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PhD Thesis

GREEN STORM-WATER INFRASTRUCTURE STRATEGY GENERATION AND ASSESSMENT TOOL

For Site-Scale and Urban Planning

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To Paty,

Mia and Leah

My compass, my anchor and my shore.

Abstract

Green Stormwater Infrastructure (GSI), which includes elements like green roofs, bioretentions, pervious pavement and cisterns, has proven to be a cost effective alternative that can achieve a wider range of benefits in stormwater management compared to the single-purpose grey/traditional infrastructure (Combined Sewer System or Municipal Separate Storm and Sewer System). However, the implementation of GSI as a replacement or support system for grey infrastructure faces some barriers preventing its adoption by planners/designers and decision makers, in the private as well as in the public sector. While understanding and quantifying the full costs and the benefits of GSI plans are critical for sound decision making and to facilitate its adoption, planners/designers face challenges pertaining to hydrologic calculations (including sizing of Green Stormwater Infrastructure Elements (GSIEs), cost estimation (life cycle costs) and benefit assessment).

This thesis presents a proof of concept tool (prototype) that is developed to help planners/designers and different stakeholders involved in conducting a comprehensive GSI planning process. The tool generates GSI alternative solutions (combination and size of GSIEs) that meet the user's financial and hydrologic objectives. These alternatives are generated to maximize benefits, reduce costs and account for design specifications and multi-functionality of GSI. The prototype has three modules:

- An Interface Module (including Input and Output Interfaces)
- A Process Module for hydrology, cost and benefit calculation and an optimization model for strategy generation.
- A Database Module for storing collected data that are used for different process module calculations.

The prototype, which is developed in Ms. Excel, was successfully tested for functionality and usability on a residential development site in Pittsburgh, PA. The prototype required minimal input from the user (site specific data) and generated strategies that double the net annual benefits compared to the plan proposed by the developer. The tool also allowed generation of strategy scenarios that responded to multiple user objectives.

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1 Motivation

Water is an essential resource for all living creatures; without it life would be impossible. Even though water covers over 70% of the earth's surface, less than 1% of it is available for human use. The demand on that available 1% is increasing (water consumption, across the globe, has tripled in the last 50 years) (EPA- Office of water 2008) and water management is becoming problematic. Even for the United States which has the largest freshwater reserve in the world, 25 of the 50 states were found to suffer from statewide or regional water shortages and 15 additional states have water shortages at the local level (GAO 2014). In addition, with continued increases in population (1 person every 13 seconds in the USA according to the Census Bureau), there will be increased pressure on existing natural water resources.

In addition to water availability and accessibility issues, the quality of water sources in the USA, is already in a dire state: currently only 28% of creek and river miles are considered to be in a good biological state and almost 1 in every 4 miles has bacteria levels that "exceed thresholds protective of human health"(US EPA 2016d).

The growth of the built environment results in a growth in demand for water and an increase in runoff volumes that are the main cause of deterioration of natural water quality (US EPA 2016d; Niemczynowicz 1999). In the USA, urban areas have been increasing at about double the rate of total population growth (Lubowski et al. 2006). At the same time, the existing stormwater and sewer infrastructure is aging and has inadequate capacity. Over 700 cities and towns are affected by Combined Sewer Overflows (CSO) that result in direct discharge of raw sewage into natural water bodies (ASCE 2013). In order to fix the existing storm and sewer infrastructure, an estimated nationwide capital investment of $271 Billion is needed (US EPA 2016a).

Moreover, the levees and dams built for flood mitigation are aging and require over $120 billion for repairs and rehabilitation (ASCE 2013), while the average annual damages from floods are estimated at $7.96 billion with 82 fatalities (NOAA's National Weather Service 2015).
The need to preserve and restore natural resources along with the condition and the limited capacity of the current grey infrastructure mandated a paradigm shift in stormwater management toward decentralization, storage and infiltration(Niemczynowicz 1999) that has led to the

development of Green Stormwater Infrastructure (GSI) practices that provide a cost effective solution (US EPA 2007c; Odefey et al. 2012). In addition, GSI can, at the same time, reduce flood risks, improve water quality and help in achieving a wide range of benefits like improving air quality, reducing energy demand and consumption, and improving public health (Stratus Consulting 2009; CNT 2011; European Environment Agency 2011;Field et al. 2006; US EPA 2013).

This paradigm shift in stormwater management had to be accompanied by a change in designing and planning methods for stormwater infrastructure toward adoption of holistic approaches that integrate the different interconnected systems in the planning process (Niemczynowicz 1999). Based on that notion, several organizations are advocating for the incorporation of Green Infrastructure (GI) in general in a comprehensive and/or strategic planning process that accounts for the multi-functionality of GI and to maximize its potential benefits (Amundsen, Allen, and Hoellen 2009; Benedict and McMahon 2006; European Environment Agency 2011; Ross & Associates Environmental Consulting 2012).

One of the primary drivers in the USA, so far, for different jurisdictions to undertake GSI planning is to meet discharge water quality standards and reduce Combined Sewer Overflow mandated by the Clear Water Act (Dunn 2010). Several towns, cities and counties have included GSI plans in Consent Decrees with EPA over breaches of the Clean Water Act (US EPA 2016b). However, the implementation of GSI as a replacement or support system for grey infrastructure faces some barriers preventing its adoption by planners/designers as well as decision makers. The dominant theme of these barriers pertains to uncertainty of the "outcomes, standards, techniques, and procedures" of GSI that will render "the risks of trying, adopting, or funding" it unacceptable (Clean Water America Alliance 2011).

While understanding and quantifying the full costs and benefits of GSI plans is critical for sound decision making to facilitate its adoption (European Environment Agency 2011; Barbosa, Fernandes, and David 2012; Wise et al. 2010a), planners/designers face challenges pertaining to hydrologic calculations(including sizing GSIE), cost estimation (capital and O&M) and benefit assessment (Backhaus, Dam, and Jensen 2012).

Clean Water America Alliance (2011) documented that one of the technical barriers to adopting GSI is the absence of access to tools that help “to design and choose green infrastructure alternatives, and quantify benefits”. Not a single one of the available GSI planning and designing tools and calculators documented in US EPA (2016c) provide a comprehensive set of capabilities that the user can refer to in order to achieve the following:

- Selecting and sizing alternatives
- Capital cost estimation
- Quantifying and/or monetizing GSI benefits

In addition, CNT (2011) underscores the need for development of existing tools to incorporate monetization of benefits and life cycle analysis capabilities.

This thesis responds to these challenges by presenting a prototype of a GSI planning tool that generates GSI strategies by selecting and sizing GSIEs while maximizing benefits and minimizing costs.

2 Research Overview

2-1 Hypothesis

This research is based on the hypothesis that a Green Stormwater Infrastructure (GSI) planning tool will fill the gaps in existing tools and generates strategies that will improve planning outcomes through:

- An Increase in the project's net benefit
- A decrease in the first cost (budget)
- Accounting for multi-functionality of GSI
- Adherence to hydrologic goals

2-2 Objectives

The main objective of this research is to present the outline, calculations method and test results of a GSI planning tool that will help Stakeholders and planners/designers in generating and assessing alternative solutions while developing GSI plans. This tool fills the gap in capabilities of existing tools and possesses the following capabilities:

- Perform accurate cost (capital and Life Cycle Costs (LCC)) estimation.
- Quantify and monetize the projected benefits of GSIE
- Generate strategies by selecting and sizing GSIEs while accomplishing the following:
    - Minimizing cost and maximizing benefits. (Maximize the annual net benefits)
    - Accounting for multi-functionality of GSI
- Risk assessment through sensitivity analysis.

2-3 Scope of Work

The scope of the research is

- To develop a tool prototype that encompasses the capabilities stated in the Objectives (previous) section and serve as a proof of concept with functions dedicated for a specific geographic region (the City of Pittsburgh, Pennsylvania).

- To test the tool for functionality and usability

- To make recommendations for further development, improvement and implementation of the tool.

2-4 Contributions

The main contribution of this research is the developed tool prototype and the provision of preliminary evidence (testing results) that it (the tool) improved the planning process by achieving the following:

- Generate alternative strategies that have lower first costs than the traditional planning outcome while achieving the planning objectives
- Automate the costs, benefits and hydrology calculations by providing algebraic formulations and integrating them in a tool that minimizes the user's inputs. These formulations also transform the collected costs and benefits data to be in function of the GSIEs functional unit. Such a formulation allows the replication of cost and benefit analysis for GSI plans at any time during the planning, design and implementation phases.
- Develop and test a mathematical programming model that advances the knowledge about applicability and solution of such models in the realm of planning and stormwater management.

In addition, this research provides a compilation of references quantifying and monetizing the different costs and benefits of GSI. While literature that provides similar information already exists (for descriptive purposes that does not account for overlapping of costs and benefits) the aim of this research is to develop a deterministic triple bottom line cost benefit model that eliminates double counting of cost/benefit values in order to be implemented in a decision support tool.

The existing decision support tools are unidimensional (are geared toward either cost/benefit estimation or hydrology simulation). Developing and testing a comprehensive tool that can provide assistance in plan development and alternatives assessment will help in increasing the knowledge about planning and decision making processes.

Furthermore, the tool quantifies and tracks different sustainability metrics and helps in meeting sustainability goals that facilitates the achievement of credits for sustainability standards such as Leadership in Energy and Environmental Design (LEED), Living Building Challenge and/or WELL Community Standards.

3 Background and Context

This chapter presents the background and context for the planning tool. After a review of the literature related to the scope and components of the tool, the hydrology objectives are set, different costs and benefits are defined and the plan for developing the tool is outlined.

3-1 GSI Definition

At the broad scale, Green Infrastructure (GI) is defined as an "interconnected network of green space that conserves natural systems and provides assorted benefits to human populations" (Benedict and McMahon 2006). In this thesis, Green Stormwater Infrastructure (GSI) is a subset of GI and refers to Wet Weather Green Infrastructure as defined by EPA as the "Infrastructure associated with stormwater management and low impact development that encompasses approaches and technologies to infiltrate, evapotranspire, capture, and reuse stormwater to maintain or restore natural hydrologies" (US EPA 2016g).

The approaches and technologies mentioned in the US EPA (2016f) definition are the structural Best Management Practices (BMPs) enumerated and described in PA DEP (2006) and Field et al. (2006). Table 1 provides a list of BMPs along with possible application variations (GSIE) and their intended hydrologic functions.

While a fully developed tool should incorporate sizing and cost calculation for all the structural BMPs listed above, the "proof of concept" version presented here takes into consideration only four BMPs: bio-retention, green roofs, porous pavement and cisterns. Collectively, the four considered BMPs possess the capability to perform all the possible hydrologic functions needed to be modeled at the early stages of planning. Hydrologic conveyance will not be modeled in the tool since, in the early stages of planning, the distribution of the BMPs around the study area, which is needed for conveyance, is unknown.

Structural BMPs	GSIE	Hydrologic Functions				
		Infiltration	Detention	Reuse	Conveyance	Evapotranspiration
Pervious Pavement	Alley, Parking, Walkway	●	●			
Swales	Grass, Bio.		●		●	●
Bioretention	With or without underdrain	●	●			●
Green Roofs	Intensive, Extensive		●			●
Infiltration Strategies	Wells, Trenches, Chambers, Basins	●				
Rainwater Harvesting	Rain Barrels, Cisterns			●		
Planter Box	Planter Box					●
Vegetated Filter Strip	Vegetated Filter Strip				●	●

Table 1: Structural BMPs hydrologic functionality

(Sources: PA DEP (2006) and Field et al. (2006))

3-2 Geographic region of applicability

Since hydrologic conditions and factors affecting costs and benefits change based on geographical location, it is necessary to select a region of applicability for the developed tool. The City of Pittsburgh, Pennsylvania is selected for the following reasons:

- The geographic location of Pittsburgh at the head of the Ohio River accentuates the impact of quality of discharge water from the city, since it might affect the downstream reaches of the river which is the drinking water source for over three million people. (Ohio River Foundation 2016)

- CSO is a serious problem in the city and the region in general. On average there are 11 CSO alerts per year in Allegheny County and average alert duration is 7 days (Allegheny County Health Department 2016). In addition to the added sedimentation and nutrient pollution, CSO's increase bacterial, metal and chemical contamination of the water that have a direct adverse impact on human and wildlife health and on recreation. Fulton, Buckwalter, and Zimmerman (2004) indicate that 63% of samples from the three rivers and their tributaries had fecal coliform concentrations higher than the Pennsylvania recreational water quality standards. And 98.6% of samples had fecal coliforms in them.

- Allegheny County Sanitary Authority (ALCOSAN), the provider of wastewater treatment services for the city of Pittsburgh, is under a consent decree to develop and implement a plan to achieve 100% reduction in CSOs. ALCOSAN adopted a Green First strategy where priority is given to solutions that stop and treat runoff at the source using Green Infrastructure practices (ALCOSAN 2016).

3-3 GSI Planning

3-3.1 Comprehensive Planning Definition

Comprehensive planning is the process of developing a comprehensive plan. According to Kelly and Becker (2000), in order for a plan to be considered comprehensive it has to fulfill the three following criteria:

- Geographical comprehensiveness: the plan must "include the entire jurisdiction of local government".
- "Comprehensiveness concerning subject matter" (adopts systems thinking)
- Long range planning horizon

In this report we refer to a comprehensive plan as the plan or section of a plan pertaining to storm water management using GSI and covering the entire jurisdiction of the local government. A comprehensive plan contains a compilation of GSI plans for each subdivision (planning unit defined in Section 3-3.4) of the local government jurisdiction. The GSI plan describes a specific GSI strategy (also referred to in short as strategy) along with its mechanisms of implementation, expected outcomes, timeline and monitoring metrics. The strategy consists of amounts, configurations and locations of GSIEs. At the early stages of planning the strategy is limited to the amounts of GSIEs needed to achieve the planning goals and objectives. The location and configuration of GSIEs will be determined and refined in later phases of the planning process.

3-3.1.1 Why comprehensive planning?

In Niemczynowicz (1999) the author argues that the growth of the built environment results in a growth in demand for water and an increase in runoff volumes that are the main cause of deterioration of natural water quality. The need to preserve natural resources along with the paradigm shift in water treatment toward decentralization and usage of GSI mandate that "the work of present urban hydrologists must be closely integrated with land use policy, city and landscape planning, development control, building construction, economy, legislation, education and social acceptance issues and local community involvement." In other words, water management should be part of a comprehensive planning process. In addition, the Planning Advisory Services (PAS) of the American Planning Association released a memo (Amundsen, Allen, and Hoellen 2009) acknowledging the need for incorporating Green Infrastructure (GI) in a comprehensive planning process. That memo relies on Benedict and McMahon (2006) that laid out the guiding principles of GI planning and design. These principles highlighted the fact that GI planning should take a holistic and multi-functional approach while keeping the planning process public and bolstering public participation. Similarly, the European Environment Agency adopted recommendations that fall along the same line of reasoning (European Environment Agency 2011).

Several towns, cities and metropolitan areas, like New York, Philadelphia, Chicago, Portland and Seattle, have already included GSI in their stormwater management plans (Wise et al. 2010a; Wise 2008).

3-3.1.2 The Comprehensive Planning Process

The planning process differs in response to the governing political system and the type of approach it takes. Planning can be initiated in two different ways. The first consists of a top down approach where decisions come from governing entities "benevolent despot" as described in Kelly and Becker (2000)) and planners follow to mobilize a general vision of that governing entity. The second consists of a grass roots approach where demands and planning interests start with the general public and make their way up in the command chain. In a democratic system, it is necessary to integrate different constituent groups in the planning process in order to improve chances of approval for implementation.

In the USA, the comprehensive planning process, adopted by the American Planning Association (APA) and described in Kelly and Becker (2000) and Branch (1985), lays down the basis and method of integrating different constituent groups, also referred to as stakeholders. The planning process consists of seven interconnected and complex tasks where every entity involved in the planning process has a specific role to play for a successful completion and implementation of the plan. These tasks are: Collect data, define planning base and objectives, develop alternative solutions, assess and evaluate alternatives, develop a draft plan, adopt the plan, and finally implement it and monitor the outcomes. The following section, based on the work of Kelly and Becker (2000) and Branch (1985), presents a description of each of the tasks along with the role of the planner in accomplishing them. The whole process is mapped in an Integration Definition for Process Modelling (IDEF0) diagram, Figure 1, from the point of view of the planner.

Collect data: this task consists mainly of collecting background data in order to portray the current conditions of the area subject to the planning process and to estimate future needs ("Where are we?"). The role of the planner here is to gather relevant data and determine what is useful for the process and what is not. This is a continuous task and has to be carried through most stages of the comprehensive planning process. The planner has to convert the collected data into meaningful information understandable by the general public. Then he/she must communicate it to the planning body, stakeholders and interested citizens. In addition the planner has to develop a list of stakeholders by researching and identifying entities that have potential interest in and or can be affected by the intended plan in order to incorporate them in the planning process.

Community and stakeholders meetings: For this task, the planner has to organize and conduct meetings, focus groups and design charrettes for community members and stakeholders. This task is critical for the success of the master plan since the Planner, through this process, collects information regarding the community needs, views, values and visions for their future. The collected information in these meetings will shape the final plan in order to get the acceptance and support of the community and stakeholders. In addition, the Planner has to convey the data collected to the stakeholders and he/she has to keep them up-to-date with all the developments in the planning process.

In order to succeed in this task the urban planner has to be skilled in presentation, communication, conducting debates, analyzing situations, design and problem solving. The planner has to register all information collected from this process, analyze and organize it in order to generate community preferences and recommendations that will form the basis for defining objectives, and generating a goal statement, and shaping the plan as a whole.

Define planning base and objectives: This task should be initiated simultaneously with the data collection task. The planner should start by determining the geographic and political boundaries for the plan as well as the time frame and budget dedicated for the planning process and for plan implementation. Then he/she should identify the issues that need to be addressed along with the possibilities that can be achieved (usually through preforming Strength, Weakness, Opportunities and Threats (SWOT) analysis).

The Planner has to communicate these possible outcomes to the community in order to develop and agree on a vision and a set of objectives for the community future.

Develop alternative solutions and strategies: In the previous task the Planner's role was to assist the community exploring "where can they go" and determining "where they want to go". This task consists mainly of exploring the different strategies to answer the "How?" question. Performing this task helps in developing and refining the definition of objectives.

Assess and evaluate alternatives: Assessing alternatives consists of weighing the projected benefits, drawbacks, risks and challenges presented by implementing these alternatives. The Planner can utilize existing tools and methods for economic, environmental, social and risk assessment in order to understand the consequences of implementing each strategy. In addition, he/she has to evaluate how well these alternatives help meet the goals and objectives and whether they align with the timeline and comply with existing laws and regulations. The outcome of this task will support the selection of the alternative that will form the basis of the final plan.

It is important to understand that the planner is not the decision maker and the developed plan has to gain the acceptance of the community and stakeholders in order to be mobilized to implementation.

Develop a draft comprehensive plan: This is where the decision onto which strategy to be implemented is made. After the selection process is concluded the planner has to develop mechanisms for implementing that strategy along with an implementation schedule and budgetary and funding plans.

Adopt a comprehensive plan: After getting the approval of stakeholders the planner has to finalize the plan and produce the necessary documents to be approved and adopted then mobilized to be implemented.

Implement and monitor: On a periodic basis the planner has to check if the plan is being implemented as designed, whether it is on schedule and check compliance with preset targets. The planner has to revise any shortcomings and reassess alternatives again if necessary.
In general, there is not a single technique that planners follow in conducting each of the tasks listed above. Some planners rely heavily on community meetings throughout the process, limiting their role to providing guidance and background information, while others adopt a more hands–on approach taking on more responsibility for developing the plan and limiting the role of the community and stakeholders meetings to communicating outcomes and to collecting feedback.

In either case there are two repeating task loops that the planning process has to go through:

- The first leads to developing and accepting strategies to be incorporated in the developed plan, and consists of repeating the following tasks: Community meetings, developing alternatives and assessing them until reaching an accepted strategy or set of strategies for implementation.

- The second consists of post plan implementation and outcome monitoring tasks that lead to revising and reassessing the strategies of the initial plan in order to do amendments and rectify its course. (Refer to Figure 1)

Developing alternative solutions and strategies and assessing them are the two tasks that are at the intersection of the two loops and get repeated if any of the loops is initiated. These two tasks are the subject of the presented tool that is intended to assist the planner in developing and assessing alternative solutions.

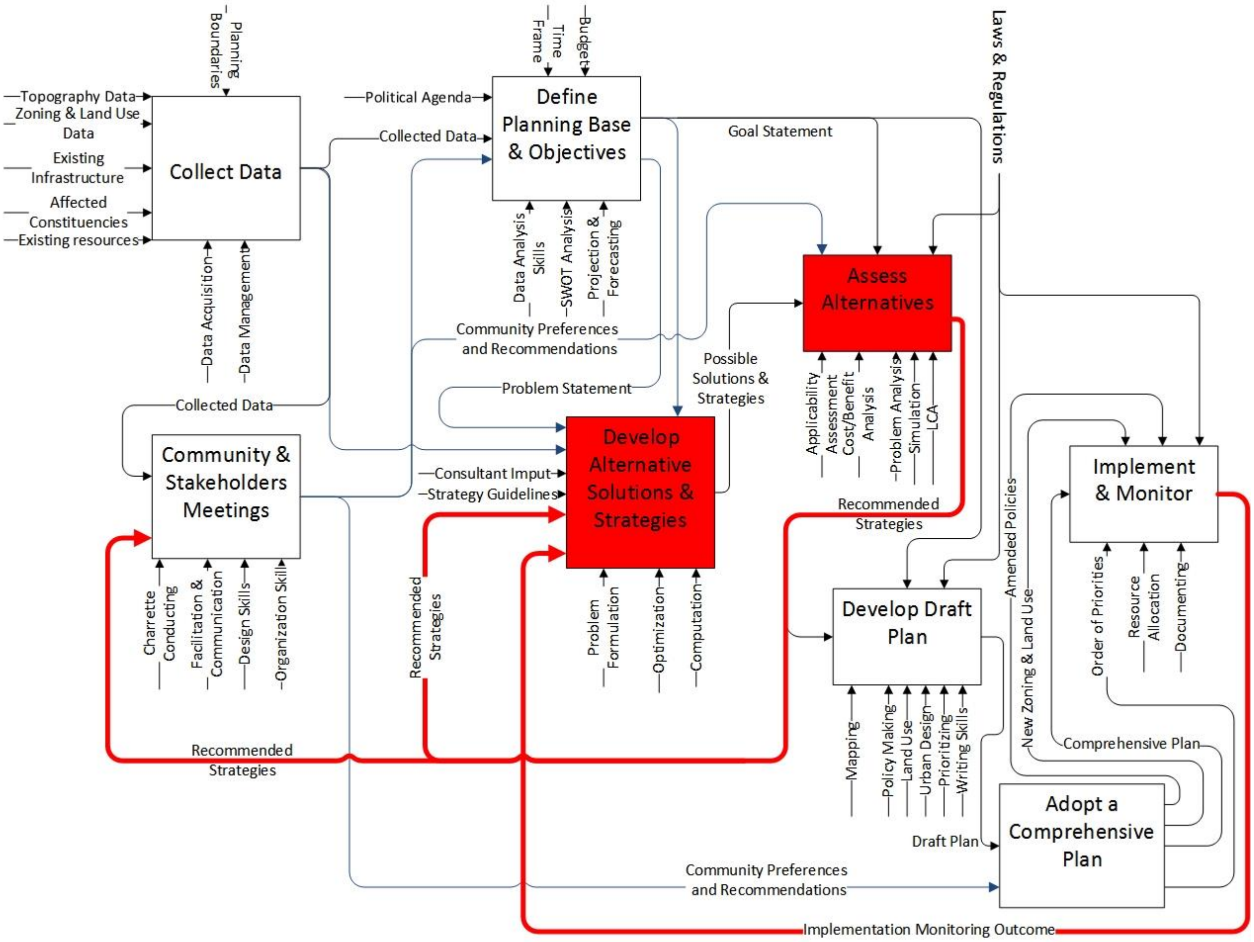


Figure 1: Comprehensive planning IDEF0 diagram

This shows that developing alternative solutions and strategies and assessing them are at the intersection of the two loops.

3-3.2 Variations of the planning process

3-3.2.1 Strategic Planning

Strategic planning, as described in Montana et al. (2000) and Mintzberg (1994), is a variation of comprehensive planning where the planner takes a strategic approach to the planning process. Strategic planning adopts a process similar to comprehensive planning. It describes the strategic method to approach the different planning tasks in addition to pitfalls to avoid. It advocates for leadership and public participation from the initiation phase and throughout the process. Visualizing the future is a critical task in Strategic planning and differs from and precedes the development of the objective statement.

3-3.2.2 Sustainable planning

The U.S. Environmental Protection Agency developed a guideline for water and stormwater sustainable planning dedicated to ensure that utilities' investments "are cost-effective over their life-cycle, resource efficient, and support other relevant community goals". (Ross & Associates Environmental Consulting 2012) The process described in this report aligns with the one described in the Comprehensive Planning Process Section (Section 3-3.1.2).

The Ecodistricts Protocol (EcoDistricts 2016) is a detailed method dedicated to developing a sustainable neighborhood/ district urban regeneration "roadmap" based on comprehensive and strategic planning processes. This protocol aims to address equity, resilience, and climate protection by achieving a set of community defined goals and objectives measured by sustainability performance indicators.

3-3.3 Decision making in planning

Most communities around the U.S. rely on planning commissions to develop comprehensive plans. These commissions depend on professional planners (in most cases) to assist in the process. However the decision to implement and release funds for implementation is held by the elected officials that require public support and approval. Based on this notion Kelly and Becker (2000) described the planning process as complex and troublesome for planners. Any planning effort has to “identify, understand, and utilize the governmental and non-governmental power structures”(Branch 1985). So even though the planning commission still holds the final decision of what strategies to be included in the final plan document, securing political support and public acceptance is critical for successful mobilization to implement the plan. Montana et al. (2000) describes the planning process as a balancing act between leadership, civic participation and expertise.

Mintzberg (1994) describes the roles that the Planner assimilates in strategic planning as:

- Strategy finder: where the planner has to “snoop around” to find these “fledgling strategies” that managers and decision makers do not know about.
- Analyst: where the Planner has to perform “quick and dirty” studies of the hard data to assess the outcomes of the proposed strategies.
- Catalyst: where the Planner does not enter the “black box of strategy making” but makes sure that everyone involved in the process “thinks about the future in creative ways”.

Based on these, the developed tool should allow the Planner to expand the search space for finding solutions and strategies. At the same time, the tool should have the capabilities of finding and testing different solution scenarios and generating estimates of their outcomes and impacts while fulfilling the planning objectives. All this should be done in a “quick and dirty” manner so the planner can communicate the findings with stakeholders, get their feedback, and refine the solution search criteria so the tool-generated strategy better fits the stakeholders’ needs and expectations.

3-3.4 Planning Unit

In the urban and regional planning domain, the neighborhood is considered as the planning unit of the city. This concept was first introduced by Clarence Perry in 1929 where “the urban neighborhood should be regarded both as a unit of the larger whole and as a distinct entity in itself.” (Perry 2013). He argues that neighborhoods have unifying characteristics of a social, economic and physical nature and spreads independently of political boundaries. The presented tool aims to assist the Planner in developing a comprehensive plan. This plan is governed mainly by community goals, objectives and preferences that are developed at the planning unit scale (the neighborhood). Thus, the neighborhood is a suitable scale for the application of the tool.

However, for water resources planning purposes it is logical to use the watershed or river basin as a planning unit since the hydrology goals and objectives are developed for watersheds and basins (Loucks et al. 2005).

The developed tool is designated to any planning activity and it allows flexibility to be used at different planning scales. It has the capability to generate strategies for sites, neighborhoods and watersheds.

In the City of Pittsburgh (area of study) neighborhoods and watersheds are defined and mapped in City of Pittsburgh Department of City Planning (2016).

3-4 GSI Performance objectives

In order to be able to design the different components of the GSI, it is necessary to determine their expected overall performance objectives. Clar, Barfield, and O'Connor (2004a) argue that these objectives can be a result of a Federal, state or local regulatory requirement, a runoff impact mitigation need, and/or other local needs. This publication identifies five objective categories:

- "flood and peak discharge control;
- specific pollutant guidelines;
- water quality control;
- multi-parameter controls, including groundwater recharge and channel protection;
- habitat protection and ecological sustainability strategies."

The hydrologic objectives (first three in the list) will be discussed in the following section taking the Pittsburgh area as an example. The ecological objectives are discussed in the GSI Benefits Section 3-7.

At the state level, the Pennsylvania Department of Environmental Protection (PA DEP 2006) sets three objectives to achieve while developing a BMP plan:

- Volume control guidelines: this consists of setting a stormwater runoff volume reduction goal for small storms (that generate the majority of annual runoff) with the aim of restoring the natural hydrology. This guideline defines small storms as any storm with runoff equal to or less than the 2year/ 24 hr. storm. Two options are provided to fulfill this objective. The first, Control Guideline 1 (CG1), consists of reducing post-development of small storm runoff to be equal or less than the 2year/24hr storm. For already developed areas, the pre-developed runoff is estimated assuming that 20% of impervious and all pervious areas are meadow. The second, Control Guideline 2 (CG2), is limited to instances where the regulated activities area is less than 1 acre, and requires the capture of the first two inches of precipitation.
- Peak rate control guideline: requires no increase in peak rate for 1 year through 100 year storms.
- Water Quality control guideline: consists of 85% reduction in Total Suspended Solids (TSS) and Total Phosphorus (TP) and 50% reduction in Nitrate-Nitrite loads (NOx) However, the NOx reduction is suggested to be achieved, not mandated.

At the regional level, the Allegheny County Sanitary Authority (ALCOSAN), the sanitary sewage treatment provider in Allegheny County, is under Consent Decree with the U.S. Environment Protection Agency, Pennsylvania Department of Environmental Protection, and Allegheny County Health Department to achieve compliance with the Clean Water Act. The Consent decree mandates ALCOSAN to develop and implement a plan that eliminates all Sanitary Sewer Overflows (SSO) and captures and treats all combined sewers (US EPA 2007a) that will entail creating more capacity for the storm water system for that purpose.

The Green First update to the original draft plan developed by ALCOSAN to meet the requirements of the consent decree, sets the consent decree goals as soft goals for the GSI plan to attempt to meet. In case the GSI plan falls short in meeting these goals, grey infrastructure will be implemented to fill in the gap (ALCOSAN 2016).

In addition to the Green First initiative to solve the CSO problem, Allegheny County's Act 167 County Wide Stormwater Management plan is an ongoing effort to develop a county wide plan and ordinance to be adopted by all Allegheny County municipalities. The second and latest draft of the plan aims to maximize the use of BMPs in managing stormwater and calls for adoption of the volume control and peak rate objectives of the PA DEP manual (Michael Baker International 2016).

Water quality is regulated at different levels of government. Section 303 of the Federal Water Pollution Control Act, also known as the Clean Water Act (CWA), mandates that states assign designated uses to their surface waters. Based on these uses, states have to decide whether these waters are impaired and develop water guidelines and Total Maximum Daily Loads (TMDL) accordingly (U.S. Senate Committee on Environment and Public Works 2002).

Chapter 93 of Title 25 of the Pennsylvania Code (Commonwealth of Pennsylvania 2013) lists five different categories of water designated uses (aquatic life, water supply, recreation and fish consumption, special protection and others like navigation). Each of these categories has a set of sub categories. This code also lists the water quality standards to be met for each of the sub categories. These standards include thresholds of physical characteristics (suspended solids, temperature, pH, dissolved Oxygen) and chemical (metals, nutrients) and microbiological (fecal coliforms, bacteria) contaminants. Based on that code the Pennsylvania Department of Environmental Protection developed TMDL plans for key watersheds within the state.

At the district/neighborhood level, different neighborhoods have developed sustainability plans that incorporate a set of goals and objectives to achieve. One of these neighborhoods is the Borough of Millvale that developed a set of objectives pertaining to different aspects of neighborhood sustainability like water quantity and quality, air quality, energy efficiency and food accessibility (Mondor et al. 2016). These objectives might differ from one neighborhood to another. Furthermore, not all neighborhoods/ districts have developed a comprehensive set of sustainability goals and objectives. Thus, the developed tool should allow flexibility in selecting objectives and their corresponding thresholds.

We can distinguish two types of objectives from the ones previously listed: the first consists of the objectives that must be achieved using GSI, like the hydrological objectives, and should be treated in the developed tool as hard constraints. The second consists of objectives that can be achieved through other existing strategies not pertaining to GSI, like energy efficiency and air quality objectives. These should be represented in the developed tool as soft constraints where it's not required to realize them in the GSI plan. However the tool should allow the user to test the implications of using GSI for partial or total achievement of these objectives.

For the proof of concept tool, Hydrologic objectives (volume control, peak rate and water quality) as defined in the (PA DEP 2006) are the minimum required objectives that must be met by generated strategies since they are adopted by different levels of governance, from state to local and through regional ordinances.

3-5 Hydrology calculation

As mentioned in the previous section, three hydrologic objectives must be achieved; volume control, peak rate and water quality. These objectives are set in relation to the pre-development hydrology of the studied area, so the developed tool will estimate the hydrologic characteristics for pre-development as well as post GSI implementation. This section presents an overview of the calculation methods used to estimate the study area hydrologic characteristics.

3-5.1 Volume Control

In order to determine whether the proposed GSI plan fulfills the required runoff volume reduction, it is necessary to estimate the pre-development as well as the post-development runoff volumes and then test if the proposed plan reduces the post development volume to pre-development levels. The test consists in estimating the runoff reduction of each GSIE and then assessing whether the total reduction restores the drainage area hydrology to pre-development levels. The runoff volume is estimated in general as the precipitation less the hydrologic abstractions; where these "abstractions include interception, surface storage, soil infiltration, and evapotranspiration"(Wurbs and James 2002).

For precipitation volumes estimation chapter 13 of Loucks et al. (2005) discusses two types of precipitation data that can be used: historical time series data and synthetic design storms. In the proposed tool, synthetic design storms will be used for meeting Control Guideline 1 (CG1) requirements (listed in section 3-4) since this guideline uses design storm runoff as a target to be met. However, in order to estimate average annual runoff abstraction by different GSIE (for different benefits estimation), historical time series will be used. The NOAA's National Weather Service (NOAA 2017) provides both types of precipitation data.

Runoff volume can be estimated using several calculation methods:

- Infiltration models: these types of models are designed mainly for pervious land cover where abstraction volume is estimated to be equal to soil infiltration volume. Examples of these models are : the Green and Ampt model (Green and Ampt 1911) that can be applied to watershed runoff estimation and the Holtan Model (Holtan, Stiltner, and Lopez 1975) that is designed mainly for agricultural watershed runoff calculations. Using these methods to model watershed runoff in an urban area (like the city of Pittsburgh) with significant amounts of impervious land cover would lead to inaccuracies in the estimation. However, the Green and Ampt model can be used to estimate the volume of abstraction by the BMPs that rely on infiltration like pervious pavement and bio-retention using the following formula (PA DEP 2006):

Equation 3-1: Infiltration volume as per PA DEP (2006)

$$\text{Infiltration Volume (Cu. Ft.)} =$$

$$\text{Bed Bottom area (sq. ft.) x infiltration design rate (in/hr) x infiltration period (hr) x } 1/12$$

Using the Green and Ampt model we can generate the infiltration design rate using the following formula:

Equation 3-2: Green & Ampt infiltration model

$$f_c = K\left(\frac{\Psi\Delta_\theta}{F} + 1\right)$$

Where:

f_c is the infiltration rate (in/hr)

K is the saturated Hydraulic conductivity (in/hr)

Ψ is hydraulic head (in)

Δ_θ is the change in moisture content of the soil (dimensionless)

F is the cumulative infiltration depth (in)

For meeting the CG1 requirement we assume that the infiltration rate is the minimum possible i.e. $f_c = K$.

Equation 3-1 will be adapted to a precipitation time series to estimate the annual runoff volume infiltrated as described in Chapter 8 of Wurbs and James (2002).

Soil types are described in USDA NRCS (2007b) and soil data like soil type, composition, and hydraulic conductivity can be obtained from the USDA soil survey web tool (USDA NRCS 2016).

Other soil parameters related to the Green and Ampt model can be obtained from (Rawls, Brakensiek, and Miller 1983)

- Curve Number (CN) method: CN is a dimensionless number between 0 and 100 that represents the hydrology of the watershed. It depends on the soil characteristics, land cover and moisture conditions of the soil. CN values per land use and the calculation method are described in USDA NRCS (2004) and USDA NRCS (1986). The CN method consist of the following formulae:

Equation 3-3: The Curve Number method formulae

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

$$S = \frac{1000}{CN} - 10$$

$$I_a = 0.2S$$

Where:

Q = runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (in)

I_a = initial abstraction (in)

The CN of the watershed can be calculated using a weighted (by area) average of the CN of each land use. However PA DEP (2006) does not allow usage of the unified watershed CN and requires runoff calculations for each separate land cover in order to ensure that the total runoff volume is not underestimated by assuming that each land cover area drains directly outside the watershed.

Similarly, in the developed tool, when estimating the runoff abstraction of each GSIE, we assume that the excess water overflowing from each GSIE will be considered runoff. This might not be true in reality where the overflow from one GSIE can be captured by another like a green roof overflowing into a bio-retention or an infiltration trench. This simplification of the hydrologic model is necessary due to the lack of hydrologic routing information at the planning stage where the planner's main task is to find out the amount of runoff that can be captured by a GSI strategy regardless of the spatial distribution of different GSIEs that will be developed later in the design phase.

3-5.2 Peak rate control

The main purpose of setting a peak rate control is to reduce flood risks and stream bank erosion. In order to ensure that this objective is reached, it is necessary to estimate pre and post-development peak flows for design storms with return periods of 2 to 100 years. The post development increase in peak flow must be offset by the implementation of the GSI plan. The Rational method is widely used to estimate peak flow in small urban watersheds with area less than 200 acres (ASCE and Water Environment Federation 1992; ASCE-Task Committee on Hydrology Handbook of Management Group D 1996). It does not require flow measurement and/or lag time estimation like Unit Hydrograph Methods (Wurbs and James 2002; USDA NRCS 2007a; Snyder 1938; Clark 1945). Such information might not be available at the planning stage.

Equation 3-4: Rational Method

$$Q_p = CiA$$

Where:

Q_p is the peak flow (Ft^3/s)

i is the rainfall intensity (in./hr.)

A is the watershed area (Acres)

C runoff coefficient ϵ [0; 1]

Assuming 1 acre-in./hr. $\approx$ 1 Ft^3/s

3-5.3 Water Quality

As previously mentioned (in Section 3-4) the PA DEP manual sets controls for three contaminants: Total Suspended Solids (TSS), Total Phosphorus (TP) and Nitrite and Nitrate (NOx). This manual describes in detail the method to be used to estimate the amount of each of these contaminants reduced by the GSI plan. It presents the typical concentration of these contaminants in runoff water for different land uses and the removal rate by each BMP. To extend the calculation to include some metal contaminants controlled by different GSIE, we can use the following data sources:

- (US EPA 1983) presents additional national runoff contaminant data (lead, zinc, and copper)

- BMP contaminant removal levels can be estimated using the method described in Strecker et al. (2001) and the statistical data can be obtained from Leisenring, Clary, and Hobson (2014).

3-6 Cost Estimation

3-6.1 Definition and Classification

By definition a Cost Estimate is "A compilation of all the probable costs of the elements of a project or effort included within an agreed upon scope." (AACE International 2016)

This definition underlines three main factors to take in consideration while developing a cost estimate:

1- "Probable costs": it is critical to keep in mind that the cost functions developed have a range of accuracy and a margin of uncertainty. Hackney (1965) describes cost estimation as a forecast of the future that can deviate from reality. The deviations from reality are caused by

- “Accidental Events during construction
- Changes in economic and other environmental conditions
- Variations in effectiveness of project performance
- Project deviation from estimate scope.”(Hackney 1965)

That deviation is not only due to the disjunction between the forecasted and actual future but also to faults in the estimation process caused by:

- “Level of non-familiar technology in the project.
- Complexity of the project.
- Quality of reference cost estimating data.
- Quality of assumptions used in preparing the estimate.
- Experience and skill level of the estimator.
- Estimating techniques employed.
- Time and level of effort budgeted to prepare the estimate.” (ASTM International 2011)

AACE International (2012) (also referenced by ASTM International (2011)) present a recommended practice to classify cost estimates based on maturity level of project definition. It suggests an engineering and construction industry specific range of accuracy in estimates for each of the five cost estimate classes. (Refer to Table 2)

Table 2 suggests that the more defined the project, the more accurate the estimate will be. Hendrickson and Au (2008) classify construction cost estimates based on their function (compared to the “End usage” column in Table 2). The authors distinguish three different uses of the estimates: estimates for design purposes, bid estimates and control estimates.

The design estimates, which are the main focus of this research, are broken down into four categories in Hendrickson and Au (2008):

- Screening estimates (or order of magnitude estimates)
- Preliminary estimates (or conceptual estimates)
- Detailed estimates
- Engineer's estimates based on plans and specifications

So, in order to determine how accurate the estimate can be we need to determine the end use of the estimate and level of maturity of the project definition at the time of preparing the estimate. This will lead us to discuss the next factor to take in consideration: the scope of the cost estimate.

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Functional area, or concept screening	SF or m^2 factoring, parametric models, judgment, or analogy	L: -20% to -30% H: +30% to +50%
Class 4	1% to 15%	or Schematic design or concept study	Parametric models, assembly driven models	L: -10% to -20% H: +20% to +30%
Class 3	10% to 40%	Design development, budget authorization, feasibility	Semi-detailed unit costs with assembly level line items	L: -5% to -15% H: +10% to +20%
Class 2	30% to 75%	Control or bid/tender, semi-detailed	Detailed unit cost with forced detailed take-off	L: -5% to -10% H: +5% to +15%
Class 1	65% to 100%	Check estimate or pre bid/tender, change order	Detailed unit cost with detailed take-off	L: -3% to -5% H: +3% to +10%

Table 2: Cost estimate classification and expected accuracy

Source: (AACE International 2012)

2- Agreed upon scope: Aaron (1997) defines the estimate scope in term of the questions it should answer; it "should answer the questions why? and how? about the project associated with the estimate". In order to determine the "why" we need to specify who will use this estimate and to what purpose. As stated in Section 2-1, this tool is intended to help designers and planners in developing and selecting a GSI strategy. So the tool should enable the user to generate cost estimates from early phases of the planning process.

   Using the classification method described in Table 2, the generated cost estimates by this tool should be class 5 or class 4. However, in the case of GSI planning, GSIEs are well defined with typical designs, component specifications and construction processes in PA DEP (2006) and other sources discussed in Section 3-6.2.1.4. Such information is specific to the design development phase, and, if taken in consideration early in the planning process, the cost estimate accuracy can reach class 3.

In order to determine the "how" it is necessary to examine and outline all the components of the GSI cost along with their estimation method(s). The following section will discuss the cost components of GSI and the methods used to estimate each one of them.

3-6.2 GSI Net Total Cost

While assessing the different alternative strategies in developing an urban plan, "the selected strategies, ideally, would be those likely to yield the largest attainable combination of net benefits, as compared with the costs of attaining them" (Lichfield 1960) with a similar notion adopted by (Hill 1968). Both Hill and Lichfield advocated for incorporation of all costs and benefits borne by individuals and society as a whole.

The Dublin Statement (ICWE 1992) stated that water has an economic value and water should be considered as an economic good (Principle 4) and "effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems"(Principle 1). Based on that notion Rogers and Bhatia (1998) defined the full cost of water from the supplier point of view and value of water to the user. The cost of water is defined as the sum of the full supply cost (capital charges plus O&M costs), opportunity cost and economic and environmental externalities. Similarly, we can apply that same cost definition for storm water management (instead of water supply) where the supply cost is replaced by the cost of the stormwater management strategy (or service cost).

In addition, Rogers and Bhatia (1998) quantifies the total value of water by adding the value of all the user benefits. Then, it defines the net user revenue from fresh water supply as the total value less the total cost. Following the same line of reasoning, the developed tool will quantify the Net Total Cost of GSI by subtracting the total benefit value from total cost

Equation 3-5: The Net Total Cost (NTC) of GSI

$$NTC = Service\ Cost + Opportunity\ Cost + \ External\ Costs - \ Value\ of\ Benefits$$

Each of the components of the NTC listed in Equation 3-5 will be defined and discussed in the following sections.

3-6.2.1 Service cost

The service cost refers to the full cost to supply the users with the required service throughout the planning period. In our case the service is stormwater control.

Hendrickson and Au (1989) outline the project life cycle phases of a constructed facility from the owner standpoint as follows:

- Market demands or perceived needs
- Conceptual planning and feasibility study
- Design and engineering
- Procurement and construction
- Startup for occupancy (acceptance of construction)
- Operation and maintenance
- Disposal of facility

Each of these phases is discussed below.

3-6.2.1.1 Market demands or perceived needs

This phase consists of establishing the need for additional infrastructure to manage excess runoff. The costs associated with this phase will not be included in the full supply cost estimation since it is achieved prior to the cost estimation process (sunk cost); including such costs in the overall estimate will not affect the decision toward strategy selection since they don't pertain to a specific strategy.

3-6.2.1.2 Conceptual planning and feasibility study and design and engineering

These two phases consist of the development of the GSI plan and the necessary implementation documents by a contracted engineering, planning and/or architecture firm (consultant). We will refer to the costs related to these two phases as development costs. These development costs consist of compensation for the contracted consultant firm based on agreement with the owner. Janda (1997) lists the commonly used agreement options between engineers and owners:

- “Cost reimbursable agreement:
  - All-in hourly or day rates
  - Hourly rates plus expenses
  - Actual salary with fixed or multiplier for overhead, expenses and/or profit
- Fixed price agreements
  - Lump sum bid
  - Percentage of construction costs
  - Unit price pre deliverables (drawings, specs, reports…)”

Regardless of the type of agreement, the overall charged cost should cover all the consultant firm expenses that consist of: payroll burdens and benefits, office expenses, overhead costs and fees or markup.

Janda (1997) lists four different methods to estimate the development costs:

- Historic relationships: based on a percentage of the overall cost. GORDIAN-RSMeans (2017) shows that the architectural fees for a construction project range between 4.9 and 16% of the total construction cost while the engineering fees range between 2.5 and 6%.
- Statistical correlation (e.g. correlation between cost and number of deliverables)
- Level of effort (linking skills required for tasks to work-hours needed)
- Detailed estimate based on tasks accomplished and deliverables.

The three latter methods are hard to implement since the project components are not well defined at the planning phase; the amounts of GSIEs are yet to be determined. The best estimate at that time is the order of magnitude estimate provided in the first method. This estimation method is best suited for a rough estimation of the whole design cost. It falls short in portraying the actual cost of the design of each of the GSIEs since the construction cost for each of the GSIEs and design level of effort might be disproportionate.

The developed tool allows the user to overwrite the order of magnitude estimate if a more accurate one is acquired.

3-6.2.1.3 Procurement and construction

This phase consists of implementing the developed plans and carrying out all the activities needed to build the planned infrastructure. The costs related to this phase are referred to in this document as production costs. As a general case, Mudge (1989) refers to the purchase price (at the user end) as first cost that includes prime costs, overhead costs, general administrative costs, selling costs and profit. In a construction project, AIA (2013) divides the production cost into three categories: site costs, hard costs and soft costs.

Site costs include:

- Land cost: in the case of public space there is no cost to acquire the land since it will be used for a public project. However, there is an opportunity cost/benefit to use this land for other than GSI that should be taken in consideration and will be discussed later in Section 3-6.2.2.

- Demolition and site work: this consists of costs to ready the land for construction (clearing vegetation cover, structure demolition). These costs are site specific and undetermined at the early planning stages. In the developed tool they will be considered as nonexistent (as a default setting) with the option to be modified by the user.

- Surveys: PA DEP (2006) shows that the only survey needed for all infiltration BMPs is a soil survey and testing. The costs of carrying out this type of survey do not pertain to any specific GSIE and does not affect the GSIE selection process. Other surveys fall under the construction costs as construction overhead.

Soft costs are the development costs previously discussed.

Hard costs consist of the sum of construction, furniture, fixtures, equipment, specialized mechanical and electrical costs (AIA 2013). Since GSIEs do not require any specialized mechanical services and FF&E, the hard costs for GSI consist mainly of construction costs.

3-6.2.1.4 Construction Cost

Construction costs consist of the sum of material costs, installation costs and overhead costs (AIA 2013).

- Material costs: several databases track construction material costs like ENR that issues quarterly costs reports along with location and temporal indices.
- The installation cost consists of labor and equipment costs. This cost is affected by three main factors:
  - Crew composition and equipment needed: the type of workers needed in a crew is mandated by the construction process to be accomplished and type of equipment needed.
  - Crew size: The size is affected by the speed the construction needs to be achieved.
  - The crew productivity.
- The overhead costs, also called contractor markups, consist of all the costs that might occur in a construction project that are not covered in material and installation costs. Neil (1982b) presents a comprehensive list of these costs that can fall into four sub categories:
  - Salaries and wages
  - Temporary structures and infrastructure
  - Support systems and equipment
  - Other general expenses (office supplies, taxes, insurances, contingencies…)

As discussed earlier, in planning stages, when detailed designs are not yet developed, the most accurate estimate that can be generated is an order of magnitude estimate (Class 5 estimate). However, this type of estimate, if applied to GSI, does not account for variations in design in each BMP and might misrepresent the actual construction costs due to its low accuracy.

In the case of GSI, several manuals are available that present typical designs of different BMPs, design variations and considerations, construction sequences and specifications. Using this information to improve the project definition will help in generating a more detailed breakdown of the construction cost and lead to a more accurate cost estimate. These manuals can be characterized under two general categories. The first consists of comprehensive manuals that encompass a wide range of BMPs. Some address stormwater issues from a general stand point; they present different BMP sizing methods and discuss their applicability to different problem settings and hydrological environments e.g. (Clar, Barfield, and O'Connor 2004a; Field et al. 2006). Others are developed by different states to serve as a guideline for BMP design and implementation, e.g. Pennsylvania (PA DEP 2006), West Virginia (W.V. Department of Environmental Protection 2016) and New York State (NYS Dept. of Environmental Conservation 2015). In most cases these guidelines are not mandatory. These guidelines present a typical design for each BMP along with possible variations, specifications, construction sequencing and maintenance requirements.

The second category consists of single BMP references where each presents a more elaborate and detailed approach to designing and constructing different components of a single BMP. Some of these references are: FLL (2002), Cantor (2008), Ferguson (2005), Clar, Barfield, and O'Connor (2004b), Clar, Barfield, and O'Connor (2004c).
The way these references will be used in this research project will be discussed in the following section.

The cost estimation method used in the developed tool is the detailed unit cost method described in Westney (1997) and Neil (1982a). This method consists of the following steps:

- Develop a Work Breakdown Structure (WBS) for each GSIE based on data collected reviewing and analyzing the design considerations and construction sequence sections in national and/or state manuals.

For example: Based on the Pennsylvania BMP manual, the excavated bottom of a permeable pavement should be levelled then covered with a geotextile membrane. This means that after excavating, a rough grading is necessary. In the case where the bedrock level is higher than the excavated area level, some drilling and blasting will be required. Figure 2 shows the WBS of the permeable pavement excavation activity. The bottom line of the WBS, which consists of construction processes, can be broken down into more detail (by worker/equipment specific tasks). However that level of detail is not necessary for the purpose of the developed tool since it is usually used by contractors to model and track the productivity of the crew.

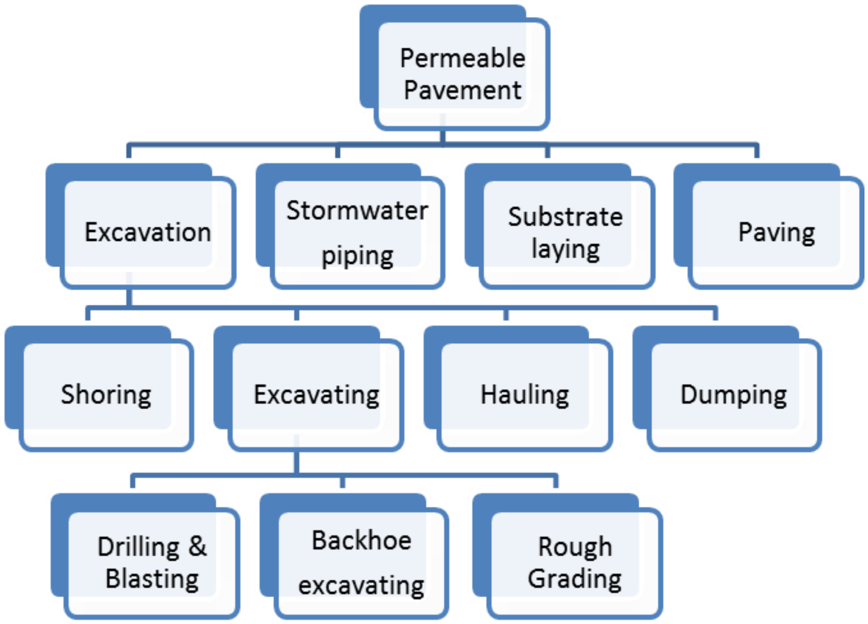


Figure 2: Permeable pavement excavation activity Work Breakdown Structure (WBS)

- Estimate amounts of each construction process. In order to accomplish this task, it is necessary to have a dimensioned typical design of each GSIE along with possible variations in component sizes of these GSIE. This requires collection of data from different sources: guideline manuals, specific BMP design references and other references.

- Estimate the cost of each construction process: a construction cost estimating database will be used to determine the unit costs of construction processes. However, that unit cost is contingent on the composition of the crew, equipment used and their productivity. RS Means provides a list of crew/equipment combinations for each construction process along with estimated productivity and cost. Selecting the crew/equipment combination is based on different factors like site accessibility, availability of equipment for contractor or even contractor preferences and experience. To overcome that variability in crew/equipment selection, the most probable and/or average crew size will be selected and the possible variability in cost will be registered for the user to take in consideration and test in the sensitivity analysis module.

As an example, excavation crews are selected based on equipment used for excavation: manual, dozer or excavator types of excavations. For alley construction, we can rule out the manual and dozer options since, usually, alleys consist of small excavation projects for dozers but not small enough for manual excavation. An average size excavator will be selected for calculation and the maximum and minimum unit cost will be documented.

- Summation of all construction processes costs factoring in overhead and profit (accounted for in the RS Means cost data)

3-6.2.1.5 Startup for occupancy

This phase consists of inspections and commissioning by the owner in order to determine whether the built infrastructure meets design specifications. The costs accrued in this phase pertain to all GSIE and do not affect the decision in selecting a strategy to be implemented in the GSI plan.

3-6.2.1.6 Operation and maintenance

This consists of recurring maintenance activities and repairs. The expected recurring maintenance activities are listed in the PA DEP (2006)manual for each BMP. Their costs can be estimated using the same method for construction cost estimation. Repair activities vary depending on several factors: how well the GSIE is built, how it is used and how well it is maintained. The developed tool will assume that the GSI are in adequate shape and well maintained. The costs of repairs are assumed to occur periodically (every year). These costs cover the described repairs in the PA DEP (2006)manual based on a set percentage of the whole amount of GSIE installed.

3-6.2.2 Opportunity cost

Opportunity cost is defined as “the earnings which will be foregone from other investment opportunities if the capital is to be committed to a project in question”(Hendrickson and

Matthews 2011). Comparing GSI to the "business as usual" option (i.e. grey infrastructure) we find that the capital that will be foregone and/or gained falls into three main categories:

- Land cost: to manage the same volume of runoff water, GSI might require more land area than grey infrastructure. However, in the case of GSI, it is necessary to examine the previous usage of the land in order to determine whether land value is lost or gained by implementing GSI. For example, if permeable pavement is implemented in place of regular pavement and fulfills the same function, this GSI, in most cases, will not require additional land. Following the same logic, green roofs, in some cases, can turn unused/inaccessible space into a recreational space with added value.

- Cost of similar function structure: this pertains mainly to permeable pavement and green roofs where a similar, traditional installation is required even if the GSI is not implemented. In that case, the cost of the traditional installation should be deducted from the GSI cost.
  (Similarly for bio-retention and bio-swales if landscaping work is needed)

- Stormwater treatment and mitigation costs: in the instance where grey infrastructure is not considered as an alternative solution, the life cycle cost and impact of grey infrastructure should be taken in consideration.

Most literature treats the opportunity costs for GSI as benefits since in most cases they are negative costs and add value to the water management plan.

3-6.2.3 External Costs

In addition to the costs discussed in Section 3-6.2.1 and 3-6.2.2, it is necessary to include external costs while estimating total cost especially for public sector projects (Hendrickson and Matthews 2011). The external costs are defined as "costs that are not included in traditional engineering estimates of the expense to build and operate facilities"(Stratus Consulting 2009). External costs consist of costs imposed on the public, especially the non-users, due to negative impacts of the GSIE along their life cycle. Air emissions, noise generation, road closure/disturbance, and solid waste generation are examples of potential externalities that should be quantified and monetized to be included in the total cost.

There is a wide range of impacts to be assessed. US EPA (2007b) lists eleven of the most common life cycle impact categories. Estimating the cost of all of them is an onerous task. For the proof of concept tool two impacts will be selected: air quality (impact extent is regional) and global warming (Greenhouse Gases with global impact).

3-7 GSI Benefits

Alteration of the natural ground cover by increasing the amount of impervious surfaces, clearing vegetation and/or grading and compacting topsoil will reduce ground water recharge and increase runoff volume and velocity that leads to increased flood risks. In addition, prolonged and more frequent high flows will impact the geomorphology and stream channel stability (increase in stream bank and channel erosion, stream widening and increase in channel cross section area, decline in stream substrate quality due to sedimentation, loss of pool and riffle structure in stream channel and degradation of stream habitat structure).

In addition, urban runoff reaches natural water bodies charged with all sorts of contaminants collected from impervious surfaces (suspended solids, nutrients, metals and bacterial contaminants). Furthermore, the temperature of runoff water from impervious surfaces and /or ones with cleared vegetative cover is higher (in warm seasons) than the temperature of natural land runoff. That increase in temperature will transfer to receiving waters, potentially impairing the habitat of existing biological creatures. (Erickson, Weiss, and Gulliver 2013; Leopold 1968; Clar, Barfield, and O'Connor 2004a; Center for Watershed Protection 2003; Toronto and Region Conservation Authority and CVC 2011)

Different GSIEs can mitigate the impact of change in ground cover by detaining (for ground infiltration or reuse) and/or retaining runoff water. PA DEP (2006) describes the method to quantify the volume of water retained, runoff peak rate reduced, and amounts of Suspended Solids, Nitrate and phosphate reduced. (Refer to Section 3-5).

The benefit generating components of GSI along with their impact on the economy, environment and society are listed in Table 3.

	Benefit Components	Impact	Economic	Environmental	Social
Hydrology	Increase Infrastructure Capacity Treatment of runoff water Reduce CSO	Improve water quality: Nutrien Sediments & TSS Dissolved solids Bacterial Other Toxins	Averted cost of treatment (WTP)	Avoided Air Contaminants emissions	Public Health
			Averted cost of Infrastructure	Avoided CO2 Emissions	
			tourrism opportunity		
			Increased property value	Aquatic biodiversity preservation	
	Runoff water reduced Infiltration Water Storage Detention		Dredging cost	Aquatic Habitat impairement	
		increase ground recharge	value of ground water		
		fresh water availability	Value of water supplied		
		Reduce flood risks	Averted damage value		Avoided Life losses
			Increased Property value		Population Displacement
Trees And Green space	Provide Shading	Reduce aquatic thermal impacts		Aquatic biodiversity preservation	
		Reduce Energy demand	Averted energy cost	Avoided Air Contaminants emissions	Public health
	Wind Break			Avoided CO2 Emissions	Beautification
	Increase insulation				Public safety
	Foliage & Natural processes	Carbon sequestration		Reduced atmospheric CO2	
		Air purification		Reduced air contaminants	
		Noise Reduction			Personal Comfort
		Reduce runoff Water	Averted cost of treatment (WTP)	Avoided Air Contaminants emissions	
			Averted cost of Infrastructure	Avoided CO2 Emissions	
		Preserve natural habitat		Biodiversity Preservation	
	Green Space Accessibility				Recreation Opportunity
Investment	Economic multiplier	Employment opportunities	Wages/jobs generated		Poverty/ Unemplyment reduced
			Increased Tax revenues		

Table 3: GSI Economic, Environmental and Social Benefits.

3-7.1 Quantifying and Monetizing Benefits

Table 3 shows that, in addition to runoff water savings, GSIEs can produce a wide range of benefits that affects the economy, environment, and the social wellbeing and health of residents. Several articles and reports are available that present methods and data to quantify and monetize the benefits of GSI. They generally fall into three categories:

1. A generalized comprehensive listing of benefits with a compilation of methods to quantify them:
   CNT (2011) examines and enumerates the benefits of five Green Infrastructure practices: Green roofs, tree planting, bioretention, permeable pavement and water harvesting. This report distinguishes eight benefit categories for the different BMPs. It captures and explains the extent of the triple bottom line benefits of GSI and presents quantification and monetization methods for some of the tangible economic and environmental benefits as shown in Table 4. For the unquantified benefit metrics, this report lists Willingness To Pay (WTP) methods described in other sources to estimate its monetary value.

2- A comprehensive, case specific benefit valuation: where each article aims to value the benefits pertaining to a specific region, project and/or GSIE.

   - Stratus Consulting (2009): prepared a report for the City of Philadelphia Water Department to evaluate the different approaches to solve the combined sewage overflow problem in the city. A triple bottom line assessment based on cost benefit analysis is developed to estimate the net benefit of the proposed solutions. These solutions consist of a set of grey infrastructure approaches and a set of green infrastructure approaches. The net benefit is calculated for all different solution sets, but, the report focuses on one grey infrastructure solution (30' wide pipe) and 1 green infrastructure solution (50% of impervious surfaces runoff treatment). The costs and benefits are calculated over a 40 year study period. Benefit categories monetized and included in cost benefit analysis:

     - Recreation: Visitation data obtained from Philadelphia Parks Alliance then number of visits per acre of park land is calculated. Recreational uses (running, playground, pet-walking…) obtained from same source. Finally willingness to pay for each activity is estimated to calculate the Unit Day Value for each activity.

        - Property Value: literature review provided a range of percent increase of property value of GI adjacent property (0% to 7% study used 3.5 as a mean and a range of 2% to 5%). Median property selling price is used as base property value.
        - Heat stress reduction: literature review to estimate the average temperature reduction (including humidity factor) then calculate the daily heat-attributable mortality to get the number of lives saved over 40 years. The value of saved life is estimated as $7M (EPA)
        - Water Quality and Aquatic Ecosystem Improvements: use benefits transfer to estimate average willingness to pay per household. Wetland Creation and Enhancement
        - Poverty Reduction from Local Green Jobs
        - Energy Savings and Carbon Footprint Reduction
        - Air Quality Improvement
        - Construction- and Maintenance-Related Disruption

    - Vandermeulen et al. (2011): This article presents an economic valuation of the green cycle belt of Bruges (Belgium) as a proposed green infrastructure project. The aim of this study is to make policy makers aware of the benefits of incorporating green functions in development and planning processes and to demonstrate the added value of green space at the regional level.
      The economic valuation occurs on two levels:
        - Project level-Direct benefits: Cost benefit analysis is used to estimate the direct benefit value.
        - Regional economy level (indirect value): use Multiplier Analysis (MA) that can be achieved by completing an Economic Input/Output analysis and economic multiplier effect of wages earned by industry workers. This consists of the regional economic impact of the initial project cost and the maintenance labor wages.

The externalities are quantified and monetized mainly using the WTP concept for the following impacts:

- Regional excess burden: “is an indirect cost caused by an increase in taxes, needed to execute the investment project”
- Regional costs of land use change
- Avoiding costs by not-commuting by car
- Health effects from cycling
- Environmental effects: improved air quality and reduced emissions
- Improved traffic safety

- US EPA (2014): this report uses the methods described in CNT (2011) to estimate the monetary value of benefits for the comprehensive GSI plan for the City of Lancaster, PA. The benefits considered here are the ones with described quantification methods pertaining to the impacts on water, energy, air quality and climate change.

- Blackhurst, Hendrickson, and Matthews (2010): This paper presents a life cycle assessment of green roofs in a typical mixed use neighborhood setting. Three phases were considered in studying this GSI Strategy:
  - Material production
  - Construction phase
  - And operation

An LCIA was performed to quantify the amount of energy used and GHG emitted during the material production and construction phases. The LCIA is performed using the EIO-LCA tool (CMU Green Design Institute 2008) by imputing the cost of each construction activity and material necessary to erect the green roof. While the impact from the operation phase (whether water reduction or energy and GHG emissions) were estimated using simple calculation relying on data gathered from existing literature

Benefit Category	Benefit metrics	Quantified	Monetized
Water	Reduce treatment need	✓	✓
	Reduce grey infrastructure need	✓	✓
	Improve water quality		
	Reduce flooding		
	Increase available water supply		
	Increase water recharge		
	Reduce salt used		
Energy	Increased Insulation	✓	✓
	Reduced heat island effect	✓	✓
	Reduced for water treatment need	✓	✓
Air quality (NO2, SO2, PM10, O3)	Tree/Plant uptake	✓	✓
	Avoided - Heating/Cooling	✓	✓
	Avoided - Water treatment	✓	✓
Climate change	CO2 Sequestrated	✓	✓
	CO2 Avoided - Heating/Cooling	✓	✓
Urban Heat Island			
Community Livability	Aesthetics		
	Recreation		
	Noise pollution reduction		
	Community Cohesion		
Habitat Improvement			
Public Education			

Table 4: Summary of GI benefits examined in CNT (2011)

3- Several papers present a dissection of a component or an impact of GSI. For example, McPherson et al. (2007) presents an assessment of the value of a tree in an urban area. EPA (2015) and Dodds et al. (2009) present the effects of nutrient pollution along with the costs associated with them. Ribaudo (1986) estimates the marginal costs of increased sedimentation. Foster et al. (2011) presents a description along with some valuation estimates of the benefits of green infrastructure for climate change resiliency.

A listing of reviewed literature pertaining to quantifying and monetizing GSI benefits is presented in Table 25 (in Appendix A-1). In addition, that table shows which benefit categories and impacts each reference is quantifying and/or monetizing along with the geographical applicability. The articles cited in Table 25 were selected based on the following criteria:

- Peer reviewed articles that present a well-defined method to quantify and/or monetize one or more of the benefits listed in Table 3.

- First Literature describing generalized methods applicable to different geographic areas (in the US)

- If generalized methods were not found, two case specific papers describing the same method were selected.

3-7.2 Benefits summary

Implementing GSI plans can generate a wide range of benefits to users and community in general. These benefits come from the following factors:

- The GSI investment economic multiplier
- GSI capability to retain, detain and/or deviate runoff from natural water bodies.
- Incorporation of trees and shrubs in several GSIE
- Increasing area and/or improving quality and accessibility of green spaces

The GSI benefits can be economic, environmental and social (as shown in Table 3). The economic and most of the environmental benefits are well defined and can be quantified and monetized using existing methods from the literature (refer to Table 25). Quantifying the Downstream benefits, such as reducing flood risks, channel erosion and sedimentation, is difficult to quantify. The Willingness to Pay (WTP) method is used to obtain a monetized value for that type of benefit. This method consists of using property value increases as a surrogate for downstream benefits.

Furthermore, social benefits are addressed in case specific papers, since the social impacts vary depending on the specific layout of the plan and the surrounding conditions.
Each one of the GSIE has the potential to generate different combination of types and amounts of benefits. Table 26 (in Appendix A-1) lists the type of benefits that can be generated by each GSIE.

CNT (2011) presents the most complete method to quantify and monetize the GSIE benefits. However, it does not account for benefits along the life cycle of the GSIE and for the economic implication of the investment.

3-8 GSI Mathematical Models

A model is defined as: "an abstract description of the real world giving an approximate representation of more complex functions of physical systems" (Papalambros and Wilde 2000). This definition emphasizes the fact that a model is a simplified representation of reality and the second is that there could be different models representing the same reality. To select the right model Loucks et al. (2005) suggest the following:

- Define the problem and determine the question to be answered
- Use the simplest method that yields adequate accuracy while answering the question
- Evaluate whether increased accuracy is worth the effort/cost.

There are two categories of models used in engineering; physical and symbolic models (Papalambros and Wilde 2000). This section (and the research in general) is geared toward symbolic mathematical models.

Radford and Gero (1988) argue that the three tasks needed to design are: identify objectives, make decisions and describe/evaluate results. Models can be developed to accomplish any one or combination of these tasks. Based on that, the authors identify three types of models:

- Simulation models: that can achieve descriptive tasks (predict performance and/or consequence of a design), where decisions and objectives identification is done externally.
- Generation models: Those generate a "field" of solutions based on a set of rules. Some decision making and evaluation capabilities are built into those models, but, they are not "purposeful" and all generated solutions cannot be ranked internally based on the final design objective. The authors present the example of an artificial light design where a model is used to generate possible solutions (number and distribution of light fixtures) to have a specific luminosity at the working plane. All solutions that achieve the luminosity criterion are equally acceptable.
- Optimization models: they are used to generate solutions as close as possible to the identified objectives, based on a set of performance rules.

Planning for GSI is no different than any design endeavor; planners utilize different types of models to best represent the problem at hand, evaluate solutions and make decisions based on predetermined objectives. We discussed earlier (in Section 3-5) the different methods to model the impact of GSI on surface water runoff. In addition, the cost estimation and the benefit sections present existing methods to model (or simulate) the impact of GSI on the economic, environmental and social systems.

Beyond simulation models, Claro et al. (2013) describe a model developed and used to rank the different New York City neighborhoods from those benefiting from the most implementation of GSI to those receiving the least GSI benefits. This optimization model utilizes normalized metrics of eight benefit types (storm water management, air quality improvement, urban heat island reduction, energy reduction, community factors and demographic vulnerability indicators) to generate the neighborhood(s) most in need for implementing GSI plans.

Shamsi, Schombert, and Lennon (2014) implemented the optimization module of SUSTAIN (discussed in Section 3-10) to generate potential sites for different BMPs in four sewer sheds in Allegheny County, PA. In addition, the cost estimation module of the same tool is used to generate the cost effectiveness of implementing each of the BMPs.

3-8.1 Water Resource Planning Models

None of the models discussed earlier in this section, dedicated to GSI planning and design, have the capability to generate solution(s) that meet the planning objectives. However, in the water resource planning domain, decision support models (optimization and multi-criteria programming) are widely used and well documented. Dorfman (1965) paved the way for the development of models applicable to practical water resources design problems by making the case for using analytical modelling in tandem with simulation models. The result is described as an optimization problem that minimizes costs or maximizes net benefits subject to design, water supply and policy constraints. The model presented in Dorfman (1965) relies on a single decision objective while in reality decision making is more complicated than that. Hence the need for multi-objective models that were described and tested in Major and Lenton (1979), Cohon and Marks (1973), Cohon et al. (1979), Loucks et al. (2005), Wurbs and James (2002) and others.

Loucks et al. (2005) presents a compilation of optimization and multi-criteria programming models pertaining to water resources planning and management. These models address the following problems:

- Water supply plan selection (using multi-criteria programming) based on economic, environmental, ecological and social criteria.
- Water allocation (water supply management) using Dynamic (Network) programming
- Reservoir design (capacity and yield) using linear programming
- Reservoir operation using Dynamic (Network) programming
- Water quality management using linear programming
- Ground water supply using linear programming

3-8.2 Description of GSI optimization model

This section provides an outline that guided the development of the optimization model discussed in Section 4-8. This outline is based on the literature review discussed in the previous sections of this chapter.

Objective function: Similar to the model described in Dorfman (1965) (that Maximizes the discounted benefits) the simplified objective function will be to minimize the net total costs calculated using Equation 3-5. The service costs, opportunity costs, externalities and benefits are represented in this formulation by their economic values (in Dollars).

Constraints: The constraints include design and performance requirements of each of the BMPs, Hydrologic targets and policies and regulations (listed in Section 3-4 as hard objectives).

Variables: The variables in this model pertain to the sizing of each of the GSIE (example: for the permeable pavement the variables should be length, width, retention and detention depth)

3-8.3 Multi-objective model necessity

The single objective optimization formulation, described in the previous section, utilizes Cost Benefit Analysis (CBA) to describe the impacts of a proposed urban strategy. This method, while valuable for facilitating the comparison and evaluation of different strategies, presents some limitations in capturing the full impact of the strategies in consideration. Lichfield (1960) underlines the limitation of this method in representing the non-economic impacts, since the market value of these impacts, if it exists, can be unreliable. Hill (1968) argues that even with full accounting of all costs and benefits, “a criterion of maximizing net benefits in the abstract is meaningless” if costs and benefits are not related to specific well defined objectives. That is due to the fact that costs and benefits cannot be compared unless related to the same objective since different communities value objectives differently. So, according to the author, in the case where an objective has little or no value to the community, the related costs and benefits are irrelevant when evaluating strategies for that community.

Based on these two arguments (the single objective formulation: 1- does not capture the full impact of a strategy, 2- does not account for the community valuation for different objectives) it is necessary to use a different approach to generate and evaluate GSI strategies that accounts for their full value to the community and stakeholders.
Multi-Criteria Decision Making (MCDM) provides an alternative formulation to the objective function that consist of replacing the monetized costs and benefit formulation with a vector of

objective functions each pertaining to a different decision criterion. Each decision criterion is quantified and represented by an objective function (refer to Equation 3-6).

Equation 3-6: General MCDM Formulation

$$Max\ Z_M = Max\ [\mathrm{Z}_1;\ \mathrm{Z}_2\ ;\ \mathrm{Z}_3; \ldots \mathrm{Z}_j]$$

Where:

Z_M is the objective function

Z_j is the decision criterion j

The multiple criteria problems do not have an "optimal" solution; rather, solving this problem entails generating the set of non-dominated (Pareto optimal) solutions. The Planner can then select the alternative from that set based on the community and stakeholders preferences for the objectives. (Huang, Keisler, and Linkov 2011; Papalambros and Wilde 2000)

In the case of GSI, as discussed in Section 3-7.1, there are three benefit generating components: hydrology (volume of water retained and detained), trees and green space (area of green space added) and investment (economic multiplier). Each one of these benefit components will be a decision criterion to be quantified and represented in the objective function and maximized. The objective function will include also the total cost as a criterion to be minimized.
The developed tool will generate a non-dominated set (Pareto optimal set) of solutions for this model. The formulation of this model is found in Section 4-8.

3-9 Recommendation for tool attributes

Jensen and Elle (2007) identify four types of urban sustainability tools (based on a review of 60 case studies):

- Process guides (frameworks, policies, regulations strategies…)
- Calculation tools (environmental impacts, LCAs, economic, social and system simulation)
- Assessment guides (evaluation, multi-criteria assessment)
- Monitoring tools

According to this study, the main drivers to use these types of tools are:

- Compliance with laws and/or regulations where evaluation and assessment of plans are required. (in our case Clean Water Act)
- Identifying problems and possible alternatives
- Need to demonstrate sustainability for accreditation and legitimization.
- Benefits from using the tool like demonstrating a more sustainable solution, measuring and tracking sustainability metrics for accreditation and as a driver for improvement.

Jensen and Elle (2007) found that in several instances the users had to rely on multiple tools to accomplish what they wanted to achieve. Among the main obstacles in using the tools are the complexity of the tool and the amount of resources needed (time, data…). Hence the need to minimize the user input.

Based on planning and decision making requirements the tool should:

- Provide information and account for regulations and guidelines.
- Account for multi-functionality of GSI so it should quantify the benefits and impact of the proposed strategies
- Estimate the costs associated with these strategies.
- Test the reliability of cost/benefits estimation

Based on the planner needs, the tool should be able to:

- Provide information and guidance about the technical limitations of different plan components
- Estimate the post implementation hydrology
- Expand the search space for strategies
- Generate alternative strategies

3-10 Existing Tools

This section presents an overview of existing tools in the US that include functions that help in the planning, design and decision support for strategy/plan development for GSI. Two types of tools are available; the first is the single purposed tools that can provide one of two functions: 1- Hydrological impact assessment, or 2- Financial and economic feasibility assessment. The second consists of the multi functionality tools that attempt to provide both hydrological and financial/economic assessments capabilities.

3-10.1 Multi-Functionality Tools

3-10.1.1 SUSTAIN

SUSTAIN (US EPA 2014a) is a GIS based tool for optimizing the cost effectiveness of Structural BMPs. This tool comprises seven modules that allow the user to:

- Determine the suitable location of twelve different BMPs (Constructed Wetland, Grassed Swale, Green Roof, Infiltration Basin, Infiltration Trench, Porous Pavement, Bioretention, Vegetated Filter Strip, Sand filter, Rain Barrel, Cistern and Wet and Dry Ponds) based on seven suitability criteria pertaining to requirements for proper functioning of the BMP (drainage area, slope, soil type and water table level) and setbacks from existing features (structures, roads and streams)

- Simulate site hydrology (runoff water quality and quantity pre and post BMP implementation). For hydrograph generation and water pollution simulation, this tool uses SWMM5 algorithms (US EPA 2016e). For sedimentation simulation, this tool uses HSPF algorithms (Bicknell et al. 1997)

- Generate construction cost estimation using unit cost approach.

- Optimize the cost effectiveness of the BMPs based on user defined decision variables pertaining to sizing the different BMPs and/or water quantity and quality factors. The optimization module uses scattered search and genetic algorithms to find the optimum solution.

SUSTAIN can be applied on a watershed of any size and allows incorporation of smaller watersheds within a larger one. Geographically, it is not limited to any specific area within the United States. While SUSTAIN has the capability of sizing different BMPs based on hydrologic goals it still requires that the user have some advance knowledge about the hydrologic performance of the watershed, especially in routing and conveyance since the user has to develop specific plan scenarios to be tested. Furthermore, the user must have knowledge in using, and have access to ArcView 9 and Microsoft Excel in order to successfully operate SUSTAIN. (US EPA 2014a; LAI et al. 2007)

3-10.1.2 WERF Select Model

WERF Select Model is an M.S. Excel based tool to estimate the whole life cost and runoff water quantity and quality savings due to GSI plan implementation. The BMPs included in this model are: extended detention, bioretention, wetland basin, swale, permeable pavement and filter. In addition, it allows a user defined BMP. The range of applicability can vary from site to watershed scale. This tool requires the input of specific GSI plans in addition to precipitation, land use and runoff water pollutant concentration data. The hydrology calculation is based on a user-defined abstraction coefficient. The whole life cost includes the base costs (planning, engineering and construction), operation and maintenance, and end of life costs. The base costs are estimated using parametric equations as functions of the area treated by the BMPs. Operation and Maintenance (O&M) and end of life costs are estimated as a percentage of the base costs. (Moeller and Rowney 2013)

3-10.1.3 CNT Green Values

CNT Green Values (CNT 2013) is a web tool to estimate water savings, costs and economic benefits. The BMPs included in this tool are: Green roofs, rain gardens, cisterns, planter boxes, vegetative filter strip and permeable pavement. It is applicable on a site scale primarily in the Chicago, IL geographic area (where the precipitation data and most of the costing references come from) and comparable geographic regions (Great Lakes area as per tool description). The cost function estimates the Net Present Value (NPV) of the construction, maintenance and opportunity costs pertaining to comparable conventional development. The costs are estimated based on unit costs collected from the literature. The water savings are estimated using the Curve Number method and peak discharge calculation is based on a single storm event. Six benefits can be monetized using this tool: trees, air pollution reduction, carbon sequestration, compensatory value of trees, ground water recharge, reduced energy use and reduced water treatment needs.

3-10.1.4 WinSLAMM

WinSLAMM (PV & Associates 2016; USGS 2016) is a tool for estimating stormwater flows and quality. It uses collected historic data to generate flows and quality estimates from the following BMPs: infiltration practices, wet detention ponds, porous pavement, street cleaning, catch basin cleaning, and grass swales. The water quality is estimated at the outfall (no downstream modelling capabilities). This tool can generate a whole life cost estimate, specific for the State of Wisconsin, for the listed BMPs.

3-10.2 **Single-Purposed Tools**

3-10.2.1 Hydrology Simulation Tools

These tools simulate the effect of implementing specific BMPs and GSI Strategies on water runoff quality and quantity. Two tools fall in this category; The Storm Water Management Model (SWMM) US EPA (2016e) and The Long Term Hydrologic Impact Analysis (L-THIA-LID) (Engel and Theller 2015). While SWMM has the capability to simulate surface runoff (including routing and surface abstraction), snow melt, evaporation, soil infiltration, base flow and ground water recharge, L-THIA-LID only simulates surface runoff (enhanced Curve Number method). (Liu et al. 2015; Ahiablame et al. 2012).

3-10.2.2 Investment Analysis Tools

Autocase is a site specific tool that can assess the costs and benefits of projects that incorporate BMPs. This tool is developed as a plug in to other CAD based Autodesk software. The costs estimated in Autocase include initial investment and O&M and the revenues include the monetized environmental and social benefits. This tool relies on user defined strategies and water savings functions to generate costs and benefits. When variability in water functions and selected strategies is depicted by the user this tool has the capacity to generate sensitivity analysis and account for risk and uncertainty in the projected costs and benefits.(Autodesk 2015)

3-10.3 Problem with the existing tools

The tools described in the previous section are dedicated to planning, design and decision support. However, all the tools require the input of a well-defined plan and none of the tools have the capability to generate alternative solutions (refer to Table 5). While SUSTAIN has the capability to modify the sizing of the specified BMPs, it requires advance engineering and hydrological knowledge to select the different combination of BMPs, acceptable size margins and proper hydrological routing. (Refer to Table 5**:** Planning and Decision Support Tools for GSI)

In addition, while accounting for the multi-functionality of GSI during the planning process, none of the tools provide benefit quantification beyond the site scale. Furthermore, the only tool that has the capability to generate Triple Bottom Line (TBL) type of analysis (Autocase) is treated as a black box tool with no information available about the benefit calculation methods. Withholding such critical information is one of the main causes that deters planner/ designers form using the tool (Jensen and Elle 2007).

Finally, none of the available tools provide life cycle cost and Life cycle assessment estimation capability and the level of detail and accuracy of the cost estimation capabilities of these tools are the lowest possible (class 5 based on AACE International (2012) classification system). (Refer to Table 5).

Tools		SUSTAIN	WERF Select Model	CNT Green Values	WinSLAMM	SWMM	L-THIA-LID	Autocase
Prerequisits		ArcView9 MS Excel	MS Excel	-	-	MS Excel	MS Excel	Autodesk CAD
Applicability	Geographic Applicability	USA	USA	Great Lakes	Wisconsin	USA	USA	USA
	Scale	Watershed	Site to watershed	Site	Site	Site to watershed	Watershed	Site
Hydrology Calculation	Runoff Volume	Yes	Yes	Yes	Yes	Yes	Yes	No
	Runoff Rate	Yes	Yes	Yes	yes	Yes	Yes	No
	Water Quality	Yes	Yes	Yes	Yes	Yes	Yes	No
Costs & Benefits	Costs Estimated	Design + Construction	Whole Life	Construction, Maintenance & Opportunity	Whole Life	No	No	Construction & O&M
	Estimation Class (1)	5	5	5	5	-	-	N/A
	Quantify Benefits	No	No	Economic	No	No	No	Economic, Environmental & Sacial
Generates Alternatives		Limited	No	No	No	No	No	No
Notes		Allows BMP size modification within the user defined ranges	Requires Hourly Precipitation data for calculation	Simplified hydrology calculation	Requires Historic data (Provided for State of Wisconsin)			Limited Hydrology calculation capability, based on user defined parameters

(1) Based on cost estimates classification in (AACE International 2012)

Table 5: Planning and Decision Support Tools for GSI

This table shows a comparative analysis of available tools in the US.

4 Tool Description

4-1 Introduction

The role of the Planner, as discussed in the GSI Planning section, is to develop a plan that gets the support of the stakeholders while fulfilling policies and technical requirements. Incorporating the stakeholders in the planning process will bolster the chances of their support.

The developed tool is designed to fill the gaps in the existing GSI planning tools outlined in Table 5 and facilitate the planning process by generating alternative strategies that maximize the net benefit while meeting the policies and technical requirements. The tool minimizes the input from the user in order to be used for fast alternative generation and assessment in community and stakeholders meetings.

This chapter presents descriptions of the tool sections: interface, process and database modules. It also describes the methods and background calculations used to accomplish the different required tasks of the proof of concept version of the tool (medium fidelity prototype). The main tasks accomplished within the prototype are:

- Formulate hydrology functions
- Formulate unit Life cycle cost
- Formulate Life cycle Assessment (LCA)
- Formulate opportunity costs, externalities and benefit functions
- Optimize solutions (generate alternative strategies)

All calculations are performed per functional unit then fed to the optimization model and the Multi-criteria decision making (MCDM) model to generate strategies.
A strategy refers to the combination of different GSI Elements design variations along with corresponding amounts of functional units to be implemented. The GSI Elements and their design variations are outlined and discussed in the following section.
In addition to the tool description, functionality and component improvement will be suggested to be included in the market-ready/more complete version of the tool.

All formulations presented in this chapter, unless stated otherwise, are generated and coded in excel by the author.

4-2 Tool Outline

Following the characterization of Beaudouin-Lafon and Mackay (2012), the developed prototype will be a throw away, online, rapid, interactive and task oriented. It will be developed in a spreadsheet format (M.S. Excel) where tasks and calculation processes are represented with high precision. Since the prototype is designed to serve as a proof of concept, advanced interaction capabilities and visualization techniques will not be included.

As previously mentioned the tool is developed to perform four types of calculation;

- Life cycle cost
- Life cycle assessment
- Hydrologic calculations
- Quantities and monetary values of benefits

All calculations are performed per functional unit then fed to the optimization model and the Multi-criteria decision making (MCDM) model to generate strategies.

4-2.1 Tool description and architecture

The prototype is comprised of three main types of spreadsheets: the user interface, the process module sheets and the databases.

The User Interface is where the user interacts with the tool, inputs information, changes settings, and orders the execution of and receives the outcomes of different calculations within this tool. The user interface is placed in a separate spreadsheet ("Interface") within the prototype. The user interface includes two modules: the input and the output interfaces.

The input interface: this is where the user inputs the case specific information needed for calculations like:

- Site specific data (soil and land cover types, land cover areas, average site slope and land use information). This type of information is necessary for cost, LCA and Hydrology calculations.
- The interest rate or the Minimum Accepted Rate of Return (MARR) for the project. This information is necessary to perform economic calculations and estimate the Net Present Values (NPVs) and Annualized costs and benefits.
- Solver settings that consist of goals and performance objectives to be met while generating solutions, like maximum projected annual expenditures, and runoff and peak rate design storms. (Figure 3)

Based on the background research, specific solver settings will be proposed as default prototype settings. The user will be able to override and modify the suggested values and settings listed above to best match the specific planning circumstances. The site specific data, in the prototype, is provided by the user.

The above listed types of information are the minimum requirement inputs by the user for successful solution generation by the proposed prototype. There is other preset information in the tool that the user can modify. These presets will be discussed in the following section (GSI Elements)

The output interface is where the generated solutions' attributes are displayed (size of each GSIE) along with the estimated most probable annual costs and benefits associated with each of the generated alternatives (in quantities and values).

The process module contains three main components:

- The database control module: the role of this module is to search for data within the available databases based on user inputs and other module needs. Since the prototype is developed in a spreadsheet format this module has limited functionality and is merged with the databases.

- The calculation module generates the following:
  - Hydrology calculations include the average annual runoff water retained and detained, peak rate reduced and runoff water quality. To generate these formulae, precipitation and site specific data in addition to the GSIEs attributes are required. The average annual hydrology functions are coded in a separate spreadsheet file "Hydrology.xls" and feed information into the main tool file "Data-Calculations.xls". This separation is due to the fact that the annual hydrology calculations include several "if" functions that increase considerably the run time of the optimization algorithm. The other remaining hydrologic functions are coded in the spreadsheet tab entitled "Hydrology".

  - Annualized life cycle costs and life cycle assessment estimated based on collected cost data and GSIEs' attributes, construction and maintenance processes. These calculations are performed in four spreadsheet tabs each pertaining to a GSIE.

  - Annual benefits quantification and monetization (including the opportunity costs) are coded into the "Benefits" tab.

- The strategy generator contains an optimization module that retrieves the formulae generated by the calculation module in a mathematical programming model to generate alternative solution(s) based on user defined goals. The generated solution(s) are displayed in the output interface.

  In addition to the optimization module, the strategy generator contains a simulation module that assesses the variability of the GSIEs costs and attributes. The simulation module uses the formulae generated by the calculation module along with the data variability to generate confidence intervals for the costs, benefits and hydrology functions. (Refer to Figure 3)

The Databases module consists of stored data pertaining to GSIEs' attributes, precipitation profiles, costs and benefit data. In the presented prototype, we did manual collection of the necessary data and stored them within two spreadsheet tabs; "Data-Cost" and "Data-Hydrology". Automated data updates capabilities will not be included in the prototype but it should be included in the market ready version. The data collected (for costs, benefits and hydrology) pertains to the geographic region of the City of Pittsburgh, PA. The currency year in the prototype is 2017 and all cost and benefit vales collected are converted to that specific year using the Consumer Price Index (CPI) (Bureau of Labor Statistics 2017) method for estimating inflation.

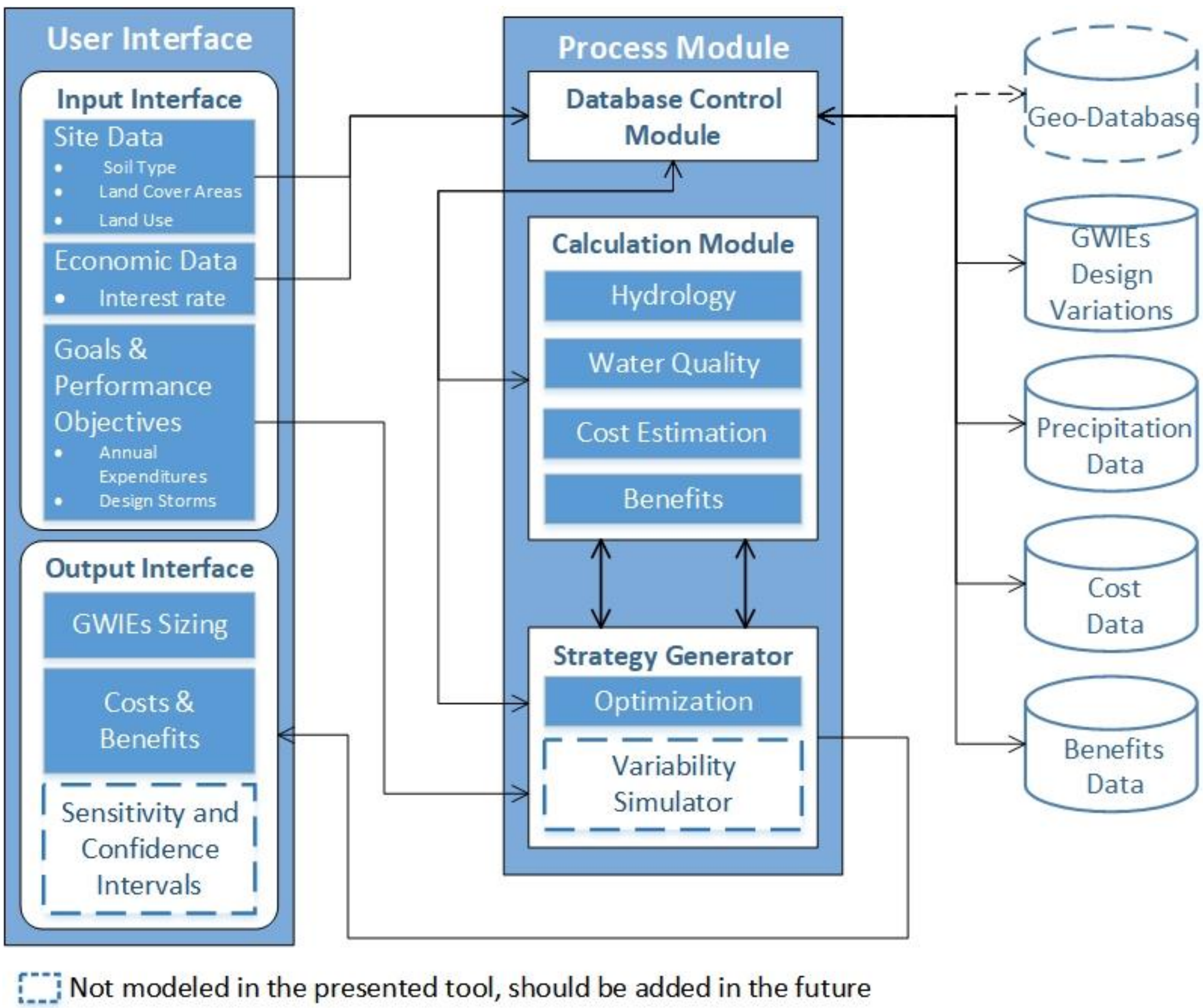


Figure 3: Tool components and architecture

To reduce the amount of information input by the user, in the market ready tool, and to increase automation in data search and retrieval, a Geographic Information System (GIS) component can be added to the Data Control Module to retrieve data from a geo-referenced database based on the user-selected neighborhood or study area. In that case, the user will not need to input the site specific data; selecting the geographic location and boundaries of the study area triggers the database control module to retrieve the site specific data from the geo-database. However, that functionality is not included in the prototype; instead, similar background data collection from geodatabases pertaining to the city of Pittsburgh will be performed beforehand by the tool developer and then used within the prototype as a static database.

The specific formulations, assumptions and data collected will be discussed and presented later in this chapter.

4-2.2 GSI Elements

Four GSIEs will be modelled in the prototype: pervious alleys and road side parking (PP), extensive green roofs (GR), rain barrels (CS) and bio-retention with dual media (BR). These GSIEs collectively include the functions that structural BMPs can provide (refer to Table 6):

- Hydrologic functions: retention (infiltration), detention, evapotranspiration and reuse.
- General use: pavement, roofing, water storage and green space. (refer to Table 6 below)

Each GSI Element has a subset of design variations pertaining to composition, sizing and material selection of different components. Each design variation is referred to, in the tool, with the two letter initials of the GSI elements along with the number of the design variation. For example, the first design variation for a green roof modelled in the tool is referred to as "GR-1", the second "GR-2" etc.

4-2.2.1 Green roofs

A green roof is composed of (refer to Figure 4):

- The vegetation cover
- Growing media
- Separation layer (geotextile)
- Storm water storage and detention media. Can be formed of stone subbase or synthetic under-drain layer or a combination of both.
- Root barrier

- Waterproofing
- Insulation layer (optional)

	BMPs	GSIE Modeled	Hydrology function	General function
Included in Prototype	**Pervious Pavement**	Asphalt alleys and roadside parking with infiltration bed	Infiltration, Detention	Pavement
	Bio-Retention	With ponding layer, Dual Media (soil & gravel) and overflow control	Infiltration, Detention and Evapotranspiration	Green space, water feature
	Green Roofs	Extensive, single media (up to 10in. deep) with underdrain	Detention and Evapotranspiration	Roofing, insulation
	Cisterns	Rain barrels	Reuse	Water Storage
Not Included	Infiltration Trench	-	Infiltration	-
	Bioswale	-	Infiltration, Detention and Evapotranspiration	Green space
	Planters	-	Evapotranspiration	Planting, decoration

Table 6: GSI Element modelled in the tool prototype.

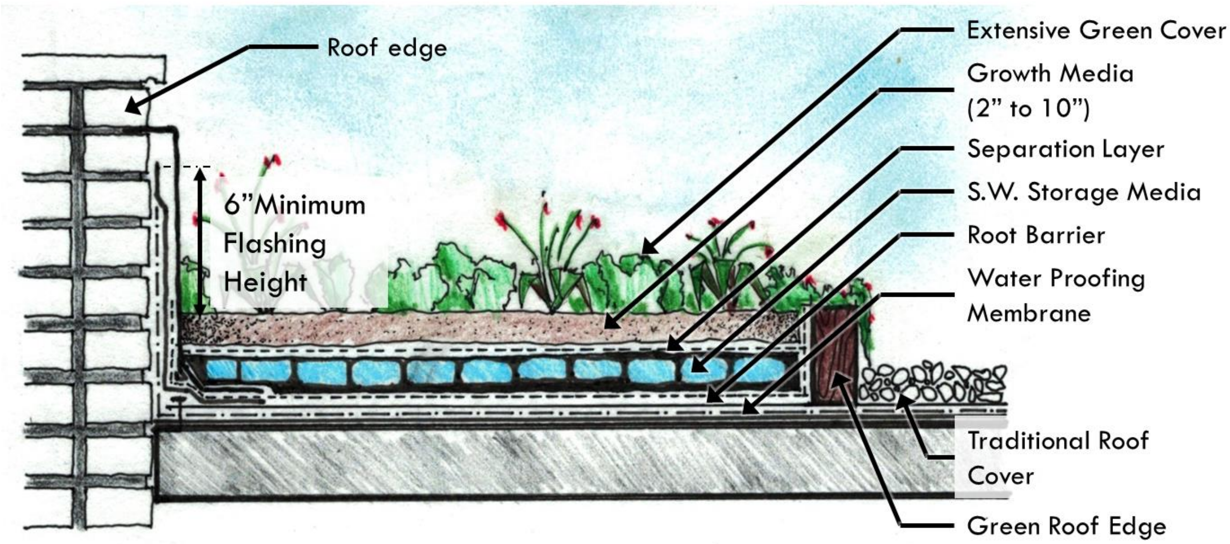


Figure 4: green roof typical composition

FLL (2002) categorize green roofs based on their plant cover:

- Extensive greening: can support vegetation sizes varying from moss to grass and herbaceous plants. Planting media depth is up to 8 inches.
- Simple Intensive greening: can support herbaceous plants, shrubs and coppices. Planting media depth can reach 40 inches.
- Intensive greening: can Support all types of vegetation including large trees. Minimum planting media depth for large trees is 60 inches.

Green roofs are modeled in the presented tool as single media systems (growing medium) with a synthetic underdrain detention layer that can support extensive greening.

Based on that, two factors determine the design variations of green roofs: media depth and capacity of the detention layer. Five design variations are modeled, GR-1 to GR-5. The media depth goes from two inches for GR-1 to ten inches for GR-5 with two-inch increments with the capability to be modified by user. The detention layer capacity is considered constant for all design variations since it is premanufactured and user selected.

The PA DEP (2006) requires that the load bearing capacity of a roof be evaluated in order to assess its compatibility with the live and dead loads of the designated green roof. However, green roofs with media depth less than six inches are used on traditional roof structures when lighter media materials are used. In the presented tool it is assumed that implemented green roofs will not require special structures for support.

The green roofs are considered to collect the precipitation from the area they cover and no other area drains on them. For that reason the drainage area factor (or catchment factor) is considered to be one for hydrologic calculations.

The functional unit for green roofs is a square foot of green roof.

4-2.2.2 Bioretention

A bioretention is composed of (refer to Figure 5 below):

- The vegetation cover

- Organic layer/Mulch
- Ponding Area
- Growing (planting) medium
- Volume storage layer (or rock medium)
- Separation layer (geotextile)
- Overflow structure
- Lining and Underdrain (for impermeable soil conditions).

In some cases, a velocity reduction apron must be installed at the inlets of a bioretention in order to protect it from erosion and disturbance of the organic layer. In most cases it consists of a small rip rap area.

In the presented tool the functional unit is considered to be a square foot of bioretention. It is measured by infiltration bed area. For hydrologic calculations, ponding area, growing soil and volume media are considered to cover the same area as the infiltration bed. For cost and life cycle assessment, additional excavation and materials usage will be factored into the functional unit calculations.

The design variables for bioretention are ponding depth, growing medium depth and volume storage layer (rock medium). The overall depth is not allowed to exceed six feet since it will require special equipment for excavation and shoring. The ponding depth should not exceed six inches in depth to avoid the necessity of safety barriers to reduce drowning hazard (PA DEP 2006).

Six design variations are considered in the presented tool for the bioretention GSIE. All six have the same ponding depth and volume storage layer of six inches for each layer. Growing media depth is eighteen inches for BR-1 (minimum requirement for Herbaceous plants (PA DEP 2006)) and increases by six inches until it reaches forty eight inches (4 feet) for BR-6.

No trees will be planted in BR-1 and BR-2, since the planting medium is too shallow to sustain fully grown trees. The impervious cover drainage to bioretention area ratio is five to one (PA DEP 2006) calculated based on effective infiltration area (refer to Figure 5).

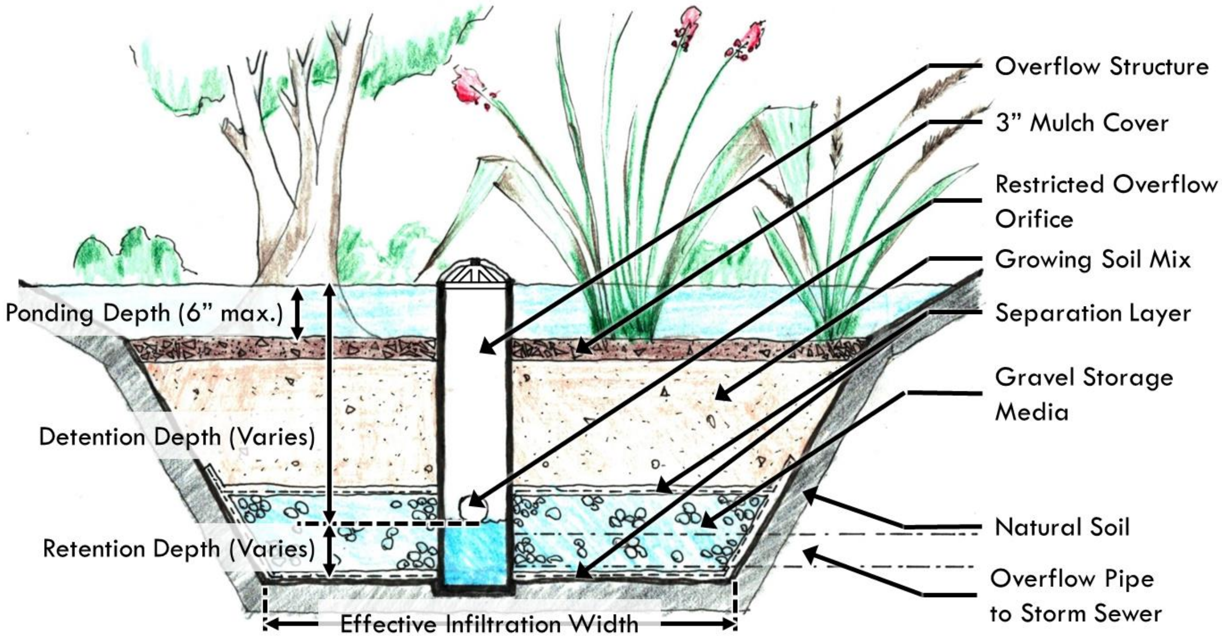


Figure 5: Bioretention typical design.

4-2.2.3 Permeable Pavement

Several materials are used as a permeable surface cover like asphalt, bituminous concrete, paver blocks and reinforcing grid system (turf or gravel filled). Pervious pavement can be installed for parking spaces (lots or road side), alleys and walkways.

At this time, only the permeable asphalt is modeled within the presented tool. To account for the site slope, the permeable pavement is installed on excavated leveled terraces. To allow flexibility in design, the user can specify the average width and length of these terraces (in other meaning, the effective infiltration area of permeable pavement sections). The preset dimensions for the tool assume a mildly sloped parallel parking or alley (5% slope).

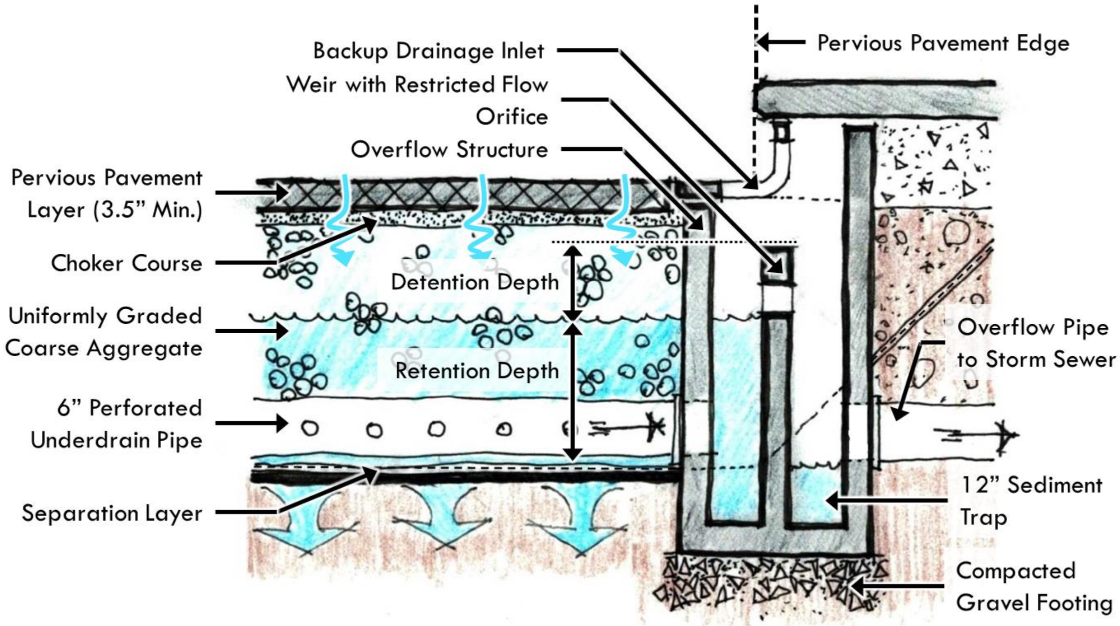


Figure 6: Porous pavement typical design.

The pervious pavement installation consists of (refer to Figure 6):

- Pervious paving surface course. The depth of this layer should not be less than 2.5 inches (for light truck load) (Ferguson 2005).
- A choker course 1 inch deep (AASHTO #57)
- Infiltration bed typically 12 to 36 inches deep. The minimum required depth is 4 inches for light truck (Ferguson 2005). However, since installation of this course is done in rises up to 9 inches deep, in the presented tool, the minimum depth is modelled as 8 inches and increases in 8 inch rises for each design variation option up to a maximum of 64 inches.
- Uniformly graded aggregate layer 1to 2 inches in diameter laying on a level excavation bed
- Continuously perforated smooth interior pipe along the bottom of the infiltration bed. Minimum pipe diameter is 6 inches.
- A geotextile layer.

- Overflow control system to prevent water in the infiltration bed from rising to the pavement surface level that includes a backup drainage to allow runoff water to enter the infiltration bed.

In the presented tool, the pervious pavement layer depth is considered constant (3 inches) for all the design variation options. The design variation options are determined by the aggregate layer depth; PP-1 with an 8 inch depth increasing in 8 inch rises for the rest until PP-8 of 64 inches deep.

The drainage area ratio preset is 2. That means the permeable pavement can collect runoff from an impervious area double its size. (Assuming parallel parking collecting runoff from one lane road). The functional unit of pervious pavement is square foot of pavement.

4-2.2.4 Cisterns

Cisterns are water containers that collect roof runoff (in most cases). They can be installed within a structure, on the surface outside the structure or underground. The cisterns can be premanufactured or constructed on site. The predominant material used for premanufactured cisterns is polyethylene resin (either for underground or surface installation). The cisterns that are constructed on site are mainly made out of concrete. However, repurposed containers of any type of material have been used including wooden and steel barrels and many types of plastic.

The size of the premanufactured cisterns also greatly varies. The available capacities range from 50 gallons to several thousands of gallons.

The collected water can be filtered, treated, pumped, and utilized for close to body uses, or pumped without treatment for external uses like toilet flushing. It also can be used without pumping for irrigation.

The presented tool models the rain barrel which is the simplest forms of cistern. Three sizes of barrel capacity are considered: 50, 60 and 100 gallons. The barrels are premanufactured resin containers, installed outside the structures to collect downspout rain water. The barrels are placed on a premanufactured tank stand. The stand is placed on a hand compacted gravel footing. The collected water is considered to be used without pumping for irrigation. (Refer to Figure 7)

The drainage area is preset as 300 square feet per cistern and can be user defined. The functional unit is a cistern installed.

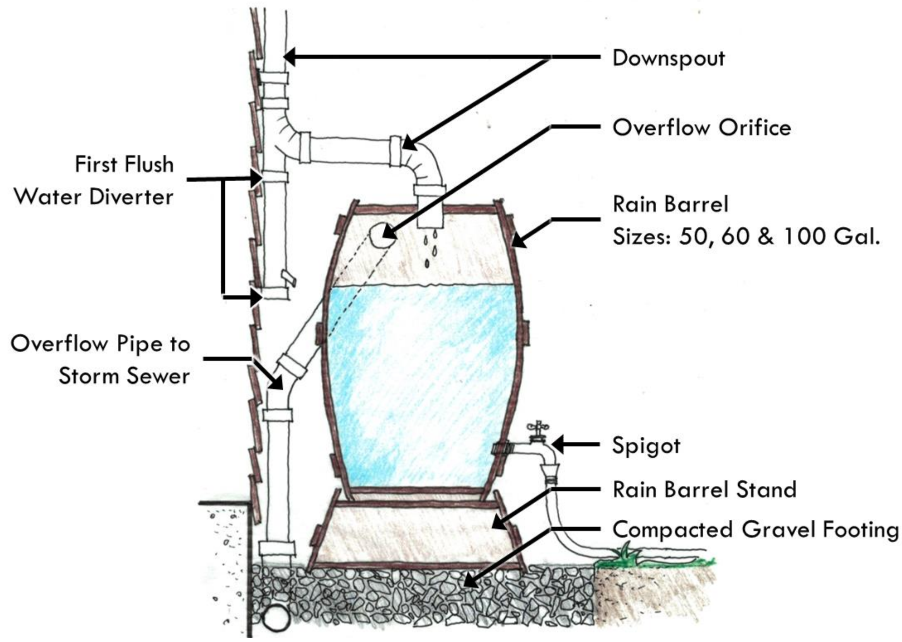


Figure 7: Rain barrel typical design.

4-3 Hydrology

4-3.1 General Considerations

The presented tool has the capability of performing four types of hydrologic calculations:

- Annual Average water retention and detention volumes
- Design storm runoff volumes for pre-development, CG1 design areas and post development
- Design storm peak rate reduction
- Total mass of water contaminants removed.

These calculations are performed by functional unit for each of the design variations of the GSI elements.

Data collected:

- Daily precipitation data for the years 2008 to 2017 (NOAA 2017)
- Precipitation Frequency estimates (design Storms) (NOAA 2017)
- Infiltration rate by hydrologic soil type (USDA NRCS 2007b)
- Evapotranspiration data (Allen et al. 1998)
- Curve number data (USDA NRCS 1986)
- Peak rate runoff coefficient (USDA- NRCS 1988)
- Runoff water quality data (PA DEP 2006)

User required input

- Percentage of Hydrologic soil types (by area) in study area

Preset information

- Design storm for volume control: 2 year 24 hour storm as per PA DEP 2006
- Design Storm for Peak rate control: 100 year 24hour storm as per PA DEP 2006. The user has the choice to modify these two selections to any storm from a list ranging from the 1 year 24 hour storm to the 200 year 24 hour storm.

Hydrology general assumptions

- Catchment areas for GSI Elements do not overlap. 100% of the rain that falls on a catchment area gets directed to the corresponding GSI.
- While it might happen in real life, for generalization purpose, the presented tool does not allow stacking of GSI Elements; runoff from GSI Elements will not be directed to another GSI Element. For example, green roof excess runoff water cannot be collected by a cistern or a bioretention system.
- Total precipitation directed to a GSI Element can be retained and/or detained, while the excess runs off. The retained water can be reused, infiltrated or evapo-transpired. The

detained water will be released as delayed and controlled runoff. The water saving capability of each GSI Element is outlined in Table 7.

	Reuse	Evapo-transpiration	Soil infiltration	Detention
Green Roofs		●		●
Bioretention		●	●	●
Permeable Pavement			●	●
Cistern	●			

Table 7: Water Saving Capability of GSI Elements

4-3.2 Hydrologic calculation

The hydrologic calculations for all GSI Elements follow the same formulation except cisterns that follow a slightly modified formulation. This deviation pertains mainly to the fact that the cistern's functional unit differs from the other GSI elements. The distinction between cistern formulation and the other GSI Element will be highlighted when present.

The first task in hydrologic calculation is to calculate the Storage capacity of each design variation. It is determined by each media layer volume and corresponding void ratio. The formula for maximum storage capacity is:

Equation 4-1: Maximum storage capacity

$$\boldsymbol{Vc_i = x_i \times \sum_{j=1}^{k} (Vm_{ij} \times \varphi_{ij})}$$

Where:

i pertains to the GSI Element design Variation

j pertains to the media layer

Vc_i is the maximum storage capacity volume of the design variation *i* (in Cu.Ft.)

x_i is the amount of functional unit of a design variation *i*. (user defined or generated by optimization model)

Vm_{ij} is the volume of media j for the design variation i in Cu.Ft. per functional unit

φ_{ij} is the void ratio of media j for the design variation i

The media layer in the case of the cistern is considered the capacity volume of the cistern. The void ratio φ_{ij} preset values are selected as defined by the PA DEP 2006 for all $\boldsymbol{i}$, and are as follows:

- Growing media (soil): 0.25
- Subbase aggregate (stone): 0.4
- Ponding and storage layers: 1

As previously mentioned the presented tool performs all calculations initially per functional unit then the values of X_i are generated by the optimization model or user specified in the case of strategy evaluation.

The retention and detention portions of the calculated capacity are determined by the design specification imposed by the PA DEP 2006 forcing each GSI element to be designed to discharge all captured water within 72 hours (3 days) of a precipitation event. So the full captured volume should be infiltrated, evapo-transpired and discharged within that period. This rule is for infiltration and detention strategies and does not apply to cisterns.

The infiltration portion of the capture volume for all infiltration strategies (refer to Table 7) is calculated as follows:

Equation 4-2: the maximum infiltration volume

$$\boldsymbol{Vin_i = x_i \times \frac{\tau_f}{12in/ft} \times \frac{72\ Hrs.}{24\ Hrs/day}}$$

Where:

$\boldsymbol{i}$ pertains to the GSI Element design Variation

Vin_i is the maximum infiltration volume of the design variation *i* (in Cu.Ft.)

x_i is the amount of functional unit of a design variation *i*. (user defined or generated by optimization model) in sq.ft.

τ_f is the soil infiltration rate determined by the hydrologic soil type selected in inches/day

The maximum potential evapotranspiration is:

Equation 4-3: The maximum potential evapotranspiration

$$\boldsymbol{ETmax_i = x_i \times \frac{Etc_i}{12in/ft} \times \frac{72\ Hrs.}{24\ Hrs/day}}$$

Where:

i pertains to the GSI Element design Variation

$ETmax_i$ is the maximum evapotranspiration volume of the design variation i (in Cu.Ft.)

x_i is the amount of functional unit of a design variation *i*. (user defined or generated by optimization model) in sq.ft.

Etc_i is the average daily evapotranspiration of corresponding crop type in design variation i, in inches/day

The crop evapotranspiration Etc_i is estimated using the crop coefficient approach outlined in chapter 5 of Allen et al. (1998):

Equation 4-4: The crop evapotranspiration

$$\boldsymbol{Etc_i = Eto \times Kc_i}$$

Where:

i pertains to the GSI Element design Variation

Eto is the average daily reference evapotranspiration estimated using the Eto Calculator (FAO 2009) that utilizes the Penman-Monteith equation (in inches). The weather data used for the Eto calculation pertain to the Pittsburgh area.

Kc_i is a unitless crop coefficient of a design variation *i* collected from chapter 5 of Allen et al. 1998 based on corresponding plant size and type as follow:

- For green roofs: Kc corresponds to ground cover 2 inches height
- For bioretention: Kc corresponds to medium sized deciduous trees with killing frost.

The crop coefficient Kci also varies based on the state of plant growth;

- Kc initial represents the evapotranspiration of the plant in dormant and bourgeoning states
- Kc Mid represent the evapotranspiration of the plant in full growth (spring and summer)
- Kc end represent the evapotranspiration of the plant in end of growth and going into the dormant phase.

Based on that, the evapotranspiration varies throughout the year. For maximum potential evapotranspiration calculation we use the smallest Etc_i possible, to be conservative.

The maximum potential retention volume ($Vret_i$) is equal to the maximum potential infiltration volume plus the maximum potential evapotranspiration (all in cubic feet):

Equation 4-5: The maximum potential retention volume.

$$\boldsymbol{Vret_i = Vin_i + ETmax_i}$$

The maximum potential retention volume for cisterns is the cistern volume.
The maximum potential detention volume $Vdet_i$ is equal to the maximum capacity less the maximum potential retention volume:

Equation 4-6: The maximum potential detention volume.

$$\boldsymbol{Vdet_i = Vc_i - Vret_i}$$

The detention daily flow ($Qdet_i$) of GSI element design variation ***i*** is estimated by dividing the maximum potential detention volume $Vdet_i$ by 3 days (the 72 hrs limit) (in Cu.Ft./day)

Equation 4-7: The detention daily flow

$$\boldsymbol{Qdet_i = Vdet_i/3\ days}$$

Figure 8 is a snapshot from the prototype showing the outcome of performing the hydrologic calculation per functional unit for all the GSIEs design variations based on the assumptions listed in Section 4-3.1.

	W X Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
5	Green Roof Type	GR-1	GR-2	GR-3	GR-4	GR-5	Unit					
6	Water storage capacity	1.56	1.87	2.18	2.49	2.81	Gal/SF					
7	design storm catchment volume	1.46	1.46	1.46	1.46	1.46	Gal/SF					
8	Retained Volume	0.03	0.03	0.03	0.03	0.03	Gal/SF					
9	Detained Volume	1.53	1.84	2.15	2.46	2.78	Gal/SF					
10	GSI abstracted volume	1.46	1.46	1.46	1.46	1.46	Gal/SF					
11	Detention flow	0.82	0.98	1.15	1.32	1.48	in/day					
12												
13	Bioretention type	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6	Unit				
14	Water storage capacity	8.04	8.98	9.91	10.85	11.78	12.72	Gal/SF				
15	design storm catchment volume	7.32	7.32	7.32	7.32	7.32	7.32	Gal/SF				
16	Retained Volume	2.69	2.69	2.69	2.69	2.69	2.69	Gal/SF				
17	Detained Volume	5.35	6.28	7.22	8.15	9.09	10.02	Gal/SF				
18	GSI abstracted volume	7.32	7.32	7.32	7.32	7.32	7.32	Gal/SF				
19	Detention flow	0.02	0.02	0.03	0.03	0.03	0.04	in/day				
20												
21	Permeable Pavement type	PP-1	PP-2	PP-3	PP-4	PP-5	PP-6	PP-7	PP-8	Unit		
22	Water storage capacity	1.99	3.99	5.98	7.98	9.97	11.97	13.96	15.96	gal/S.F.		
23	design storm catchment volume	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	Gal/SF		
24	Retained Volume	1.99	2.69	2.69	2.69	2.69	2.69	2.69	2.69	Gal/SF		
25	Detained Volume	0.00	1.30	3.29	5.29	7.28	9.28	11.27	13.27	Gal/SF		
26	GSI abstracted volume	1.99	2.93	2.93	2.93	2.93	2.93	2.93	2.93	Gal/SF		
27	Detention flow	0.00	0.00	0.01	0.02	0.03	0.03	0.04	0.05	in/day		
28												
29	Cistern Type	CS-1	CS-2	CS-3	Unit							
30	Water storage capacity	55	65	75	gal							
31	design storm catchment volume	439.48	439.48	439.48	gal							
32	Retained Volume	55.00	65.00	75.00	gal							
33	Detained Volume	0.00	0.00	0.00	gal							
34	GSI abstracted volume	55.00	65.00	75.00	gal							
35	Detention flow	0	0	0								

Interface / Optimization / Data-Cost / Green roofs / Bioretention / Permeable Pavement / Cisterns / **Data-Hydrology** / Hydrology / Benefits

Figure 8: Hydrologic calculations per functional unit of each GSI element design variation.

4-3.2.1 Annual Average Hydrology functions

These Hydrology functions pertain to annual average runoff, and retained and detained precipitation volumes by each of the design variations of the GSI elements. These annual averages, which are used for benefit estimation (ground recharge and water reuse values). These annual averages are estimated by functional unit of each GSI element. Daily time series over the period of ten years is used for these calculations. The daily precipitation data, used for this calculation, for the period spanning from January 1, 2008 to December 31, 2017 pertaining to the Pittsburgh PA region, is retrieved from NOAA 2017.

The algorithm used to perform the time series annual average hydrologic calculations for green roofs, cisterns and permeable pavement is outlined in a flow chart (Figure 9) while the cisterns algorithm is outlined in Figure 10. The calculations are done per functional unit so for the first algorithm the volumes are represented in inches and gallons for the second algorithm.

The first algorithm:

Let's consider three consecutive days: day 0, day 1and day 2. At the start of day 1 the available water for the GSIEs is the sum of remaining water in the system from day 0 plus the drainage area runoff from storm event on day 1.

The drainage area runoff (or runoff directed to a GSIE) is calculated by multiplying the precipitation of day 1 (in inches) by the drainage area ratio. This way we get the volume in inches per functional unit (sq.ft.)

After calculating the total water available for the GSI system, the algorithm checks if this volume exceeds the system maximum capacity calculated using Equation 4-1. If it does the excess water will overflow and run off. The run off volume is calculated and documented for day 1. If not, all available water is captured.

The remaining water volume in the system is checked for evapotranspiration capacity. If the maximum evapotranspiration, for that specific date, ($ETmax_i$), calculated using Equation 4-3, exceeds the available volume, all water in the system will evaporate. If not, $ETmax_i$, will evaporate and leave the system. For permeable pavement the ETmax is considered equal to zero (assuming evaporation is negligible).

The remaining water volume in the system is now checked for soil (base) infiltration. If the remaining volume exceeds the maximum infiltration volume (Vin_i) calculated using Equation 4-2, then the Vin_i will be removed from the system; if not, all the water volume in the system will be infiltrated.

The final step is the detention runoff calculation. If the remaining water volume in the system exceeds the detention daily flow ($Qdet_i$) calculated using Equation 4-7, $Qdet_i$ runs off and leaves the system. The remaining water volume in the system will be transferred to day 2.

If the remaining water in day 1 does not exceed $Qdet_i$, all the water remaining in the system will run off as detention discharge and the only water volume available at day 2 is the drainage area volume. (Refer to Figure 9)

The second algorithm:

The first couple of steps in this algorithm (calculating available water volume, capacity check and excess water runoff volume calculations) do not differ from the first algorithm. However the volume calculation unit is Gallons per cistern.

The retained water in cisterns can be discharged only for irrigation. So this algorithm has a set of rules for the water to leave the system in order to model real life assumptions and conditions. There will be no irrigation during frost periods and irrigation does not happen every day. So, in the presented tool an irrigation period test is modeled where zero water leaves the system in the period extending between October and April. In addition, irrigation is assumed to occur once a week.

The volume of water that leaves the system (or irrigation volume) is estimated on a weekly basis and is equal to the maximum needed irrigation volume less the effective precipitation volume on the irrigated area (since a portion of the precipitation volume is not captured by the plants due to several factors including runoff and evaporation). That volume cannot exceed the total water volume stored in the system.

The weekly maximum needed irrigation volume is estimated as the total weekly evapotranspiration volume added to the irrigation inefficiency volume (wasted irrigation water volume). The irrigation inefficiency volume is estimated using an inefficiency coefficient that is determined by the irrigation method (drip, flood or spray irrigation).

The evapotranspiration volume is estimated using Equation 4-3. The irrigation efficiency and precipitation efficiency are considered the same in this model. The used preset is 60% efficiency.

The preset value for average irrigated area by each cistern is 100Sq.Ft. planted with shrubs. The remaining water in the cistern will remain until the next irrigation day. (Refer to Figure 10)

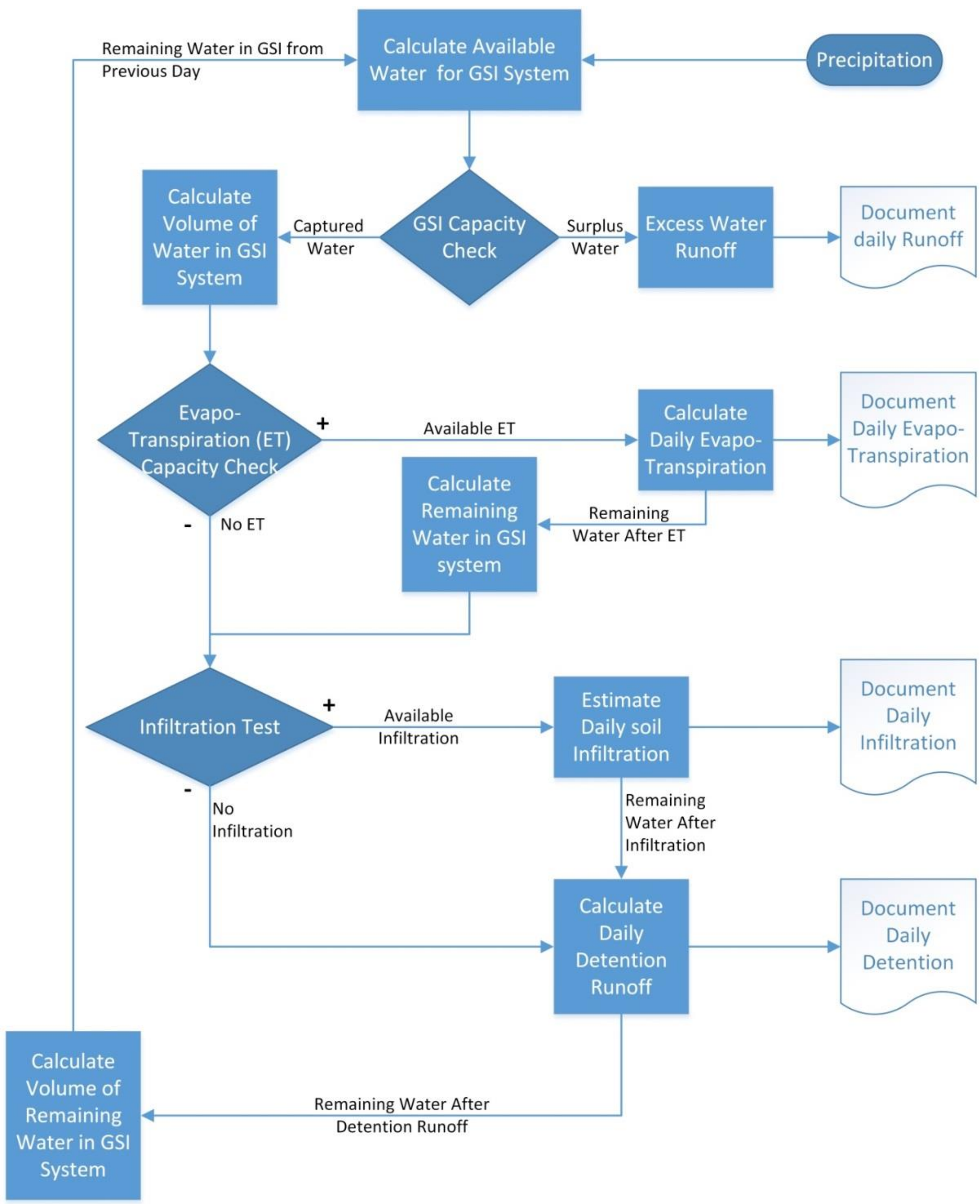


Figure 9: The algorithm used to perform the time series annual average hydrologic calculations for green roofs, cisterns and permeable pavement.

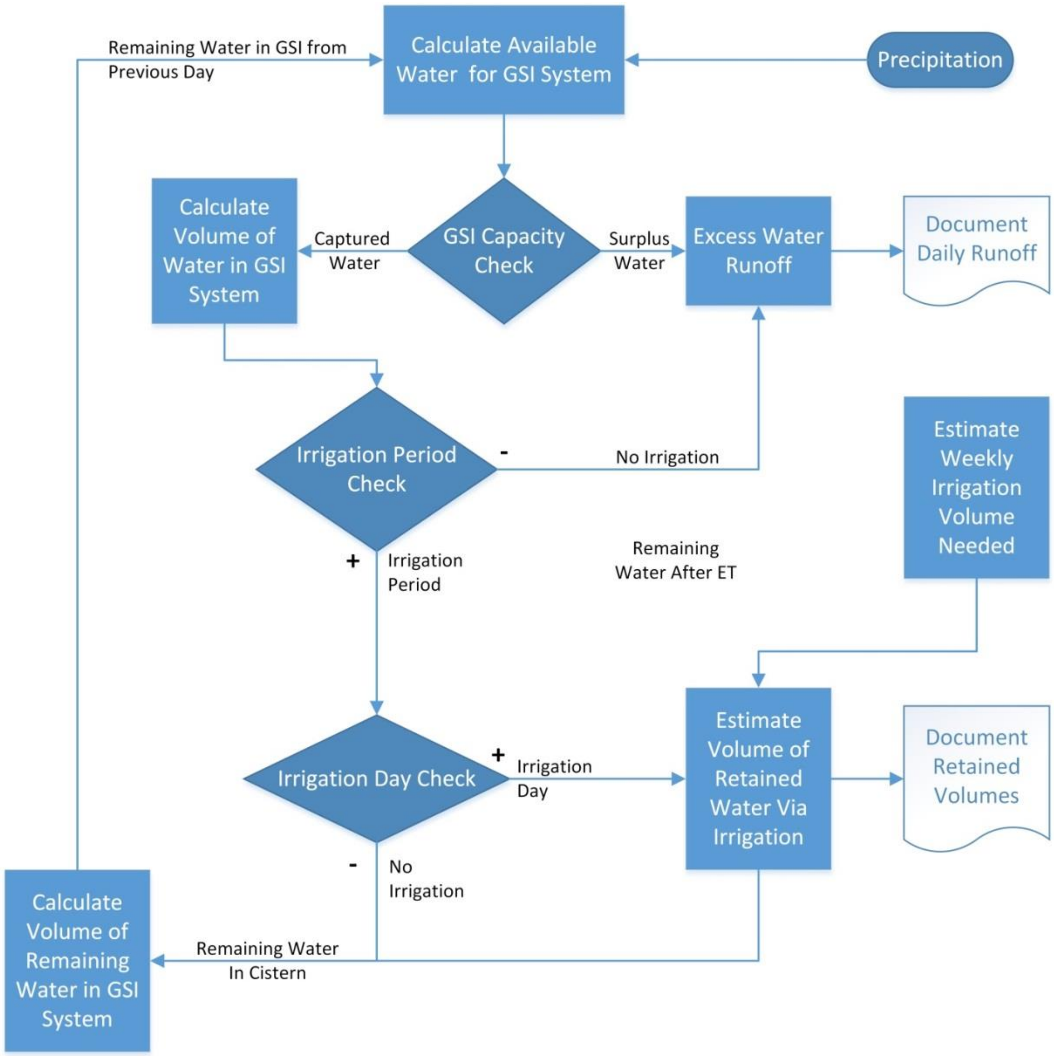


Figure 10: The algorithm used to perform the time series annual average hydrologic calculations for cisterns

4-3.2.2 Runoff Volume Control

As discussed in Section 3-5.1 this calculation is mandated by the PA DEP 2006 to restrict the runoff volume from the design storm (2 year 24 hour storm) so that the post development value matches the "CG1 Predevelopment Area" runoff volume, based on the user input of land cover areas and utilizing the Curve Number method. The CG1 Predevelopment Area runoff volumes are calculated based on the following (refer to Section 3-5):

- 20% of predevelopment impervious cover is considered meadow
- All pervious cover is considered meadow.
- Forested areas are considered forests

The Curve Number runoff calculation method, outlined in Equation 4-8, is performed by the tool for each land cover. The runoff volumes are calculated by square foot and listed in Table 8.

Equation 4-8: The Curve Number method formulae

$$\boldsymbol{Q = \frac{(P - I_a)^2}{(P - I_a) + S}}$$

$$S = \frac{1000}{CN} - 10$$

$$I_a = 0.2S$$

Where:

Q = runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (in)

Ia = initial abstraction (in)

Runoff Calculation	CN	S	I_a	Q	Unit
Roofs	98	0.20	0.04	2.12	inch
Impervious	98	0.20	0.04	2.12	inch
Meadow	71	4.08	0.82	0.42	inch
Woods	70	4.29	0.86	0.39	inch
Open Space (fair)	79	2.66	0.53	0.74	inch

Table 8: Design storm runoff, Curve Number calculations per Square foot.

The tool calculated the design storm runoff volumes captured by each functional unit of GSI element design variation as shown in Figure 8. The abstracted volumes shown in Figure 8 are multiplied by the amount of functional unit of each GSI element design variation to obtain the total site GSI abstracted volume.

The post development volumes are equal to post development land cover runoff less the GSI abstracted volume.

	Pre-Development	**CG1 Area**	**Post Development**	Unit
Roofs	171938.25	137550.6	237104.17	Gal
Impervious	309488.85	247591.08	281240.72	Gal
Meadow	0	106966.1	0	Gal
Woods	0	0	0	Gal
Open Space (fair)	155309.48	0	142457.58	Gal
GSI Abstraction			-275981.17	Gal
Runoff	**636,736.60**	**492,107.80**	**384,821.31**	Gal

Table 9: Run off volumes of a test strategy showing calculation of Pre and Post development as well as CG1 areas runoff from the design storm.

4-3.2.3 Peak rate Calculations

Peak rates are calculated using the rational method:

Equation 4-9: The rational method

$$Q_p = CiA$$

Where:

Q_p is the peak flow (Ft^3/s)

i is the rainfall intensity (in./hr.)

A is the watershed area (Acres)

C runoff coefficient ϵ [0; 1]

Assuming 1 acre-in./hr. ≈ 1 Ft^3/s

The design storm is defined by PA DEP 2006 as the 100 year 24 hour storm. The runoff coefficient is selected as shown in **Error! Reference source not found.**. The same onsiderations as Volume Control are applied regarding pre and post development covers. So the predevelopment peak rate is calculated using the “CG1 Predevelopment Areas”, while the post development peak rates are calculated using post development ground cover less the GSI drainage areas plus the detention runoff rates. To perform these calculations we assume that the Green roofs and Cisterns collect runoff water from roofs so their drainage area is deducted from total roof area. Similarly bioretention and pervious pavement collect water from other impervious areas and their drainage area will be deducted from the post-development impervious areas.

Runoff Coefficient (C)	Min	Max	Model presets
Roofs	0.75	0.95	0.95
Impervious	0.7	0.95	0.95
Meadow	0.1	0.6	0.2
Forest	0.1	0.6	0.1
Open space	0.05	0.35	0.3

Table 10: Runoff Coefficient for Manning Equation.

4-3.2.4 Water quality calculation

As mentioned in Section 3-5.3, the quality of runoff water is controlled on a watershed or sewer-shed level by an allowable effluent contaminant concentration (or Total Maximum Daily Loads-TMDL). This type of calculation requires detailed knowledge of the hydrology of the watershed(s) receiving effluents from the study area (such as all point and nonpoint sources loads). In addition, not all watersheds have target TMDLs to be achieved.

The PA DEP 2006 suggests a more generalized method to establish water quality targets that can be implemented on various project scales. It consists of controlling three main contaminants by reduced effluent mass. These contaminants are Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrate (TN). The percentage removal (by mass) is respectively 85%, 85% and 50%.

Event Mean Contaminant Concentration		Total Suspended Solids, EMC (mg/l)	Total Phosphorus, EMC (mg/l)	Nitrate-Nitrite EMC (mg/l as N)
Impervious Surfaces				
	Roofs	21	0.13	0.32
	Other	113	0.33	0.58
Meadow		47	0.19	0.3
Forest		39	0.15	0.17
Open space		180	0.4	0.44

Table 11: Mean Contaminant concentration in surface runoff (PA DEP 2006)

Each of the contaminant concentrations in runoff water varies depending on the surface cover type. These concentrations are listed in Table 12. The total mass of each contaminant is calculated for pre and post development by using the data in

Event Mean Contaminant Concentration		Total Suspended Solids, EMC (mg/l)	Total Phosphorus, EMC (mg/l)	Nitrate-Nitrite EMC (mg/l as N)
Impervious Surfaces				
	Roofs	21	0.13	0.32
	Other	113	0.33	0.58
Meadow		47	0.19	0.3
Forest		39	0.15	0.17
Open space		180	0.4	0.44

Table 11 &Table 12 in the Equation 4-10 for calculating total site contamination mass:

Equation 4-10: Total generated mass of contaminant

$$\boldsymbol{\mu_i = \sum_j (Q_j \times \rho_{ij} \times 3.78\ l/Gal)}$$

Where:

i refers to the type of contaminant

j refers to the type of surface cover

μ_i is the total generated mass of contaminant *i* in mg

Q_j is the runoff flow from the design storm from a surface cover *j* in gal/day

ρ_{ij} is the concentration of contaminant *i* in runoff from surface cover *j* in mg/gal

The design storm in this case is considered to be the same as the one used in volume control.

In the presented tool, similar to the peak rate calculation assumptions, green roofs and cisterns are assumed to collect runoff from roofs while bioretention and pervious pavement collect runoff water from other impervious areas.

	Total Suspended Solids	**Total Phosphorus**	**Nitrate-Nitrite**
Green Roof	85.00%	85.00%	30.00%
Bioretention	85.00%	85.00%	30.00%
Permeable Pavement	85.00%	85.00%	30.00%
Cistern	100.00%	100.00%	100.00%

Table 12: Percentage removal of contaminants from abstracted runoff by GSI Elements. (PA DEP 2006)

So for post development calculations, the total mass of contaminants is:

Equation 4-11: Post development total mass of contaminants

$$\boldsymbol{\mu_{post_i} = \mu_{unc_i} + \mu_{GSI_i}}$$

Where:

μ_{post_i} is the total mass of contaminant i generated by the post development strategy.

μ_{unc_i} is the mass of contaminant i generated by the surface covers uncontrolled by GSI

μ_{GSI_i} is the mass of contaminant i in GSI detention runoff

The surface cover areas are adjusted to exclude the GSI Elements drainage areas and then plugged into Equation 4-10 to get the site uncontrolled runoff mass; μ_{unc_i}. The mass of contaminants in GSI detention runoff is estimated using the following formula:

Equation 4-12: Total mass of contaminants in GSI detention runoff

$$\mu_{GSI_i} = \sum_j X_j \times (Qret_j + Qdet_j) \times (1 - \theta_{ij}) \times \rho_{ij} \times 3.78\ l/Gal$$

Where:

μ_{GSI_i} is the mass of contaminant i in GSI detention runoff

X_j is the amount of GSI element (j) to be implemented (in functional unit)

$Qret_j$ is the design storm flow retained by a GSI element j in gal/day

$Qdet_j$ is the design storm flow detained by a GSI element j in gal/day

θ_{ij} is the removal rate of a contaminant i by a GSI element j. (See Table 12)

ρ_{ij} is the concentration of contaminant *i* in runoff from surface cover pertaining to GSI element *j* in mg/l. (See Table 11)

By implementing this method the designer insures that the disturbed soil (or impervious surfaces) effluent quality would match or surpass the ones pertaining to natural land covers.

4-4 Life Cycle Cost Calculation

The main objective of this task is to estimate the Life Cycle Cost (LCC) per functional unit of each GSIE and determine what factors affect the variability of that cost.

There is no information required to be provided by the user in order to successfully accomplish this task. However, the user will have the capability to override the unit costs or the design parameters. These design parameters will be discussed in detail later in this section for each GSIE. The collected cost data are the national average costs for the year 2017 which are transformed to match the local economy of Pittsburgh,PA.

As discussed in the cost estimation section of the literature review (Section 3.6), estimating the service cost consist of the sum of the estimated cost of the following phases:

- Market demands or perceived needs
- Conceptual planning and feasibility study
- Design and engineering
- Procurement and construction
- Startup for occupancy (acceptance of construction)
- Operation and maintenance (O&M)
- Disposal of facility

The costs pertaining to market demand are sunk costs and are not included in the total cost. Conceptual planning, design and engineering costs in addition to other soft costs are preset in the tool to be estimated as a function of the construction cost, as shown in Table 13. The user has the option to use these preset percentages, modify them or enter another value for the estimated cost per functional unit. Startup for occupancy costs are non-existent in the case of GSI. So in addition to the site and soft costs, the main components of the LCC are the construction, O&M and disposal costs.

Site and Soft Costs	% of Construction Cost
Project Management	7.50%
Engineering & Design	10.90%
Office Expenses	8.00%
Field Personnel & Traffic Control	0.00%
Legal Services	0.00%
Permitting Fees	0.00%
Inspection & Testing	0.00%
Contingency	20.00%
Temporary Utilities	0.00%

Table 13: Tool preset site and soft costs as a percentage of the total construction cost (GORDIAN-RSMeans 2017)

4-4.1 Construction cost

This section presents the method used to estimate the construction cost per functional unit of the four GSIE considered in the presented tool. The construction cost is estimated using cost data collected from GORDIAN-RSMeans (2017). The collected cost data are applied to the functional unit's allocated construction quantities. In order to calculate these allocation quantities and collect corresponding cost data we generated typical designs for each GSIE based on analysis of information pertaining to design, specifications, components and construction of each GSIE. In the presented tool we registered the typical design data (that will serve as the default setting) in addition to the potential variations in design, sizing and specifications (PA DEP 2006; FLL 2002; Cantor 2008; Ferguson 2005; Clar, BARFIELD, and O'Connor 2004b; Clar, BARFIELD, and O'Connor 2004c; Clar, BARFIELD, and O'Connor 2004a). As previously mentioned in this chapter the variation in sizing of GSIEs runoff storage components are represented in the tool as decision variables to be determined by the optimization model. Other variations related to site/project specific conditions should be accounted for in a variability simulator module (not included in the presented prototype).

After collecting relevant data, we estimated the size and amount of components per functional unit of GSIE. First, we started by determining the functional unit of each GSIE: square foot for green roofs, bioretentions and pervious pavement, and number of units installed for cisterns. Then, we estimated the size and amounts of each component of the GSIE per functional unit (example: volume of gravel in the subbase of a square foot of pervious parking). These calculations are coded in the tool to be performed for each design variation of GSIE in the background. Then the tool estimates the amounts of construction processes per unit of GSIE: These calculations consist of translating GSIE components amounts quantified in the previous section into amounts of construction processes based on the Work Breakdown Structure developed from collected data (discussed in detail in Section 3.6-Cost Estimation).

So the Construction Cost per functional unit for each design variation of GSIE formulation is as follows:

Equation 4-13: Unit Construction cost for a GSIE

$$Cc_j = \sum_{i=1}^{i=n} q_i * C_i$$

$Where$:

$Cc_j = Service\ cost\ of\ GSIE\ _j$

$q_i = quantity\ of\ construction\ process\ i\ per\ unit\ of\ GSIE$

$C_\mathrm{i} = cost\ of\ construction\ process\ i$

The construction activities (including corresponding assumptions and typical designs for GSIE modeled in the tool) are as follows:

- Green roofs:
    - Mobilize crane to construction site: the cranes are used to hoist green roofs construction materials to the roof level. Depending on the roof height two types

of cranes are considered, 55 ton and 100 ton cranes. The first is considered to be used for roofs 5 stories or less while the second is for roofs ranging from 6 to 10 stories. This cost is estimated per project and is allocated to the functional unit based on an average project/roof size. The average project size is preset in the tool as 4000 sq. ft. with the option to be modified by the user.

- Hoist materials used in green roof construction up to the roof level: the crane assumptions mentioned above apply here too. So this cost varies depending on the roof height. In the presented tool, the user selects the percentage of green roofs 5 stories or less and 6 to 10 stories high. This selection allows the tool to estimate a weighted average cost for hoisting the construction materials.

- Rubber membrane installation (waterproofing) including flashing
- Root barrier installation
- Water retention/detention layer and barrier installation
- Planting Sedum: estimated based on 2 plants per square foot
- Edging of the green roof: this follows the assumption that some roofs might not have edges to contain the different layers of green roofs or the green roof might not cover the full surface of the roof and additional edges have to be erected. The cost is estimated based on building 200 linear feet (preset) of pretreated lumber.

In addition to these construction activities, a green roof project might include additional interior gutters, drains, plumbing, check boxes and thermal insulation layer installation. The corresponding costs to these construction activities are not included in the presented tool. However, the user has the option to redefine them.

- Bioretention
  - Site Clearing & Grubbing: this applies in case the site of the bioretention has dense vegetation and trees. We assume, in the tool presets, that the site is clear and this activity will not accrue any costs.

- Excavation: three factors affect the excavation cost:
    - The soil type affects the excavation cost; soft soils like sand are cheaper to excavate than heavy ones like stiff clay. Level of soil wetness also adds to the excavation cost. Presence of boulders and rock layer will mandate the usage of specialized crew and equipment and contribute to an increase in excavation costs. In the presented tool we assume that the excavated soil is dry common soil with no additional costs accrued for drilling and blasting.
    - The equipment used: since bioretentions are usually small in size and do not require deep excavations we assume that the equipment used is a half cubic yard wheel mounted excavator.

    - The excavated volume in a functional unit of a bioretention (square foot) is calculated by multiplying 1sq.Ft. by the total depth of the media (including the ponding depth). We add to that the allocation of extra excavation needed to stabilize the excavation banks, site slope and additional grading needed around the bioretention. The sum of these additional excavations are estimated and preset, in the presented tool, as 40 percent of the media volume. The excavation cost is estimated using the bank soil volume:
      Bank soil Volume= Excavation volume x (1+swell factor)
      Where: the swell factor is preset as 25%.
      The allocations of costs to the functional unit are estimated based on a preset average bioretetion area of 480 sq. Ft.

- Loading onto trucks is estimated as a percentage of the excavation cost (as suggested in GORDIAN-RSMeans (2017)).
- Rough Grading of the excavation bottom.
- Haul/Dispose of Excavated Material is estimated based on the bank soil volume and the assumption that trucks travel 4 miles to the dumping site at a speed of

20MPH with a 15 min wait time for dumping. We assume that there is no dumping surcharge/fee.

- Rock Media is installed in 8 inch rises and lightly compacted.
- Geotextile membrane wraps the rock media.
- Planting Media is mixed and filled manually.
- Outflow Structure is considered as precast concrete.
- Overflow piping is considered as 4 inches PVC pipe installed at 4 feet depth and 40 feet long (preset distance from overflow to storm manhole).
- Energy Dissipation Apron 4 square feet of riprap.
- Revegetation/planting:
  - 300 trees per acre of bioretention.
  - 700 Shrubs per acre of bioretention.
- Mulching 3 inches deep and hand spread.

- Permeable pavement: the presented tool models permeable alleys and parallel parking. Since infiltration beds should be placed on a level plane and to account for site slope, the subbase should be terraced. Based on that, the cost of permeable parking will be estimated based on the alley/parking width of 9 feet and terrace length of 60 feet. So we assume that the permeable pavement will be installed in sections of 9 by 60 feet.

  - Excavation/Grading: since the permeable pavement installation has a well-defined shape (contrary to the bioretention case) the excavation volume can be estimated more accurately based on the media depth, excavation sides slope (preset as 1:1) and the average site slope. The equipment used is a ¾ cubic yard wheel mounted excavator.

  - Haul/Dispose of Excavated Material is estimated based on the bank soil volume and the assumption that trucks travel 4 miles to the dumping site at a speed of 20MPH with a 15 min wait time for dumping. We assume that there is no dumping surcharge/fee.

- Subbase Rock Media is installed in 8 inch rises and lightly compacted.
- Subdrainage: perforated 6 inch PVC pipe placed along the length of the excavation bottom and connected to the outflow structure.
- Geotextile membrane placed along the excavation bottom
- Permeable Surface consists of open graded plant mix asphalt.
- Outflow Structure made of precast concrete

Some additional construction activities might be required depending on the specificity of the placement of the permeable pavement like curb installation, revegetation and erosion control that are necessary to prevent clogging of the permeable surface. These additional costs are not included in the presented tool, but, the user has the option to add them.

- Cisterns:
  - Excavation for footing is performed manually and 2 feet deep
  - Footing placement consists of hand compacting and leveling crushed stone.
  - Installation of the water tank includes the cost of the tank and the manual labor of the installation including additional piping and overflow.

4-4.2 Operation and maintenance costs

These costs are estimated based on the recurring maintenance activities conducted on the GSIE to ensure their proper functioning as outlined in the PA DEP 2006.
Maintenance activities for planting beds of green roofs and bioretentions are similar; they both require weeding and trash policing twice a year. In addition to these activities, during the first year, it is required to replant die offs, fertilize and water four times. bioretentions need to be mulched every other year. Permeable pavement requires vacuuming twice a year and small area patching every third year. Cisterns need to be cleaned and shutoff once a year before frost season.

System failures and major repairs are not modeled in the tool since these are incidental occurrences and might happen to any system installed (whether gray or green).

4-4.3 End of useful life costs

In the presented tool we estimate end of life costs as demolition costs for the GSIE. The main expenditure to demolish a bioretention and a pervious pavement in order to replace them is the cost pertaining to excavation, hauling and dumping of the excavated materials. Since these activities are covered in the construction process of these GSIE, we assume that the end of life costs for bioretention and permeable pavement are negligible and considered null in order to avoid double counting. Also, for cisterns the main expenditure for removing the cistern is dumping fees, and since these fees are small, we estimate the end of life cost for cisterns to be negligible.

Demolition costs for green roof are estimated based on manual excavation of planting soil and removal of different layers of the roof and manual loading. Hoisting down, hauling and dumping assumptions are the same as corresponding activities in construction.

4-4.4 LCC Net Present Value and Annualized costs

Each of the costs discussed so far in this section accrues over a different time period of the GSIE life cycle as shown in Figure 11. The acquisition costs of the GSI, including site, soft and construction costs, are considered to occur at year zero. The operation and maintenance costs occur along the useful life of the GSIE and the demolition costs occur at the end of the useful life of GSIE. The presented tool discounts these costs to year zero using the preset interest rate.

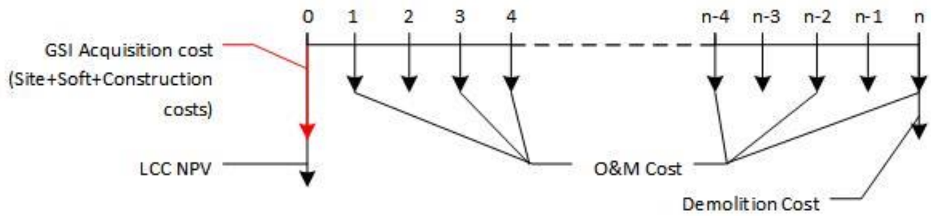


Figure 11: Life Cycle Cost cash flow diagram

The expected useful life varies between GSIE; green roofs and bioretentions are expected to last 40 years, permeable pavement 20 and cisterns 30. These values are presets in the tool and can be modified by the user. In order to be able to compare the LCC of the GSIEs and incorporate them in the optimization model, the presented tool estimates the annualized LCC. Using this value rather than the NPV removes the life expectancy variability from the comparison and provides more accurate evaluation of strategies.

4-5 Life Cycle Assessment

The presented tool has the capability to perform the Life Cycle Inventory (LCI) portion of the Life Cycle Assessment (LCA). The LCI has two main objectives:

- To estimate the additional economic activity generated by the investment in 1 functional unit of each GSIE design variation.
- To estimate GreenHouse Gases (GHG) emitted by implementing 1 functional unit of each GSIE design variation in tons of CO2equivalent.

As previously mentioned, the functional unit for green roofs, bioretention and permeable pavement is a square foot of these GSIE. While the functional unit for cisterns is a cistern as a unit.

The Economic Input-Output model of the EIOLCA tool (CMU Green Design Institute 2008) is used to estimate the added economic activity and quantity of CO2e generated over the life cycle of the functional unit of GSIE. The added economic activity per functional unit is used by the tool to estimate the additional tax revenues (discussed in Section 4-7) and the mass of CO2e generated by the functional unit implementation is considered as a negative externality and the tool uses this amount to estimate the total mass of CO_2e generated by the generated strategies and their economic values (discussed in Section 4-7).

We followed the same method of using the EIOLCA tool as Blackhurst, Hendrickson, and Matthews 2010; construction materials production and construction activities are considered within the scope of this LCI. The manufacturing of equipment utilized is not considered in this LCI. (refer to Figure 12)

The economic sectors used for construction and end of life demolition LCI calculations for different GSIE pertain to the 2007 US National Producer model and are listed in Table 14. The allocation of outputs from each sector is defined by the land use information provided by the user. The construction sector for highways, streets and bridges is used only for construction activities of permeable pavement. All cost data collected is transformed to 2007 dollars before running it through the EIOLCA tool.

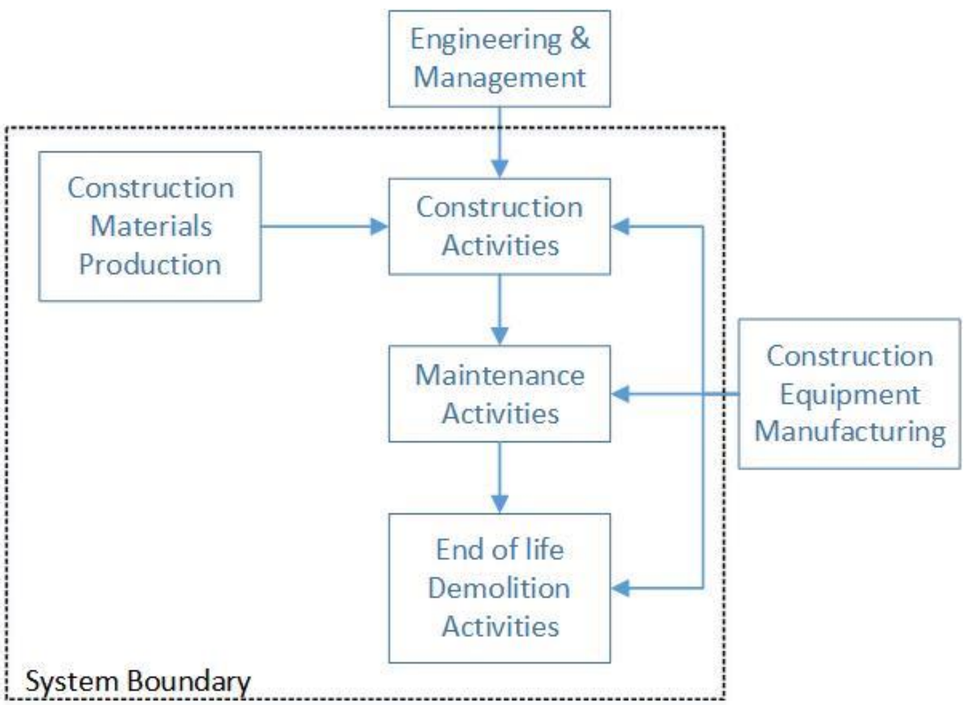


Figure 12: Life Cycle Assessment process and system boundary diagram.

Sector #	Sector Name
2332A0	Commercial Structures, Including Farm Structures
233411	Single-Family Homes
2334A0	Other Residential Structures
2332B0	Other Nonresidential Structures
233293	Highways, Streets, And Bridges

Table 14: Construction activities corresponding economic sectors

Economic sectors corresponding to the construction materials are listed for each GSIE in Table 15. The maintenance activities LCI is generated using two economic sectors; Nonresidential and Residential Building Repair and Maintenance selected based on the land use information provided by the user.

	Construction Materials	Sector #	Sector Name
Green Roof	Vegetation	111400	Greenhouse Crops, Mushrooms, Nurseries, And Flowers
	Planting Medium (soil)	325310	Fertilizers
	Waterproofing	324122	Asphalt shingle and coating materials manufacturing
	Root Barrier	325211	Plastics
	Water retention/detention layer + Barrier	326190	Other Plastic Products
	Edging	113000	Timber And Raw Forest Products
Bioretention	Rock Media	2123A0	Sand, Gravel, Clay, Phosphate, Other Nonmetallic Minerals
	Geotextile membrane	3252A0	Synthetic Rubber And Artificial And Synthetic Fibers
	Planting Media	325310	Fertilizers
	Outflow Structure	327330	Concrete Pipe, Bricks, And Blocks
	Overflow piping	326120	Plastic Pipe, Fittings, And Sausage Casings
	Energy Dissipation Apron	2123A0	Sand, Gravel, Clay, Phosphate, Other Nonmetallic Minerals
	Revegetation/planting	111400	Greenhouse Crops, Mushrooms, Nurseries, And Flowers
	Mulching	111400	Greenhouse Crops, Mushrooms, Nurseries, And Flowers
Permeable Pavement	Subbase Rock Media	2123A0	Sand, Gravel, Clay, Phosphate, Other Nonmetallic Minerals
	Subdrainage perforated pipes	326120	Plastic Pipe, Fittings, And Sausage Casings
	Geotextile membrane	3252A0	Synthetic Rubber And Artificial And Synthetic Fibers
	Permeable Surface Paving	324121	Asphalt Pavement
	Outflow Structure/Pipe	327330	Concrete Pipe, Bricks, And Blocks
Cisterns	Storage tank	326190	Other Plastic Products
	Gravel fill	2123A0	Sand, Gravel, Clay, Phosphate, Other Nonmetallic Minerals

Table 15: Economic sectors corresponding to the construction materials

4-6 Opportunity Cost

Two types of costs will be considered as opportunity costs: Land cost and cost of equivalent function installations.

Land opportunity cost: If land is purchased to be used for GSI implementation, the cost of land is considered part of the procurement costs (service cost) and should be defined by the user. In the case of land use forgone or gained by implementing GSI, the value of the lost or gained use of that land should be taken in consideration in total cost estimation. However, at the planning phase there is no way of getting such information since it is specific to the location of implementation. This cost should be defined by the user; otherwise it will be assumed to equal zero.

Cost of installations with equivalent function: this consists of estimating the cost of a traditional installation fulfilling similar functions in case that function is needed regardless of GSI plan implementation. This cost pertains to the value of the general function of the GSIEs as listed in Table 6 (not for their hydrologic function). It is different from the cost of equivalent grey infrastructure described in 4-7.2 and used as a Willingness To Pay (WTP) value for water benefits. Two GSIEs considered in the presented tool have equivalent functions that does not pertain to hydrology; green roofs (as waterproofing and insulation) and permeable pavement (as road/parking).

The method used to estimate the unit cost of the equivalent traditional (grey) installation is similar to the method used while formulating the service unit cost. However, in this case there will not be a hydrology variable included since the grey installation does not have any hydrologic functionality. So first we estimate the component amounts of grey installation per functional unit. Then, we estimate the unit cost based on collected cost data.

Since the presented tool accounts for the external costs of each GSIE, the external costs of these installations are quantified and monetized in order to discount it from the GSIEs external cost. Similar to the external costs of GSIEs, the impact that will be quantified and monetized is GHG emissions. An LCA will be performed using the EIO-LCA tool to quantify these impacts

following the same method outlined in Section 4-5. The monetization method is described in Section 4-7.2. (Also refer to
Figure **19** in Appendix A-2)

The cost and LCA of a traditional roof are calculated based on a 25 year rated asphalt roof shingle. The "grey" pavement cost and LCA are estimated based on 3.5 inches of plant mixed asphalt pavement with 8 inches of subbase of compacted gravel and a storm drainage manhole every 180 feet.

4-7 Externalities and Benefits Calculations

This section presents the quantification and monetizing methods of externalities and benefits used in the tool. The calculations discussed in this section are performed by functional unit of each GSIE.

4-7.1 External costs

The external costs or externalities are the costs accrued from negative impacts of implementing the GSI plan. These costs pertain to the emission of GHG and air, water and solid contaminants over the life cycle of each GSIE included within the GSI plan.

As previously mentioned (in Section 4-5) the external cost considered in the presented tool is the GHG emissions. The method to quantify the amounts of GHG emitted by functional unit of each GSIE over its life cycle is described in Section 4-5 in terms of mass of CO2e. For green roofs and permeable pavements this amount of GHG emitted is discounted by the amount of GHG emitted by the equivalent traditional (grey) installation as discussed in Section 4-6.

The monetary value of GHG emission is estimated by Capoor and Ambrosi (2009) using the Willingness to Pay (WTP) method for estimating the market value of carbon (investments in carbon reduction and mass of resulting carbon saved). This value is estimated as $26.26/tCO2e (in 2008 dollars).

Shelanski and Obstfeld (2015) and Environmental Defense Fund (2019) report that the US Government estimates the monetary value of carbon using a cost avoidance method where this value is considered to be equivalent to the rising health care costs, damages to property, increased food prices and other costs accrued by different entities in the US (individuals, businesses and government) due to GHG emissions. This value is estimated to be at minimum $40 (in 2018 dollars). In the presented tool we use this value since it better represents the American market.

4-7.2 Benefits value

There are three main components of the GSI plan that generate benefits; the economic multiplier of the service cost, water savings (retention, detention and water treatment) and trees and green spaces. (Refer to Table 16)

Benefit Category	Impact	Metrics	Economic Valuation
Hydrology	Improve water quality: Nutrients Sediments & TSS Dissolved solids Bacterial & Other Toxins	Mass of water contaminant removed (TSS, TP & TN)	LCC of a Sedimentation basin with flow rate capacity equivalent to the peak rate captured by GSI. Construction & O&M cost Source: (Walker et Al. 1993)
	Fresh water availability	Volume of water reused	Cost of fresh water (PWSA 2018) Rates
	Reduce flood risks	Peak rate reduced	Cost of storage/detention basin (Walker et Al. 1993) (Heaney et Al. 2002)
	Increase ground recharge	Volume of water infiltrated	Tetratec (2016), Reese & Risser (2010)
Trees And Green space	Reduce aquatic thermal impacts	Number of Trees & Green Space area	McPherson et al. (2007) for trees Stratus Consulting (2009) for Green Space CNT (2013) for green roofs reduced energy demand
	Reduce energy demand		
	Carbon sequestration		
	Air purification		
	Noise Reduction		
	Reduce runoff Water		
	Preserve natural habitat		
Investment	Employment opportunities, Tax Revenues	Additional Economic Activity (EIO-LCA)	Potential Tax revenues

Table 16: Benefits Metrics and Monetization Methods

The potential tax revenue is used as a surrogate for the socio-economic benefit of investing in the GSI plan. It represents the added economic activity that generates employment opportunities and funds for the local governments for social improvement projects. While this benefit is not relevant for private sector investors, it is widely used by planners and policy makers for public project planning. It is estimated by multiplying a user defined tax rate by the added economic activity estimated by the LCI calculation module in the tool and discussed in Section 4-5.

The cost avoidance valuation concept is applied to estimate the economic value of water saving; the costs of grey infrastructure that provide similar retention, detention and water treatment functions is used as a surrogate for hydrologic benefits. The hydrologic benefits are quantified and monetized in the presented tool as follows:

- Improving water quality: in Section 4-3.2.4 we presented the formulae for calculating μ_i (the total generated mass of contaminant *i)* and μ_{post_i} (the total mass of contaminant i generated by the post development strategy). To quantify the improvement of water quality as a result of implementing the GSI plan we calculate $\Delta_{\mu i}$ the net reduction in contaminants mass:

  Equation 4-14: GSI net reduction in contaminants mass

  $$\Delta_{\mu i} = \boldsymbol{\mu_i} - \boldsymbol{\mu_{post_i}}$$

  Where: i refers to the contaminant (TSS, TP and TN)

  This type of calculation is useful for the Multi Criteria Decision Making model that uses $\Delta_{\mu i}$ as one of the objectives to be maximized.

  The monetary value of the GSI water treatment function is estimated as the avoided cost of implementing a comparable sedimentation basin. These basins are sized based on the maximum water flow (rate) capacity. For that, we used the peak rate reduction (captured by GSIEs) described in Section 4-3.2.3 in the cost formulation by Walker et al. (1993) that define the construction and operation and maintenance costs of the sedimentation basin as a function of that flow rate. The soft costs are estimated using the same method used in LCC (refer to Section 4-4) and the end of life decommissioning is estimated to be negligible.

- The peak rate reduction benefit monetary value is estimated as equivalent to the avoided cost of building a detention basin that has the same capacity as the total abstracted volume by all GSIEs for the peak rate design storm. We used Walker et al. (1993) construction and operation and maintenance costs formulae to estimate this value. The soft costs are estimated using the same method used in LCC (refer to Section 4-4) and the end of life decommissioning is estimated to be negligible.

- The monetary value of water reused is estimated using the avoided cost of purchasing fresh water. This value is estimated by multiplying the average annual volume of water reused (refer to Section 0) by the cost of water provided by Pittsburgh Water and Sewer Authority (2018). The cost of water is selected based on 1 inch residential meter and 5000 gallon supplied. This cost includes the sewer cost allocation.

- The value of aquafer recharge due to soil infiltration is quantified and monetized in the presented tool using the method outlined in Tetratec (2016). The water recharge is defined by the hydrologic soil type. The marginal value of water recharge is estimated for the state of Pennsylvania as $110 /acre foot (in 2011 dollars). Tetratec (2016) estimated this value based on the WTP for extracted high quality fresh water in bulk (wholesale purchase).

- The life cycle impact of the grey infrastructure and the potential benefits that green infrastructure can provide in terms of reducing carbon and air emissions. This can be quantified using the EIO-LCA tool then valuated using the unit cost of CO2 and should be incorporated in the market ready tool.

To estimate the value of trees and green space components, McPherson et al. (2007) presents the value of trees (costs and impacts) of different sizes over their whole life (refer to Table 17). To estimate the number of trees in a green space, PA DEP (2006) states the average number of trees in an acre of each BMP. However, the value of treeless green spaces (like green roofs and some design variations of bioretention) is not captured by this valuation method. For these types of green spaces, monetary values of benefits are estimated using Stratus Consulting (2009) estimates for the increase of property value due to green space adjacency. This increase is estimated to be 2%. The median residential property value in Pittsburgh is $108,500 (Census Bureau, 2017). In the presented tool, we use this information along with the assumption that 5 residential properties are adjacent to 1/3 acre of green space to allocate the value of property increase to the area of additional green space.

Trees Benefit	**Monetization Method**
Reduced heat island effect and wind break	Avoided heating and cooling costs
Improve air quality	Avoided pollution costs
Rain water capture	Willingness to pay for water management and treatment
Improved esthetics	Increase in property value

Table 17: Monetizing values of trees benefits in McPherson et al. (2007)

In addition to these benefits, green roofs serve as thermal barriers and increase the thermal insulation factor of the roof. This decreases the amount of heating and cooling needed. So the avoided heating and cooling costs are used as a surrogate for the increase in thermal insulation for green roofs. The calculation for this monetary benefit is outlined in CNT (2013) as follows:

Equation 4-15: Green roofs thermal insulation heating monetary benefit

$$B_{Heating} = \left(\frac{1}{R_{Grey}} - \frac{1}{R_{Green}}\right) \times Hdd \times Gas\ heat\ content \times C_{Gas}$$

Where:

$B_{Heating}$ is the monetary value of avoided heating

R_{Grey}= 11.34 SF x °F x hrs/Btu (R value for conventional roofs. Source: CNT (2013))

R_{Green}= R = 23.4 SF x °F x hrs/Btu (R value for green roofs. Source: CNT (2013))

Hdd is heating degree days. Source: Pittsburgh Weather Forecast Office (2019)

C_{Gas} is the average cost of natural gas. Source: US EIA (2019)

$Gas\ heat\ content$ Source: US EIA (2019b)

Similarly we estimate the value of cooling benefit:

Equation 4-16: Green roofs thermal insulation cooling monetary benefit

$$B_{cooling} = \left(\frac{1}{R_{Grey}} - \frac{1}{R_{Green}}\right) \times Cdd \times C_{Electricity}$$

Where:

$B_{Cooling}$ is the monetary value of avoided cooling

R_{Grey}= 11.34 SF x °F x hrs/Btu (R value for conventional roofs. Source: CNT (2013))

R_{Green}= R = 23.4 SF x °F x hrs/Btu (R value for green roofs. Source: CNT (2013))

Cdd is Cooling degree days. Source: Pittsburgh Weather Forecast Office (2019)

$C_{Electricity}$ is the average cost of electricity. Source: US EIA (2019a)

All units in these calculations are transformed to be compatible.

In all benefits calculations, we transform all collected data pertaining to costs and benefits monetary values to match the functional unit of each GSIE and to be in 2017 dollars.

4-8 Optimization

The role of the optimization model is to generate the best attainable solution to the problem at hand. In the case of GSI planning the main objective is to generate a combination of GSIEs (a strategy) that maximizes the potential benefits to be reaped and minimizes the costs while meeting different design, hydrology and Stakeholders' objectives. Unless otherwise stated, we developed all formulations presented in this chapter specifically for the tool and are coded in M.S. Excel to be interoperable with all previous formulations.

4-8.1 Optimization formulation

The optimization model formulation will be as follows:

Equation 4-17: Optimization objective function

$$Max\ Z = \sum_i (B_i - C_{T_i}) X_i$$

$$X_i \in \mathbb{R}^+$$

Where:

X_i is the amount of GSI element (i) to be implemented (in functional unit)

$C_{T_i}$is the Annualized Total cost of GSI element (i) per functional unit (includes service, opportunity and externality costs)

B_i is the Annualized total benefits of GSI element (i) per functional unit

Subject to:

- Budget constraint:

Equation 4-18: Budget Constraint

$$g_1 = \sum_i (C_{Si} X_i) \leq T_B$$

Where:

C_{Si} is the first cost of GSI element (i) per functional unit (includes construction and soft costs.

T_B is the expected acquisition budget.

- Runoff volume Control Guideline 1 (CG1) from PA DEP (2006) requires post development runoff volume be reduced to predevelopment levels (all volumes calculated based on volume control design storm, refer to Section 4-3.2.2):

Equation 4-19: Runoff volume constraint

$$g_2 = Q_{Pre} - \sum_i ((R_i + D_i)X_i) \leq Q_0$$

Where:

Q_{Pre} = Total Pre-GSI plan implementation runoff volume.

Q_0 = Total Pre-development runoff volume.

R_i = Retention volume per functional unit of GSI element (i).

D_i = Retention volume per functional unit of GSI element (i).

- Peak rate control as outlined in PA DEP (2006) and calculated based on a peak rate design storm (refer to Section 4-3.2.3):

Equation 4-20: Peak rate constraint

$$g_3 = \Psi_{Pre} - \sum_i (\Psi_i X_i) \leq \Psi_0$$

Where:

Ψ_{Pre} = Pre-GSI plan implementation runoff Peak rate flow.

Ψ_0 = Pre-development runoff Peak rate flow.

Ψ_i = Runoff peak rate reduction of GSI element (i) per functional unit

- Water quality constraints: GSIEs have to capture 85% of TSS and P and 50% of NOx of the post development site generated mass of contaminants. (refer to Section 4-3.2.4). Since the PA DEP (2006) does not require the NOx target to be met, the tool performs all NOx calculations. However, the user has the choice to include or exclude the NOx constraint from the optimization model.

Equation 4-21: Contaminant amounts constraints

$$g_{j_4} = \mu_{post_i} \leq \mu_{pre_i} \times (1 - \theta_{Ri})$$

Where:

μ_{post_i} is the total mass of contaminant i generated by the post development strategy

μ_{pre_i} is the total mass of contaminant i generated by the site pre GSI strategy implementation

θ_{Ri} is the required removal rate of contaminant i

- Other constraints like restricting the total area that drains to GSIE to be less or equal to the total impervious area.

In this formulation the Net Total Benefits (B_i) is the estimated economic value of benefits: where each benefit is represented by a dollar value and the objective function will consist of maximizing the monetary value of the net benefit. This method will generate specific values for the decision variables. As discussed in Section 3-8.3, the drawback of this formulation is that the environmental and social benefits are underestimated and misrepresented in the objective function. In addition the economic multiplier cannot be part of the benefit formulation.

4-8.2 Multi-Criteria Decision Model

This model is developed to overcome the limitations of the monetary formulation of the previous model and to represent the preferences of different stakeholders in generating strategies. In this model, the annual net benefit is divided into four categories each representing a decision criterion to be maximized based on its relative importance to the stakeholders. We attach a weight to each criterion which can represent stakeholders' preferences. The user can test different values for the weights to generate the solutions that correspond to different preferences. Alternatively, the weights can also be used to generate non-dominated solutions as discussed further below.

The Objective function for this model is as follows:

Equation 4-22: Multi-criteria objective function

$$Max\ Z_M = \sum_j (\omega_j \mathrm{Z}_j)$$

Where:

Z_j is the decision criterion quantifying cost or benefit j where j pertains to the hydrologic, environmental and socio-economic benefits and the annualized LCC. Z_j is a function of X_i.

ω_j is an assigned weight of value between 0 and 1, with the sum of all ω_j is equal to 1.

The constraints remain the same as in the monetary optimization formulation.

In this model we developed two formulations:

- The firsts consists of using the monetary value of each criterion:
    - Hydrology criterion: is considered as the sum of the values of water infiltrated, treated and captured, in addition to the value of peak rate reduced.
    - Environmental criterion: consists of the sum of the values of green spaces and trees less the value of the life cycle GHG emissions of the GSI strategy.
    - The socio-economic criterion: the potential added tax revenues from the economic activity generated by the implementation of the strategy are considered as a surrogate for the socio-economic benefits.
    - The net expenditures are the net value of the life cycle cost.

- The second consists of using the physical quantities, not monetary values, for each criterion. So each criterion is expressed in a different unit. The modeled criteria in this formulation are:
    - Hydrologic criterion: the peak rate reduction amount is used as a surrogate for this benefit category.
    - Environmental criterion is represented by the number of trees planted
    - The socio-economic criterion is represented by the monetary value of additional economic activity generated, estimated using EIO LCA tool (Carnegie Mellon University Green Design Institute 2008).
    - The net expenditures remain as the net value of the life cycle cost.

This formulation is similar to the M. Hill's planning method (Hill 1968) that consists of developing a goal matrix (by stakeholders) that ranks achievement criteria that are represented by corresponding quantities.

We explored the tradeoffs among the criteria by considering three pairs of criteria: the net LCC criterion paired with each of the other three. We used the the NISE algorithm (Cohon et Al. 1979; Solanki and Cohon 1989) to generate the non-dominated solutions to each combination formulation. The NISE method starts by finding the non-dominated optima of individual criteria. Call Z_j^* the optimal value of criterion j. the algorithm then finds the next non-dominated solution so on to improve the approximation of the non-dominated set as much as possible. It does this by solving the weighted objective function in Equation 4-22 with:

$$-\frac{\omega_j}{\omega_{j+1}} = s$$

Where:

s is the slope of the line connecting Z_j^* and Z^*_{j+1}.

Further iterations of the NISE algorithm can be coded by the user to generate the full non-dominated set.

4-8.3 Optimization Solving Algorithms

All functions included in the optimization model are linear except three formulae for estimating the cost of traditional stormwater infrastructure. These formulae are in the form of $f(x) = ax^b$ where "a" and "b" are constants and "b" is positive and less than 1, making these formulae concave. We used Generalized Reduced Gradient (GRG) algorithm, run for 100 iterations, each with a random starting point in order to avoid local maximum solutions.

4-8.4 Sensitivity analysis

The tool allows the user to perform manual iterations of costs and hydrologic parameters in order to generate maximum/minimum potential variations in the generated strategy. The collected cost data includes variation of cost estimation based on variability of construction methods. For example: different excavation methods along with corresponding costs are listed in the construction cost database; the user can modify the cost function of each GSIE to reflect the change in construction methods. In addition, the user can test the impact of different storms on the hydrology profile of the generated strategy by changing the selected design storm. Further automation of the development of the sensitivity analysis and the incorporation of Monte Carlo simulation is recommended in the future development of a market ready tool.

5 Tool testing

The tool was tested on a residential site in the City of Pittsburgh. The test site was a subject of a redevelopment project that included a GSI plan. The tool testing described in this chapter consists of using the site data and redevelopment areas as inputs to the tool in order to generate alternative strategies. This chapter presents an assessment of the tool performance and outcome based on a comparison between these strategies and the developer's proposed plan.

5-1 Test Site Information

The test site total area is 16.1 acres (701,316 square feet). The developer plans to demolish all structures on site and redevelop it as a residential complex. The proposed building types are either two story row houses or five to six story high condominiums. The existing site slope varies between 1 to 5 percent. The hydrologic soil type is "C". The existing site and proposed development land cover areas are listed in Table 18. The proposed site is densely developed and 100 percent of the site area will be disturbed due to construction activity.

Areas in Sq. Ft.	**Existing Site**	**Proposed Development**
Roof tops	130,000*	179,271
Impervious	234,000*	212,642
Meadow	0	0
Woods	0	0
Open Space (fair)	337,316	309,403
Total Area	**701,316**	**701,316**
* Estimated and rounded to the nearest thousand		

Table 18: Test site existing and proposed land cover areas.

The figures presented in Table 18 are estimated using area takeoff from the site plan included in the GSI plan.

5-2 Proposed GSI plan

The proposed development included a GSI plan that was developed to meet the PA DEP (2006) requirements in runoff volume, peak rate and quality. The GSI plan includes the implementation of green roofs, bioretentions and permeable pavements as listed in Table 19. (For GSI Types parameters refer to Appendix A-3). In addition to the GSIE, the plan includes the application of some non-structural measures like street sweeping that improve runoff water quality and help meet the PA DEP (2006) required quality measures. The type and amount of GSI presented in Table 19 are estimated based on a combination of methods: areas taken from plans, analysis of detailed drawings and provided hydrologic capacity of each GSIE.

GSIE	Design Type	Capacity (Gal/SF)	Amount	Unit
Green Roof	GR-1	1.56	23,256.00	Sq.Ft.
Bioretention	BR-5	11.78	21,995.00	Sq.Ft.
Permeable Pavement	PP-1	1.99	23,186.00	Sq.Ft.
	PP-6	11.97	6400.00	Sq.Ft.
	PP-8	15.96	3192.00	Sq.Ft.

Table 19: Test site planned GSIE

5-3 Test Site Calculations

The data presented in Sections 5-1 and 5-2 was entered in the tool that instantly generated two types of data as follows:

- Target hydrologic objectives to be met:
    - Maximum allowed runoff volume
    - Maximum allowed peak rate
    - Maximum amounts of contaminants in runoff water.
    - Maximum drainage areas for GSIE.

- Proposed plan calculations:
    - All hydrologic calculations to be compared to the hydrologic objectives listed above.
    - Estimate of the first cost of the proposed plan.
    - The annualized net benefit value including a breakdown list of values for all included costs and benefits.

Table 20.presents a summary of the calculations. It shows that the proposed plan first cost was estimated around $3 million and that it met the runoff and peak rate requirements of the PA DEP (2006). However, the proposed plan does not meet the water quality requirements for TSS, TP and NOx. This outcome was expected since the proposed plan included non-structural measures to improve runoff water quality discussed in Section 5-2. These measures are beyond the scope of the prototype and their impacts on water quality are not quantified.

		Proposed Plan	Objectives		Unit
Budget Control	First cost NPV	3.03			M $ (2017)
Runoff Control	2 year/24 hr storm	391	≤	492	K. Gal
Peak Rate Control	100 year/24 hr storm	1.68	≤	1.68	Cu. Ft/s
Water Quality Control	TSS load	148303	≤	37781	g
	TP load	419	≤	106	g
	Nitrate load	974	≤	573	g
GSI Drainage Area Control	Impervious surfaces	176	≤	213	K Sq.Ft.
	Roofs	23	≤	179	K Sq.Ft.
Annual Net Benefits		97			K $ (2017)

Table 20: Test site objectives versus proposed plan outcome

5-4 Strategy Generation Tests

5-4.1 Optimization Test

The aim of this test is to check whether the tool can find potential solutions/ strategies (combination of GSIE) that costs less (first cost) and yield higher net benefit than the proposed plan.

Test 1: The first optimization test consists of using the site data discussed in Section 5-1 and a target budget of $2.8 million (about $200,000 less than estimated budget of the proposed plan).

The GRG algorithm is used to solve the optimization as described in Section 4-8.3. However no feasible solutions were found due to unmet water quality requirements even with all runoff water from impervious surfaces directed to GSIEs.

Test 2: Based on the outcome of Test 1, a second test was performed. The same inputs and formulation are used in this second test as the first one with the exception of relaxing the water quality constraints to be less than or equal to the amounts of contaminants in the predevelopment natural site conditions. Since this site was already developed and natural conditions are unknown, PA DEP (2006) presents a method to generate the predevelopment hydrologic profile of a site referred to as "CG1 Predevelopment Areas" and described in Section 4-3.2.2. Doing so will allow a significant increase in runoff water contaminants (from around 37.8 million to 135.8 million mg of TSS) but limit them to be less than the amount generated by the proposed plan (148.3 million mg of TSS).

The GRG algorithm found a strategy (referred to as Test 2 strategy) that satisfies all constraints and meets all decision criteria and is located (geometrically) at the intersection of the two bounding constraints; the budget and TSS load. This means that Test 2 strategy is a result of a balance between first cost and water quality requirements.

This strategy consists of implementing 79,157 square Feet of PP-3 permeable pavements and 6,015 square Feet of BR-4 bioretentions. Doing so will cost $200,000 less than the proposed plan and generate over double the annual net benefits. The generated strategy also improves all hydrologic functions' outcomes including the ones pertaining to water quality compared to the proposed plan (refer to Table 21).

Test 2 strategy maximizes the selection of pervious pavement. However site suitability for implementing this GSIE might be limited due to the susceptibility to clogging by washed-over debris from surrounding surfaces. Based on this notion an additional test is conducted.

Test 3: This test consists of using the same formulation as Test 2 with the exception of adding an additional constraint that limits the total area of permeable pavement to be less or equal to the proposed plan pervious pavement area; 32,778 Square Feet. The GRG algorithm found a solution (referred to as Test 3 strategy) that also bests the proposed plan in every aspect. This strategy consists of implementing 29,417 Square Feet of bioretention (BR-6 design variation) and 32,778 square Feet of pervious pavement (PP-3 design variation). Test 3 strategy costs about $500,000 less than the proposed plan and generates a little less than double the net annual benefits but less than Test 2. (Refer to Table 21).

		Proposed Plan	Test 2	Test 3		Constraints	Unit[c]
Annual Net Benefits		97.3	208.8	185.0		Maximize	K $ (2017)
Budget Control	First cost NPV	3.0	2.8	2.5	≤	2.8	M $ (2017)
Runoff Control	2 year/24 hr storm	391.3	384.8	349.3	≤	492.1	K. Gal
Peak Rate Control	100 year/24 hr storm	1.68	1.42	1.43	≤	1.68	Cu. Ft/s
Water Quality Control	TSS load	148,303	135,873	122,956	≤	135,873	g
	TP load	419	391	353	≤	454	g
	Nitrate load[a]	974	960	937	≤	832	g
GSI Drainage Area Control	Impervious surfaces	175.5	188.4	212.6	≤	212.6	K Sq.Ft.
	Roofs	23.3	0.0	0.0	≤	179.3	K Sq.Ft.
GSIE Limit	Green Roofs	23.3	0	0	≤	-	K Sq.Ft.
	Bioretention	22.0	6.0	29.4	≤	-	K Sq.Ft.
	Porous Pavement	32.8	79.2	32.8	≤	32.8[b]	K Sq.Ft.
	Cisterns	0	0	0	≤	-	Gal

(a) Not required constraint and not included in generating Tests 2 and 3.
(b) For Test 3 only
(c) K = in thousands, M = in millions

Table 21: Comparison between test 2, test 3 and proposed plan outcomes.

5-4.2 MCDM Tests

This section discusses the outcome of a series of tests performed using the tool to search for strategies that reflect the needs and/or preferences of different stakeholders. As discussed in Section 4-8.2, four criteria are considered in the MCDM model; hydrology (Z1), environment (Z2), socio-economic (Z3) and annual expenditures (Z4). The tests consist of maximizing or minimizing and then finding other non-dominated solutions and their associated tradeoffs for Z4 paired with each of the other three criteria. In addition, Z2 and Z3 were also analyzed. The results of these tests are presented in Table 22 and

Table 23. These results show that:

- The tool generated strategies that reduce the first cost and improve site hydrology (reduce runoff volume, peak rate and contaminants load) over the proposed plan regardless of the decision criteria.

- The generated strategies that aim to maximize hydrologic and environmental benefits and/or minimize annual expenditures, yielded higher net annual benefits than the proposed plan. Only strategies geared toward maximizing socio-economic benefits yielded low net annual benefits.

  Test 3 (discussed in Section 5-4.1) and optimizing Z1 and Z4 criteria together generated the same solution that yields the highest net annual benefit of $185,011 (for this specific formulation). The net annual benefit is significantly reduced in any other tradeoff solution with a minimum of $55,614 obtained by optimizing Z3 with Z4.

- Bioretentions are the only GSIE present in all generated strategies. Green roofs are selected by the tool for strategies that maximize environmental and socioeconomic benefits, permeable pavements are selected for Hydrologic and annual expenditures benefits and finally, cisterns are selected for hydrologic and socio-economic benefits.

- The NISE method coupled with the GRG algorithm converged on a none-dominated solution for each of the pairwise optimizations. These solutions are represented in decision domain charts shown in Figure 13.

  Figure 13 shows that the non-dominated solution that optimizes the tradeoff between the environmental benefits (Z2) and the annual expenditures (Z4) criteria is skewed in favor of the latter criterion: Z2 value decreased by $34,650 from a maximum value of $53,611 while Z4 value decreased by only $9,693 from a maximum of ($107,874).

  The tradeoff is more balanced between Z1 and Z4 criteria where Z1 value decreases by $37,495 from $355,702 while Z4 value decreased by $46,301 from ($107,874) with a slight favor toward Z1 in weight distribution (0.46 for Z1 and 0.54 for Z4)

The minuscule tradeoff value of Z3 compared respectively to Z2 and Z4is well reflected by the weight distribution that largely favors Z3 over Z2 and Z4 (0.96 for Z3 in both cases) the tradeoff. In the first comparison, Z3 value drops by $523 from $9,841 while Z2 value drops by $21,040. In the second comparison, Z3 value decreases by $1,025 and Z4 value decreases by $82,118.

		Z1-Hydrology	Z2-Environment	Z3-Socio-Economic	Z4-Annual Expenditures		Constraints	Unit[3]
Budget Control	First cost NPV	2.8	2.8	2.8	1.8	≤	2.8	M $ (2017)
Runoff Control	2 year/24 hr storm	304	331	294	385	≤	492.1	K. Gal
Peak Rate Control	100 year/24 hr storm	1.42	1.68	1.46	1.68	≤	1.68	Cu. Ft/s
Water Quality Control	TSS load	119,393	131,438	118,740	135,873	≤	135,873	g
	TP load	331	366	327	391	≤	454	g
	Nitrate load[1]	882	940	881	960	≤	832	g
GSI Drainage Area Control	Impervious surfaces	213	206	213	188	≤	213	K Sq.Ft.
	Roofs	179	35	179	0	≤	179	K Sq.Ft.
GSIE Limit	Porous Pavement	28	0	0	33	≤	33	K Sq.Ft.
Annual Net Benefits		109	100	87	141		Maximize	K $ (2017)

		Z1 Vs Z4	Z2 Vs Z4	Z3 Vs Z4	Z2 Vs Z3		Constraints	Unit
Budget Control	First cost NPV	2.5	1.7	1.9	2.8	≤	2.8	M $ (2017)
Runoff Control	2 year/24 hr storm	349	385	325	304	≤	492.1	K. Gal
Peak Rate Control	100 year/24 hr storm	1.43	1.68	1.68	1.66	≤	1.68	Cu. Ft/s
Water Quality Control	TSS load	122,956	135,873	126,743	126,516	≤	135,873	g
	TP load	353	391	352	347	≤	454	g
	Nitrate load[1]	937	960	896	883	≤	832	g
GSI Drainage Area Control	Impervious surfaces	213	200	213	213	≤	213	K Sq.Ft.
	Roofs	0	0	179	179	≤	179	K Sq.Ft.
GSIE Limit	Porous Pavement	33	18	0	0	≤	33	K Sq.Ft.
	Objective weight Wj[2]	0.46	0.71	0.96	0.04			-
Annual Net Benefits		185	139	56	81		Maximize	K $ (2017)

(1) Not required constraint and not included in generating any of the the solutions

(2) Generated using the NISE method and Wj+1 = 1-Wj

(3) K = in thousands, M = in millions

Table 22: MCDM outcome: individual criterion optimization and pairwise none dominated solution.

Design Variations in Functional Units		Z1-Hydrology	Z2-Environment	Z3-Socio-Economic	Z4-Annual Expenditures	Z1 Vs Z4	Z2 Vs Z4	Z3 Vs Z4	Z2 Vs Z3
Green Roofs	GR-1	0	34,998	0	0	0	0	0	0
	GR-2	0	0	0	0	0	0	0	0
	GR-3	0	0	0	0	0	0	0	27,569
	GR-4	0	0	0	0	0	0	0	0
	GR-5	0	0	8,256	0	0	0	0	0
Bioretention	BR-1	0	30,000	0	0	0	21,302	25,943	30,000
	BR-2	0	0	0	24,567	0	0	0	0
	BR-3	0	0	0	0	0	0	0	0
	BR-4	0	0	0	0	0	8,698	4,057	0
	BR-5	0	0	0	0	0	0	0	0
	BR-6	31,371	11,234	42,528	0	29,417	2,796	12,528	12,528
Permeable Pavement	PP-1	0	0	0	0	0	0	0	0
	PP-2	0	0	0	11,481	0	0	0	0
	PP-3	27,893	0	0	21,297	32,778	17,870	0	0
	PP-4	0	0	0	0	0	0	0	0
	PP-5	0	0	0	0	0	0	0	0
	PP-6	0	0	0	0	0	0	0	0
	PP-7	0	0	0	0	0	0	0	0
	PP-8	0	0	0	0	0	0	0	0
Cisterns	CS-1	0	0	0	0	0	0	0	506
	CS-2	0	0	0	0	0	0	0	0
	CS-3	598	0	570	0	0	0	598	0

Table 23: Generated GSIEs design variations using NISE method

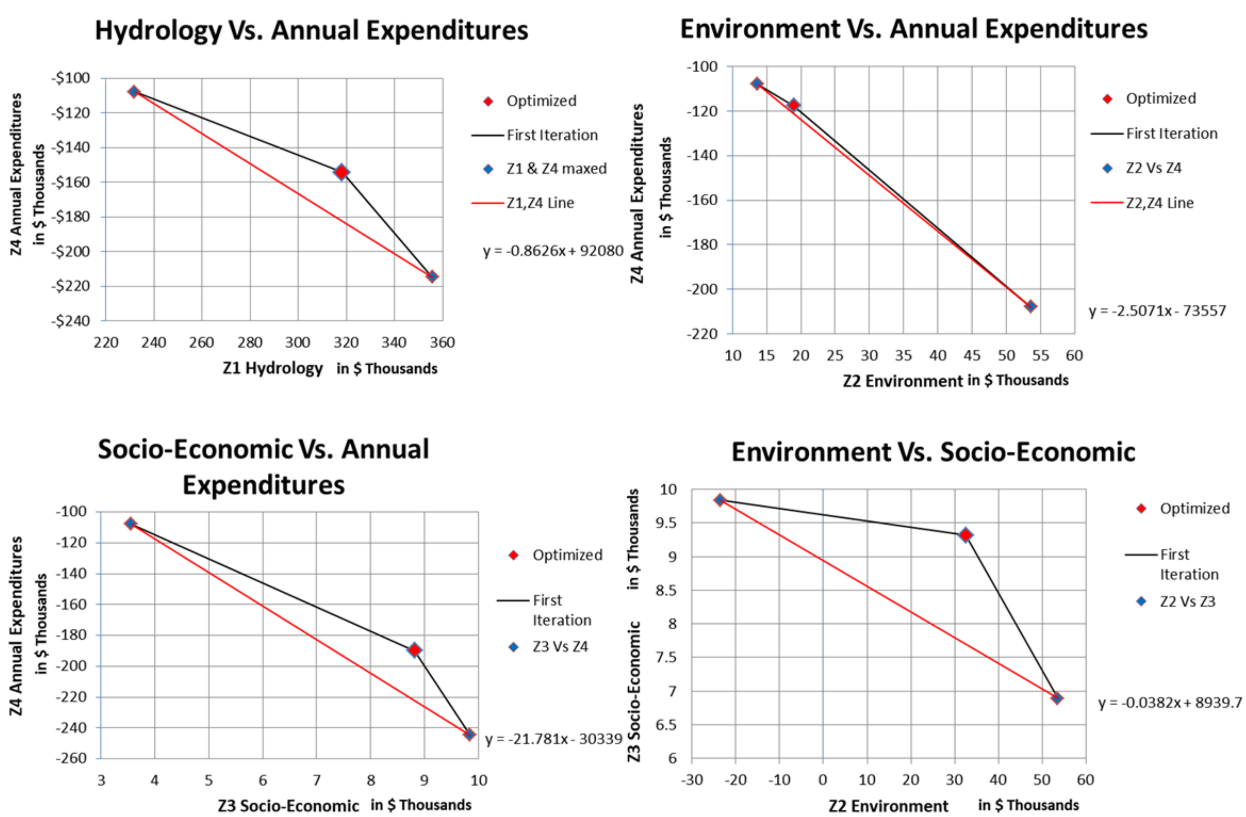


Figure 13: Decision space plots of MCDM none dominated solutions generated using NISE method.

5-4.3 Checking Solutions Optimality

As discussed in Section 4-8.3, the GRG algorithm is used with 100 randomly selected starting points to solve the annual net benefit and MCDM optimizations. The tests were performed on a Lenovo Personal Computer (PC) running Windows 10 as its operating System. The PC Processor is a 64 bit Intel Core i7 and has 8 GB installed memory (RAM). The GRG algorithm accomplished all iterations for each optimization under 20 minutes. However, the optimum solution was found within 3 minutes. That means the algorithm converged on a solution in the first few iterations. As a result, the number of starting points was reduced to 40.

As another test, the Evolutionary Genetic Algorithm (GA) was used to solve the same optimizations. The only stopping criterion used is 300 seconds without best solution improvement. The maximum runtime for a GA was about 7 minutes; this means that the best solution was found in about 2 minutes. The GA could not improve the solutions found with the GRG algorithm, supporting the conclusion that we had obtained global optima.

5-5 Hydrologic Sensitivity Test

The optimization generated Test-2 and Test-3 strategies outlined in Section 5-4.1 are checked for resiliency against change in hydrologic conditions. The runoff volume design storm was modified from 2 year/24 hour to 5 year/24hour then to 10 year/24 hour storms and the peak rate design storm was modified from 100 year/24 hour to 200 year/24 hour storm. Both strategies yielded runoff volumes and peak rates within the allowable range set by PA DEP (2006). However, the TSS in the runoff water surpassed the allowable limit.

6 Findings

The main driver behind this research is the need to propagate the use of GSI by developing a tool that facilitates the planning process and improves understanding of the full benefits and capabilities of GSI. This chapter outlines the outcome of carrying out this task: what was achieved by developing the tool; what are its successes and limitations and how can it be approved.

6-1 Conclusion

A GSI planning tool was developed to assist planners and to be used by any stakeholder involved in GSI plan development regardless of their level of knowledge in hydrology, cost/benefit estimation and construction and design.

The presented tool is successfully developed and filled in the gaps and limitations of existing tools (refer to Table 24). This tool is developed in a spreadsheet format (in a widely accessible MS Excel software). It is purposed to be used as a GSI strategy generator and/or a calculator for existing strategies. It minimizes the needed user input data to site specific land cover areas and soil types to generate an early planning strategy. At the same time it allows detailed inputs to fine tune calculations dedicated to a highly defined specific project.

The tool range of applicability is Pittsburgh area and has the capability and flexibility to perform all hydrologic calculations on development sites, watersheds and neighborhoods. In addition, the costs and benefits are estimated on a life cycle basis. The costs are estimated using work breakdown structures of construction activities that yield higher accuracy in cost estimation and extend the usability of the tool from the early planning stages till the end of design development and bid phases. Economic, environmental and social benefits (triple bottom line) are quantified and monetized within the tool. Furthermore, the tool allows the user to modify costs and hydrologic inputs to test the sensitivity of the generated strategies to change in conditions.

	Tools	SUSTAIN	WERF Select Model	CNT Green Values	WinSLAMM	SWMM	L-THIA-LID	Autocase	Developed Tool
	Prerequisits	ArcView9 MS Excel	MS Excel	-	-	MS Excel	MS Excel	Autodesk CAD	MS Excel
Applicability	Geographic Applicability	USA	USA	Great Lakes	Wisconsin	USA	USA	USA	Pittsburgh, PA
Applicability	Scale	Watershed	Site to watershed	Site	Site	Site to watershed	Watershed	Site	Site, Watershed & Neighborhood
Hydrology Calculation	Runoff Volume	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Hydrology Calculation	Runoff Rate	Yes	Yes	Yes	yes	Yes	Yes	No	Yes
Hydrology Calculation	Water Quality	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Costs & Benefits	Costs Estimated	Design + Construction	Whole Life	Construction, Maintenance & Opportunity	Whole Life	No	No	Construction & O&M	LCC
Costs & Benefits	Estimation Class (1)	5	5	5	5	-	-	N/A	Up to 3
Costs & Benefits	LCA	No	No	No	No	No	No	No	LCI
Costs & Benefits	Quantify Benefits	No	No	Economic	No	No	No	Economic, Environmental & Social	Economic, Environmental & Social
	Generates Alternatives	Limited	No	No	No	No	No	No	Yes
	Notes	Allows BMP size modification within the user defined ranges	Requires Hourly Precipitation data for calculation	Simplified hydrology calculation	Requires Historic data (Provided for State of Wisconsin)			Limited Hydrology calculation capability, based on user defined parameters	Allowes limited sensitivity analysis

(1) Based on cost estimates classification in (AACE International 2012)

Table 24: Attributes and capabilities comparison between developed tool and existing GSI planning tools.

Testing the tool demonstrated that it was able to generate strategies that cost less and yield double the annual net benefits and improve the outcome of the hydrologic formulation compared to the developer proposed plan.

Furthermore, the MCDM features of the model allow the user to generate strategies that optimize environmental, hydrologic or socioeconomic benefits and the annual expenditure individually and to find new solutions that tradeoff of the various criteria. The application of the MCDM model on the test site shows that all generated strategies reduced the first cost and improved hydrological functions outcome compared to the developer proposed plan.

Also, the MCDM model testing shows that the only GSIE that was used to maximize all combinations of decision criteria was bioretentions.

6-2 Limitations

The developed prototype presents three types of limitations:

- Limited databases availability: as previously mentioned, the applicability of the tool is limited to Pittsburgh area and only 4 GSIEs are included in the tool. Expanding the tool applicability can be achieved by expanding the databases pertaining to precipitation and GSIE data since the formulation presented in the prototype is applicable to any area and GSIE.

- Underdeveloped components: Due to time constraint, two components require further improvement:
    - The GSIEs environmental life cycle assessment capabilities of the tool are limited to one indicator (GHG emissions) while other environmental issues might be more relevant to different users, such as: air quality and solid waste generation.
    - The sensitivity analysis module is limited to user defined iterations of single attributes which limits the risk assessment of the generated strategies.

- Automation and aesthetics of the tool: the prototype is developed in a spreadsheet format with limited automation and little attention to aesthetics and presentation since its purpose is to provide a proof of concept not for market release. The lack of automation consists mainly in modifying and running the optimization model where the user have to start Solver add-in and select individual cells to build constraints. Doing so requires some knowledge in optimization and defies the purpose of the tool.

6-3 Future work

The proposed future work consists on addressing the limitations listed in Section 6-2 that and carrying the following tasks:

- Expanding the hydrologic database to include precipitation profiles of regions all around the USA.

- Include all GSIEs attributes in the tool and investigate the incorporation of none-structural measures in the formulation.

- Expanding the MCDM model to generate the full none-dominated set of solutions and explore the viability of generating none-dominated set to more than two criteria.

- Expand the tool capability to perform sensitivity and risk assessment by incorporating Monte Carlo simulation within the tool that has the capability to run thousands of iterations while registering the outcomes to generate the risk profile for a specific alternative solution. The Monte Carlo Simulation will be used to generate confidence intervals and tornado chart for variability factors impact on the objective function value.

- Improve automation and aesthetics of the tool to facilitate its usability and link the tool to cost and hydrologic databases for live data update. This task should be accompanied by series of beta testing to improve the general design of the tool.

- Finally, an additional beta test is recommended in order to further validate the usefulness of this tool for planner/designer with limited knowledge in engineering, hydrology and/or economics. So, for this test, a group of testers that fulfill these criteria should be selected. The group of testers must try first to generate a draft plan using traditional methods and existing tools. Then the developed tool should be used to generate alternatives. The outcomes of the two planning exercises should be compared and the feedback from testers will be collected in form of surveys including successes and failures in using the tool and recommendations for future improvements. The surveys collected will be analyzed along with the observed outcomes of the planning exercise in order to script potential improvements.

A Appendix

A-1 GSI Benefits Literature Review Summary

Table 25: Literature Quantifying and Monetizing Benefits

		Reference Type					Economic												Environmental				Social							
				Benefit Category Applicability																										
		Quantify	Monetize	Hydrology	Trees & green space	Investment	Avoided cost of treatment	Avoided cost of Infrastructure	tourism opportunity	Property value (Water Quality)	Dredging & Maintenance costs	value of ground water	Value of water supplied	Averted damage value	Property value (flood)	Tax Revenues	Jobs Created	Avoided energy cost	Avoided Air Emissions	Avoided CO2 Emissions	Biodiversity preservation	Habitat preservation	Public Health	Avoided Life losses	Population Displacement	Beautification	Public safety	Recreation Opportunity	Personal Comfort (noise)	Notes
General	CNT (2011)	●	●	●	●		G	G		Cs			Cs		Cs			G	G	G	Cs							Cs	Cs	
	Wise et al. (2010)	●	●	●	●		G	G				Cs	Cs		G			G	G	G								Cs	Cs	Manual ASCE
	(Stratus Consulting 2009)	●	●	●	●	●											Cs	Cs	Cs	Cs		Cs		Cs		Cs		Cs		Philadelphia
	(US EPA 2014)	●	●	●	●		Cs	Cs					Cs					Cs	Cs	Cs										Lancaster
	(Entrix Inc. 2016)	●		●	●														Cs	Cs	Cs	Cs				Cs	Cs	Cs	Cs	Portland OR
	(CH2M Hill and CDM Smith 2013)		●	●	●	●	Cs	Cs									Cs	Cs	Cs	Cs						Cs				Milwaukee
Air	iTree tools	●	●		●													G	G	G										
	(Muller and Mendelsohn 2007)		●	●	●														G											APEEP Air Quality damage
	(Capoor and Ambrosi 2009)		●	●	●															G										Market value for carbon
	(Wang and Santini 1995)		●	●	●														G											
	(US EPA 2016)		●	●	●															G										
Water Quality	(Heaney et Al. 2002)		●	●	●		G	G			G																			Cost of SW controls
	(PWSA 2016)		●	●	●		P						P																	Rates (water & Sewer)
	(Field et al. 2000)	●	●	●	●		G	G			G																			
	(Walker et al. 1993) EPA		●	●			G	G																						Grey inf. cost functions
	(EPA 2015)		●	●	●		G		Cs	Cs			Cs										CS							Cost of Nutrients
	(Ribaudo 1986)		●	●	●				G		G			G																Erosion cost
	(Tetratec 2016) EPA	●	●	●								G																		Quantification and Value
	(Braden and Johnston 2004)		●	●											G															Down stream impact
	(Johnston, Braden, and Price 2006)		●	●											Cs															
trees & Green Space	(McPherson et al. 2007) EPA	●	●		●		G											G	G	G						G				Tree guide
	(Conway et al. 2010)		●		●																					Cs	Cs	Cs		Green areas property value
	(Anderson and Cordell 1985)		●		●																	Cs				Cs			Cs	
	(Aiello et al. 2010)		●		●																	P	P			P	P	P	P	
	(Vandermeulen et al. 2011)		●		●	●										Cs	Cs		Cs	Cs										
	(Navrud 2002)		●		●																								Cs	Noise Value

Geographic Area of Applicability: (G) Generalized to USA, (Cs) Case specific, (P) Pittsburgh, Pa

Table 26: GSIE Potential Benefits

		Benefits																
		Reduce Storm water Runoff					Reduce Energy Use		Improve Water Quality									
GWIE		Reduce Grey Infrastructure need	Reduce Stream channel erosion	Reduce Peak Flow	Reduce water treatment needs	Reduce Fresh water demand	From Water treatment	From Heating/ Cooling	Water Treatment	Reduce Pollutant Load	Increase GroundWater Recharge	Improve Air Quality	Reduce Urban Heat island effect	Noise reduction	Improve Habitat	Improve Aesthetics	Increase life expectancy of supporting structure	Reduce aquatic thermal impacts
Rainwater Harvesting	Cisterns	●	○	●	●	●	●			●								
	Rain Barrels	●	○	○	●	●	●			●								
	Planter Box	○	○	○	○				●		○				●	●		
Green roofs		●	●	●	●		○	●	●	○		●	●	●	●	●	●	
SoakWays, Dry wells, Infiltration Trenches and Chambers		●	●	●	●		○			○	●							
Infiltration basin		●	●	●	●		○			○	●							
Bioretention	Without underdrain	●	●	●	●		○	○	●	●	●	●	●	○	○	●		●
	With Underdrain	●	○	○	●		○	○	●	●	○	●	●	○	○	●		●
	with Impermeable liner	●	○	○	●		○	○	●	●		●	●	○	○	●		●
Vegetated Filter Strips		●	○	●	●		○		●	●		○						
Permeable Pavement	Porous Concrete	●	●	●	●		○			●	○		●	●				
	Porous Asphalt	●	●	●	●		○			●	○		●	●				
	Interlocking pavers	●	●	●	●		○			●	○		●					
	Grid Systems	●	●	●	●		○			●	○		●					
Swales	Grass lined Swale	●	○	●	○				○	○	○					○		
	Bioswale	●	●	●	●		○		●	●	○	●	●	○	○	●		●

● Yes ○ Maybe

A-2 Method Used for Developing the Tool

Figure 14: IDEF0 Parent Diagram - Develop Tool Tasks

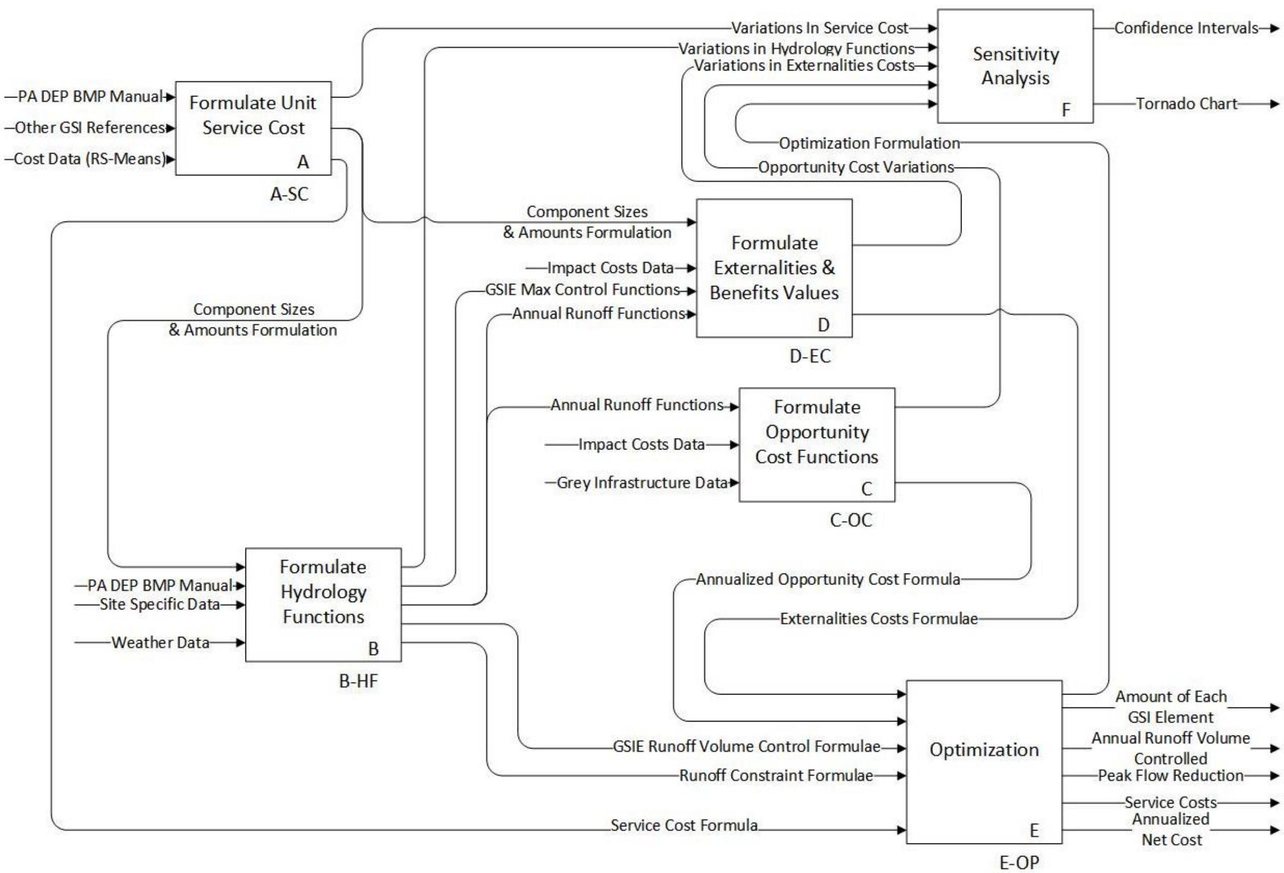


Figure 15: Formulate Unit Service Cost Sub-tasks (refer to task A in Figure 14)

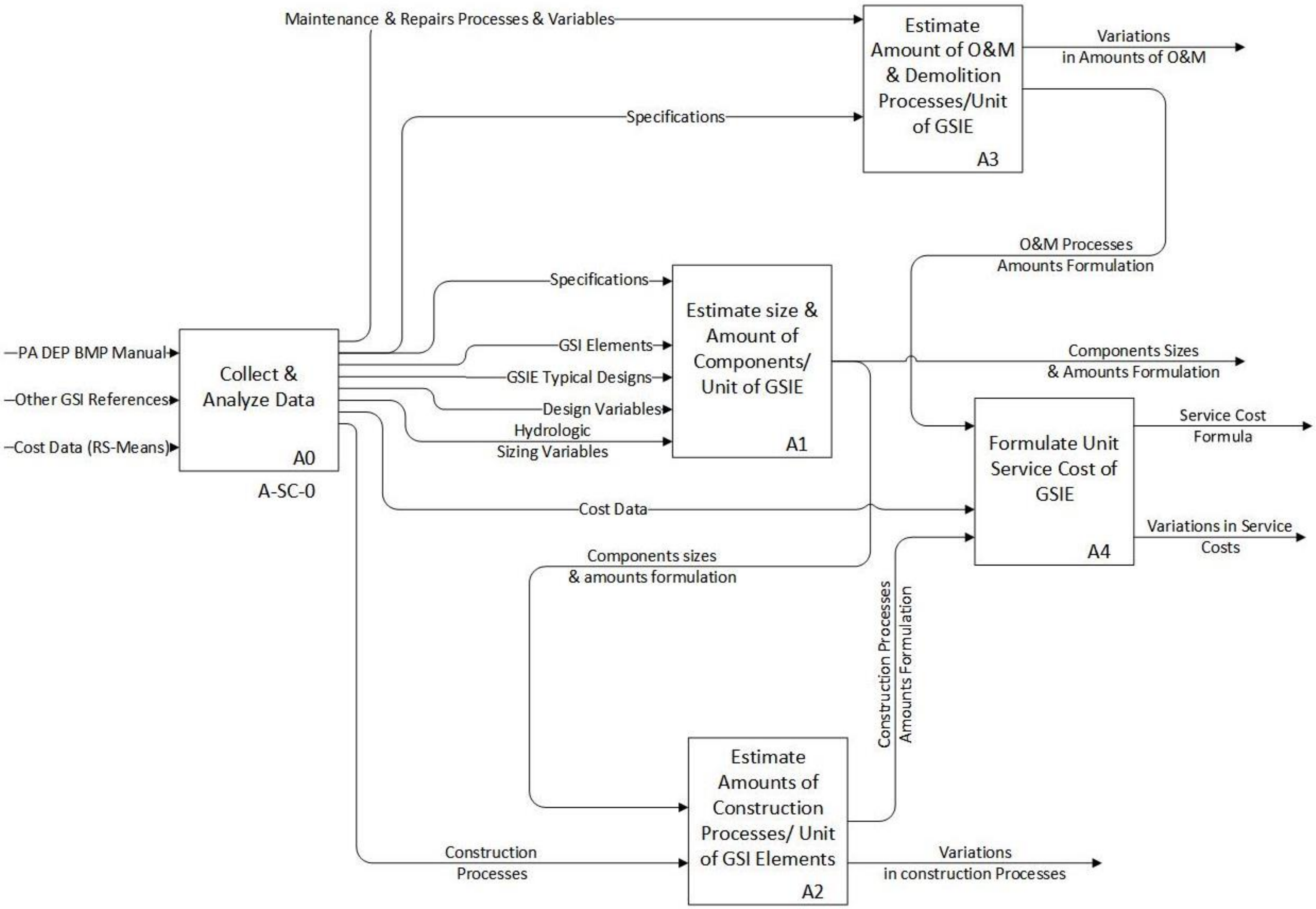


Figure 16: Collect and Analyze Data Sub-tasks (refer to Task A0 in Figure 15)

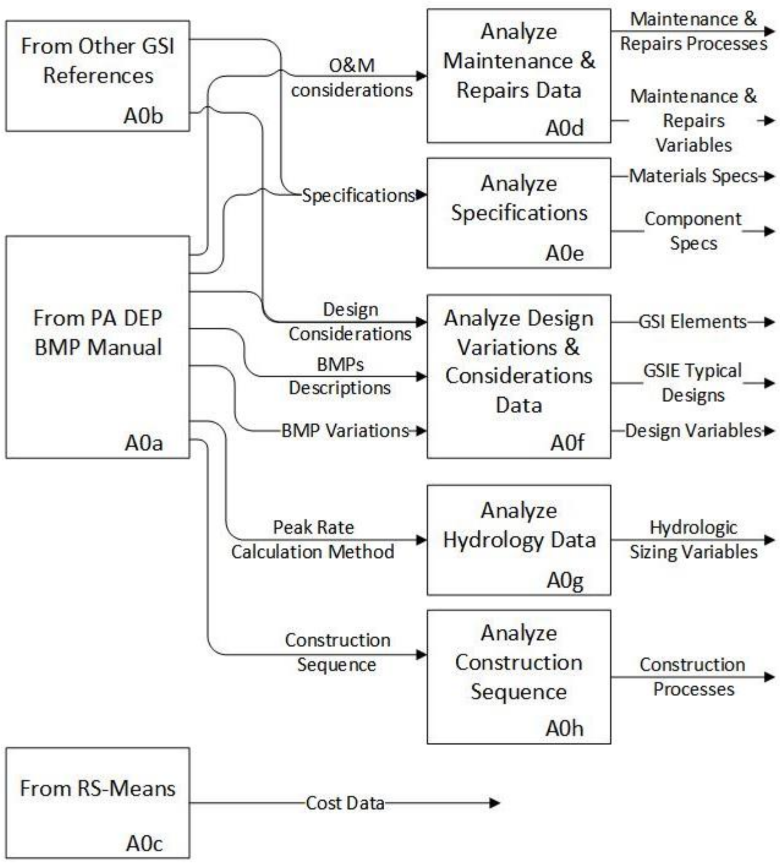


Figure 17: Formulate Externalities and Benefits Values Sub-tasks (refer to Task D in Figure 14)

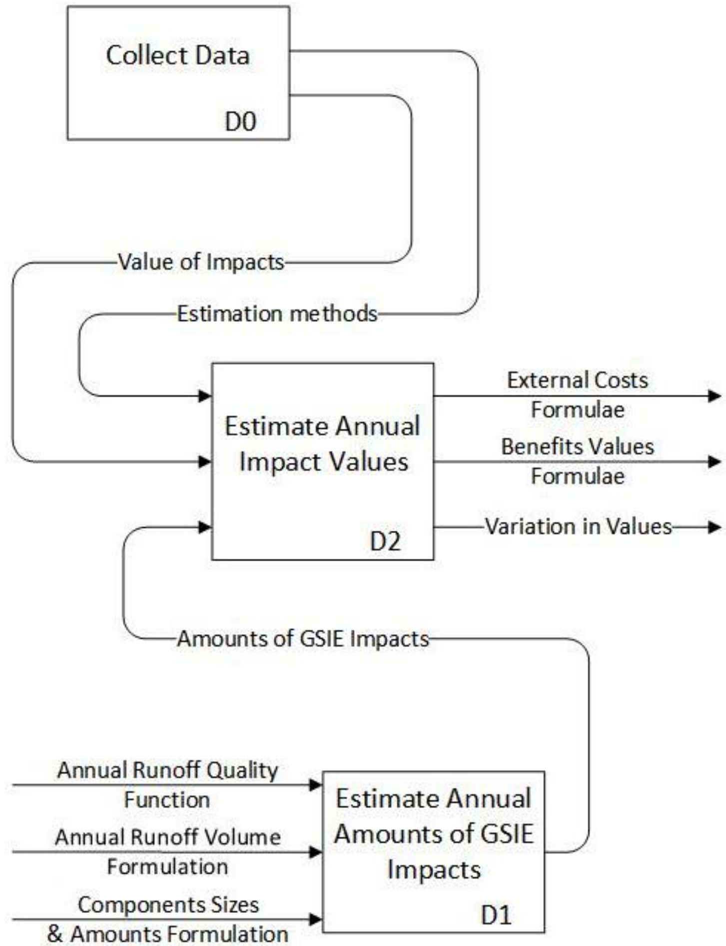


Figure 18: Formulate Hydrology Functions Sub-tasks (refer to Task B in Figure 14)

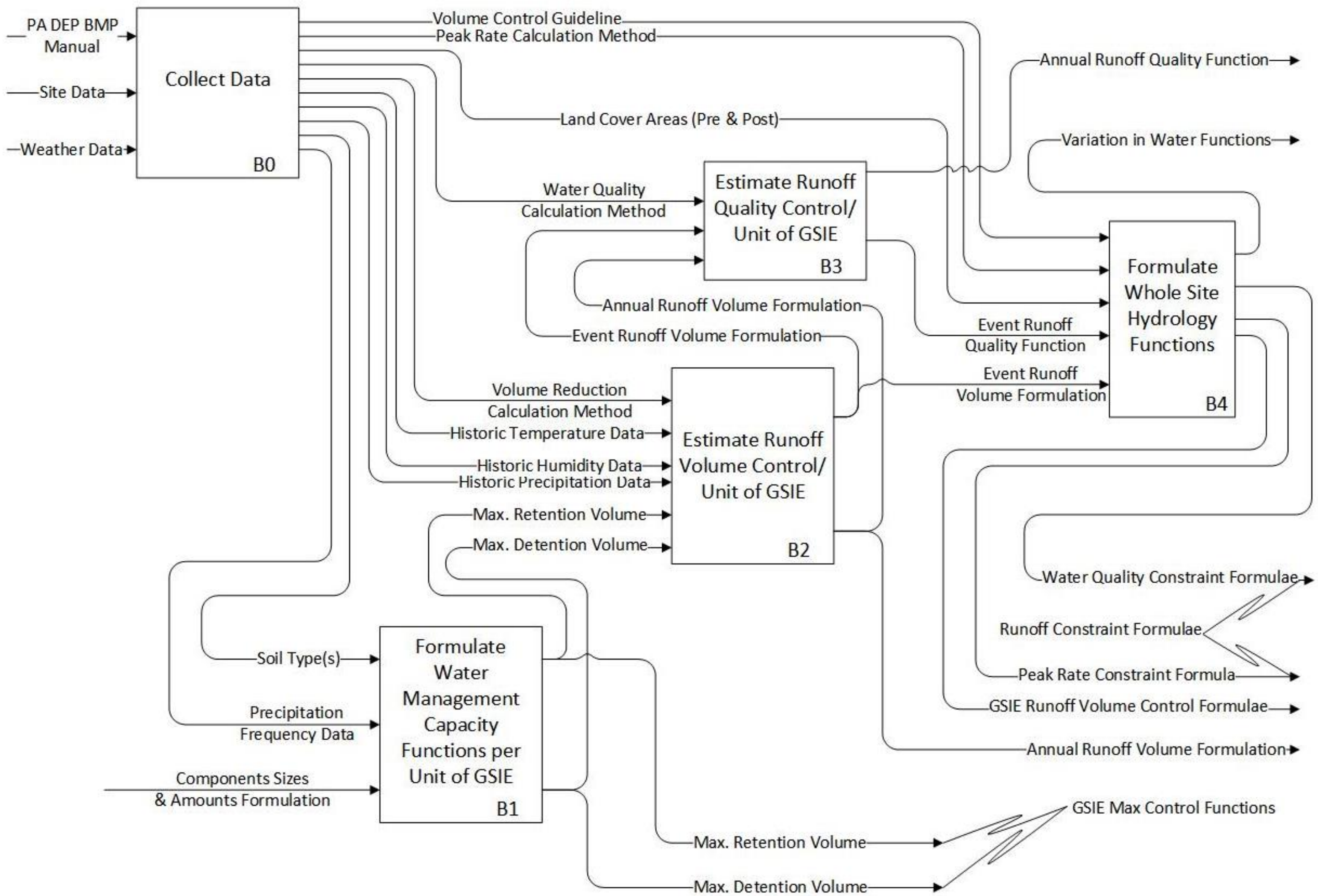


Figure 19: Formulate Opportunity Cost Functions Sub-tasks (refer to Task C in Figure 14)

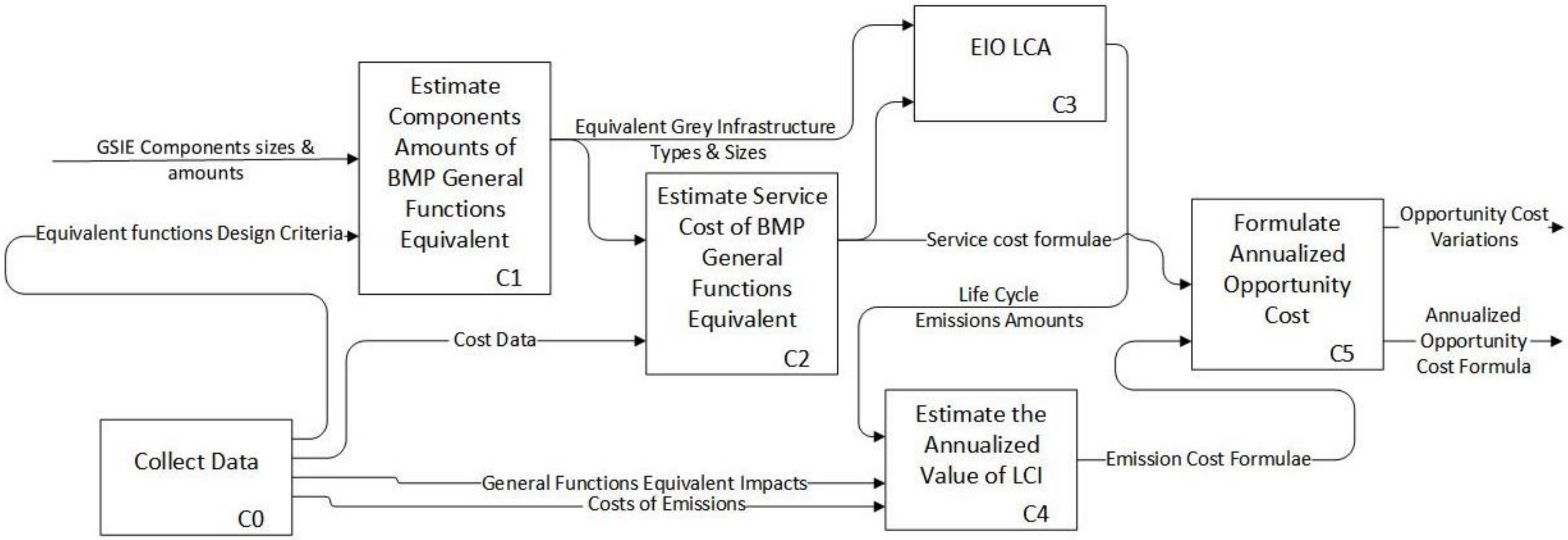
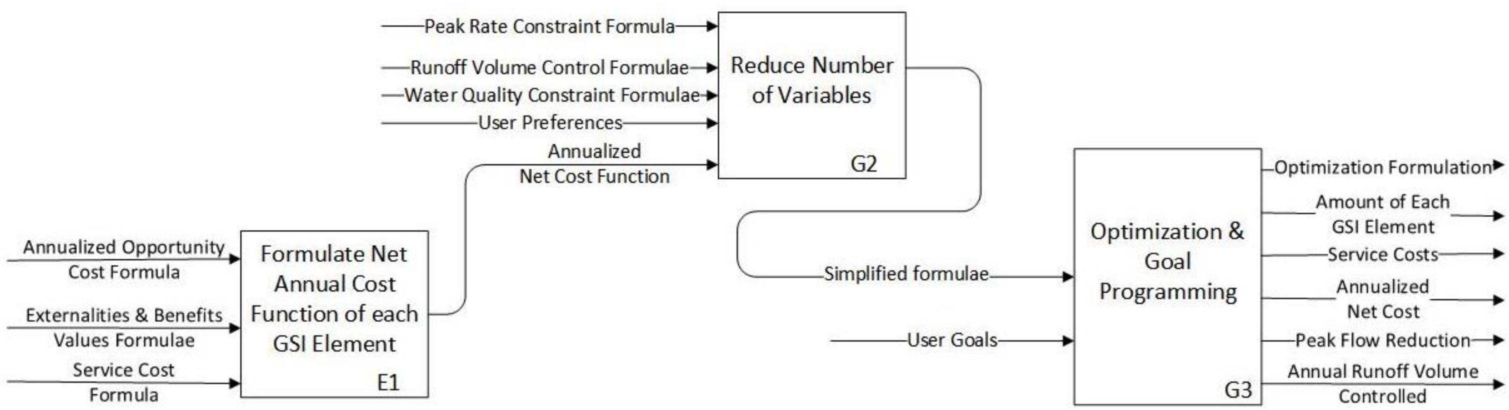


Figure 20: Optimization Sub-tasks (refer to Task G in Figure 14)



A-3 GSIE Design Variations

Green Roof Type	GR-1	GR-2	GR-3	GR-4	GR-5	Unit
Soil Depth	2	4	6	8	10	Inches
Storage Layer Depth	2	2	2	2	2	Inches
Water storage capacity	1.56	1.87	2.18	2.49	2.81	Gal/SF
Retention Volume	0.03	0.03	0.03	0.03	0.03	Gal/SF
Detention Volume	1.84	2.15	2.46	2.78	3.09	Gal/SF

Bioretention Type	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6	Unit
Ponding Depth	0.5	0.5	0.5	0.5	0.5	0.5	Ft.
Planting Media Depth	1.5	2	2.5	3	3.5	4	Ft.
Rock Media Depth	0.50	0.50	0.50	0.50	0.50	0.50	Ft.
Water storage capacity	8.04	8.98	9.91	10.85	11.78	12.72	Gal/SF
Retention Volume	2.69	2.69	2.69	2.69	2.69	2.69	Gal/SF
Detention Volume	3.85	4.79	5.72	6.66	7.59	8.53	Gal/SF

Permeable Pavement Type	PP-1	PP-2	PP-3	PP-4	PP-5	PP-6	PP-7	PP-8	Unit
Subbase Depth	0.67	1.33	2.00	2.67	3.33	4.00	4.67	5.33	Ft.
Water storage capacity	1.99	3.99	5.98	7.98	9.97	11.97	13.96	15.96	gal/S.F.
Retention Volume	1.99	2.69	2.69	2.69	2.69	2.69	2.69	2.69	Gal/SF
Detention Volume	0.00	1.30	3.29	5.29	7.28	9.28	11.27	13.27	Gal/SF

Cistern Type	CS-1	CS-2	CS-3	Unit
Cistern volume	50	60	100	gal.
Water storage capacity	50	60	100	gal
Retention Volume	50	60	100	gal
Detention Volume	0	0	0	gal

A-4 Prototype Screen Shots

Input Interface

	A	B	C	D	E	F
1						
2	**Cost Calculations Input**					
3	**Interst Rate**	**5.00%**				
4	**Excavation Swell Factor**	**25.00%**				
5	**Available Budget**	**$ 500,000.00**				
6	**Tax rate**	**3%**				
7						
8	**Hydrology Calculation input**					
9	Hydrology	Design storm	Precipitation	Unit		
10	Volume Control Storm	2Years/24hrs	2.35	in/day		
11	Peak Rate control Storm	100Years/24hrs	4.91	in/day		
12						
13						
14		**Existing Site (pre)**		**Post development**		
15		Acres	Sq. Feet	Acres	Sq. Feet	
16	**Total Area**	**16.10**	**701,316**		**701,316**	
17	Roof tops		130,000	4.115496	179,271	
18	Impervious		234,000	4.881589	212,642	
19	Meadow		0		0	
20	Woods		0		0	
21	Open Space (fair)		337,316		309,403	
22						
23	Disturbed Area	701,316	Sq. Feet			
24						
25	**Predominant Soil Type**	**C**				
26						
27						
28	**Life Cycle Calculation Input**					
29	Land Use		% of Total Area			
30	Commercial					
31	Single-Family Homes					
32	Other Residential Structures		100%			
33	Other Nonresidential Structures					
34		Total sum	100.00%			
35						
36						

Interface | Optimization | All Results | Data-Cost | Green roofs | Bioretention

Output Interface

Decision Variables									
Green Roof Type	GR-1	GR-2	GR-3	GR-4	GR-5	Unit			
Area of green roof	0.00	0.00	0.00	0.00	2,199.37	S.F.			
Bioretention type	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6	Unit		
Bioretention Bottom Area	0.00	0.00	0.00	14,708.60	0.00	1,266.81	S.F.		
Permeable Pavement type	PP-1	PP-2	PP-3	PP-4	PP-5	PP-6	PP-7	PP-8	Unit
Area of Permeable Pavement	0.00	0.00	32,778.00	0.00	0.00	0.00	0.00	0.00	S.F.
Cistern Type	CS-1	CS-2	CS-3	Unit					
Number of cisterns	0.00	0.00	590.24	S.F.					

Quantities		Hydrology				Trees and Green space		Life Cycle Assessment	
		Ground Rechar	Peak Rate Red	Water Quality	Water Reuse	Trees	New Green	Net Economic	GHG emissions
	Annual LCC	Volume	Δ Velocity	TSS Reduced	Volume	Planted Numbe	Area	Activity	Mass
Green Roof	$6,349.11	0		217704.6061	0	0	2199.3688	$18,299.65	1.030902376
Bioretention	$53,190.06	46201.07367		42545216.89	0	110	1597.5411	$1,150,399.12	13.44942213
Permeable Pavement	$89,346.01	38039.52456		34917339.49	0	0	0	$253,012.55	23.66077296
Cistern	$58,115.12	0		4692021.063	119,294.02	0	0	$58,115.12	1430.410272
Total	**$207,000.30**	**84,240.60**	**0.46**	**82,372,282**	**119294.02**	**110**	**1597.5411**	**$1,479,826.44**	**1468.551369**
Unit	2017$	Cu.Ft.	Cu. Ft/s	mg	Cu. Ft/s	Trees	Sq. Ft.	2017$	tCO2 e

Monetary Values		Hydrology				Trees and Green space		Life Cycle Assessment		Opportunity cost
		Ground Rechar	Peak Rate Red	Water Quality	Water Reuse	Trees	New Green	Annual	GHG emissions	Annual value
	Annual LCC	Value	Value	Water treatmer	Value	Value	Value	Additional Tax	Value	
Green Roof	$6,349.11	$0.00			$0.00	$0.00	$1,867.13	$137.09	$ 41.24	$313.69
Bioretention	$53,190.06	$127.13			$0.00	$8,761.49	$1,193.75	2057.554126	$ 537.98	$0.00
Permeable Pavement	$89,346.01	$104.68			$0.00	$0.00	$0.00	623.0800989	$ 946.43	$49,925.33
Cistern	$58,115.12	$0.00			$20,279.98	$0.00	$0.00	3454.969597	$ 57,216.41	$0.00
Total	$207,000.30	**$231.81**	**$233,984.91**	**$26,030.28**	**20279.98**	**$8,761.49**	**$3,060.89**	**6272.697799**	**$ 58,742.05**	**$50,239.03**
Unit	2017$	2017$	2017$	2017$	2017$	2017$	2017$	2017$	2017$	2017$

Life Cycle Cost		Green Roof	Bioretention	Permeable P	Cistern
Development & Other Associated Costs		30575.82267	152235.4026	336335.4862	96456.35876
Construction Cost		65896.16954	491081.9439	724860.9617	232424.9609
Operation and Maintenance		6664.695409	248855.4898	27218.79624	544404.9957
End of life Demolition		3358.769518	0	0	0
Net Present Value (NPV)		106495.4571	892172.8363	1088415.244	873286.3153
Equivalent Annual Cost per Square Foot (Pitt. adjusted)		6349.105681	53190.05877	89346.012	58115.12419
LCA Annual/ Functional Unit	**Net Economic Activity ($)**	80375.93741	1150399.118	559459.9962	1730575.136
	Additional Tax Revenues	2411.278122	34511.97354	16783.79989	51917.25409
	Annualized Tax revenues	143.7569267	2057.554126	1377.751363	3454.969597
	Greenhouse Gases (tCO2e)	1.030902376	13.44942213	23.66077296	1430.410272

Optimization and MCDM

Constraints						
g1	Budget for first cos	First cost	$2,129,867	≤	$2,800,000	2017 $
g2:	Runoff control	Post implementation	660,802	≤	492,108	Gal
g3:	Peak Rate Control		1.64	≤	1.68	Cu. Ft/s
g4:	Water Quality Con	Post TSS load	153,843,944	≤	135,872,607	mg
		Post TP load	427,094	≤	453,909	mg
		Post Nitrate load	928,965	≤	831,688	mg
g5	GSI Control Area	Drainage Area Imper	145,433	≤	212,642	Sq. Ft.
		Roofs	179,271	≤	179,271	Sq. Ft.
g6	GSI Area Limitatior	Green Roofs	2,199	≤	179,271	Sq. Ft.
		Bioretention	15,975	≤	30,000	Sq. Ft.
		Porous Pavement	32,778	≤	32,778	Sq. Ft.
		Cisterns	59,024	≤	100,000	Gal
Annual Net Benefits			**$83,118.73**			2017$

	Z1 Vs Z4			Z2 Vs Z4			Z3 Vs Z4			Z2 Vs Z3		
	Z1	Z4	Max	Z2	Z4	Max	Z3	Z4	Max	Z2	Z3	Max
	$108,489.55	140710.2516	180408.9604	100646.3944	140710.2516	141778.9487	78866.11419	140710.2516		100646.3944	78866.11419	
	348599.3429	-108338.1053	63293.66208	52782.45368	-108338.1053	-20157.11225	5805.981688	-108338.1053	859.5840367	52782.45368	9808.621438	4581.342177
GR-1	0.00	0.00	0.00	35800.26	0.00	0.00	0.00	0.00	0	35800.26	0.00	0.00
GR-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
GR-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
GR-4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
GR-5	2199.37	0.00	0.00	0.00	0.00	0.00	12688.96	0.00	0	0.00	12688.96	0.00
BR-1	0.00	0.00	0.00	21229.38	0.00	29873.34	0.00	0.00	1215	21229.38	0.00	0.00
BR-2	0.00	19284.25	0.00	0.00	19284.25	0.00	0.00	19284.25	26317	0.00	0.00	0.00
BR-3	0.00	5282.83	0.00	0.00	5282.83	0.00	0.00	5282.83	0	0.00	0.00	0.00
BR-4	14708.60	0.00	14708.60	8770.62	0.00	0.00	12528.40	0.00	0	8770.62	12528.40	0.00
BR-5	0.00	0.00	0.00	0.00	0.00	0.00	17471.60	0.00	0	0.00	17471.60	0.00
BR-6	1266.81095	52793.98303	52793.98303	10302.39864	52793.98303	93185.38825	0	52793.98303	0	10302.39864	0	24379.13
PP-1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
PP-2	0.00	13956.65	0.00	0.01	13956.65	0.00	0.00	13956.65	0	0.01	0.00	0.00
PP-3	32778.00	18821.35	32778.00	0.00	18821.35	27457.37	0.00	18821.35	25232	0.00	0.00	0.00
PP-4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	9301.51
PP-5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
PP-6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	8775.17
PP-7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
PP-8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	14701.36
CS-1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
CS-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00
CS-3	590.24	0.00	0.00	0.00	0.00	0.00	555.27	0.00	82	0.00	555.27	83.97
W variations	Z1 Vs Z4		S	Z2 Vs Z4			Z3 Vs Z4			Z2 Vs Z3		
1	348599.3429	-209197.0572		52782.45368	-205744.1453		9808.621438	-244292.6053		52782.45368	6680.589104	
2	231795.8767	-108338.1053	-0.863492799	13682.29217	-108338.1053	-2.49119278	3570.188005	-108338.1053	-21.79305133	-18361.94174	9808.621438	-0.043967375
3	304569.7699	-$145,046.52		17037.21319	-112445.9832		8633.069111	-187081.888		4839.907281	4627.075785	
W	0.463373295	0.536626705	-0.863492799	0.713564944	0.286435056	-2.49119278	0.95612698	0.04387302	-21.79305133	0.04211566	0.95788434	-0.043967375

GSI Elements Calculations

	A	B	C	D	E	F	G	H	I	J
1	**Green Roofs**									
2	**Decision Formulation**								Unit	
3	Green Roof Type			GR-1	GR-2	GR-3	GR-4	GR-5		
4	Soil Depth			2	4	6	8	10	Inches	
5	Area of green roof			0	0	0	0	2199	S.F.	
6	Equivalent Annual Cost per S.F.			$2.55	$2.64	$2.71	$2.81	$2.89		
7	Total Estimated Cost			$0.00	$0.00	$0.00	$0.00	$6,349.11		
8										
9	Average Area of projects			4000	S.F.					
10	Building Height total area ratio									
11		5 Stories or less		80.00%						
12		6-10 Stories		20.00%						
13	Soil Void ratio			25.00%						
14	Additional storage depth (retention layer)			2.00	inches					
15										
16	Life Expectancy			40	Years					
17	Green Roof Type			GR-1	GR-2	GR-3	GR-4	GR-5	Inches	Total Project
18	Development & Other Associated Costs			$12.40	$12.77	$13.08	$13.55	$13.90		$30,575.82
19	Construction Cost			$26.73	$27.51	$28.19	$29.20	$29.96		$65,896.17
20	Operation and Maintenance			$3.03	$3.03	$3.03	$3.03	$3.03		$6,664.70
21	End of life Demolition			$0.68	$0.89	$1.07	$1.31	$1.53		$3,358.77
22	Net Present Value (NPV)			$42.83	$44.20	$45.37	$47.09	$48.42		$106,495.46
23		Total NPV		$0.00	$0.00	$0.00	$0.00	$106,495.46		
24	**Equivalent Annual Cost per Square Foot (Pitt. adjusted)**			**$2.55**	**$2.64**	**$2.71**	**$2.81**	**$2.89**		$6,349.11
25										
26	**LCA**	**Net Economic Activity ($)**		**$30.45**	**$31.94**	**$33.76**	**$35.05**	**$36.55**		$80,375.94
27	**Annual/Sq.Ft.**	Additional Tax Revenues		$0.91	$0.96	$1.01	$1.05	$1.10		$2,411.28
28		**Annualized Tax revenues**		**$0.05**	**$0.06**	**$0.06**	**$0.06**	**$0.07**		$143.76
29		**Greenhouse Gases (tCO2e)**		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	tCO2/Unit	$1.03
30										
31										

Interface | Optimization | All Results | Data-Cost | **Green roofs** | Bioretention | Permeable Pavement | Cisterns | Data-Hydrology | Hydrology | Benefits

Construction Cost

Green Roof Type	GR-1		GR-2		GR-3		GR-4		GR-5	
Mobilize crane to construction site.	$0.06		$0.06		$0.06		$0.06		$0.06	
Hoist materials used in green roof construction up to the roof leve	4.025		4.775		5.335		6.295		7.059	
Rubber membrane installation (waterproofing) including flashing	8.5		8.5		8.5		8.5		8.5	
Root barrier installation	2.28		2.28		2.28		2.28		2.28	
Water retention/detention layer+Barrier	4.23		4.23		4.23		4.23		4.23	
Planting Sedum	7.4		7.4		7.4		7.4		7.4	
Edging of the green roof	0.2265		0.265		0.38		0.4275		0.4275	
Interior gutters installation										
Drains, detention and check boxes and plumbing installation.										
Thermal insulation layer										
Other										
Other										
Total	$26.73	$0.00	$27.51	$0.00	$28.19	$0.00	$29.20	$0.00	$29.96	$0.00
Model Total	**$26.73**		**$27.51**		**$28.19**		**$29.20**		**$29.96**	

End of life Demolition

life expectancy	40.00	years			
Green Roof Type	GR-1	GR-2	GR-3	GR-4	GR-5
Soil Depth	2	4	6	8	10
Mobilize crane to construction site.					
Hand Excavation up to 6' deep	$0.37	$0.75	$1.12	$1.49	$1.87
Hand load demolished material	$0.31	$0.63	$0.94	$1.25	$1.56
Hoist materials used in green roof Down to Haul	$4.03	$4.78	$5.34	$6.30	$7.06
Hauling	$0.05	$0.10	$0.16	$0.21	$0.26
Total	$4.76	$6.25	$7.55	$9.25	$10.75
NPV	**$0.68**	**$0.89**	**$1.07**	**$1.31**	**$1.53**

Life Cycle Assessment						
Construction		Green Roof Type ($/Sq.Ft.)				
		GR-1	GR-2	GR-3	GR-4	GR-5
Material	Vegetation	5.7	5.7	5.7	5.7	5.7
	Planting Medium (soil)	0.24	0.35	0.47	0.59	0.71
	Hoisting	0	0	0	0	0
	Waterproofing	0.3	0.3	0.3	0.3	0.3
	Root Barrier	0.7	0.7	0.7	0.7	0.7
	Water retention/detention layer+Barrier	2.66	2.66	2.66	2.66	2.66
	Edging	0.07	0.10	0.19	0.21	0.21
	Mobilizing Crane	0.00	0.00	0.00	0.00	0.00
LCA Total	**Economic Activity ($)**	**17.99319926**	**18.28073031**	**18.6740767**	**18.95031**	**19.20559424**
	Greenhouse Gases (tCO2e)	**0.008179975**	**0.008422725**	**0.00870292**	**0.008961**	**0.009214065**

Labor	Vegetation	0.75	0.75	0.75	0.75	0.75
	Planting Medium (soil)	0.6	0.9	1.21	1.51	1.81
	Hoisting	1.2	1.2	1.2	1.2	1.2
	Waterproofing	4.47	4.47	4.47	4.47	4.47
	Root Barrier	0.89	0.89	0.89	0.89	0.89
	Water retention/detention layer+Barrier	0.77	0.77	0.77	0.77	0.77
	Edging	0.10	0.10	0.11	0.13	0.13
	Mobilizing Crane	0.04	0.04	0.04	0.04	0.04
	Total	8.82	9.12	9.44	9.76	10.06

Equipment	Vegetation	0	0	0	0	0
	Planting Medium (soil)	0.306	0.456	0.612	0.762	0.918
	Hoisting	0.61	0.61	0.61	0.61	0.61
	Waterproofing	0.52	0.52	0.52	0.52	0.52
	Root Barrier	0	0	0	0	0
	Water retention/detention layer+Barrier	0	0	0	0	0
	Edging	0	0	0	0	0
	Mobilizing Crane	0.0028	0.0028	0.0028	0.0028	0.0028
	Total	1.44	1.59	1.74	1.89	2.05
LCA Total	**Economic Activity ($)**	**20.42914653**	**21.32530584**	**22.2752347**	**23.21521**	**24.12331438**
	Greenhouse Gases (tCO2e)	**0.004681808**	**0.004887184**	**0.00510488**	**0.00532**	**0.005528412**

Hydrology Calculations

Soil Infiltration							
Soil Type	distribution of GWIE	Infiltration Rate Minimum	Maximum	Model	Unit	Annual Recharge (percent of annual precipitation)	
A	0.00%	1.42		1.42	in/hr	55.00%	
B	0.00%	0.57	1.42	0.57	in/hr	36.00%	
C	100.00%	0.06	0.57	0.06	in/hr	18.00%	
D	0.00%	0	0.06	0	in/hr	9.00%	
	average soil infiltration			**0.06**	in/hr		
				1.44	in/day		

Evapotranspiration		Kc				
Crop Coefficient		Initial	Mid	End	Model	Notes
Ground cover						$ET_c = K_c\ ET_o$
	2" height	0.40	0.85	0.75		based on strawberry plants
	Turf grass (cool Season)	0.90	0.95	0.95		
Shrubs						
	Reed Swamp, standing water	1.00	1.20	1.00		
	Reed Swamp, moist soil	0.90	1.20	0.70		
	Berries (bushes)	0.3	1.05	0.5		
Trees						
	Conifer Trees	1.00	1.00	1.00		
	Apples, Cherries,	0.50	1.20	0.95		

	Eto		Green Roof		Bioretention	
Month	mm/day	inch/day	Kc	ETc	Kc	ETc
Jan	1.00	0.04	0.40	0.02	0.50	0.02
Feb	1.30	0.05	0.40	0.02	0.50	0.03
Mar	2.40	0.09	0.40	0.04	0.50	0.05
Apr	3.60	0.14	0.85	0.12	1.20	0.17
May	4.50	0.18	0.85	0.15	1.20	0.21
Jun	5.20	0.20	0.85	0.17	1.20	0.25
Jul	5.30	0.21	0.85	0.18	1.20	0.25
Aug	4.50	0.18	0.85	0.15	1.20	0.21
Sep	3.60	0.14	0.75	0.11	0.95	0.13
Oct	2.60	0.10	0.75	0.08	0.95	0.10
Nov	1.70	0.07	0.40	0.03	0.50	0.03
Dec	1.10	0.04	0.40	0.02	0.50	0.02

Water Capture for Peak Rate Calculation

Green Roof Type	GR-1	GR-2	GR-3	GR-4	GR-5	Unit
Water storage capacity	1.56	1.87	2.18	2.49	2.81	Gal/SF
design storm catchment volume	3.06	3.06	3.06	3.06	3.06	Gal/SF
Retained Volume	0.03	0.03	0.03	0.03	0.03	Gal/SF
Detained Volume	1.84	2.15	2.46	2.78	3.09	Gal/SF
GSI abstracted volume	1.87	2.18	2.49	2.81	3.06	Gal/SF
Detention Velocity	0.98	1.15	1.32	1.48	1.65	in/day
Catchment area	0.00	0.00	0.00	0.00	2199.37	SF
Total Flow	0.00	0.00	0.00	0.00	0.00	Cu. Ft/s
Flow for grey calculation	0.00	0.00	0.00	0.00	0.00	Cu. Ft/s
Total Abstracted volume	0.00	0.00	0.00	0.00	6731.78	Gal

Cistern Type	CS-1	CS-2	CS-3	Unit
Water storage capacity	50	60	100	gal
design storm catchment volume	918.23	918.23	918.23	gal
Retained Volume	50.00	60.00	100.00	gal
Detained Volume	0.00	0.00	0.00	gal
GSI abstracted volume	50.00	60.00	100.00	gal
Detention Velocity	0	0	0	in/day
Catchment area	0	0	177071.6	SF
Total Flow	0.00	0.00	0.75	Cu. Ft/s
Flow for grey calculation	0.00	0.00	0.75	Cu. Ft/s
Total Abstracted volume	0.00	0.00	59023.88	gal

Bioretention type	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6	Unit
Water storage capacity	8.04	8.98	9.91	10.85	11.78	12.72	Gal/SF
design storm catchment volume	15.30	15.30	15.30	15.30	15.30	15.30	Gal/SF
Retained Volume	2.69	2.69	2.69	2.69	2.69	2.69	Gal/SF
Detained Volume	3.85	4.79	5.72	6.66	7.59	8.53	Gal/SF
GSI abstracted volume	6.55	7.48	8.42	9.35	10.29	11.22	Gal/SF
Detention Velocity	0.01	0.02	0.02	0.02	0.03	0.03	in/day
Catchment area	0.00	0.00	0.00	73543.00	0.00	6334.05	SF
Total Flow	0.00	0.00	0.00	0.14	0.00	0.01	Cu. Ft/s
Flow for grey calculation	0.00	0.00	0.00	0.14	0.00	0.01	Cu. Ft/s
Total Abstracted volume	0.00	0.00	0.00	########	0.00	14214.61	Gal

Permeable Pavement type	PP-1	PP-2	PP-3	PP-4	PP-5	PP-6	PP-7	PP-8	Unit
Water storage capacity	1.99	3.99	5.98	7.98	9.97	11.97	13.96	15.96	Gal/SF
design storm catchment volume	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12	Gal/SF
Retained Volume	1.99	2.69	2.69	2.69	2.69	2.69	2.69	2.69	Gal/SF
Detained Volume	0.00	1.30	3.29	5.29	7.28	9.28	11.27	13.27	Gal/SF
GSI abstracted volume	1.99	3.99	5.98	6.12	6.12	6.12	6.12	6.12	Gal/SF
Detention Velocity	0.00	0.00	0.01	0.02	0.03	0.03	0.04	0.05	in/day
Catchment area	0.00	0.00	65556.00	0.00	0.00	0.00	0.00	0.00	SF
Total Flow	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	Cu. Ft/s
Flow for grey calculation	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	Cu. Ft/s
Total Abstracted volume	0.00	0.00	196157.19	0.00	0.00	0.00	0.00	0.00	Gal

Control Guidline Calculation

	Pre-Development	CG1 Area	Post Development	Unit
Total Area	701,316	701,316	701,316	Sq. Feet
Roofs	130,000	104,000	179,271	Sq. Feet
Impervious	234,000	187,200	212,642	Sq. Feet
Meadow	0	410,116	0	Sq. Feet
Woods	0	0	0	Sq. Feet
Open Space (fair)	337,316	0	309,403	Sq. Feet

Runoff Calculation	CN	S	I_a	Q	Unit
Roofs	98	0.20	0.04	2.12	inch
Impervious	98	0.20	0.04	2.12	inch
Meadow	71	4.08	0.82	0.42	inch
Woods	70	4.29	0.86	0.39	inch
Open Space (fair)	79	2.66	0.53	0.74	inch

GSI CG1 Capture		Unit		Catchment Area	
Green Roofs	3221.932757	Gal		2199.37	Sq.Ft.
Bioretention	117014.7065	Gal		79877.05	Sq.Ft.
Permeable Pavement	96035.28979	Gal		65556.00	Sq.Ft.
Cisterns	59023.87705	Gal		177071.63	Sq.Ft.

	Pre-Development	CG1 Area	Post Development	Unit
Roofs	171938.2551	137550.6041	237104.1764	Gal
Impervious	309488.8592	247591.0874	281240.7265	Gal
Meadow	0	106966.1038	0	Gal
Woods	0	0	0	Gal
Open Space (fair)	155309.4891	0	142457.5824	Gal
GSI Abstraction			-275295.8061	
Runoff	**636,736.60**	**492,107.80**	**660,802.49**	Gal

Interface | Optimization | All Results | Data-Cost | Green roofs | Bioretention | Permeable Pavement

Benefit Calculations

	A	C	D	E	F
4	**Hydrology Benefits**				
5					
6	**Ground Recharge**				
7	Estimated Value	$ 110.00	2011$/ Ft.Acre		
8		$0.003	$/Cu.Ft.		
9	Annual recharge	18.00%	%of precipitation		
10		20%	%of precipitation		
11					
12	Annual recharge Volume		84,240.60	Cu.Ft.	
13	Value of Ground Recharge		$231.81		
14					
15	**Peak rate reduction**				
16	flow reduction		0.465859635	Cu. Ft/s	0.46586
17	Equivalent Basin volume		0.41	MGal	
18	Construction Cost of equivalent basin		$3,064,860.57		
19	Soft Costs		$950,106.78		
20	Cost of equivalent basin		$4,014,967.34		
21	Annual O&M		$0.00		
22	Annualized cost		$233,984.91		
23					
24	**Water Quality improvement**				
25	flow reduction		0.465859635	Cu. Ft/s	
26	Sedimentation basin flow rate		0.301092968	MGD	
27	Sedimentation basin construction cost		$165,337.83		
28	Sedimentation basin Soft cost		$76,716.75		
29	Annualized cost		$13,258.96		
30	Annual O&M		$12,771.32		
31					
32	**Water Reuse**				
33	Annual Water Reuse		119,294.02	Cu.Ft.	
34	Water Supply cost		$0.17	$/Cu.Ft.	

	M	P
4	**Opportunity cost**	
5		
6	**Traditional roof**	
7	Life Expectancy	25
8	Construction cost	$ 4,321.76
9	Annualized LCC	**$313.69**
10	LCA	
11	Economic Activity ($)	$7,452.00
12	Net Economic Activity ($)	$3,130.24
13	Annualized Tax revenues	**$6.66**
14	Greenhouse Gases (tCO2e)	**$7.22**
15		
16	**Asphalt Pavement**	
17	Construction cost	$ 399,071.51
18	Annualized LCC	**$49,925.33**
19	LCA	
20	**Economic Activity ($)**	**$306,447.44**
21	Annualized Tax revenues	**$754.67**
22	Greenhouse Gases (tCO2e)	**13.71**

Interface | Optimization | All Results | Data-Cost | Green roofs | Bioretention | Permeable Pavement | Cisterns | Data-Hydrology | Hydrology | **Benefits**

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