SUSTAIN Applications for Mapping and Modeling Green Stormwater Infrastructure

Uzair (Sam) Shamsi, John W. Schombert and Lawrence J. Lennon

Abstract

The United States Environmental Protection Agency's System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) software program is a GIS based decision support system to help development, evaluation and selection of optimal green stormwater infrastructure (GSI) combinations on the basis of cost and performance. SUSTAIN's best management practices siting tool (BST) supports the selection of suitable GSI locations that meet user defined site suitability criteria. This paper describes SUSTAIN applications for mapping and modeling GSI. A case study is presented from a recent project in Allegheny County, Pennsylvania in which SUSTAIN BST was used along with other computer programs for a county-wide GSI planning project for combined sewer overflow control.

Keywords: stormwater, SUSTAIN, LID–BMP, GIS, CSO–SSO.

1 Introduction

Stormwater management systems in many cities are inadequate and based on old paradigms which collect and transport stormwater flow to a downstream outfall or treatment facility. This approach increases flooding problems, causes sewer overflows and results in deteriorated water quality in receiving waters.

A stormwater best management practice (BMP) is a stormwater management facility or activity used to protect, maintain, reclaim or restore the quantity and quality of receiving waters and the designated water uses. BMPs increase infiltration, decrease runoff, and improve water quality. There are two types of BMPs: structural BMPs are constructed facilities, such as rain gardens and porous pavement; non-structural BMPs are activities such as planting trees and street cleaning.

Stormwater low impact development (LID) controls are new sustainable development practices and BMPs designed to capture stormwater surface runoff using some combination of detention, infiltration and evapotranspiration. As a means to reduce volume entering a stormwater or wastewater system and reduce its peak flows, LIDs can be applied through source controls to infiltrate, evapotranspirate or store stormwater runoff for beneficial uses. These approaches prevent stormwater runoff from entering a sewer system and reduce overflows (Shamsi 2010; 2011). Rain gardens and porous pavement are examples of LID controls.

Gray infrastructure is defined as traditional brick, mortar and concrete construction to remove stormwater from its source and transport it to a downstream outfall or treatment facility. Sewers, deep tunnels and storage tanks are examples of gray infrastructure. Green stormwater infrastructure (GSI) is defined as the specific sets of source controls that use natural processes to reduce the volume of stormwater entering the sewer system. The same as LIDs and structural BMPs and also referred to as sustainable infrastructure, GSI is designed to capture surface runoff close to its source at distributed (decentralized) locations (Michael Baker Corporation 2008). Rain gardens or bioretention, subsurface infiltration, green roofs, porous pavement and street planter boxes are common GSI examples (Trimbath and Shamsi 2013). Rain gardens, street planters and green roofs (Chen and Li 2011) are all variations of bioretention cells. To avoid confusion, GSI is used as an all-inclusive term for all sustainable structural BMP and LID technologies.

While interest in the application of GSI has increased recently, there is little hard data, and less in the way of engineering assessment tools available to water resources engineers to facilitate an area-wide evaluation of GSI for comparison to conventional gray wet weather control technologies. In the absence of well-defined regional GSI siting methodologies, engineers are hard pressed to develop alternatives or render opinions on green versus gray infrastructure in routine practice, particularly in a regulatory context which requires compliance with enforceable orders (Lennon et al. 2013).

Though some new land development is using GSI, most existing development used gray infrastructure. GSI retrofit is a structural stormwater management practice implemented after development has occurred, to improve water quality, protect downstream channels, reduce flooding or to meet other specific objectives. Retrofits include new installations or upgrades to existing BMPs in developed areas lacking adequate stormwater control.

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GSI implementation planning requires the mapping and modeling of existing gray infrastructure and GSI retrofits. Hydrologic and hydraulic (H&H) modeling can be used to verify and quantify the GSI benefits and to design appropriate LID controls (Behr and Montalto 2009). GSI modeling can be done using SWMM5 and PCSWMM software (Shamsi 2010; 2012; McCutcheon et al. 2012); WinSLAMM, from the University of Alabama (Tuscaloosa, Alabama) is another GSI modeling software program (Pitt and Voorhees 2011).

2 SUSTAIN

The United States Environmental Protection Agency's (USEPA) SUSTAIN software program provides an integrated ArcGIS-based GSI mapping and modeling platform (USEPA 2013; Shoemaker et al. 2009) to facilitate the selection and placement of GSI facilities at strategic locations in urban watersheds. SUSTAIN incorporates sophisticated algorithms for evaluating GSI effectiveness (Urbonas et al. 2013). For GSI planning, SUSTAIN can answer three questions:

1. Siting: Where are the best GSI locations?
2. Performance: How effective are they in reducing runoff and pollutants? and
3. Cost: How much will they cost?

SUSTAIN is designed as an integrated mapping–modeling package to support geographic information system (GIS) mapping and linkage to other related models such as detailed sewer system models (e.g. SWMM) or receiving water models of affected rivers. Where existing sewer and watershed models are available, SUSTAIN can be used to predict the most inexpensive GSI practices that will result in reduced overflow volumes and frequency.

SUSTAIN has the following seven modules (USEPA 2013).

1. Framework Manager: It manages the data exchanges between system components, coordinates external inputs, calls various modeling components (land, BMP, conveyance) and provides output information to the post-processor;
2. BMP Siting Tool (BST): It facilitates the selection and placement of GSI facilities;
3. Land Simulation Module: It computes runoff and pollutant loads from land surface;
4. BMP Module: It provides process-based simulation of flow and pollutant transport for various GSI types. It also provides GSI cost estimation using an MS Access unit cost database and an aggregation of distributed GSI features to assess the effectiveness of multiple GSI features;
5. Conveyance Simulation Module: It performs routing of flow and pollutants through a pipe or open channel;
6. Optimization Module: It identifies cost effective GSI placement and selection strategies based on known feasible sites and applicable GSI types and size ranges. This module uses evolutionary optimization techniques to search for cost effective GSI features that meet user defined decision criteria. It uses two search algorithms: scatter search and non-dominated sorting genetic algorithm-II (NSGA-II); and
7. Post-Processor: It uses MS Excel to provide a central location for analysing and interpreting simulation outputs at multiple locations, scenarios (e.g. pre-development conditions, and post-development conditions with and without GSI), and parameters of interest (e.g. inflow, outflow, pollutant load and concentration).

2.1 GSI Mapping Using SUSTAIN

In SUSTAIN, GSI mapping is done using the BST module. BST runs inside ESRI ArcMap GIS software as a special toolbar and creates GSI location maps in ESRI ArcGIS compatible shapefile format.

SUSTAIN BST requires extensive input data for GIS layers. Raster input data layers include:

- digital elevation model (DEM);
- land use; and
- impervious area.

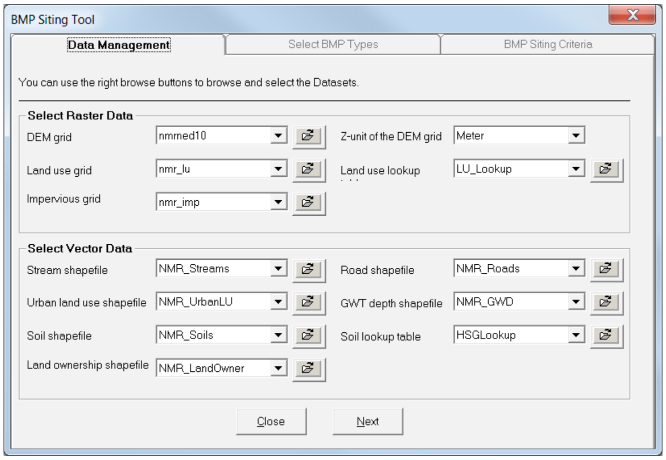
Vector input data layers include:

- streams;
- roads;
- urban land use;
- GWT depth;
- soils; and
- land owner.

Two lookup tables are also input:

- land use: which land use is suitable for GSIs; and
- soil: assigns HSG to soil polygons.

Figure 1 shows a screenshot of BST's Data Management dialog box where the user selects input GIS layers. The screenshot shows input GIS layers for the Nine Mile Run (NMR) sewershed of the case study project discussed later.



You can use the right browse buttons to browse and select the Datasets.

Select Raster Data

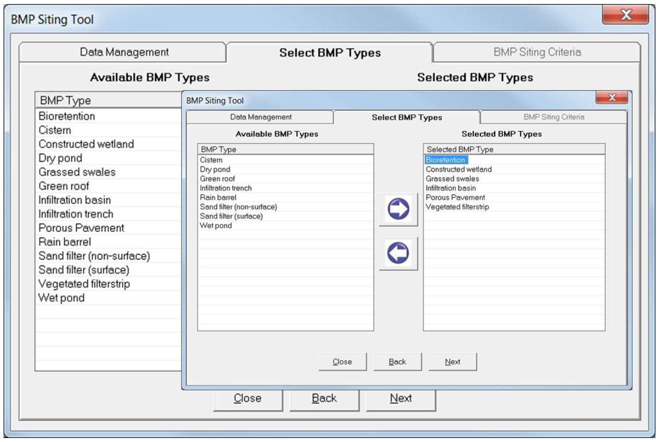
DEM grid: nmrned10
Z-unit of the DEM grid: Meter
Land use grid: nmr_lu
Land use lookup: LU_Lookup
Impervious grid: nmr_imp

Select Vector Data

Stream shapefile: NMR_Streams
Road shapefile: NMR_Roads
Urban land use shapefile: NMR_UrbanLU
GWT depth shapefile: NMR_GWD
Soil shapefile: NMR_Soils
Soil lookup table: HSGLookup
Land ownership shapefile: NMR_LandOwner

Figure 1 **SUSTAIN BST data management dialog box showing input GIS layers for one of the case study sewersheds.**

SUSTAIN BST can analyze 14 types of GSI technologies, shown in Figure 2. The inset shows six GSI types in the right column selected for BST analysis.



BMP Type
Bioretention
Cistern
Constructed wetland
Dry pond
Grassed swales
Green roof
Infiltration basin
Infiltration trench
Porous Pavement
Rain barrel
Sand filter (non-surface)
Sand filter (surface)
Vegetated filterstrip
Wet pond

BMP Type
Cistern
Dry pond
Green roof
Infiltration trench
Rain barrel
Sand filter (non-surface)
Sand filter (surface)
Wet pond

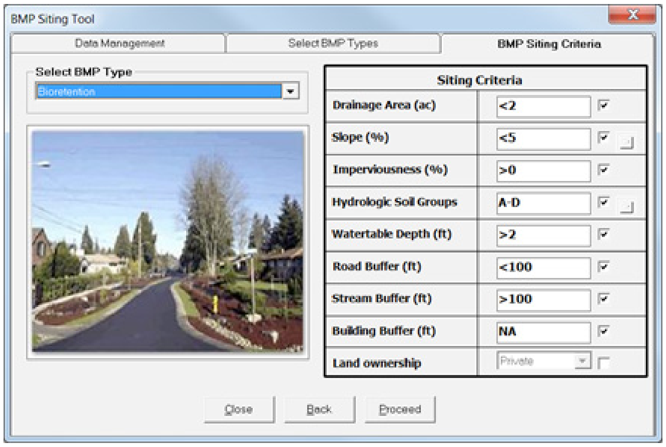
Selected BMP Type
Bioretention
Constructed wetland
Grassed swales
Infiltration basin
Porous Pavement
Vegetated filterstrip

Figure 2 Fourteen GSI types in SUSTAIN and the six GSI types included in the analysis.

BST provides potential GSI locations at strategic locations in urban watersheds that meet the following nine user defined site suitability criteria:

1. Drainage area;
2. Slope;
3. Imperviousness;
4. Hydrological soil group;
5. Groundwater table depth;
6. Road buffer;
7. Stream buffer;
8. Building buffer; and
9. Property type (public or private).

All but the drainage area criterion pertain to the GSI facility footprint. Out of the box, SUSTAIN BST defines nine generic default siting criteria values for each GSI technology, for size of drainage area, slope, hydrological soil group, groundwater table depth, property type, and buffer distance from buildings, roads and streams. Figure 3 shows a screenshot of BST's Siting Criteria dialog box for Bioretention populated with program's default values. Table 1 shows the default siting criteria for all 14 GSI types.



Select BMP Type: Bioretention

Siting Criteria		
Drainage Area (ac)	<2	☑
Slope (%)	<5	☑
Imperviousness (%)	>0	☑
Hydrologic Soil Groups	A-D	☑
Watertable Depth (ft)	>2	☑
Road Buffer (ft)	<100	☑
Stream Buffer (ft)	>100	☑
Building Buffer (ft)	NA	☑
Land ownership	Private	☐

Figure 3 SUSTAIN BST default GSI siting criteria for bioretention.

2.2 GSI Modeling Using SUSTAIN

GSI modeling is done using the Land and BMP modules in SUSTAIN. The Land module computes runoff and pollutant loads from land surface using one of two methods: hydrograph and pollutograph algorithms adapted from SWMM5; or sediment algorithms adapted from HSPF.

The BMP module simulates the following GSI processes:

1. Flow routing: stage outflow or kinematic method;
2. Infiltration: Green–Ampt or Horton method;
3. Evapotranspiration: constant, monthly average, daily values or potential ET from Harmon's method;

Table 1 SUSTAIN BST default GSI siting criteria.

No.	GSI Type	Drainage Area (acre)	Drainage Slope (%)	Impervious (%)	Hydrological Soil Group	Water Table Depth (ft)	Road Buffer (ft)	Stream Buffer (ft)	Building Buffer (ft)
1	Bioretention / Rain garden	< 2	< 5%	> 0%	A–D	> 2	< 100	> 100	-
2	Cistern	-	-	-	-	-	-	-	< 30
3	Constructed Wetland	> 25	< 15%	> 0%	A–D	> 4	-	> 100	-
4	Dry Pond	> 10	< 15%	> 0%	A–D	> 4	-	> 100	-
5	Grassed Swale / Bioswale	< 5	< 4%	> 0%	A–D	> 2	< 100	-	-
6	Green Roof	-	-	-	-	-	-	-	-
7	Infiltration Basin	< 10	< 15%	> 0%	A–B	> 4	-	> 100	-
8	Infiltration Trench	< 5	< 15%	> 0%	A–B	> 4	-	> 100	-
9	Porous Pavement (Concrete /Asphalt), Permeable Interlocking Paver	< 3	< 1%	> 0%	A–B	> 2	-	-	-
10	Rain Barrel	-	-	-	-	-	-	-	< 30
11	Sand Filter (non-surface)	< 2	< 10%	> 0%	A–D	> 2	-	> 100	-
12	Sand Filter (surface)	< 10	< 10%	> 0%	A–D	> 2	-	> 100	-
13	Vegetated Filter Strip / Grass Buffer	-	< 10%	> 0%	A–D	> 2	< 100	-	-
14	Wet Pond	> 25	< 15%	> 0%	A–D	> 4	-	> 100	-

4. Pollutant routing: completely mixed or continuously stirred tank reactors in series;
5. Pollutant removal: first order decay or Kadlec and Knight's first order kinetic method;
6. Sheet flow routing for buffer strip: kinematic wave overland flow routing;
7. Sediment trapping from buffer strip: University of Kentucky sediment interception simulation method as applied in VFSMOD model; and
8. Sheet flow pollutant removal for buffer strip: first order decay.

3 Case Study

Allegheny County Sanitary Authority (ALCOSAN) provides wastewater treatment services to approximately 900 000 people in 83 Allegheny County communities including the city of Pittsburgh. The location map is shown in Figure 4. The 83 communities own and operate their own collection systems but discharge to interceptor and treatment facilities owned and operated by ALCOSAN. Located along the Ohio River in Pittsburgh's Northside, ALCOSAN treats an average of 200 000 000 gallons (760 000 m^3) wastewater daily. ALCOSAN is not a county agency but a joint city–county authority operating under state guidelines and receiving no tax monies, with revenues generated solely by rates.

Figure 4 Study area location.

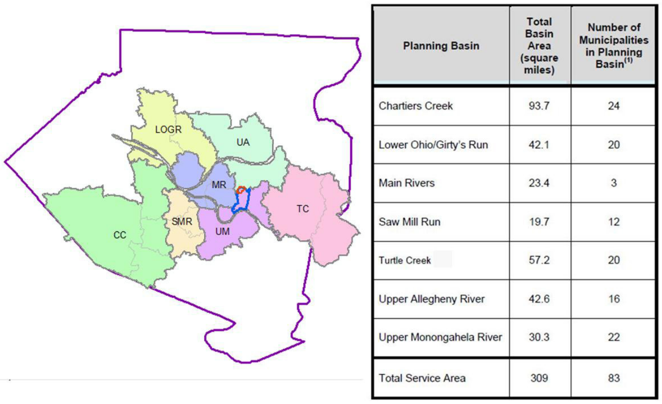
In 2008, ALCOSAN entered into a federal consent decree that required it to develop a plan to meet the requirements of the federal Clean Water Act. The consent agreement requires the elimination of the system's 52 sanitary sewer overflows and reduction of 153 combined sewer overflows by 85%. (The consent decree is available on www.alcosan.org.)

In July 2012, ALCOSAN released its draft *Wet Weather Plan* for public comment to address sewer overflows in accordance with its federal consent decree mandate. The plan included construction of deep storage tunnels and expanded treatment facilities to capture and treat 5 400 000 000 gal (20 000 000 m^3) raw sewage and stormwater overflows a year. With a $2.8 billion implementation cost, this plan represented one of the largest wet weather planning projects in Allegheny County, and the single largest infrastructure project in the Pittsburgh region. The draft plan was met with public demands for use of green infrastructure as an alternative to the gray technologies proposed in the plan. The final plan, identical to the plan was released in January 2013. However, at the same time, ALCOSAN requested an 18 month extension to study the feasibility of source control and green infrastructure to address the feedback received at public meetings.

Located in Pittsburgh, Pennsylvania, 3 Rivers Wet Weather (3RWW, www.3riverswetweather.org) is a nonprofit organization with a mission to improve the quality of Allegheny County's water resources by helping communities address the issue of untreated sewage and stormwater overflowing into the region's waterways. To promote the most cost effective long term sustainable solutions, 3RWW benchmarks sewer technology, provides financial grants, educates the public and advocates inter-municipal partnerships.

ALCOSAN communities had already evaluated conventional gray alternatives and would undoubtedly pursue the gray options as opposed to green solutions, absent the availability of green feasibility and cost analyses to the same level of effort and detail as those for the gray infrastructure. To help the ALCOSAN combined sewer communities with GSI planning, 3RWW conducted a study in 2012–13 to develop a methodology utilizing existing public domain software (SUSTAIN and RainWays) to assess the development of a candidate list of site specific GI projects. SUSTAIN BST was used to conduct a macro scale (watershed level) analysis to support the micro scale (site level) analysis of GSI by the RainWays program.

The analysis started by sub-dividing the 309 mi^2 (800 km^2) study area covering 83 municipalities into seven planning basins, shown in Figure 5. The boundaries of these basins are based on watersheds and the ALCOSAN *Wet Weather Plan*.



Planning Basin	Total Basin Area (square miles)	Number of Municipalities in Planning Basin[1]
Chartiers Creek	93.7	24
Lower Ohio/Girty's Run	42.1	20
Main Rivers	23.4	3
Saw Mill Run	19.7	12
Turtle Creek	57.2	20
Upper Allegheny River	42.6	16
Upper Monongahela River	30.3	22
Total Service Area	309	83

Figure 5 Study area planning basins (ALCOSAN serves all or portions of 83 municipalities; some municipalities are in more than one planning basin).

3.1 Mapping Application: SUSTAIN BST

SUSTAIN BST setup needs extensive input data for the required GIS layers. Obtaining or creating these layers with appropriate resolution and attributes is a challenging task for GSI analysis. Table 2 presents a listing of the GIS data and sources used in the BST siting analysis.

Table 2 Case study input data sources for SUSTAIN BST.

GIS Data	Type	Data Source
Soils	Vector	U. S. Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) GIS data
Groundwater Table Depth	Vector	NRCS SSURGO
Roads	Vector	Allegheny County Surface Cover *
Streams	Vector	U. S. Geological Survey (USGS) National Hydrography Dataset (NHD)
Urban Land Use	Vector	Allegheny County Surface Cover *
Land Owner (Public or Private)	Vector	Allegheny County Parcels
Digital Elevation Model (DEM)	Raster	USGS National Elevation Dataset (NED) at 10 m resolution
Impervious Area	Raster	Allegheny County Surface Cover and LiDAR data *
Land Use	Raster	Allegheny County Parcels and 2006 National Land Cover Database (NLCD)

* Original data enhanced for this project.

SUSTAIN BST can analyze up to fourteen types of GSI technologies as was shown in Table 1. Based on their relevance in study area, some of these 14 GSI types were not included in the GSI siting analysis. The remaining GSI types were consolidated into the following six broader GSI categories considered more appropriate for an area-wide assessment.

1. Bioretention–Rain Garden;
2. Constructed Wetland–Wet Pond;
3. Grassed Swale–Bioswale;
4. Infiltration Basin–Trench;
5. Porous Pavement; and
6. Vegetated Filter Strip–Grass Buffer.

The default siting criteria values summarized in Table 1 are understood to be widely applicable throughout the United States. However, for the study area evaluation, initial BST runs utilizing the default criteria values produced results which were inconsistent with local site conditions. To correct for this finding, siting criteria were modified to be more representative of conditions in the study area, using knowledge of local conditions and engineering judgment. The final siting criteria used in the project are presented in Table 3.

After GSI siting criteria were finalized, all the seven planning basins were analyzed using SUSTAIN BST. Nearly 525 000 potential GSI locations were identified including 156 360 bioretention locations in the form of GIS features (polygons). Initial SUSTAIN BST runs resulted in tens of thousands of GIS features (polygons) based on default GSI siting criteria. Because implementing so many GSI facilities is impractical, the default GSI siting criteria were revised to reflect the study area soils, slopes and climate. This process required running the SUSTAIN BST program repeatedly for a 2 mi^2 (5.2 km^2) pilot project area in the Nine Mile Run combined sewer sewershed, located in the Upper Monongahela planning basin. Pilot results were discussed in weekly workshops, input GIS data were cleaned up and enhanced, and initial siting criteria were refined until GSI results started to look reasonable and practical. This processes generally eliminated >70% of the initial GSI features. Table 4 summarizes the initial and revised GSI feature count for the Nine Mile Run sewershed. Figure 6 shows a GSI map of pilot project area displaying 739 potential bioretention locations.

Table 4 SUSTAIN GSI features for the Nine Mile Run sewershed.

No.	BMP	Count	
		Default Criteria	Revised Criteria
1	Dry pond	545	116
2	Wet pond	378	
3	Constructed wetland	378	
4	Infiltration basin	2 112	608
5	Infiltration trench	2 002	
6	Bioretention	1 516	2 544
7	Sand filter (surface)	4 585	
8	Sand filter (non-surface)	3 735	
9	Porous pavement	60	622
10	Grassed swales	1 228	2 201
11	Vegetated filter strip	3 916	1 212
12	Rain barrel	845	
13	Green roof	5 695	
	Total	26 995	7 303
	Percent Reduction		73%

Table 3 Revised GSI siting criteria used in the case study.

No.	GSI Type	Drainage Area (acre)	Drainage Slope (%)	Impervious (%)	Hydrological Soil Group	Water Table Depth (ft)	Road Buffer (ft)	Stream Buffer (ft)	Building Buffer (ft)
1	Bioretention–Rain garden	< 2	< 5	NA	A–D	> 2	>5	>25	>15
2	Constructed Wetland–Wet Pond	> 25	< 15	NA	B-D	>2	>25	> 100	>100
3	Grassed Swale–Bioswale	< 5	< 4	NA	A–D	> 2	< 100	NA	>15
4	Infiltration Basin–Trench	< 10	< 15	NA	A–B	> 4	>25	> 100	>25
5	Porous Pavement	< 3	< 5	> 0	A-D	> 2	NA	>100	NA
6	Vegetated Filter Strip–Grass Buffer	NA	< 10	NA	A–D	> 2	< 100	NA	>50

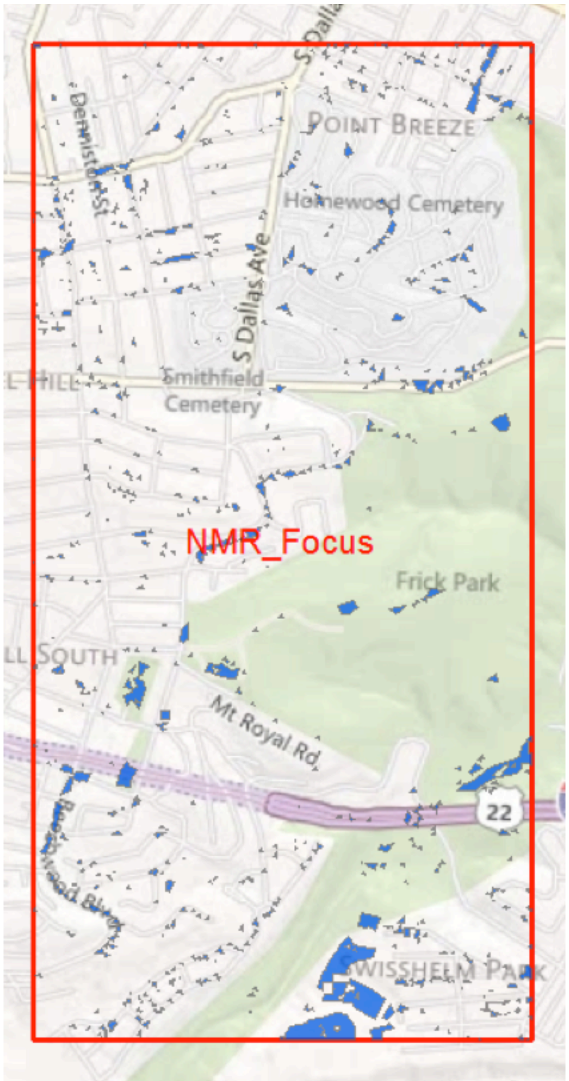


Figure 6 SUSTAIN bioretention features (blue polygons) for Nine Mile Run pilot area.

3.2 Engineering Analysis

As of early 2013, detailed engineering analysis and the RainWays modeling described below had been completed for the following four test combined sewersheds:

- Nine Mile Run sewershed located in the Upper Monongahela planning basin;
- West View sewershed located in the Lower Ohio River–Girty's Run planning basin;
- Millvale sewershed located in the Lower Ohio River–Girty's Run planning basin; and
- McNeilly Run sewersheds located in the Saw Mill Run planning basin.

Utilizing the project-specific revised GSI siting criteria (Table 3) yielded a mapping of thousands of potential GSI features (GIS polygons) in these sewersheds, depicting locations where all siting criteria were met for the GSIs under consideration. As part of the detailed engineering analysis, these raw GIS features were screened (based on knowledge of the area and engineering judgment) to eliminate infeasible GSI locations, retaining only the most practical ones. For example, proposed bioretention locations with existing trees were eliminated to preserve the trees. The GSI features were subsequently consolidated into few hundred implementable conceptual GSI projects. Figure 7 shows a sample engineering analysis map of the Nine Mile Run sewershed area, showing GIS features and GSI projects.

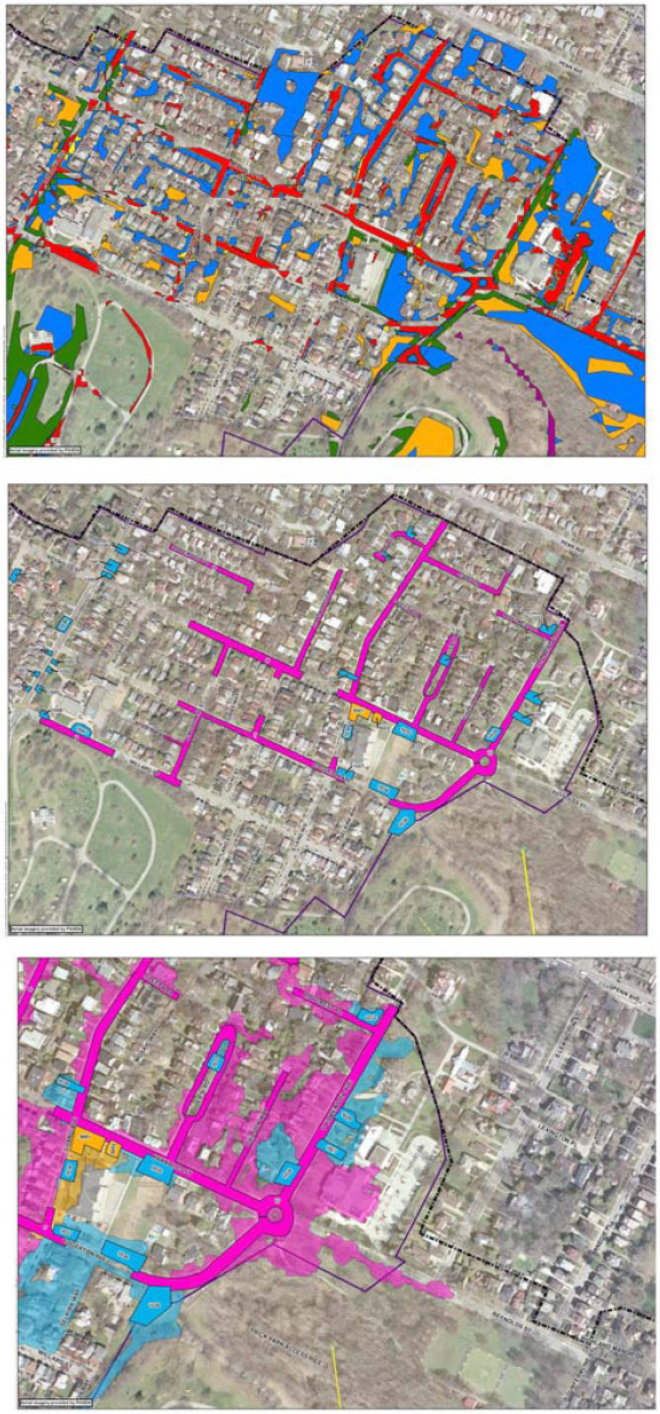


Figure 7 Sample engineering analysis map: SUSTAIN BST GIS features (top); GSI projects (centre); GSI project tributary drainage areas (bottom).

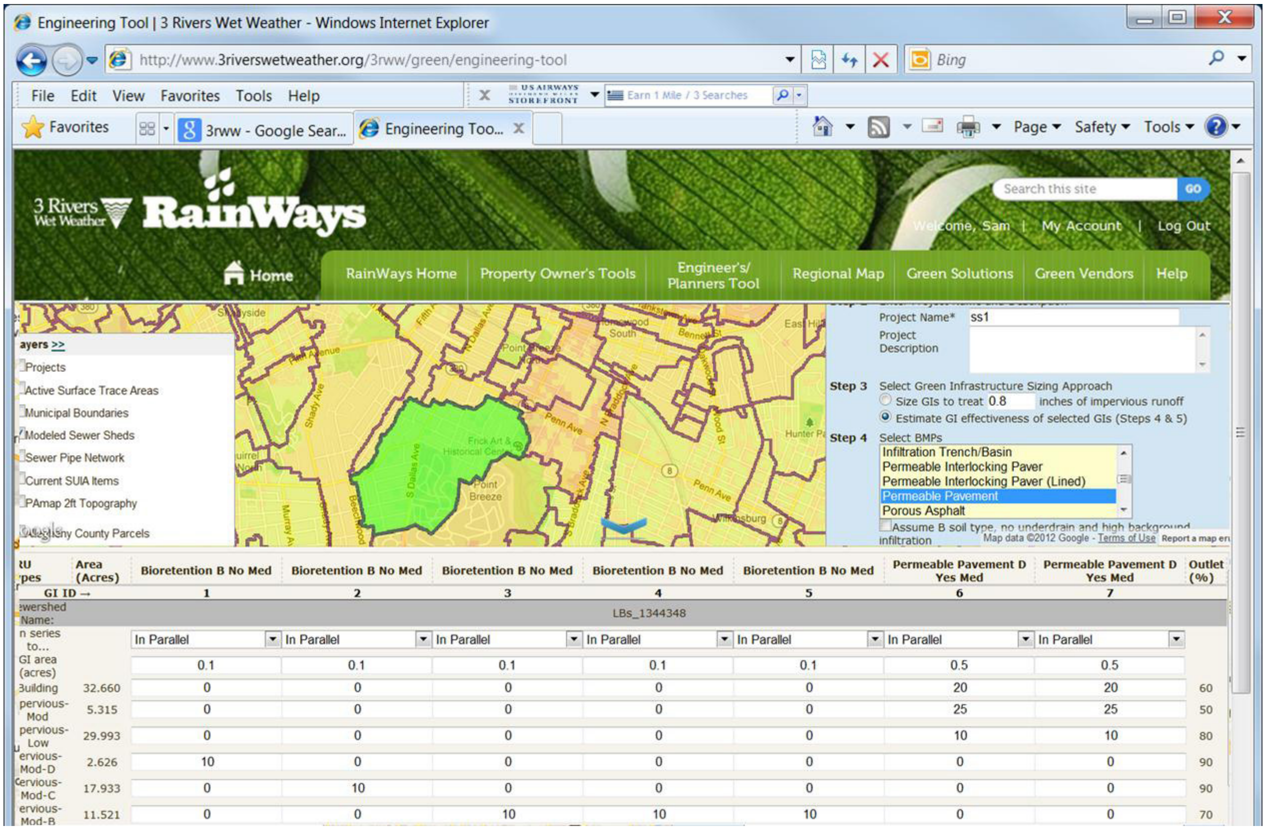
GSI projects were then evaluated using the RainWays application to establish tributary drainage area, to size the GSI facility to capture the first inch of tributary runoff, to estimate effectiveness of annual volumetric runoff reduction, and to estimate cost. RainWays analysis is presented in the next section.

3.3 Modeling Application: RainWays

RainWays is a Web-based GSI assessment and planning application developed by TetraTech Inc. for 3RWW. It is an Allegheny County specific GSI tool for the ALCOSAN service area that includes both an individual lot based Property Owner's tool and a project site level Engineer's–Planner's tool.

Running inside a web browser, the application has an easy-to-use intuitive interface. RainWays is designed to allow a user to select a location and assess the implementation of various GSI technologies based on local geography, soils and level of control desired. It assesses stormwater reduction effectiveness in terms of runoff volume for a user designed rainfall amount. Figure 8 shows a screenshot of the RainWays Engineer's–Planner's tool. RainWays is a free application that can be used from the 3RWW Web site. No software download is required. Use of RainWays is limited to 83 ALCOSAN municipalities. RainWays, rather than SUSTAIN, was used for GSI modelling because it was easier to use and did not require ArcGIS software.

RainWays uses SUSTAIN algorithms to perform GSI cost–performance (runoff reduction vs cost) analysis and can be considered a Web implementation of SUSTAIN's Land and BMP modules. It leverages processes from the SUSTAIN BMP model, which uses GSI performance curves to evaluate the GSI effectiveness. The GSI performance curves are a computationally efficient



Project Name* ss1

Project Description

Step 3 Select Green Infrastructure Sizing Approach

○ Size GIs to treat 0.8 inches of impervious runoff

● Estimate GI effectiveness of selected GIs (Steps 4 & 5)

Step 4 Select BMPs

Infiltration Trench/Basin
Permeable Interlocking Paver
Permeable Interlocking Paver (Lined)
Permeable Pavement
Porous Asphalt

☐ Assume B soil type, no underdrain and high background infiltration

U pes	Area (Acres)	Bioretention B No Med	Bioretention B No Med	Bioretention B No Med	Bioretention B No Med	Bioretention B No Med	Permeable Pavement D Yes Med	Permeable Pavement D Yes Med	Outlet (%)
GI ID →		1	2	3	4	5	6	7	
ewershed Name:		LBs_1344348							
n series to...		In Parallel	In Parallel	In Parallel	In Parallel	In Parallel	In Parallel	In Parallel	
GI area (acres)		0.1	0.1	0.1	0.1	0.1	0.5	0.5	
Building	32.660	0	0	0	0	0	20	20	60
pervious-Mod	5.315	0	0	0	0	0	25	25	50
pervious-Low	29.993	0	0	0	0	0	10	10	80
ervious-Mod-D	2.626	10	0	0	0	0	0	0	90
ervious-Mod-C	17.933	0	10	0	0	0	0	0	90
ervious-Mod-B	11.521	0	0	10	10	10	0	0	70

Figure 8 RainWays application screenshot.

way of predicting a GSI response, while eliminating the need for on-the-fly computationally intensive modeling through the web. The GSI performance curves were created by conducting the following four tasks (Hill et al. 2012).

1. Thirteen unique hydrologic response unit (HRU) types were created in a GIS layer based on three land uses (pervious, impervious and rooftop), three hydrologic soil groups (B, C and D) and three slopes (low, moderate and steep). Each HRU type potentially provides a different rainfall–runoff response;
2. Existing calibrated SWMM models from ALCOSAN's *Wet Weather Plan* for the baseline scenario and the typical year NEXRAD rainfall data were used to model the rainfall–runoff response from each HRU on a unit area basis (1 acre, 0.405 ha). These HRU time series were used as a boundary condition in the SUSTAIN BMP module;
3. A set of 131 unique SUSTAIN modeling scenarios was developed for a unique combination of 16 GSI types, three soil types (low, medium and high infiltration rates), and an option of underdrain pipe for poorly drained soil types; and
4. The SUSTAIN model was run for a range of treatment depth (runoff depth to be captured) versus treatment capacity (GSI size) for each scenario, to develop 131 performance curves. Each performance curve provides the runoff volume captured and the GSI cost for the given treatment depth or treatment capacity.

Table 5 presents a summary of the RainWays output for the Nine Mile Run sewershed. As shown, 353 concept GSI projects were identified in the 785 acre (3.18 km^2) combined sewer area that could potentially control the runoff from approximately 175 acres (0.71 km^2). Annual runoff reduction was estimated at 25% or about 60 MG (227 000 m^3) annual volume based on capture of the first 1 in. (25.4 mm) runoff for the typical year (2003) precipitation pattern. The capital cost was estimated at $8.7 million. There were 32 commercial and institutional green roof and porous pavement projects that could potentially control the runoff from approximately 15 acres (0.06 km^2), yielding an additional estimated 3.87% effective annual runoff reduction or about 9.2 MG (35 000 m^3) annual volume at a capital cost of $5.35 million. It should be noted here that sometime the reduction in the capture target can be less as some of the rainwater infiltrated through GSI may still find its way into the aging sewer system via inflow and infiltration.

4 Conclusions

From the case study results presented in this chapter it can be concluded that USEPA's SUSTAIN program is a useful GSI mapping and modeling program. SUSTAIN's BST module can be used to identify the highest potential green stormwater infrastructure sites and projects for the combined sewer communities that want to reduce their CSO discharges. SUSTAIN BST results depend on user specified site specific siting criteria. From the case study results, it was noted that SUSTAIN BST can provide plenty of GSI opportunities even in regions with predominantly clay soils and steep slopes like Allegheny County. As demonstrated, an engineering screening analysis of GSI features can be done to create implementable site specific GSI projects. Finally, SUSTAIN BST should be used with caution because the output GSI maps are as good (or bad) as the quality of input GIS layers.

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Table 5 SUSTAIN GSI features for the Nine Mile Run sewershed.

Concept GI Project Parameters	Candidate Municipal Projects							Commercial/Institutional Projects		Total Cost
	Porous Pavement	Bioretention	Infiltration Basin	Grass Swale	Vegetated Filter Strip	Constructed Wetland	Municipal Cost	Porous Pavement	Green Roofs	
Effective design area of concept GSI projects to capture first 1.0 inch of runoff	3.86	1.51	0.09	0.00	0.00	0.02	5.47	0.64	4.90	11.01
Number of candidate GSI projects	46	264	9	1	0	1	321	16	16	353
Drainage area tributary to concept GSI projects (acres)	77.50	77.74	4.58	0.00	0.00	1.31	161.12	9.94	4.90	175.96
Annual combined sewer area runoff captured (MG)	30.19	18.93	1.49	0.00	0.00	0.28	50.88	5.05	4.13	60.06
Combined sewer area runoff capture (%)	12.7%	8.0%	0.6%	0.0%	0.0%	0.1%	21.4%	2.13%	1.74%	25.3%
			Opinion of Probable Cost							
Construction cost	$1,869,000	$ 1,455,000	$ 53,000			$ 2,000	$3,379,000	$ 306,000	$ 5,041,000	$ 8,726,000
O&M cost (20 years)	$ 74,000	$ 88,000	$ 6,000				$ 168,000	$ 14,000	$88,000	$ 270,000
Present worth cost	$1,935,000	$ 1,534,000	$ 59,000			$ 2,000	$3,530,000	$ 318,000	$ 5,121,000	$ 8,969,000
Present worth cost per drainage area treated ($/acres)	$ 25,000	$ 20,000	$ 13,000			$ 2,000	$ 21,909	$ 32,000	$ 1,045,000	$ 50,971

Total Combined Sewer Area: 785.08 acres

Total Annual Combined Sewer Area Runoff from RainWays: 237.25 MG

Michael Baker Corporation (prime consultant), Lennon, Smith, Souleret Engineering, Inc. (Subconsultant to Michael Baker Corporation), and Wade Trim Inc. (Subconsultant to Michael Baker Corporation). The RainWays application was developed by TetraTech Inc. for 3RWW. Landbase Systems Inc. (3RWW consultant) provided GIS data for GSI drainage areas.

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