Spatial Sustainability Assessment of Green Stormwater Infrastructure for Surface Transportation Planning, Phase II

Center for Transportation, Environment, and Community Health
Final Report

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February 28, 2019

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2.Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Spatial Sustainability Assessment of Green Stormwater Infrastructure for Surface Transportation Planning		5. Report Date March 1, 2019 6. Performing Organization Code
7. Author(s) Qiong Zhang, Qing Lu, Xiaofan Xu, Dylan Schreiber		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of South Florida 4202 E Fowler Ave, Tampa, FL 33620		10. Work Unit No. 11. Contract or Grant No. 69A3551747119
12. Sponsoring Agency Name and Address U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final Report 12/1/2017-9/30/2018 14. Sponsoring Agency Code US-DOT
15. Supplementary Notes		

16. Abstract

Stormwater runoff can cause both flooding and the spread of pollutants, so it is important that it be managed effectively. This project investigates the watershed scale implementation of green infrastructure: technologies that reduce the imperviousness and promote the retention and treatment of the runoff at the source, rather than move the water to centralized locations for treatment and release. The aim of the project is to create a modeling framework to be used in transportation planning. It will model the effect of green infrastructure on flooding and water quality, and assess their life cycle costs and environmental and health impacts. The project is conducted in phases. Phase I work is completed, which is to develop a method for creating a GIS layer of existing green infrastructure that can be overlaid with transportation and grey stormwater infrastructure network. Phase II aims to integrate hydrological and water quality modeling for scenario analysis of combination of transportation planning and green infrastructure design.

17. Key Words	18. Distribution Statement
Stormwater management, Green infrastructure, Spatial optimization, Human health benefits, LCA, LCCA	Public Access Xu, X., Schreiber, D., Lu, Q., & Zhang, Q. (2018). A GIS-Based Framework Creating Green Stormwater Infrastructure Inventory Relevant to Surface Transportation Planning. Sustainability, 10(12), 4710. doi: 10.3390/su10124710.

19. Security Classif (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)

Spatial Sustainability Assessment of Green Stormwater Infrastructure for Surface Transportation Planning

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Abstract: Transportation authorities are responsible for managing the stormwater runoff that carries pollutants from the transportation-adjacent land and vehicles. The proper stormwater management approach like green infrastructure can help control flooding and the runoff pollutants that may impair water environment and threaten the ecosystem and human health. Furthermore, green infrastructure that can be applied at different spatial scales and decentralized arrangements, have been adopted and implemented in the transportation infrastructure design. However, such implementation is project-based without analysis at system level or sewer scale. A framework is needed to design and evaluate the integration of green stormwater infrastructure in transportations planning at systems level. The overall goal of the proposed project is to develop a modeling framework integrating hydrological simulation, water quality modeling, life cycle assessment (LCA) and cost analysis (LCCA) that can be used for design and planning for surface transportation with spatial implementation of green infrastructures. The phase II of the project was completed in the second year with the deliverable of an integrated hydrological and water quality modeling for scenario analysis of combination of transportation planning and green infrastructure design using Tampa as a case study area.

Keywords: Stormwater management, Green infrastructure, Spatial optimization, Human health benefits, LCA, LCCA

INTRODUCTION

National Pollutant Discharge Elimination System (NPDES) regulates that transportation authorities are responsible for managing the stormwater runoff that carries pollutants from the transportation-adjacent land and vehicles. The proper stormwater management can help control flooding and the runoff pollutants that may impair water environment and threaten the ecosystem and human health. Green stormwater infrastructure (GSI) is a stormwater management approach with many economic and human health benefits including: flood mitigation, erosion control, improved water quality, groundwater recharge, mitigated effect of urban heat islands, reduced energy demands for cooling, and enhanced aesthetics and access to green space (Bowen and Lynch 2017; Demuzere et al. 2014; Wendel et al. 2011). Unlike grey stormwater infrastructure systems that are often large and centralized, GSI can be designed at different spatial scales and implemented in decentralized arrangements (Suppakittpaisarn et al. 2017). GSI like basins (Belizario et al. 2016), bioswales (Lucas et al. 2015), bioretention (Lucke and Nichols 2015), and constructed wetlands (Li et al. 2016) have been adopted and implemented in the transportation infrastructure design. These technologies have proven effective in terms of reducing runoff and pollutant loads at the individual site or project level. However, implementation and analysis of GSI at system level or urban watershed scale is generally lacking. As Roy et al. (2008) pointed out that "sustainable urban stormwater management must be planned and implemented at the watershed scale," a framework is needed to design and evaluate the integration of GSI in transportations planning at system level.

The ***overall goal*** of the proposed project is to develop a modeling framework integrating hydrologic simulation, water quality modeling, life cycle assessment (LCA) and cost analysis (LCCA) that can be used for design and planning for surface transportation with the spatial implementation of GSI. The objectives of the project include (1) developing a method for constructing an inventory of the implemented GSI using Tampa as a case study area; (2) integrating hydrologic modeling with water quality modeling for scenario analysis of GSI implementation at watershed scale; and (3) developing a spatial optimization model for GSI implementation based on the integrated LCA-LCCA-optimization framework. Corresponding to the set of objectives, the project is conducted in phases. The completed Phase I work developed a method for creating a geographical information system (GIS) layer of existing GSI that can be overlaid with transportation and grey stormwater infrastructure network. In the reporting period, Phase II research is close to completion, which is working on the integration of hydrologic and water quality modeling for scenario analysis of combination of transportation planning and GSI design. The trade-off between environmental, human health, and economic impacts is investigated for the scenario implemented.

Phase II Project

Phase II project aims to complete with the deliverables of an integrated model of both hydrology and water quality, and a scenario analysis of water quality, environmental impacts, and cost of existing and candidate GSI implementation. Three major activities were performed in Phase II.

First, the scenarios with different combination of existing and candidate GSI in a hot spot were generated. The hot spot for future implementation of GSI was identified according to the need of stormwater control, urban planning, and data availability. The existing GSI was acquired from the GSI inventory created in Phase I. A collection of candidate GSI in the hot spot with their location, size, and type was created as a GIS layer. Second, the water quality discharging to Tampa Bay is evaluated by an integrated simulation of hydrology and water quality for two scenarios, i.e., the baseline of implemented GSI, and one scenario of both implemented and candidate GSI. The integrated simulation model was built using the US EPA Storm Water Management Model (SWMM) and the dynamic flow patterns were simulated by adding the GSI to the model. Third, LCA and LCCA were conducted to evaluate the environmental and economic impacts of different scenarios, using the collected material and energy data of different GSI alternatives for life cycle inventory. Eventually, the evaluation of water quality, environmental impacts, and cost for the two scenarios were completed. Some discussion was made for future GSI planning according to the results of scenario analysis.

METHODOLOGY

Methodology Development

The Phase II research were conducted into three major activities, including scenario development, integrated hydrology-water quality simulation, and environmental and economic impacts assessment (Figure 1).

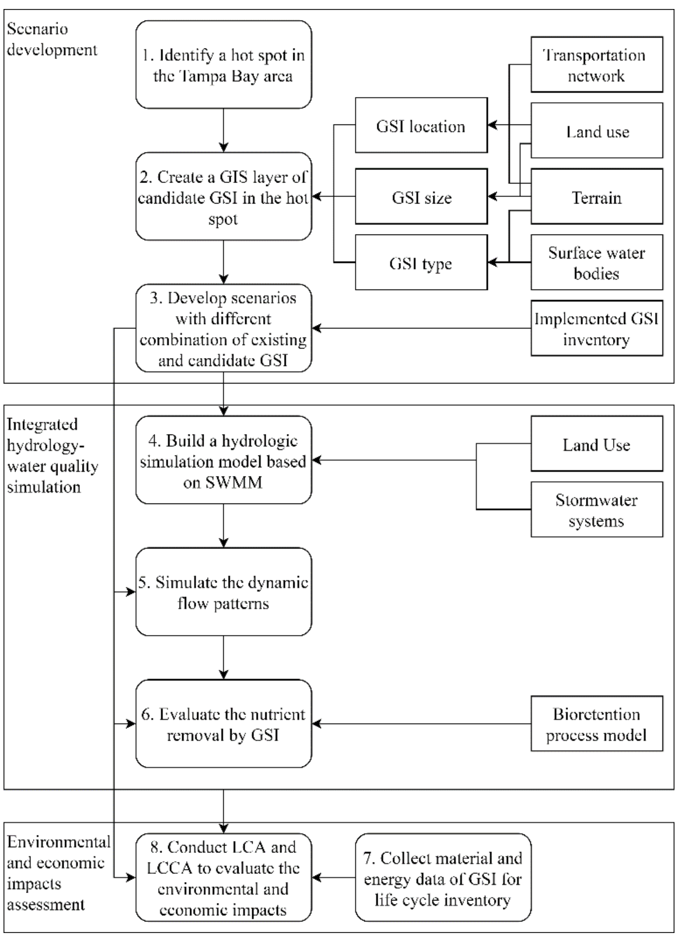

Figure 1. The process diagram in Phase II research.

In detail, the entire research was conducted in the following eight steps (Figure 1).

Step 1: identify a hot spot for future implementation of GSI in the Tampa Bay area. The potential hot spot is located in the hydrologic units containing the areas with frequent flooding complaints, high population density, minimal existing green infrastructure, and future transportation projects. The hot spot (i.e., the study area) was determined as the common area by overlapping the GIS layers of mentioned information.

Step 2: create a GIS layer of candidate GSI sites in the hot spot. The low-lying areas in the hot spot, which have lower elevation than the surroundings, were found in ArcGIS using the elevation images by the U.S. Geological Survey (USGS). The processes in ArcGIS looking for the expected low-lying areas follows the procedure of Cloudburst Model in the ArcGIS lessons, which is designed to find areas at risk of flooding. The low-lying areas (assigned as bluespots) in the public land were considered as the potential GSI sites. The potential GSI sites with an area of >20,000 sq.ft. were then selected as candidate GSI sites for further study. For each candidate site, the GSI was assigned with its surface size according to the drainage area and the percentage of its impervious area. The GSI types can vary according to the terrain and spatial proximity to surface water bodies. For this report, however, bioretention systems were considered for all candidate GSI sites due to its capability for nutrient removal and water quality improvement. Since the Phase II research aimed at evaluating the impacts of GSI implementation at the system level, and the difference between GSI types was not considered in this Phase.

Step 3: develop scenarios with different combination of existing and candidate GSI. The existing GSI mapped in Phase I was used as baseline scenario. Another scenario was generated by adding bioretention systems at all candidate GSI sites along with the existing GSI. These two scenarios would be evaluated in the future steps.

Step 4: build a hydrologic simulation model using SWMM and the GIS layer of existing and candidate GSI. A modified script was used to convert the GIS data of stormwater infrastructure in the hot spot into SWMM inputs, including the subcatchments, nodes, and flow paths. A SWMM-based model was built with existing grey and green infrastructures.

Step 5: simulate the dynamic flow patterns. The output of flow information was obtained from the SWMM-based model with the design of the two GSI scenarios.

Step 6: evaluate the nutrient removal by GSI. The nutrient (i.e., nitrogen and phosphorus) removal would be evaluated in the study area using the bioretention process model (Xu & Zhang, n.d.) and the flow information from the SWMM-based model.

Step 7: collect material and energy data of GSI for life cycle inventory. For both implemented and candidiate GSI, the material and energy data were collected in the life cycle inventory for further LCA and LCCA.

Step 8: conduct LCA and LCCA to evaluate the environmental and economic impacts. For each scenario of GSI implementation, the LCA using SimaPro and LCCA using Matlab would be conducted to investigate the environmental, human health, and economic impacts at the system level.

GIS Data Collection

Table 1 summarizes the GIS data collected for the first four steps. All the data of road system and stormwater management facilities were formatted as shapefiles and available to the public with the open data link. The reported street flooding provided by City of Tampa Transportation & Stormwater

Services recorded the flooding locations during 2015-2017. The land use of Hillsborough County and population data by the U.S. Census Bureau were acquired in the year of 2018. The raster image of Digital Elevation Models (DEM) by USGS has horizontal resolution of 1m by 1m and vertical of 0.05m. The Watershed Boundary Dataset by USGS defines the national hydrological boundary at six different geographical levels from regions to sub-watersheds. The non-public raster image of Tampa land cover was created with a rule-based object-orientated classification method utilizing high-resolution imagery, LIDAR data and ancillary GIS data by USF Water Institute. It has a 1-foot-by-1-foot resolution, providing extremely high accuracy as a reference map. All the data were adjusted to the GCS_North_American_1983 geographic coordinate system, or the NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet projected coordinate system when measurement was needed.

Table 1. The GIS dataset used in this research.

Dataset	Source
Reported flooding spots	Tampa Transportation & Stormwater Services
Watershed Boundary Dataset (WBD)	U.S. Geological Survey (USGS)
Digital Elevation Models (DEM)	
Population (2018)	U.S. Census Bureau
Existing GSI inventory	Phase I research
Land Use of Hillsborough County (2018)	Plan Hillsborough http://www.planhillsborough.org/gis-maps-data-files/
Tampa land cover	USF Water Institute
Road centerline Stormwater inlets Stormwater basins Stormwater discharge points Stormwater detention areas Stormwater gravity mains Stormwater pressured mains Stormwater open drains	City of Tampa GeoHub http://city-tampa.opendata.arcgis.com/ Hillsborough County Public Works Department City of Temple Terrace Public Works Department

Find Candidate GSI Sites

The processes to find candidate GSI sites were conducted in two steps using ArcGIS (Figure 2). The first step is to identify the low-lying areas (known as bluespots) by adapting the Cloudburst Model developed by ESRI. Figure 2 shows geoprocessing tools used, the data inputs and the intermediate GIS products when looking for candidate GSI sites.

With the help of elevation data, i.e., DEM by USGS, the bluespots were found by calculating the elevational differences between entire filled sinks and small one with vertical accuracy of 0.167 ft. Those bluespots were then grouped, converted from raster to polygons, and dissolved by gridcode. The bluespots identified in Step 2.1 were used for further potential GSI sites lookup.

In Step 2.2, the bluespots were re-projected to measure their actual size in sq.ft. A vector layer of water cover was generated from the land cover image. All the bluespots covered by surface water were excluded because most of them were located lower than surroundings as the surface water flow paths, such as ponds or rivers. A single land use layer of public ownership was generated from the Hillsborough County land use dataset according to Table 2. All the bluespots containing >50% public lands were selected for further consideration. It is because the GSI in this research is related to the public infrastructure and surface transportation planning, and the possibility of GSI implementation in private properties (e.g., rain gardens in single houses) were excluded. With the exclusion of the implemented GSI, the potential GSI sites were generated from the selected bluespots. Taken into consideration of the feasibility of potential GSI implementation, only the sites with an area of over 20,000 sq.ft. were selected as the candidate GSI sites, which were used for further research.

Table 2. The categorization of land use for GSI implementation.

Land Use Type	Public Ownership	Availability for GSI Implementation
Agricultural	No	No
Educational	Maybe	Yes
Heavy Commercial	No	No
Light Commercial	No	No
Light Industrial	No	No
Mobile Home Park	No	No
Multi-Family	No	No
Natural	Yes	Yes
Not Classified	Maybe	Yes
Public / Quasi-Public / Institutions	Yes	Yes
Public Communications / Utilities	Yes	Yes
Recreational / Open Space	Yes	Yes
Right of Way / Roads / Highways	Yes	Yes
Single Family / Mobile Home	No	No
Two Family	No	No
Unknown	Maybe	Yes
Vacant	Maybe	Yes

All the inputs and their values related to the geoprocessing tools in Figure 2 were summarized in Table 3.

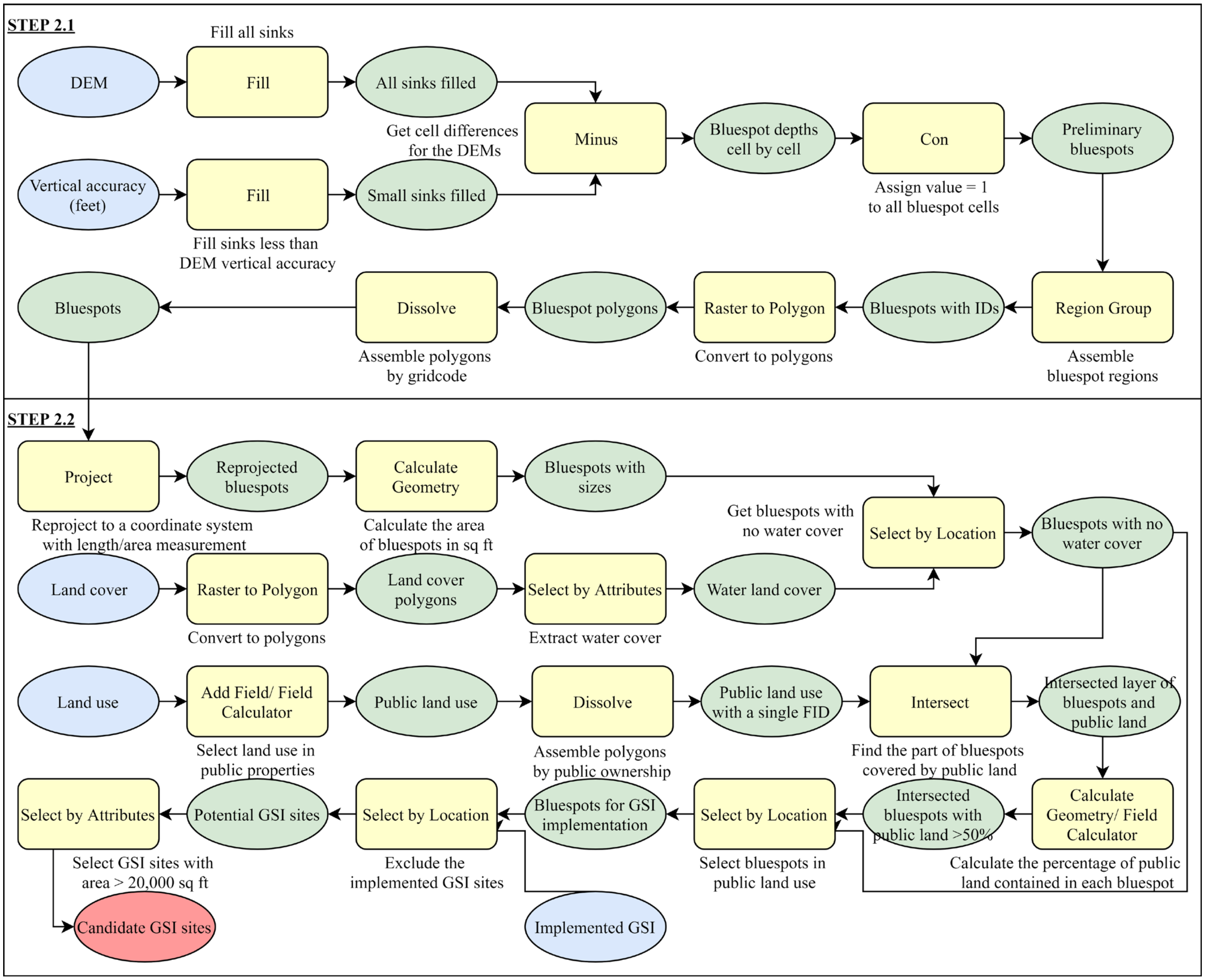

Figure 2. The process diagram to look for candidate GSI sites in ArcGIS. Step 1 is adapted from ArcGIS lessons (ESRI, 2019). The items in blue ellipse are the data inputs, the ones in yellow rectangle are the geoprocessing tools in ArcGIS (each has a short description below), and the ones in green ellipse are the intermediate products as GIS layers.

Table 3. The inputs and values for the geoprocessing tools used for finding potential GSI sites.

Geoprocessing tool	Inputs and values
STEP 2.1	
Con	Expression: Value > 0
	Input true raster or constant value: 1
Region Group	Number of neighbors to use: EIGHT
	Zone grouping method: WITHIN
Raster to Polygon	Field: Value
Dissolve	Dissolve field: GRIDCODE
STEP 2.2	
Project	Output coordinate system: PCS: NAD 1983 StatePlane Florida West FIPS 0902 Feet
Calculate Geometry (1)	Use coordinate system of the date frame: PCS: NAD 1983 StatePlane Florida West FIPS 0902 Feet Units: Square Feet US [sq ft]
Select by Location (1)	Spatial selection method for target layer feature: intersect the source layer feature
Dissolve	Dissolve field: Public Ownership
Intersect	JoinAttributes: ALL
Calculate Geometry (2)	Property: Area, in a new field "InterArea"
	Use coordinate system of the date frame: PCS: NAD 1983 StatePlane Florida West FIPS 0902 Feet Units: Square Feet US [sq ft]
Field Calculator	A new field "Percentage" = [InterArea]/[Area]*100
Select by Location (2)	Spatial selection method for target layer feature: completely contain the source layer feature
Select by Location (3)	Spatial selection method for target layer feature: intersect the source layer feature
Select by Attributes	SELECT * FROM * WHERE: Area >= 20000

Determine the GSI size for candidate sites

All the candidate GSI sites were mapped with the information of related drainage area, i.e., the area collecting the stormwater runoff to the GSI. The GSI (assumed as bioretention systems in the Phase II research) surface area was sized according to the equations below from the Minnesota Stormwater Manual (2018).

$$A_S = \frac{\frac{12in}{ft} * IA_D}{rt} \quad (1)$$

In the equation, A_D is the drainage area (in sq.ft.), A_S is the bioretention surface area (in sq.ft.), I is the impervious percentage, r is the average rainfall rate (in inch per hour), and t is the allowable water drain time in the treatment unit (assumed as 48 hours). The average rainfall rate was assumed as 4.5 inches per hour according to 2018 International Plumbing Code. The impervious percentage was determined by the land use (Table 7).

Each GSI candidate was assigned with the calculated surface area, which was saved in the attribute table of the GIS layer.

Build a SWMM-based hydrologic simulation model

The hydrologic simulation model in this project were developed using the EPA's SWMM. SWMM is a rainfall-runoff simulation model that can be used to model the quantity and quality of runoff for storm events. The model is meant to simulate areas of land with the runoff being routing into a stormwater network (at varying scales). The program allows a user to define catchment areas with detailed parameters, as well as input individual stormwater infrastructure components. SWMM was chosen because it is a free and publicly available tool with the ability to construct a model of a large area but still contain a high level of detail. Data for the simulations came in the form of GIS shapefiles that were created by, and received from, the local municipalities.

The following methodology was developed to effectively create a detailed model for a large area. Models created in SWMM are usually input manually, and so the level of detail diminishes as the scale increases. To avoid this issue, GIS shapefiles were used as the data source so the parameters for a large number of inputs can be calculated in an efficient manner. Once all parameters are calculated, the GIS data can be easily converted into a SWMM file for simulations.

Data collection

SWMM requires information on stormwater systems and land use in order to construct a model. Every component in SWMM, whether it's a land parcel or part of the stormwater network, has a list of parameters to be filled, and this information was taken from GIS data or was assumed. All types of stormwater infrastructure can be made into an item in a model within SWMM, including but not limited to gravity mains, inlets, discharge points, retention basins, and various types of green infrastructure. To get this data, the local municipalities that fell within the study area were contacted; these were the City of Tampa, Hillsborough County, and Temple Terrace. The data from these groups came as GIS datasets, but were not all organized the same. All datasets used are shown in Table 1. The datasets did contain some overlap; the overlap dataset was located manually and whichever data points in the overlapped dataset with less information would be deleted.

Data processing

SWMM categorizes most of the physical objects in the model into three groups: subcatchments (polygons), nodes (points), and links (lines). Subcatchments refer to physical areas of land, with data such as land use and slope being factored into the model. Nodes can be representative of a number of stormwater infrastructures such as inlets, discharge points, and storage units. Links are used to represent things such as pipes, open channels, and weirs. Other parameters such as temperature

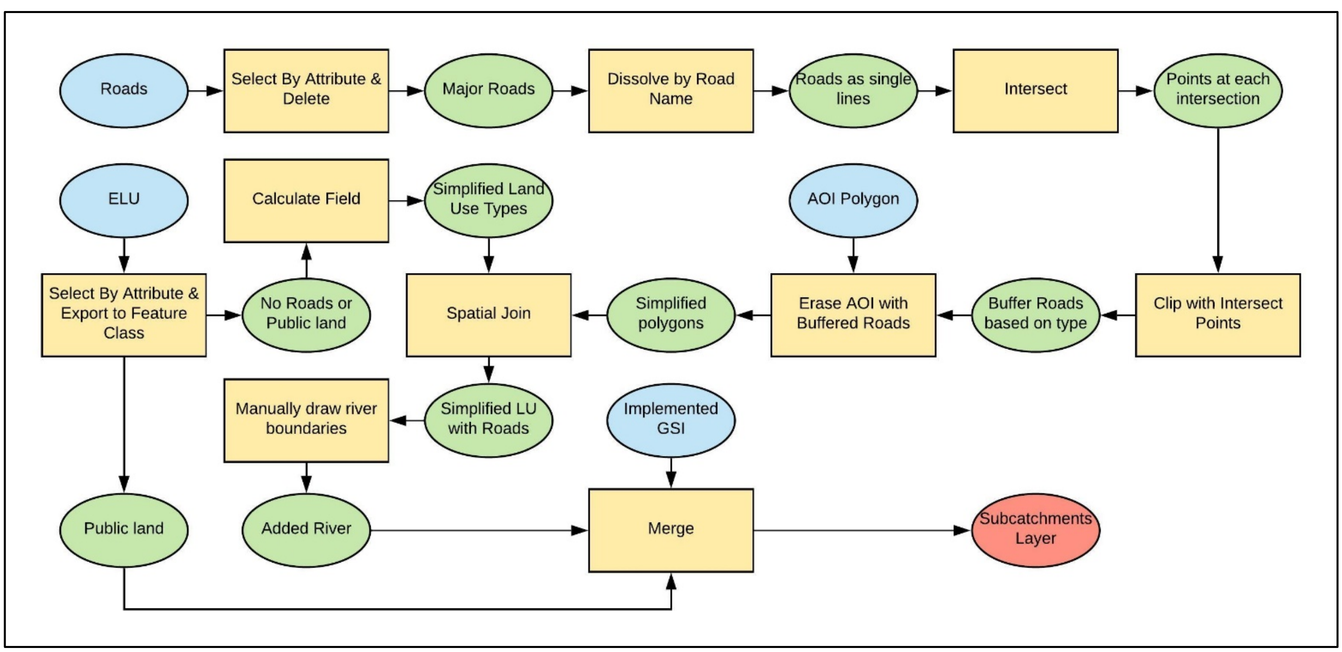

Figure 3. The process diagram to simplify the subcatchments for SWMM use in ArcGIS.

and evaporation rates are entered into the model separately from the physical objects.

"Subcatchment" is any area that acts as a catchment for rainfall. The subcatchments in the model were created from land use data that came from the Hillsborough County Existing Land Use layer. The original dataset contained over 100,000 individual polygons, so this was simplified using the process described in Figure 3 and GIS tools listed in Table 4.

Table 4. The inputs and values for the geoprocessing tools used for subcatchment simplification process.

Geoprocessing tool	Inputs and values
Select by Attribute	Field: ROADCLASS Attribute: Local
Dissolve	Field: FULLNAME Uncheck "Create multipart features"
Intersect	Output Type: POINT
Clip	Input: Dissolved Roads Clip Feature: Intersect Points
Erase	Input Feature: AOI Erase Feature: Buffered Roads
Buffer	Buffer Roads based on values in Table 5
Select by Attribute	Fields: Not Classified & Public
Spatial Join	Target: AOI Erase Join: HC Existing Land Use Join One-to-One Check Keep all Target Features Merge Rule for LU Type: Mode
Merge	Input: Existing GSI, Simplified Land Use, Public Land

The road buffers were created according to the road type using the values in Table 5.

Table 5. The buffer distance for each road type.

Road Type	Buffer Distance (ft)	Total Final Width (ft)
Collector	30	60
Freeway	40	80
Minor Arterial	50	100
Neighborhood Collector	18	36
Principal Arterial	60	120
Ramp	14	28
Right of Way	25	50

With all the subcatchments created and organized by land uses, the different parameters for each can now be calculated and added to the attribute table in ArcMap.

The first parameter to be calculated for subcatchments is the node to which the runoff will be routed. This process is shown in Figure 4. Table 6 summarizes the parameters to be calculated, estimated, or assumed. Each of these parameters was input as a new field in the attribute table of the subcatchment layer.

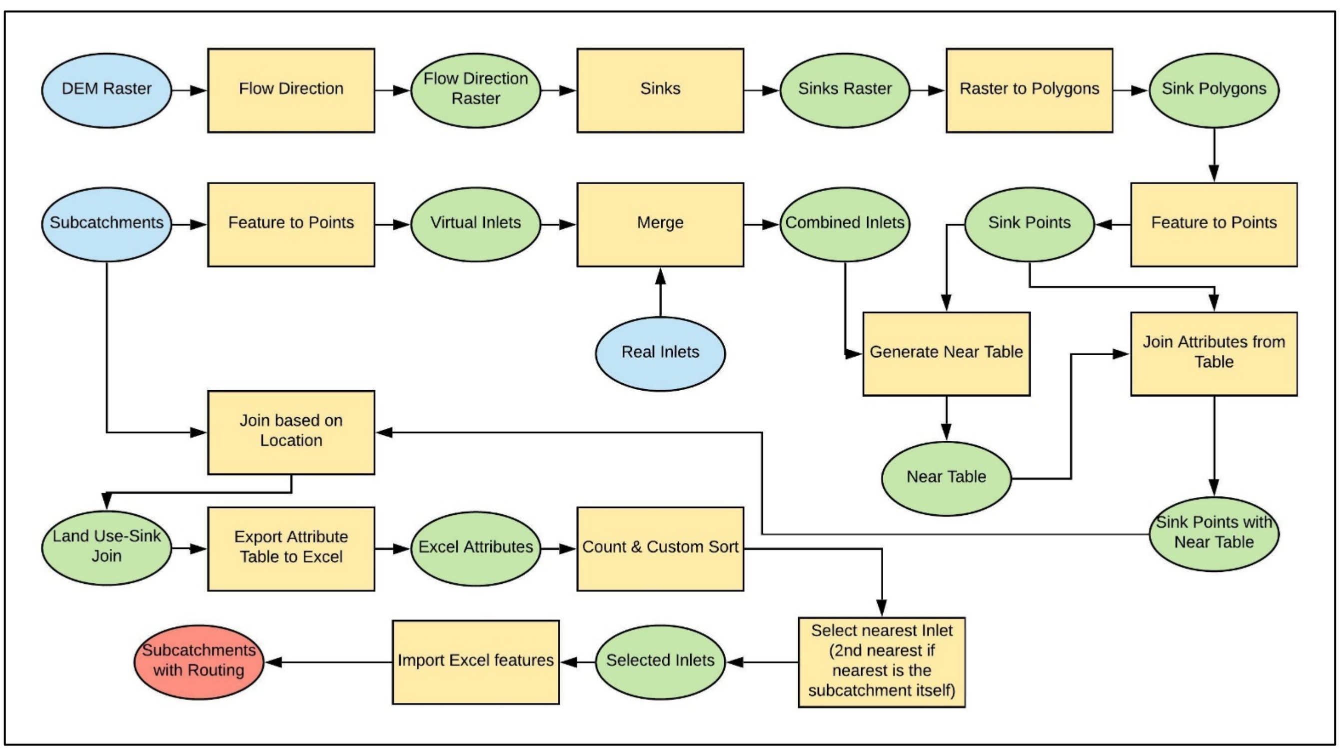

Figure 4. The process diagram for subcatchment routing in ArcGIS.

Table 6. The parameters identified for the subcatchment layer.

Parameter	Values and Methods
Rain Gage	G1 (Rain Gages are discussed later)
Area	Calculate Area Tool in ArcGIS
Characteristic Width	Calculate Field: 4*area/perimeter
% Slope	Slope tool with DEM raster; convert to points; spatial join by location, join type intersect, search 100 ft, mean as merge rule
% Impervious	Calculate Field based on assumed values in Table 7
Mannings Number for impervious/pervious area	Assume based on SWMM User Manual
Depth of depression storage for impervious/pervious area	0.05 in/ 0.1 in
% of impervious area with no depression storage	Use default value of 25%
Subarea routing	Outlet
Infiltration	Modified Green Ampt
Snow Pack	None

The impervious percentage was assumed according to land use type using the values in Table 7.

Table 7. The impervious percentage assumed for each land use type.

Land Use Type	LU #	% Impervious
Residential	1	40
Commercial	2	75
Open/Natural	3	0
Public	4	50
Agriculture	5	0
Vacant	6	50
Road	7	95

"Nodes" are one of the other major types of physical objects used in SWMM. The most used type of node is the Junction node, since it can represent numerous types of intersections in a stormwater network. The data for stormwater points came in a few different organizational formats from the different municipalities, but all three municipalities provided clear designations for inlets and regular pipe intersections, which are the two main groups. They also had fairly clear designations for discharge points. First, all points, (excluding weirs and pump stations) were combined into one layer. This was done so that each could be given a unique name that designates them as a Junction ("J" + their object ID). The combined inlet data was used with the subcatchments to determine runoff routing in the process described earlier. For junctions, the main parameters needed are the invert elevation, which is the elevation of the bottom of the structure (be it a manhole, regular pipe intersection, etc.), and also the distance from the bottom of the invert to the ground surface (labelled as Max Depth). The different data sets did not provide the invert elevation for the most part (a few of them had the information, but most of the 22,000+ points did not). Some however did provide the distance to the ground surface. For those that did not, an assumed value was used based on the structure type and the recommended values in the Florida Department of Transportation Drainage Design Guide. Then, using a DEM dataset, the elevation of the ground at each of the points was extracted as an attribute to each point using the Extract by Points tool. By subtracting the distance to ground value from the elevation of each point, the invert elevation was determined for each of the junction points.

The next parameters for junctions are Initial Depth, Surcharge Depth, and Ponded Area. Both Initial Depth and Surcharge Depth are assumed to be 0. Initial Depth is set to be 0 because the simulations will be assuming that there was not significant rainfall before the simulations. The Surcharge Depth is a parameter representing the additional depth a junction can fill up with before it floods, which is used to simulate manholes or pressurized mains. This is assumed to be 0 since these simulations are not meant to be testing the normal stormwater infrastructure in the network, just green infrastructure's effect on the system. Ponded area is an attribute that designates the area of the space that will fill with water when a junction floods,

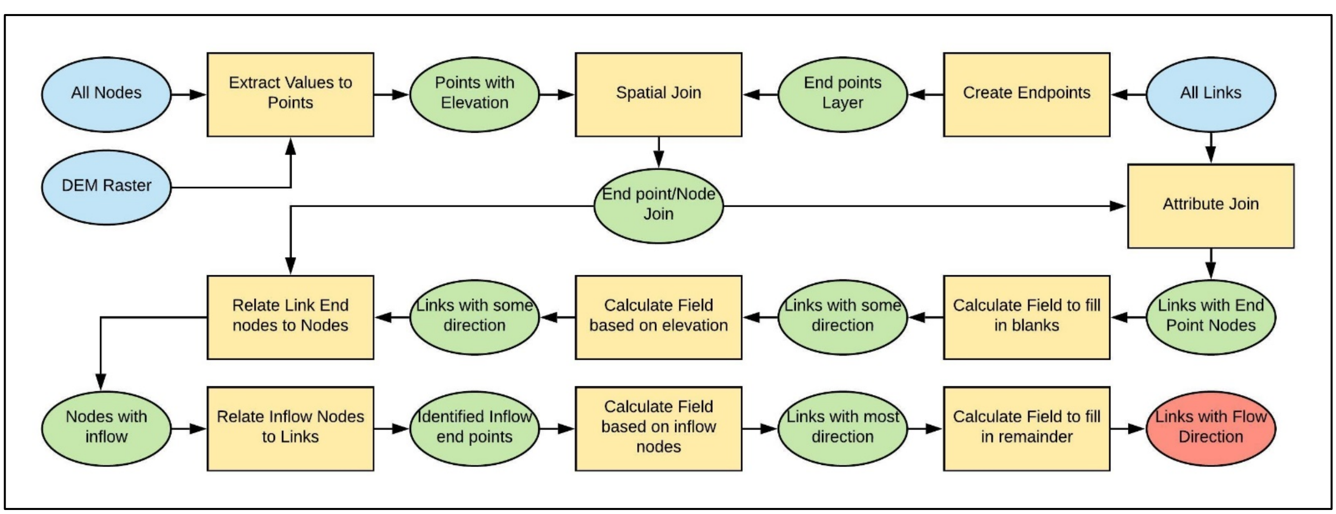

Figure 5. The process diagram to identify the flow direction for links in ArcGIS.

where the water will be stored until the system is able to allow it back in. For inlets, the assumed value will be 10 square feet, and this is based on an average of values recommended in the SWMM User Manual. For all other junctions, the value is assumed to be 0.

"Links" are the other major type of physical objects in SWMM. These are used to represent pipes and channels that convey water from one node to another. One of the important parameters for links are the nodes they are connecting, because this provides the flow direction. Some of the GIS data already contained the start and ending nodes for each link, but most did not, so these had to be assumed, using the process described in Figure 5. The other necessary parameters for the links are summarized in Table 8 (any parameter not listed in the table is assumed to have a value of 0).

Table 8. The parameters identified for the link layer.

Parameter	Values and Methods
Shape	Circular or parabolic, based on Link type
Length	Calculate Geometry Tool in ArcGIS
Max Depth	Given in Attribute Table
Mannings Roughness	Assumed based SWMM User Manual

Once all the parameters have been calculated in ArcGIS, the layers are exported as shapefiles. A Python code is used to rewrite the data in the shapefiles into a SWMM input file.

After opening the file in SWMM, a time series is manually entered to represent a 100-year, 1-day storm, based on data from the Florida Department of Transportation Drainage Design Guide. The model is first run as is with the time series to serve as a baseline for future simulations. After this, potential GSI are added to the layer in GIS and the same process will follow to get the SWMM input file for the alternative scenario (Figure 6).

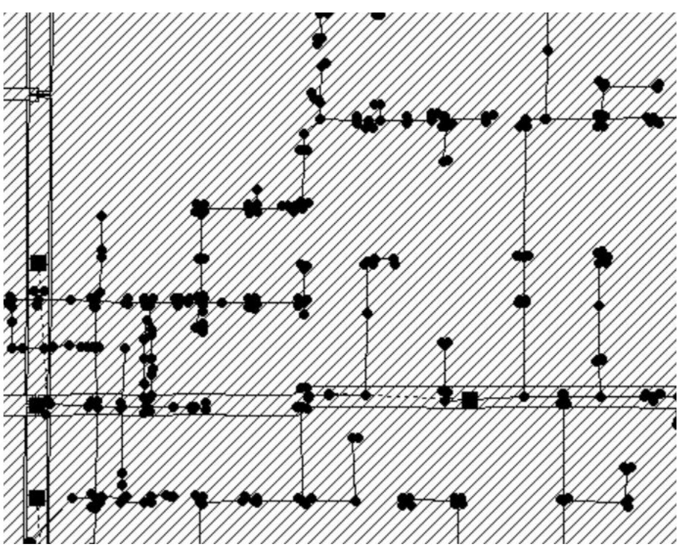

Figure 6. An example section of the model in SWMM, showcasing the separation of subcatchments and the network of stormwater infrastructure.

Life Cycle Assessment (LCA)

The LCA in this study follows the ISO 14044 (2006) standard, containing four primary steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. The LCA goal is to evaluate the environmental impacts of each GSI scenario in the hot spot. The LCA in this study follows the work of Xu and Zhang (n.d.) on the sustainability of bioretention systems, including the life cycle inventory of bioretention systems.

Each bioretention system follows the design with engineered internal water storage zone (IWSZ) of 45-cm depth and ground plants of medium total nitrogen (TN) uptake capacity, which is a bioretention configuration scenario in the research of Xu and Zhang (n.d.). The lifetime of a bioretention system was assumed to be 15 years. In terms of the life cycle of a full-scale bioretention system, the construction and operation and maintenance (O&M) stages were considered within the system boundary, including the processes of manufacturing, transportation, installation, operation, routine maintenance, and corrective maintenance like consumable material replacement. The LCA was conducted with the SimaPro PhD software (version 8.0) by PRé Consultants. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1 by the US EPA was used for the assessment. The impact categories analyzed for each scenario include eutrophication, ecotoxicity, and global warming potential.

A series of LCA were conducted for the bioretention systems with the surface areas of 200, 500, 1,000, 2,000, 5,000, and 10,000 sq.ft. Then, the regression model was built between the bioretention surface area and its environmental impacts, i.e., eutrophication, ecotoxicity, and global warming potential. Each GSI was assigned with the impact values of eutrophication, ecotoxicity, and global warming potential, based on its surface area using the regression model. Eventually, the environmental impacts over the whole study area were normalized with respect to the function unit (FU) of 1 kg TN removed, since the study targeted on nitrogen as the primary nutrient responsible for eutrophication in coastal areas (Howarth & Marino 2006).

Life Cycle Cost Analysis (LCCA)

The life cycle cost (LCC) in this study, following the work of Xu and Zhang (n.d.), included the capital cost, routine maintenance cost (i.e., regular inspection, vegetation management, trash and debris removal, and unclogging drain), corrective maintenance cost (i.e., tilling soil, replacing mulch and IWSZ wood chips), and the material replacement and electricity cost involved in the maintenance activities. The LCC as net present value (NPV) was calculated by discounting all the costs mentioned above to present values. The lifetime was assumed to be 15 years, and the discount rate d was assumed to be 5%. All the cost data was acquired from Xu and Zhang (n.d.).

Similarly, the regression model was developed to estimate LCC based on the bioretention surface area. Each GSI was assigned with the LCC calculated using the regression model and GSI's surface area.

SCENARIO DEVELOPMENT

The Hot Spot in This Research

To define the hot spot in this study, some rules mentioned previously were taken into consideration:

1. a region under flood risk;
2. an area consisted of diverse land uses;
3. an area could work as input to the hydrologic model SWMM;
4. An area has high population density, but few existing GSI.

To meet the requirements, the Middle Hillsborough River-Spillway 20 subwatershed area (HUC12 code: 031002050503) was selected for this project (see Figure 7). It covers an area of 125 km^2, approximately 30% area of Tampa City. According to the reported street flooding in the last three years, about half of the study area has been suffered from the flooding incidents and better stormwater management is a need in the area. Adjacent to the downtown Tampa, most of the study area is for urban use, including business, commercial, residential, recreational and some other community mixed uses. Moreover, the subwatershed area could be imported into SWMM as a standard hydrologic unit input. The GSI inventory was created for this study area and only 89 GSI were detected. The region of the hot spot is suitable for future GSI implementation and the system-level analysis in this research.

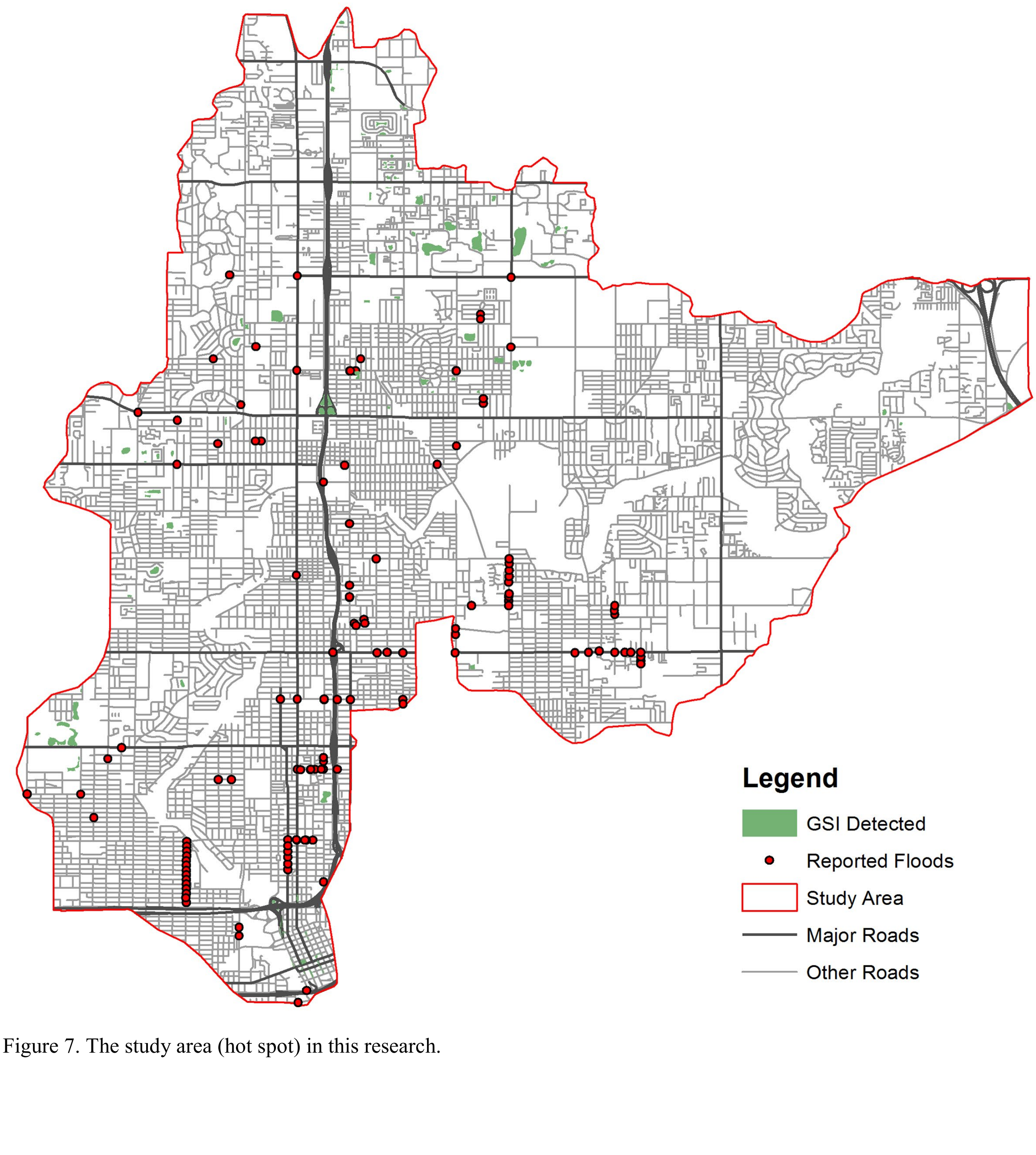

Figure 7. The study area (hot spot) in this research.

The Candidate GSI Sites

Total 262 candidate GSI sites were identified for this research (Figure 8). All the bluespots located in the surface water area or non-public land were excluded from the potential GSI. Table 9 summarizes the amounts of bluespots in each step when generating the GIS layer of potential GSI sites. Specifically, only the ones with size of over 20,000 sq.ft. were selected for further research, limiting the amount of potential GSI sites from over 2,000 to 262.

The urban area in Tampa expanded from south to north, indicating the communities in the north were newly built. In line with the characteristics of city development, most of the implemented GSI as new practices of stormwater management are located in the north of the study area. Compared to the existing GSI that are mostly located in the north, the candidate GSI are evenly distributed within the study area. It shows the great possibility of future GSI implementation throughout the study area with the consideration of geographic background (e.g., terrain) and urban planning (e.g., land use). Specifically, GSI could be a feasible solution for stormwater management in the developed area in the south that needs rehabilitation.

Table 9. The amounts of potential GSI or bluespots in each step.

	Amount
Bluespots in the hot spot	4,515
Bluespots with water cover (excluded)	176
Bluespots with public ownership	2,212
Potential GSI	2,035
Candidate GSI with size of over 20k sq.ft.	262

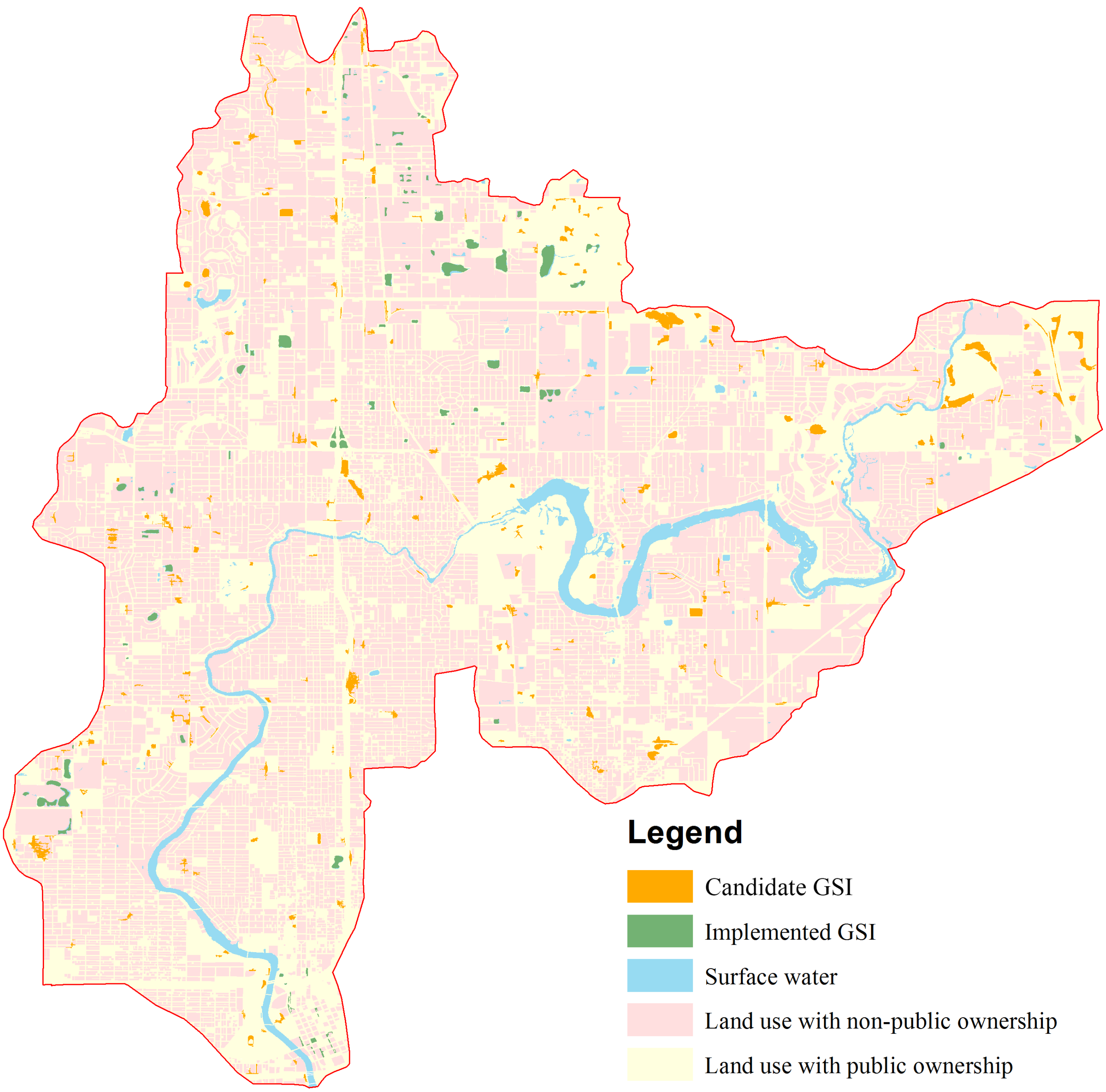

Figure 8. The candidate GSI in the study area.

SCENARIO ANALYSIS

Flood Reduction

The flow patterns were simulated using the SWMM-based model, and the stormwater runoff information at each subcatchment was exported from the model. Figure 9 shows the runoff distribution in the study area during a storm event with the implementation of existing GSI (Scenario 1) or both the existing and candidate GSI (Scenario 2).

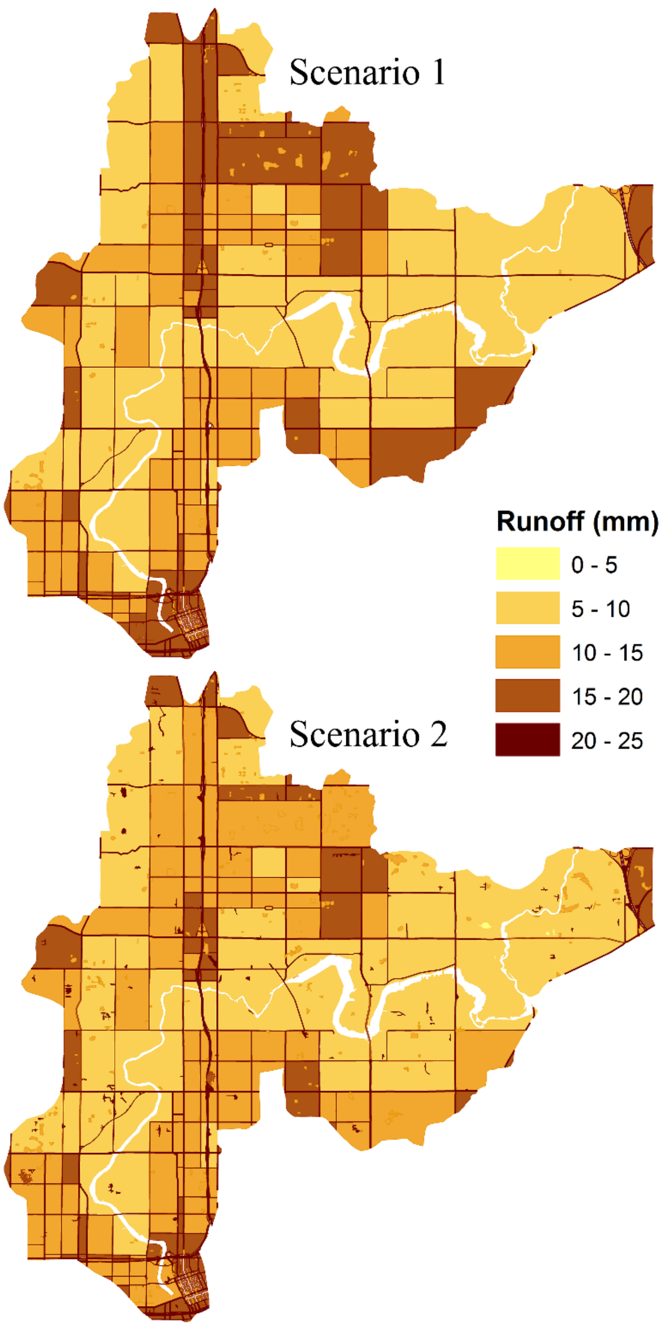

Figure 9. The runoff simulated for Scenarios 1 and 2.

It can be seen that the major roads, the North Tampa area, and the downtown Tampa in the south have higher runoff. This indicates that these areas have higher possibility to experience street flooding and the flood control measures should be implemented in the high-runoff regions.

The runoff results from the two scenarios shows that Scenario 2 can effectively reduce the stormwater runoff with the implementation of additional 262 candidate GSI. Specifically, Scenario 2 greatly reduces the areas with runoff over 20mm compared with Scenario 1. This demonstrates the effectiveness of the candidate GSI identified in the study for flood reduction. It indicates that the regions with the reduced runoff could be benefited from the implementation of GSI nearby.

Nutrient Removal

Through the simulation of SWMM-based model, the total effective area of implemented and candidate GSI are 6.25 and 79.94 hectares, respectively. The hydrologic retention time (HRT) for all GSI was also simulated (Figure 10). About 40% GSI have HRT less than 10 hrs. The rest 60% GSI are mainly in the groups of either 44.8-hr HRT or 85.0-hr HRT. The HRT is highly correlated with the ratio of GSI surface area to drainage area because the precipitation rate and soil infiltration rate obtained from the SWMM-based model are the same and all GSI are designed with the same optimal depth of the internal water storage zone. Since the impervious percentage is dependent on the land use type and the ratio of GSI surface area to drainage area is proportional to the impervious percentage, the HRT of candidate GSI are highly grouped according to the land use type.

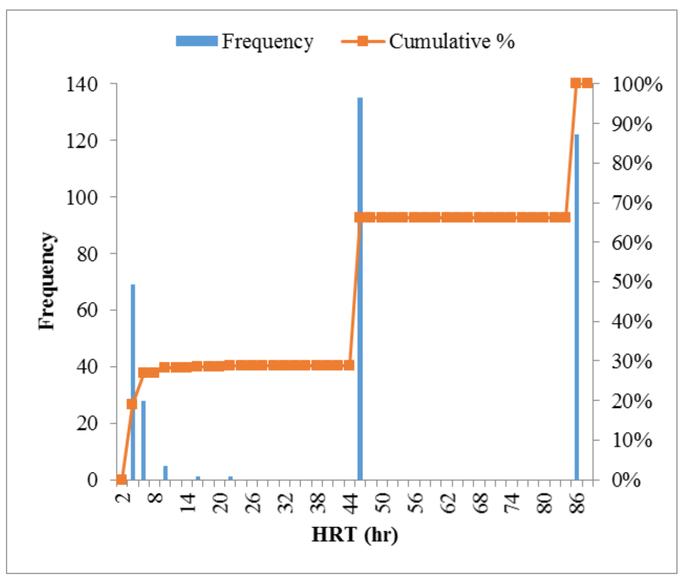

Figure 10. The histogram of HRT for the existing and candidate GSI.

Based on the individual HRT of bioretention systems, the mass of total nitrogen (TN) removed by each bioretention system in its lifetime of 15 years was evaluated using the bioretention process model (Xu & Zhang, n.d.). The TN removal for each scenario was calculated as the sum of TN removed by individual bioretention system. Compared to the 66% TN removal in Scenario 1, Scenario 2 has a higher TN

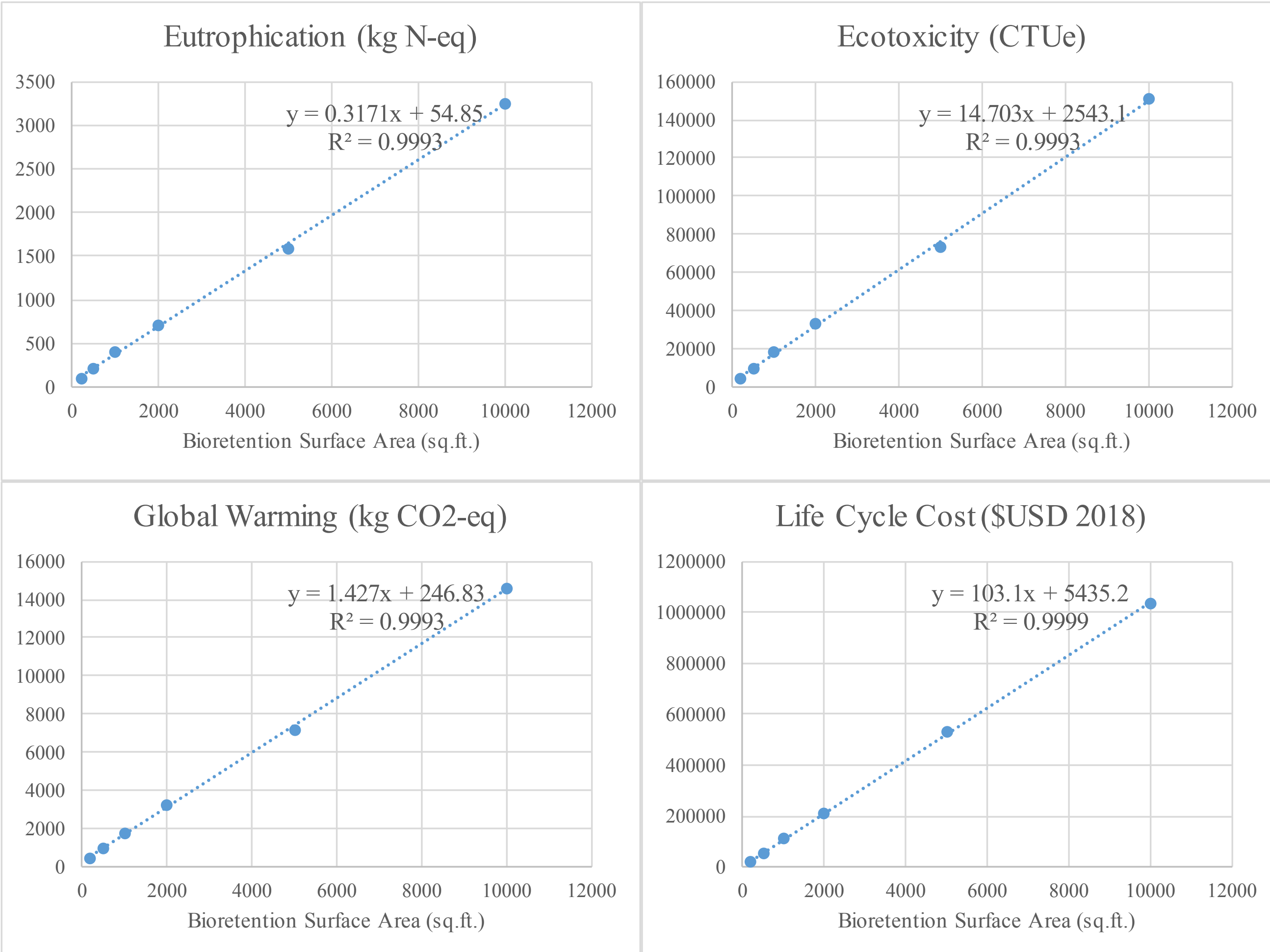

Figure 11. The linear regression between bioretention surface area and its eutrophication, ecotoxicity, global warming potential, and cost.

removal up to 74%. Over 60% of the candidate GSI in Scenario 2 has longer HRT than the GSI in the baseline (Scenario 1), providing more time for the bacteria of nitrifiers and denitrifiers in the bioretention system to convert and remove nitrogen in the runoff.

Environmental Impacts

The regression model was built using Excel between the bioretention surface area and its eutrophication, ecotoxicity, global warming potential, and cost (Figure 11). All the evaluated impacts have the linear correlation with bioretention surface area. This is because the evaluation of environmental impacts and cost highly relies on the energy and material inputs. The energy and material inputs for the bioretention system depend on the volume of the bioretention unit, which is proportional to the bioretention surface area since all GSI are designed with the same optimal depth.

The environmental impacts of individual GSIs, including both the implemented and candidate ones, were evaluated using the regression model developed. For each impact category, i.e., eutrophication, ecotoxicity, and global warming potential, the impact of individual GSI in each scenario were summed up to get the total impact of the GSI in the study area. The total impacts for each scenario were then normalized by the FU to investigate the effects of GSI implementation on nutrient control (eutrophication), human health (ecotoxicity), and energy consumption (global warming) for every mass unit of TN removed. Figure 12 shows the results of normalized environmental impacts.

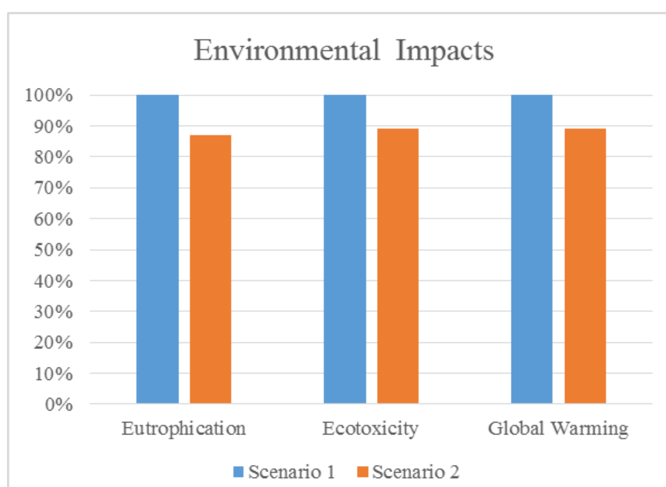

Figure 12. The normalized environmental impacts evaluated for the two scenarios.

Overall, Scenario 2 with both existing and candidate GSI has about 10-12% lower impacts across all three categories than Scenario 1 with existing GSI. The location of GSI could be the contributor to the lower impacts of Scenario 2. Compared to the implemented GSI, the candidate GSI are usually located at low-lying places with higher impervious area, as well as longer HRT. For example, the bioretention system of 10,000 sq.ft. surface area, can remove 58% TN under 2.5-hr HRT but 72% TN under 24-hr HRT. The location with longer HRT for GSI benefits the nutrient removal of the candidate GSI. Thus, the environmental impacts per unit of TN removed would be lower for Scenario 2. This indicates that the higher nutrient removal with more GSI implemented (Scenario 2) can compensate the incurred environmental impacts associated with the construction and maintenance of additional GSI. In another word, it is more environmentally beneficial with additional GSI implementation.

Cost

The LCC by the GSI in the study area for each scenario were summed up and converted to annualized net present value (ANPV). The ANPV was also normalized by the FU like the environmental impact evaluation, to reflect the cost for unit TN removed. Scenario 2 has slightly lower cost of $1.42/FU than Scenario 1 of $1.49/FU due to the better location selection of candidate GSI.

All the three environmental impacts were also normalized by the LCC for each scenario to investigate the marginal environmental impacts. Comparing Scenarios 1 (89 GSI) and 2 (additional 262 candidate GSI), it was found that eutrophication, ecotoxicity, and global warming could be reduced by 5%, 4%, and 3.7% respectively for every additional dollar invested for GSI implementation. It means the GSI implementation at watershed scale is cost effective for the impact control of nutrient discharge, energy consumption, and human health.

CONCLUSION

The Phase II research makes contribution to identifying potential GSI sites and modeling the hydrologic flow patterns with GSI implementation in a large spatial scale, which are challenges in current surface transportation planning and stormwater management. The methods developed for solving these two issues are transferrable to other locations.

The results of scenario analysis indicate the positive impacts of additional GSI implementation in the study area on nutrient control, energy consumption, and human health. The additional investment on GSI implementation would realize those benefits.

REFERENCE

Belizario, P.; Scalize, P.; Albuquerque, A. heavy metal removal in a detention basin for road runoff. *Open Eng* **2016**, *6*, 412-417, doi: 10.1515/eng-2016-0060.

Bowen, K.J.; Lynch, Y. The public health benefits of green infrastructure: The potential of economic framing for enhanced decision-making. *Curr Opin Env Sust* **2017**, *25*, 90-95, doi:10.1016/j.cosust.2017.08.003.

Demuzere, M.; Orru, K.; Heidrich, O.; Olazabal, E.; Geneletti, D.; Orru, H.; Bhave, A.; Mittal, N.; Feliu, E.; Faehnle, M. Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *J Environ Manage* **2014**, *146*, 107-115, doi:10.1016/j.jenvman.2014.07.025.

ESRI. Find Areas at Risk of Flooding in a Cloudburst. Availabe online: https://learn.arcgis.com/en/projects/find-areas-at-risk-of-flooding-in-a-cloudburst/ (accessed on 15 Feburary 2019).

Howarth, R. W.; Marino, R. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnol Oceanogr* **2006**, 51, 364–376.

International Code Council. 2018 – International Plumbing Code. Availabe online: https://codes.iccsafe.org/content/IPC2018/appendix-b-rates-of-rainfall-for-various-cities (accessed on 15 Feburary 2019).

Li, J.; Liang, Z.; Gao, Z.; Li, Y. Experiment and simulation of the purification effects of multi-level series constructed wetlands on urban surface runoff. *Ecol Eng* **2016**, *91*, 74-84, doi: 10.1016/j.ecoleng.2016.01.061.

Lucas, S.; Clar, M.; Gracie, J. A. Green street retrofit in a Chesapeake Bay community using bioswales. In Proceedings of 2011 Low Impact Development Conference, Philadelphia, PA, 25-28 Septemter, 2011. (Published in **2015**, doi: 10.1061/9780784413883.009).

Lucke, T.; Nichols, P.W. The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation. *Sci Total Environ* **2015**, *536*, 784-792, doi: 10.1016/j.scitotenv.2015.07.142.

Minnesota Pollution Control Agency. Minnesota Stormwater Manual - Design criteria for bioretention. Availabe online: https://stormwater.pca.state.mn.us/index.php/Design_criteria_for_bioretention (accessed on 15 Feburary 2019).

Roy, A.H.; Wenger, S.J.; Fletcher, T.D.; Walsh, C.J.; Ladson, A.R.; Shuster, W.D.; Thurston, H.W.; Brown, R.R. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *J Environ Manage* **2008**, *42*, 344-359, doi: 10.1007/s00267-008-9119-1.

Suppakittpaisarn, P.; Jiang, X.; Sullivan, W.C. Green Infrastructure, green stormwater infrastructure, and human health: A review. *Current Landscape Ecology Reports* **2017**, *2*, 96-110, doi:10.1007/s40823-017-0028-y.

Wendel, H.E.W.; Downs, J.A.; Mihelcic, J.R. Assessing equitable access to urban green space: The role of engineered water infrastructure. *Environ Sci Technol* **2011**, *45*, 6728-6734, doi:10.1021/es103949f.

Xu, X.; Zhang, Q. Sustainable configuration of bioretention systems for nutrient management through life cycle assessment and cost analysis. *J Environ Eng*, doi: 10.1061/(ASCE)EE.1943-7870.0001526 (In press).