Tisbury MA Impervious Cover Disconnection (ICD) Project: An Integrated Stormwater Management Approach for Promoting Urban Community Sustainability and Resilience

A Technical Direct Assistance Project Funded by the U.S. EPA Southeast New England Program (SNEP)

Task 4J. Project Final Report

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EXECUTIVE SUMMARY

The goal of the project was to improve the quantification and communication of the benefits of relatively small, distributed green infrastructure (GI) and other stormwater control measures (SCMs). Specifically, the project focused on investigating the range of expected benefits, including flood mitigation and nutrient and pathogen load reductions, that may result from implementing cost-effective stormwater management strategies in the space-constrained urbanized setting of Tisbury, MA. An equally important project goal was to build a municipal understanding of GI and other SCMs and facilitate the capacity for integrating these practices into land use planning decision making.

The project leveraged the strengths of various stakeholders and team-members, incorporating local knowledge and feedback from members of Martha's Vineyard planning commission, Tisbury conservation commission and public works department, Massachusetts's Department of Transportation, and the town's stormwater committee. The result was a highly collaborative and transparent approach to understanding the impact of impervious cover in Tisbury and investigating options for disconnecting impervious cover runoff from flowing directly to surface waters (i.e., "disconnection"). The approach included state-of-the-science watershed modeling and the development of innovative SCM designs while also identifying and addressing practical concerns that may have presented barriers to local GI SCM implementation.

The study helped the town quantify the return on investment that may be expected by adopting GI SCM strategies. The flood mitigation benefits of GI SCM are especially valuable in urbanized areas with poor stormwater transmission where even relatively small storms can result in flooding. Not only may GI SCM implementation help to mitigate flooding, but it can also reduce total nitrogen (TN) and pathogen loading to Tisbury's marine ecosystems. The summary table below provides town-wide modeling results for baseline conditions and an optimized GI SCM implementation solution. These estimated cost results assume that there is no cost-sharing with other redevelopment type projects to fund GI SCMs. However, because of the flexible optimized approach employed for Tisbury, they represent significantly lower average retrofit costs than those typically reported for other locations. Moreover, if a community were to adopt long-term strategies to opportunistically have GI SCMs incorporated into future private and public redevelopment projects, they could substantially reduce the community's cost burden for effective stormwater management. Importantly, the outfall study included in this report found that the town can still achieve substantial benefits and at lower costs by initially focusing on GI SCM implementation in the business and commercial districts.

Summary of Analyses Results for Tisbury, MA

Baseline Conditions	Result
Average Runoff Flow Volume (gallons/year)	728,415,636
Average TN Load (pounds/year)	7,352
Total Impervious Cover (acres)	613.17
Benefits and Costs of an optimized solution	**Result**
Impervious Cover Treated (acres)	611.7
Flow Volume Removed (gallons/year)	567,684,698) (78% reduction from baseline)
TN Load Removed (pounds/year)	5,982 (81% reduction from baseline)
% Bacteria Load Reduction	66.5% - 80%
% Discharge Events from Impervious Cover Eliminated	78%
Cost per Gallon Flow Removed ($)	$0.02
Cost per Pound TN Removed ($)	$2,264
Cost per Acre Impervious Cover Treated ($)	$22,135
Total Cost	$13,539,752

This project provides a framework for other municipalities seeking to address issues surrounding the quantity and quality of their stormwater. Trust and understanding among project members and stakeholders were developed throughout the study through in-person meetings in which project updates and results were presented and questions and concerns were addressed. Critical to this process was establishing an understanding of why directly connected impervious areas can cause flooding and water quality issues and quantifying the benefits of GI SCM implementation in ways that were relatable and easily communicable. This included the use of metrics in units of gallons, dollars, and pounds, and visual aids such as flow duration curves, hydrographs, and GI SCM performance curves.

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1 INTRODUCTION

1.1 Town of Tisbury Background

The town of Tisbury is located in Dukes County, Massachusetts on the island of Martha's Vineyard. The island is approximately seven miles off the southern coast of Cape Cod. Martha's Vineyard has a strong seasonal economy and several industries, including education, construction, recreation, and commercial fishing (Martha's Vineyard Commission, 2019). The Martha's Vineyard Commission is the regional planning agency for the island, tasked with assisting the island's towns with planning expertise and protecting and enhancing the island's environment, economy, character, and social fabric. Tisbury town governance and administration includes a board of selectmen, a town administrator, a planning board, a zoning board of appeals, a department of public works, and a board of health. The town requested assistance from the United States Environmental Protection Agency (EPA) to address chronic (even acute) flooding and the generally poor transmission of stormwater runoff related to and resulting from impervious cover. In response to the request, a project team was formed that included staff from EPA Region 1, the University of New Hampshire Stormwater Center, and Paradigm Environmental.

1.2 Municipal Coordination Meetings

The success of the project largely depended on developing a close partnership with the community so that they understood the foundational technical work performed and were engaged in continued two-way dialogs that were essential for achieving technical objectives such as identifying areas of local concern, and refining conceptual designs, as well as building local knowledge to support future progress in mitigating stormwater impact. Through this approach, the community built an understanding of the benefits of GI SCM and its capacity for implementation. To facilitate understanding and capacity building, three municipal coordination meetings, attended by the project team and stakeholders, occurred at Tisbury town hall on November 29, 2018, September 12, 2019, and March 6, 2020.

The purpose of the 2018 meeting was to review the background and goals of the project and to introduce team members and municipal and regional officials. Meeting participants discussed challenges and practical solutions to managing municipal stormwater systems and reviewed a Dover, New Hampshire case study on the implementation of GI SCM opportunities. Data demonstrating the reduction in runoff and nutrients due to the disconnection of impervious surfaces at the Dover site was presented and discussed. The meeting also included a review of how physical characteristics of Tisbury's landscape, such as land use, soils, and slope can impact the stormwater quantity and quality and the results of preliminary GIS analyses to quantify these attributes in the community. A key outcome of the meeting was a recognition that Tisbury needed expansion of the community's stormwater 'toolbox' to include innovative strategies to address stormwater issues. The design, implementation, and maintenance of stormwater BMPs including rain gardens and subsurface gravel infiltration filters were reviewed. Participants also discussed the proposed project milestones and the timeline on which they would be completed. The meeting concluded with a tour of Tisbury's watershed including stops at locations with historical flooding and erosion issues.

The purpose of the 2019 meeting was to review completed tasks associated with field investigations, concept designs, and watershed modeling. Before the meeting, team members conducted field investigations in areas in town that had been identified as susceptible to flooding and erosion. During the meeting, proposed GI SCM designs for these areas were reviewed. Additional GIS analyses completed since the last meeting were presented, including the Hydrologic Response Unit (HRU) development and GI SCM opportunity screening. Participants reviewed the results of baseline modeling to characterize runoff and total nitrogen (TN) loading. The development of bacteria performance curves showing cumulative reduction estimates of indicator bacteria loading for GI SCM of varying design capacities was also presented. This information built a local understanding of the usefulness of having cumulative reduction estimates for a range of sizes of GI SCM in capturing and treating runoff. Moreover, the community partners recognized that the high cumulative reduction estimates for the specific GI SCM being developed for Tisbury, even for small design capacities, meant that there are many implementation opportunities across Tisbury's developed landscape. Additionally, EPA Region 1 has determined that the bacteria performance curves developed under this project have regional applicability for New England (see Appendix A for EPA's recommended use of bacteria curves in the New England region).

The purpose of the 2020 meeting was to review the final results and conclusions of the field investigation/site design and modeling tasks and discuss the next steps. Three generalized GI SCM opportunity designs were reviewed, and participants discussed the assumptions and limitations of the designs, as well as potential modifications that would help facilitate adoption and implementation by the town. The nutrient, pathogen, and stormwater reduction benefits of these opportunities were presented. Modeling results demonstrating the costs and benefits of optimized GI SCM implementation were presented. Meeting participants agreed that the modeling and field investigations/site designs provided strong support for the town to begin pursuing the implementation of GI SCM opportunities on both private and public lands. The meeting concluded with a discussion of near-term (1-6 months) intermediate-term (6 months – 1.5 years) and long-term (1.5-5 years) goals for the town to complete.

1.3 Overview of Report Contents

Section 2 describes the meteorological and physical characteristics of Tisbury. The section also describes the development of Hydrological Response Units (HRUs) using GIS layers that included land use, soils, and slope.

Section 3 describes the process for identifying locations for the implementation of GI SCM in Tisbury. The process involved both a desktop analysis of GIS information, which focused on existing pervious surfaces that could be retrofitted to treat stormwater, as well as on-the-ground assessments of locations of local concern.

Section 4 describes the approach for quantifying the benefits of GI SCM implementation is Tisbury. Section 4.1 provides an overview of the Opti-Tool model used in this project. Section 4.2 describes the development of indicator bacteria curves for inclusion into the Opti-Tool and their application to Tisbury. Section 4.3 reviews the metrics that were used to assess the benefits of GI SCM implementation on flood mitigation and TN load reduction. Section 4.4 provides a detailed approach for the Opti-Tool Implementation Level Analysis that assessed the GI SCM implementation in the watersheds of two stormwater outfalls in Tisbury. Section 4.5 provides a detailed review of the Opti-Tool Planning Level Analysis that assessed GI SCM implementation throughout the entire municipality and its zoning districts.

Section 5 contains conclusions drawn from the project, including a discussion of how such an approach may be applied to other New England towns and urbanized areas. Section 6 contains town-specific recommendations and specific goals to achieve in the near, intermediate, and long term. The report includes several appendices of supporting information, Appendix B contains a technical support document on impervious cover disconnection strategies, providing technical guidance for Tisbury as well as useful technical support information that is applicable to other communities.

2 WATERSHED CHARACTERIZATION

2.1 Precipitation & Climate

Local meteorological conditions were summarized using hourly precipitation timeseries and daily air temperature data collected at the NCDC Global Hourly Surface Data gauge located at Martha's Vineyard Airport (USAF-ID 725066). This data was used as input for the EPA Stormwater Management Model (SWMM) (U.S. EPA., 2016) to generate HRU timeseries for stormwater runoff and TN and pathogen loading. The SWMM output was used as input into the Opti-Tool (U.S. EPA. 2016), discussed further in

Section 4.1. The gauge is located approximately three miles from the southern coastline of Marsha's Vineyard and approximately four miles from downtown Tisbury. Table 2-1 summarizes station metadata for the gauge. The table lists two separate locations. The reporting location was switched on January 1, 2006. Records for these two locations were merged to develop a continuous, twenty-one-year timeseries (January 1, 1998 – December 31, 2018). No significant data gaps (missing records) were found during the data review. Data flagged as suspect accounted for less than 1% of the long-term timeseries.

A dry year (year-2001), wet year (year-2018), and an average year (year-2012) were estimated based on the total precipitation and the number of rain days (Table 2-2). The data suggest that an event exceeding 1.5 inches in 24 hours was very likely to occur in Tisbury, MA in any given year during the period of review (Figure 2-1). A less frequent event, one which exceeds 4.2 inches, had an approximately 10% chance of occurring in any given year. While these numbers represent probabilities for annual maximum 24-hr rainfall, surprisingly, over 50% of total annual precipitation events (24-hr rainfall) in Tisbury were 0.1 inches or less in-depth.

Table 2-1. Summary of NCDC gauge location metadata

Station Name	USAF-ID	Latitude	Longitude	Elevation (ft.)
Martha's Vineyard Airport	725066	41.393	-70.615	20.7
Martha's Vineyard	725066	41.400	-70.617	20.0

Table 2-2. Number of rain days, maximum daily, and annual rainfall depth for 21 years (1998-2018) in Tisbury, MA.

Year	Total Rainfall (in./year)	Maximum Rainfall (in./day)	No. of Rain Days
1998	44.5	2.54	145
1999	36.3	2.57	133
2000	39.9	2.81	153
2001	27.5	2.65	147
2002	40.1	1.51	153
2003	41.5	3.40	135
2004	37.3	3.84	129
2005	42.6	3.03	132
2006	43.4	4.16	141
2007	33.7	2.12	135
2008	39.2	2.43	138
2009	42.8	3.70	143
2010	46.3	4.18	119
2011	43.8	4.26	133
2012	40.5	2.33	137
2013	40.4	1.92	147
2014	40.3	2.27	122
2015	37.5	2.71	115
2016	30.8	2.02	100
2017	46.5	3.05	133
2018	51.8	3.13	137
Long-Term Average:	40.3	2.88	134

Dry Year | Average Year | Wet Year

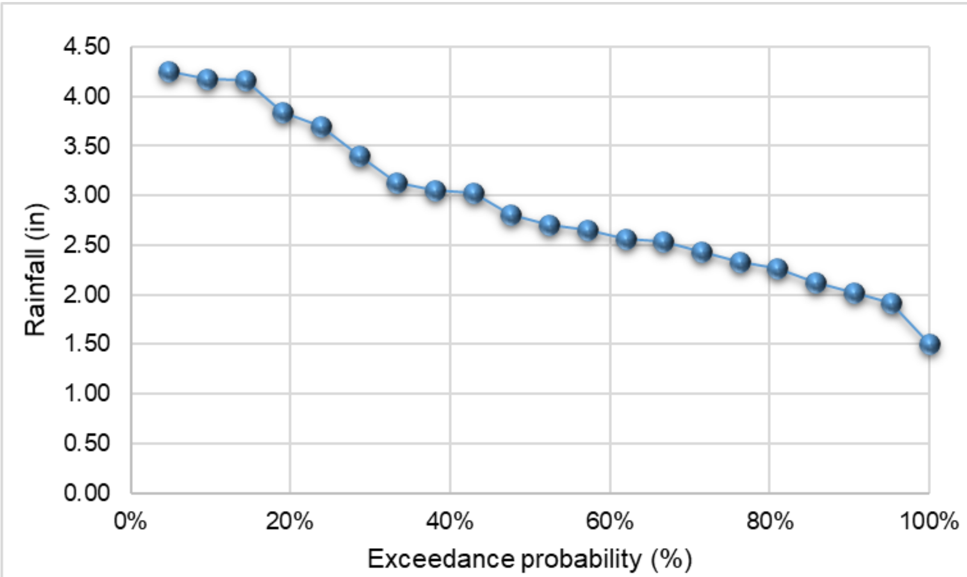

Figure 2-1. Exceedance probability for annual maximum daily rainfall depths for 21 years (1998-2018) in Tisbury, MA.

The air temperature was required for the SWMM hydrology model when using the Hargreaves method for calculating potential evapotranspiration (U.S. EPA 2015). This method requires only daily minimum and maximum air temperature data as inputs to estimate the daily potential evapotranspiration. Air temperature data was available as part of the same Global Hourly Surface Dataset from which precipitation data was obtained. The hourly air temperature data were assessed for data gaps by reviewing the quality flags provided with the raw data and reviewing summary statistics. Daily maximum and minimum temperatures were derived from hourly temperature data by searching the 24 hours between midnight and midnight of each day for the highest and lowest temperatures. Similar to the precipitation data analyses, temperature data quality was assessed using NCDC supplied data flagging. Values were filled forward to patch short-term data gaps. Figure 2-2 shows the monthly average minimum and maximum temperatures at Martha's Vineyard Airport.

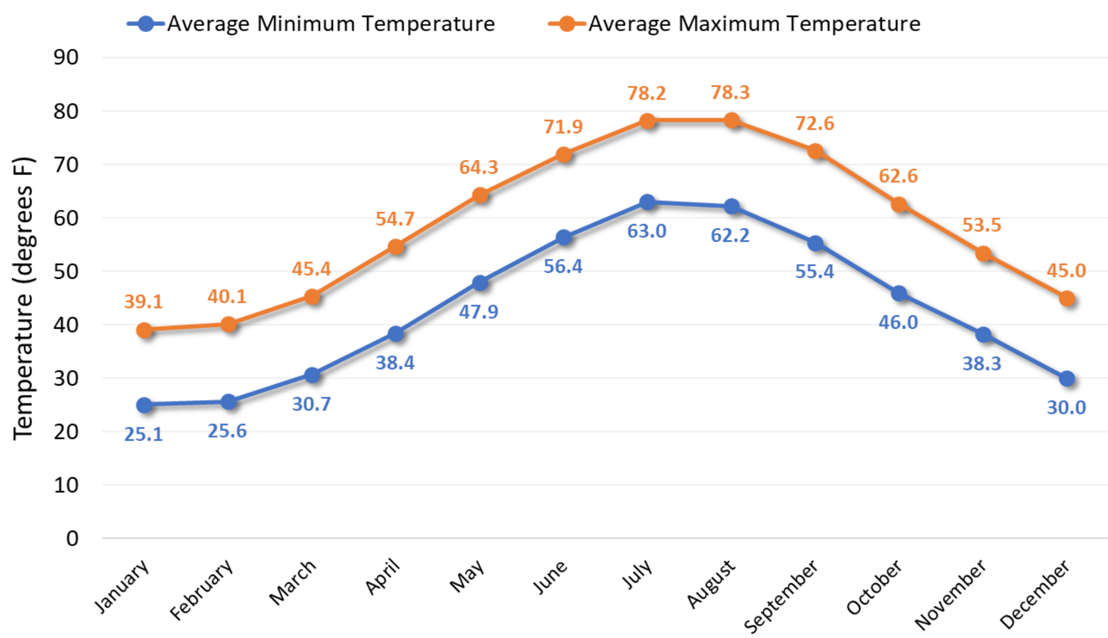

Figure 2-2. Monthly average minimum and maximum temperature recorded at Martha's Vineyard Airport (1/1/1998-12/31/2018).

Seasonal variation in daily minimum and maximum temperature are typical for a New England community. Peak temperatures occur in July and August with lows in January and February. The Martha's Vineyard gauge may be affected by its location on an island and the influence of wind and/or ocean currents, including the Labrador Current, a cold current originating from the Arctic Ocean.

2.2 Hydrologic Response Unit Development

Characterization of the Tisbury landscape relied on GIS datasets including land use, slope, soils, and impervious cover, which can all influence runoff and pollutant loading. GIS data for the project was primarily obtained from the Massachusetts Bureau of Geographic Information Systems (MassGIS) website. The following datasets were identified as primary inputs for the watershed characterization and are discussed further in this section:

- Land Use: *Describes the principal programmatic use and/or vegetation type. The programmatic, or zoning element of this attribute is critical for water quality simulation.*
- Hydrologic Soil Group: *Represents one of four soil classes (i.e., A, B, C, and D) commonly associated with a spectrum of infiltration rates with HSG-A having the highest and HSG-D having the lowest.*
- Landscape Slope: *Represents the overland flow slope derived from a digital elevation model. The percent slope was categorized into three groups: low (<5%), medium (5% - 15%), and high (>15%).*

An inventory of GIS datasets identified for developing the watershed characterization can be found in Appendix C.

2.2.1 Land Use

A 2005 land use dataset was obtained from MassGIS which used 0.5-meter (1.6 ft) resolution digital orthophotography from 2005 to represent land use across the Commonwealth using forty (40) unique categories (MassGIS 2009). These categories were adapted from the Massachusetts land use datasets schema. Within the Town of Tisbury, there were 26 land use categories. Table 2-3 presents the original land use categories along with reclassification to ten (10) categories consistent with the scheme used in the Massachusetts MS4 permit. A map of the land use dataset is presented in Figure 2-3.

2.2.2 Hydrologic Soil Group

The soils dataset available from MassGIS included the NRCS SSURGO-Certified dataset. This data includes four primary hydrologic soil groups (HSG) used to characterize soil runoff potential. Group A generally has the lowest runoff potential whereas Group D has the highest runoff potential. Soil characteristics of each hydrologic soil group within Tisbury are presented in Table 2-4. The dominant soil group in the watershed representing 92% of Tisbury is Group A which typically has the highest infiltration rates. HSG is unknown for approximately 6% of the Tisbury developed area and were considered as HSG-C for analysis purposes. A map of the dataset categorized by HSG is presented in Figure 2-4.

It should be noted that the NRCS SSURGO-Certified soils layer downloaded from MassGIS contains a field for "slope" which is a reclassification of the landscape slope into six categories using the A through E designation with a value of zero used for water. These reclassification codes are similar to values one would expect to see in a soils database representing HSG, therefore care should be given when navigating this dataset as not to confuse the attributes.

Table 2-3. Summary of MassGIS land cover classifications and areas for the Town of Tisbury

Original Land Use Class	Reclassified Land Use	Total Area (acres)	Percent of Total Area
Brushland/Successional	Agriculture	147	4%
Cropland			
Pasture			
Commercial	Commercial	113	3%
Transitional			
Urban Public/Institutional			
Forest	Forest	2,398	57%
Transportation	Highway	3	0%
Industrial	Industrial	42	1%
Waste Disposal			
Low Density Residential	Low Density Residential	553	13%
Very Low Density Residential			
Medium Density Residential	Medium Density Residential	479	11%
High Density Residential	High Density Residential	28	1%
Multi-Family Residential			
Cemetery	Open Land	336	8%
Forested Wetland			
Golf Course			
Non-Forested Wetland			
Open Land			
Participation Recreation			
Powerline/Utility			
Saltwater Sandy Beach			
Saltwater Wetland			
Water-Based Recreation			
Water	Water	86	2%
Total[1]		4,183	100%

1. The total area of the land use layer is approximately 11 acres less than that Town of Tisbury area due to the presence of polygon slivers and void areas in the land use layer along with parts of the coastline.

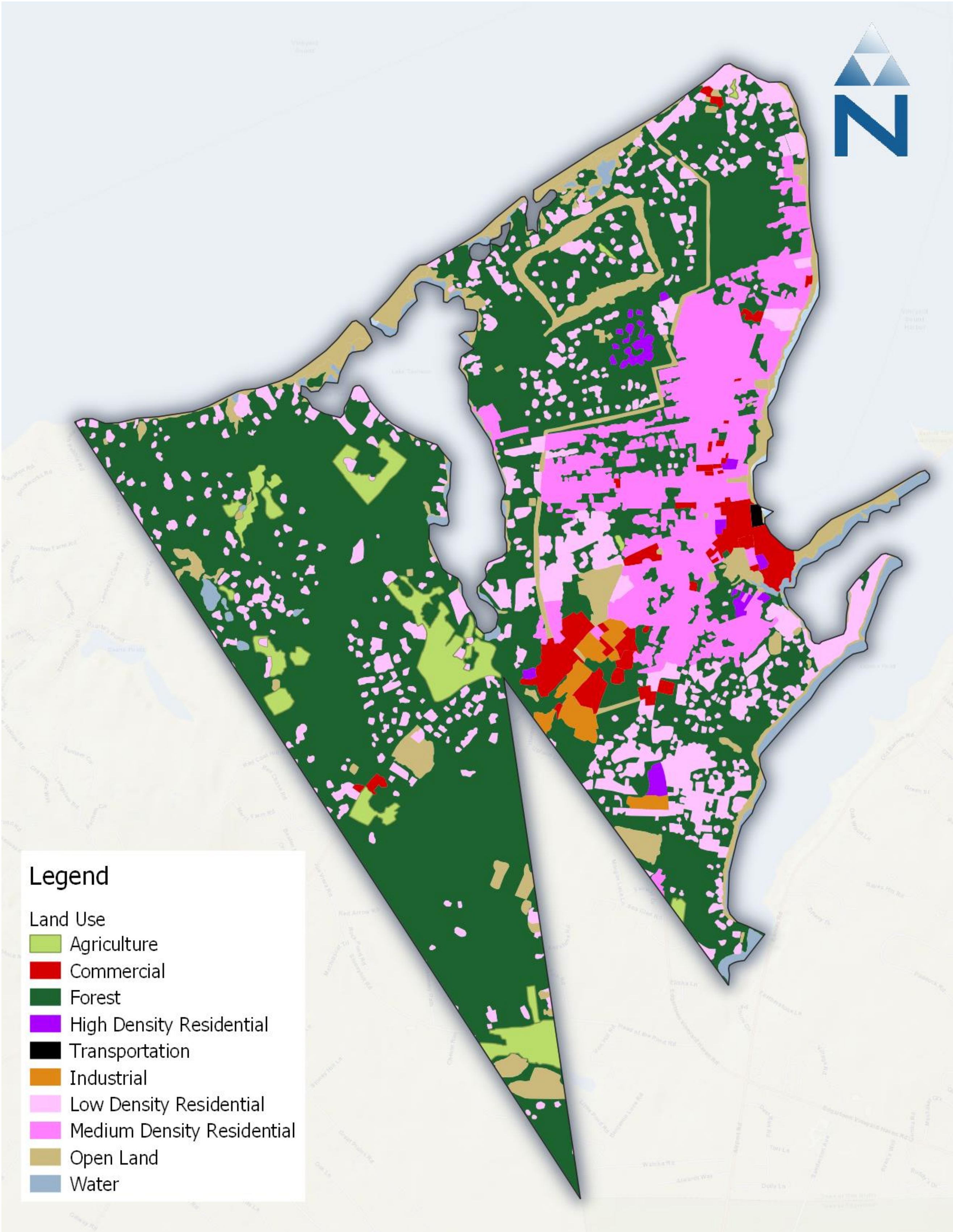

Figure 2-3. Reclassified land use categories for the Town of Tisbury, MA.

Table 2-4. NRCS Hydrologic Soil Group summary for the Town of Tisbury, MA.

Hydrologic Soil Group	Reclassified Soil Group	Total Area (acres)	Percent of Total Area
A	A	3,841	92%
B	B	25	<1%
C	C	4	<1%
A/D	D	74	2%
B/D	D	16	<1%
Unknown	C	233	6%
Total		4,194	100%

2.2.3 Elevation & Slope [1 meter (m) = 3.28084 feet (ft)]

MassGIS published a 1:5,000 resolution Digital Elevation Model (DEM) which represents the surface elevation for the entire Commonwealth of Massachusetts. This dataset expresses the landscape elevation through a raster grid data product with 5-meter by 5-meter (16.4 ft by 16.4 ft) resolution (MassGIS 2005). The value of each raster cell represents the landscape elevation for a 25 square-meter (82 ft2) area. Within Tisbury, the landscape elevation ranges from approximately 1-meter (3.28 ft) along the coastline to approximately 40 meters (131.2 ft) at the highest elevation along inland portions of the town. As a geoprocessing input, this DEM was used to calculate the landscape slope, which in turn was used to derive Hydrologic Response Units (HRUs), stormwater management categories, and BMP opportunity screening criteria. The ground slope was classified into three groups as shown in Table 2-5. A map of Tisbury slopes is presented in Figure 2-5.

Table 2-5. Landscape slope classifications

Landscape Slope	Reclassified Slope Category
<= 5%	Low
> 5% - 15%	Medium
> 15%	High

2.2.4 Impervious Cover

MassGIS data included a spatial layer representing impervious surfaces, the layer was developed from 2005 orthophotos at the 1-meter (3.28 ft) pixel resolution. This coverage represents surfaces that are deemed impervious to rainwater and therefore generate a higher rate of runoff than pervious surfaces. Example features identified in this layer include buildings, roads, parking lots, brick, asphalt, concrete, and highly compacted soils without vegetative cover including mining operations (MassGIS 2007). A map of the impervious cover dataset is presented in Figure 2-6.

2.2.5 Building Structures

A MassGIS data layer of building structures representing rooftops was derived for the eastern half of Massachusetts using 2011-2012 orthophotos and Light Detection and Ranging (LiDAR) data collected during the 2002-2011 period. Typical structures represented in this dataset include residential, commercial, and industrials buildings. Garages, sheds, and other isolated structures of at least 150 square feet (45.7 m) in size are also included (MassGIS 2017). This building structures dataset was used in conjunction with the impervious cover dataset to identify rooftops separately from other impervious surfaces. The distinction allowed for a more detailed assessment of GI SCM implementation based on whether the treated surface was a rooftop or other impervious surface. A map of the building structures dataset is presented in Figure 2-7.

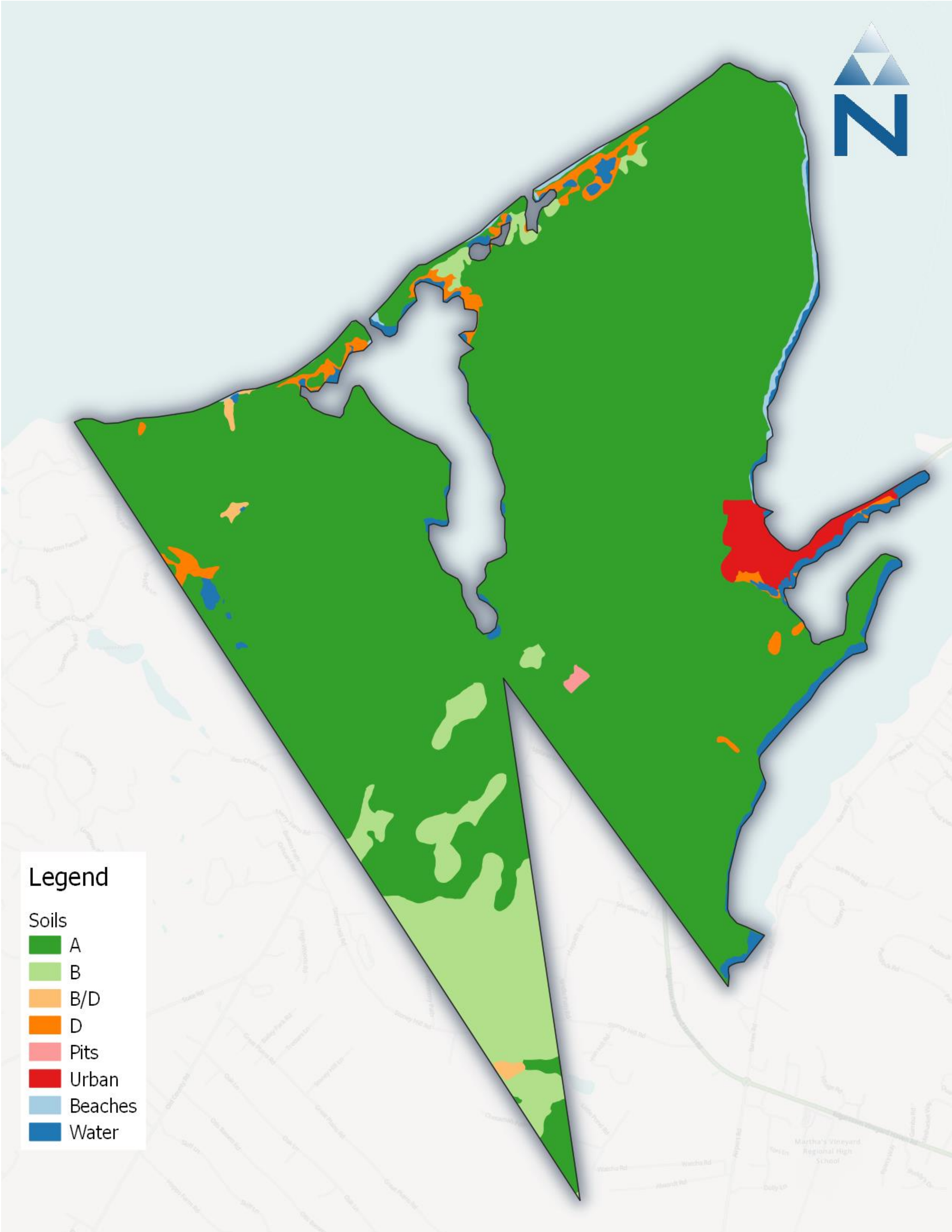

Figure 2-4. Hydrologic soil groups for the Town of Tisbury, MA.

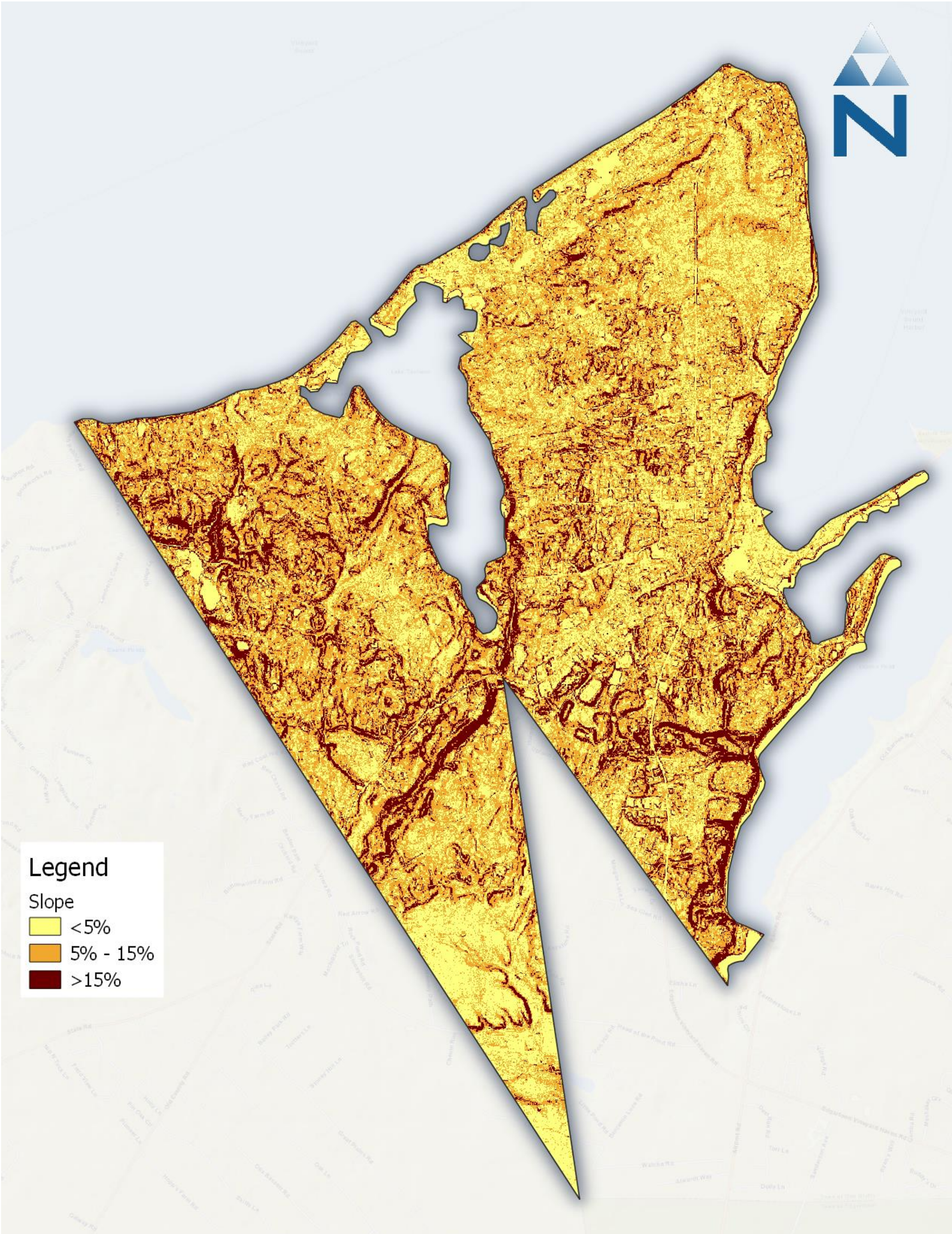

Figure 2-5. Landscape slope for the Town of Tisbury, MA.

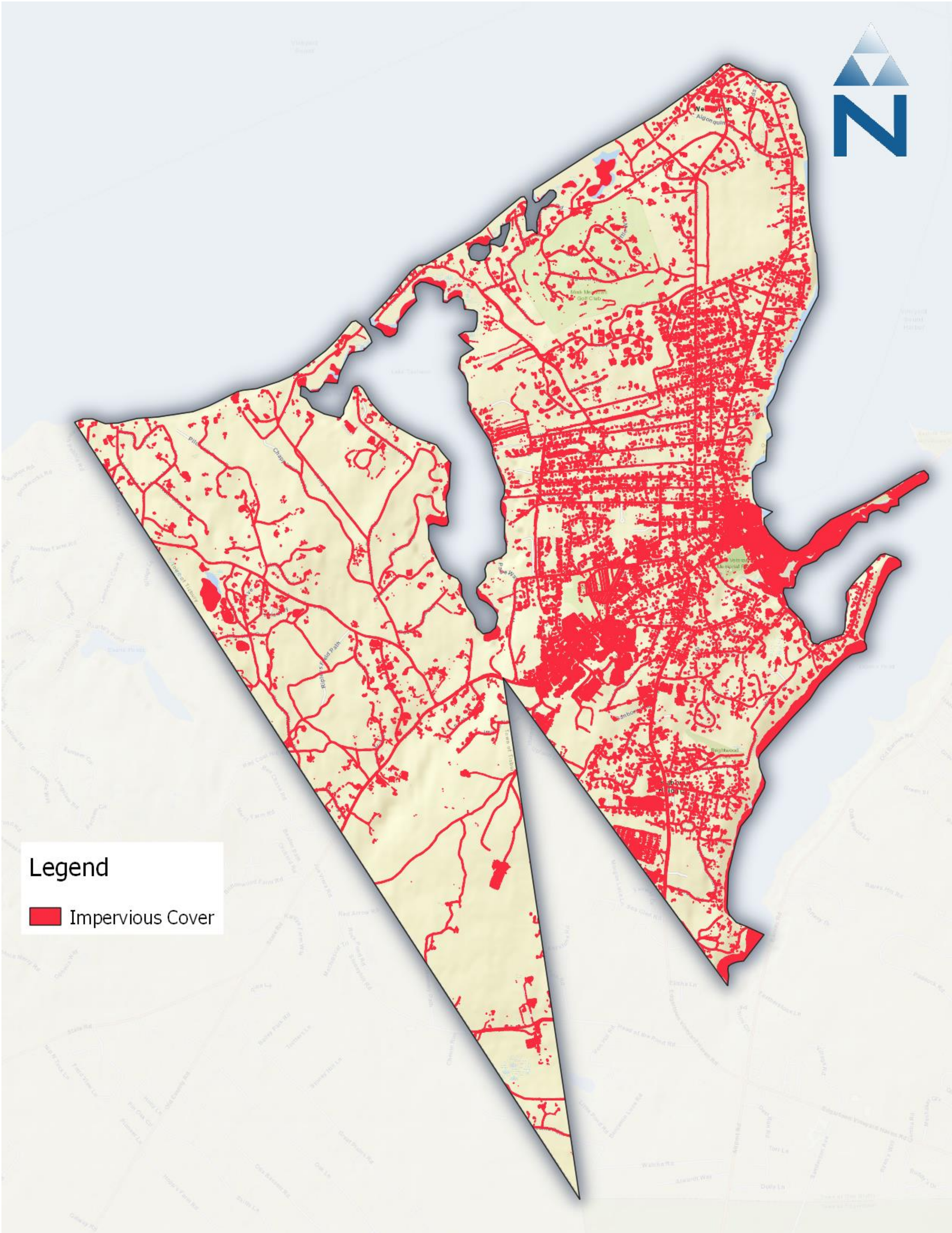

Figure 2-6. Mapped impervious cover for the Town of Tisbury, MA.

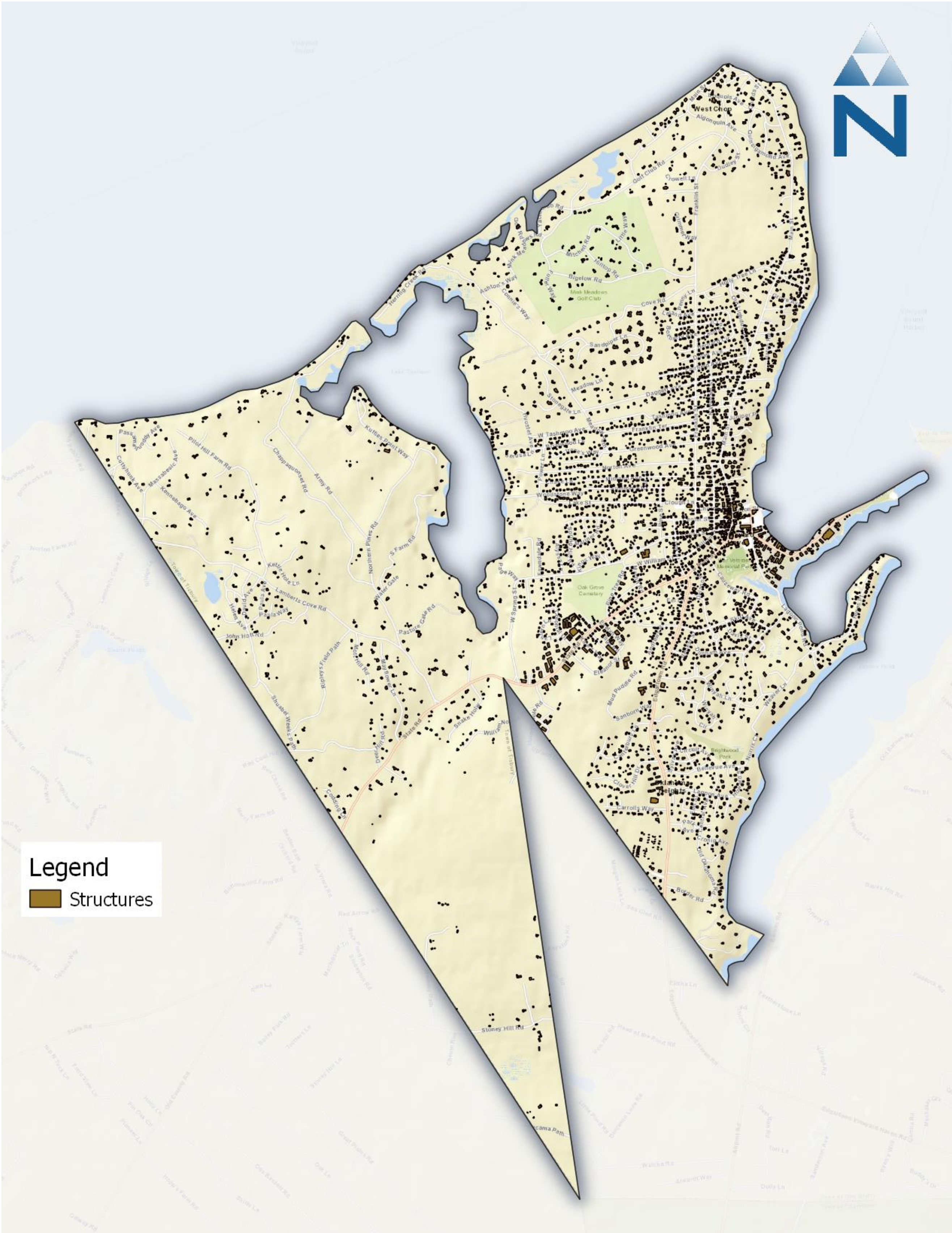

Figure 2-7. Building and structure footprints for the Town of Tisbury, MA.

2.2.6 Hydrological Response Units

Hydrologic Response Units (HRUs) are the core hydrologic modeling land unit that drives runoff and pollutant loading in the EPA developed Opti-Tool (U.S. EPA. 2016) watershed model. A detailed discussion of Opti-Tool and its application in this project is presented in Section 4. Each HRU represents areas of similar physical characteristics attributable to core processes identified through GIS overlays of the spatial datasets described in the previous sections. The HRU layer combined the land use, slope, soils, impervious and structure layers (Figure 2-8) into a single layer with unique categories. After overlaying each of these layers within a GIS raster framework, 33 unique categories were identified for representation within the Opti-Tool Tisbury model. These 33 HRUs are presented in Table 2-6 and Figure 2-9. All areas in Tisbury were classified into one of these HRU categories and represented within the Opti-Tool simulation.

Figure 2-8. Visual representation of the overlaying of land use, soil, slope, imperviousness, and structure layers to create a single HRU layer for Tisbury, MA

Table 2-6. The final assignment of Tisbury HRU categories

HRU ID	HRU CODE	Land Use	Land Cover	Hydrologic Soil Group	Slope
1	13110	Agriculture	Pervious	A	Low
2	13120				Med
3	13130				High
4	13210			B	Low
5	13220				Med
6	13230				High
7	2001		Impervious	n/a	n/a
8	12110	Forest	Pervious	A	Low
9	12120				Med
10	12130				High
11	12210			B	Low
12	12220				Med
13	12230				High
14	1001		Impervious	n/a	n/a
15	11110	Developed	Pervious	A	Low
16	11120				Med
17	11130				High
18	11210			B	Low
19	11220				Med
20	11230				High
21	11310			C	Low
22	11320				Med
23	11330				High
24	11410			D	Low
25	11420				Med
26	11430				High
27	3001	Commercial	Impervious	n/a	n/a
28	4001	Industrial			
29	5001	Low Density Residential			
30	6001	Medium Density Residential			
31	7001	High Density Residential			
32	8001	Highway			
33	9001	Open Space			

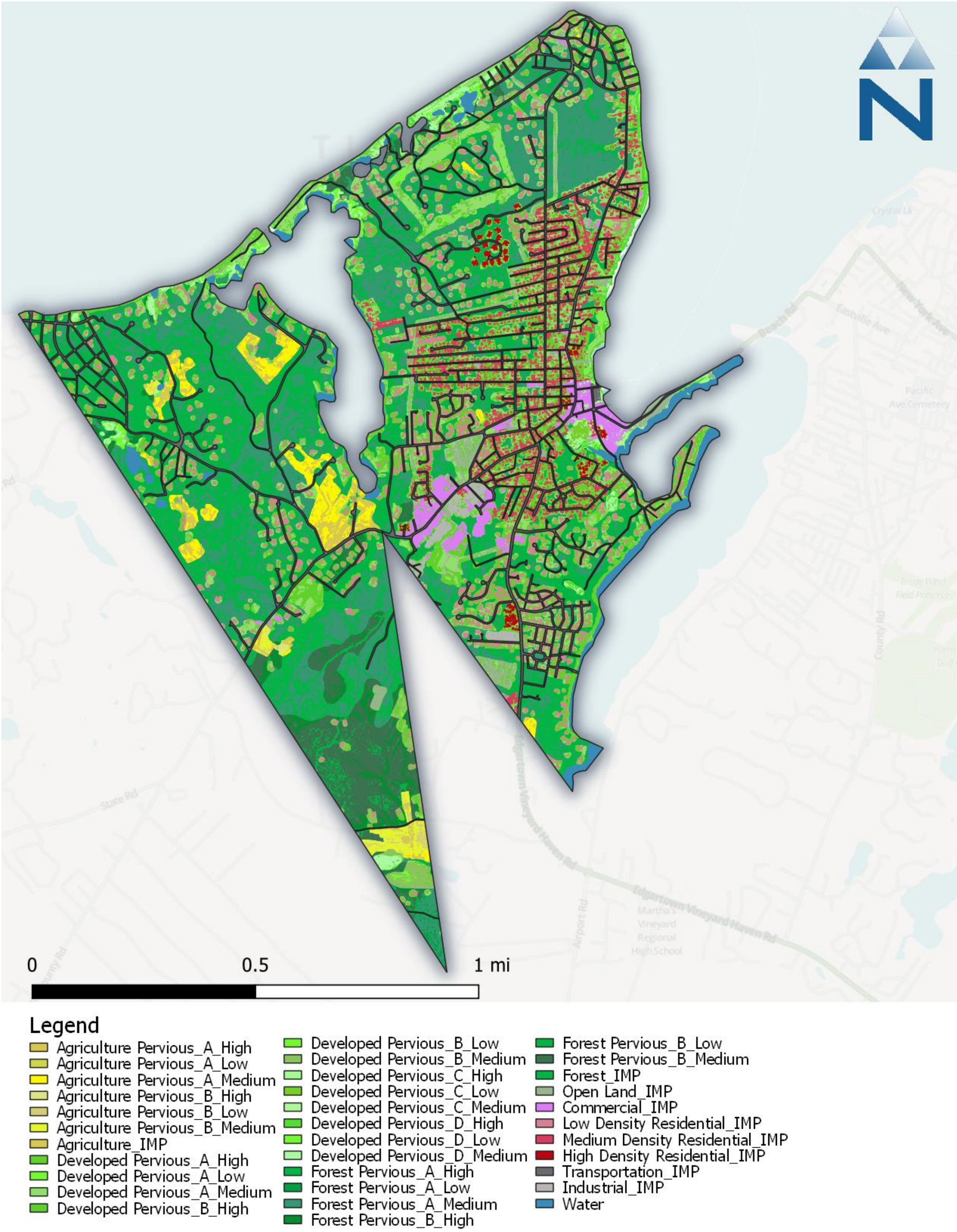

Figure 2-9. Hydrological Response Units for the Town of Tisbury, MA.

2.3 Development of HRU Timeseries

One of the most important steps in stormwater management planning is establishing the baseline condition runoff and pollutant loading. When performing simulation for BMP planning, the baseline condition becomes the basis for evaluating all management scenarios. The climate data discussed in Section 2.1 were the primary inputs to the SWMM-HRU model used by the Opti-Tool to simulate watershed hydrology and water quality processes. The Opti-Tool can generate hourly surface runoff volumes and concentrations for total nitrogen (TN), total phosphorous (TP), total zinc (Zn), and total suspended solids (TSS) based on hydrologic and water quality. The Opti-Tool installation provides default access to climate data from the Logan Airport gauge, and the model was previously calibrated using these timeseries along with New England's regional monitoring data and observed pollutant event mean concentrations (EMCs) in stormwater runoff.

This application applied the same calibrated model along with precipitation and temperature data from the Martha's Vineyard Airport (USAF-ID 725066) to account for locally distinct precipitation characteristics. Specifically, the distribution of generally small, more frequent storms observed at the Martha's Vineyard Airport gauge (Section 2.1) was expected to impact the optimization of GI SCM implementation, with a focus on smaller sized opportunities. The results of the SWMM model simulation, which include 20-year hourly runoff volume timeseries and total nitrogen loading timeseries, are shown in Table 2-7. Figure 2-10 shows the Tisbury zoning districts. Figure 2-11 and Figure 2-12 show the spatial distribution of annual average runoff depth (inches/year) and TN unit-area loading (pounds/acre/year) by HRU types for Tisbury. These timeseries and the HRU distribution for Tisbury form the foundation of the Opti-Tool analysis. The HRUs results highlight the hot spot areas (high runoff and pollutant loading) as shown in Figure 2-11 and Figure 2-12 and provide primary inputs to all management scenarios simulating BMPs.

2.4 Runoff Volume & Total Nitrogen

Using the HRU land use distribution by zoning district, the HRU timeseries was summarized to evaluate annual average runoff volume and annual average total nitrogen load over the full 21-year simulation period. The results are presented in Figure 2-13 and Figure 2-14, summarized by HRU category, in Figure 2-15 summarized by the zoning district, and in Figure 2-16 summarized by the zoning district on a normalized area basis. Note the HRU categories shown in the figures are the full set of 33 HRU discussed in Section 2.2, generalized for presentation purposes. Hydrologic soil group and slope were excluded, and the results were grouped by combinations of land use and land cover (i.e., either pervious or impervious). The following broad observations are seen within these four figures:

- Low density residential and medium density residential impervious areas are the largest sources of runoff and total nitrogen within Tisbury. These two HRUs had the largest area of all the impervious HRU categories. Impervious forest cover had the third highest area and consequently, the third highest runoff and pollutant load.
- Pervious forest HRUs were the fifth largest source of both runoff volume and total nitrogen. While pervious areas generally contribute less runoff and pollutant load on a normalized-area basis, pervious forest HRUs accounted for almost 50% of the entire Tisbury area.
- The higher density residential districts have higher runoff and total nitrogen loading areas than the lower density residential districts. Despite having lower per-acre runoff and total nitrogen loading rates, the residential districts *R50* and *R3A* have the second and third highest runoff volume and total nitrogen load because of their large area. Combined, these two zoning districts account for just over 62% of the area in Tisbury.

Because of flooding concerns in the downtown area, the three commercial districts *Business District (B1), Light Business District (B2), and Waterfront Commercial (W/C)* were compared separately to identify and target source areas with the potential to generate the highest runoff volume and total nitrogen loading. Figure 2-17, and Figure 2-18 present the subset of results for these three zoning districts. Like the plots presenting land use area, runoff volume, and total nitrogen load for all of Tisbury, the HRU categories presented in these three figures have been generalized for presentation purposes. The following observations were made from examining these summaries:

- Commercial impervious area dominates as the major source of runoff and total nitrogen within all three of the zoning districts. The industrial impervious area also shows a relatively large contribution of both runoff and total nitrogen within the *Light Business District (B2)*.
- Residential areas do not appear to be major sources in these districts which is consistent with the expected programmatic uses designated by commercial zoning.

Figure 2-19 and Figure 2-20 show the area-normalized (i.e., per acre) annual average runoff depth and annual average total nitrogen load, respectively, from the zoning districts in Tisbury. The trends for both runoff volume and total nitrogen loading are consistent between these two figures which show the following:

- The three commercial districts *Business District (B1), Light Business District (B2), and Waterfront Commercial (W/C)* have the highest per-acre runoff and total nitrogen loading rates of any of the ten districts. In most cases, these rates are more than double the rates seen for any of the residential districts.
- Similar to the trend described in Figure 2-16, the higher density residential districts have higher runoff and total nitrogen loading areas than the lower density residential districts.

Appendix D presents the HRU distribution for each of the 10 zoning districts separately, along with the overall HRU distribution for Tisbury.

Table 2-7. Tisbury HRUs unit-area based annual average runoff volume (in/yr) and TN loading (lb/ac/yr)

HRU ID	HRU CODE	HRU Description	Flow (in/yr)	TN (lb/ac/yr)
1	13110	Agriculture Pervious-A-Low	0.72	0.92
2	13120	Agriculture Pervious-A-Med	0.90	1.44
3	13130	Agriculture Pervious-A-High	0.97	1.66
4	13210	Agriculture Pervious-B-Low	2.30	2.82
5	13220	Agriculture Pervious-B-Med	2.70	3.77
6	13230	Agriculture Pervious-B-High	2.84	4.02
7	2001	Agriculture Impervious	37.53	10.65
8	12110	Forest Pervious-A-Low	0.72	0.19
9	12120	Forest Pervious-A-Med	0.90	0.28
10	12130	Forest Pervious-A-High	0.97	0.32
11	12210	Forest Pervious-B-Low	2.30	0.58
12	12220	Forest Pervious-B-Med	2.70	0.76
13	12230	Forest Pervious-B-High	2.84	0.81
14	1001	Forest Impervious	37.53	10.65
15	11110	Developed Pervious-A-Low	0.31	0.15
16	11120	Developed Pervious-A-Med	0.40	0.22
17	11130	Developed Pervious-A-High	0.44	0.25
18	11210	Developed Pervious-B-Low	2.30	1.23
19	11220	Developed Pervious-B-Med	2.70	1.63
20	11230	Developed Pervious-B-High	2.84	1.74
21	11310	Developed Pervious-C-Low	5.41	2.54
22	11320	Developed Pervious-C-Med	6.11	3.07
23	11330	Developed Pervious-C-High	6.39	3.23
24	11410	Developed Pervious-D-Low	10.25	3.94
25	11420	Developed Pervious-D-Med	11.15	4.56
26	11430	Developed Pervious-D-High	11.48	4.71
27	3001	Commercial	37.53	14.19
28	4001	Industrial	37.53	14.19
29	5001	Low Density Residential	37.53	13.26
30	6001	Medium Density Residential	37.53	13.26
31	7001	High Density Residential	37.53	13.26
32	8001	Highway	37.53	9.55
33	9001	Open Space	37.53	10.65

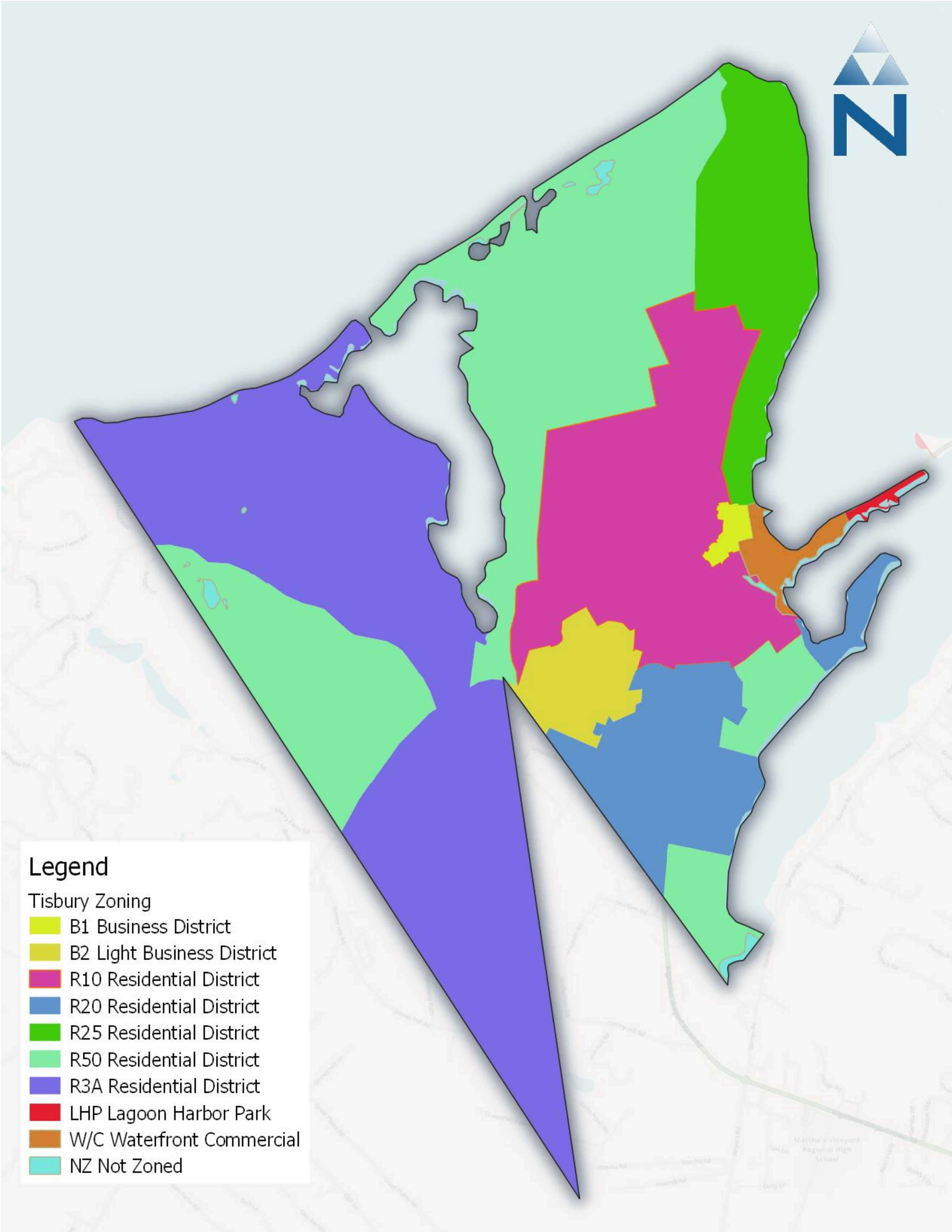

Figure 2-10. Tisbury zoning districts

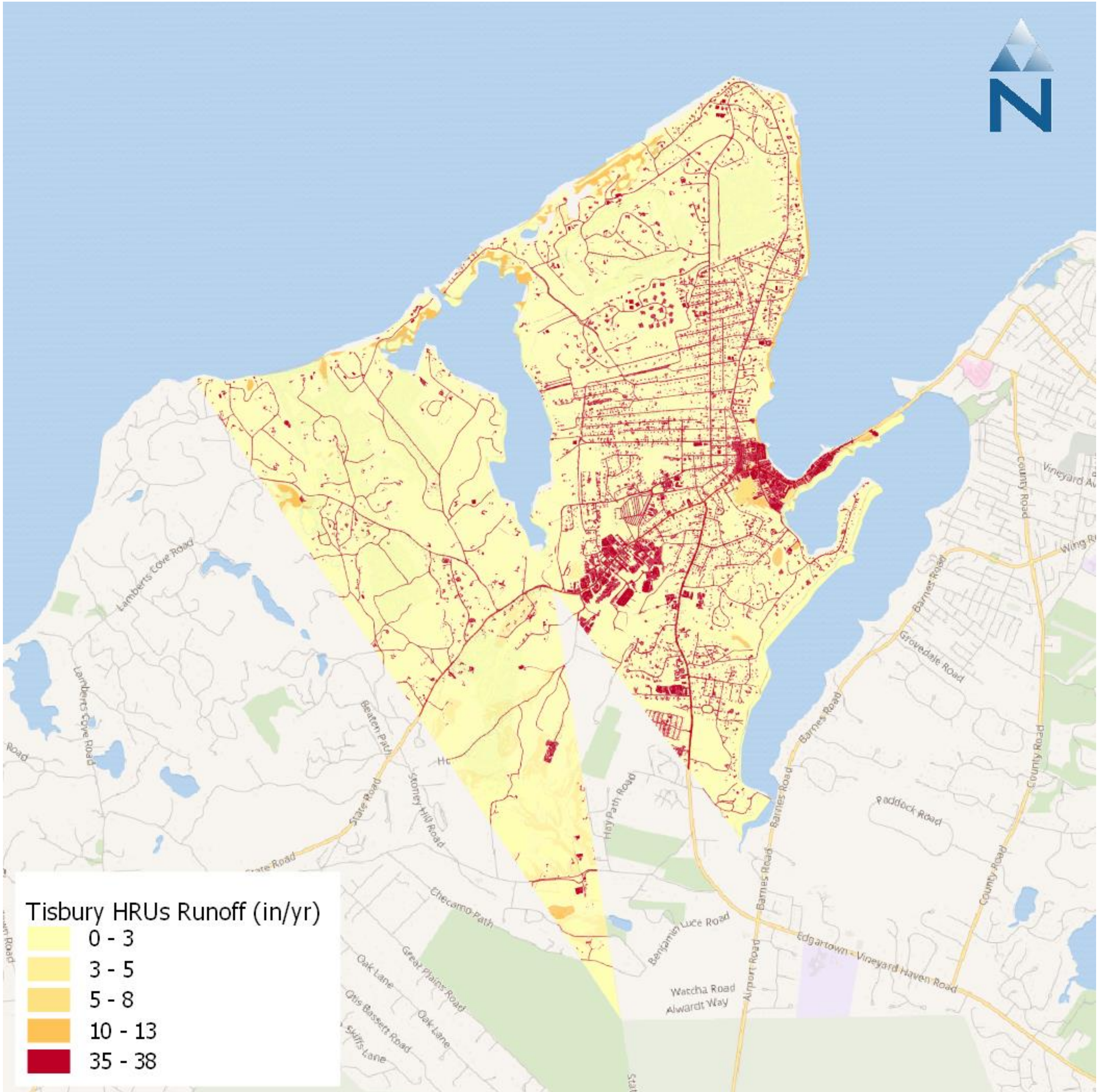

Figure 2-11. Tisbury HRUs unit-area based annual average runoff volume (inches/year).

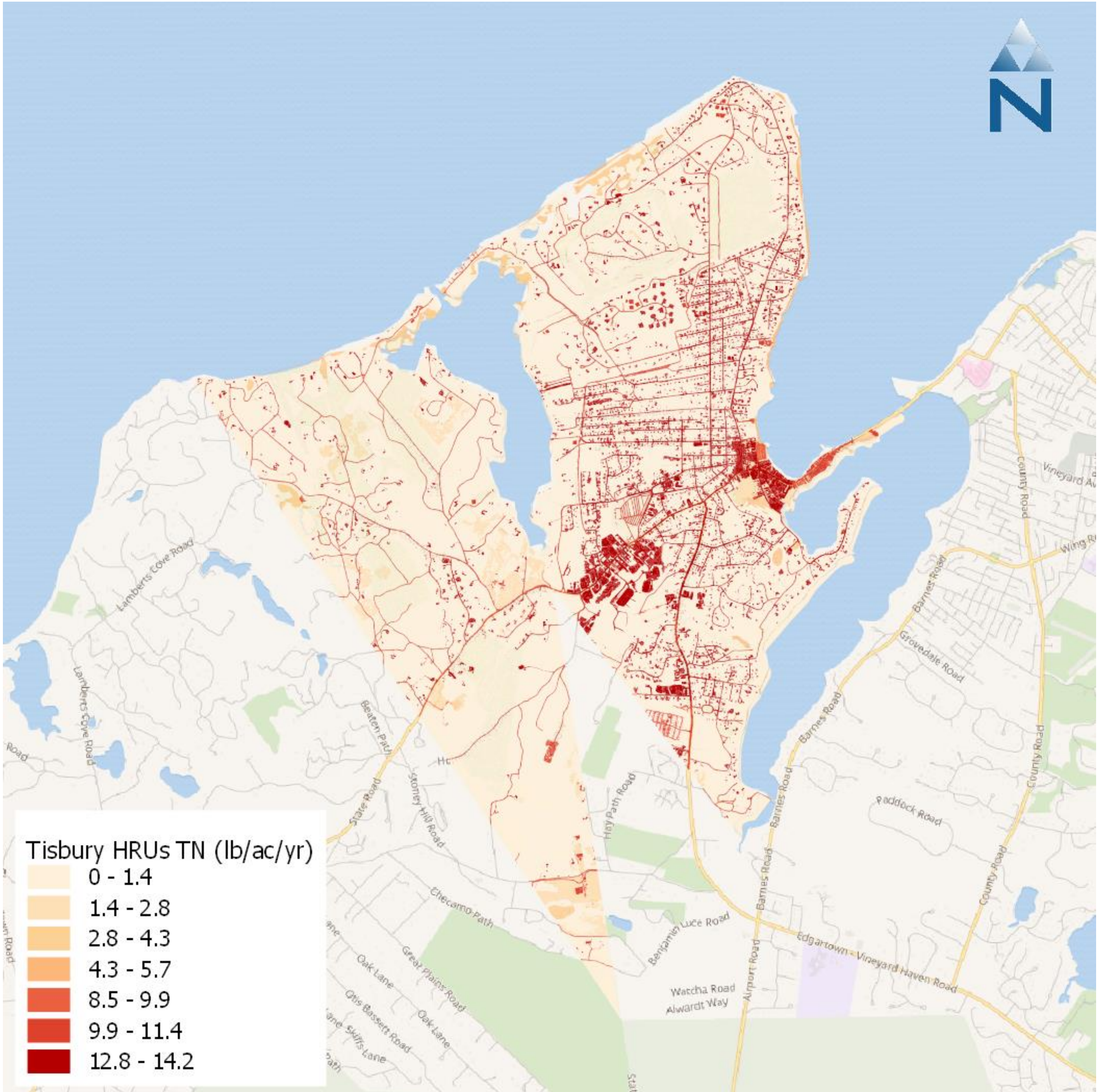

Figure 2-12. Tisbury HRUs unit-area based annual average total nitrogen load (pounds/acre/year).

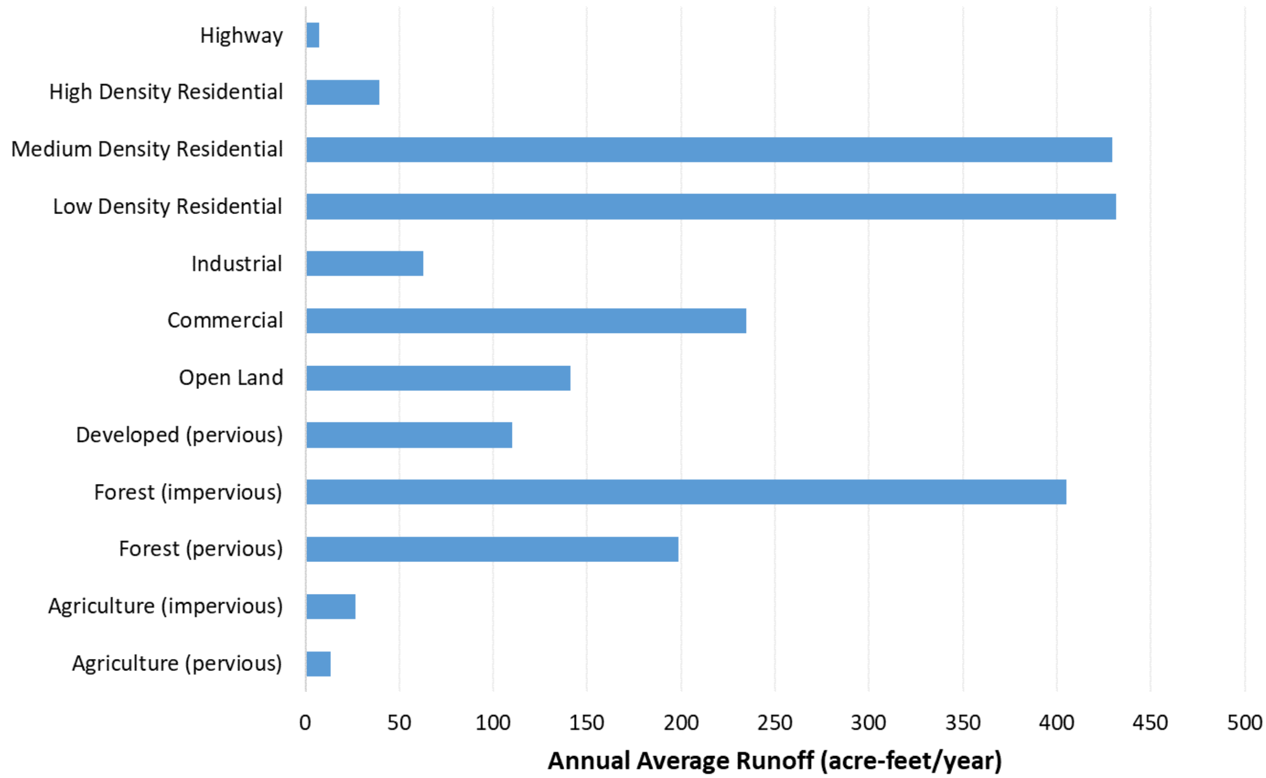

Figure 2-13. Summary of annual average runoff by generalized HRU category for Tisbury.

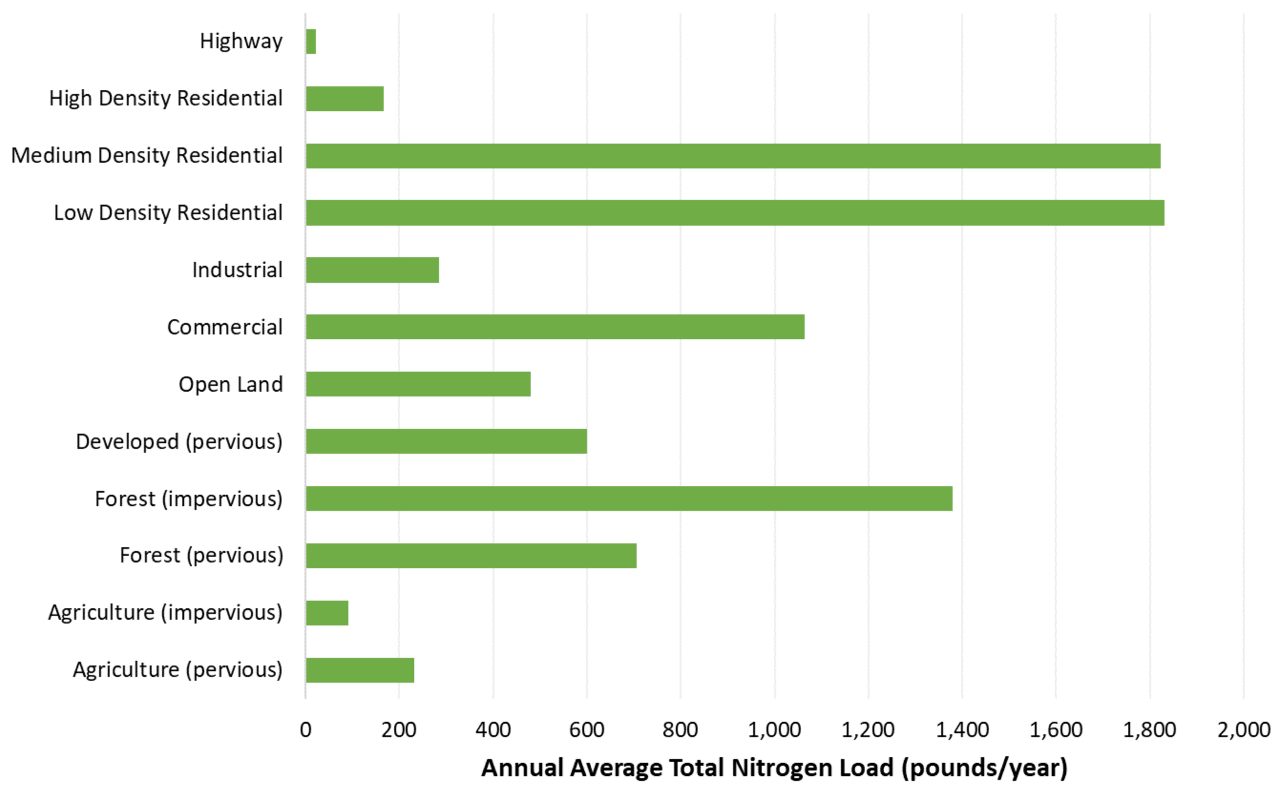

Figure 2-14. Summary of annual average total nitrogen by generalized HRU category for Tisbury.

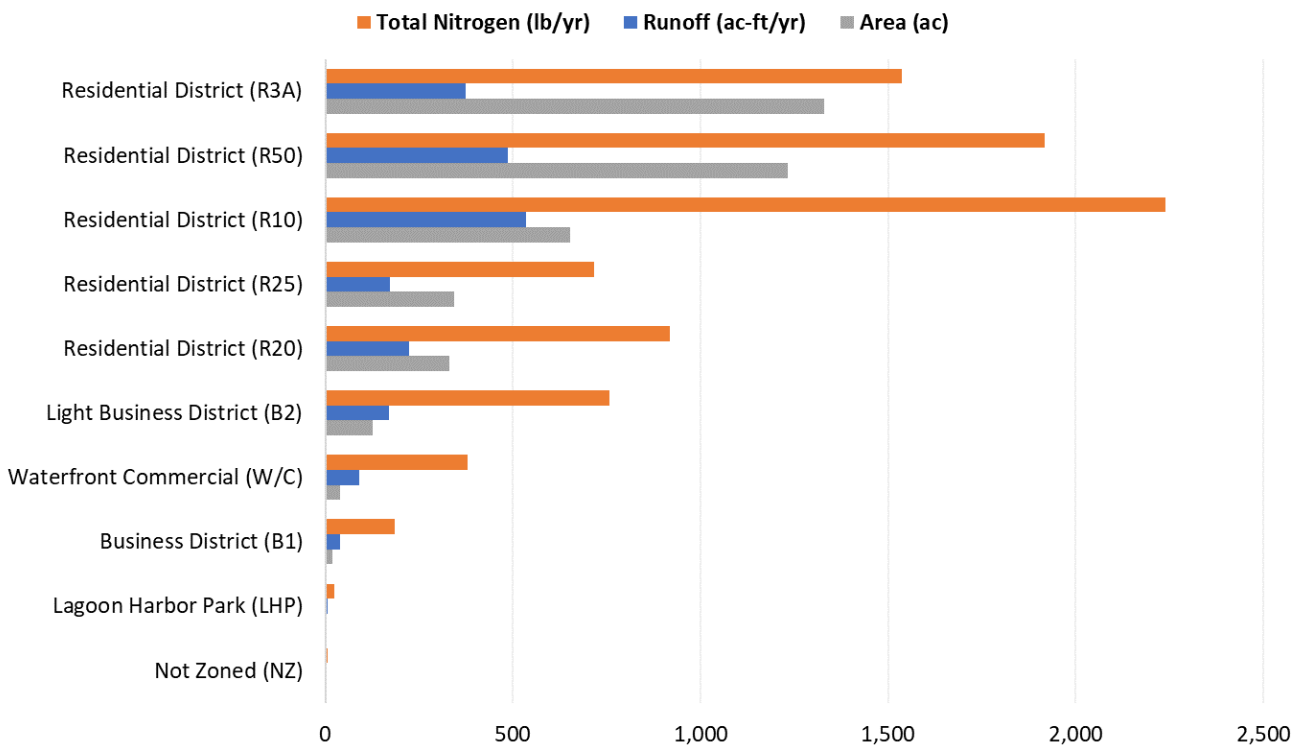

Figure 2-15. Summary of total area, runoff volume, and total nitrogen load by zoning district.

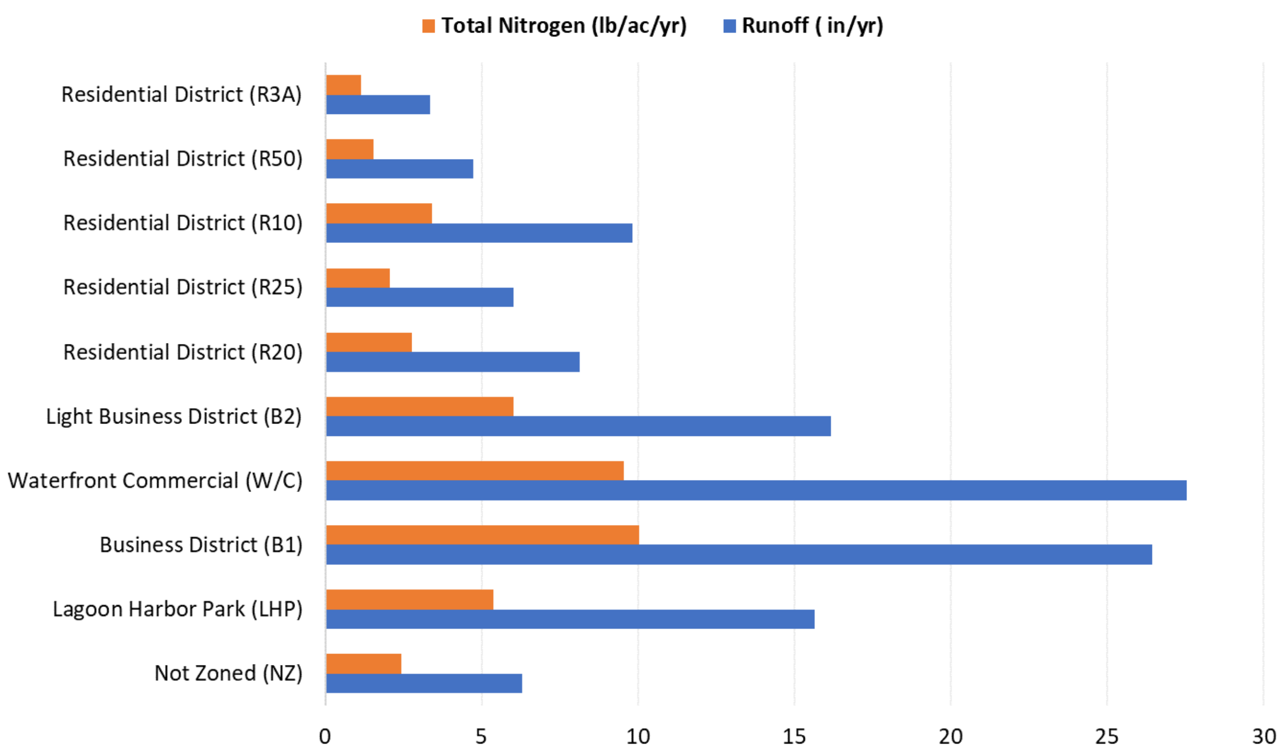

Figure 2-16. Summary of normalized runoff volume and total nitrogen load by zoning district.

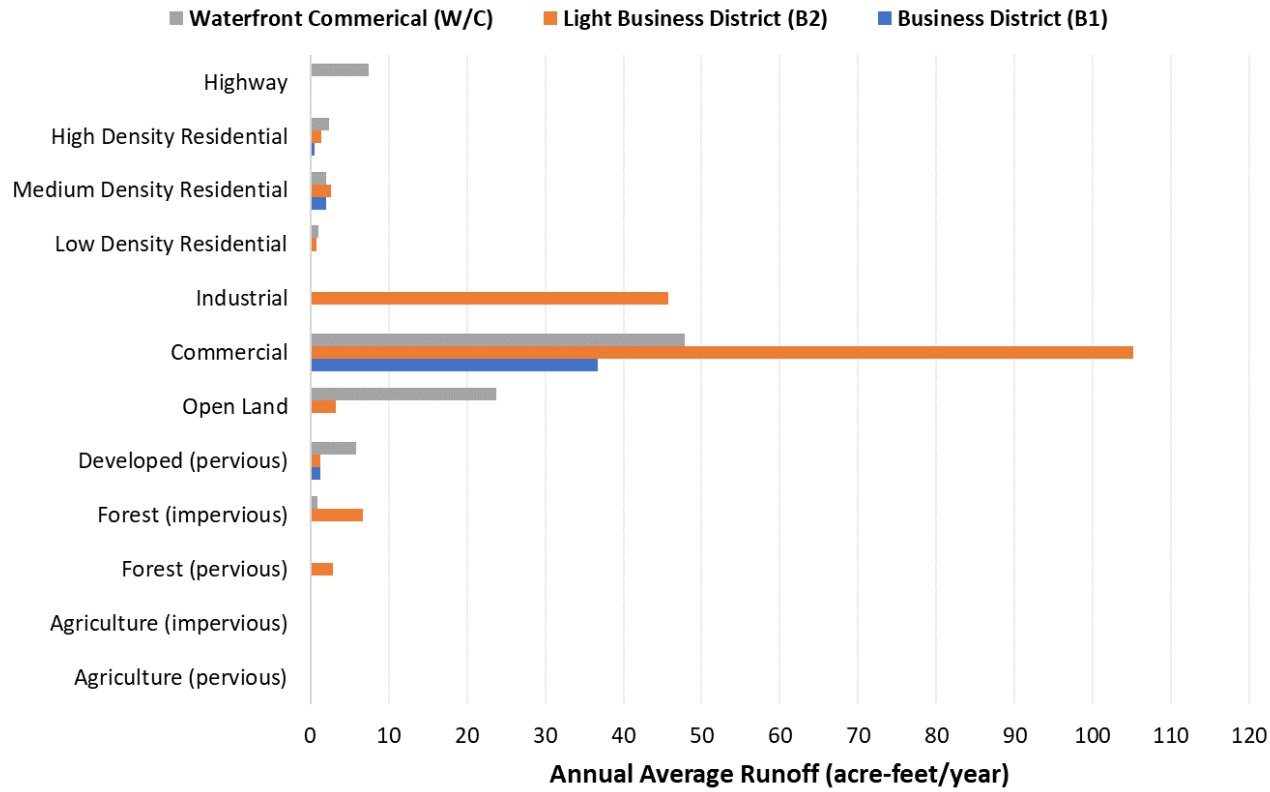

Figure 2-17. Summary of annual average runoff by generalized HRU category for commercial zoning districts.

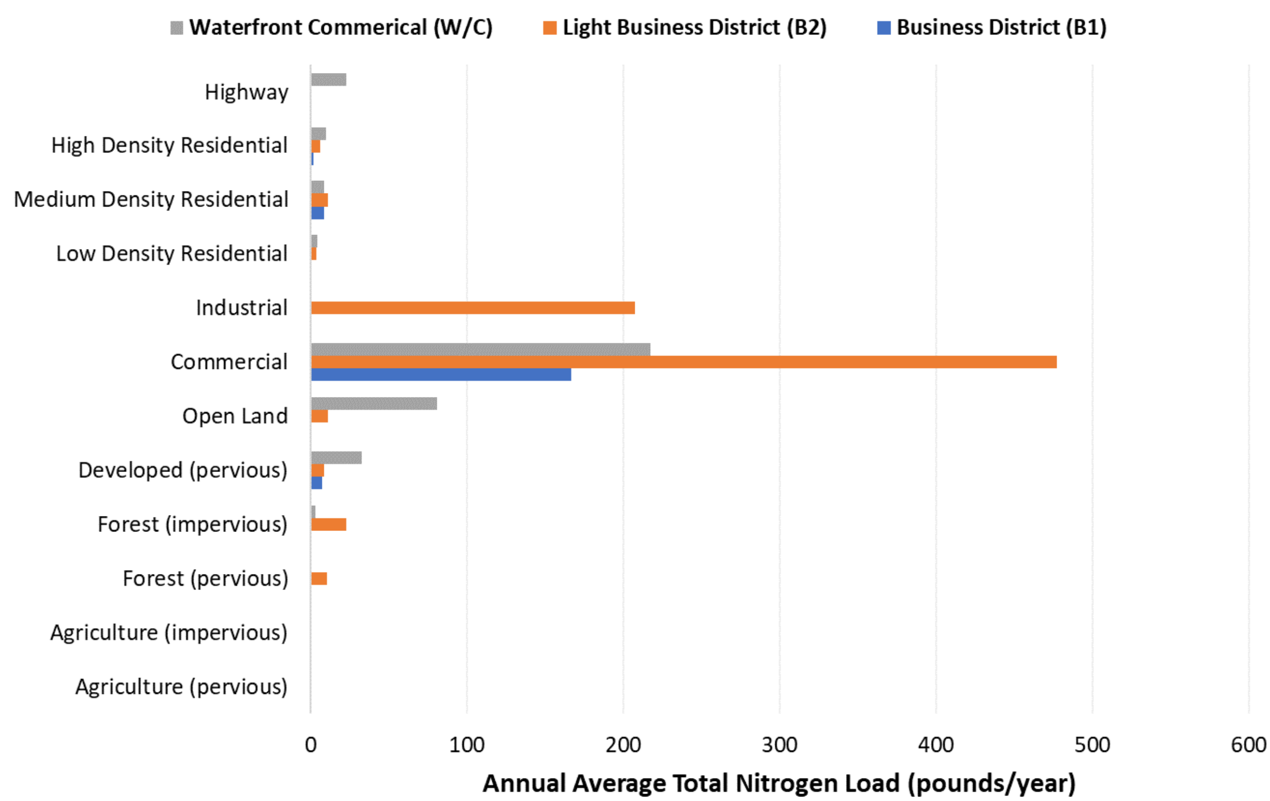

Figure 2-18. Summary of annual average total nitrogen by generalized HRU category for commercial zoning districts.

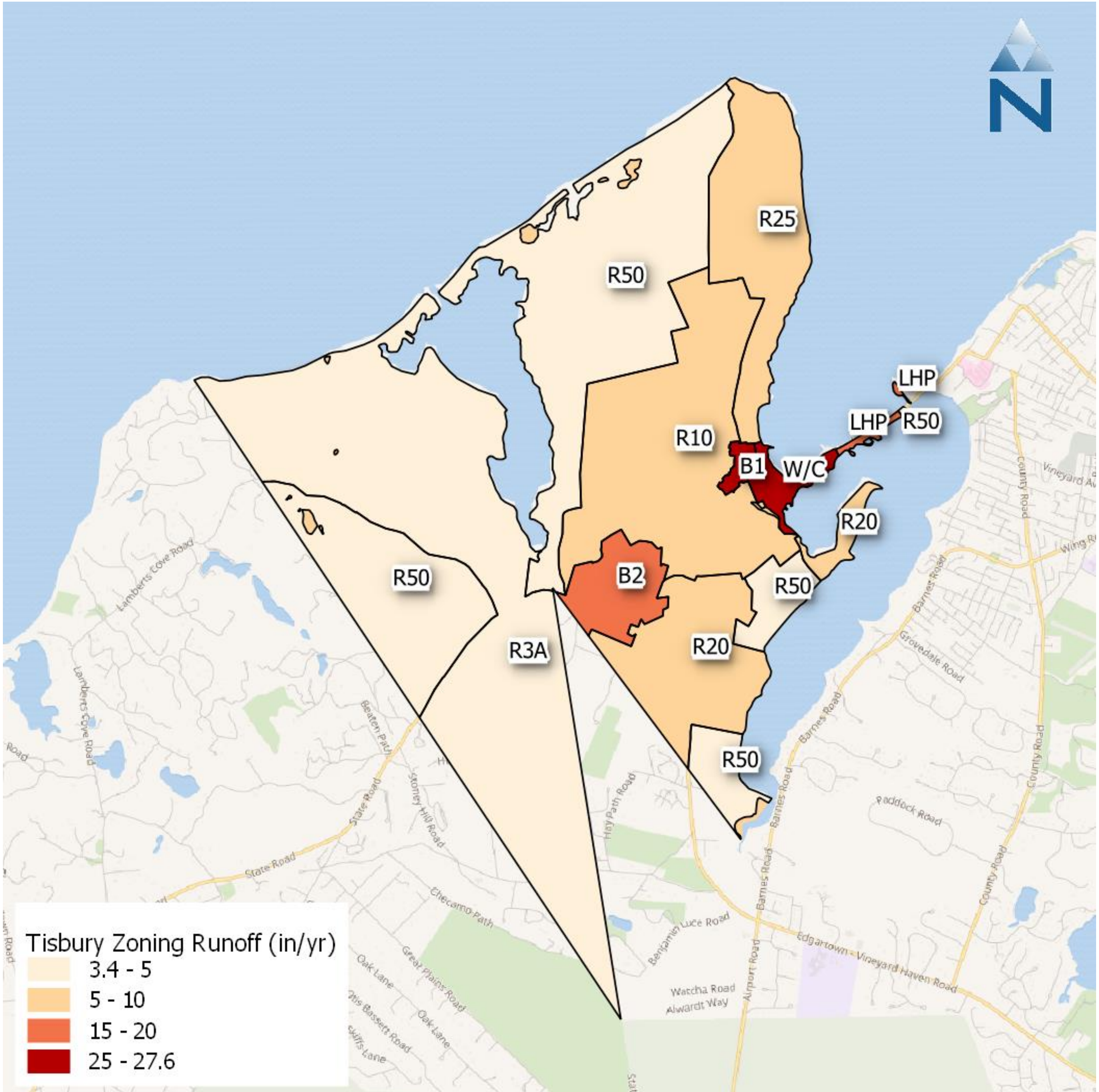

Figure 2-19. Tisbury annual average runoff volume (inches/year) normalized for zoning districts.

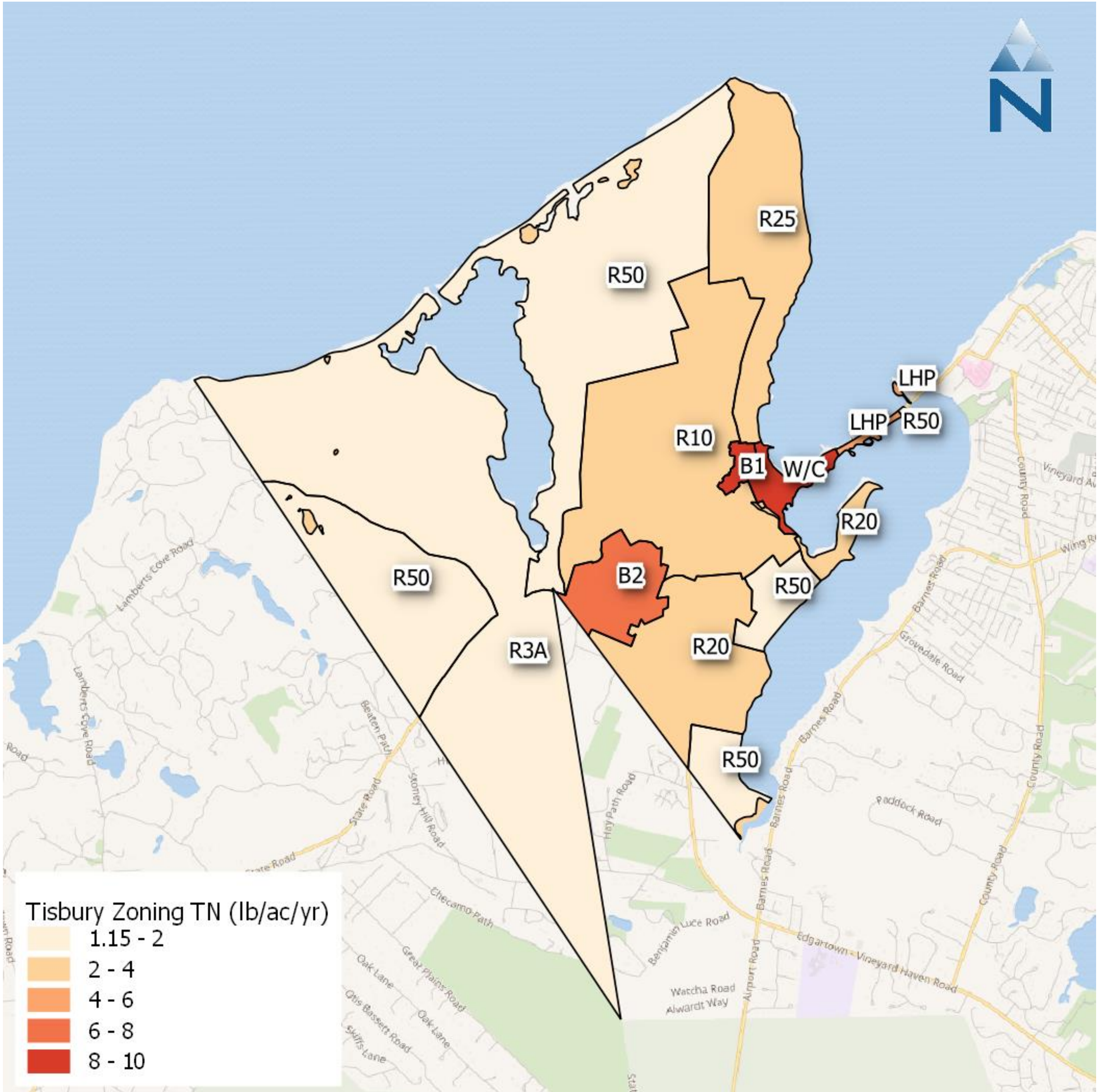

Figure 2-20. Tisbury annual average total nitrogen load (pounds/acre/year) normalized for zoning districts.

3 GI SCM OPPORTUNITIES & DESIGNS

3.1 Identifying GI SCM Opportunities & Strategies

The project approach coupled innovative and cost-effective pollutant load and runoff volume reduction modeling with a parallel process of community engagement. The community engagement included investigating sites of local concern and developing conceptual designs that could address the local site conditions but were also flexible enough to be applied in other areas. This process of engagement ensured effective technical information transfer for a better understanding of sustainable implementation opportunities and co-production of solutions as the basis upon which to build trust and support positive adoption decisions.

This innovative engagement approach was identified as critical to the success of a recently completed 10-year study implementing a watershed management plan in the Berry Brook watershed in Dover, NH. The partnership between EPA, New Hampshire Department of Environmental Services, University of New Hampshire Stormwater Center, and the City led to implementation efforts that reduced the effective impervious cover (EIC) in the 185-acre urban watershed from 30% down to 10% effective impervious cover. This unique partnership between academics, regulators and committed city staff reduced the best management practice implementation costs, increased the effectiveness, and led to more maintainable stormwater management systems.

The focus of the technical assistance effort included prioritization of cooperative identification of problems and co-development of solutions with project end-users. This direct participation of respected and trusted staff addresses three fundamental problems that are often associated with municipal adoption of innovative stormwater management approaches; compatibility, complexity and trialability, or in other words, does it fit the management culture, can people understand it, and can local staff adapt the designs for greater utility? It also forges a relationship of cooperation and trust amongst partners that do not always start from such critical working foundations. While the conventional optimization modeling approach largely identifies stormwater controls by suitable site characteristics, these interventions do not generally address site-specific issues concerning long-term operation and maintenance. The engagement discussed in this approach, therefore, brings critical components of stormwater controls like maintenance and municipal preferences into optimization planning. Importantly, both the modeling and the conceptual design approaches focused on generalized, infiltration-based practices that could be implemented widely and efficiently.

Engagement of town leadership is critical especially considering the potential for staff turnover in key positions. This process also identifies town resources and historical knowledge and expertise on issues around prioritizing stormwater problems. In Tisbury, a stormwater committee had already been established to identify and rank drainage problems. The Committee established a top tier of problem areas that were visited by town representatives and project team members. These were areas identified and tracked over time by staff and volunteers to begin the process of solving the drainage issues. Starting with these priorities not only established trust but acknowledged longstanding town needs and enhanced the probability of implementing successful intervention efforts. The stormwater committee consisted of the town administrator, the director of the Martha's Vineyard Commission, the director of the town Department of Public Works, members of a local non-profit water quality advocacy group, Massachusetts Department of Transportation employees.

The goal of the Stormwater Committee was to provide expertise and local knowledge to the identification of stormwater problems and the ranking of priorities for solutions to those problems. This project implemented a process of engaging project end-users and working with them to identify problems and co-develop solutions. As the goal of the project was to help early adopter municipalities make substantial progress in thinking through site-specific stormwater management options, hands-on technical assistance coupled with a sophisticated state of the science modeling was conducted in parallel. Having end-user partners identify locally prioritized problem areas and co-developing implementable solutions to solve self-identified problems allows for a more meaningful demonstration of the power of the modeling efforts. The co-production of site-specific concept design to solve local problems offers an opportunity to increase understanding and utility of modeled outcomes and begin the process of implementing solutions.

3.2 Summary of Opportunities

Table 3-1 presents the results of the GIS analysis to quantify the maximum area, by zoning district, to implement GI SCM opportunities. The data represents existing pervious areas by land use type that may be retrofitted to treat stormwater runoff from impervious surfaces. While it is possible to install GI SCM within areas with impervious surfaces, these areas are excluded from this analysis because GI SCM opportunities in impervious areas are typically more constrained and costly. The information in Table 3-1 identifies the maximum area and does not account for the feasibility of implementation, an important consideration discussed in Section 3.1. For example, the majority of pervious land is located in forested areas in the town and it is unlikely that these areas will become the focus of stormwater management solutions. The table does provide valuable insight into the existing opportunities within the more developed, urbanized zoning districts and was the basis for the GIS and Opti-Tool analyses to further investigate cost-effective solutions to reducing storm volume and TN loading. While the analyses in Section 2.4 highlighted the business and commercial districts as major sources of stormwater runoff and TN loading, there are limited pervious areas in these districts to install GI SCM opportunities. The more limited availability of pervious opportunity areas suggests that an optimization approach would be beneficial.

Table 3-2 presents the siting criteria used for all potential GI SCM opportunities in Tisbury, which were derived from GIS analysis. Figure 3-1 presents the locations of GI SCM opportunities in Tisbury. The desktop analysis focused on pervious areas that could be retrofitted to capture stormwater. Assessing impervious areas required additional screening and field investigations, discussed in Section 3.3. Some pervious areas were associated with conditions that could complicate the installation of GI SCM opportunities. These areas included proximity to coastlines, wetlands, and structures and were excluded from further analysis.

The treated impervious areas by land use group were split into two categories: roofs and other impervious surfaces. For this pilot study, it was assumed that rooftops could be disconnected by redirecting their runoff to infiltrations trenches, while all other types of impervious areas, such as roads and driveways, could be disconnected by diverting their runoff to infiltration basins. Both public and private property were assumed to be available for GIS SCM implementation. Six practices from a range of potential stormwater management methods were evaluated. The six practices were two infiltration techniques, basins and trenches, on soil groups A, B, and C. Infiltration trenches were used to treat roof runoff while infiltration basins were used to treat runoff from all other impervious surfaces. Table 3-3 presents the treated impervious area for the six SCM types by land use and zoning district. The analysis assumed that all impervious areas were treated by GI SCM opportunities.

Table 3-1. Potential infiltration GI SCM opportunity areas (maximum footprints) by Tisbury zoning district.

Land Use Group	HSG	Pervious Opportunity Areas for Infiltration GI SCM in Tisbury by Zoning District (acres)									
		Business District (B1)	Light Business District (B2)	Residential District (R10)	Residential District (R20)	Residential District (R25)	Residential District (R50)	Residential District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercial (W/C)	Total
Forest	A	0.41	31.39	143.69	131.90	152.18	754.68	753.24	-	0.35	1,967.83
	B	-	2.41	1.37	-	-	10.12	225.95	-	-	239.85
	C	0.04	-	0.32	-	-	-	-	-	-	0.35
Agriculture	A	-	-	1.05	-	0.79	26.01	79.52	-	-	107.37
	B	-	-	-	-	-	0.05	27.55	-	-	27.60
	C	-	-	-	-	-	-	-	-	-	0.00
Commercial	A	1.42	12.46	7.38	1.79	2.14	2.20	1.11	-	-	28.49
	B	-	0.20	-	-	-	0.01	0.28	-	-	0.49
	C	1.51	-	0.10	-	0.30	-	-	-	3.70	5.61
Industrial	A	-	19.72	0.15	1.34	-	-	-	-	-	21.21
	B	-	-	-	-	-	-	-	-	-	0.00
	C	-	-	-	-	-	-	-	-	-	0.00
Low Density Residential	A	-	0.41	45.21	95.49	32.30	134.43	55.00	-	0.59	363.44
	B	-	-	0.24	-	-	1.86	10.87	-	-	12.96
	C	-	-	-	-	-	-	-	-	-	0.00
Medium Density Residential	A	1.15	1.29	238.82	2.68	69.05	5.44	-	-	-	318.43
	B	-	-	-	-	-	-	-	-	-	0.00
	C	-	-	0.00	-	0.00	-	-	-	1.00	1.01
High Density Residential	A	0.07	0.92	3.57	2.84	0.84	5.24	-	-	-	13.47
	B	-	-	-	-	-	-	-	-	-	0.00
	C	-	-	-	-	-	-	-	-	0.63	0.63
Highway	A	-	-	-	-	-	-	-	-	-	0.00
	B	-	-	-	-	-	-	-	-	-	0.00
	C	-	-	-	-	0.00	-	-	-	0.17	0.17
Open Land	A	0.02	3.06	19.73	6.52	6.05	56.06	14.50	-	0.00	105.94
	B	-	-	-	-	-	0.07	20.71	-	-	20.78
	C	0.43	-	4.62	-	0.00	-	-	-	0.97	6.02
Total	A	3.07	69.25	459.61	242.55	263.35	984.05	903.37	-	0.94	2,926.20
	B	-	2.61	1.61	-	-	12.10	285.36	-	-	301.68
	C	1.97	-	5.03	-	0.30	-	-	-	6.47	13.78

Table 3-2. Stormwater management categories and SCM types

Land Use	Landscape Slope (%)	Within 100 feet of Coastline?	Within 25 feet of Structure?	Soil Group	Management Category	SCM Type(s) in Opti-Tool
Pervious Area	<= 15	Yes	Yes	All	SCM with complicating characteristics	--
		No	No	A/B/C	Infiltration	Surface Infiltration Basin (e.g., Rain Garden)
				D	Biofiltration	Biofiltration (e.g., Enhanced Bioretention with ISR and underdrain option)
	> 15	--	--	--	SCM with complicating characteristics	--
Impervious Area	<= 5	Yes	Yes	All	SCM with complicating characteristics	--
		No	No	A/B/C	Infiltration	Infiltration Trench
				D	Shallow filtration	Porous Pavement
	> 5	--	--	--	SCM with complicating characteristics	--

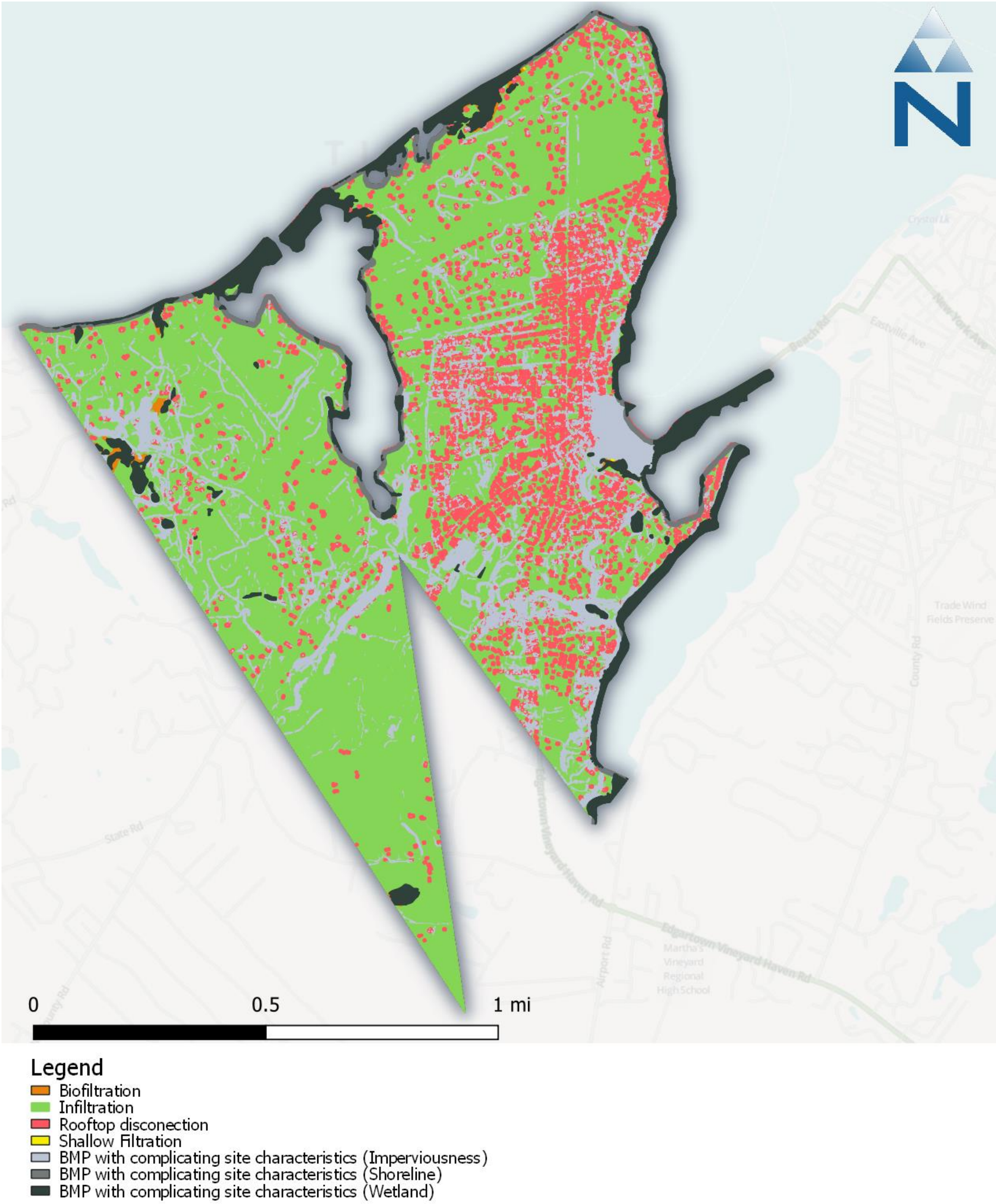

Figure 3-1. GI SCM opportunities in Tisbury, MA

Table 3-3. Infiltration GI SCM treated impervious area (impervious cover disconnected) for Tisbury, MA

Land Use Group	SCM Type	HSG	Treated Impervious Area for Infiltration GI SCM in Tisbury by Zoning District (acres)									
			Business District (B1)	Light Business District (B2)	Residential District (R10)	Residential District (R20)	Residential District (R25)	Residential District (R50)	Residential District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercial (W/C)	Total
Forest	Infiltration Trench (Rooftop disconnected)	A	0.045	0.066	1.669	0.810	0.631	1.907	0.752	-	-	5.879
		B	-	0.005	0.016	-	-	0.026	0.226	-	-	0.272
		C	0.004	-	0.004	-	-	-	-	-	-	0.008
	Infiltration Basin (Other IC disconnected)	A	0.053	1.980	9.901	12.024	7.361	53.779	32.876	-	0.293	118.268
		B	-	0.152	0.095	-	-	0.721	9.862	-	-	10.830
		C	0.005	-	0.022	-	-	-	-	-	-	0.026
Agriculture	Infiltration Trench (Rooftop disconnected)	A	-	-	0.006	-	-	0.083	0.697	-	-	0.786
		B	-	-	-	-	-	0.000	0.241	-	-	0.242
		C	-	-	-	-	-	-	-	-	-	-
	Infiltration Basin (Other IC disconnected)	A	-	-	-	-	0.114	1.893	4.343	-	-	6.351
		B	-	-	-	-	-	0.003	1.505	-	-	1.508
		C	-	-	-	-	-	-	-	-	-	-
Commercial	Infiltration Trench (Rooftop disconnected)	A	1.957	6.020	2.197	0.613	0.504	0.390	0.125	-	-	11.805
		B	-	0.097	-	-	-	0.002	0.031	-	-	0.130
		C	2.087	-	0.029	-	0.070	-	-	-	3.825	6.012
	Infiltration Basin (Other IC disconnected)	A	4.036	27.418	6.212	2.280	1.228	0.848	0.360	-	-	42.382
		B	-	0.442	-	-	-	0.004	0.090	-	-	0.536
		C	4.304	-	0.083	-	0.172	-	-	-	11.798	16.357
Industrial	Infiltration Trench (Rooftop disconnected)	A	-	2.188	0.031	0.386	-	-	-	-	-	2.605
		B	-	-	-	-	-	-	-	-	-	-
		C	-	-	-	-	-	-	-	-	-	-
	Infiltration Basin	A	-	12.662	0.497	4.521	-	-	-	-	-	17.679
		B	-	-	-	-	-	-	-	-	-	-

Land Use Group	SCM Type	HSG	Treated Impervious Area for Infiltration GI SCM in Tisbury by Zoning District (acres)									
			Business District (B1)	Light Business District (B2)	Residential District (R10)	Residential District (R20)	Residential District (R25)	Residential District (R50)	Residential District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercial (W/C)	Total
	(Other IC disconnected)	C	-	-	-	-	-	-	-	-	-	-
Low Density Residential	Infiltration Trench (Rooftop disconnected)	A	-	0.030	5.491	12.053	4.065	18.279	6.768	-	0.017	46.704
		B	-	-	0.029	-	-	0.253	1.337	-	-	1.619
		C	-	-	-	-	-	-	-	-	-	0.000
	Infiltration Basin (Other IC disconnected)	A	-	0.228	18.402	30.302	7.355	33.765	11.037	-	0.305	101.394
		B	-	-	0.096	-	-	0.468	2.180	-	-	2.744
		C	-	-	-	-	-	-	-	-	-	-
Medium Density Residential	Infiltration Trench (Rooftop disconnected)	A	0.254	0.109	38.645	0.305	10.635	0.781	-	-	-	50.729
		B	-	-	-	-	-	-	-	-	-	-
		C	-	-	0.000	-	0.000	-	-	-	0.258	0.258
	Infiltration Basin (Other IC disconnected)	A	0.504	0.740	83.954	1.119	17.123	2.256	-	-	-	105.695
		B	-	-	-	-	-	-	-	-	-	0.000
		C	-	-	0.000	-	0.000	-	-	-	0.483	0.484
High Density Residential	Infiltration Trench (Rooftop disconnected)	A	0.097	0.163	0.924	0.759	0.332	2.261	-	-	-	4.537
		B	-	-	-	-	-	-	-	-	-	-
		C	0.001	-	-	-	-	-	-	-	0.226	0.227
	Infiltration Basin (Other IC disconnected)	A	0.098	0.316	1.310	2.299	0.407	3.598	-	-	-	8.028
		B	-	-	-	-	-	-	-	-	-	-
		C	0.001	-	-	-	-	-	-	-	0.599	0.600
Highway	Infiltration Trench (Rooftop disconnected)	A	-	-	-	-	-	-	-	-	-	-
		B	-	-	-	-	-	-	-	-	-	-
		C	-	-	-	-	-	-	-	-	0.211	0.211
	Infiltration Basin	A	-	-	-	-	-	-	-	-	-	-
		B	-	-	-	-	-	-	-	-	-	-
		C	-	-	-	-	0.012	-	-	-	2.159	2.171

Land Use Group	SCM Type	HSG	Treated Impervious Area for Infiltration GI SCM in Tisbury by Zoning District (acres)									
			Business District (B1)	Light Business District (B2)	Residential District (R10)	Residential District (R20)	Residential District (R25)	Residential District (R50)	Residential District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercial (W/C)	Total
	(Other IC disconnected)											
Open Land	Infiltration Trench (Rooftop disconnected)	A	0.000	0.044	0.066	0.531	0.226	0.421	0.115	-	0.000	1.403
		B	-	-	-	-	-	0.001	0.165	-	-	0.165
		C	0.000	-	0.015	-	0.000	-	-	-	1.766	1.782
	Infiltration Basin (Other IC disconnected)	A	0.002	0.994	9.071	4.768	3.358	9.257	2.306	-	0.002	29.757
		B	-	-	-	-	-	0.011	3.295	-	-	3.307
		C	0.040	-	2.123	-	0.001	-	-	-	5.942	8.104
Total	Infiltration Trench (Rooftop disconnected)	A	2.353	8.620	49.029	15.457	16.393	24.122	8.457	-	0.017	124.448
		B	-	0.102	0.045	-	-	0.281	2.000	-	-	2.428
		C	2.092	-	0.049	-	0.071	-	-	-	6.286	8.497
	Infiltration Basin (Other IC disconnected)	A	4.692	44.337	129.347	57.313	36.947	105.397	50.922	-	0.600	429.555
		B	-	0.594	0.191	-	-	1.207	16.932	-	-	18.924
		C	4.348	-	2.228	-	0.185	-	-	-	20.981	27.743

3.3 Tisbury Field Investigations

The main objective of the field investigations was to identify feasible and practical solutions for disconnecting impervious cover to address flooding and water quality problems. As mentioned previously, the project team and partners took an innovative approach with an emphasis on participation by the town and staff. Participation of community partners in identifying and prioritizing locally known problem areas and co-developing implementable solutions tallowed for a more meaningful demonstration of the power of the modeling efforts. This critical component provided an opportunity to improve understanding of the larger prioritization efforts investigated through modeling. Participating partners learned how the retrofit process works, allowing personnel who have the responsibility and authority to implement solutions a chance to vet ideas and discuss practical concerns that may hinder future adoption. Field investigations in Tisbury led to the development of a list of locally prioritized problems the town wanted to address including the following:

1. Outfall Pipe # 2 at Beach St extension design.
2. Subsurface Gravel Filter under the old fire station parking lot and linear gravel wetland establishing a new outfall to mud creek
3. Infiltration catch basins and subsurface gravel filter designs for Grove Ave and Harborview Drive.
4. Concept design for media box filters for Spring St. and the Tisbury School
5. A bioretention control measure to disconnect flow at the bus turnaround at the ferry terminal.
6. A set of controls at the end of Lake Street like that of Grove Ave and Harborview.

A full list of locally identified priorities can be found in Appendix E. More detail on the solutions and the innovative engagement process can be found in Appendix B.

3.4 GI SCM Conceptual Designs

The list of locally prioritized problem areas identified discussed in Section 3.3 led to the development of small scale GI SWM designs that were co-developed with the project team and partners through various field visits and meetings. These designs were vetted by the town leaders and public works staff to be locally sourced, adaptable and implementable with town staff and town owned equipment. This was a critical component of the effort as co-developed small-scale designs gave town partners examples of what the modeled solutions might look like. Only with implementation comes the hands-on experience necessary to understand and adopt GI SCM solutions. Without implementation, local municipal knowledge and understanding of the stormwater management technologies and their inherent flexibility are not fully transferred.

More details about the conceptual designs and their attendant water quality improvements can be found in Appendix F.

4 QUANTIFYING GI SCM BENEFITS

4.1 Opti-Tool Background and Description

The Opti-Tool provides the ability to evaluate options for determining the best mix of structural BMPs to achieve water quality goals. Structural BMPs are permanent structures, provide stormwater storage capacity, and rely upon vegetation and soil mechanisms to perform as intended. The tool incorporates long-term runoff responses (Hydrologic Response Unit [HRU] timeseries) for regional climate conditions that are calibrated to regionally representative stormwater data and annual average pollutant load export rates from nine land uses. The tool uses regionally representative BMP cost functions and regionally calibrated BMP performance parameters for four pollutants, including total phosphorus (TP), to calculate long-term cumulative load reductions for a variety of structural controls. Structural controls simulated by the tool include low impact development (LID) and green infrastructure (GI) practices, such as infiltration systems, bio-filtration, and gravel wetlands.

The technical approach for applying the Opti-Tool is organized into three general steps:

1. Develop stormwater management categories for SCMs known to be highly effective at removing phosphorus (e.g., shallow filtration, infiltration, biofiltration) based on the site suitability analysis of GIS layers. The categories were previously presented in Table 3-2;
2. Estimate the available opportunity by BMP type (i.e., physical footprint area) within each management category and summarize the upstream impervious drainage area that can be managed for each management category. This analysis is presented in Table 3-3 and
3. Set up and run the Opti-Tool application to identify the most cost-effective combination of BMP options that achieve the desired management objectives. This process is discussed in Sections 4.4 and 4.5.

4.2 GI SCM Performance Curves for Indicator Bacteria

As part of the study, performance curves representing indicator bacteria (*E. coli*) load reductions that may be achieved by SCM treatment of stormwater were developed based on simulated runoff from impervious HRUs. The curves may also be applied to other indicator bacteria, such as *Enterococcus* load reductions if the underlying mechanisms for the SCM performance are similar to other indicator bacteria. The SCM performance curves represent long-term average annual indicator bacteria load reductions (as a percent) that can be expected for a wide range of SCM storage capacities. Rainfall-runoff response timeseries from impervious HRUs were simulated using the SWMM hydrology model (U.S. EPA. 2015). The SCM performance curves were developed using the SUSTAIN GI simulation engine (U.S. EPA. 2009) through Opti-Tool (U.S. EPA. 2016). This modeling approach has previously been used to provide performance curves for TN, TP, TSS, and Zn. Both models (SWMM and SUSTAIN) for Opti-Tool were calibrated using New England's regional monitoring data, observed pollutant event mean concentrations (EMCs) in stormwater runoff and observed inflow/outflow pollutant concentrations from stormwater SCMs that were studied to assess pollutant reduction performances. HRU timeseries for bacteria were developed for the impervious surfaces of the urbanized New England community of Tisbury, MA, located on Martha's Vineyard. A literature review identified concentration, loading, and buildup/washoff values used to develop the timeseries. The resulting concentrations and loadings represent generalized conditions for purposes of SCM performance curve development and do not reflect the specific bacteria loading conditions in Tisbury, MA. A literature review was also completed to identify SCM efficiency values to include in SUSTAIN GI simulation. For a given depth of runoff volume storage capacity from the impervious cover captured by an SCM, the curves provide an estimated bacteria load reduction given as a percentage of total loading. Due to a lack of literature values for SCM removal efficiencies for *Enterococcus*, the rates for *E. col*i were used for both fecal bacteria indicators.

4.2.1 Impervious HRU Timeseries for Indicator Bacteria

The SUSTAIN model requires hourly timeseries of flow and pollutant load as a boundary condition to run. To develop impervious HRU timeseries, the HRU SWMM hydrology model, developed previously for Opti-Tool, was used for hourly flow simulation. The same model was updated for water quality by adding two fecal bacteria indicators (*E. coli* and *Enterococcus*). The hourly precipitation timeseries and daily air temperature data collected at the Martha's Vineyard Airport was used in the HRU SWMM model to represent the local patterns of precipitation, including dry periods between storm events when pollutants accumulate on impervious surfaces. The output timeseries from the SWMM model were formatted for the Opti-Tool using a utility tool, *SWMM2Opti-Tool*, available in the Opti-Tool package. The following subsections describe the steps for developing the impervious HRU timeseries for indicator bacteria.

4.2.2 Indicator Bacteria Literature Review

A literature review was conducted to find stormwater related EMCs (MPN[1]/100 ml) and average annual export rates (MPN/ac/yr) for *E. coli* and *Enterococcus* from impervious land cover. Recent journal publications, conference papers, and data from the national stormwater quality database (NSQD) were reviewed to obtain information specific to these types of indicator bacteria. Several published sources of bacteria EMCs from urban areas were identified and summarized. A limited number of observed average annual export rates were found, therefore the literature review was expanded to include published export rates for fecal coliform. The literature review also included an evaluation of previous SWMM models and associated buildup/washoff values for *E. coli* and *Enterococcus*.

Indicator Bacteria Event Mean Concentrations

An EMC is a flow proportional concentration of a pollutant when applied to bacteria it is calculated as the total constituent number of bacteria divided by total runoff volume for a single event. Several physical, biological, and chemical factors can impact the fate and transport of microbes within a watershed, including temperature, moisture, sunlight, nutrients, settling, adsorption/desorption processes, hydrologic processes and predation (Ferguson et al., 2003). While sanitary sewage pollution contamination can contribute to high bacteria concentrations, elevated levels are often observed in areas not impacted by sewage (Shergill and Pitt, 2004). Unsurprisingly, monitoring studies often show tremendous variability in bacteria concentrations (Table 4-1). Figure 4-1 and Figure 4-2 summarize the EMCs for residential, commercial, industrial, and transportation land uses. Residential areas generally had the highest *E. coli* EMCs, followed by commercial, industrial, and transportation. While residential EMS were also relatively high for *Enterococcus*, the highest observed EMC (Stein et al., 2008) was from commercial land. Additionally, transportation had a higher EMC than industrial land uses. However, care should be taken in concluding the relative bacteria loading from different impervious surfaces given the limited and highly variable data. Because of the uncertainty associated with bacteria EMCs, models such as the water treatment model (WTM) use the median urban runoff value for fecal coliform from National Urban Runoff Program (NURP) data (Pitt, 1998) of 20,000 MPN/100 ml as the default model value for bacteria (Caraco, 2013). Table 4-1 presents published EMC for *E. coli* and *Enterococcus* from developed land uses. Values with associated error, designated with a ± in Table 4-1 indicate EMCs reported as a mean of multiple events, potentially from multiple sites of the same land use. EMCs from six studies as well as the NSQD were found for *E. coli.* Only three studies were identified that reported EMCs for *Enterococcus*.

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[1] where, MPN refers to "most probable number". Fecal coliform and E. coli in compost or leachate is usually reported in MPN per g compost or MPN per 100 mL water (or leachate). MPN/100ml is a statistical probability of the number of organisms. Refer to, American Public Health Association, American Water Works Association, Water Environment Federation (2012), Standard Methods for the Examination of Water and Waste Water. Depending on circumstances, US EPA may prefer MPN rather than Colony Forming Units (CFU) (actual plate count) "because a colony in a CFU test might have originated from a clump of bacteria instead of an individual, the count is not necessarily a count of separate individuals." Environmental Regulations and Technology. Control of Pathogens and Vector Attraction in Sewage Sludge (Including Domestic Septage) Under 40 CFR Part 503, EPA/625/R-92/013 (https://www.epa.gov/sites/production/files/2015-04/documents/control_of_pathogens_and_vector_attraction_in_sewage_sludge_july_2003.pdf).

Table 4-1. Observed Event Mean Concentration (EMC) for *E. coli* and *Enterococci* by land use type

	EMC (MPN/100ml)				
Land use	Residential	Recreational	Commercial	location	Source
E. coli	$(3.0 \pm 1.8) \times 10^4$ (Low Residential)	$(5.3 \pm 1.7) \times 10^5$	$(1.1 \pm 0.88) \times 10^4$	CA	Stein, 2008
	$(8.2 \pm 7.7) \times 10^3$ (High Residential)	-	-	CA	Stein, 2008
	2.938×10^3	-	-	NC	Krometis et al., 2009
	$1 \times 10^1 – 3.5 \times 10^4$	-	-	MA	NSQD
	25.671×10^3 (Medium Residential)	-	-	NC	Hathaway and Hunt, 2010
Enterococcus	2.166×10^4	-	-	NC	Krometis et al., 2009
	$(5.5 \pm 3.7) \times 10^4$ (Low Residential)	$(1.4 \pm 0.82) \times 10^5$	$(7.7 \pm 9.2) \times 10^4$	CA	Stein et al, 2008
	$(2.7 \pm 3.6) \times 10^4$ (High Residential)	-	-	CA	Stein et al, 2008
	25.155×10^3 (Medium Residential)	-	-	NC	Hathaway and Hunt, 2010
	18.00×10^3 (Multifamily)		13.00×10^3	MA	Breault et al., 2002
	27.00×10^3 (Single Family)			MA	Breault et al., 2002

	EMC (MPN/100ml)				
Land use	Urban	Industrial	Transportation	location	Source
E. coli	-	$(3.8 \pm 2.3) \times 10^3$	$(1.4 \pm 2.7) \times 10^3$	CA	Stein, 2008
	10.846×10^3	-	-	TN, TX, WA, WI	Schueler, 2000
	15.01×10^3	-	-	NC	McCarthy et al., 2012
	-	-	5	MD	Li and Davis, 2009
	-	-	92	MD	Li and Davis, 2009
	$25.671 \times 10^3 \pm 24.393 \times 10^3$	-	-	NC	Hathaway and Hunt, 2010
Enterococcus	-	$(2.1 \pm 2.2) \times 10^4$	$(8.9 \pm 4.4) \times 10^3$	CA	Stein et al, 2008

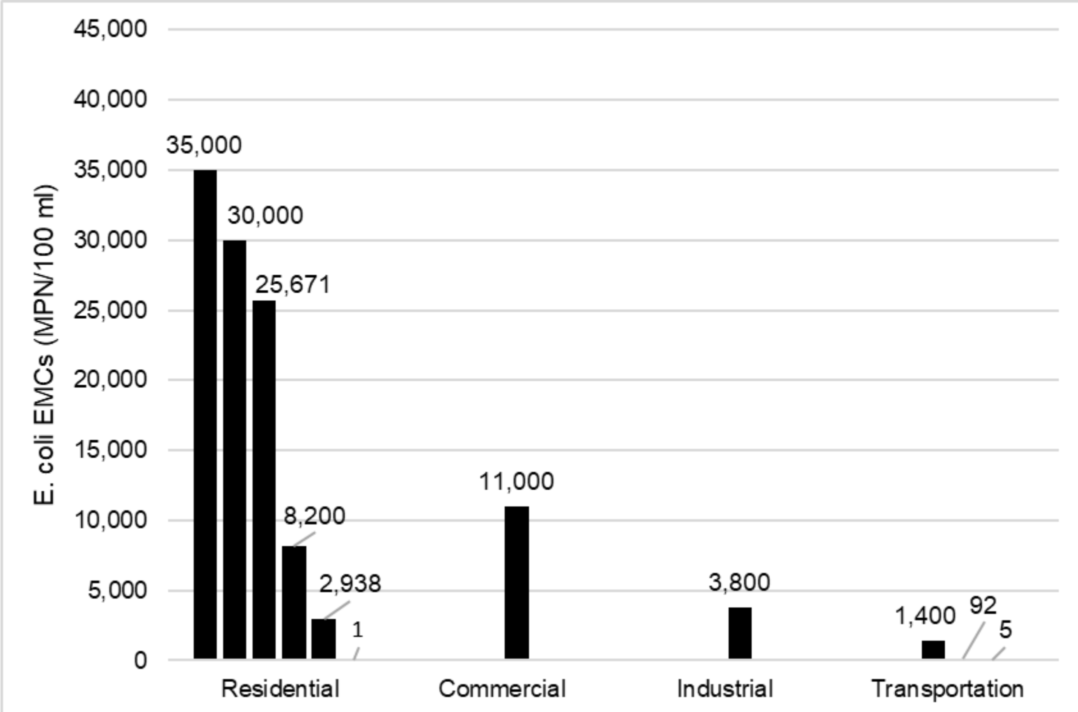

Figure 4-1. Mean observed EMCs for E. coli from literature (See Table 4-1)

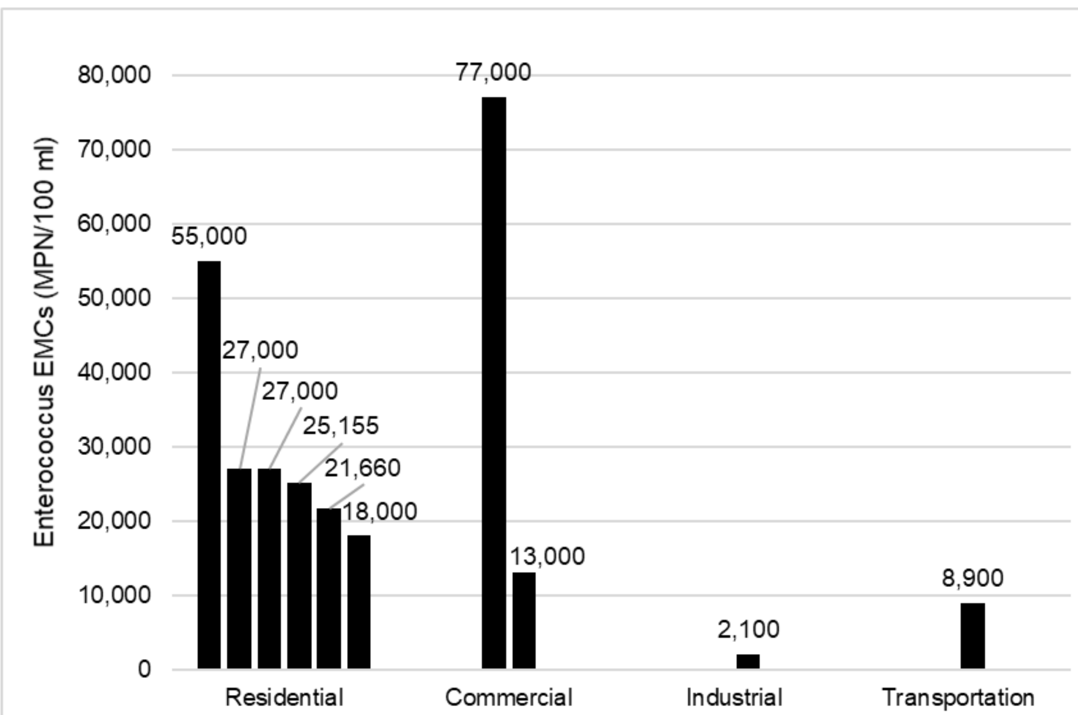

Figure 4-2. Mean observed EMCs for Enterococcus from literature (See Table 4-1)

EMCs for *E. coli* ranged from a low of 5/100 ml from a parking lot (transportation land use) in Maryland (Li and Davis, 2009) to a high of (5.3 ± 1.7) x 10^5/100 ml from recreational land in California (Stein et al., 2008). Hathaway and Hunt (2010) found a mean *E. coli* EMC of 2.5671 x 10^3/100 ml from an urban watershed in Raleigh, North Carolina, although individual samples ranged from 0.71 x 10^3 to 85.233 x 10^3 /100 ml. Additionally, Hathaway and Hunt (2010) found a mean *Enterococcus* EMC of 2.155 x 10^3/100 ml from the same urban watershed, although individual samples ranged from 1.306 x 10^3 to 181.846 x 10^3/100 ml. *Enterococcus* EMCs from urban land uses in California ranged from (8.9 ± 4.4) x 10^3 from transportation to (1.4 ± 0.82) x 10^5 from recreational areas (Stein, 2008).

Indicator Bacteria Export rates

Studies of bacteria export from urban areas relied on stream sampling for estimates. Therefore, there is additional uncertainty associated with applying these rates to areas such as Tisbury, MA where stormwater is not conveyed to a receiving stream or river but is instead discharged directly into a coastal ecosystem. Line et al. (2008) monitored stream concentrations of fecal coliform from industrial and residential sites in North Carolina. Loading from these urban areas ranged from 180,024 to 477,654 million MPN/ac/yr. These values were higher than observed *E. coli* loading estimated in Maryland from a watershed consisting of medium-to-high density residential and open urban land uses resulted (EA Engineering, 2010) (Table 4-2). CDM (2012) estimated loading from several sites in Boston's municipal separate storm sewer system (MS4). Export was highly variable, *E. coli* ranged from 22 billion CFU/ac/yr to 1.4 trillion CFU/ac/yr. Site imperviousness ranged from 25% to 94%, although the loading estimates did not distinguish between urban land use types.

Indicator Bacteria Buildup/Washoff Values

The pollutant buildup and washoff functions in SWMM are similar to the equations developed for the accumulation and washoff of dust and dirt on street surfaces (APWA, 1969; Sartor et al., 1974). Previous applications of SWMM to simulate the buildup and washoff of *E. coli* and *Enterococcus* were reviewed and summarized. Two studies were identified, one for Boston's MS4 (CMD Smith, 2012) and another for the city of Lakewood, Ohio (CT Consultants, 2016). Both studies relied on local bacteria monitoring data to calibrate the models. The calibrated parameter values for both studies are presented in Appendix G.

Table 4-2. Observed Bacteria Loading from urban areas

	Land use	Billion MPN/ac/yr	Source
Fecal Coliform	Urban	190.024 – 477.654	(Line et al, 2008)
E. coli	Open Urban	13.789 – 60.482	(EA Engineering, 2010)
	Residential/Commercial	9.00 – 3.80	
	Various	22 - 1,397	CDM Smith, 2012*
Enterococcus	Various	64 – 930	CDM Smith, 2012*

*Units in CFUs, not MPN

Buildup in SWMM can occur as either a mass per unit of the sub catchment area or per unit of curb length (Rossman, 2010). The amount of buildup is a function of antecedent dry weather days. The user can choose a power, exponential, or saturation function to compute buildup, or use an external time series to describe the rate of buildup per day as a function of time (Rossman, 2010). CMD Smith (2012) used an exponential buildup and a rate constant (1/days) of 2, which is equivalent to 0.3 days to reach ½ max buildup. Alternatively, CT Consultants (2016) used the saturation function and a value of 10 days to reach ½ max buildup. The exponential function builds up pollutants very rapidly, then slows down to the maximum value while the saturation function has a less rapid buildup and a more gradual approach to the maximum value. Additionally, CMD Smith (2012) also added a term to represent bed load growth of bacteria to account for the potential for rapid population changes within the collection system, although this had minimal impact on overall model results.

SWMM can simulate washoff on user-defined land use categories using exponential, rating curve, or EMC functions. Exponential functions have been used to describe the washoff of dust and dirt from the streets

(Sartor et al., 1974). SWMM relies on user defined values for washoff coefficients and exponents, the runoff rate per unit area and the pollutant buildup in mass units to calculate exponential washoff. Both CDM Smith (2012) and CT Consultants (2016) used the exponential function to simulate washoff, with coefficients ranging from 10 to 18 and exponents ranging from 0.5 to 2.2.

Conclusions from Indicator Bacteria Literature Review

Results of studies on the export of bacteria from urban watersheds had highly variable results; observed EMCs range over orders of magnitude. Fewer studies evaluated *Enterococcus* than *E. coli* and limited data was found on observed bacteria loading from urban areas. Previous studies using SWMM to model bacteria buildup and washoff relied on both exponential and saturation buildup functions. Using functions originally developed for the buildup and washoff of dust and dirt on streets to simulate the export of organisms is a simplified approach to a complex phenomenon. Several factors that can influence the propagation and die-off of bacteria in a watershed are necessarily omitted. For any bacteria export modeling effort, robust local monitoring data can help to inform model calibration and increase confidence in modeling results.

4.2.3 HRU SWMM Model for Indicator Bacteria (Initial Setup and Run)

Local climate data (Section 2.1) was used to update the boundary conditions in the Opti-Tool HRU SWMM model. Buildup/wash off parameters for modeling indicator bacteria load on the impervious HRU was initially set to the calibrated parameters used for Boston's MS4 (CMD Smith, 2012). The model output timeseries were used to statistically summarize the predicted indicator bacteria EMC distributions and average annual pollutant export rates. For further analysis, box and whisker plots and bar graphs were created to compare these model timeseries to literature values.

4.2.4 HRU Timeseries for Indicator Bacteria (Hourly Flow and Bacteria Concentration and Load Estimates)

SWMM model output timeseries were structured into the required format for the SUSTAIN model using a spreadsheet-based utility tool, SWMM2Opti-Tool, available in Opti-Tool (Figure 4-3). The HRU timeseries format for the Opti-Tool is identical to the format needed in SUSTAIN (the Opti-Tool uses the SUSTAIN model as a backend GI simulation engine).

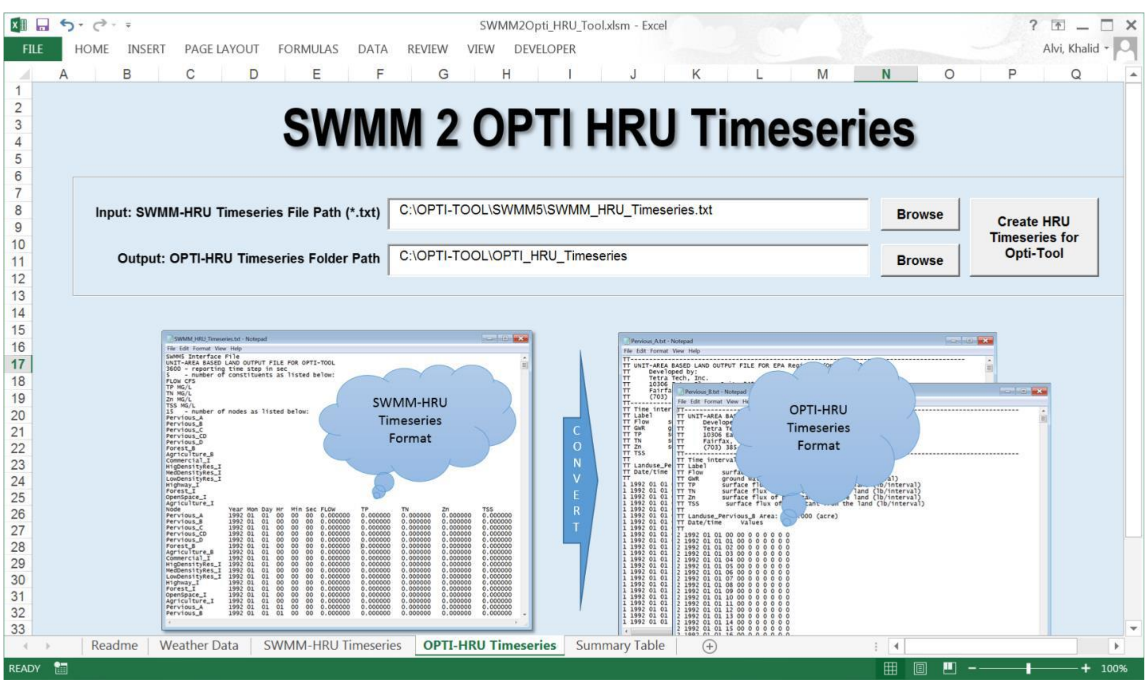

Figure 4-3. The user interfaces for SWMM2Opti-Tool, a utility to reformat SWMM output to Opti-Tool HRU timeseries.

Figure 4-4 and Figure 4-5 present simulated *E. coli* and *Enterococci* concentrations, respectfully, based on the calibrated buildup/washoff values from CDM Smith (2012). Bacteria concentrations were highest from residential land uses and lowest from transportation. These results are reflective of the maximum buildup values attributed to each land use (Appendix G) Maximum buildup for residential land uses was set to 85.6 x 10^9 MPN/acre while the maximum buildup on transportation land uses was set to 0.001 x 10^9 MPN/acre. Sources of *E. coli* and *Enterococcus* include both human and animal sources. Therefore, it is not surprising that bacteria export is lower from transportation land uses than from other land uses where it is more likely to find warm-blooded animals interacting with the land surface. Additionally, this pattern is representative of the EMCs presented in Figure 4-1. The median simulated *E. coli* concentration from residential areas of 33,651/100ml is similar to observed EMCs found in the literature. Based on NSWD data, the highest *E. coli* EMC from residential land uses in Massachusetts was 35,000 MPN/100ml. Relatively high EMCs were also observed by Stein (2008) who found *E. coli* EMCs of 30,000 ± 18,000 MPN/100ml from residential areas in California. Simulated concentrations of *Enterococcus* were generally lower than observed EMCs presented in Figure 4-5. Data from Breault et al. (2002) was included in Figure 4-5 since median and upper and lower quartiles were reported and therefore allowed for visual comparison with the distribution of the simulated data. Observed values included data from single family and multifamily residential land uses as well as the entire Charles River Watershed. The median simulated concentration for residential land use was 10,456 MPN/100ml, which was lower than the median observed values. The lowest observed EMC was 13,000 CFU/100 ml observed in the Charles River watershed (Breault et al., 2002) while the highest was 55,000 ± 37,000 CFU/100 ml (Stein et al., 2008).

Figure 4-6 and Figure 4-7 present simulated *E. coli* and *Enterococci* unit area loading, respectfully, based on the calibrated buildup/washoff values from CDM Smith (2012). The values are generally in good agreement with observed data. The mean simulated *E. coli* unit area loading ranged from 0.32 to 1,753 billion/ac/yr while CDM Smith (2012) observed an *E. coli* export of 22 - 1,397 billion/ac/yr from Boston's MS4. Simulated *Enterococcus* unit area loading ranged from 0.04 to 544.84 Billion/ac/yr, while observed loading from the Boston's MS4 ranged from 64 – 930 Billion/ac/yr (Table 4-2). The unit area loadings for bacteria show the same trend as the concentrations. For example, *E. coli* has the highest concentrations and loadings from residential land uses, followed by industrial, commercial, then transportation. This is expected given that loading was calculated as concentration multiplied by volume. While the four land uses have different build up and washoff values for bacteria, they all represent an impervious surface which converts the same amount of rainfall to runoff. The same stormwater volume applied to different concentrations will result in the same pattern of loading compared to concentration.

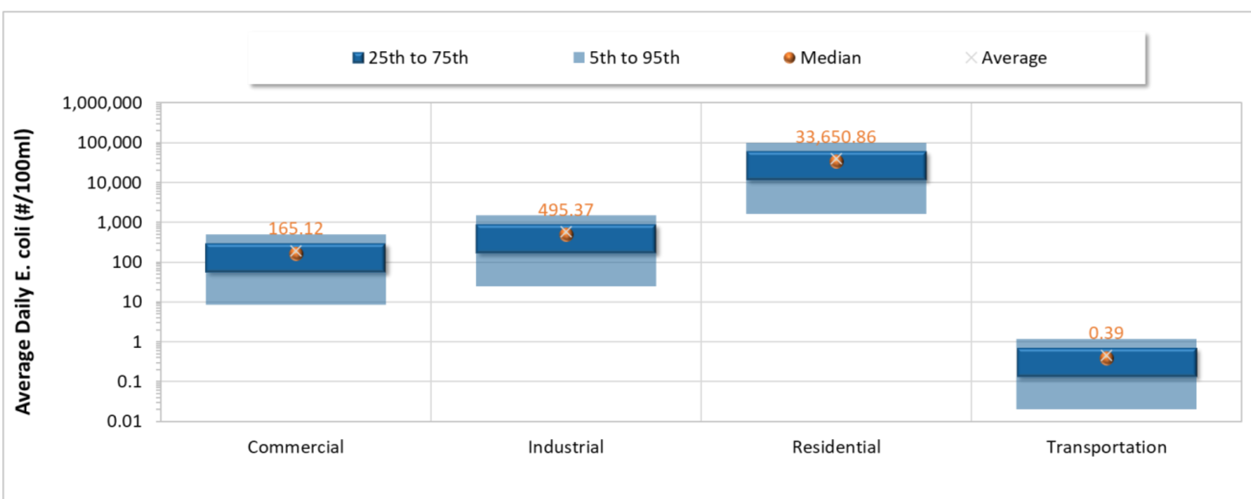

Figure 4-4. Simulated average daily *E. coli* concentrations from developed land uses in Tisbury, MA for the period

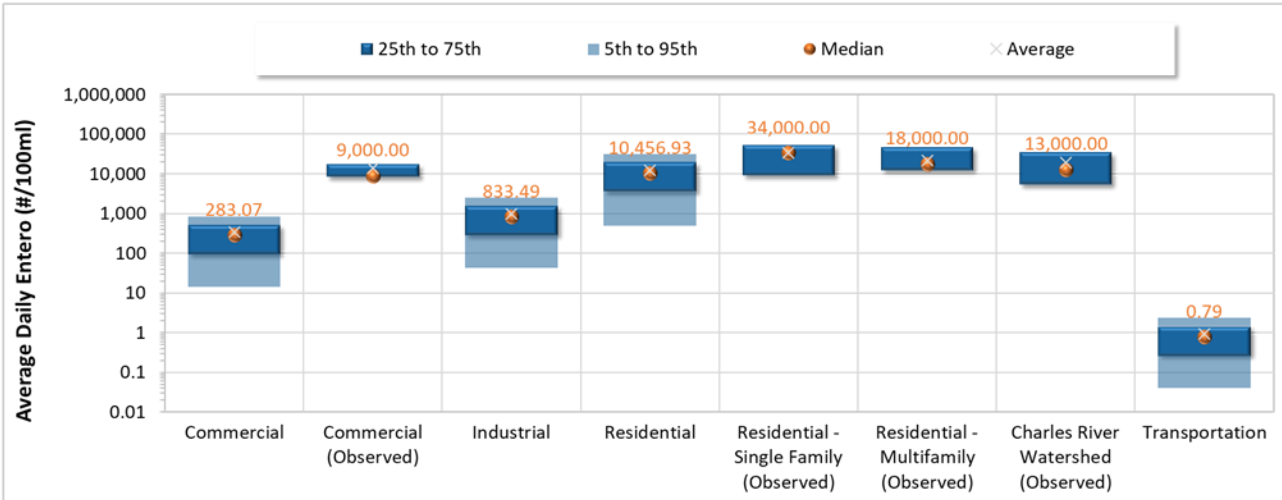

Figure 4-5. Simulated average daily Enterococci concentrations from developed land uses in Tisbury, MA for the period 1998-2018. (Observed data source: Breault et al., 2002)

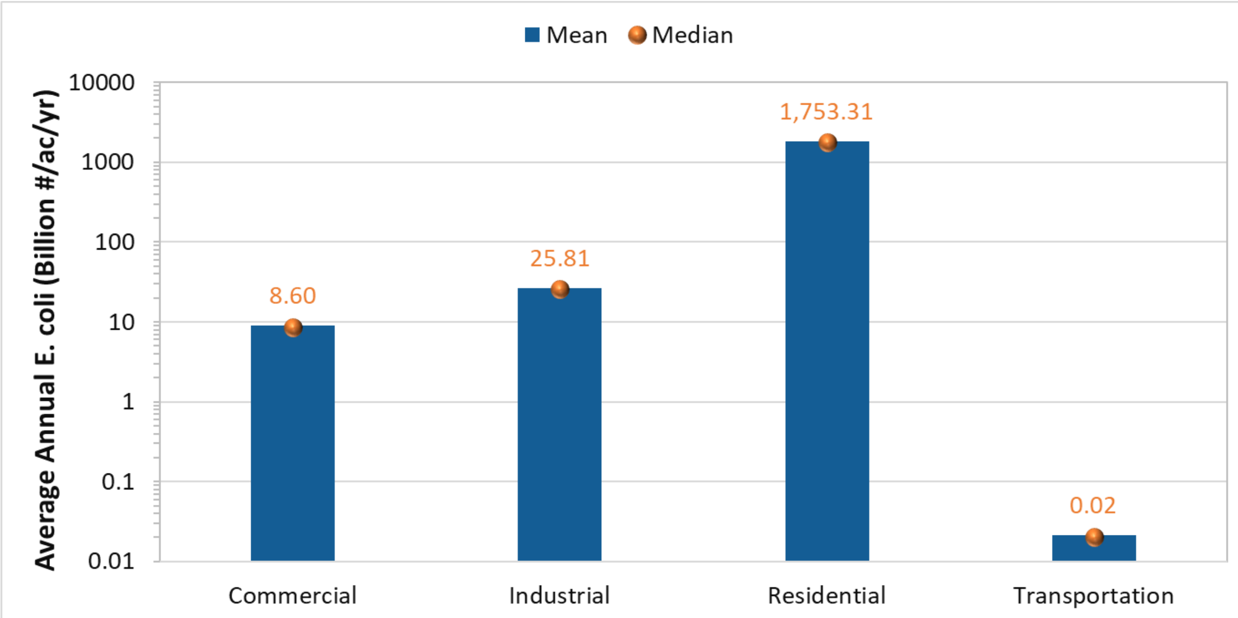

Figure 4-6. Average annual *E. coli* export from developed land uses in Tisbury, MA for the period 1998-2018.

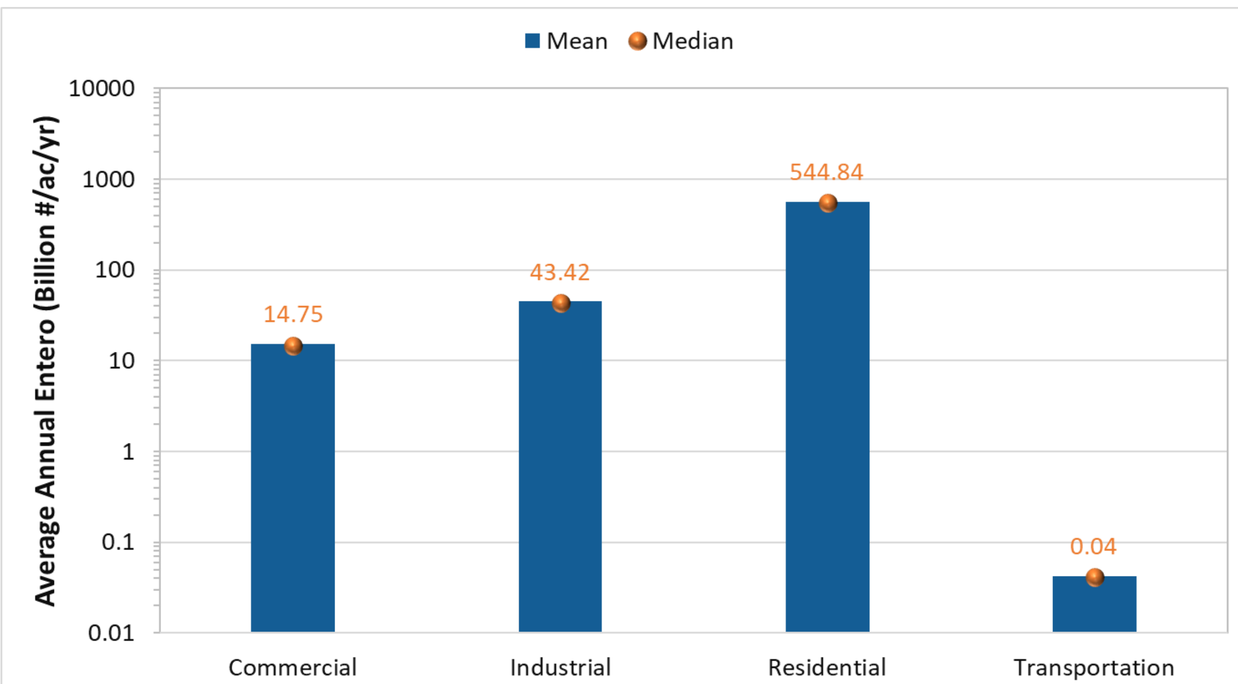

Figure 4-7. Average annual *Enterococcus* export from developed land uses in Tisbury, MA for the period 1998-2018.

4.2.5 SCM Performance Curves for Indicator Bacteria

The Opti-Tool previously included SCM performance curves (U.S. EPA. 2010) for estimating the cumulative pollutant load reductions from infiltration, filtration, and detention practices for nutrients (TP, TN), sediments (TSS) and Zn. The Opti-Tool performance curves for indicator bacteria were developed for the SCM types shown in Table 4-3. The SCM efficiencies for *E.coli* and *Enterococcu*s in Table 2-5 are based on an analysis of published data presented in Table 4-4. Since some of the SCMs used in Opti-Tool did not have published information on their bacteria load reduction efficiencies, it was necessary to equate the SCMs without data to those that did in Table 4-4. For example, the efficiencies attributed to Infiltration Basin, Infiltration Trench, and Sand Filter in Table 4-3 are based on data for media filters (Table 4-4) obtained from the International Stormwater BMP Database (Clary et al., 2017). Additionally, only three studies with SCM efficiencies of *Enterococcu*s were identified. Due to insufficient data, efficiencies for *E. coli* were used for *Enterococcu*s. Since removal efficiencies were assumed to be identical, only curves for *E. coli* were developed.

Table 4-3. SCM types and associated removal efficiencies for developing indicator bacteria performance curves

SCM Type	Underdrain Option	*E. coli* Efficiency	*Enterococcus* Efficiency	Major Processes for Bacteria Removal
Biofiltration	Yes	0.76	0.76	Adsorption, filtration
Biofiltration with ISR	Yes	0.76	0.76	Adsorption, filtration
Dry Pond	No	0.64	0.64	Settling
Infiltration Basin	No	0.76	0.76	Adsorption, filtration
Infiltration Trench	No	0.76	0.76	Adsorption, filtration
Sand Filter	Yes	0.76	0.76	Filtration
Subsurface Gravel Wetland	Yes	0.60	0.60	Adsorption, filtration
Wet Pond	No	0.96	0.96	Settling

Table 4-3 includes the major processes that are assumed to be responsible for bacteria removal. However, the major mechanisms which remove bacteria in SMCs are not fully understood. While dominant removal processes include settling, filtration and adsorption, there are other biological and physical processes occurring in SCMs that may reduce bacteria concentrations as well as increase them. Settling is likely the dominant removal process occurring within the water column. Bacteria may enter a SCM 'free', existing as individual organisms/groups, or maybe associated with particles. Bacteria attached to denser particles will tend to settle out of the water column more quickly than free phase organisms or those associated with less dense, more mobile particles. Characklis et al. (2005) found that an average of 30-55% of *E. Coli* and *Enterococcus* organisms were associated with settleable particles in stormwater samples. *E. coli* is a rod-shaped bacteria with a diameter ranging from 2-6 µm and a length ranging from 1.1-1.5 µm. Within porous soil media, adsorption is likely a major removal mechanism due to the small size of *E. coli* (Lan et al., 2010). Sorption rates can be affected by several factors, including media texture, organic matter, temperature, flow rate, ionic strength, pH, hydrophobicity, chemotaxis and electrostatic charge (Stevik et al., 2004). Temperature has also been cited as an important environmental factor for bacteria die-off, with increasing temperatures associated with higher removal rates (USEPA, 2006). Additionally, sun exposure can result in increased pathogen inactivation and removal through treatment by ultraviolet light.

The wet, nutrient rich environments found in many stormwater SCMs can limit their ability to reduce bacteria loading (Hathaway et al., 2008). Rusciano and Obropta (2007) found viable bacteria retained in the soil substrate of a bioretention column 36 days after performing the last stormwater simulation. SCMs can result in increased bacteria concentrations, indicated by negative values in Table 4-4. Performance data of infiltration SCMs only represents removal processes that occur within the infiltration SCM as filtered runoff is captured by an underdrain to assess the performance of an in-system removal. Consequently, these data do not reflect the additional removal accomplished as exfiltrate flows through subsoils beyond the performance monitoring collection system. Runoff events that are completely captured and infiltrated achieve 100% removal of bacteria.

Unpublished research (Houle, et al., 2014) evaluated SCMs in New Hampshire whose primary treatment mechanisms included settling, enhanced settling using a hydrodynamic separator, and filtration. The results suggest SCMs using conventional settling techniques were often a source of bacteria, having higher outflow concentrations compared to inflow, especially during summer months when concentrations were highest and conditions for regrowth are most favorable. The study also found that systems using filtration and infiltration performed better, generally having lower concentrations in the outflow compared to inflow. Periods of high influent flow rates can cause turbulent conditions within SCMs, resuspending sediment and associated bacteria, resulting in possible increases in effluent concentrations. Sediment resuspension is more likely to occur in SCMs that are poorly designed, not well maintained, or have reached their design life (EPA, 2006). Zarriello et al (2002) estimated the effect of SCMs and street sweeping on reducing fecal coliform in the Lower Charles River, MA watershed. The SCMs treated runoff depths ranging from 0.25 to 1.0 and had a median removal efficiency for fecal coliform of 13%.

Bioretention areas, wet ponds, and infiltration-based SCMs appear to be the most effective at reducing bacteria concentrations (Table 4-4). EPA (2006) found that settling was a contributing but not a primary factory in bacteria removal and that bacteria concentrations decreased with time in a constructed wetland and dry pond. Bacteria load reduction may be higher in SCMs which limits the opportunity for sediment resuspension, such as infiltration based SCMs.

4.2.6 SUSTAIN SCM Model for Indicator Bacteria Curves (Setup and Run)

After the literature review was completed, the SCM performance curves were developed using based on observed data and previously calibrated model parameters identified in the published material. The SUSTAIN GI module is a process-based continuous simulation model that requires two performance parameters to estimate cumulative load reduction: 1) a first-order decay rate in the ponded water column and 2) an underdrain pollutant removal rate to account for the filtration mechanism. These parameters were adjusted to predict SCM performance comparable to SCM efficiency numbers reported in the literature. A value of 0.1 was used as a default decay rate for *E.coli* for all SCMs. The model output timeseries were summarized into average annual pollutant loads with and without SCM simulation to estimate long-term pollutant load reductions. The SCM scenarios for a wide range of storage capacities, up to 2 inches of runoff depth from the impervious area, were developed for each SCM type listed in Table 4-3. Three hundred and sixty SCM simulation scenarios for 8 SCM types and a range of infiltration rates for infiltration-based SCMs were developed and a continuous hourly flow and pollutant load simulation for 21 years was performed. Each SCM was sized to have a physical capacity to instantaneously store 20 runoff depths ranging from 0.1 to 2.0 inches from a 100% impervious drainage area. A wilting point of 0.01 was included in the representation of each SCM's soil layer to account for unavailable storage due to strongly retained water.

4.2.7 SCM Performance Curves (Storage Capacity versus Pollutant Load Reduction)

The SUSTAIN model output for each scenario was processed to estimate the indicator bacteria load reduction for modeled storage capacity to develop performance curves for SCMs listed in Table 4-3. For comparison, Opti-Tool *E. coli* performance curves for a dry pond and an infiltration trench with an infiltration rate of 8.27 in/hr are shown in Figure 4-8 and Figure 4-9, respectively. A full set of curves for a range of SCMs and infiltration rates is presented in Appendix H. Table-H-1, Table-H-2, and Table-H-3 contain the tabular data for the curves. The infiltration practices were the most effective SCMs for bacteria load reduction due to the infiltration mechanism of water loss through background soil. The wet pond was the least effective due to the bottom sealed without any infiltration loss from the available storage. The performance curves reflect the effectiveness of infiltration techniques compared to ones relying on settling and filtration mechanisms. Appendix I shows SCMs design specifications modeled in the Opti-Tool to develop the performance curves. Appendix J shows methods for determining stormwater control design volume for using the SCMs performance curves and provides a crosswalk between stormwater control types and the SCMs available in Opti-Tool.

Table 4-4. Observed SCM efficiencies for E. coli and Enterococcus

	SCM with published efficiency data							Location	Source
	Bioretention	Grass swale	Dry detention	Media Filter	Wet Pond	Wetland	Wetland/ Retention Pond		
	Opti-Tool equivalent								
	Biofiltration Biofiltration with ISR	NA	Dry Pond	Infiltration Basin/Trench, Sand Filter	Wet Pond	Subsurface gravel wetland	Wet Pond		
E. coli	0.71							NC	Hunt et al., 2008
	0.48 – 0.97							TX	Kim et al., 2012
	0.72 – 0.97							Laboratory & synthetic stormwater	Zhang et al., 2011
	0.71		0.05 - 0.14		0.18	0.22-0.92		North Carolina	Hathaway et al. 2008
	0.80	-0.26	0.64*	0.76*	0.96	0.64	0.80 – 0.96	National	Clary et al., 2017
Enterococcus	-0.76 – 0.01				0.49	0.06-0.93		NC	Hunt et al., 2008
			0.63			0.61	0.78	National	Clary et al., 2017
		-0.60	-1.96			0.21	0.78	NH	Houle et al., 2014 unpublished

*Data for fecal coliform

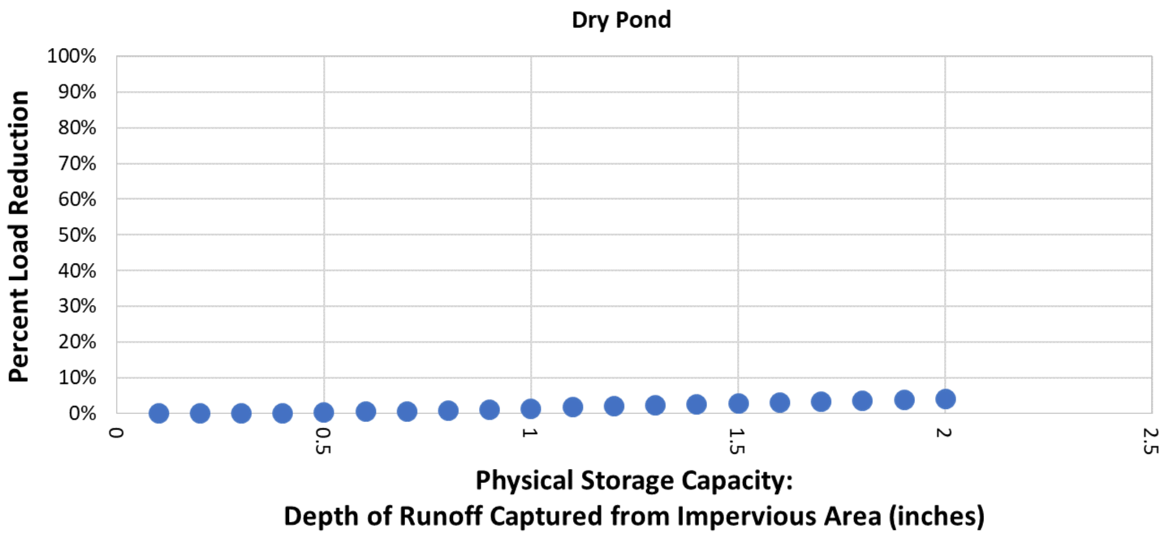

Figure 4-8. Dry Pond performance curve for annual average E. coli load reduction.

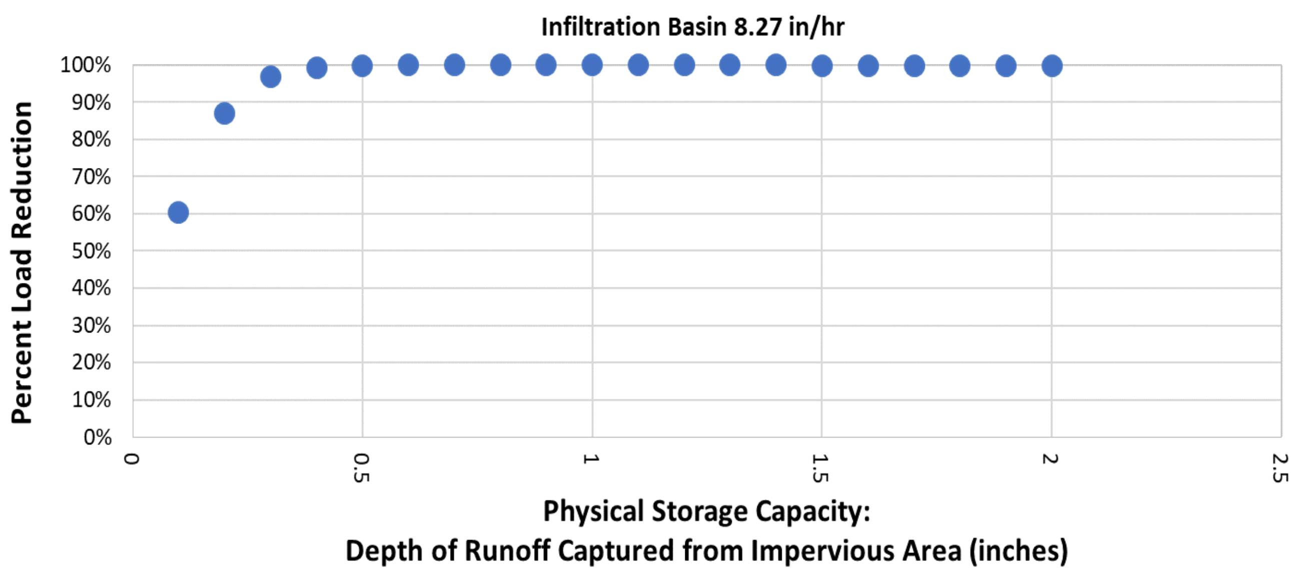

Figure 4-9. Infiltration Basin (8.27 in/hr) performance curve for annual average E. coli load reduction.

4.3 Discussion of Management Metrics

To increase the capacity of a municipality to implement GI SCM and adopt the approach into land use decision making, the benefits must be clearly communicated to town officials as well as the public. Therefore, management metrics were used that relayed the benefits of GI SCM-based stormwater management using units that were easily understood such as gallons, pounds, acres, days and dollars (Table 4-5). Additionally, hydrographs and performance curves were used as visual aids to help demonstrate the benefits of GI SCM implementation.

Table 4-5. Summary of Management Metrics

Description	Unit
Flow volume capture	gallons/yr
TN load removed	lbs/yr
Disconnected impervious cover	acres
Unit Cost	$/gallon; $/lb TN
Discharge days eliminated	Days

4.4 Outfall Strategy Analysis & Modeling

Opti-Tool (U.S. EPA, 2016) was used to evaluate stormwater quantity and quality at two outfalls in Tisbury, MA under existing conditions and the expected benefits of GI SCM implementation in the outfalls drainage areas. The outlet study used the Opti-Tool Implementation Level Analysis which allows users to apply the SUSTAIN optimization engine to estimate SCM performance and obtain optimization results to provide cost-effective SCM sizing strategies. The approach was supported by a rainfall analysis that assessed the number of discharge-producing days that could be eliminated by capturing and infiltrating surface runoff through implementing GI SCM opportunities for a range of storm sizes. The study demonstrated that distributed GI SCM practices can provide cost-effective solutions that achieve volume and load reduction targets while also effectively integrating within urbanized landscapes. An analytical framework and summary metrics are provided which can be readily customized and applied in other settings to inform stormwater management planning efforts. A comparison of flow volumes, flow duration curves, and total nitrogen (TN) loads delivered at the two selected outfall locations before and after the implementation of GI SCM opportunities is presented. Cost-effectiveness curves were created to visualize the level of investment needed to obtain a range of flow volume and TN load reductions. Summary tables present the optimal level of SCM implementation for various land uses.

Summarized study results are presented in Table 4-6. The results suggest that GI SCM practices can infiltrate approximately 50.7 million gallons of stormwater volume within the combined catchments of outfall #2 and #7 (129 acres) if sizing those infiltration practices to capture 0.35 inches of runoff from the impervious cover. This equates to an 80% reduction in annual stormwater volume compared to existing, baseline conditions. The total estimated cost to achieve this overall reduction in both outfalls was approximately $1,160,000. This cost represents an optimization goal of reducing stormwater volume. The solution would achieve a co-benefit of approximately 90% reduction in TN. Additionally, assuming a moderate infiltration rate of 1.02 in/hr (U.S. EPA, 2019a), the optimized solution would also result in a 62%-75% reduction in average annual bacteria loading. The estimated cost for flow volume reduction was $0.02 per gallon for both outfalls. The implementation of GI SCM practices was also optimized for TN reduction, a target solution that achieved a 91% reduction in loading would also have the co-benefit of achieving an 80% reduction in annual stormwater volume. The estimated cost to achieve this overall reduction in both outfalls was approximately $1,174,000. Cost estimates assume no cost-sharing or use of town labor and equipment, which could help lower costs. The costs for TN load reduction varied by outlet, the cost for removing a pound of TN was between $1,700 and $2,000. While actual costs may vary depending on local conditions, the cost estimates provide a useful comparison of relative differences in optimization scenarios. Overall, it appears that an optimized solution that focuses on either stormwater volume or TN load reduction can achieve similar reductions for both benefits for approximately the same costs.

Table 4-6. Summary of Analyses Results for Tisbury, MA Outlets #2 and #7,

	Outfall #2	Outfall #7
Baseline Average Flow Volume (gallons/yr)	23,193,061	40,174,307
Baseline Average TN Load (lbs/yr)	261.87	420.63
Flow Volume Removed (gallons/yr)	18,551,813	32,192,534
TN Load Removed (lbs/yr)	233.27	386.14
Cost per Gallon Flow Removed ($)	$0.02	$0.02
Cost per Pound TN Removed ($)	$1,727	$1,996
Total Cost	$406,122	$753,076

Strategically optimizing the selection and placement of distributed SCMs within highly urbanized settings through continuous simulation can help to develop management strategies that are more cost-effective than the traditional approach of sizing SCMs at fixed locations to treat a design storm. The flood mitigation benefits of GI SCM are especially valuable in urbanized areas with poor stormwater transmission where even relatively small storms can result in flooding. The relatively small size of distributed GI facilities substantially increases the feasibility of treating runoff from impervious surfaces in constrained developed spaces and achieving meaningful water quantity and quality benefits. This application of Opti-Tool demonstrates that relatively small GI facilities and SCMs can provide a cost-effective stormwater management approach in an opportunity-limited, urban setting like Tisbury, MA. Additionally, this study highlights the value of conducting strategic planning to address stormwater impacts for achieving multiple water resource goals. The results of this study are based on an assessment of a twenty-one-year time series of simulated overland flow. The modeling focused on watershed-scale hydrologic processes including the conversion of rainfall to runoff and the capture and infiltration of that runoff. The modeling did not include an explicit representation of Tisbury's stormwater conveyance network, therefore hydraulic processes such as transportation losses and pipe surcharge are not simulated. Despite these limitations, the modeling provides valuable insight into the existing conditions in Tisbury and the potential benefit of GI SCM opportunities.

4.4.1 Rainfall Analysis for Tisbury gauge

Green infrastructure and SCM opportunities can be built to capture a range of storm sizes. Before running an Opti-Tool-based optimization, a simplified, spreadsheet-based analysis was conducted to assess the potential benefits of implementing GI SCM opportunities over a range of sizes designed to capture runoff depths ranging from 0.1 to 2.0 inches.

A twenty-one year (Jan 1998 – Dec 2018) hourly precipitation timeseries were analyzed to determine the average annual number of daily precipitation events and their respective depths to assess the benefits of implementing GI SCM opportunities of various sizes (Section 2.1). Table 4-7 shows the number of precipitation days that can be captured by implementing infiltration GI SCM opportunities over a range of sizes. Since over 50% of annual events are 0.1 inches or less in-depth, sizing infiltration GI SCM opportunities throughout the community to capture 0.1 inches of runoff can be expected to reduce the number of discharge days by the same amount.

The rainfall analysis provides important results at the conceptual level that highlight the benefit of implementing small, distributed GI SCM. The analysis is especially applicable in communities where occurrences of flooding, algal blooms, and bacteria-related beach closings may occur multiple times a year. For Tisbury, implementing relatively small infiltration systems designed to capture 0.2 inches is estimated to eliminate 66% of the days that would have otherwise resulted in stormwater discharge. The results also provide a strong foundation on which additional analyses using Opti-Tool optimization and continuous simulation can provide further insights into the benefits of GI SCM implementation.

Table 4-7. The number of storms captured/retained and percent of discharge days eliminated with infiltration SCMs of various sizes.

Infiltration SCM Size to Capture Runoff Depth from Impervious Surfaces (in.)	Captured Number of 24-hour Storms (per year)	% Number of Discharge Days Eliminated (per year)
0.1	73	54%
0.2	88	66%
0.3	98	73%
0.4	105	78%
0.5	110	82%
0.6	114	85%
0.7	118	88%
0.8	120	90%
0.9	123	92%
1.0	125	93%
1.1	126	94%
1.2	128	96%
1.3	129	96%
1.4	129	96%
1.5	130	97%
1.6	131	98%
1.7	131	98%
1.8	132	99%
1.9	132	99%
2.0	132	99%

4.4.2 Outfalls (#2 and #7) Catchments Characteristics

The study areas were adjacent catchments draining to two stormwater outfalls (Figure 4-10) in the town of Tisbury MA. The sub-catchments to each catch basin within the study area were auto-delineated using 1-meter high-resolution elevation data in ArcGIS software (Figure 4-11). The outfalls are located off the shore of the municipality. The catchments varied in size and land cover. The area distribution for Hydrologic Response Units (HRUs), unique land segments with an attribute of land use, land cover, soil, and slope combinations, in these two catchments is shown in Table 4-8. The catchment draining to outfall #2 was approximately 66% impervious surfaces, while the larger catchment draining to outfall #7 was approximately 40% impervious surfaces (Table 4-9). The previously completed Task 4B memo (U.S. EPA, 2019b) provides a detailed discussion on the development of Hydrologic Response Units (HRUs) for the area, including summary figures of hydrologic soil groups, land use, land cover, and slope in the area.

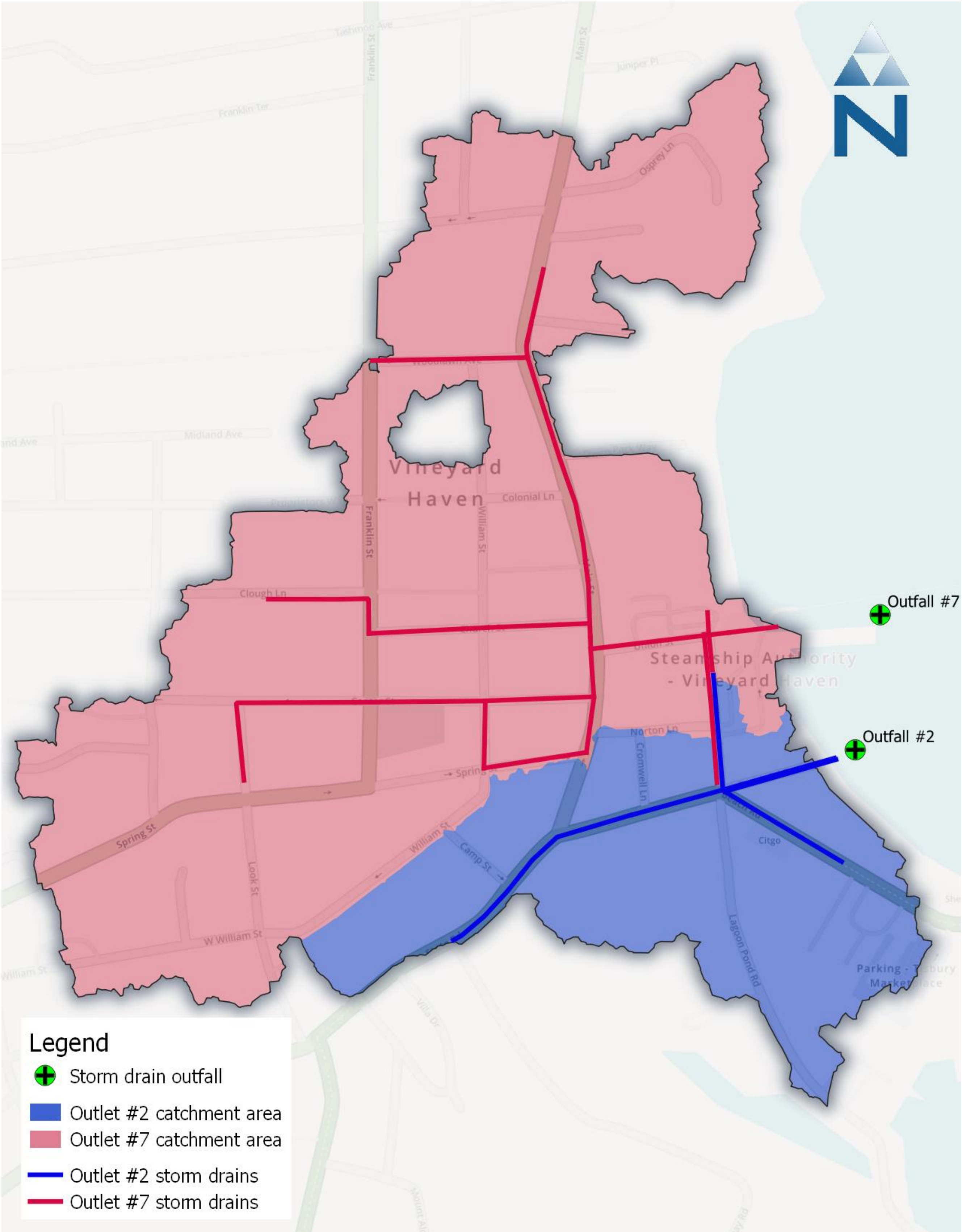

Figure 4-10. Storm drains, outfalls, and catchment areas

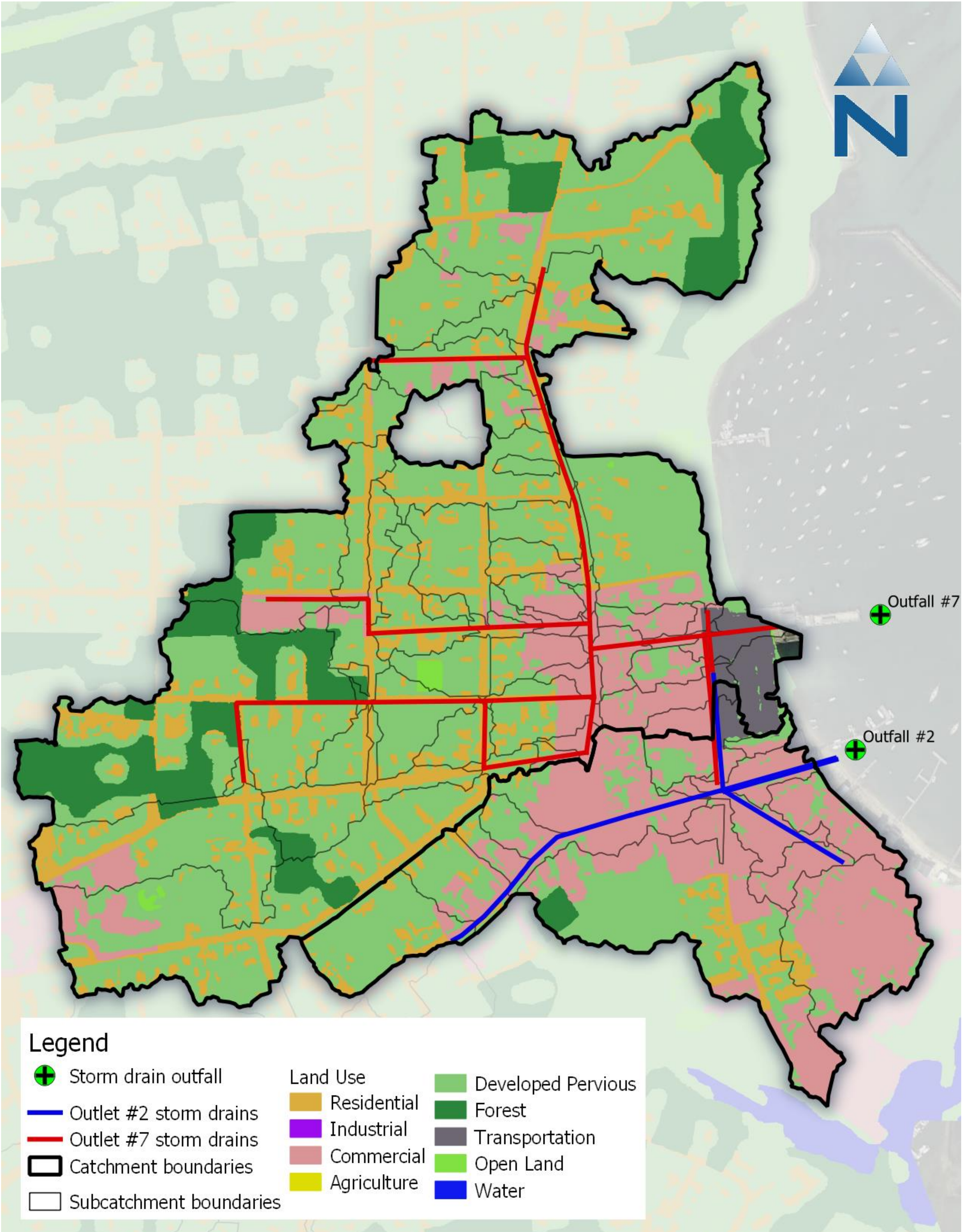

Figure 4-11. Sub-catchment delineation and major land use in the drainage areas to outfall #2 and #7.

Table 4-8. HRU area distribution in drainage catchments to selected two outfall locations.

HRU	Land Use	Catchment Area (acres)		
		Catchment #2	Catchment #7	Total
1001	Forest	0.060	1.611	1.670
2001	Agriculture	-	-	-
3001	Commercial	17.973	11.378	29.352
4001	Industrial	-	-	-
5001	Low Density Residential	-	-	-
6001	Medium Density Residential	2.010	21.760	23.770
7001	High Density Residential	0.918	0.900	1.818
8001	Transportation	0.473	1.937	2.410
9001	Open Land	0.002	0.449	0.451
11110	Developed Pervious-A-Low	1.118	18.037	19.156
11120	Developed Pervious-A-Med	2.336	22.628	24.963
11130	Developed Pervious-A-High	0.935	6.880	7.814
11210	Developed Pervious-B-Low	-	-	-
11220	Developed Pervious-B-Med	-	-	-
11230	Developed Pervious-B-High	-	-	-
11310	Developed Pervious-C-Low	4.390	0.476	4.866
11320	Developed Pervious-C-Med	1.634	0.490	2.123
11330	Developed Pervious-C-High	0.429	0.115	0.545
11410	Developed Pervious-D-Low	0.000	0.006	0.006
11420	Developed Pervious-D-Med	-	0.033	0.033
11430	Developed Pervious-D-High	-	0.010	0.010
12110	Forest Pervious-A-Low	0.069	3.402	3.470
12120	Forest Pervious-A-Med	0.116	4.480	4.596
12130	Forest Pervious-A-High	0.079	1.745	1.824
12210	Forest Pervious-B-Low	0.020	-	0.020
12220	Forest Pervious-B-Med	0.012	-	0.012
12230	Forest Pervious-B-High	-	-	-
13110	Agriculture Pervious-A-Low	-	-	-
13120	Agriculture Pervious-A-Med	-	-	-
13130	Agriculture Pervious-A-High	-	-	-
13210	Agriculture Pervious-B-Low	-	-	-
13220	Agriculture Pervious-B-Med	-	-	-
13230	Agriculture Pervious-B-High	-	-	-
Total Area		32.573	96.336	128.908

Table 4-9. Pervious and impervious areas for catchments draining to outfalls #2 and #7

	Total Area (acres)	Impervious Area (acres)			Pervious Area (acres)
		Roofs	Other Impervious	Total Impervious	
Outfall #2 Catchment	32.6	6.2 (19.0%)	15.2 (46.8%)	21.4 (65.8%)	11.1 (34.2%)
Outfall #7 Catchment	96.3	12.4 (12.9%)	25.6 (26.6%)	38.0 (39.5%)	58.3 (60.5%)

4.4.3 Technical Approach

Stormwater Management Categories

Spatial data analyses were previously conducted (U.S. EPA, 2018) to characterize watershed features and identify the corresponding stormwater management categories that were suitable for application with the Opti-Tool for the two outfall catchments. The GIS data used for the evaluation of stormwater management categories for the Tisbury catchments included: land use coverage, impervious cover, Hydrologic Soil Group (HSG), and LiDAR-derived Digital Elevation Model (DEM) for ground slopes. All data are from Massachusetts GIS (MassGIS) data layers.

Table 3-2, presented previously, shows the siting criteria used for all potential GI SCM opportunities in Tisbury, which were derived from GIS analysis. Based on the dominant HSG of 'A' within the two catchments, the assessed GI SCM opportunities all fell under the "infiltration" management category (Figure 4-12). For this pilot study, it was assumed that rooftops could be disconnected by redirecting their runoff to infiltrations trenches, while all other types of impervious areas, such as roads and driveways, could be disconnected by diverting their runoff to infiltration basins. Both public and private property were assumed to be available for GIS SCM implementation.

Estimating SCM Footprints and Drainage Treatment Areas

The distribution of the SCM opportunity areas (i.e., SCM footprints) was estimated by land use category group. This distribution represents the maximum available SCM footprint in the pilot watersheds, based on GIS spatial data analysis, and does not necessarily represent the feasibility of such opportunity areas. The treated impervious areas by land use group were split into two categories; roofs and others (Table 4-10). The total drainage treatment area was 59 acres of impervious surface, this represents all impervious surfaces in the study catchment (Table 4-9). While all impervious surfaces were routed to an SCM, treatment was contingent on the SCM size. For this case study, the maximum SCM footprints that could be considered during optimization were limited the capture up to 2 inches of runoff from the impervious drainage areas by land use group (Table 4-11).

The GI SCM types are derived from five land uses having the possibility of either an infiltration trench or an infiltration basin placed on it, due to most land uses having both roofs and other types of impervious areas. However, the transportation land use only included impervious road surfaces associated with it, therefore the land use category contained no roofs and no opportunities for infiltration trenches.

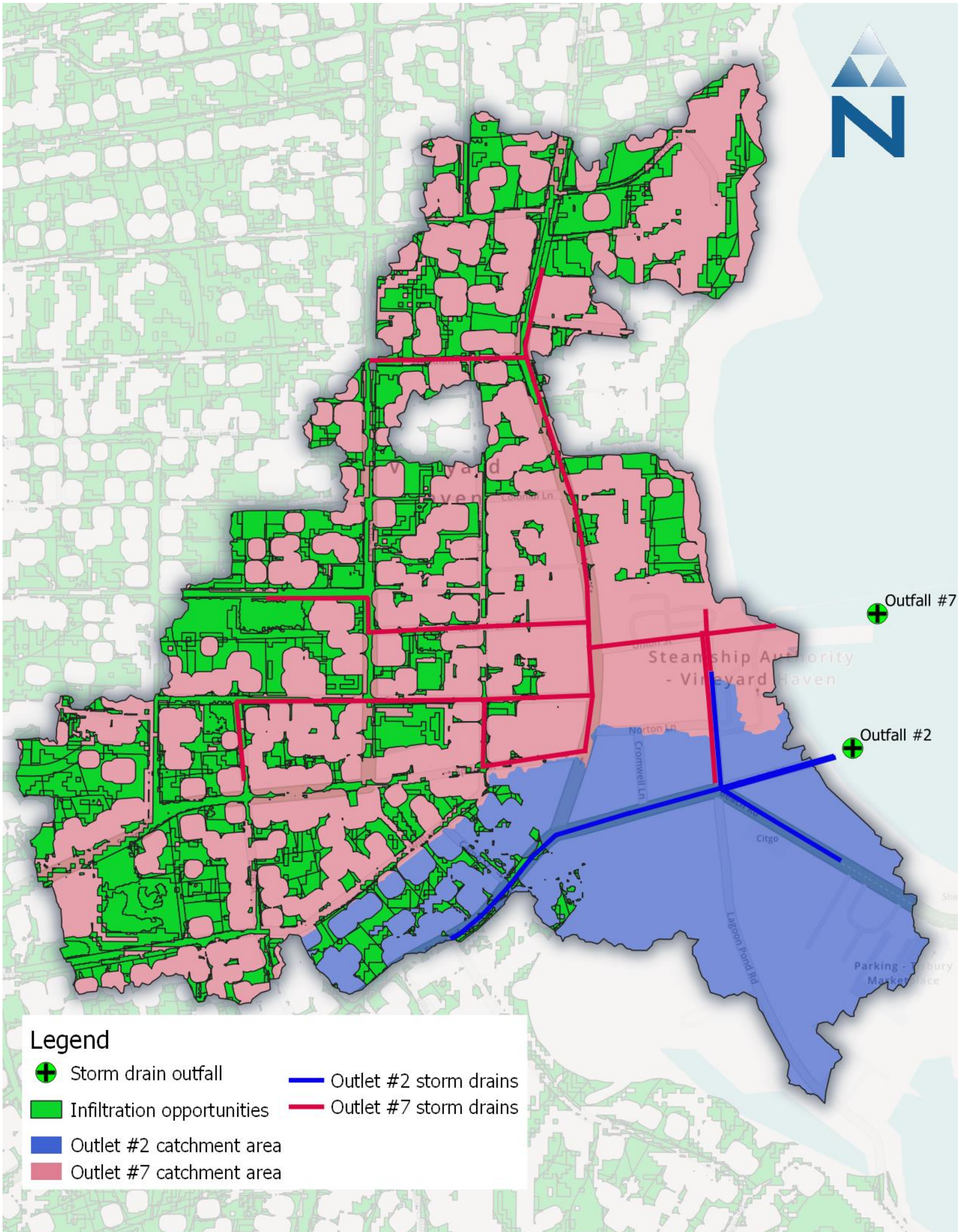

Figure 4-12. Infiltration-based GI SCM opportunities in the two outfall catchments.

Table 4-10. SCM-treated impervious area (drainage treatment area)

Land cover/Land use	Impervious Type	Drainage Treatment Area (acres)		
		Catchment 2	Catchment 7	Total
Forest	Roofs	0.048	0.237	0.285
	Other	0.011	1.373	1.384
Commercial	Roofs	4.893	3.678	8.571
	Other	13.080	7.700	20.78
Medium Density Residential	Roofs	0.915	7.953	8.868
	Other	1.095	13.807	14.902
High Density Residential	Roofs	0.283	0.358	0.641
	Other	0.635	0.543	1.178
Transportation	Other	0.473	1.937	2.41
Open Land	Roofs	-	0.026	0.026
	Other	-	0.423	0.423
Total	Roofs	6.491	12.437	18.928
	Other	14.942	25.598	40.54

Table 4-11. Potential SCM opportunity areas (maximum footprints) in the two outfall catchments

Land cover/Land use	Impervious Type	SCM Type	Maximum Footprint (acres)		
			Catchment 2	Catchment 7	Total
Forest	Roofs	Infiltration trench - A	0.003	0.014	0.017
	Other	Infiltration basin - A	0.001	0.114	0.115
Commercial	Roofs	Infiltration trench - A	0.220	0.211	0.431
	Other	Infiltration basin - A	0.257	0.642	0.899
Medium Density Residential	Roofs	Infiltration trench - A	0.039	0.457	0.496
	Other	Infiltration basin - A	0.091	1.150	1.241
High Density Residential	Roofs	Infiltration trench - A	0.001	0.021	0.022
	Other	Infiltration basin - A	0.027	0.045	0.072
Transportation	Other	Infiltration basin - B	0.039	0.161	0.2
Open Land	Roofs	Infiltration trench - A	-	0.001	0.001
	Other	Infiltration basin - A	-	0.035	0.035
Total	Roofs	Infiltration trench	0.289	0.728	1.017
	Other	Infiltration basin	0.389	2.123	2.512

Opti–Tool Setup

The following steps were performed to set up the Opti-Tool for the Implementation Level outlet analysis.

1. Establish baseline condition: Unit-area HRU timeseries for the period of interest (Jan 1998 – Dec 2018) were used as the boundary condition to the SCM simulation model. The Opti-Tool provides a utility tool that runs the SWMM models, calibrated to Region 1 specific land use average annual loading export rates, and generates the HRU hourly time series in the format needed for the Opti-Tool. The HRU hourly timeseries were developed using the hourly rainfall and temperature data from a local rain gage located at the Martha Vineyard's airport.
2. Set Management objective: The management objective was to identify the most cost-effective stormwater controls (types and sizes) for achieving a wide range of TN loading, stormwater volume, and storm flow rate reductions at the two outfall locations.
3. Set Optimization target: Cost effectiveness-curves for average annual TN load and average annual stormwater volume reduction were developed.
4. Incorporate Land use information: The area distribution for the major land use groups within the pilot watershed was estimated. Each land use group in the model was assigned the corresponding unit-area HRU timeseries.
5. Incorporate SCM information: Two SCM types, infiltration trench and infiltration basin, were selected for six major land use categories based on the Management Category analysis. SCM specifications were set using the default parameters and SCM cost function available in the Opti-Tool (Table 4-12). Impervious drainage areas were assigned to be treated by each SCM type in the model.
6. Run optimization scenario: The simulation period (Jan 1998 – Dec 2018), the stormwater metrics of concern (flow volume and TN loading), the objective function (minimize cost) were defined and input files were created for the optimization runs. The optimization was performed using the continuous simulation SCM model to reflect actual long-term precipitation conditions that included a wide range of actual storm sizes to find the optimal SCM storage capacities that provided the most cost-effective solution at the watershed scale. Each optimization runs generated a CE-Curve showing the optimal solutions frontier for a wide range of stormwater volume and TN load reduction targets.

4.4.4 Results for Outfall Analyses

Outfall #7

Stormwater Volume

The optimal mix of GI SCM types and sizes was assessed for the management objective of flood mitigation through a reduction in stormwater volume. Figure 4-13 presents the cost-effectiveness curve (CE-Curve) for the stormwater volume reduction objective for outlet #7. The blue diamonds form the most cost-effective combination of GI SCM configurations for reducing flow volume. The grey dots on the curve are inferior solutions; compared to these solutions, cheaper alternatives exist that would achieve the same flow volume reduction. The red triangle presents a theoretical target solution. The target solution generally represents some environmentally beneficial, socially acceptable, and economically feasible goals. The cost estimates are based on regional unit cost information for the control types, a 35% add-on for engineering and contingencies and a site factor multiplier to account for anticipated difficulties associated with installations. For this analysis, a multiplier of 2X was assumed for all controls.

Table 4-12. SCM design specifications

General Information	SCM Parameters	Infiltration Trench - A	Infiltration Basin - A	Infiltration Basin - B
SCM Dimensions	Surface Area (ac)	Table 4-11	Table 4-11	Table 4-11
Surface Storage Configuration	Orifice Height (ft)	0	0	0
	Orifice Diameter (in.)	0	0	0
	Rectangular or Triangular Weir	Rectangular	Rectangular	Rectangular
	Weir Height (ft)/Ponding Depth (ft)	0.5	2	2
	Crest Width (ft)	30	30	30
Soil Properties	Depth of Soil (ft)	6	0	0
	Soil Porosity (0-1)	0.4	0.4	0.4
	Vegetative Parameter A	0.9	0.9	0.9
	Soil Infiltration (in/hr)	8.27	8.27	2.41
Underdrain Properties	Consider Underdrain Structure?	No	No	No
	Storage Depth (ft)	0	0	0
	Media Void Fraction (0-1)	0	0	0
	Background Infiltration (in/hr)	8.27	8.27	2.41
Cost Parameters	Storage Volume Cost ($/ft3)	$12.49	$6.24	$6.24
Cost Function Adjustment	SCM Development Type	New SCM in Developed Area	New SCM in Developed Area	New SCM in Developed Area
	Cost Adjustment Factor	2	2	2
Decay Rates	TN (1/hr)	0.13	0.27	0.27
Underdrain Removal Rates	TN (%, 0-1)	0	0	0

The target solution presented in Figure 4-13 shows that it would cost $750,000 to achieve an 80% reduction in annual average flow volume. All costs presented in Opti-Tool derived CE-Curves are intended for planning level purposes and meant to highlight *relative* cost differences between various solutions. The CE curve presented in Figure 4-13 demonstrates how relative cost differences are relatively lower for reductions of 0% to approximately 80%, but the rate at which solutions become more expensive quickly increases for reductions higher than 80%.

Table 4-13 presents the optimized mix of GI SCM opportunity implementation which achieved an 80% reduction in annual flow volume. Design depths ranged from 0.10 to 1.47 inches. Overall, the solution was equivalent to a total design storage volume of 0.35 inches. Based on the rainfall analysis presented in Section 4.4.1, the target solution would result in a 76% reduction in the annual number of runoff discharge days from the impervious surfaces being treated. While it is important to note that a reduction in annual discharge days is not directly comparable to a reduction in annual flow volume, both metrics provide valuable quantification of the potential benefits of GI SCM implementation.

The reduction in peak flows resulting from achieving the target solution, which focused on flow volume, can be seen in Figure 4-14. Peak flows across the driest, wettest and average years were all reduced compared to the baseline simulation reflecting existing conditions. Figure 4-15 highlights the impact of the target solution to storm hydrographs over selected periods of rainfall and runoff. A storm occurring on 5/17/2012 had the peak flow reduced from approximately 17 cubic feet per second (cfs) in the baseline condition to approximately 4.5 cfs in the optimized solution, a reduction of close to 74%. Other storms, occurring in March 2012, had their respective runoff contribution from treated impervious surfaces eliminated due to the optimized GI SCM implementation.

The impact of the target solution on the entire range of flow rates was also assessed. Figure 4-16 presents flow duration curves for both the baseline and optimized solutions. The curves characterize the storm flows of various magnitudes discharging from the outlet. The analysis assumes that the outlet is in good condition and not clogged or otherwise obstructed. The graph only includes data from days in which rainfall and discharge occurred. The graph demonstrates that for the same exceedance probability, the optimized scenario had lower flows for all but the largest and most infrequent storms. For storms that occur only 5% of the time (infrequent larger storm events that cause runoff), the optimized solution reduced the total flow at Outfall #7 from about 9 to 2 cfs, a reduction of about 78%. For more frequently occurring storms, whose flows exceeded more than 20% in baseline conditions, the total flow at Outfall #7 was reduced from 3 to 0.06 cfs, a reduction of about 98%. From the curve, the larger reductions occur for the more frequent *comparatively* smaller storm events, meaning that overall, more precipitation is being infiltrated and recharging the aquifer.

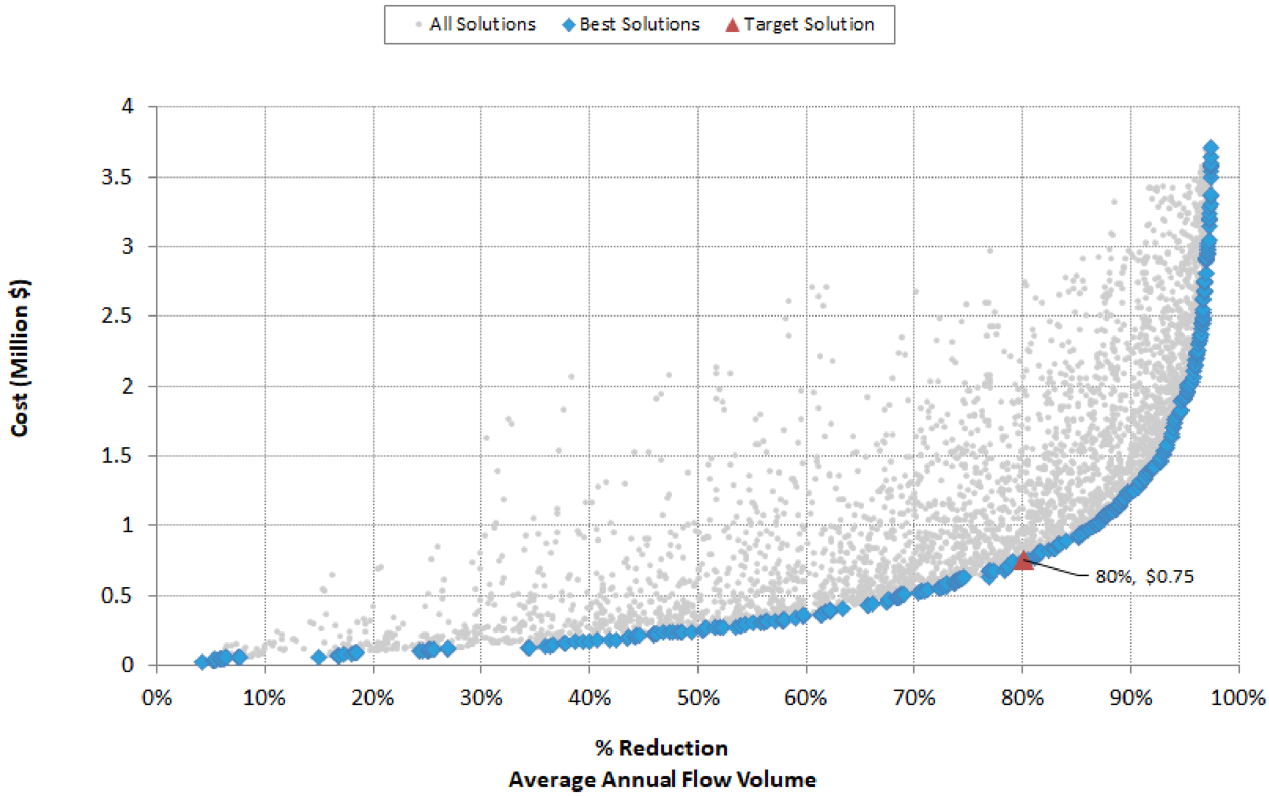

Figure 4-13. Opti-Tool Outfall cost effectiveness curve for annual average flow volume for outfall #7

Table 4-13. Optimized GI SCM opportunities for achieving an 80% reduction in annual average storm volume at outfall #7

SCM ID	SCM Type	Land Use	Treated Impervious Area (acres)	Runoff Depth (in.)	SCM Storage Capacity (gallon)	SCM Cost ($)
SCM1	Infiltration Basin - A	Forest	1.37	0.30	11,186	$18,662
SCM2	Infiltration Trench - A	Forest	0.24	0.89	5,803	$19,380
SCM3	Infiltration Basin - A	Commercial	7.7	0.40	83,636	$139,532
SCM4	Infiltration Trench - A	Commercial	3.68	0.40	39,951	$133,410
SCM5	Infiltration Basin - A	Medium Density Residential	13.81	0.40	149,968	$250,196
SCM6	Infiltration Trench - A	Medium Density Residential	7.95	0.20	43,191	$144,228
SCM7	Infiltration Basin - A	High Density Residential	0.54	0.10	1,474	$2,460
SCM8	Infiltration Trench - A	High Density Residential	0.36	0.40	3,884	$12,970
SCM9	Infiltration Basin - B	Transportation	1.94	0.30	15,778	$26,322
SCM10	Infiltration Basin - A	Open Land	0.42	0.10	1,149	$1,916
SCM11	Infiltration Trench - A	Open Land	0.03	1.47	1,198	$4,000
		Total	38.04	0.35	357,217	$753,076

Figure 4-14. Rainfall and runoff for the driest (top), wettest (middle), and average years (bottom) for outfall #7. Grey area highlights the wettest week for the period shown.

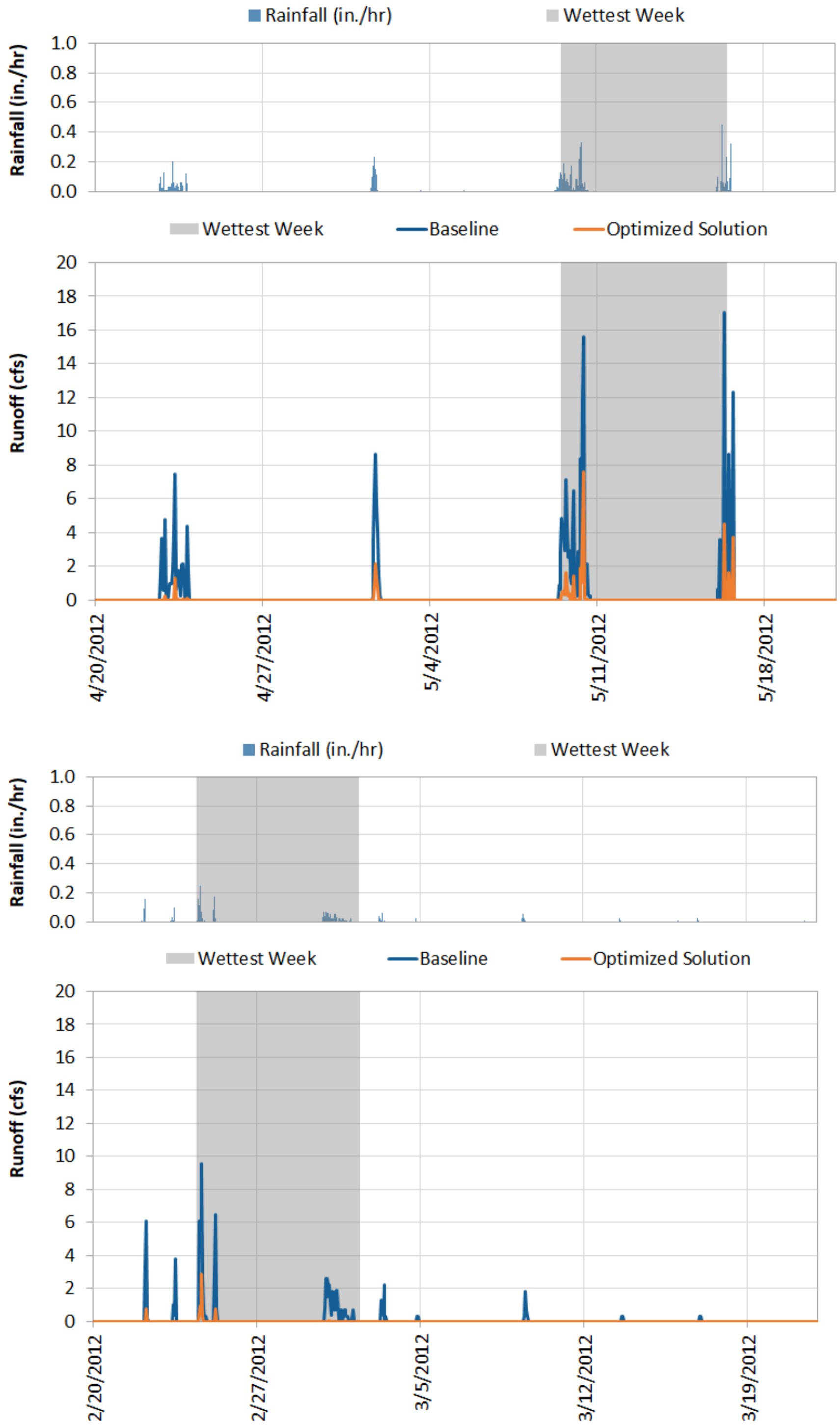

Figure 4-15. Selected periods of rainfall and runoff for outfall #7 during 2012, a year representing an average amount of precipitation for Tisbury, MA. Grey area highlights the wettest week for the period shown.

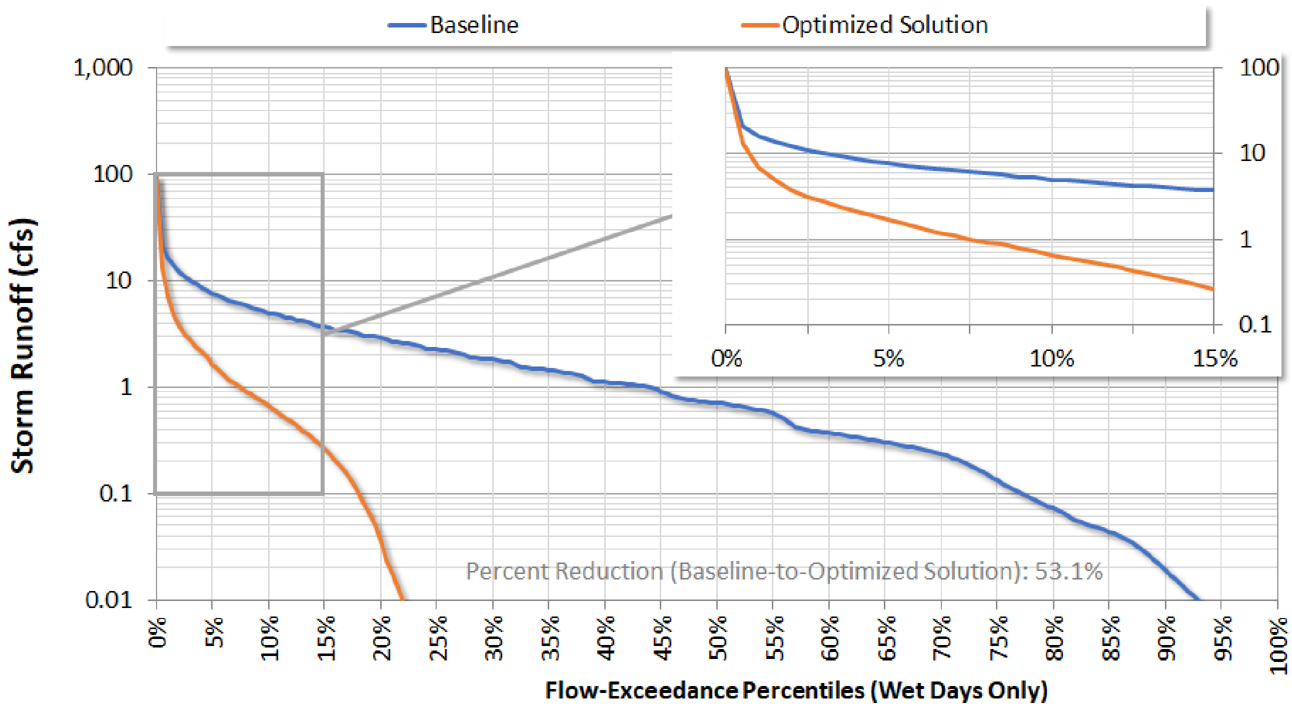

Figure 4-16. Opti-Tool derived flow duration curves (wet days only) for outfall #7

This not only reduces flooding in the Commercial district but helps to restore the hydrologic and hydrogeologic imbalance caused by the relatively high percentage (40%) of impervious cover that characterizes the catchment draining to Outfall #7. During all days which had rainfall and discharge, the baseline conditions show that 77% of flows were equal to or greater than 0.1 cfs. The optimized solution reduced the frequency of 0.1 cfs or greater flows to approximately 17%. A 0.1 cfs flow was as frequent in the optimized scenario as a 2 cfs flow was in the baseline scenario. The flow rate for overall wet days was reduced by an average of 53% due to GI SCM implementation.

Total Nitrogen

Figure 4-17 presents the CE curve for optimizing average annual TN load reduction at outfall #7. The highlighted target solution achieved a 92% reduction in TN loading. This solution was chosen because it also achieved an 80% reduction in average annual storm flow volume. However, since the solution was optimized for TN reduction, the characteristics of the GI SCM implementation were different. The solution achieves a 92% reduction in TN, with a co-benefit of 80% reduction in storm flow volume would cost approximately $770,600 (Table 4-14). The cost is approximately $17,600 more expensive (2.3% higher) than it would be to achieve the same volume reduction based on volume reduction optimization. Cost differences are due in part to the variable nature of TN export. While the impervious surfaces simulated in this study all convert the same amount of rainfall to runoff, different land use types export TN at differing rates. Therefore, optimization may have allocated more resources to treating land uses with higher TN concentrations. Cost-effectiveness is a function of the efficiency of a GI SCM opportunity at treating TN as well as how much TN is in the baseline runoff. Conveying runoff with very high concentrations of TN with a GI SCM opportunity that has relatively low efficiency can still be more cost effective than treating relatively clean water with a GI SCM opportunity with very high efficiency.

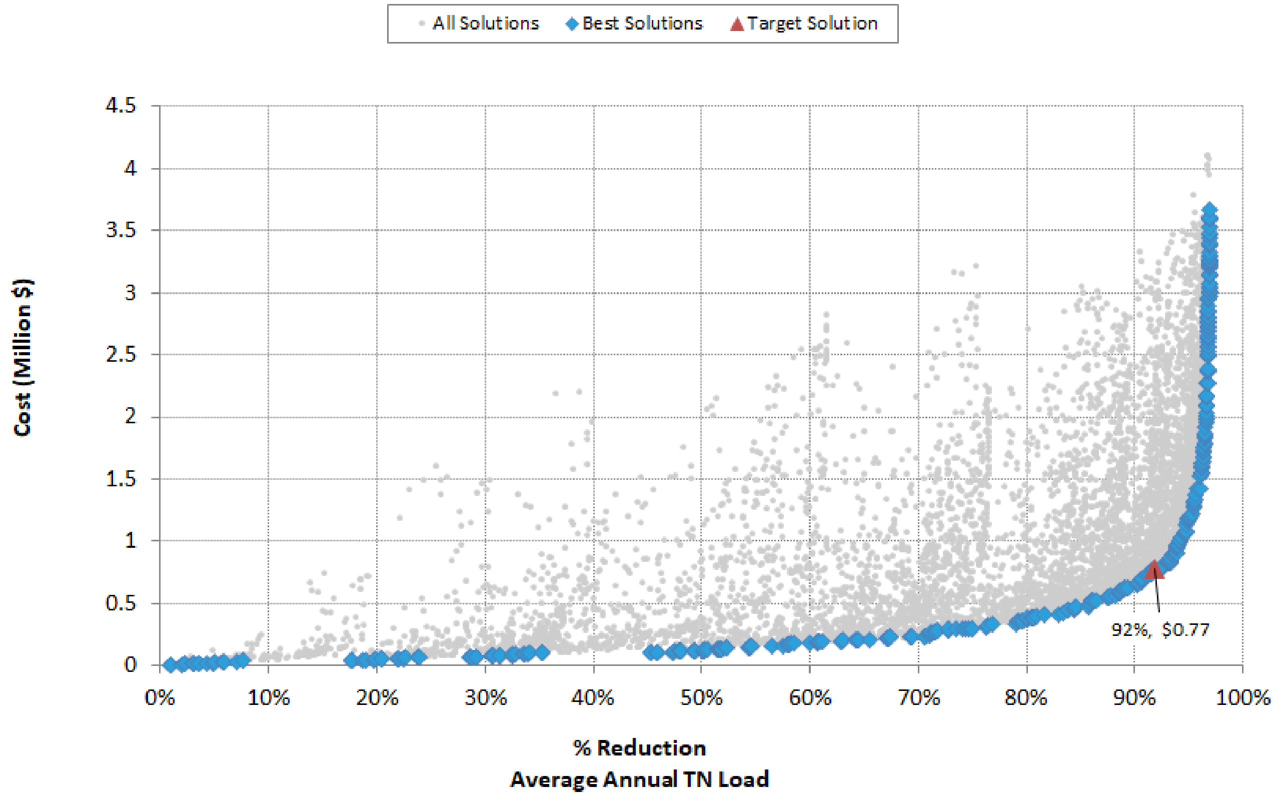

Figure 4-17. Opti-Tool cost effectiveness curve for TN annual average load reduction for outfall #7

Table 4-14. Optimized GI SCM opportunities for achieving a 92% reduction in annual TN loading at outfall #7

SCM ID	SCM Type	Land Use	Treated Impervious Area (acres)	Runoff Depth (in.)	SCM Storage Capacity (gallon)	SCM Cost ($)
SCM1	Infiltration Basin - A	Forest	1.37	0.30	11,186	$18,662
SCM2	Infiltration Trench - A	Forest	0.24	0.49	3,224	$10,766
SCM3	Infiltration Basin - A	Commercial	7.7	0.20	41,818	$69,766
SCM4	Infiltration Trench - A	Commercial	3.68	0.40	39,951	$133,410
SCM5	Infiltration Basin - A	Medium Density Residential	13.81	0.30	112,476	$187,648
SCM6	Infiltration Trench - A	Medium Density Residential	7.95	0.40	86,381	$288,458
SCM7	Infiltration Basin - A	High Density Residential	0.54	0.30	4,423	$7,378
SCM8	Infiltration Trench - A	High Density Residential	0.36	0.89	8,738	$29,180
SCM9	Infiltration Basin - B	Transportation	1.94	0.20	10,519	$17,548
SCM10	Infiltration Basin - A	Open Land	0.42	0.20	2,297	$3,832
SCM11	Infiltration Trench - A	Open Land	0.03	1.47	1,198	$4,000
		Total	38.04	0.31	322,211	$770,650

Outfall #2

Stormwater Volume

Outfall # 2 was also assessed for the optimal mix of GI SCM types to achieve the management objective of flood mitigation through a reduction in stormwater volume. Figure 4-18 presents the CE-curve for the stormwater volume reduction objective for outlet #2. The target solution presented in Figure 4-18 shows that it would cost $410,000 to achieve an 80% reduction in annual average flow volume. The same percent reduction was estimated to cost approximately $750,000 for outlet #7. The estimated costs are useful for planning purposes because they suggest that it would cost twice as much to obtain an 80% reduction in storm volume for outlet #7 as it would for outlet #2 because of almost double impervious footprints in the contributing drainage area to outlet #7. It is important to note that outlet #2 has a smaller contributing drainage area.

Table 4-15 presents the optimized mix of GI SCM opportunity implementation which achieved an 80% reduction in annual flow volume. Design depths ranged from 0.15 to 1.75 inches. Like outfall #7, the solution for outfall #2 was equivalent to a total design storage volume of 0.35 inches (weighted average of design depths based on the impervious area treated).

The impact of achieving the target solution, which focused on flow volume, on peak flows, can be seen in Figure 4-19. Peak flows across the driest, wettest and average years were all reduced compared to the baseline simulation reflecting existing conditions. Figure 4-20 highlights the impact of the target solution to storm hydrographs over selected periods of rainfall and runoff. The same storm assessed for outlet #7, which occurring on 5/17/2012 had the peak flow reduced from approximately 11 cfs in the baseline condition to approximately 3 cfs in the optimized solution, a reduction of about 73%. Other storms had their respective discharge eliminated due to the optimized implementation.

The impact of the target solution on the entire range of flow rates was also assessed. Figure 4-21 presents flow duration curves for both the baseline and optimized solutions. The curves characterize the storm flows of various magnitudes discharging from the outlet. The graph only includes data from days in which rainfall and discharge occurred. The graph demonstrates that for the same exceedance probability, the optimized scenario had lower flows for all but the largest and most infrequent storms. For storms that occur only 5% of the time (infrequent larger storm events that cause runoff), the optimized solution reduced the total flow at Outfall #2 from about 3 to 1 cfs, a reduction of about 67%. For more frequently occurring storms, whose flows exceeded more than 20% in baseline conditions, the total flow at Outfall #2 was reduced from 1.75 to 0.01 cfs, a reduction of about 99%. From the curve, the larger reductions occur for the more frequent *comparatively* smaller storm events, meaning that overall, more precipitation is being infiltrated and recharging the aquifer. This not only reduces flooding in the Commercial district but helps to restore the hydrologic and hydrogeologic imbalance caused by the relatively high percentage (66%) of impervious cover that characterizes the catchment draining to Outfall #2

During all days which had rainfall and discharge, the baseline conditions show that 73% of flows were equal to or greater than 0.1 cfs. The optimized solution reduced the frequency of 0.1 cfs or greater flows to approximately 15%. A 0.1 cfs flow was as frequent in the optimized scenario as a 2 cfs flow was in the baseline scenario. The flow rate for overall wet days was reduced by an average of 57% due to GI SCM implementation.

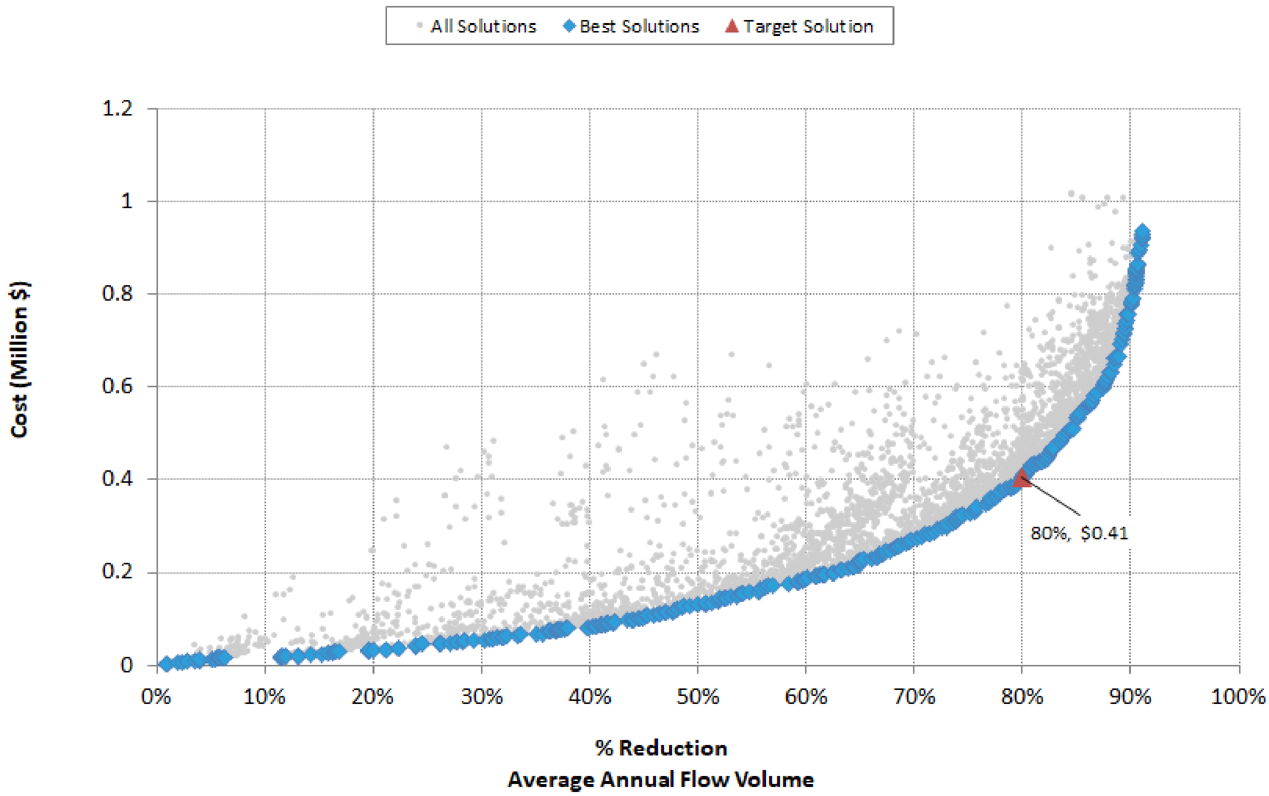

Figure 4-18. Opti-Tool Outfall cost effectiveness curve for annual average flow volume for outfall # 2

Table 4-15. Optimized GI SCM opportunities for achieving an 80% reduction in annual average storm volume at outfall #2

SCM ID	SCM Type	Land Use	Treated Impervious Area (acres)	Runoff Depth (in.)	SCM Storage Capacity (gallon)	SCM Cost ($)
SCM1	Infiltration Basin - A	Forest	0.01	1.32	359	$600
SCM2	Infiltration Trench - A	Forest	0.05	1.75	2,382	$7,954
SCM3	Infiltration Basin - A	Commercial	13.08	0.38	133,886	$223,366
SCM4	Infiltration Trench - A	Commercial	4.89	0.24	31,206	$104,208
SCM5	Infiltration Basin - A	Medium Density Residential	1.1	0.50	14,867	$24,802
SCM6	Infiltration Trench - A	Medium Density Residential	0.92	0.30	7,428	$24,804
SCM7	Infiltration Basin - A	High Density Residential	0.63	0.21	3,573	$5,962
SCM8	Infiltration Trench - A	High Density Residential	0.28	0.15	1,113	$3,716
SCM9	Infiltration Basin - B	Transportation	0.47	0.50	6,420	$10,710
		Total	21.43	0.35	201,234	$406,122

Figure 4-19. Rainfall and runoff for the driest (top), wettest (middle), and average years (bottom) for outfall #2

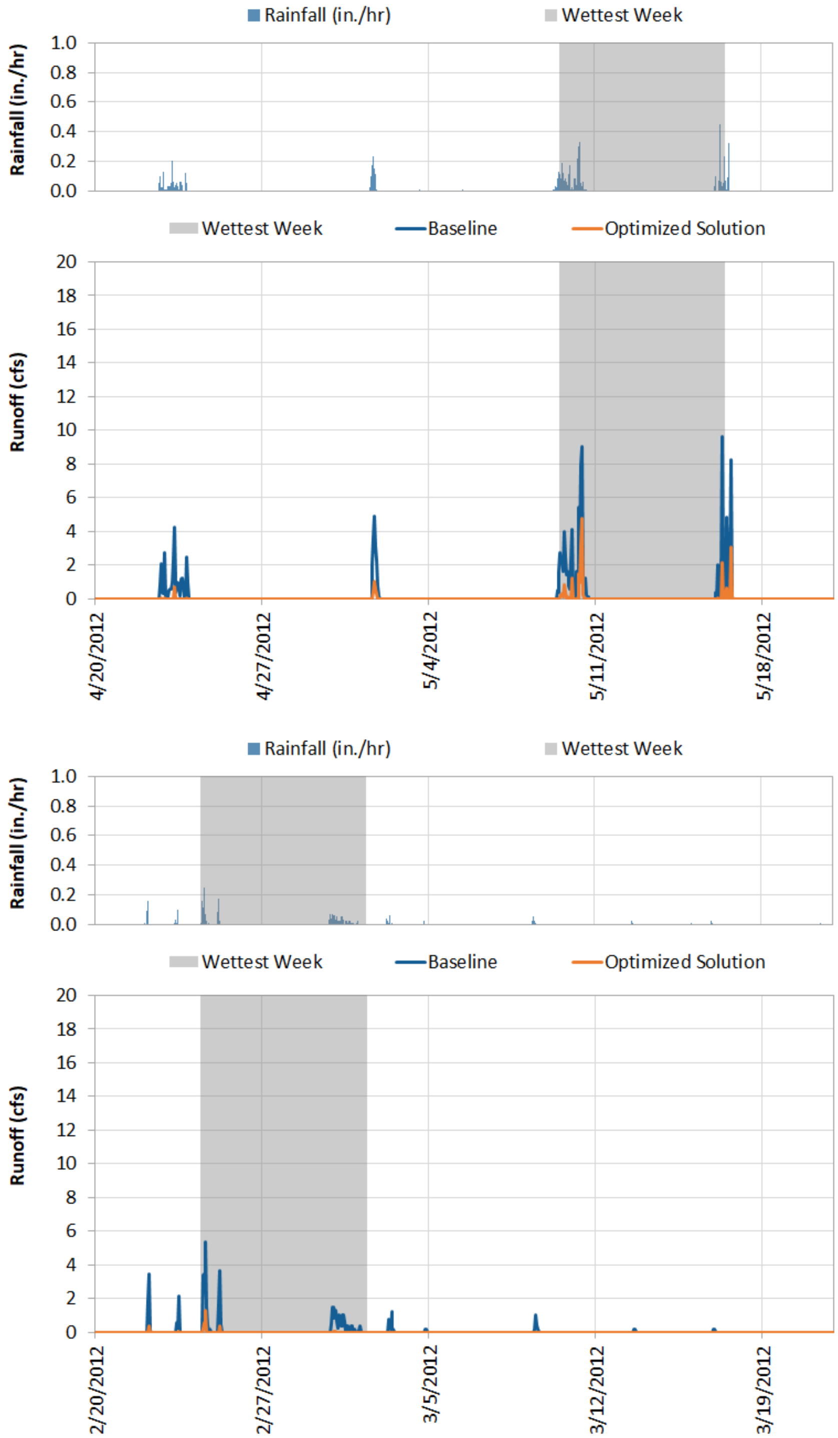

Figure 4-20. Selected periods of rainfall and runoff for outfall #2 during 2012, a year representing an average amount of precipitation for Tisbury, MA.

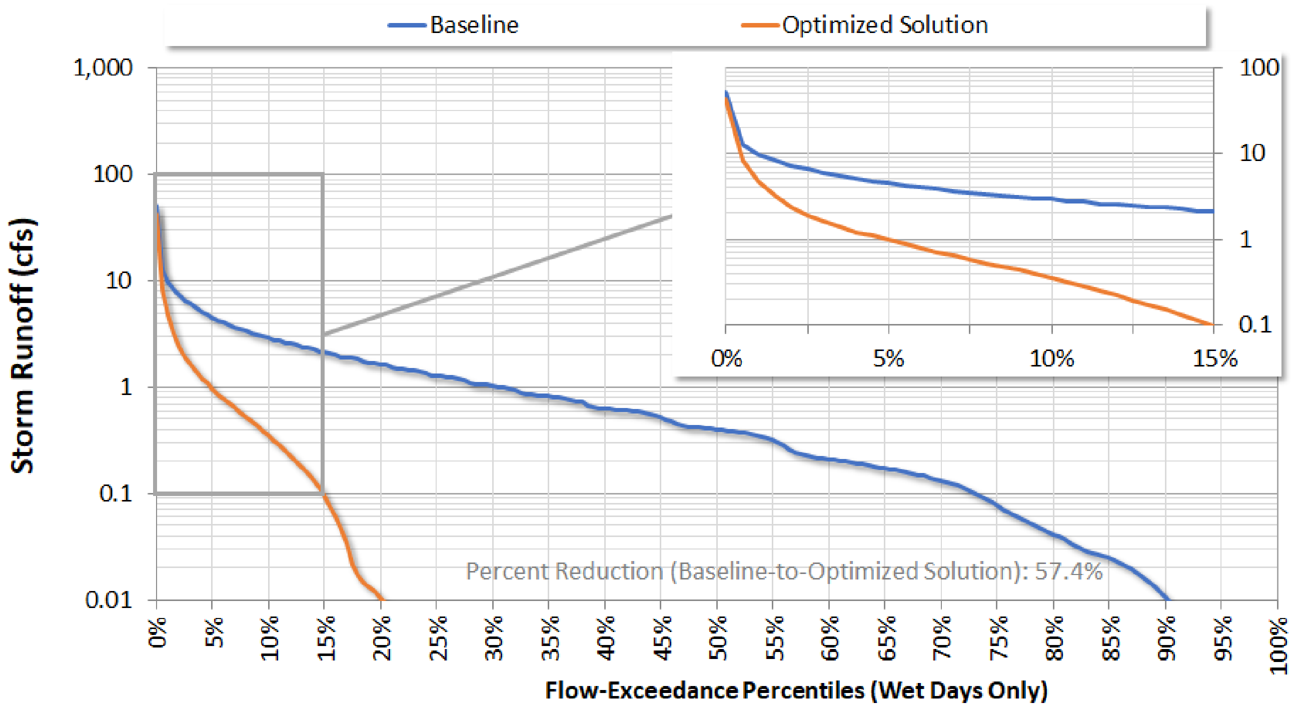

Figure 4-21. Opti-Tool derived flow duration curves for outfall #2

Total Nitrogen

Figure 4-22 presents the CE curve for optimizing average annual TN load reduction at outfall #2. The highlighted target solution achieved an 89% reduction in TN loading. This solution was chosen because it also achieved an 80% reduction in storm flow. However, since the solution was optimized for TN reduction, the characteristics of the GI SCM implementation were different. The 92% reduction in TN, with a co-benefit of 80% reduction in storm flow would cost approximately $402,000 (Table 4-16). The cost is approximately $4,000 less expensive (1% lower) than it would be to achieve the same volume reduction based on volume reduction optimization. Cost differences are due in part to the variable nature of TN export. While the impervious surfaces simulated in this study all convert the same amount of rainfall to runoff, different land use types export TN at differing rates. Therefore, optimization may have allocated more resources to treating land uses with higher TN concentrations.

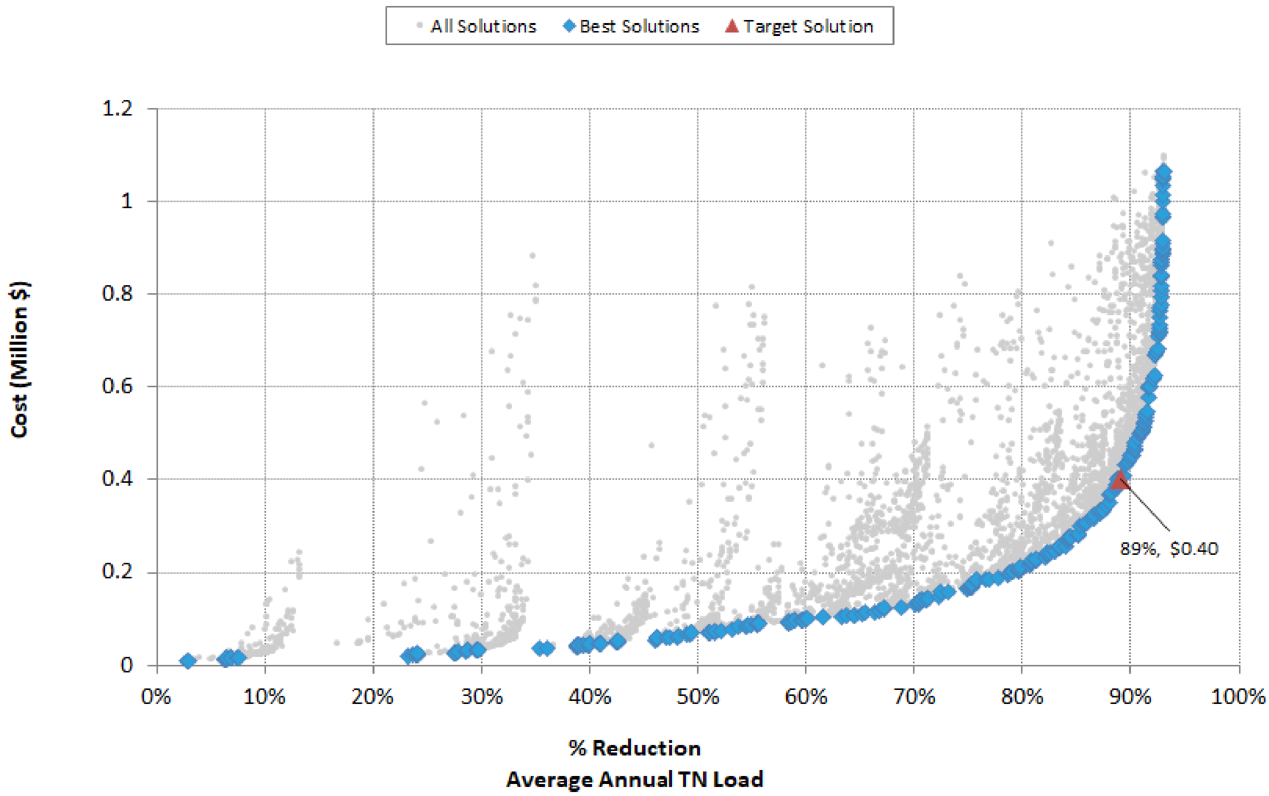

Figure 4-22. Opti-Tool Outfall cost effectiveness curve for TN annual average load reduction for outfall #2

Table 4-16. Optimized GI SCM opportunities for achieving an 89% reduction in annual average total nitrogen loading at outfall #2

SCM ID	SCM Type	Land Use	Treated Impervious Area (acres)	Runoff Depth (in.)	SCM Storage Capacity (gallon)	SCM Cost ($)
SCM1	Infiltration Basin - A	Forest	0.01	0.44	120	$200
SCM2	Infiltration Trench - A	Forest	0.05	0.78	1,059	$3,536
SCM3	Infiltration Basin - A	Commercial	13.08	0.26	92,047	$153,564
SCM4	Infiltration Trench - A	Commercial	4.89	0.39	52,010	$173,680
SCM5	Infiltration Basin - A	Medium Density Residential	1.1	0.50	14,867	$24,802
SCM6	Infiltration Trench - A	Medium Density Residential	0.92	0.22	5,571	$18,604
SCM7	Infiltration Basin - A	High Density Residential	0.63	0.37	6,253	$10,432
SCM8	Infiltration Trench - A	High Density Residential	0.28	0.12	879	$2,934
SCM9	Infiltration Basin - B	Transportation	0.47	0.70	8,987	$14,994
		Total	21.43	0.31	181,792	$402,746

Outfall Summary

Table 4-17 presents a summary of the optimized solutions for reducing storm flow and TN at outlets #7 and #2. The cost of removing one gallon of stormwater volume from either of the outfalls was $0.02 while the cost for removing a pound of TN was $1,727 for outfall #2 and $1,996 for outfall #7. Outfall #7 had higher runoff and TN loading in the baseline conditions. This can be mainly attributed to the larger catchment area (almost double impervious footprints) contributing the Outfall #7. The percent reduction in TN load was similar for both outlets, GI SCM implementation reduced TN loading 89% for outfall #2 and 92% for outfall #7.

Table 4-17. Cost and effectiveness of LID SCM implementation within the catchments of two stormwater outlets in Tisbury, MA

	Outfall #2	Outfall #7
Baseline Average Flow Volume (gallons/yr)	23,193,061	40,174,307
Baseline Average TN Load (lbs/yr)	261.87	420.63
Flow Volume Removed (gallons/yr)	18,551,813	32,192,534
TN Load Removed (lbs/yr)	233.27	386.14
Cost per Gallon Flow Removed ($)	$0.02	$0.02
Cost per Pound TN Removed ($)	$1,727	$1,996

4.4.5 Outfall Analysis and Modeling Summary

The results of this pilot study provide quantitative results to support watershed-based GI management planning. Opti-Tool analyses helped to identify optimal stormwater controls, including GI SCM types and sizes, that could guide retrofitting strategies in the developed catchments of two stormwater outfalls in Tisbury, MA. This study highlights the computational power of optimization algorithms in Opti-Tool for evaluating thousands of possible GI SCM combinations to identify the most cost-effective solutions over a range of target reductions.

Eleven GI SCM opportunity types were considered which treated stormwater runoff from impervious surfaces associated with a variety of land uses. For both catchments, GI SCM implementation resulted in reduced flow volume, peak flows, and TN loading. Comparison of baseline and optimized flow duration curves demonstrate reduced flow magnitudes across nearly the entire range of flow storm flows, with only the largest, most infrequent storms generating approximately the same amount of runoff despite GI SCM implementation. A visual assessment of hydrographs for dry, wet, and average precipitation years demonstrated a reduction in peak flows. The impact on peak flows ranged from relatively small reductions for some large storms, to eliminating runoff and therefore peak flows for several smaller storms. Since the area underneath a hydrograph represents flow volume, the shape of the baseline optimized solution hydrographs also demonstrated reduced stormwater volume. The cost of removing a gallon of water from storm flows was estimated to be $0.02 for both outfalls. The average cost to remove a pound of TN was between $1,700 and $2,000. Whether optimizing for a management objective of reduced stormwater volume or reduce TN loading, the resulting cost-benefit analyses suggest that an approximately 80% reduction in volume and a 90% reduction in TN loading can be achieved at a total cost around $1,160,000 - $1,173,000 for implementing distributed infiltration practices sized to capture 0.35 inches (weighted average) of runoff from the impervious cover.

4.5 Municipal Long-Term GI SCMs Implementation Strategies

The Planning Level Analysis functionality in Opti-Tool was used to compare the cost-effectiveness of various Green Infrastructure (GI) and Stormwater Control Measures (SCM) design scenarios for the entire town of Tisbury, MA. The assessment describes opportunities and their associated costs and benefits within the town's nine zoning districts an expands on the study of the two outfalls, #2 and #7. Together, the studies leverage both the Planning Level and Implementation Level Analyses options of Opti-Tool. The Planning Level Analysis provides a watershed-based overview of stormwater management opportunities for decision-makers to consider. The Planning Level Analysis uses Excel Solver to find optimal solutions using existing SCM performance curves. Unlike the Implementation Level analysis, which produces cost effectiveness curves based on hundreds of thousands of possible SCM type and size combinations, the Planning Level Analysis assesses cost effectiveness over incremental SCM sizes. The Planning Level Analysis for Tisbury assumed that for each size increment (i.e. 0.1, 0.2 inches, etc), all SCMs in the watershed were built to that size.

Cost-effectiveness curves were generated town-wide and for each zoning district. The curves assess the costs and benefits, in terms of stormwater volume and TN load reduction, which can be expected over a range of GI-SCM sizes. At a planning level, the results demonstrate that if infiltration-based GI-SCM opportunities were designed to capture 0.4 inches of runoff from impervious surfaces, the result would be a 78% reduction in annual storm flow volume and an 81% in annual TN loading. An additional co-benefit of this level of control is to reduce annual indicator bacteria load in the runoff by an estimated 66.5% - 80% assuming a GI-SCM infiltration rate of 1.02 in/hr. Approximately 78% of the runoff discharge events from treated IC areas per year would also be eliminated. This benefit could immediately lower impacts on recreational uses in local surface waters. The estimated cost to achieve these reductions was $13.54 million for the town's entire area of 6.37 square miles (4,079 acres).

4.5.1 Technical Approach – Planning Level Analysis

The purpose of the Planning Level Analysis within Opti-Tool is to quickly evaluate multiple design scenarios with minimum data requirements and compare them without running a continuous SCM simulation in the more detailed Implementation Level Analysis mode of Opti-Tool. Two management goals we evaluated, the goal of reducing TN loading and the goal of reducing stormwater volume. For these two management goals, eight design scenarios were evaluated. The design scenarios represented incremental SCMs design sizes to capture between 0.1 and 2 inches of runoff from the contributing impervious cover. A design between 0.31 and 0.35 was previously identified as optimal sizes for TN and volume reduction for outfalls #2 and #7 (U.S. EPA, 2020). Analyzing a range of large and small design capacities was intended to facilitate a better understanding of relative costs ($) and maximum load and volume reductions (%) achievable for given design SCM capacities in Tisbury, MA.

The Planning Level Analysis option used the annual pollutant loading rate by land use category to estimate the baseline loads, a unit volume cost to estimate the SCM total cost, SCM performance curves (e.g., the relationship between SCM size and associated TN load or stormwater volume reduction) to estimate the load and volume reduction. Local climate data were used to develop the HRU-based annual pollutant loading rates, U.S. EPA (2019) provides further information on the development of the timeseries. The local data was used instead of the default land loading rates provided in the Opti-Tool. However, the analysis did use default SCM unit volume costs and SCM performance curves, which are also provided in the Opti-Tool and use region-specific data. Special attention should be given before using the Planning Level Analysis to make sure that default data are representative of your study area. In this case study, local precipitation data were used from Martha's Vineyard Airport station to develop the HRU timeseries, as described above.

4.5.2 Results for Municipal Long-Term GI SCM Implementation

Over half the area of Tisbury is forest (Table 4-18). The majority of residential and commercial land uses are concentrated in the eastern part of the town while agriculture and forested areas are more common in the west. Table 4-19 presents the HRU area distribution by the zoning district. Residential districts R3A and R50 are the two largest zoning districts, accounting for approximately 63% of the total area of the town. Unsurprisingly the business districts (B2 light business district, B1 business district, and the waterfront commercial) have the most acreage of impervious commercial land while the residential districts have the highest concentration of impervious residential areas. A summary of impervious and pervious areas by zoning district is presented in Table 4-20. Impervious areas were identified as either being roofs or other impervious areas. Other impervious areas included driveways, parking lots and roads. The distinction allowed for an assessment of different GI SCM opportunities depending on the type of imperviousness. As previously discussed, the GI SCM opportunities assessed in this study were infiltration-based, rooftop disconnections were simulated as an infiltration trench, while all other impervious areas were treated using an infiltration basin. The use of two practices, simulated on three soil types, helped to simplify the analysis, however, the practices predicted benefits from rooftop disconnection may be achieved by a variety of on-the-ground implementations, including barrels/cisterns that drain slowly to permeable areas. The opportunity analysis was previously described in Section 3.

Town-wide, the Planning Level Analysis suggests that a 78% reduction in annual stormwater volume and an 81% reduction in annual TN load could be achieved at a cost of approximately $13.54 million (Figure 4-23). The optimal solutions fall at the inflection point or ‘knee’ of the curves where reduction has been maximized but costs have not begun to increase substantially. The result is based on the simplifying assumption that all GI SCM opportunities were sized to capture 0.4 inches of runoff, which is close to the optimization-derived result of 0.31-0.35 inches estimated to achieve similar reductions in the catchments for outfalls #2 and #7 (Section 4.4). Importantly, the curve also demonstrates that a 100% percent reduction in flow volume and TN reduction should not be expected since only impervious surfaces are treated in the simulation; pervious surfaces are still capable of producing stormflow and contributing to TN loading.

The distribution of the total cost of implementation across zoning districts is presented in Table 4-21. Overall, planning level analysis requires more money spent on implementation is the residential areas versus the business/commercial districts. This is largely attributed to the distribution of total impervious surfaces (Table 4-19), there are more acres of impervious surfaces in the larger, residential zones. Table 4-22 presents the amount each SCM, distributed across the various land uses in the town, disconnects impervious surface, stores and captures stormwater, and removes TN. Table 4-22 also provides a breakdown of the total costs in Table 4-21. Rooftop disconnections account for 36% of total costs while treating all other impervious surfaces account for the remaining 64%.

Table 4-18. Land use area distribution in Tisbury zone districts

Land Use	Total Area by Zone District (acres)									
	Business District (B1)	Light Business District (B2)	Residential District (R10)	Residential District (R20)	Residential District (R25)	Residential District (R50)	Residential District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercial (W/C)	Total
Forest	0.5	36.0	157.7	145.9	160.5	849.4	1,040.6	-	0.8	2,391.5
Agriculture	-	-	1.1	-	0.9	28.2	116.8	-	-	146.9
Commercial	15.3	46.9	16.0	4.7	4.4	3.5	2.0	-	20.0	112.7
Industrial	-	34.8	0.7	6.2	-	-	-	-	-	41.7
Low Density Residential	-	0.7	69.7	142.4	47.0	195.4	95.3	-	1.0	551.5
Medium Density Residential	1.9	2.1	361.4	4.1	97.7	9.2	-	-	1.7	478.1
High Density Residential	0.3	1.4	5.8	5.9	1.6	11.1	-	-	1.5	27.5
Highway	-	-	-	-	0.0	-	-	-	2.7	2.7
Open Land	0.5	4.1	40.5	21.1	32.2	135.4	76.1	4.5	12.2	326.7
Total Area (acres)	18.5	126.0	652.9	330.4	344.3	1,232.1	1,330.8	4.5	39.8	4,079.3

Table 4-19. HRU area distribution in Tisbury Zone districts

HRU-Model	Total Area by Zone District (acres)									
	Business District (B1)	Light Business District (B2)	Residentia l District (R10)	Residentia l District (R20)	Residentia l District (R25)	Residentia l District (R50)	Residentia l District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercia l (W/C)	Total
Forest_IMP	0.1	2.2	11.7	12.8	8.0	56.4	43.7	0.0	0.3	135.3
Agriculture_IMP	0.0	0.0	0.0	0.0	0.1	2.0	6.8	0.0	0.0	8.9
Commercial_IMP	12.4	34.0	8.5	2.9	2.0	1.2	0.6	0.0	15.6	77.2
Industrial_IMP	0.0	14.8	0.5	4.9	0.0	0.0	0.0	0.0	0.0	20.3
Low Density Residential_IMP	0.0	0.3	24.0	42.4	11.4	52.8	21.3	0.0	0.3	152.5
Medium Density Residential_IMP	0.8	0.8	122.6	1.4	27.8	3.0	0.0	0.0	0.7	157.2
High Density Residential_IMP	0.2	0.5	2.2	3.1	0.7	5.9	0.0	0.0	0.8	13.4
Highway_IMP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.4
Open Land_IMP	0.0	1.0	11.3	5.3	3.6	9.7	5.9	1.1	7.7	45.7
Developed Pervious_A_Low	0.5	11.7	104.1	32.1	49.9	90.2	27.9	0.0	0.1	316.5

HRU-Model	Total Area by Zone District (acres)									
	Business District (B1)	Light Business District (B2)	Residential District (R10)	Residential District (R20)	Residential District (R25)	Residential District (R50)	Residential District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercial (W/C)	Total
Developed Pervious_A_Medium	1.3	14.0	158.0	59.3	59.5	117.4	47.1	0.0	0.4	457.1
Developed Pervious_A_High	0.9	12.6	53.5	31.8	16.1	38.2	21.8	0.0	0.3	175.1
Developed Pervious_B_Low	0.0	0.1	0.2	0.0	0.0	1.5	17.1	0.0	0.0	18.8
Developed Pervious_B_Medium	0.0	0.1	0.1	0.0	0.0	1.1	13.8	0.0	0.0	15.1
Developed Pervious_B_High	0.0	0.1	0.0	0.0	0.0	0.1	2.5	0.0	0.0	2.7
Developed Pervious_C_Low	1.0	0.0	4.6	0.0	0.1	0.0	0.0	0.6	5.6	11.9
Developed Pervious_C_Medium	0.7	0.0	0.4	0.0	0.2	0.0	0.0	0.8	2.9	4.9
Developed Pervious_C_High	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.4	0.8	1.5
Developed Pervious_D_Low	0.0	0.0	2.0	0.4	1.6	21.6	10.4	0.6	0.6	37.3
Developed Pervious_D_Medium	0.0	0.0	1.7	0.6	6.5	9.2	4.2	0.6	0.4	23.2
Developed Pervious_D_High	0.0	0.0	0.3	0.4	3.4	2.6	0.9	0.4	0.3	8.3
Forest Pervious_A_Low	0.1	5.8	30.0	27.1	67.2	203.3	196.4	0.0	0.0	529.9
Forest Pervious_A_Medium	0.2	15.0	73.6	59.2	75.2	408.3	399.7	0.0	0.1	1,031.3
Forest Pervious_A_High	0.1	10.6	40.1	46.5	10.2	158.3	171.0	0.0	0.2	437.1
Forest Pervious_B_Low	0.0	0.8	0.8	0.0	0.0	11.4	130.0	0.0	0.0	143.0
Forest Pervious_B_Medium	0.0	1.5	1.1	0.1	0.0	9.5	81.7	0.0	0.0	94.0
Forest Pervious_B_High	0.0	0.1	0.4	0.1	0.0	2.2	18.1	0.0	0.0	21.0
Agriculture Pervious_A_Low	0.0	0.0	0.8	0.0	0.3	7.0	27.1	0.0	0.0	35.2
Agriculture Pervious_A_Medium	0.0	0.0	0.3	0.0	0.5	15.4	42.4	0.0	0.0	58.5
Agriculture Pervious_A_High	0.0	0.0	0.0	0.0	0.0	3.7	11.1	0.0	0.0	14.9
Agriculture Pervious_B_Low	0.0	0.0	0.0	0.0	0.0	0.0	21.5	0.0	0.0	21.5
Agriculture Pervious_B_Medium	0.0	0.0	0.0	0.0	0.0	0.0	6.9	0.0	0.0	6.9
Agriculture Pervious_B_High	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0
Total Area (acres)	18.5	126.0	652.9	330.4	344.3	1,232.1	1,330.8	4.5	39.8	4,079.3

Note: The color scale represents the lowest (blue) to the highest (red) footprint of a model HRU across the zoning districts (color gradient varies horizontally).

Table 4-20. Pervious and impervious areas in Tisbury

Description	Total Area (acres)	Impervious Area (acres)			Pervious Area (acres)
		Roofs	Other Impervious	Total Impervious	
Business District (B1)	18.53	4.44	9.04	13.48	5.04
Light Business District (B2)	125.99	8.72	44.93	53.65	72.33
Residential District (R10)	652.92	49.12	131.77	180.89	472.03
Residential District (R20)	330.40	15.46	57.31	72.77	257.63
Residential District (R25)	344.27	16.46	37.13	53.60	290.67
Residential District (R50)	1,232.14	24.40	106.60	131.01	1,101.13
Residential District (R3A)	1,330.80	10.46	67.85	78.31	1,252.48
Lagoon Harbor Park (LHP)	4.53	0.02	1.12	1.15	3.38
Waterfront Commercial (W/C)	39.75	6.30	21.58	27.88	11.87
Total Area (acres)	4,079.32	135.40	477.34	612.74	3,466.58

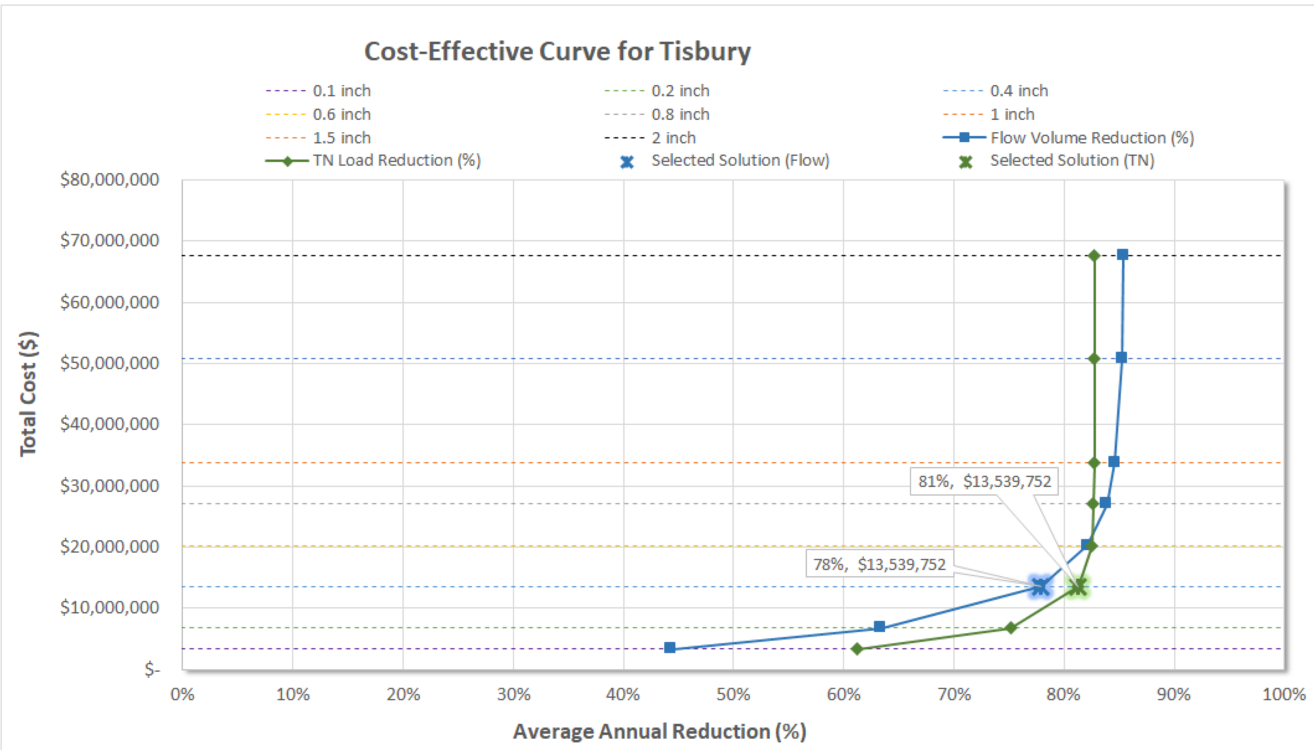

Figure 4-23. Cost effectiveness curves for incremental sizing of GI SCM opportunities in Tisbury, MA.

Table 4-21. Costs by development zone to achieve town-wide reductions of 78% and 81% in stormwater volume and TN loading, respectively for the town of Tisbury, MA

Development Zone									
B1 Business District	B2 Light Business District	LHP Lagoon Harbor Park	R3A Residential District	R10 Residential District	R20 Residential District	R25 Residential District	R50 Residential District	WC Waterfront Commercial District	Total
325038	$1,130,554	--	$1,608,886	$4,169,444	$1,599,198	$1,270,024	$2,816,910	$619,698	$13,539,752

Note: The color scale represents the least expensive (blue) to most expensive (red).

Table 4-22. Infiltration GI SCM Solution (0.4 inches) Tisbury, MA

Land Use Group	SCM Type	HSG	Infiltration GI SCM Solution (0.4 inches) for Tisbury				
			IC Disconnected (acres)	Storage Capacity (gallons)	Flow Volume Captured (gallons/yr)	TN Load Removed (lbs/yr)	SCM Cost ($)
Forest	Infiltration Trench (Rooftop disconnected)	A	5.879	63,858	5,547,883	46.176	$213,242
		B	0.272	2,956	217,188	2.072	$9,872
		C	0.008	82	5,231	0.056	$274
	Infiltration Basin (Other IC disconnected)	A	118.268	1,284,599	112,569,011	938.393	$2,143,140
		B	10.830	117,630	8,586,227	82.456	$196,246
		C	0.026	286	17,597	0.194	$478
Agriculture	Infiltration Trench (Rooftop disconnected)	A	0.786	8,542	742,087	6.177	$28,524
		B	0.242	2,624	192,750	1.839	$8,762
		C	-	-	-	-	-
	Infiltration Basin (Other IC disconnected)	A	6.351	68,978	6,044,544	50.388	$115,078
		B	1.508	16,378	1,195,480	11.481	$27,324
		C	-	-	-	-	-
Commercial	Infiltration Trench (Rooftop disconnected)	A	11.805	128,218	11,139,465	133.671	$428,164
		B	0.130	1,413	103,768	1.428	$4,716
		C	6.012	65,299	4,178,287	63.909	$218,058

Land Use Group	SCM Type	HSG	Infiltration GI SCM Solution (0.4 inches) for Tisbury				
			IC Disconnected (acres)	Storage Capacity (gallons)	Flow Volume Captured (gallons/yr)	TN Load Removed (lbs/yr)	SCM Cost ($)
	Infiltration Basin (Other IC disconnected)	A	42.382	460,348	40,340,116	484.825	$768,014
		B	0.536	5,820	424,851	5.882	$9,710
		C	16.357	177,664	10,934,736	173.881	$296,404
Industrial	Infiltration Trench (Rooftop disconnected)	A	2.605	28,300	2,458,676	29.504	$94,504
		B	-	-	-	-	-
		C	-	-	-	-	-
	Infiltration Basin (Other IC disconnected)	A	17.679	192,023	16,826,934	202.233	$320,358
		B	-	-	-	-	-
		C	-	-	-	-	-
Low Density Residential	Infiltration Trench (Rooftop disconnected)	A	46.704	507,285	44,072,479	486.545	$1,693,998
		B	1.619	17,585	1,291,823	16.350	$58,722
		C	-	-	-	-	-
	Infiltration Basin (Other IC disconnected)	A	101.394	1,101,316	96,507,964	1,067.068	$1,837,362
		B	2.744	29,805	2,175,576	27.711	$49,724
		C	-	-	-	-	-
Medium Density Residential	Infiltration Trench (Rooftop disconnected)	A	50.729	551,008	47,871,095	528.481	$1,840,004
		B	-	-	-	-	-
		C	0.258	2,806	179,539	2.526	$9,370
	Infiltration Basin (Other IC disconnected)	A	105.695	1,148,037	100,602,069	1,112.336	$1,915,308
		B	-	-	-	-	-
		C	0.484	5,254	323,387	4.731	$8,766
High Density Residential	Infiltration Trench (Rooftop disconnected)	A	4.537	49,279	4,281,291	47.264	$164,558
		B	-	-	-	-	-
		C	0.227	2,461	157,440	2.215	$8,216
	Infiltration Basin (Other IC disconnected)	A	8.028	87,201	7,641,373	84.489	$145,480
		B	-	-	-	-	-
		C	0.600	6,519	401,210	5.869	$10,876
Highway	Infiltration Trench (Rooftop disconnected)	A	-	-	-	-	-
		B	-	-	-	-	-

Land Use Group	SCM Type	HSG	Infiltration GI SCM Solution (0.4 inches) for Tisbury				
			IC Disconnected (acres)	Storage Capacity (gallons)	Flow Volume Captured (gallons/yr)	TN Load Removed (lbs/yr)	SCM Cost ($)
		C	0.211	2,289	146,493	1.341	$7,646
	Infiltration Basin (Other IC disconnected)	A	-	-	-	-	-
		B	-	-	-	-	-
		C	2.171	23,582	1,451,376	13.818	$39,342
Open Land	Infiltration Trench (Rooftop disconnected)	A	1.403	15,238	1,323,877	11.019	$50,886
		B	0.165	1,793	131,722	1.257	$5,988
		C	1.782	19,356	1,238,500	13.139	$64,636
	Infiltration Basin (Other IC disconnected)	A	29.757	323,215	28,323,260	236.107	$539,232
		B	3.307	35,915	2,621,534	25.175	$59,918
		C	8.104	88,028	5,417,858	59.757	$146,860
Total	Infiltration Trench (Rooftop disconnected)	A	124.448	1,351,727	117,436,853	1,288.837	$4,513,878
		B	2.428	26,371	1,937,250	22.946	$88,060
		C	8.497	92,293	5,905,491	83.187	$308,196
	Infiltration Basin (Other IC disconnected)	A	429.555	4,665,717	408,855,270	4,175.840	$7,783,972
		B	18.924	205,548	15,003,669	152.706	$342,922
		C	27.743	301,332	18,546,165	258.250	$502,724

A summary of the results of the town-wide analysis is presented in Table 4-23. The residential zoning districts which encompass a majority of the area of the town, unsurprisingly also had the highest baseline stormwater volume (gallons/yr) and TN loading (lbs/yr). However, commercial and industrial HRUs generated more TN per acre than in residential areas (U.S. EPA, 2019). The overall cost ($/gallon) to reduce stormwater volume was $0.01, a penny per gallon, however, when treating with millions of gallons of runoff, costs can still add up quickly. The total cost for removing TN ($/lb) was $2,264. Unlike surface runoff, which all impervious surfaces generate identically (all impervious areas convert the same amount of rainfall to runoff), TN loading differs by land use type. The cost-effectiveness of GI SCM solutions tends to increase with TN runoff concentrations. Based on annual TN loading and stormwater volume (Table 4-23) 99,066 gallons of stormwater needs to be treated, at a 100% removal rate, to remove 1 lb of TN. Therefore, if TN concentrations were higher in the runoff, it would take less volume, and therefore less money, to remove a pound of TN. Local water quality monitoring data could help inform these costs. Appendix K provides details including the HRU distribution, available opportunities, CE curve, and costs and benefits of the selected implementation solution for each of Tisbury's zoning districts.

Table 4-23. Summary table for baseline conditions, costs, and effectiveness of the GI SCM solution (0.4 inches) for Tisbury, MA

	Results Summary by Zone District									
	Business District (B1)	Light Business District (B2)	Residential District (R10)	Residential District (R20)	Residential District (R25)	Residential District (R50)	Residential District (R3A)	Lagoon Harbor Park (LHP)	Waterfront Commercial (W/C)	Total
Impervious Cover Disconnected (acre)	13.485	53.653	180.888	72.770	53.595	131.007	78.311	-	27.884	612
Baseline Average Flow Volume (gallons/yr)	14,086,926	56,021,249	193,152,326	79,092,890	62,856,054	166,124,955	124,907,630	1,926,511	30,247,094	728,415,636
Baseline Average TN Load (lbs/yr)	159.679	622.274	1,984.825	789.530	635.617	1,579.136	1,253.917	19.411	307.774	7,352
Flow Volume Removed (gallons/yr)	11,046,984	50,887,420	171,090,623	69,136,916	50,808,604	124,262,584	71,469,201	-	18,982,366	567,684,698
TN Load Removed (lbs/yr)	147.406	599.656	1,845.838	724.391	533.597	1,200.446	671.385	-	259.047	5,982
Total Cost for Selected Solution ($)	$325,038	$1,130,554	$4,169,444	$1,599,198	$1,270,024	$2,816,910	$1,608,886	-	$619,698	$13,539,752
Cost per Gallon Flow Removed ($)	$0.03	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	-	$0.03	$0.02
Cost per Pound TN Removed ($)	$2,206	$1,886	$2,258	$2,208	$2,380	$2,346	$2,396	-	$2,392	$2,264

5 CONCLUSIONS

This project has piloted a new approach to addressing stormwater management in which regulators and technical experts work collaboratively with community leaders to identify opportunities for innovative stormwater controls. In this project, a single municipality (Tisbury) worked with a team of subject matter experts to determine cost-effective and efficient ways to address stormwater issues within their town. The team and the leaders of this motivated municipality collaboratively developed strategic approaches and identified the technical support needed to advance their flood mitigation and water quality restoration efforts.

Working with municipal officials in communities such as Tisbury to collaboratively develop effective strategic stormwater approaches creates a transformative setting within which the municipality and its citizens elevate the concept of stormwater management as an essential and integral land use management priority for the community. The effort seeks to shift stormwater management from a reactionary, ad-hoc approach that often exacerbates flooding and water quality issues, to one that is mitigatory, cost-effective and resilient. The watershed modeling conducted for this project helped the town understand how impervious surfaces contribute to the baseline conditions (i.e. excessive runoff and nutrient loading) in their municipality. The modeling also provided an assessment of how the town may implement GI SWM strategies in a cost-effective manner.

For small towns with limited resources, the analysis helps to quantify the return on investment achieved with such strategies. Critically, the modeling was coupled with hands-on, site-based assessments whereby stakeholders identified local areas of concern and worked with the project team to develop workable GI SWM solutions that would be widely applicable for implementation throughout the town. The project provides estimated costs for the optimal solutions that would achieve substantial runoff volume and pollutant reductions by assuming that the installation of controls is accomplished independently of other redevelopments, urban renewal and municipal roadway projects. Going forward, the town could realize considerable cost savings, while making sustained progress towards its stormwater management objectives, by adopting opportunistic strategies that would ensure GI SCM solutions are incorporated into future development and redevelopment projects.

For this project, initial success meant incorporating GI SWM innovations into Tisbury's stormwater toolbox by raising awareness and increasing local knowledge within its constituency and community leaders. Future outreach strategies should focus on facilitating peer to peer transfer of lessons learned. These would include sharing the results of successful GI SCM implementation activities, as well as identifying the constraints and unexpected challenges and outcomes of the process. Dissemination of municipal experiences with real-life retrofit sites can be used to encourage further adoption and provide effective training or outreach approaches to inform municipal officials (staff and boards) in surrounding communities that are ready to adopt new strategies to address their stormwater challenges.

Conclusions to date have identified municipal implementation experience as a critical step for adapting research-based designs into the pragmatic workflow of a public works department working in an urban setting. The methods have been successful in Dover NH, Arlington, MA and now on Martha's Vineyard. Creative thinking about methods and approaches is needed. Success depends on establishing a common understanding and agreement of the fundamentals involved in up-to-date science-based solutions. It sets a foundation upon which to build stormwater-based asset management approaches.

6 RECOMMENDATIONS

This study relied on surface runoff modeling to make conclusions about the benefits of GI SCM implementation for achieving goals of storm volume and TN load reduction. A more robust assessment would take into account the Tisbury stormwater routing network, including lengths and sizes of storm drains, as well as any reduced capacity in the system due to sedimentation in the pipes and clogged catch basins. Additionally, flow-related monitoring data can help inform design options and provide valuable data for future modeling efforts. For example, in-system flow depth, flow rate, and rainfall monitoring to document the frequency and duration of flooding events would be a practical and inexpensive approach to more fully inform Tisbury of the potential benefits of the GI SCM approach described herein. For example, a more detailed hydraulic modeling analysis of the business district system could identify an optimal level of an initial phase GI SCM implementation that would yield substantial flood reduction benefits for a manageable investment. Regardless, the analyses and data presented in this report strongly support and clearly demonstrate that it will be in the best interest of the town of Tisbury to begin pursuing the implementation of GI SCM opportunities on both public and private lands.

Specific recommendations for goals are presented below.

<u>Near-term goals (1 to 6 months)</u>

- Review candidate locations for a pilot GI SCM opportunity installation. Consider design options, including rain gardens, infiltration trenches, rain barrels for rooftop disconnection that can be readily implemented in these drainage areas and throughout Tisbury.
- Consider the development and adoption of implementation strategies to opportunistically incorporate GI SCMs into all feasible infrastructure projects on municipal lands and rights of ways and through typical redevelopment and urban renewal projects. This may involve an evaluation of local bylaws/ordinances relating to stormwater management.
- Begin recording flood events, including smaller-scale nuisance flooding. Information to record includes date and location of flooding, total rainfall depth, duration, pictures of the affected area. This information can help better characterize flooding in town with valuable qualitative and quantitative information.
- Clean out catch-basins and other components of the stormwater conveyance system.
- Consider a more frequent and consistent catch basin cleaning schedule.

<u>Intermediate goals (6 months to 1.5 years)</u>

- Adopt generic GI SCMs design templates suitable for Tisbury and gain experience through the installation of pilot stormwater GI SCMs using town labor and equipment or local contractors. Further, investigate optimal site design and supply chain opportunities.
- Adopt long-term GI SCM strategies for opportunistically implementing controls as part of municipal infrastructure-related work and private redevelopment projects.
- Continue community engagement and outreach, use pilot SCM(s) to facilitate community adoption. Enlist community members (e.g., students) for planting rain gardens.
- Update stormwater infrastructure datasets to facilitate future hydraulic modeling of the system. Municipal GIS stormwater infrastructure datasets lack some data and appear to show some discrepancies with on-the-ground observations. Additional information that would facilitate hydraulic modeling includes dimensions, such as depth, width, and invert elevations of catch basins, conveyance pipes, and outlets. Update the attribute table describing catch basins that are 'good', 'need cleaning' and 'need repair'.
- To the extent possible, incorporate the results of this project into the Federal Emergency Management Agency (FEMA) Hazard Mitigation Plans (HMP). Although not all green infrastructure projects meet FEMA funding criteria, the small-scale GI is potentially eligible for FEMA funding if the project meets certain requirements. Implementation of small-scale GI can demonstrate a tangible effect on flooding, particularly when implemented town-wide or areawide.

Also, DPW personnel can implement small-scale GI flexibly and cost-effectively. As stormwater-related flooding is highly correlated with impervious cover, projects or other efforts (e.g., ordinance/bylaws) aimed at reducing impervious cover, particularly in combination with green infrastructure, can be effective strategies to include in Hazard Mitigation Plans.

Long-term goals (1.5 – 5 years)

- Use lessons learned from the pilot GI SCM implementation site to facilitate additional implementations on both private and public land.
- Continue to implement long-term strategies for installing GI SCMs throughout Tisbury as opportunities arise (e.g., municipal infrastructure work and redevelopment projects)
- Ensure that GI SCM opportunities receive adequate maintenance.
- Conduct a detailed hydrologic and hydraulic study that incorporates the rainfall-runoff analysis, simulation of the GI SCM being installed on the ground, and flow routing through the storm drain system accounting the backwater effects due to tidal influence at the outfall locations.

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APPENDIX-A TECHNICAL INFORMATION FOR USE AND APPLICATION OF PERFORMANCE CURVES FOR INDICATOR BACTERIA.

APPENDIX-B TECHNICAL SUPPORT DOCUMENT (TSD): Next-Generation Stormwater Management

APPENDIX-C: AN INVENTORY OF GIS DATASETS

APPENDIX-D: SUMMARY OF HRU AREA, RUNOFF, AND TOTAL NITROGEN LOADS

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