 'Permeable Pavement' and "Water Harvesting' blank. The conversion factor in the 'Benefit Monetization' category was set at the default, 1.42, and was the same for both scenarios.

Table XXIV

INPUT VALUES FOR 'SOCIAL IMPACT'

Category	Sub-Category	Scenario 1 Input	Scenario 2 Input
Latitude and Longitude		35.052257, -85.106411	
Nearby Parks	Radius	2.0 miles	

Category	Sub-Category	Scenario 1 Input	Scenario 2 Input
Enhanced Property Value	Median property value for that area	-	400,000
	Anticipated enhancement in value	-	0.01
	Approx. number of properties in the area	-	30
Total monetary gain		-	$120,000
Recreational Use	Total anticipated vegetation area	-	-
	Total anticipated parking lot area to be vegetated	-	-
	Total anticipated green roof area	-	-
Total anticipated vegetated area for recreational use		-	-

The latitude and longitude initially entered in the toolbox under the 'Social Impact' tab is the user's current location coordinates; however, these can easily be changed by entering the coordinates of the project site. The latitude and longitude used for the case study was 35.052257, -85.106411 with a radius of 2.0 miles resulting in 8 nearby parks. 'Enhanced Property Value' and 'Recreational Use' was left blank for Scenario 1 because a small cistern would not offer either type of social benefit. For Scenario 2, the median property value was estimated to be $400,000, the anticipated enhancement in value was estimated to be 0.01 (i.e., 1% of $400,000 median property value), and the approximate number of properties in the area was estimated to be 30. 'Recreational Use' values were left blank for Scenario 2 because bioretention systems don't typically offer green roof area or vegetation area for recreational purposes.

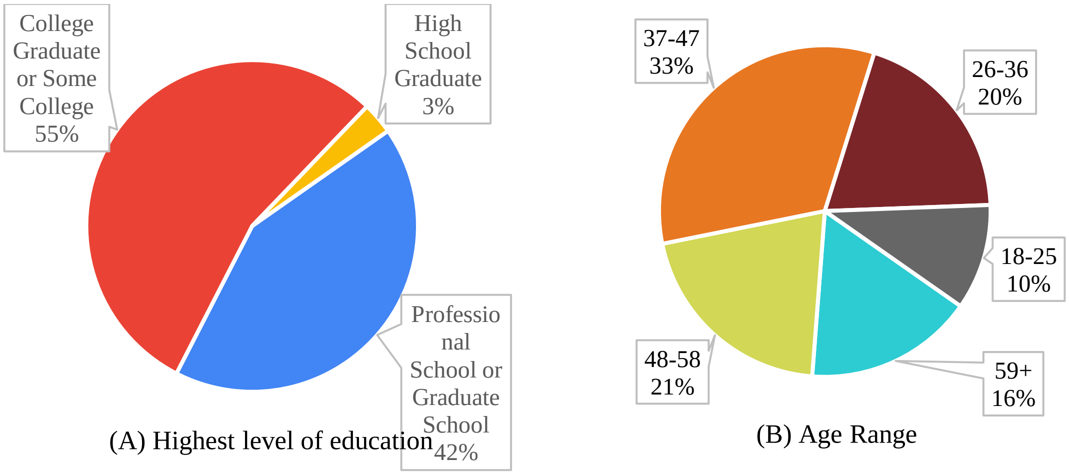
It may be noticed that "impact" and "benefit" are often used interchangeably throughout the tool and in this report. While an impact is not always beneficial, the reason for this is because in the context of environmental and social impacts of implementing GI, these impacts are benefits. For example, the environmental and social *impacts* (Table XXIII and Table XXIV, respectively) of implementing any type of GI are stormwater runoff reduction, air pollutant reduction, energy savings, monetary gain through property value enhancement, and recreational space creation. These are the impacts of GI, but they are also all beneficial. As for economic impacts, these are not also considered benefits because they define the economic cost.

Chapter 5 Results and Discussion

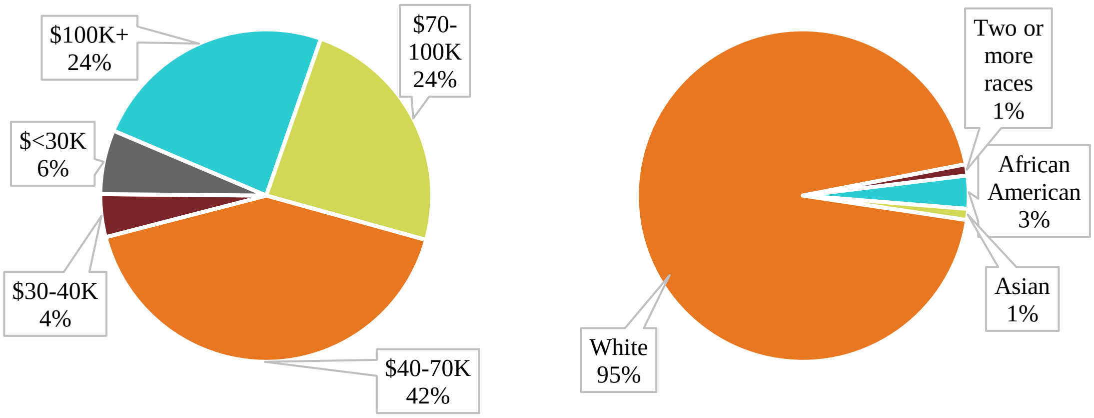
State and federal authorities across the United States are currently implementing sustainable practices, such as GI and LID, into their infrastructure management strategies and plans. Their aim is to meet sustainability goals, while also promoting economic growth and enhancing public safety and quality of life. While traditional infrastructure planning and design has focused on the economic impacts of a project the environmental and social benefits have most been ignored. As state departments of transportation (SDOTs) move toward integrating GI practices into transportation infrastructure, there is a need for a standardized framework that considers economic, environmental, and social benefits along with public opinion and a hierarchy of importance of different benefits to aid decision making. With this in mind, the proposed research aims to develop a systematic quantification framework that captures economic, environmental and social impacts of infrastructure projects, including spatially specific and temporally dynamic metrics, objective weights, practical quantification methods, and calculations to value tangential benefits. The study will propose a framework that can be used by practitioners to promote sustainable infrastructure practices by assessing the applicability and quantified benefits of possible GI for development projects.

5.1 Survey, AHP and MCS Results

To determine a hierarchy of importance and integrate public opinion into the frameworks, two surveys—using the Likert scale—were conducted. The first surveyed citizens at the community level throughout the state of Tennessee and the second surveyed administrators on a national scale across all SDOTs. Survey responses were rated by the Likert scale approach, which is a widely used rating scale used to measure opinions. This approach consists of a statement or question, followed by a series of five answer statements (e.g., 1- ‘Strongly Disagree’ to 5- ‘Strongly Agree’). Respondents choose the option that best corresponds with how they feel about the statement or question. Due to the range of possible answers respondents are offered, Likert scales are great for expressing their level of agreement or feelings about the topic in a subtle way.



(A) Highest level of education (B) Age Range



(C) Annual Income Range (D) Race

Figure 5-1 Pie Graphs Descriptive statistics of the citizen participants in the survey showing- (A) Highest education level, (B) Age range, (C) Annual income range, and (D) Race of the participants.

The first survey received 98 responses from citizens in Tennessee. Figure 5-1 shows the general demographics of these citizen participants. While gender was not considered a critical demographic in understanding opinions about GI, demographics that were thought to be influential were 'Highest level of education,' 'Age Range,' 'Annual Income Range,' and 'Race.' More than half of the citizen respondents (55%) are college graduates or have some college education, while 42% have some amount of professional or graduate school education, and only 3% have high school education as their highest form of education. A third of respondents are aged 37-47, while only 10% are aged 18-25. The large majority of citizen respondents (90%) earn more than $40K annually and 95% of respondents identify as "White." In the survey, the participants were asked to rank the importance of GI in contributing to the social aspects (ref. Figure 5-2) and environmental (ref. Figure 5-3). More than half of respondents said GI is "Very Important" in contributing to "Recreational Opportunity" and health benefits from heat reduction, while respondents appear to believe GI does not contribute as significantly to economic development from job creation. Citizen respondents believe GI contributes to health benefit from heat reduction and reduced stormwater runoff more so than it contributes to reducing air pollutants.

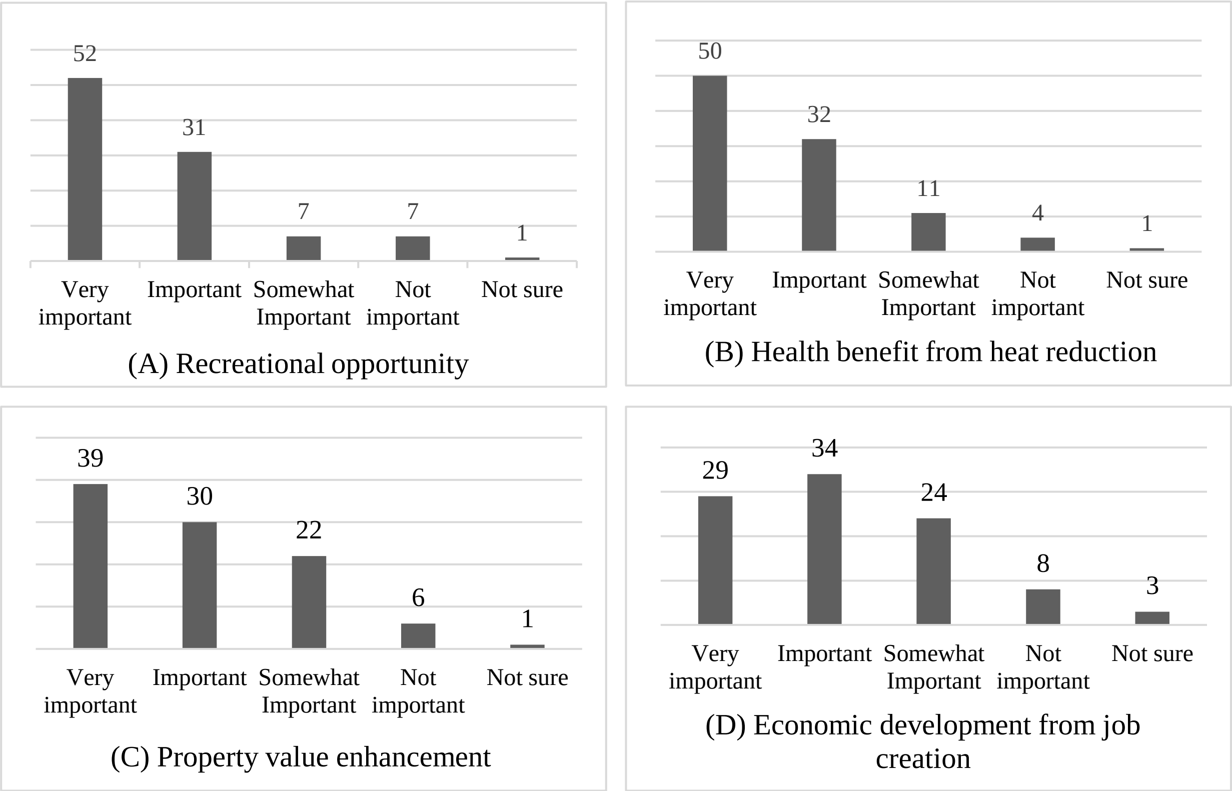


Figure 5-2 Bar Graphs Survey results showing citizen participants' opinion about GI in contributing to social impacts. (A) Recreational opportunity. (B) Health benefit from heat reduction, (C) Property value enhancement, (D) Economic development from job creation.

From the second survey—sent to all SDOTs nationwide—responses from 18 SDOTs were received, mostly from the north-eastern region. From these 18 SDOT responses, more than half currently do not use GI analysis, although almost 94% are at least somewhat knowledgeable about GI practices. When considering GI and conducting GI analysis, 100% of SDOTs rank "Environmental" as the most important aspect, and 75% of SDOTs rank "Social" as the second most important aspect and "Economic" as the last, while the rest (25%) deem "Economic" as the second most important aspect. Figure 5-4 portrays changes over the past five years in the responding SDOT's analysis of GI regarding social, environmental, and economic impacts. Concerning SDOT's analysis of social impacts of GI projects and how it has changed, 38% responded with "We are doing a little more analysis," 31% responded with "We are doing the same amount of analysis," and 31% responded with "We do no analysis," out of 13 responses. GI analysis of social impacts is the only category in which some SDOTs are doing no analysis, while GI analysis of environmental impacts is the only category in which some SDOTs have been doing "a lot more." As for current analysis being performed within respondent SDOTs, 44% (or 8 out of 18) conduct GI analysis—although 78% (or 14 out of 16) use GI measures on some level—while only 28% (or 5 out of 18) analyze GI on the basis of their social, economic and environmental impacts and benefits. Furthermore, from these surveys it was discovered that public opinion and the opinion of national SDOT employees was similar. Opinions of GI and the benefits it can present are overwhelmingly positive and are understood and accepted by the majority.

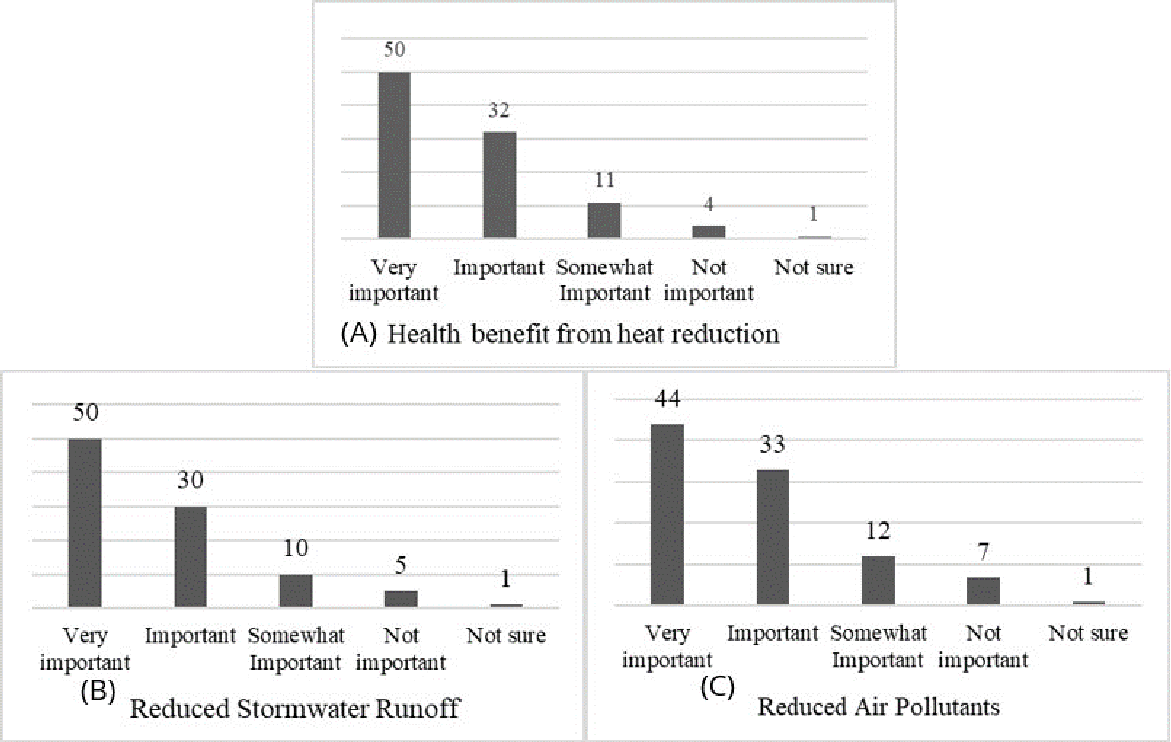


Figure 5-3 Bar Graphs Survey results showing citizen participants' opinion about GI in contributing to environmental impacts.

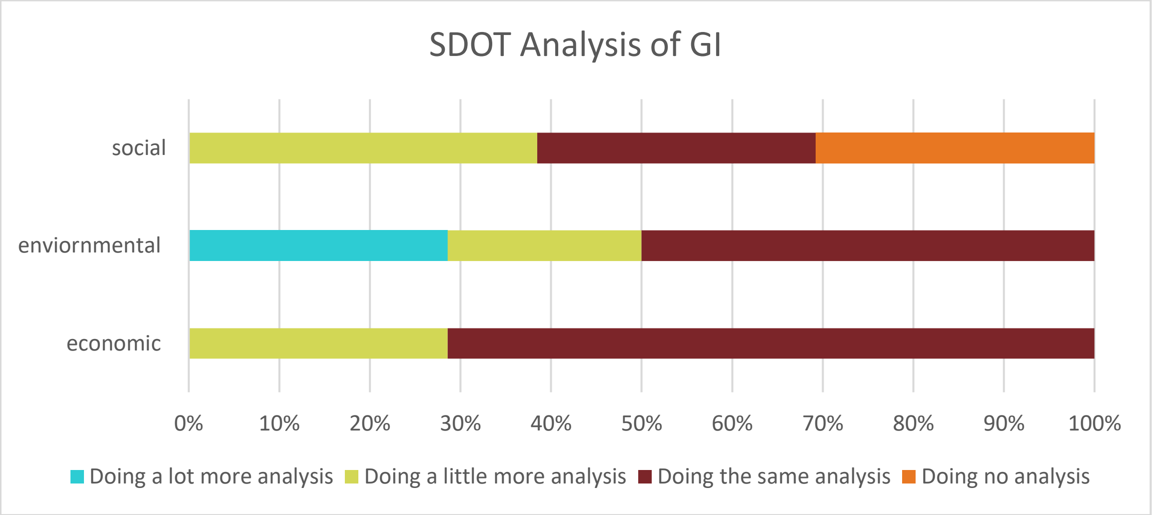
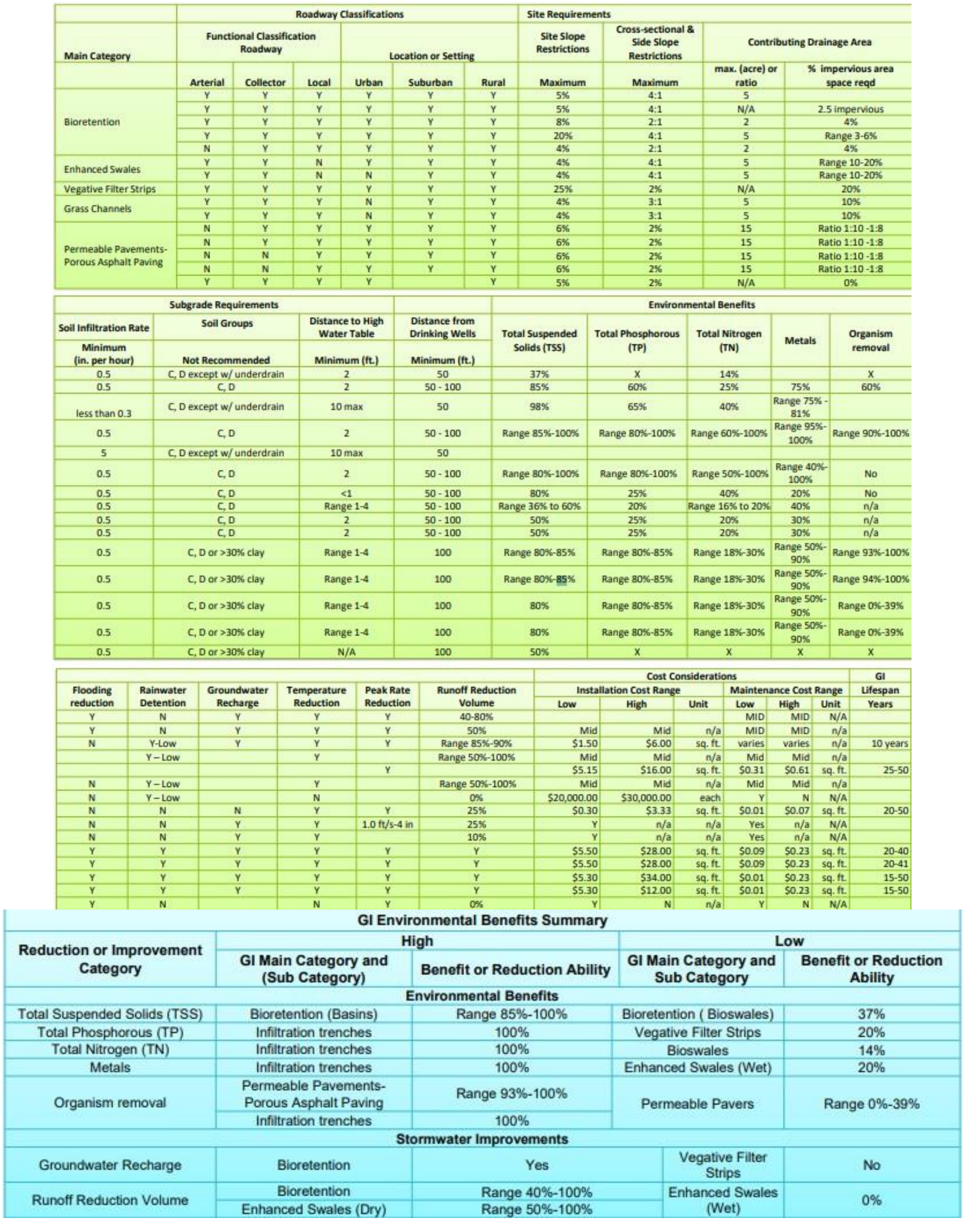


Figure 5-4 Bar Graph Survey results showing SDOT responses regarding how their agency's analysis of GI has changed in the past 5 years in respect to social, environmental, and economic impacts.

5.2 GI Repository

A design repository of GI measures—in the form of an excel spreadsheet—was developed to be used as a reference in the construction of the web-based toolbox. This database contains information—from site requirements to cost breakdowns—pertaining to each GI practice that will be referenced and integrated into the algorithm used in the framework so the toolbox can determine which GIs are applicable for specific project parameters. For a very simple example,



	Roadway Classifications						Site Requirements			
Main Category	Functional Classification Roadway			Location or Setting			Site Slope Restrictions	Cross-sectional & Side Slope Restrictions	Contributing Drainage Area	
	Arterial	Collector	Local	Urban	Suburban	Rural	Maximum	Maximum	max. (acre) or ratio	% impervious area space reqd
Bioretention	Y	Y	Y	Y	Y	Y	5%	4:1	5	
	Y	Y	Y	Y	Y	Y	5%	4:1	N/A	2.5 impervious
	Y	Y	Y	Y	Y	Y	8%	2:1	2	4%
	Y	Y	Y	Y	Y	Y	20%	4:1	5	Range 3-6%
	N	Y	Y	Y	Y	Y	4%	2:1	2	4%
Enhanced Swales	Y	Y	N	Y	Y	Y	4%	4:1	5	Range 10-20%
	Y	Y	N	N	Y	Y	4%	4:1	5	Range 10-20%
Vegative Filter Strips	Y	Y	Y	Y	Y	Y	25%	2%	N/A	20%
Grass Channels	Y	Y	Y	N	Y	Y	4%	3:1	5	10%
	Y	Y	Y	N	Y	Y	4%	3:1	5	10%
Permeable Pavements-Porous Asphalt Paving	N	Y	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	N	Y	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	N	N	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	N	N	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	Y	Y	Y	Y		Y	5%	2%	N/A	0%

Subgrade Requirements				Environmental Benefits				
Soil Infiltration Rate	Soil Groups	Distance to High Water Table	Distance from Drinking Wells	Total Suspended Solids (TSS)	Total Phosphorous (TP)	Total Nitrogen (TN)	Metals	Organism removal
Minimum (in. per hour)	Not Recommended	Minimum (ft.)	Minimum (ft.)					
0.5	C, D except w/ underdrain	2	50	37%	X	14%		X
0.5	C, D	2	50 - 100	85%	60%	25%	75%	60%
less than 0.3	C, D except w/ underdrain	10 max	50	98%	65%	40%	Range 75% - 81%	
0.5	C, D	2	50 - 100	Range 85%-100%	Range 80%-100%	Range 60%-100%	Range 95%-100%	Range 90%-100%
5	C, D except w/ underdrain	10 max	50					
0.5	C, D	2	50 - 100	Range 80%-100%	Range 80%-100%	Range 50%-100%	Range 40%-100%	No
0.5	C, D	<1	50 - 100	80%	25%	40%	20%	No
0.5	C, D	Range 1-4	50 - 100	Range 36% to 60%	20%	Range 16% to 20%	40%	n/a
0.5	C, D	2	50 - 100	50%	25%	20%	30%	n/a
0.5	C, D	2	50 - 100	50%	25%	20%	30%	n/a
0.5	C, D or >30% clay	Range 1-4	100	Range 80%-85%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 93%-100%
0.5	C, D or >30% clay	Range 1-4	100	Range 80%-85%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 94%-100%
0.5	C, D or >30% clay	Range 1-4	100	80%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 0%-39%
0.5	C, D or >30% clay	Range 1-4	100	80%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 0%-39%
0.5	C, D or >30% clay	N/A	100	50%	X	X	X	X

						Cost Considerations						GI
Flooding reduction	Rainwater Detention	Groundwater Recharge	Temperature Reduction	Peak Rate Reduction	Runoff Reduction Volume	Installation Cost Range			Maintenance Cost Range			Lifespan
						Low	High	Unit	Low	High	Unit	Years
Y	N	Y	Y	Y	40-80%				MID	MID	N/A	
Y	N	Y	Y	Y	50%	Mid	Mid	n/a	MID	MID	n/a	
N	Y-Low	Y	Y	Y	Range 85%-90%	$1.50	$6.00	sq. ft.	varies	varies	n/a	10 years
	Y – Low		Y		Range 50%-100%	Mid	Mid	n/a	Mid	Mid	n/a	
				Y		$5.15	$16.00	sq. ft.	$0.31	$0.61	sq. ft.	25-50
N	Y – Low		Y		Range 50%-100%	Mid	Mid	n/a	Mid	Mid	n/a	
N	Y – Low		N		0%	$20,000.00	$30,000.00	each	Y	N	N/A	
N	N	N	Y	Y	25%	$0.30	$3.33	sq. ft.	$0.01	$0.07	sq. ft.	20-50
N	N	Y	Y	1.0 ft/s-4 in	25%	Y	n/a	n/a	Yes	n/a	N/A	
N	N	Y	Y		10%	Y	n/a	n/a	Yes	n/a	N/A	
Y	Y	Y	Y	Y	Y	$5.50	$28.00	sq. ft.	$0.09	$0.23	sq. ft.	20-40
Y	Y	Y	Y	Y	Y	$5.50	$28.00	sq. ft.	$0.09	$0.23	sq. ft.	20-41
Y	Y	Y	Y	Y	Y	$5.30	$34.00	sq. ft.	$0.01	$0.23	sq. ft.	15-50
Y	Y	Y	Y	Y	Y	$5.30	$12.00	sq. ft.	$0.01	$0.23	sq. ft.	15-50
Y	N		N	Y	0%	Y	N	n/a	Y	N	N/A	

GI Environmental Benefits Summary				
Reduction or Improvement Category	High		Low	
	GI Main Category and (Sub Category)	Benefit or Reduction Ability	GI Main Category and Sub Category	Benefit or Reduction Ability
Environmental Benefits				
Total Suspended Solids (TSS)	Bioretention (Basins)	Range 85%-100%	Bioretention (Bioswales)	37%
Total Phosphorous (TP)	Infiltration trenches	100%	Vegative Filter Strips	20%
Total Nitrogen (TN)	Infiltration trenches	100%	Bioswales	14%
Metals	Infiltration trenches	100%	Enhanced Swales (Wet)	20%
Organism removal	Permeable Pavements-Porous Asphalt Paving	Range 93%-100%	Permeable Pavers	Range 0%-39%
	Infiltration trenches	100%		
Stormwater Improvements				
Groundwater Recharge	Bioretention	Yes	Vegative Filter Strips	No
Runoff Reduction Volume	Bioretention	Range 40%-100%	Enhanced Swales (Wet)	0%
	Enhanced Swales (Dry)	Range 50%-100%		

Figure 5-5 Examples of GI repository spreadsheet (top) and GI environmental benefits summary (bottom).

bioretention basins are mostly applicable for arterial roadways but permeable pavements are mostly not suitable for that type of roadway, exceptions are due to specific site requirements such as maximum slope. To compile a comprehensive database, the team thoroughly researched GIs that have the potential or that are currently being used across the US including municipalities, states, and federal government. After gathering this information, standards and classifications of different GI practices were cataloged based on their limitations, design requirements, costs, and benefits. The GI repository includes 12 main categories: Bioretention, Enhanced Swales, Vegetative Filter Strips, Grass Channels, Permeable Pavements, Basins, Infiltration Beds/Basins, Landform Grading, Manufactured Treatment Devices, Wetlands, Amended Soils, and Land Conservation/Restoration. These 12 main categories are further subcategorized into more than 30 GI measures. Standards and classification categories are: Roadway Classification, Site Requirements, Subgrade Requirements, Set Back Requirements, Environmental Benefits, Stormwater Improvements, and Cost Considerations.

The framework developed in this study includes a comprehensive, searchable database of GI practices in which environmental, social and economic benefits are quantified and monetized so that SDOTs and practitioners can assess the costs and applicability of GI for transportation projects. The quantification methods used in this toolbox take into account spatial and temporal variables, as well as the hierarchy of importance concluded from the AHP. This study is a further step in producing a standardized method of quantifying GI features and can assist SDOTs in accurate cost-benefit analysis for GI implementation. Furthermore, this toolbox assesses environmental and social impacts in addition to the economic benefits which traditional infrastructure planning has prioritized, thus promoting the use of GI and LID practices over gray infrastructure determined by real-time and space cost-benefit evidence.

Further quantification and integration of *indirect* economic costs should be added to this framework to add further accuracy to the cost-benefit analysis. This study did not take into consideration the extent of economic costs avoided by GI practices compared to gray infrastructure. For example, although 'reduced flood damage' was considered in economic costs, the avoided expenses from remediating other wet weather damages possibly exacerbated by traditional infrastructure such as combined sewer overflows (CSO) or property erosion were not. Undoubtedly, quantifying these hypothetical costs proves challenging, but should not be ignored. Savings enabled by GI practices transcend economic benefits, the social and environmental benefits of CSO prevention and deterring bank erosion is substantial, but perhaps even more difficult to quantify.

5.3 Case Study

The results of this case study explicitly show the quantification and monetization of the economic, environmental, and social impacts of implementing GI in a project site. The end result of the toolbox, when benefits are quantified, offers the user a comparative analysis portrayed as a 'Weight by Density' graph concluding the best scenario in terms of benefits, as it equates to the quantified values. Scenario 1, analyzing rain harvesting with a cistern, and Scenario 2, analyzing a bioretention system, for the same project site were considered with the toolbox, comparing their quantified economic, environmental, and social impacts. Scenario 2—implementing bioretention—was identified as the better option—over Scenario 1. The results of 'Quantifying Benefits' produces a weight by density graph portraying the profiles compared, the profile with the greater weight density is determined to be the better option, regarding the quantified and monetized economic, environmental, and social impacts.

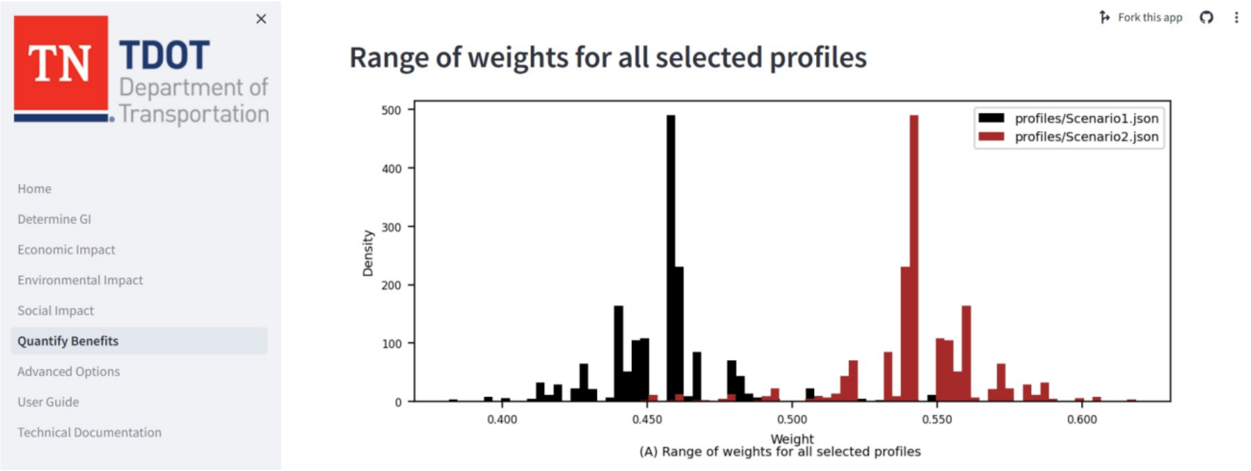


Figure 5-6 'Weight by Density' graph showing the results of the case study's comparative analysis between Scenario 1 and Scenario 2. Scenario 2 was found to be the better option.

The case study results determining Scenario 2 as the better option was not overtly surprising, since the bioretention system offers much greater monetized environmental and social benefits ($37,593.81/year and a monetary gain of $120,000, respectively) compared to a cistern ($3,009.26/year and $0, respectively), despite its much greater capital cost ($178,056). However, Scenario 1 and Scenario 2 were compared again with a singular change: leaving the 'Social Impacts' of Scenario 2 blank. Meaning all values described above remained the same; however, the social impacts (i.e., enhanced property value and recreational use) were left blank for both Scenario 1 and Scenario 2. Surprisingly, Scenario 2 remained the better option and highlights just how financially impactful long-term benefits can be over short-term capital costs. The cistern scenario undoubtedly offered a substantially lower capital cost ($9,948.40 versus the bioretention's $178,056.00), but still was not the best option since the bioretention scenario's environmental and social benefits quickly surpass the cistern's combined impacts. This case study will resonate well with anyone who has ever implemented TI over GI based solely on initial capital costs, which is often the reason TI is chosen over GI. Implementing GI elements may appear disadvantageous if only considering the capital costs, but when all other costs are considered—environmental and social—the overall cost of GI is considerably lower than TI.

There are several limitations to the toolbox and associated frameworks that require further research and implementation. Multiple profiles can be created in the tool to analyze numerous GI scenarios; however, the tool is only presently capable of comparing two profiles at once and to compare three or more profiles, individually paired comparisons must be performed. The framework does not account for the direct benefits of transportation infrastructure, such as congestion reduction, travel time reduction, and fuel savings. This omission was based on the assumption that GI elements would not influence these direct benefits. Further research is needed to substantiate this assumption. As of now, there is no way to validate the results of the social benefit quantification frameworks. Most of the frameworks are also based on methods that are survey based which still brings some subjectivity into the assessment. However, a benchmark can be set by authorities to follow on a local/state/federal scale to assess all the projects on a general scale. The Likert scale—used in the surveys—was based in such a way that the survey did not have the scope to facilitate the participants to deem the GI is inefficient when compared to TI. Instead of having only positive choices, there should also be some choices from the other side of the spectrum which would make this framework more valid. Additionally, the toolbox may exhibit some bias due to the limited participation of only 18 SDOTs in the survey. The survey serves as a tool for assessing the relative significance of economic, environmental, and social aspects of GI. To mitigate potential bias, obtaining more responses from SDOTs is essential.

Chapter 6 Conclusion

Green Infrastructure (GI) is rapidly gaining acceptance as an alternative to traditional infrastructure due to its multifold benefits. GI can provide economic, environmental, and social benefits to the community and to society. However, unlike economic benefits, the environmental and social benefits of GI are challenging to quantify which is why they are often overlooked when comparing the benefits of GI to other alternative options like gray/traditional infrastructure. Incorporating the environmental and social benefits into the cost-benefit assessment framework can make GIs much more attractive alternatives to policymakers. Which is why this study aimed to develop a tool that can be used by practitioners to assess the environmental and social benefits along with economic benefits of GI practices. But most importantly, environmental and social benefits will no longer be overlooked and disused, this toolbox can undoubtedly lead to increased implementation of GI practices and in turn will benefit the environment, the community, and its citizens. The environmental and social impacts assessed with the toolbox are equally benefits, and so used synonymously. For example, the social impacts of reducing urban heat, increasing green spaces that can be used as parks, and eliminating potential sanitation hazards like combined sewer overflows are all undeniably advantageous. Similarly, environmental impacts of improved water and air quality, reduced stormwater runoff and increased groundwater recharge are easily identified as beneficial.

This framework incorporates the Analytical Hierarchy Process and Monte Carlo simulation to integrate GI's social benefits and public opinion into the decision-making process and determine the effectiveness of different alternatives in accruing monetary gain from benefits over the lifetime of the project. With the tool developed in this study, departments of transportation across the U.S. can efficiently and accurately assess the applicability of GI and LID practices based quantified benefits—environmental, social and economic—not just the economic impacts. This cost-benefit analysis is based on real-time and space variables, with the hierarchy of importance and public opinion considered. It will surely improve the analysis of GI measures for their use in transportation infrastructure projects, as we move toward further sustainability and improving social welfare.

With less than half of the nation’s SDOTs conducting GI analysis for transportation projects, and only a little more than half of *these* analysis consider social, environmental, and economic benefits, TDOT can use this toolbox to lead the nation in efficient and effective GI analysis and implementation. In analyzing GI in terms of social, environmental, and economic impacts, TDOT will not only be able to unveil aspects of a cost-benefit analysis they and many other SDOTs have been ignoring and/or missing, but they will also be ahead of many agencies since nearly a third of SDOTs do no assessment of social impacts when analyzing GI for transportation projects.

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Appendices

Appendices should be separated by category and may include correspondences, interview transcripts, non-textual elements, questionnaires or surveys, research instruments, sample calculations, or raw statistical data. Include raw data used in the making of the report. If the raw data is extensive and would be cumbersome to include, provide the documentation to TDOT Lead Staff and the Research Office in a separate, readable file. Deliverables that are separate from the research project should be provided separately in this manner as well.

THE UNIVERSITY OF TENNESSEE
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Computer Science

Quantification and Integration of Social Benefits of Green Infrastructure in Screening Transportation Project Alternatives

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Background

- Green infrastructure (GI) practices are being implemented in the US to promote economic development and improve quality of life.
- Examples of GI practices include green sidewalks, permeable pavement, bioretention etc.
- GI also brings social benefits in addition to economic and environmental benefits.
- Traditional infrastructure (TI) planning often ignores social benefits but incorporating them into cost-benefit analysis can make GI more attractive.
- This research develops a framework which integrates social benefits into decision-making process and assesses the effectiveness of alternatives in monetary gain from social benefits over the lifetime of projects.

Analytical Hierarchy Process

- AHP involves breaking down a problem into a hierarchy of smaller, more manageable sub-problems, and then evaluating them in relation to one another.
- AHP uses a pairwise comparison method to assign weights to different options or criteria, allowing for a more objective and systematic approach to decision-making.
- AHP can be useful in helping to identify the most important factors in a decision, and in providing a clear and defensible rationale for the final decision made.

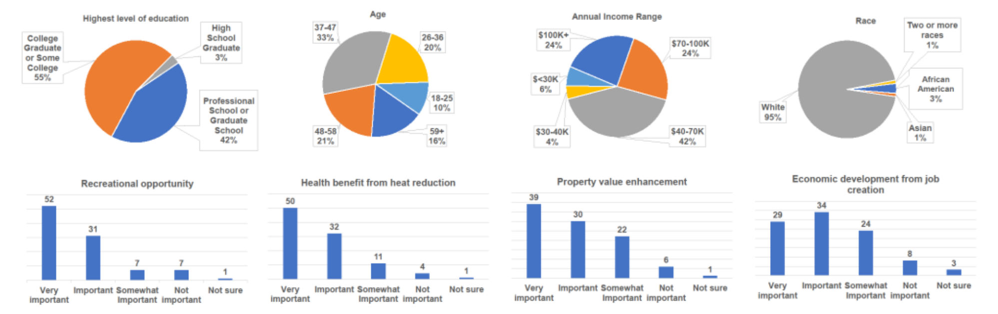
Monte-Carlo Simulation

- Monte Carlo simulation is a computational method that uses random samples to track behavior and determine the sensitivity and uncertainty of a statistic.
- The method is useful for dealing with subjective expert opinions or personal preferences when applying weights.
- The steps for Monte Carlo simulation include establishing the distribution function and probability cumulative distribution for each outlined uncertainty, generating a random number, and assigning values using the probability cumulative distribution.
- The final step is to draw the target function's probability cumulative distribution.
- The Monte Carlo simulation method is useful for quantifying uncertainty and sensitivity in statistical analysis.

Methodology

1. The first hierarchy structure in the figure 1 can be used to determine the best choice among green infrastructure (GI), traditional infrastructure, and combined infrastructure.
2. The research reported here considers only the social impacts and determines the efficiency of infrastructure based on its social impacts.
3. The resulting hierarchy structure in the figure 2 considers only the social impacts and has four criteria: recreational use, heat reduction, job creation, and enhanced property value.
4. A survey with 98 responses was conducted and used to rank the importance of GI in contributing to the social aspects of GI
5. The survey results were used to construct 93 pairwise matrices, one for each participant, which compare the relative efficiency of each criteria.
6. Six cumulative distributive functions (CDFs) were extracted for each entry in the pairwise matrix.
7. Second level pairwise matrices were populated by comparing the monetary gain from different aspects.
8. The weights were used to determine the priority of each alternative.

Survey Statistics



Analytical Hierarchy Structure

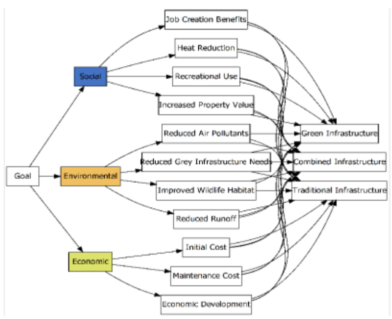


Figure 1

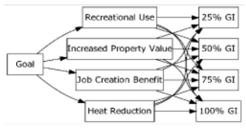
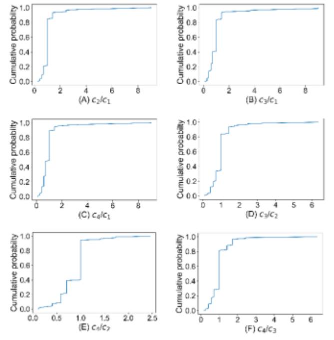
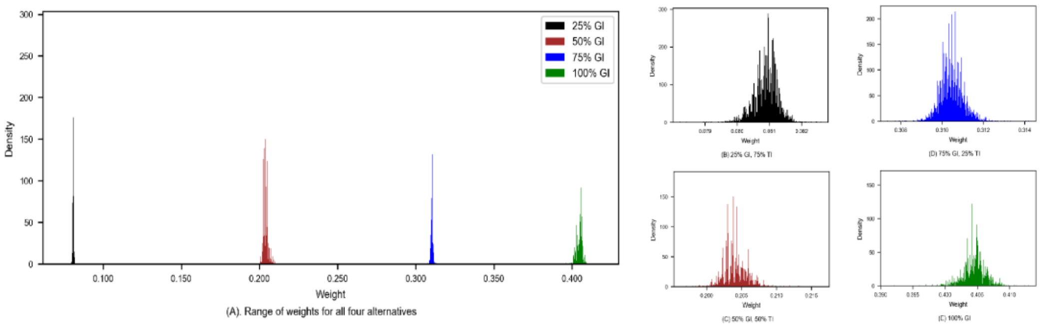


Figure 2

CDF of Each Entry in the Pairwise Matrix



Result after 10,000 Simulation



(A). Range of weights for all four alternatives

(B) 25% GI, 75% TI

(D) 75% GI, 25% TI

(C) 50% GI, 50% TI

(E) 100% GI

Result and Conclusion

- The 100% GI option is the most efficient choice for earning monetary value from social aspects.
- A novel framework was developed for determining the effectiveness of different alternatives in accruing monetary gain from social aspects.
- Monte Carlo simulation was used to handle randomness in public acceptance and the AHP was used to transform subjectivity into a quantifiable system.
- Social benefit assessment frameworks are effective in determining monetary gain across different spatial and temporal variables.
- The framework is flexible and can be used to consider social, environmental, and economic aspects.

Limitations

- The framework has a limited Likert scale that only allows for positive choices, which limits its validity.
- The AHP may not be necessary for determining the efficiency of GI compared to TI, but it is useful for considering environmental and economic aspects in a larger framework.
- The results of the social benefit quantification frameworks cannot currently be validated.
- Most of the frameworks rely on survey-based methods, which introduces subjectivity into the assessment.

Future Work

- An improved survey with a Likert scale having both positive and negative responses can be utilized to modify the framework.
- Similar method will be implemented for environmental and economic aspects to functionalize the comprehensive framework in figure 1.
- Further research is required to validate the result regarding the monetary gain from social benefits.
- A benchmark set by authorities can be developed to assess all projects on a general scale.

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Green Infrastructure (GI) for Transportation Design

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What is Green Infrastructure?

- Green infrastructure is a practice used in stormwater management that uses natural means or a made environment similar to nature to improve runoff.
- Removes contaminants and sedimentation from stormwater runoff.
- Infiltrates stormwater to recharge groundwater levels.
- Reduces levels of TSS, total nitrogen, total phosphorus, and bacteria from runoff.
- Native species included in designs to increase biodiversity.
- Typical designs are used in urban settings.
- Implementation of green infrastructure can positively enhance aesthetics of the built environment.

Limitations of Green Infrastructure

- × Limited information on applications and uses in transportation.
- × Information about GI's are not in a central database.
- × Many GI's work only under specific design considerations but that can be location specific.
- × Currently GI's are implemented after initial design instead of as part of the planning process.
- × Some GI's can be cost prohibitive to install and maintain.
- × More research needs to be performed to understand the Environmental, Social, and Economics of Green Infrastructure.

Project Objectives

Objective 1: Research all Green Infrastructure (GI's) used across the United States including municipalities, state, and federal government.

Objective 2: Develop a design repository of GI's that have the potential or that are currently used in various Department of Transportation in U.S. States.

Objective 3: Catalog standards and classifications of different GI's based on their limitations, design requirements, cost, and benefits.

Objective 4: Work with the team to provide a database to facilitate development of a web based planning tool that uses machine learning and site applicability of each GI's for use on a State Design Project.

Gray Infrastructure vs Green Infrastructure (GI)

Grey Infrastructure	*Green Infrastructure*

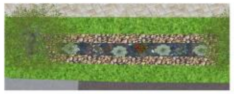
Traditional Pavement Designs

Permeable Pavements

Curb and Gutter

Retention Ponds and Natural Basins

Concrete Conveyances



Raingardens and Bioswales

Process to Develop GI Repository

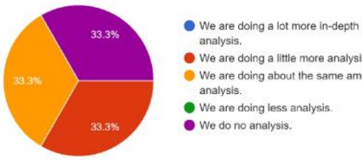
Research Sources
- Local Government Standards
- Nationwide State DOTs GI design guidelines
- Scientific Literature and Research Papers

Data Collection
- GI specifications
- Standards Drawings
- National State DOT's GI Survey

Results Format
- Excel Spreadsheet
- Webtool using spreadsheet data
- Machine Learning application.

Example DOT Survey Data and Analysis

16. Over the past 5 years, how has your agency's analysis of the **social** impacts of GI projects changed? (check only **one** response)
12 responses



<u>Results and Summary</u>

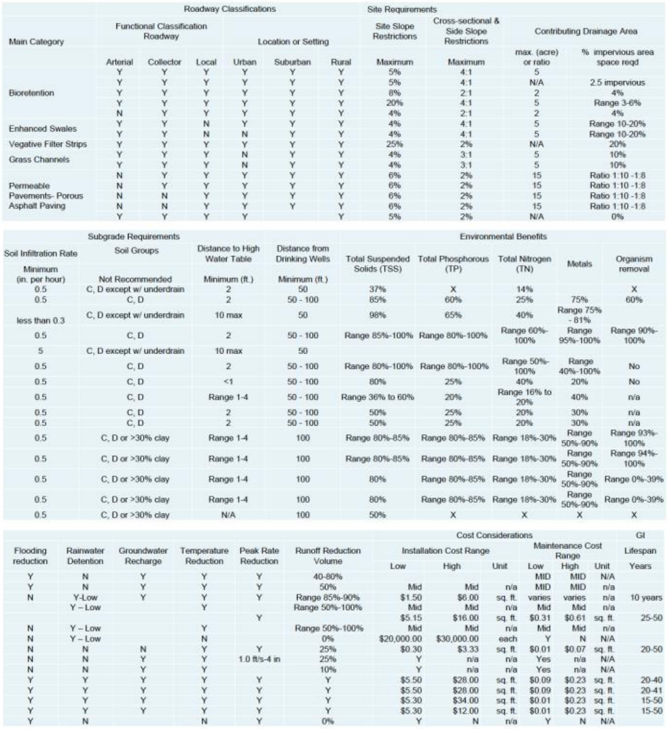
- 16 Total Responses
- Mostly from the north-eastern region
- More than half do not use GI analysis although almost 94% are at least somewhat knowledgeable about GI.
- 100% of the DOTs rank 'Environmental' as the most important aspect when conducting GI analysis (75% of these DOTs are knowledgeable about GI and the rest are somewhat knowledgeable)
- 75% of the DOTs rank 'Social' as the second most important aspect and 'Economic' as the last while the rest deem 'Economic' aspect as the second most important

GI Repository Categories

<u>Main GI Categories</u>
- Bioretention
- Enhanced Swales
- Vegetive Filter Strips
- Grass Channels
- Permeable Pavements-Porous Asphalt Paving
- Basins
- Infiltration Bed/Basins
- Landform Grading
- Manufactured treatment devices
- Wetlands
- Amended Soils
- Land Conservation/ Restoration

<u>Primary Repository Headings</u>
- Roadway Classification
- Site Requirement
- Subgrade Requirement
- Set Back Requirement
- Environmental Benefits
- Stormwater Improvement
- Cost Considerations

GI Repository Spreadsheet Example



Main Category	Roadway Classifications						Site Requirements			
	Functional Classification Roadway			Location or Setting			Site Slope Restrictions	Cross-sectional & Side Slope Restrictions	Contributing Drainage Area	
	Arterial	Collector	Local	Urban	Suburban	Rural	Maximum	Maximum	max. (acre) or ratio	% impervious area space reqd
Bioretention	Y	Y	Y	Y	Y	Y	5%	4:1	5	
	Y	Y	Y	Y	Y	Y	5%	4:1	N/A	2.5 impervious
	Y	Y	Y	Y	Y	Y	8%	2:1	2	4%
	Y	Y	Y	Y	Y	Y	20%	4:1	5	Range 3-6%
	N	Y	Y	Y	Y	Y	4%	2:1	2	4%
Enhanced Swales	Y	Y	N	Y	Y	Y	4%	4:1	5	Range 10-20%
	Y	Y	N	N	Y	Y	4%	4:1	5	Range 10-20%
Vegative Filter Strips	Y	Y	Y	Y	Y	Y	25%	2%	N/A	20%
Grass Channels	Y	Y	Y	N	Y	Y	4%	3:1	5	10%
	Y	Y	Y	N	Y	Y	4%	3:1	5	10%
Permeable Pavements- Porous Asphalt Paving	N	Y	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	N	Y	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	N	N	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	N	N	Y	Y	Y	Y	6%	2%	15	Ratio 1:10 -1:8
	Y	Y	Y	Y		Y	5%	2%	N/A	0%

Subgrade Requirements				Environmental Benefits				
Soil Infiltration Rate	Soil Groups	Distance to High Water Table	Distance from Drinking Wells	Total Suspended Solids (TSS)	Total Phosphorous (TP)	Total Nitrogen (TN)	Metals	Organism removal
Minimum (in. per hour)	Not Recommended	Minimum (ft.)	Minimum (ft.)					
0.5	C, D except w/ underdrain	2	50	37%	X	14%		X
0.5	C, D	2	50 - 100	85%	60%	25%	75%	60%
less than 0.3	C, D except w/ underdrain	10 max	50	98%	65%	40%	Range 75% - 81%	
0.5	C, D	2	50 - 100	Range 85%-100%	Range 80%-100%	Range 60%-100%	Range 95%-100%	Range 90%-100%
5	C, D except w/ underdrain	10 max	50					
0.5	C, D	2	50 - 100	Range 80%-100%	Range 80%-100%	Range 50%-100%	Range 40%-100%	No
0.5	C, D	<1	50 - 100	80%	25%	40%	20%	No
0.5	C, D	Range 1-4	50 - 100	Range 36% to 60%	20%	Range 16% to 20%	40%	n/a
0.5	C, D	2	50 - 100	50%	25%	20%	30%	n/a
0.5	C, D	2	50 - 100	50%	25%	20%	30%	n/a
0.5	C, D or >30% clay	Range 1-4	100	Range 80%-85%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 93%-100%
0.5	C, D or >30% clay	Range 1-4	100	Range 80%-85%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 94%-100%
0.5	C, D or >30% clay	Range 1-4	100	80%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 0%-39%
0.5	C, D or >30% clay	Range 1-4	100	80%	Range 80%-85%	Range 18%-30%	Range 50%-90%	Range 0%-39%
0.5	C, D or >30% clay	N/A	100	50%	X	X	X	X

						Cost Considerations						GI
Flooding reduction	Rainwater Detention	Groundwater Recharge	Temperature Reduction	Peak Rate Reduction	Runoff Reduction Volume	Installation Cost Range			Maintenance Cost Range			Lifespan
						Low	High	Unit	Low	High	Unit	Years
Y	N	Y	Y	Y	40-80%				MID	MID	N/A	
Y	N	Y	Y	Y	50%	Mid	Mid	n/a	MID	MID	n/a	
N	Y-Low	Y	Y	Y	Range 85%-90%	$1.50	$6.00	sq. ft.	varies	varies	n/a	10 years
	Y – Low		Y		Range 50%-100%	Mid	Mid	n/a	Mid	Mid	n/a	
				Y		$5.15	$16.00	sq. ft.	$0.31	$0.61	sq. ft.	25-50
N	Y – Low		Y		Range 50%-100%	Mid	Mid	n/a	Mid	Mid	n/a	
N	Y – Low		N		0%	$20,000.00	$30,000.00	each	Y	N	N/A	
N	N	N	Y	Y	25%	$0.30	$3.33	sq. ft.	$0.01	$0.07	sq. ft.	20-50
N	N	Y	Y	1.0 ft/s-4 in	25%	Y	n/a	n/a	Yes	n/a	N/A	
N	N	Y	Y		10%	Y	n/a	n/a	Yes	n/a	N/A	
Y	Y	Y	Y	Y	Y	$5.50	$28.00	sq. ft.	$0.09	$0.23	sq. ft.	20-40
Y	Y	Y	Y	Y	Y	$5.50	$28.00	sq. ft.	$0.09	$0.23	sq. ft.	20-41
Y	Y	Y	Y	Y	Y	$5.30	$34.00	sq. ft.	$0.01	$0.23	sq. ft.	15-50
Y	Y	Y	Y	Y	Y	$5.30	$12.00	sq. ft.	$0.01	$0.23	sq. ft.	15-50
Y	N		N	Y	0%	Y	N	n/a	Y	N	N/A	

Conclusion and Future Work

- The database repository of GI has been created and is currently being used to rank GI's based on their applicability for transportation purposes.
- The data table will be updated based on State-wide surveys to DOT's based on their use of GI's in transportation. Community surveys will collect additional information from the publics perspective of Green Infrastructure.
- Once the data is collected it will used to asses the Social and Economic benefits of GI's and in development of planning tools.