HOLISTIC WATERSHED MANAGEMENT FOR EXISTING AND FUTURE LAND USE DEVELOPMENT ACTIVITIES: OPPORTUNITIES FOR ACTION FOR LOCAL DECISION MAKERS: PHASE 2 – FDC APPLICATION MODELING (FDC 2A PROJECT)

SUPPORT FOR SOUTHEAST NEW ENGLAND PROGRAM (SNEP) COMMUNICATIONS STRATEGY AND TECHNICAL ASSISTANCE

FINAL PROJECT REPORT

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EXECUTIVE SUMMARY

Holistic watershed management considers hydrological interactions and the impacts of hydromodifications across all flow regimes. Both surface water infiltration and groundwater recharge are connected aspects of a single process of stormwater management. The spatial and temporal magnitude of that process has hydrological, water quality, and economical implications. A Flow Duration Curve (FDC) is a temporal summary of hydrology, which can be generated for different conditions including current/historical and future/managed hydrological conditions (Figure ES-1). This report presents a quantitative analysis of FDCs and other associated metrics for understanding the impact of land use decision-making on freshwater flow regimes and ecosystem health. These analyses are based on long-term continuous hydrologic models developed under Phase 1 of this project for the Taunton River Basin in eastern Massachusetts using the Loading Simulation Program in C++ (LSPC) and EPA's stormwater best management practices optimization (Opti-Tool) models. The goal of this report (Phase 2A) is to conceptualize, evaluate, and communicate the costs and benefits of next-generation conservation-focused development and stormwater management practices.

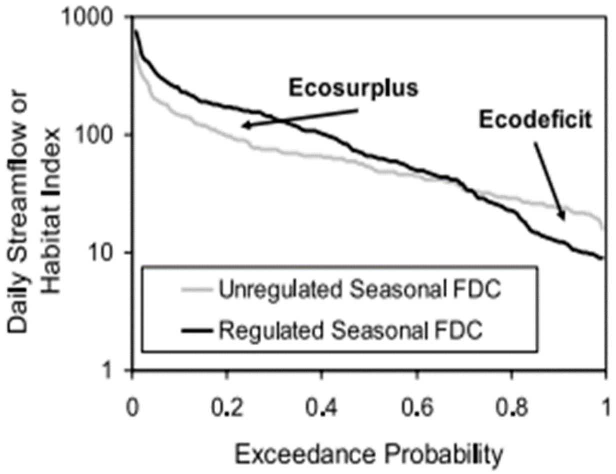

Figure ES-1. FDC example showing ecodeficit and ecosurplus regions between unregulated (predevelopment) and regulated (post-development) conditions (from Vogel et al., 2007).

The project goals are demonstrated by modeling and evaluating stormwater control measures (SCMs) [also commonly called Best Management Practices (BMPs)] in several scenarios at three different spatial scales: (1) individual SCMs, (2) development project scale involving conservation-focused conceptual new and redevelopment sites, and (3) a small, urbanized watershed using both historical and future projections of land use and climate. Evaluating the performance of these SCMs using continuous long-term simulations, as opposed to conventional design practices based on a few synthetic design storms, provides a more realistic and holistic representation of SCM performance. The SCMs evaluated include conventionally sized Municipal Separate Storm Sewer Systems (MS4) and conservation-focused infiltration SCMs (High control) that are sized to maintain predevelopment hydrologic and nutrient export conditions (Table ES-1).

Table ES-1. Selected sizing requirements for conventional MassDEP/MS4 and conservation-focused High control surface and subsurface SCMs by Hydrologic Soil Group (HSG)

HSG	Required TP Reduction (%)		Required Capture for Groundwater Recharge (in)		
	MassDEP/MS4	High	MassDEP/MS4	High	
				Surface Infiltration	Subsurface Infiltration
A	60%	**98%**	0.60	0.36	0.56
B	60%	**93%**	0.35	0.46	0.60
C	60%	**86%**	0.25	0.50	0.68
D	60%	77%	0.10	**0.86**	**1.25**

* Bold values represent the parameter controlling SCM size

Results presented in this report indicate that individual conservation-focused infiltration SCMs, can achieve significant reductions in annual average Total Nitrogen (TN) and Total Phosphorous (TP) load (see Table ES-2), while also achieving predevelopment annual groundwater recharge targets. These High control SCMs outperform conventionally sized MS4 control SCMs assuming varying soil permeabilities and associated infiltration rates. When individual High control SCMs are combined within a new or redevelopment site, they can be configured as a system to achieve goals such as maintaining resilient, predevelopment hydrology (e.g., recharge and peak runoff rates) with little to no net increase in nutrient loads. This was demonstrated for a high-density residential site, a high-density commercial site, and a low-density residential site in this report.

Table ES-2. Average annual pollutant reductions (%) for individual conventional (MS4) and conservation (High) control SCMs

SCM Category	HSG	Infiltration Rate (in/hr)	Flow Volume		TSS		TN		TP		Zn	
			MS4	High	MS4	High	MS4	High	MS4	High	MS4	High
Infiltration Basin	A	8.27	89%	91%	99%	99%	97%	98%	98%	99%	99%	99%
		2.41	82%	89%	99%	100%	97%	98%	96%	98%	99%	100%
	B	1.02	56%	76%	99%	100%	88%	96%	84%	94%	97%	99%
		0.52	49%	76%	99%	100%	87%	96%	81%	94%	97%	99%
	C	0.27	34%	61%	98%	100%	81%	93%	70%	88%	96%	99%
		0.17	29%	58%	98%	100%	81%	93%	69%	87%	96%	99%
	D	0.1	22%	41%	99%	100%	79%	90%	65%	81%	95%	98%
		0.05	18%	36%	99%	100%	82%	92%	68%	83%	97%	99%
Infiltration Trench	A	8.27	79%	91%	98%	99%	95%	98%	94%	98%	96%	99%
		2.41	71%	90%	98%	100%	94%	99%	91%	98%	95%	99%
	B	1.02	46%	78%	95%	99%	86%	97%	76%	94%	89%	98%
		0.52	40%	76%	95%	99%	86%	97%	72%	93%	88%	98%
	C	0.27	33%	61%	96%	99%	85%	95%	69%	87%	87%	96%
		0.17	29%	57%	96%	99%	85%	95%	68%	87%	88%	96%
	D	0.1	22%	38%	96%	99%	85%	92%	66%	80%	87%	94%
		0.05	17%	35%	97%	99%	87%	95%	69%	84%	89%	96%

One of the key comparisons made in this report is the reduction in pollutants for a watershed with conventional SCMs based on current MassDEP and MS4 standards and a watershed with conservation-focused infiltration SCMs. This was evaluated using the Upper Hodges Brook subwatershed, a small urbanized subwatershed within the Taunton River Basin, which was selected as a pilot for this study. This comparison is visualized in Figure ES-2. With Conservation Development (High control SCMs and regulations that require treating flow from 80% of impervious cover [assumed 1/8th of an acre land disturbance threshold for stormwater (SW) management requirements to apply]) the watershed's TP load is reduced by 64% compared to 20% for the Business-as-Usual scenario (current MS4 post-construction level of control SCMs and 30% of IC area treated [assumed for the 1-acre land disturbance threshold applicable to the MS4 post construction requirements]). FDCs for these comparisons are presented in the report and illustrate impacts on the flow regime of Upper Hodges Brook. Across the FDCs, the amount of flow above or below the predeveloped condition curve can be summarized as ecosurpluses and ecodeficits, respectively. Compared to the Business-as-Usual scenario, the Conservation Development scenario indicates promising results for minimizing impacts by showing reduced ecosurpluses and essentially eliminated ecodeficits.

The SCMs evaluated in this report represent structural infiltration controls for capturing and treating runoff from impervious surfaces. While the performance of Conservation Development SCMs at the SCM scale and site scale represents a marked improvement over conventional stormwater management designs and development approaches, at the watershed scale their impact ultimately depends on the amount of impervious cover and the percentage of that IC that is being treated or will be treated as future development occurs. Thus, regulatory thresholds specifying land disturbance or impervious cover area that trigger SW management requirements at the site scale (e.g., 1/8th,1/4th, 1/2-acres of disturbance) become an essential consideration for developing and adopting local SW management standards to build community resilience. Also, how newly created pervious landscapes (e.g., conversion of forest to managed grass area) are addressed by local land development and SW management is another opportunity to minimize future impacts. Protective stormwater management requires multifaceted approaches including structural controls, as well as source controls including restoration of disturbed soils, careful fertilizer use, and pet waste collection to be most effective and achieve the desired goals. Evaluating the impact of a combination of structural and source controls at the watershed scale in future work would provide valuable insights for next-generation conservation development and stormwater management.

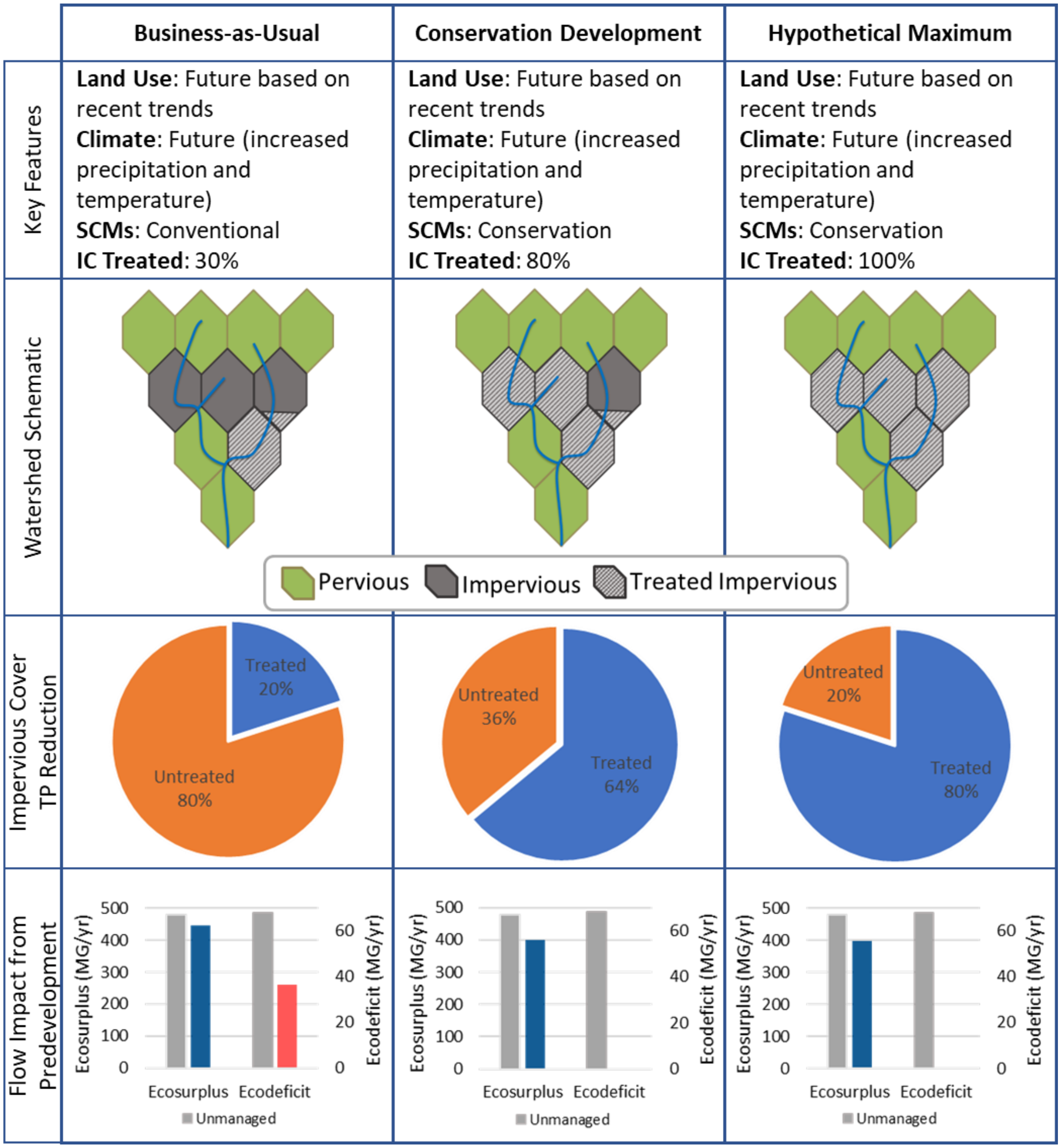

Figure ES-2. Summary information for Business-as-Usual, Conservation development, and hypothetical maximum watershed management scenarios and their impact on Total Phosphorous and flow regime in the Upper Hodges Brook watershed.

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1. INTRODUCTION

Stormwater management is a key component of holistic watershed management to minimize the impact of development on freshwater ecosystems. The health of these ecosystems is influenced by the characteristics of a long-term flow regime (Walsh et al., 2016); however, stormwater management is largely focused on matching pre-development peak flow for a small set of design storms. The purpose of this project has been to (1) demonstrate the use of flow duration curves (FDCs) as a more holistic metric for stormwater management (Phase 1) and (2) envision the next generation of stormwater management structures, regulations, and bylaws (Phase 2).

Land use decision-making, especially in terms of the extent and connectedness of impervious cover (IC), is a driving factor behind changes to freshwater flow regimes and ecosystem health. FDCs provide a powerful tool to illustrate the effect of land use decision-making at scales ranging from large basins to individual sites. Through FDC application at the site scale, potential next-generation local regulatory options (i.e., municipal bylaws/ordinances that address stormwater management and site development activities) can be conceptualized and evaluated. This information can help to inform land use planning by local decision-makers, particularly for new development and/or redevelopment (nD/rD). Quantifying hydrologic, water quality, and other impacts, as well as implementation costs and benefits of potential management solutions (in part by applying the FDC and continuous modeling simulation approaches at the site scale), will facilitate municipal practitioner appreciation of how nD/rD impacts water quality, flooding frequency and duration, channel stability, ecohydrological function, and hydrogeomorphology. With increased appreciation for land use impacts at multiple scales, the next generation of nD/rD practices for robust stormwater management, here termed Conservation Development (CD) practices, can be envisioned.

As contemplated here, CD practices promote the conservation of site-scale ecology to help ensure the preservation of pre-development-like hydrology, hydrogeology, pollutant export, and ecological diversity and vitality. Such practices are anticipated to include, among others, a de-emphasis of impervious cover (e.g., primarily access roads, driveways, parking lots, and rooftops), and increased reliance on low-impact development (LID) practices that emphasize next-generation site design and green infrastructure (GI) management practices (e.g., dispersed hydrologic controls and soil management practices), architecture (e.g., green roofs, LID) and landscape architecture. Additionally, CD practices can emphasize the value of permeable vegetated land cover including opportunities for local agriculture uses to increase the sustainability of local food systems and the use of forest canopy and landscape architecture to promote evapotranspiration for hydrologic benefits and to offset the "heat island effect" that results from excessive IC.

A key component of the evaluation of CD practices is consideration of projected future land use and climate conditions. Recent research from the New England Landscape Futures (NELF) project indicates that recent land cover changes over the 1990-2010 period are based on the conversion of forests into low- and high-density development, as well as some land conservation within core forests (Thompson et al., 2017). Over time, the impact of these development trends, without additional management, will continue to reduce evapotranspiration (ET) and carbon sequestration, as well as increase pollutant load carried by greater volumes of stormwater runoff. The impact of future development on hydrologic regimes and ecosystem conditions will be compounded by the effects of an uncertain and changing climate. Projections of future climate in the Massachusetts Climate Change Report (MA EOEE, 2011) estimate that annual precipitation in the state will increase 5-8% in 2035-2064 and 7-14% in the period 2070-2099, with increased precipitation rates especially occurring during winter months (Hayhoe et al., 2006). Similar trends are expected for the entire New England region.

This project is about envisioning a different future in watershed management. Phase 1 (Paradigm Environmental and Great Lakes Environmental Center, 2021) demonstrated the utility of FDCs and provided a foundation for Phase 2 to develop an understanding between FDCs and watershed development. In Phase 2, practitioners were asked to compare and consider likely scenarios ranging from inaction (status quo policies) to actions that incorporate flooding risks, stream-channel stability, increased pollutant export and reduced base flows. These insights were used in Phase 2A (presented in this report) and Phase 2B (presented in a companion report), which conceptualizes site-scale CD practices and next-generation by-laws/ordinances. The Phase 2A work documented in this report uses FDCs and other metrics to communicate the impacts of watershed management decision-making for a wide range of scenarios, including future status quo development and stormwater management which are compared to CD practices at the site- and watershed scales for historical and future climate conditions. By quantifying and communicating these impacts, practitioners can have an increased appreciation of the impact of nD/rD on the future of their watersheds and glean the future of a watershed managed for optimal sustainability and resilience, compared to one that acquiesces, or continues to facilitate by inertia, the phenomenon of "urban sprawl."

2. GIS DATA REVIEW FOR THE TAUNTON RIVER WATERSHED

The Phase 2 methodology uses previously acquired data from MassGIS (Bureau of Geographic Information) during Phase 1, as well as new sources of future land use - land cover data from the NELF project. The subset of data used for Phase 2 is shown in Table 2-1.

Table 2-1. Landscape GIS data

Description	Dataset	Data Type	Period	Resolution	Source
Baseline Land Use-Land Cover	LULC_2016	polygon	2016	-	MassGIS
Future Land Cover	Recent_Trends_2010	raster	1990-2010	30m	NELF
	Recent_Trends_2060	raster	2010-2060	30m	NELF
Municipalities	Towns	polygon	2020	-	MassGIS
Buildings	Structures	polygon	2019	-	MassGIS
Baseline HRUs	Baseline_HRUs_2016	raster	2016	1m	FDC Phase 1

2.1. Baseline Land Use Land Cover Data

MassGIS 2016 land use – land cover (LULC) layer contains a combination of land cover mapping from 2016 aerial imagery and land use derived from standardized assessor parcel information for Massachusetts. It contains both land use and land cover information as separate attributes and can be accessed independently or in a useful combination with one another. For example, it is possible to measure the portions of pervious and impervious surfaces for a commercial parcel. Figure 2-1 shows the land use – land cover map for the Taunton River watershed.

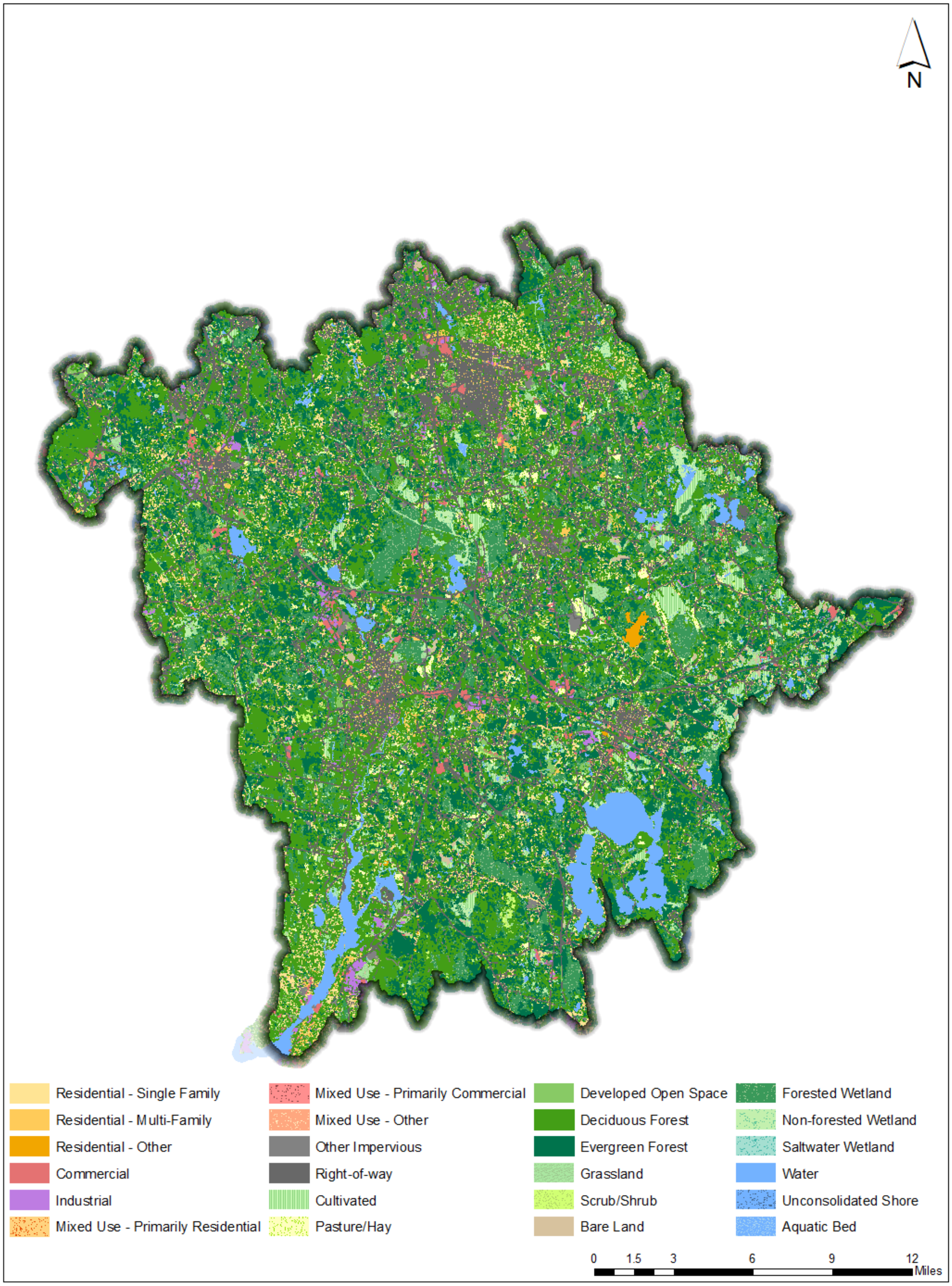


Figure 2-1. A map showing 2016 land use – land cover for the Taunton River watershed.

2.2. Future Land Cover Data

NELF is a multi-institutional project with the overarching goal of building and evaluating scenarios that show how land use choices could shape the landscape over the next 50 years. The NELF project envisions potential trends and impacts of landscape change in New England based on community collaboration and expert analysis (NELF, n.d.). Future land cover data (FLULC) representing historical and projected trends was acquired from the NELF project data repository (available on request at: https://databasin.org/groups/26ceb6c7ece64b0d9872e118bae80d41/). These datasets were created with a cellular land-cover change model using satellite imagery from 1990-2010 (Thompson et al., 2017). The historical data represents observed trends from 1990-2010; the statistical relationships of land cover change rate and spatial patterns were then linearly projected to the year 2060 as a baseline business-as-usual scenario (Figure 2-2). Major land cover changes over the 1990-2010 period include forest loss to low- and high-density development, as well as new land conservation (Thompson et al., 2017). Over 50 years between 2010 and 2060, the largest changes in land use across all of New England (not just the Taunton River watershed) were a 37% increase in developed areas and a 123% increase in conserved areas (Thompson et al., 2020). However, the conserved area is concentrated in core forest areas in northern New England (e.g., Maine and Vermont), while the more developed southern areas saw lower land conservation. At 30-m resolution, both of these datasets are consistent with the National Land Cover Databases (NLCD), however, they are limited to land cover projections of seven lumped categories and do not directly estimate the percent imperviousness within the land cover category. Both the Recent Trends 2010 and 2060 datasets, as well as other NELF future scenarios, can be explored on their web viewer.

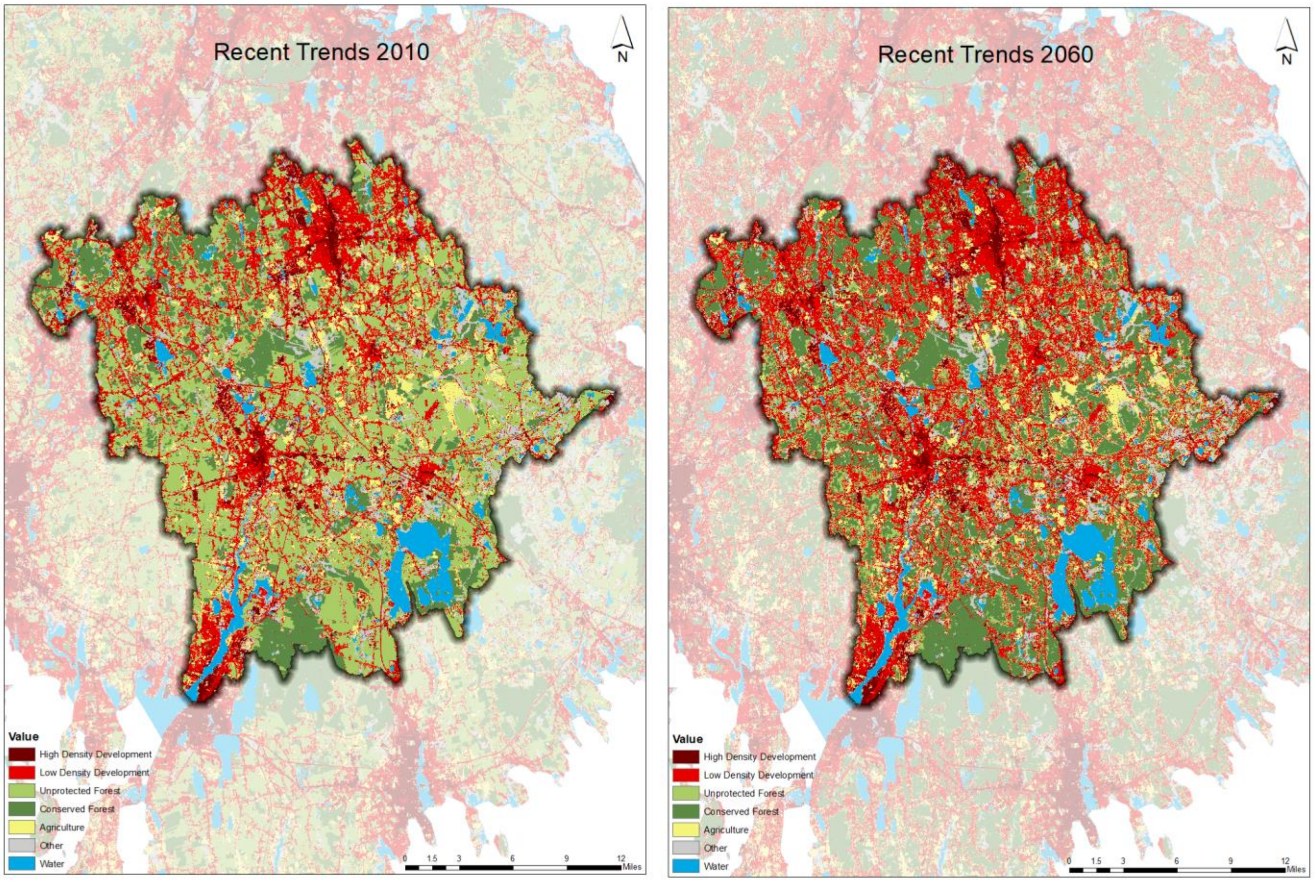


Figure 2-2. A historical land use trend for the year 2010 (left) and projected future land use trend for the year 2060 (right) for the Taunton River watershed.

2.3. Municipalities

MassGIS 2020 municipal boundaries were created by MassGIS by adjusting older U.S. Geological Survey (USGS) topo map town boundaries to connect the survey points of a community. In many areas, boundary creation was simply a matter of "connecting the dots" from one boundary point to the next. Where boundaries follow a stream/river or road right-of-way (ROW) the boundary was approximately delineated using the 2001 Aerial Imagery as a base. Figure 2-3 shows the municipal boundaries within the Taunton River watershed.

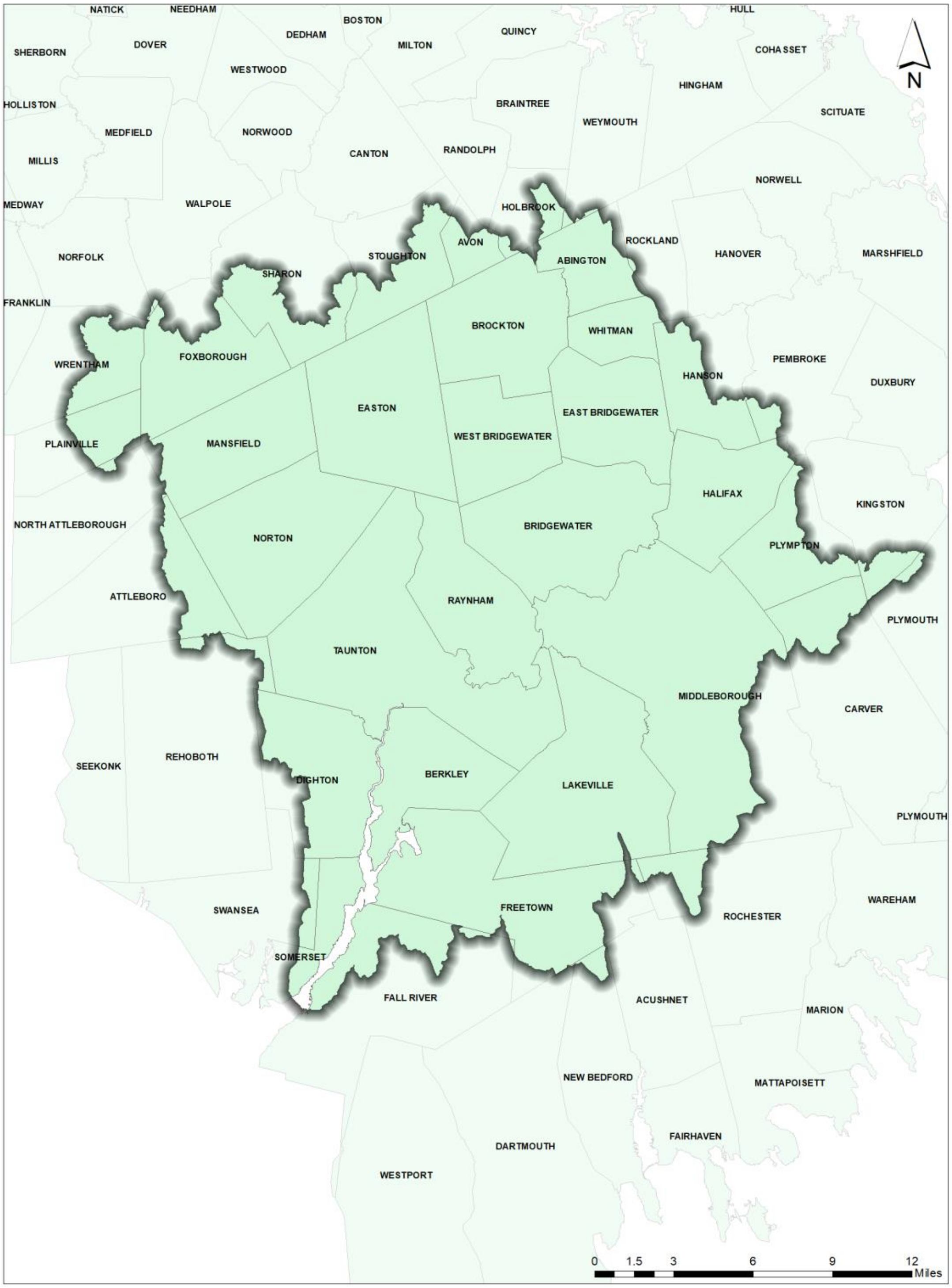


Figure 2-3. A map showing the municipal boundaries in the Taunton River watershed.

2.4. Buildings

MassGIS 2021 buildings dataset consists of 2-dimensional roof outlines ("roof-prints") for all buildings larger than 150 square feet in all of Massachusetts. In 2019, MassGIS refreshed the data to a baseline of 2016 and continues to update features using newer aerial imagery that allows MassGIS staff to remove, modify and add structures to keep up with more current ground conditions. In March 2021, the layer was updated with 2017 and 2018 structure review edits along with the first data edits compiled atop spring 2019 imagery. In July 2021, MassGIS completed the statewide update based on 2019 imagery. Figure 2-4 shows the building boundaries within the Taunton River watershed.

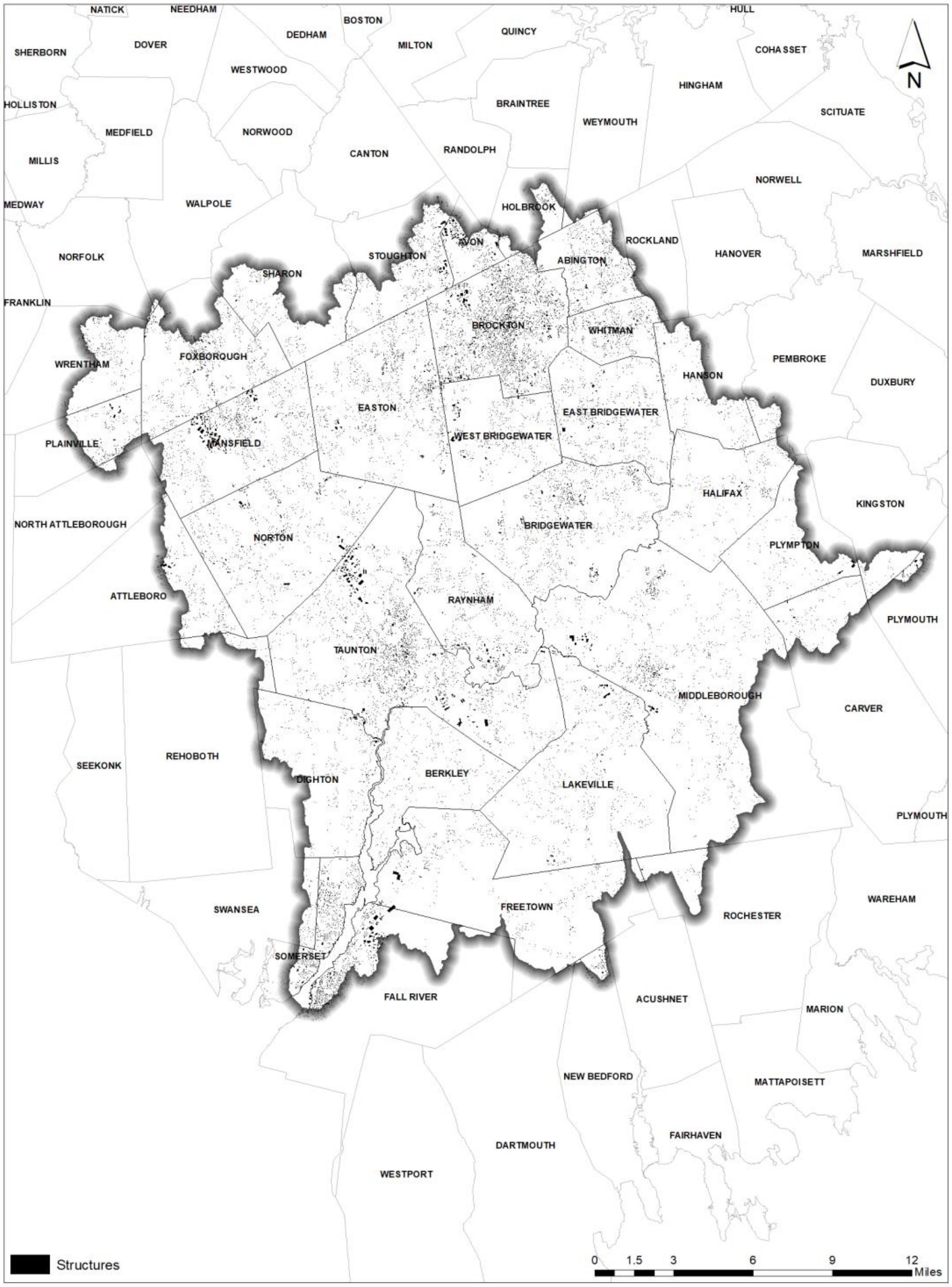


Figure 2-4. A map showing the building footprints in the Taunton River watershed.

2.5. Baseline HRUs Layer

Hydrologic Response Units (HRUs) are key components of watershed modeling and spatially represent areas of similar physical characteristics that drive watershed hydrology and water quality. A baseline HRU layer representing the land use, land cover, soil, and slope characteristics in the Taunton River watershed was developed during Phase 1 of the FDC project (Paradigm Environmental and Great Lakes Environmental Center, 2021). The baseline HRU layer for the Taunton River watershed combines spatial information into a single raster layer with 36 unique categories. The unit-area HRU time series for the baseline conditions were developed using the most recent 20-year period of observed meteorological boundary conditions and calibrating the rainfall-runoff response on each HRU along with reach routing processes in the LSPC model under Phase 1 of the FDC project.

Figure 2-5 shows the spatial overlay process used to develop the baseline HRU categories. During the HRU development process, raw spatial data were reclassified into relevant categories. Table 2-2 shows the reclassification of Mass GIS 2016 land use and land cover data to derive the modeled land use categories in the Opti-Tool. Table 2-3 shows the reclassification of the Soil Survey Geographic (SSURGO) database and the State Soil Geographic (STATSGO2) database to derive the modeled Hydrologic Soil Group (HSG) categories in the Opti-Tool. Table 2-4 shows the reclassification of the percent slope attribute to derive the modeled slope categories in the Opti-Tool. Table 2-5 shows the final 36 HRU categories developed for the Taunton River watershed. Figure 2-6 shows the spatial location of the baseline HRUs in the Taunton River watershed.

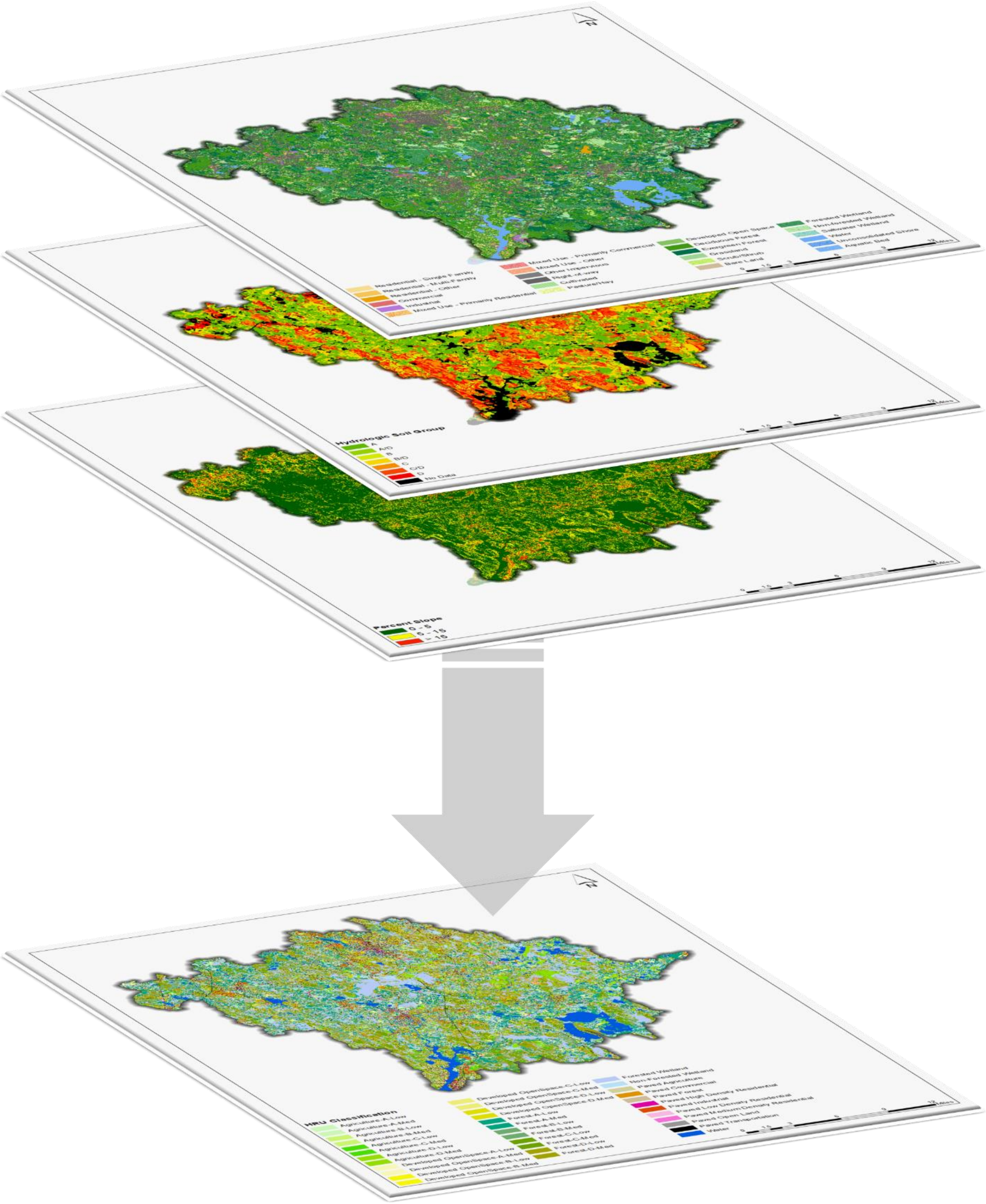


Figure 2-5. Baseline HRUs spatial overlay process (from top to bottom: land use – land cover, soil, and slope layers).

Table 2-2. Land use – land cover reclassification

Land Cover Code	Land Cover Description	Land Use Code	Land Use Description	Land Use Reclassification	Cover Type
2	Impervious	0	Unknown	Paved Open Land	Impervious
2	Impervious	2	Open land	Paved Open Land	Impervious
2	Impervious	3	Commercial	Paved Commercial	Impervious
2	Impervious	4	Industrial	Paved Industrial	Impervious
2	Impervious	6	Forest	Paved Forest	Impervious
2	Impervious	7	Agriculture	Paved Agriculture	Impervious
2	Impervious	8	Recreation	Paved Open Land	Impervious
2	Impervious	9	Tax exempt	Paved Open Land	Impervious
2	Impervious	10	Mixed use, primarily residential	Paved Medium Density Residential	Impervious
2	Impervious	11	Residential - single family	Paved Low Density Residential	Impervious
2	Impervious	12	Residential - multi-family	Paved High Density Residential	Impervious
2	Impervious	13	Residential - other	Paved Medium Density Residential	Impervious
2	Impervious	20	Mixed use, other	Paved Open Land	Impervious
2	Impervious	30	Mixed use, primarily commercial	Paved Commercial	Impervious
2	Impervious	55	Right-of-way	Paved Transportation	Impervious
2	Impervious	88	Water	Paved Open Land	Impervious
5	Developed Open Space	N/A	N/A	Developed Open Space	Pervious
6	Cultivated	N/A	N/A	Agriculture	Pervious
7	Pasture/Hay	N/A	N/A	Agriculture	Pervious
8	Grassland	N/A	N/A	Agriculture	Pervious
9	Deciduous Forest	N/A	N/A	Forest	Pervious
10	Evergreen Forest	N/A	N/A	Forest	Pervious
12	Scrub/Shrub	N/A	N/A	Agriculture	Pervious
13	Palustrine Forested Wetland	N/A	N/A	Forested Wetland	Pervious
14	Palustrine Scrub/Shrub Wetland	N/A	N/A	Non-Forested Wetland	Pervious
15	Palustrine Emergent Wetland	N/A	N/A	Non-Forested Wetland	Pervious
18	Estuarine Emergent Wetland	N/A	N/A	Water	Pervious
19	Unconsolidated Shore	N/A	N/A	Water	Pervious
20	Bare Land	N/A	N/A	Developed Open Space	Pervious
21	Water	N/A	N/A	Water	Pervious
22	Palustrine Aquatic Bed	N/A	N/A	Water	Pervious

Table 2-3. Soil – HSG reclassification

HSG - SSURGO	HSG - STATSGO2	HSG Reclassification	Justification
No Data	A	A	When no other information was available, the STATSGO2 data layer was used to fill the gaps. -
No Data	B	B	
No Data	C	C	
No Data	D	D	
A	N/A	A	
A/D	N/A	D	Dual HSGs were represented, and their undrained condition ('D') was selected as a conservative choice.
B	N/A	B	-
B/D	N/A	D	Dual HSGs were represented, and their undrained condition ('D') was selected as a conservative choice.
C	N/A	C	-
C/D	N/A	D	Dual HSGs were represented, and their undrained condition ('D') was selected as a conservative choice.
D	N/A	D	-

Table 2-4. Percent slope reclassification

Percent Slope	Slope Reclassification
<5%	Low
5% - 15%	Medium
>15%	High

Table 2-5. Summary of final HRU categories

HRU Code	HRU Description	Land Use	Soil	Slope	Land Cover
1000	Paved Forest	Paved Forest	N/A	N/A	Impervious
2000	Paved Agriculture	Paved Agriculture	N/A	N/A	Impervious
3000	Paved Commercial	Paved Commercial	N/A	N/A	Impervious
4000	Paved Industrial	Paved Industrial	N/A	N/A	Impervious
5000	Paved Low Density Residential	Paved Low Density Residential	N/A	N/A	Impervious
6000	Paved Medium Density Residential	Paved Medium Density Residential	N/A	N/A	Impervious
7000	Paved High Density Residential	Paved High Density Residential	N/A	N/A	Impervious
8000	Paved Transportation	Paved Transportation	N/A	N/A	Impervious
9000	Paved Open Land	Paved Open Land	N/A	N/A	Impervious
10110	Developed OpenSpace-A-Low	Developed OpenSpace	A	Low	Pervious
10120	Developed OpenSpace-A-Med	Developed OpenSpace	A	Med	Pervious
10210	Developed OpenSpace-B-Low	Developed OpenSpace	B	Low	Pervious
10220	Developed OpenSpace-B-Med	Developed OpenSpace	B	Med	Pervious
10310	Developed OpenSpace-C-Low	Developed OpenSpace	C	Low	Pervious
10320	Developed OpenSpace-C-Med	Developed OpenSpace	C	Med	Pervious
10410	Developed OpenSpace-D-Low	Developed OpenSpace	D	Low	Pervious
10420	Developed OpenSpace-D-Med	Developed OpenSpace	D	Med	Pervious

HRU Code	HRU Description	Land Use	Soil	Slope	Land Cover
11000	Forested Wetland	Forested Wetland	N/A	N/A	Pervious
12000	Non-Forested Wetland	Non-Forested Wetland	N/A	N/A	Pervious
13110	Forest-A-Low	Forest	A	Low	Pervious
13120	Forest-A-Med	Forest	A	Med	Pervious
13210	Forest-B-Low	Forest	B	Low	Pervious
13220	Forest-B-Med	Forest	B	Med	Pervious
13310	Forest-C-Low	Forest	C	Low	Pervious
13320	Forest-C-Med	Forest	C	Med	Pervious
13410	Forest-D-Low	Forest	D	Low	Pervious
13420	Forest-D-Med	Forest	D	Med	Pervious
14110	Agriculture-A-Low	Agriculture	A	Low	Pervious
14120	Agriculture-A-Med	Agriculture	A	Med	Pervious
14210	Agriculture-B-Low	Agriculture	B	Low	Pervious
14220	Agriculture-B-Med	Agriculture	B	Med	Pervious
14310	Agriculture-C-Low	Agriculture	C	Low	Pervious
14320	Agriculture-C-Med	Agriculture	C	Med	Pervious
14410	Agriculture-D-Low	Agriculture	D	Low	Pervious
14420	Agriculture-D-Med	Agriculture	D	Med	Pervious
15000	Water	Water	N/A	N/A	Pervious

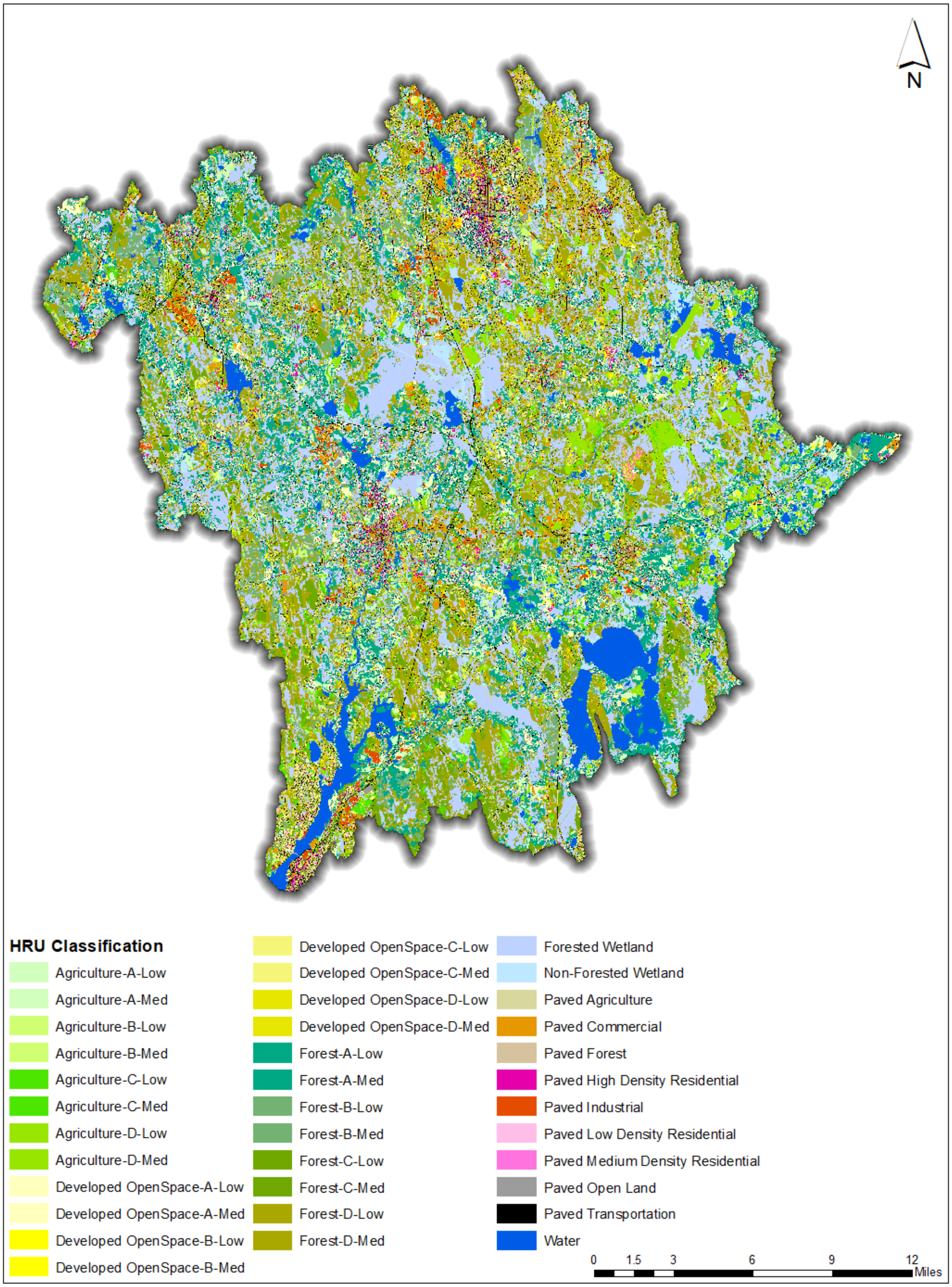


Figure 2-6. A map showing the 2016 baseline HRU raster layer for the Taunton River watershed.

3. DEVELOPMENT OF FUTURE HRU LAYER FOR TAUNTON RIVER WATERSHED

To simulate future hydrological conditions within the Taunton River watershed, the NELF projected 2060 land cover datasets were analyzed and processed to update the 2016 baseline HRU layer. The baseline HRUs were built with high-resolution (1-m) impervious cover data across the Taunton River watershed. However, the projected 2060 land cover data is at 30-m; this coarser resolution also does not provide the percent imperviousness associated with the given land use classification which is needed to develop HRUs. Additionally, the land use classification is much coarser and does not differentiate between commercial, industrial, residential, and open space but instead is lumped into just two developed categories: high-density and low-density development. The methodology to develop a 1-m resolution future HRU layer consistent with the baseline HRU layer includes five main steps:

1. Compare the land cover change between the recent trends 2010 and 2060 NELF datasets and preserve the spatial footprints for the developed areas presented in the 2060 NELF dataset for developing the future HRU layer for the Taunton River watershed.
2. Establish mapping rules between the major land use categories used in the Opti-Tool and the land use categories used in the NELF dataset. These rules define how to disaggregate the two developed land use (high-density and low-density) classifications from the NELF dataset into 7 major developed land use (commercial, industrial, high-density residential, medium-density residential, low-density residential, open land, and transportation) classifications for the Opti-Tool.
3. Estimate the percent imperviousness rules for the 7 major developed land use categories established in step 2 by using the MassGIS 2016 land use – land cover dataset for the Taunton River watershed. These rules are assumed to remain the same at different spatial extents. For example, the percent imperviousness for commercial land use remains the same for future development areas regardless of where they are located in the watershed. The projected future commercial areas in any municipal boundary will have the same percent imperviousness as it is overall in the Taunton River watershed based on the MassGIS 2016 land use - land cover dataset.
4. Estimate the area distribution rules between the 7 major developed land use categories (i.e., commercial, industrial, high-density residential, medium-density residential, low-density residential, open space, and transportation) by the municipality within the Taunton River watershed. Apply these rules to new development areas to break down the two developed NELF categories (high-density and low-density) into 7 developed Opti-Tool categories at the municipal level. These rules are derived at the municipality level and remain the same within the given municipal boundary but can vary from one municipality to another. It is assumed that area distribution between developed land use categories follows the same trend for the projected 2060 future land use – land cover classification.
5. Identify the undeveloped areas from the baseline HRU layer that are subject to future development based on an overlay with the 2060 NELF dataset and apply the rules established in steps 3 and 4 at the municipality level. Apply the peppered raster method developed in Phase 1 of the FDC project to convert one-to-many HRU categories using the probabilistic raster reclassification algorithm. For example, if there are 100 acres of forest category within a given municipality that is subject to high-density development, then those acres are split into paved commercial, paved industrial, paved high-density residential, paved transportation, and developed open space based on the established area distribution rules of those developed categories within the same municipal boundary. The underlying soil (i.e., HSG) and slope classifications remain the same as in the baseline HRU layer.

The following sections provide more detail on the process of developing the future HRU raster layer and summarize the change in the baseline HRUs due to the projected future development in the Taunton River watershed.

3.1. Land Cover Change Between 2010 and 2060 NELF Dataset

Within the Taunton River watershed, both low- and high-density development increased between the NELF 2010 and 2060 recent trend datasets (Table 3-1). This is generally due to the conversion of unprotected forest areas to developed areas. However, the recent trends underpinning the NELF datasets also indicate an increase in conserved forests. The baseline HRUs developed under Phase 1 of the FDC project use higher resolution MassGIS 2016 land use – land cover data, so the NELF 2060 projected future dataset was overlayed with the baseline HRU layer to identify the areas subject to projected future development.

Table 3-1. NELF recent trend 2010 and 2060 land cover comparison

NELF Land Use Classification	Recent Trend 2010 (acre)	Recent Trend 2060 (acre)	Change (%)
Agriculture	23,735	24,568	4%
Conserved Forest	44,372	79,238	79%
High Density Development	14,889	20,906	40%
Low Density Development	79,795	112,477	41%
Other	32,758	32,758	0%
Unprotected Forest	129,871	55,474	-57%
Water	16,032	16,032	0%

3.2. Mapping Between Opti–Tool and NELF Land Use Classification

Table 3-2 shows a mapping table between NELF, Continuous Change Detection and Classification (CCDC), and NLCD datasets. These datasets were used in the NELF project and, where CCDC data was not available, NLCD data was used to fill the gaps. The CCDC and NLCD maps were reclassified to a common legend consisting of High-Density Development, Low-Density Development, Forest, Agriculture, Water, and a composite "Other" class for developing the NELF datasets (Thompson et al., 2017). Based on the land use description shown in Table 3-2, new mapping rules were developed to disaggregate the NELF classification into the Opti-Tool land use classification as shown in Table 3-3. These mapping rules are assumed to remain the same across any municipal boundary within the Taunton River watershed.

Table 3-2. Reclassification Scheme for CCDC and NLCD Data for NELF Land Cover (Thompson et al., 2017)

NELF Classification	CCDC Class	CCDC Class Description	NLCD 2001/2011 Class	NLCD 2001/2011 Class Description
High Density Developed	Commercial/ Industrial	Area of urban development; impervious surface area target 80-100%	Developed High Intensity	Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, rowhouses, and commercial /industrial. Impervious surfaces account for 80% to 100% of the total cover.

NELF Classification	CCDC Class	CCDC Class Description	NLCD 2001/2011 Class	NLCD 2001/2011 Class Description
	High Density Residential	Area of residential urban development with some vegetation; impervious surface area target 50-80%	Developed, Medium Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
Low Density Developed	Low Density Residential	Area of residential urban development with significant vegetation; impervious surface area target 0-50%	Developed, Low Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
			Developed, Open Space	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
Agriculture	Agriculture	Non-woody cultivated plants; includes cereal and broadleaf crops	Pasture/Hay	Areas of grasses, legumes, or grass-legume mixtures are planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
			Cultivated Crops	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.

NELF Classification	CCDC Class	CCDC Class Description	NLCD 2001/2011 Class	NLCD 2001/2011 Class Description
Forest	Mixed Forest	Forested land with at least 40% tree canopy cover comprising no more than 80% of either evergreen needle leaf or deciduous broadleaf cover	Mixed Forest	Areas dominated by trees are generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of the total tree cover.
	Deciduous Broadleaf Forest	Forested land with at least 40% tree canopy cover comprising more than 80% deciduous broadleaf cover	Deciduous Forest	Areas dominated by trees are generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
	Evergreen Needleleaf Forest	Forested land with at least 40% tree canopy cover comprising more than 80% evergreen needle leaf cover	Evergreen Forest	Areas dominated by trees are generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
	Woody Wetland	An additional class of wetland that tries to separate wetlands with considerable biomass from mainly herbaceous wetlands	Woody Wetlands	Areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
			Shrub/Scrub	Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions.
Other	Wetland	Vegetated land (woody and non-woody) with inundation from high water table; includes swamps, salt, and freshwater marshes and tidal rivers/mudflats	Emergent Herbaceous Wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

NELF Classification	CCDC Class	CCDC Class Description	NLCD 2001/2011 Class	NLCD 2001/2011 Class Description
	Herbaceous / Grassland	Non-woody naturally occurring or slightly managed plants; includes pastures	Barren Land (Rock/Sand/Clay)	Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, dunes, strip mines, gravel pits, and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
	Bare	Non-vegetated land comprised of above 60% rock, sand, or soil		
Water	Water	Lakes, ponds, rivers, and ocean	Open Water	Areas of open water, generally with less than 25% cover of vegetation or soil.

Table 3-3. Mapping table between NELF and Opti-Tool land use classification

NELF ID	NELF Land Use Classification	Opti-Tool Land Use Classification
1	High Density Development	Commercial
		Industrial
		High-Density Residential
		Transportation
2	Low Density Development	Low-Density Residential
		Medium-Density Residential
		Open Land
		Transportation
3	Unprotected Forest	Forest
4	Conserved Forest	
5	Agriculture	Agriculture
6	Other	Wetland
7	Water	Water

3.3. Percent Imperviousness for Developed Land Use Classification

Using the MassGIS 2016 land use – land cover dataset, the percent imperviousness was estimated for the 7 developed land use categories used in the Opti-Tool (Table 3-4). As well as the total percentage of IC, the percent of IC from buildings (i.e., roof-area) was calculated for each developed land use classification. These rules were developed at the Taunton River watershed scale and are assumed to hold at any spatial scale within the Taunton River watershed. For example, the projected future commercial land use in any municipality within the Taunton River watershed will have 66.8% impervious area, with 23.8% building rooftops representing 23.8% of that total IC.

Table 3-4. Summary of percent imperviousness for developed land use classification

Developed Land Use Classification	Total Impervious Cover (%)	Buildings (% of Total IC)
Commercial	66.8%	23.8%
Industrial	75.3%	38.2%
High-Density Residential	51.4%	35.4%
Transportation	80.6%	0.0%
Low-Density Residential	31.5%	40.1%
Medium-Density Residential	43.0%	29.5%
Open Land	30.0%	19.9%

3.4. Developed Land Use Distribution by Municipality in Taunton River Watershed

For each municipality within the Taunton River watershed, the breakdown of developed land use area was calculated from the MassGIS 2016 land use – land cover data. This allowed conversion between the NELF and Opti-Tool classes (as shown in Table 3-3). Table 3-5 summarizes high-density developed areas into commercial, industrial, high-density residential, and transportation categories. Table 3-6 summarizes the breakdown of low-density developed areas into low-density residential, medium-density residential, open space, and transportation categories. These rules were developed at the municipality level to allow different development patterns across different municipalities based on the baseline development trends. It was assumed that the area distribution between the developed land use categories shown in Table 3-5 and Table 3-6 holds for the projected future development within the same municipal boundary.

Table 3-5. Summary of high-density development land use area distribution by municipality in the Taunton River watershed

Municipality		High-Density Development (MassGIS 2016)			
ID	Name	Commercial	Industrial	High Density Residential	Transportation
1	ABINGTON	40.5%	0.7%	34.4%	24.4%
16	ATTLEBORO	10.3%	43.8%	16.3%	29.6%
18	AVON	28.8%	38.0%	5.3%	27.9%
27	BERKLEY	31.6%	4.7%	27.7%	36.0%
42	BRIDGEWATER	22.9%	11.7%	40.7%	24.7%
44	BROCKTON	34.8%	8.9%	31.8%	24.5%
52	CARVER	43.2%	7.3%	6.0%	43.6%
72	DARTMOUTH	32.3%	16.2%	24.8%	26.7%
76	DIGHTON	35.8%	20.6%	16.1%	27.5%
83	EAST BRIDGEWATER	27.2%	19.3%	26.1%	27.4%
88	EASTON	32.4%	15.2%	26.8%	25.7%
95	FALL RIVER	16.3%	28.0%	30.2%	25.5%
99	FOXBOROUGH	39.4%	8.1%	20.1%	32.4%
102	FREETOWN	23.9%	38.0%	6.4%	31.6%
118	HALIFAX	34.7%	6.9%	35.0%	23.4%
123	HANSON	28.4%	24.7%	20.1%	26.8%

Municipality		High-Density Development (MassGIS 2016)			
ID	Name	Commercial	Industrial	High Density Residential	Transportation
133	HOLBROOK	36.2%	14.3%	18.7%	30.8%
145	KINGSTON	0.0%	0.0%	62.7%	37.3%
146	LAKEVILLE	37.0%	21.7%	15.7%	25.6%
167	MANSFIELD	25.1%	31.6%	15.2%	28.2%
182	MIDDLEBOROUGH	38.8%	10.3%	19.1%	31.9%
201	NEW BEDFORD	33.9%	0.0%	30.3%	35.8%
208	NORFOLK	32.3%	16.2%	24.8%	26.7%
211	NORTH ATTLEBOROUGH	64.9%	0.0%	0.0%	35.1%
218	NORTON	21.2%	19.9%	32.2%	26.7%
231	PEMBROKE	20.6%	9.6%	41.5%	28.3%
238	PLAINVILLE	46.0%	8.1%	20.9%	25.0%
239	PLYMOUTH	61.0%	0.0%	24.4%	14.6%
240	PLYMPTON	54.1%	9.9%	8.6%	27.3%
245	RAYNHAM	46.5%	9.5%	15.0%	28.9%
247	REHOBOTH	31.5%	0.0%	37.9%	30.5%
250	ROCHESTER	0.0%	0.0%	63.3%	36.7%
251	ROCKLAND	53.3%	0.0%	20.1%	26.6%
266	SHARON	47.4%	0.3%	10.3%	42.0%
273	SOMERSET	36.5%	12.8%	23.7%	27.0%
285	STOUGHTON	29.4%	34.4%	8.1%	28.1%
292	SWANSEA	9.4%	0.0%	61.2%	29.5%
293	TAUNTON	32.1%	12.0%	32.7%	23.3%
307	WALPOLE	32.3%	16.2%	24.8%	26.7%
322	WEST BRIDGEWATER	34.2%	26.6%	11.3%	27.8%
336	WEYMOUTH	0.1%	0.0%	65.9%	34.0%
338	WHITMAN	26.8%	12.5%	34.3%	26.3%
350	WRENTHAM	30.9%	5.6%	29.5%	34.0%

Table 3-6. Summary of low-density development land use area distribution by the municipality in the Taunton River watershed

Municipality		Low-Density Development (MassGIS 2016)			
ID	Name	Medium Density Residential	Low Density Residential	Open Land	Transportation
1	ABINGTON	0.6%	64.6%	20.4%	14.4%
16	ATTLEBORO	0.0%	72.9%	10.9%	16.1%
18	AVON	0.2%	57.9%	27.3%	14.6%
27	BERKLEY	5.7%	58.5%	12.9%	22.9%
42	BRIDGEWATER	1.3%	51.4%	32.8%	14.6%

Municipality		Low-Density Development (MassGIS 2016)			
ID	Name	Medium Density Residential	Low Density Residential	Open Land	Transportation
44	BROCKTON	0.6%	52.5%	32.8%	14.1%
52	CARVER	1.6%	59.2%	12.3%	26.8%
72	DARTMOUTH	2.1%	57.1%	24.9%	15.9%
76	DIGHTON	3.2%	53.5%	28.0%	15.3%
83	EAST BRIDGEWATER	1.8%	61.0%	21.5%	15.7%
88	EASTON	0.2%	58.4%	26.9%	14.6%
95	FALL RIVER	2.1%	41.6%	42.0%	14.3%
99	FOXBOROUGH	1.3%	54.8%	24.8%	19.1%
102	FREETOWN	6.2%	52.3%	24.1%	17.4%
118	HALIFAX	4.0%	66.3%	15.9%	13.8%
123	HANSON	1.9%	58.8%	24.3%	14.9%
133	HOLBROOK	1.2%	72.5%	8.4%	17.9%
145	KINGSTON	0.0%	31.0%	42.7%	26.3%
146	LAKEVILLE	0.7%	67.9%	17.3%	14.0%
167	MANSFIELD	0.5%	66.1%	17.9%	15.4%
182	MIDDLEBOROUGH	10.7%	50.6%	19.4%	19.3%
201	NEW BEDFORD	0.9%	62.4%	14.1%	22.7%
208	NORFOLK	0.0%	89.4%	0.2%	10.4%
211	NORTH ATTLEBOROUGH	0.0%	70.4%	9.3%	20.2%
218	NORTON	3.1%	59.0%	22.3%	15.6%
231	PEMBROKE	1.2%	69.3%	12.1%	17.4%
238	PLAINVILLE	0.1%	54.4%	31.4%	14.0%
239	PLYMOUTH	0.0%	81.3%	10.8%	7.9%
240	PLYMPTON	6.4%	62.3%	16.0%	15.4%
245	RAYNHAM	1.4%	56.9%	25.3%	16.4%
247	REHOBOTH	0.5%	73.5%	6.9%	19.2%
250	ROCHESTER	2.9%	52.1%	18.6%	26.4%
251	ROCKLAND	0.0%	84.0%	0.6%	15.4%
266	SHARON	0.0%	67.3%	6.6%	26.1%
273	SOMERSET	0.3%	68.2%	16.0%	15.5%
285	STOUGHTON	1.4%	66.8%	16.7%	15.1%
292	SWANSEA	0.3%	66.2%	13.8%	19.7%
293	TAUNTON	0.5%	52.9%	33.3%	13.3%
307	WALPOLE	0.0%	76.0%	0.1%	23.9%
322	WEST BRIDGEWATER	5.0%	50.2%	29.5%	15.3%
336	WEYMOUTH	0.0%	73.3%	2.7%	24.1%
338	WHITMAN	1.7%	60.6%	22.2%	15.5%
350	WRENTHAM	0.9%	43.0%	35.3%	20.9%

3.5. Future HRU Layer for the Taunton River Watershed

Based on the relationships established between the MassGIS 2016 baseline and NELF future datasets, the future mapped HRU area distribution was estimated for each municipality based on the change from baseline undeveloped areas (e.g., agriculture and forest) to the developed areas in the projected NELF data. The spatial overlay process shown in Figure 3-1 illustrates how the relevant layers are aligned. Any areas that are undeveloped in the projected future NELF data layer maintain their baseline HRU values; areas that are undeveloped in the baseline but subject to development in the future layer are reclassified to the appropriate class from the baseline HRU layer. As an example, parcels of unprotected forest within a municipality boundary that are subject to projected future development are converted to developed parcels; the percentage distribution rules for the detailed developed land use categories (Table 3-5 and Table 3-6) and the corresponding imperviousness rules (Table 3-4) are used to predict the future HRUs. Table 3-7 summarizes the change in each HRU category between the baseline and future HRUs; Figure 3-2 shows the spatial distribution of future HRUs. Figure 3-3 shows the comparison between coarse resolution 2060 NELF classification and high resolution 2060 Future HRUs for the Upper Hodges Brook sub-watershed.

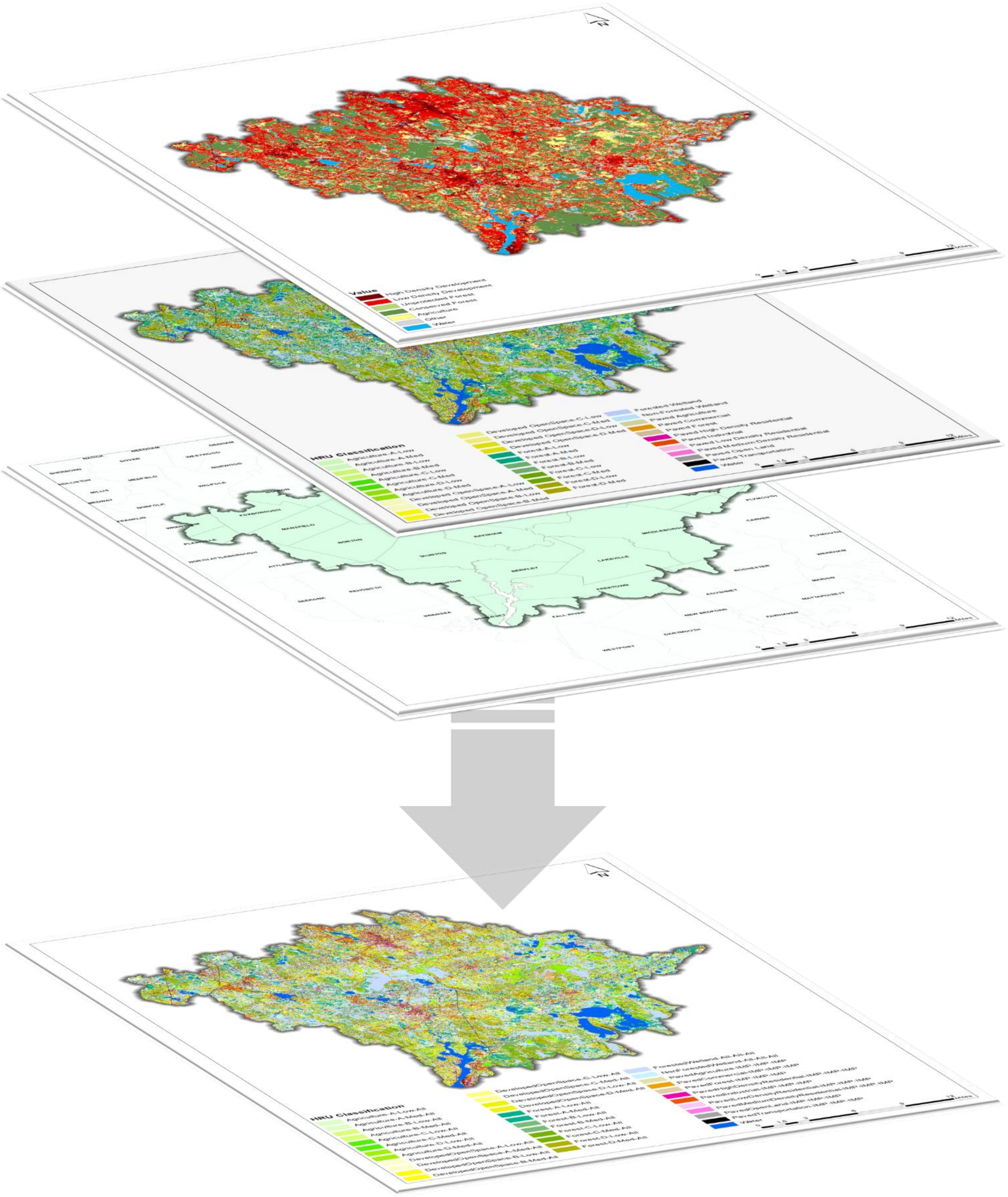


Figure 3-1. Mapped future HRU spatial overlay process (from top to bottom: NELF 2060 land cover, baseline HRUs, municipalities, and final future HRU layer).

Table 3-7. Comparison of HRU area distribution between the MassGIS 2016 baseline and NELF 2060 future conditions in the Taunton River watershed

HRU Code	Land Use Classification	Land Cover	Soil	Slope	Baseline (acre)	Future (acre)	Change (%)
1,000	Paved Forest	Impervious	N/A	N/A	9	9	0.0%
2,000	Paved Agriculture	Impervious	N/A	N/A	128	158	23.0%
3,000	Paved Commercial	Impervious	N/A	N/A	4,858	6,873	41.5%
4,000	Paved Industrial	Impervious	N/A	N/A	2,745	3,892	41.8%
5,000	Paved Low Density Residential	Impervious	N/A	N/A	9,951	20,717	108.2%
6,000	Paved Medium Density Residential	Impervious	N/A	N/A	489	1,133	131.7%
7,000	Paved High Density Residential	Impervious	N/A	N/A	2,856	4,041	41.5%
8,000	Paved Transportation	Impervious	N/A	N/A	11,852	21,709	83.2%
9,000	Paved Open Land	Impervious	N/A	N/A	4,138	8,377	102.4%
10,110	Developed OpenSpace	Pervious	A	Low	13,210	18,203	37.8%
10,120	Developed OpenSpace	Pervious	A	Med	5,864	14,785	152.1%
10,210	Developed OpenSpace	Pervious	B	Low	3,621	5,792	59.9%
10,220	Developed OpenSpace	Pervious	B	Med	1,897	4,483	136.3%
10,310	Developed OpenSpace	Pervious	C	Low	4,326	7,243	67.4%
10,320	Developed OpenSpace	Pervious	C	Med	2,488	4,809	93.3%
10,410	Developed OpenSpace	Pervious	D	Low	7,944	17,328	118.1%
10,420	Developed OpenSpace	Pervious	D	Med	1,604	3,478	116.9%
11,000	Forested Wetland	Pervious	N/A	N/A	66,463	66,463	0.0%
12,000	Non-Forested Wetland	Pervious	N/A	N/A	9,734	9,734	0.0%
13,110	Forest	Pervious	A	Low	17,071	7,615	-55.4%
13,120	Forest	Pervious	A	Med	33,959	17,511	-48.4%
13,210	Forest	Pervious	B	Low	7,649	3,553	-53.6%
13,220	Forest	Pervious	B	Med	10,948	6,320	-42.3%
13,310	Forest	Pervious	C	Low	12,123	6,470	-46.6%
13,320	Forest	Pervious	C	Med	9,548	4,954	-48.1%
13,410	Forest	Pervious	D	Low	43,764	26,559	-39.3%
13,420	Forest	Pervious	D	Med	9,331	5,850	-37.3%
14,110	Agriculture	Pervious	A	Low	4,780	4,426	-7.4%
14,120	Agriculture	Pervious	A	Med	3,095	3,590	16.0%
14,210	Agriculture	Pervious	B	Low	1,204	1,187	-1.4%
14,220	Agriculture	Pervious	B	Med	1,106	1,090	-1.4%
14,310	Agriculture	Pervious	C	Low	1,925	1,966	2.1%
14,320	Agriculture	Pervious	C	Med	1,092	1,178	7.9%
14,410	Agriculture	Pervious	D	Low	10,907	11,157	2.3%
14,420	Agriculture	Pervious	D	Med	1,146	1,173	2.4%
15,000	Water	N/A	N/A	N/A	17,628	17,628	0.0%

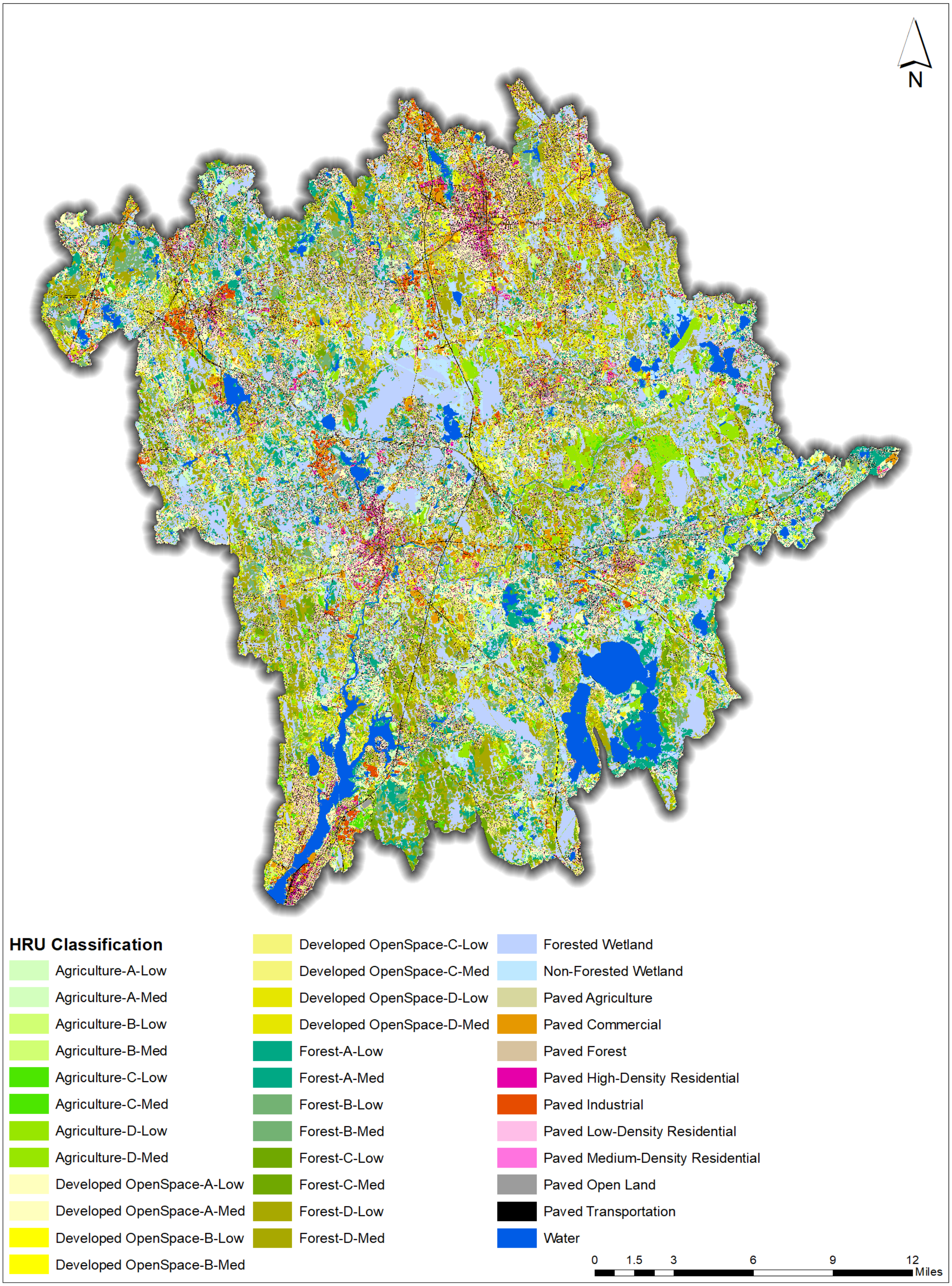


Figure 3-2. A map showing the 2060 future HRU raster layer for the Taunton River watershed.

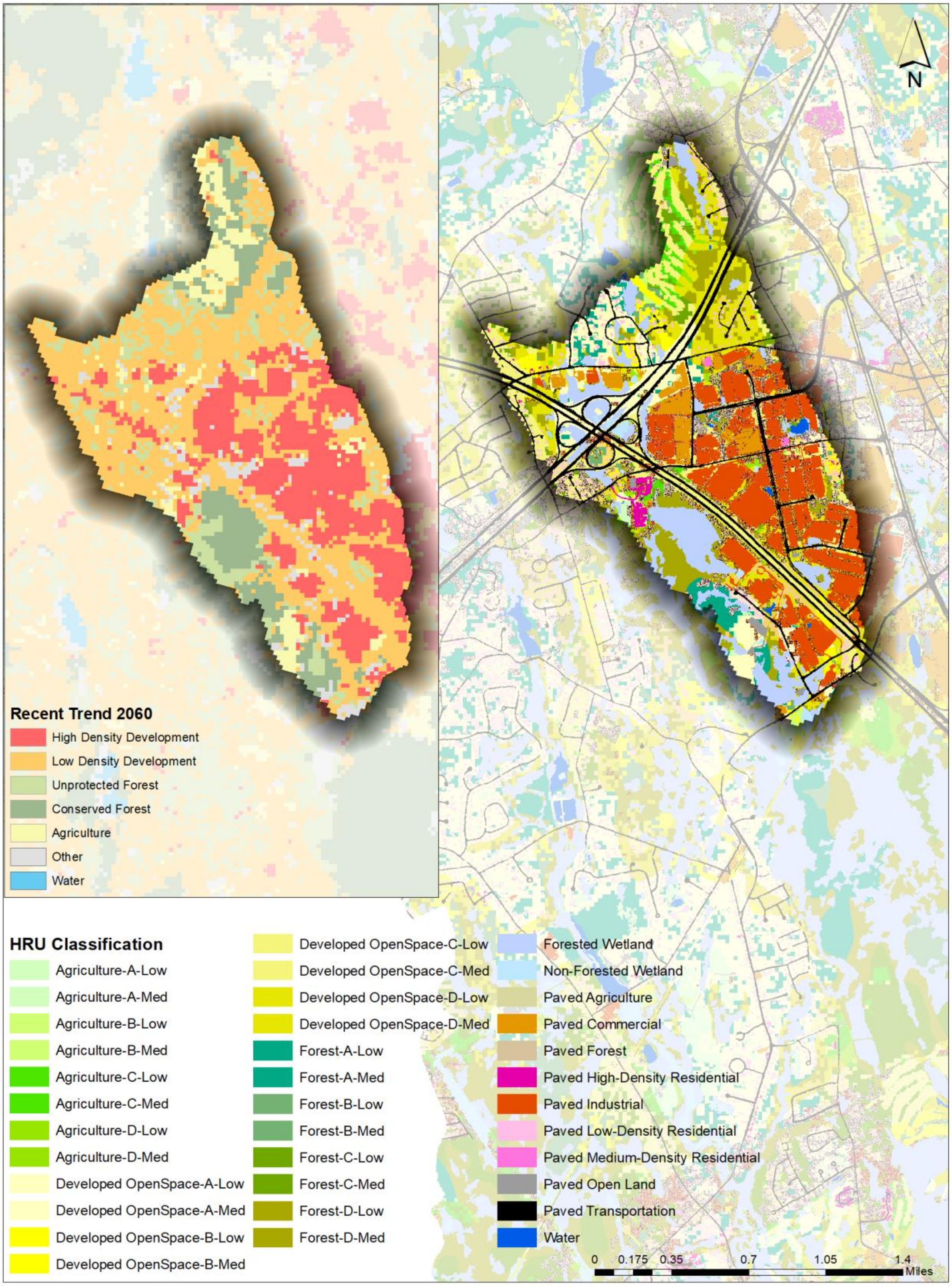


Figure 3-3. A map showing the comparison between the 30-m resolution 2060 future NELF layer (left) and 1-m resolution 2060 future HRU layer (right) for the Upper Hodges Brook sub-watershed.

4. SELECTION OF FUTURE CLIMATE MODELS

To simulate future climate conditions, meteorological time series from three Global Circulation Models (GCMs) were selected from those used in FDC Phase 1 (Table 4-1) (Paradigm Environmental and Great Lakes Environmental Center, 2021). The GCMs for use in Phase 2 were selected to represent the greatest increase in both precipitation and temperature, as well as the modeled ecodeficits and ecosurpluses for the Upper Hodges Brook watershed from FDC Phase 1 (Figure 4-1 and Table 4-2). As shown in Table 4-1, these climate projections are from Representative Concentration Pathway (RCP) 8.5, which represents a scenario in which carbon emissions continue to climb at historical rates (in contrast, RCP 4.5 predicts a stabilization of carbon emissions by 2100). Using these models in conjunction with the projected future land cover conditions should provide "bookends" within which to evaluate innovative stormwater control measures and protective ordinances. The downscaled meteorological data for the selected GCMs will be used to drive the LSPC hydrology model in FDC Phase 2.

Table 4-1. FDC Phase 1 selected models from ensemble results for future climate projections (2079-2099)

RCP	Scenario [1]	Ecosuplus Model	Ecodeficit Model
RCP 4.5	Dry	hadgem2-cc-1	mpi-esm-mr-1
	Median	bcc-csm1-1-m-1	bcc-csm1-1-m-1
	Wet	bcc-csm1-1-1	miroc-esm-chem-1
RCP 8.5	Dry	inmcm4-1	miroc-esm-1
	Median	cesm1-cam5-1	cesm1-cam5-1
	Wet	cesm1-bgc-1	mri-cgcm3-1

1: Dry, Median, and Wet correspond to the 20th, 50th, and 80th percentile hydrological responses.
Models chosen for FDC Phase 2 are highlighted in yellow.

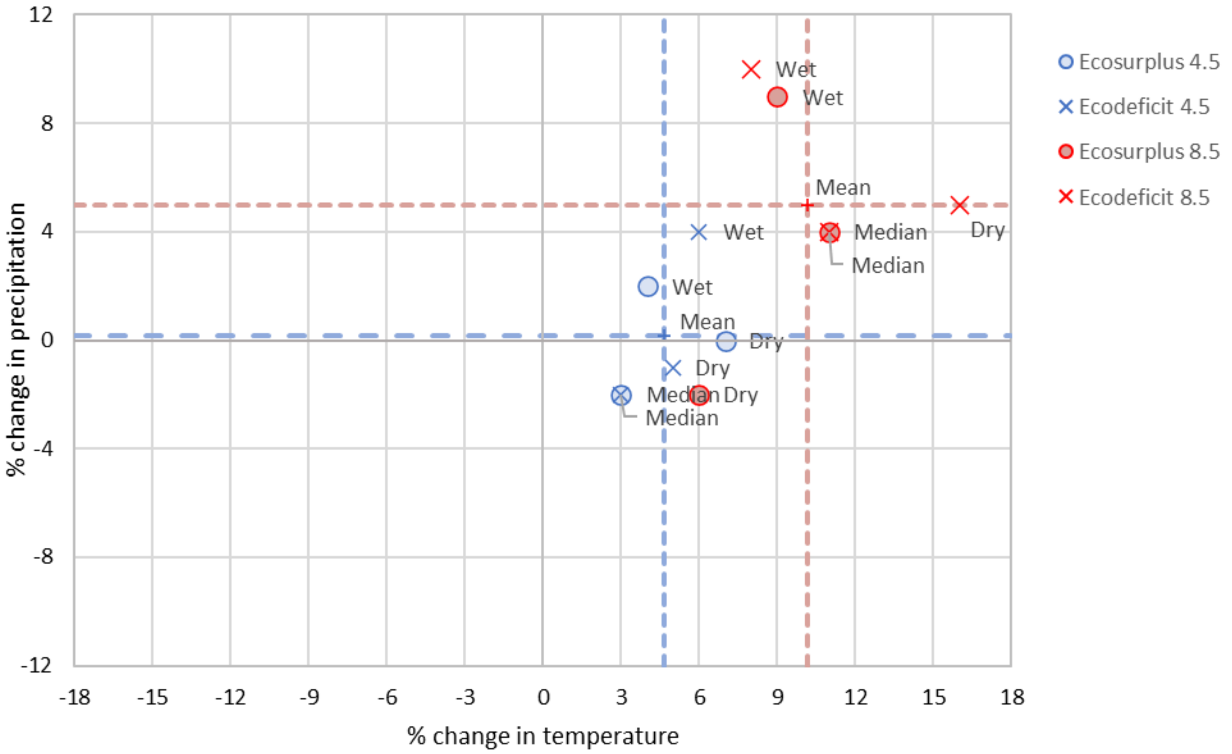


Figure 4-1. Percent change in annual average precipitation and temperature from baseline conditions for the FDC Phase 1 selected models presented in Table 4-1.

Table 4-2. Summary of ecosurpluses and ecodeficits (million gallons per year) within the Upper Hodges Brook watershed for RCP 4.5 and 8.5 scenarios

Scenario	Ecodeficit models					
	Ecodeficits			Ecosurplus		
	Dry	Median	Wet	Dry	Median	Wet
RCP 4.5	98.1	78.8	36.1	19.0	43.1	31.8
RCP 8.5	121.4	91.1	49.2	7.1	14.6	90.8
Scenario	**Ecosurplus models**					
	Ecodeficits			**Ecosurplus**		
	Dry	**Median**	**Wet**	**Dry**	**Median**	**Wet**
RCP 4.5	122.0	78.8	52.1	7.6	43.1	60.3
RCP 8.5	112.2	91.1	44.1	14.7	14.6	57.6

5. COMPARISON OF EXISTING AND FUTURE (IC AND CLIMATE) CONDITIONS IN THE TAUNTON RIVER WATERSHED

This section compares the results between the 2016 baseline, projected 2060 future land use – land cover conditions, and the three selected future climate scenarios. These comparisons include future estimates of IC (assuming conventional development patterns) and estimates of unattenuated average annual run-off volume, groundwater recharge, evapotranspiration, and nutrients (TN and TP) load export for both existing and future land cover and climate conditions for each municipality within the Taunton River watershed.

5.1. Change in Impervious Cover by 2060 in the Taunton River Watershed

The change in impervious areas between the 2016 baseline and 2060 future conditions for 7 major land use categories, transportation (TRANS), commercial (COM), industrial (IND), high-density residential (HDR), medium-density residential (MDR), low-density residential (LDR), and open land (OPEN), are summarized by the municipality in Table 5-1. The change in IC reflects the increase in impervious cover due to the NELF 2060 projected future development in the Taunton River watershed. The impervious cover area for each municipality for the 2016 baseline and 2060 future conditions is given in Appendix A (Table 1 and Table 2, respectively).

Table 5-1. Summary of increase in impervious cover by the municipality in the Taunton River watershed

Municipality		Increase in Impervious Cover (acre)						
ID	Name	TRANS	COM	IND	HDR	MDR	LDR	OPEN
1	ABINGTON	198.9	85.8	1.5	55.6	3.3	241.6	72.6
16	ATTLEBORO	125.4	4.1	19.4	4.9	0.0	197.9	28.3
18	AVON	95.4	29.9	44.3	4.2	0.4	94.3	42.4
27	BERKLEY	374.9	15.3	2.5	10.2	46.6	355.5	74.9
42	BRIDGEWATER	501.5	90.6	52.0	122.7	17.8	531.5	323.2
44	BROCKTON	506.2	218.2	63.0	152.4	6.8	470.6	280.0
52	CARVER	194.4	27.8	5.3	2.9	5.1	139.4	27.7
72	DARTMOUTH	0.2	0.0	0.0	0.0	0.0	0.3	0.1
76	DIGHTON	287.3	14.4	9.3	4.9	29.6	375.7	187.0

Municipality		Increase in Impervious Cover (acre)						
ID	**Name**	**TRANS**	**COM**	**IND**	**HDR**	**MDR**	**LDR**	**OPEN**
83	EAST BRIDGEWATER	409.4	81.9	65.3	60.1	19.0	472.3	158.6
88	EASTON	517.0	43.2	22.8	27.3	2.7	750.1	329.4
95	FALL RIVER	125.1	30.8	59.5	43.8	5.1	76.5	73.6
99	FOXBOROUGH	434.2	54.1	12.5	21.0	13.6	429.0	185.5
102	FREETOWN	438.9	30.8	55.1	6.3	72.8	461.1	202.1
118	HALIFAX	146.5	14.7	3.3	11.3	20.5	254.4	58.3
123	HANSON	130.9	11.2	11.0	6.1	7.8	182.8	72.1
133	HOLBROOK	60.8	26.2	11.6	10.3	1.2	54.4	6.0
145	KINGSTON	83.7	0.0	0.0	6.3	0.0	36.1	47.4
146	LAKEVILLE	386.6	36.8	24.2	12.0	9.1	676.5	164.6
167	MANSFIELD	466.5	125.5	177.2	57.9	4.9	501.0	129.5
182	MIDDLEBOROUGH	926.7	133.1	39.7	50.1	232.9	820.6	299.7
201	NEW BEDFORD	27.3	7.2	0.0	4.9	0.4	19.7	4.2
208	NORFOLK	0.9	0.3	0.2	0.2	0.0	2.0	0.0
211	NORTH ATTLEBOROUGH	6.3	0.7	0.0	0.0	0.0	8.0	1.0
218	NORTON	517.1	59.6	62.6	69.0	44.3	637.2	229.6
231	PEMBROKE	29.4	1.5	0.8	2.3	0.9	42.2	7.0
238	PLAINVILLE	116.0	72.9	14.4	25.2	0.3	104.6	57.6
239	PLYMOUTH	4.4	8.4	0.0	2.6	0.0	8.0	1.0
240	PLYMPTON	123.2	10.4	2.2	1.3	25.4	186.0	45.6
245	RAYNHAM	503.9	204.8	47.2	50.5	15.4	479.2	202.8
247	REHOBOTH	37.4	1.1	0.0	1.0	0.5	54.4	4.8
250	ROCHESTER	31.2	0.0	0.0	1.7	1.7	23.0	7.8
251	ROCKLAND	1.8	0.5	0.0	0.1	0.0	3.4	0.0
266	SHARON	259.0	7.4	0.0	1.2	0.0	254.1	23.8
273	SOMERSET	144.3	50.5	19.9	25.0	1.2	172.7	38.6
285	STOUGHTON	229.8	89.3	117.3	18.7	6.2	221.9	52.9
292	SWANSEA	49.9	0.3	0.0	1.5	0.4	64.3	12.8
293	TAUNTON	838.2	322.2	134.8	250.9	11.9	874.7	524.2
307	WALPOLE	2.7	0.6	0.3	0.3	0.0	2.6	0.0
322	WEST BRIDGEWATER	209.9	54.3	47.5	13.7	27.1	202.1	113.2
336	WEYMOUTH	3.1	0.0	0.0	1.4	0.0	2.3	0.1
338	WHITMAN	147.4	32.8	17.2	32.1	6.2	166.9	58.4
350	WRENTHAM	163.4	15.8	3.2	11.5	3.2	115.4	90.2
Total		**9,857**	**2,015**	**1,147**	**1,186**	**644**	**10,766**	**4,239**

Land cover classes: TRANS – transportation, COM – commercial, IND – industrial, HDR – high-density residential, MDR – medium-density residential, LDR – low-density residential, OPEN – open land

5.2. Change in Hydrology and Water Quality by 2060 in Taunton River Watershed

Hydrology and water quality were calibrated for the modeled HRU categories during Phase 1 of the FDC project. The pollutant build-up and wash-off parameters from the Opti-Tool Stormwater Management Model (SWMM) models were used as a starting point and were adjusted to calibrate the long-term annual average loading rates reported in the Opti-Tool. The model was simulated for 20 years (Oct 2000 – Sep 2020) and annual average loading rates from the model prediction were compared against the pollutant export rates for the similar HRU type in the Opti-Tool. Table 5-2 presents the summary of unit-area annual average runoff, groundwater recharge (GW), evapotranspiration (ET), and nutrients (TN and TP) loading rates by HRU from the calibrated watershed model in Phase 1 of the FDC project. Table 5-3 to Table 5-5 presents the same summaries for the Ecodeficit 8.5 Dry, Median, and Wet climate change scenarios (Oct 2079 – Sep 2099), respectively.

Table 5-2. Summary of unit-acre-based annual average (Oct 2000 – Sep 2020) runoff volume, groundwater (GW) recharge, evapotranspiration (ET), total nitrogen (TN) load, and total phosphorus (TP) load for the modeled HRU types in the Wading River watershed (FDC Phase 1)

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
1000	Paved Forest	1.234	0.000	0.126	11.480	1.502
2000	Paved Agriculture	1.234	0.000	0.126	11.480	1.502
3000	Paved Commercial	1.234	0.000	0.126	15.240	1.794
4000	Paved Industrial	1.234	0.000	0.126	15.240	1.794
5000	Paved Low Density Residential	1.234	0.000	0.126	14.270	1.503
6000	Paved Medium Density Residential	1.234	0.000	0.126	14.270	1.970
7000	Paved High Density Residential	1.234	0.000	0.126	14.260	2.381
8000	Paved Transportation	1.234	0.000	0.126	10.260	1.532
9000	Paved Open Land	1.234	0.000	0.126	11.480	1.568
10110	Developed OpenSpace-A-Low	0.218	0.686	0.455	0.230	0.020
10120	Developed OpenSpace-A-Med	0.218	0.686	0.455	0.250	0.022
10210	Developed OpenSpace-B-Low	0.380	0.514	0.464	0.930	0.097
10220	Developed OpenSpace-B-Med	0.378	0.516	0.464	1.210	0.126
10310	Developed OpenSpace-C-Low	0.493	0.396	0.469	2.260	0.209
10320	Developed OpenSpace-C-Med	0.495	0.395	0.469	2.390	0.220
10410	Developed OpenSpace-D-Low	0.592	0.294	0.472	3.300	0.305
10420	Developed OpenSpace-D-Med	0.590	0.296	0.472	4.040	0.374
11000	Forested Wetland	0.331	0.159	0.876	0.520	0.109
12000	Non-Forested Wetland	0.333	0.160	0.874	0.520	0.109
13110	Forest-A-Low	0.077	0.614	0.673	0.120	0.023
13120	Forest-A-Med	0.077	0.614	0.673	0.120	0.025
13210	Forest-B-Low	0.170	0.513	0.681	0.520	0.102
13220	Forest-B-Med	0.170	0.514	0.681	0.550	0.109
13310	Forest-C-Low	0.259	0.421	0.684	1.100	0.204
13320	Forest-C-Med	0.258	0.422	0.684	1.170	0.217
13410	Forest-D-Low	0.453	0.223	0.689	1.780	0.360

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
13420	Forest-D-Med	0.451	0.224	0.689	1.840	0.373
14110	Agriculture-A-Low	0.125	0.661	0.577	0.510	0.088
14120	Agriculture-A-Med	0.124	0.661	0.577	0.540	0.093
14210	Agriculture-B-Low	0.244	0.529	0.589	2.320	0.409
14220	Agriculture-B-Med	0.244	0.530	0.589	2.490	0.439
14310	Agriculture-C-Low	0.346	0.422	0.595	5.040	0.773
14320	Agriculture-C-Med	0.345	0.423	0.595	5.410	0.829
14410	Agriculture-D-Low	0.437	0.326	0.599	8.020	1.366
14420	Agriculture-D-Med	0.436	0.328	0.599	8.490	1.447

Units: MG – million gallons, lb – pounds, ac – acre, yr – year

Table 5-3. Summary of unit-acre-based annual average (Oct 2079 – Sep 2099) runoff volume, groundwater (GW) recharge, evapotranspiration (ET), total nitrogen (TN) load, and total phosphorus (TP) load for the modeled HRU types in the Wading River watershed (Ecodeficit 8.5 Dry)

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
1000	Paved Forest	1.245	0.000	0.120	10.806	1.425
2000	Paved Agriculture	1.245	0.000	0.120	10.806	1.425
3000	Paved Commercial	1.245	0.000	0.120	14.351	1.631
4000	Paved Industrial	1.245	0.000	0.120	14.351	1.631
5000	Paved Low Density Residential	1.245	0.000	0.120	13.430	1.366
6000	Paved Medium Density Residential	1.245	0.000	0.120	13.430	1.840
7000	Paved High Density Residential	1.245	0.000	0.120	13.424	2.175
8000	Paved Transportation	1.245	0.000	0.120	9.661	1.391
9000	Paved Open Land	1.245	0.000	0.120	10.806	1.425
10110	Developed OpenSpace-A-Low	0.175	0.656	0.519	0.237	0.021
10120	Developed OpenSpace-A-Med	0.175	0.664	0.518	0.259	0.023
10210	Developed OpenSpace-B-Low	0.308	0.509	0.531	0.896	0.094
10220	Developed OpenSpace-B-Med	0.305	0.504	0.531	1.126	0.118
10310	Developed OpenSpace-C-Low	0.404	0.398	0.539	1.968	0.182
10320	Developed OpenSpace-C-Med	0.405	0.399	0.538	2.071	0.191
10410	Developed OpenSpace-D-Low	0.495	0.303	0.544	2.827	0.261
10420	Developed OpenSpace-D-Med	0.491	0.303	0.544	3.422	0.316
11000	Forested Wetland	0.264	0.107	0.994	0.418	0.087
12000	Non-Forested Wetland	0.263	0.105	0.992	0.414	0.086
13110	Forest-A-Low	0.058	0.537	0.776	0.100	0.020
13120	Forest-A-Med	0.057	0.535	0.775	0.105	0.021
13210	Forest-B-Low	0.132	0.446	0.787	0.452	0.089
13220	Forest-B-Med	0.131	0.444	0.787	0.476	0.094
13310	Forest-C-Low	0.204	0.363	0.793	0.908	0.168

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
13320	Forest-C-Med	0.203	0.362	0.793	0.963	0.178
13410	Forest-D-Low	0.370	0.186	0.801	1.438	0.291
13420	Forest-D-Med	0.369	0.186	0.801	1.490	0.302
14110	Agriculture-A-Low	0.099	0.605	0.653	0.508	0.087
14120	Agriculture-A-Med	0.098	0.604	0.653	0.536	0.092
14210	Agriculture-B-Low	0.197	0.488	0.668	2.165	0.381
14220	Agriculture-B-Med	0.196	0.488	0.668	2.305	0.406
14310	Agriculture-C-Low	0.282	0.391	0.677	4.436	0.680
14320	Agriculture-C-Med	0.281	0.391	0.677	4.730	0.725
14410	Agriculture-D-Low	0.361	0.303	0.684	6.842	1.165
14420	Agriculture-D-Med	0.359	0.304	0.684	7.237	1.233

Units: MG – million gallons, lb – pounds, ac – acre, yr – year

Table 5-4. Summary of unit-acre-based annual average (Oct 2079 – Sep 2099) runoff volume, groundwater (GW) recharge, evapotranspiration (ET), total nitrogen (TN) load, and total phosphorus (TP) load for the modeled HRU types in the Wading River watershed (Ecodeficit 8.5 Median)

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
1000	Paved Forest	1.251	0.000	0.126	11.147	1.477
2000	Paved Agriculture	1.251	0.000	0.126	11.147	1.477
3000	Paved Commercial	1.251	0.000	0.126	14.805	1.691
4000	Paved Industrial	1.251	0.000	0.126	14.805	1.691
5000	Paved Low Density Residential	1.251	0.000	0.126	13.854	1.416
6000	Paved Medium Density Residential	1.251	0.000	0.126	13.854	1.906
7000	Paved High Density Residential	1.251	0.000	0.126	13.848	2.254
8000	Paved Transportation	1.251	0.000	0.126	9.966	1.442
9000	Paved Open Land	1.251	0.000	0.126	11.147	1.477
10110	Developed OpenSpace-A-Low	0.185	0.674	0.498	0.209	0.019
10120	Developed OpenSpace-A-Med	0.185	0.682	0.498	0.232	0.021
10210	Developed OpenSpace-B-Low	0.327	0.520	0.508	0.901	0.094
10220	Developed OpenSpace-B-Med	0.323	0.516	0.508	1.144	0.120
10310	Developed OpenSpace-C-Low	0.428	0.405	0.515	1.999	0.184
10320	Developed OpenSpace-C-Med	0.429	0.406	0.515	2.108	0.194
10410	Developed OpenSpace-D-Low	0.522	0.307	0.519	2.893	0.267
10420	Developed OpenSpace-D-Med	0.518	0.308	0.519	3.525	0.326
11000	Forested Wetland	0.293	0.119	0.960	0.442	0.092
12000	Non-Forested Wetland	0.292	0.117	0.957	0.439	0.092
13110	Forest-A-Low	0.062	0.572	0.743	0.089	0.018
13120	Forest-A-Med	0.062	0.570	0.743	0.093	0.018
13210	Forest-B-Low	0.144	0.474	0.753	0.460	0.091

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
13220	Forest-B-Med	0.143	0.473	0.753	0.490	0.097
13310	Forest-C-Low	0.224	0.385	0.758	0.977	0.181
13320	Forest-C-Med	0.223	0.384	0.758	1.035	0.192
13410	Forest-D-Low	0.401	0.198	0.765	1.504	0.305
13420	Forest-D-Med	0.399	0.197	0.765	1.558	0.315
14110	Agriculture-A-Low	0.106	0.628	0.630	0.431	0.074
14120	Agriculture-A-Med	0.106	0.627	0.630	0.458	0.079
14210	Agriculture-B-Low	0.214	0.503	0.644	2.267	0.399
14220	Agriculture-B-Med	0.213	0.503	0.644	2.426	0.427
14310	Agriculture-C-Low	0.305	0.402	0.651	4.658	0.714
14320	Agriculture-C-Med	0.303	0.402	0.651	4.966	0.761
14410	Agriculture-D-Low	0.388	0.312	0.657	7.102	1.210
14420	Agriculture-D-Med	0.386	0.312	0.657	7.502	1.278

Units: MG – million gallons, lb – pounds, ac – acre, yr – year

Table 5-5. Summary of unit-acre-based annual average (Oct 2079 – Sep 2099) runoff volume, groundwater (GW) recharge, evapotranspiration (ET), total nitrogen (TN) load, and total phosphorus (TP) load for the modeled HRU types in the Wading River watershed (Ecodeficit 8.5 Wet)

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
1000	Paved Forest	1.336	0.000	0.119	11.761	1.551
2000	Paved Agriculture	1.336	0.000	0.119	11.761	1.551
3000	Paved Commercial	1.336	0.000	0.119	15.623	1.777
4000	Paved Industrial	1.336	0.000	0.119	15.623	1.777
5000	Paved Low Density Residential	1.336	0.000	0.119	14.617	1.488
6000	Paved Medium Density Residential	1.336	0.000	0.119	14.617	2.056
7000	Paved High Density Residential	1.336	0.000	0.119	14.614	2.377
8000	Paved Transportation	1.336	0.000	0.119	10.517	1.514
9000	Paved Open Land	1.336	0.000	0.119	11.761	1.551
10110	Developed OpenSpace-A-Low	0.206	0.742	0.489	0.205	0.018
10120	Developed OpenSpace-A-Med	0.206	0.750	0.489	0.230	0.021
10210	Developed OpenSpace-B-Low	0.364	0.573	0.498	0.863	0.090
10220	Developed OpenSpace-B-Med	0.361	0.568	0.498	1.102	0.115
10310	Developed OpenSpace-C-Low	0.479	0.445	0.504	2.000	0.185
10320	Developed OpenSpace-C-Med	0.480	0.446	0.504	2.120	0.196
10410	Developed OpenSpace-D-Low	0.584	0.337	0.507	3.152	0.291
10420	Developed OpenSpace-D-Med	0.580	0.339	0.507	3.903	0.361
11000	Forested Wetland	0.368	0.147	0.939	0.575	0.120
12000	Non-Forested Wetland	0.367	0.146	0.936	0.573	0.119
13110	Forest-A-Low	0.079	0.640	0.740	0.092	0.018

HRU	HRU Category	Runoff (MG/ac/yr)	GW (MG/ac/yr)	ET (MG/ac/yr)	TN (lb/ac/yr)	TP (lb/ac/yr)
13120	Forest-A-Med	0.079	0.638	0.740	0.097	0.019
13210	Forest-B-Low	0.177	0.531	0.747	0.463	0.092
13220	Forest-B-Med	0.176	0.529	0.747	0.493	0.098
13310	Forest-C-Low	0.271	0.428	0.751	1.031	0.191
13320	Forest-C-Med	0.270	0.427	0.751	1.101	0.204
13410	Forest-D-Low	0.478	0.216	0.755	1.788	0.362
13420	Forest-D-Med	0.476	0.215	0.755	1.859	0.376
14110	Agriculture-A-Low	0.126	0.699	0.618	0.426	0.073
14120	Agriculture-A-Med	0.126	0.698	0.618	0.453	0.078
14210	Agriculture-B-Low	0.250	0.561	0.630	2.231	0.393
14220	Agriculture-B-Med	0.249	0.561	0.630	2.387	0.420
14310	Agriculture-C-Low	0.356	0.447	0.636	4.805	0.737
14320	Agriculture-C-Med	0.355	0.447	0.636	5.161	0.791
14410	Agriculture-D-Low	0.452	0.344	0.641	7.890	1.344
14420	Agriculture-D-Med	0.450	0.344	0.641	8.395	1.430

Units: MG – million gallons, lb – pounds, ac – acre, yr – year

The unit-acre unattenuated values were applied to the baseline and future development HRU areas to estimate the net change in hydrology and water quality for the Taunton River watershed. As expected, with the same historical climate data and increased IC from the 2060 land use, runoff and pollutant loads increased, while groundwater recharge and evapotranspiration decreased (Figure 5-1, blue). The selected future climate scenarios had increased precipitation and temperature compared to the baseline. Of the future scenarios, the 2060 land use Ecodeficit 8.5 Dry combination had the smallest change in the runoff, TN, and TP compared to the 2016 baseline with historical climate, but the greatest decrease in groundwater recharge (Figure 5-1, orange). While the Ecodeficit 8.5 Dry scenario has a 5% increase in annual average precipitation, it also has a 16% increase in annual average temperature (Figure 4-1). The increase in temperature increased ET by 18MG/yr compared to the 2016 baseline with historical climate and drove the reduced runoff and groundwater recharge, and subsequently the lower changes in TN and TP. At the other extreme, the Ecodeficit 8.5 Wet scenario had the greatest changes in runoff, groundwater recharge, and TN (Figure 5-1, red). The 8% increase in temperature for this scenario did lead to a lower reduction in ET compared to the 2060 land use-historical climate scenario, however, the 10% increase in precipitation still drove the increases in the other parameters. Results for the Ecodeficit 8.5 Median climate scenario fell between the Wet and Dry extremes with a consistent pattern across all of the parameters (Figure 5-1, green).

The trends seen at the Taunton River watershed scale are also reflected at the municipality level (annual average runoff and loadings and the change between baseline and future conditions by the municipality are shown in Appendix A (Table 3 through Table 11). As an example (Table 8 in Appendix A), IC in the Taunton Municipality increased by nearly 3,000 acres. This led to an increase in runoff of nearly 3,600 million gallons/year and an additional 38,000 pounds and 4,500 pounds of TN and TP per year on average for the 2060 land use-historical climate scenario. Correspondingly, groundwater recharge and evapotranspiration decreased by 1,300 and 2,300 million gallons/year.

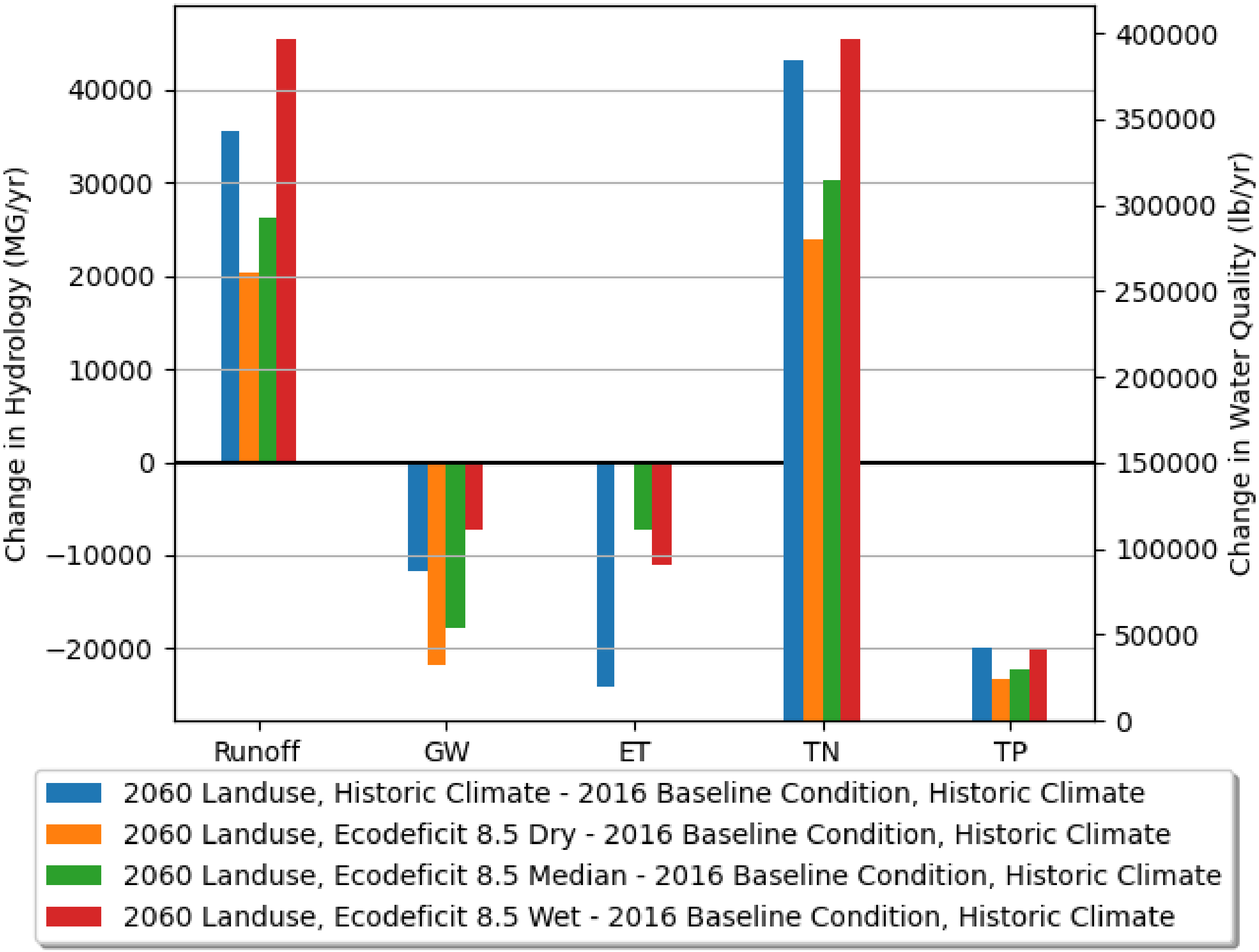


Figure 5-1. Comparison of changes in hydrology (runoff, groundwater recharge GW, and evapotranspiration ET) and water quality parameters (total nitrogen TN and total phosphorous TP) between the baseline and future land use/climate conditions across the entire Taunton River watershed.

5.3. Summary of Changes from Future IC and Climate

The future HRU distribution reflects increased development due to the conversion of unprotected forest areas into land uses with greater impervious cover (Table 5-6). The loss of vegetative cover (forests) shifts the water balance towards higher runoff. As impervious surfaces increase, baseflows may fall due to more water being conveyed immediately to receiving waters with fewer opportunities for infiltration and evapotranspiration. When the future distribution of HRUs is applied to the unattenuated modeling results from FDC Phase 1 (e.g., using historical climate data), net increases in runoff (35,674 million gallons/year) and nutrient loadings (383,765 lbs and 42,545 lbs of TN and TP per year on average) are observed across the entire Taunton River watershed while groundwater recharge and evapotranspiration decreased by 11,734 and 24,240 million gallons per year, respectively (Table 5-7). Simulating future climate conditions increases the variability of these results, with differences between the scenarios being driven by the amount of increase in precipitation and temperature compared to the historical climate data.

A standard water tower can hold 1 million gallons of water and a typical large dump truck can carry about 28,000 pounds. Using the 2060 land use and historical climate results as an example, these numbers can be visualized as 35.7 thousand water towers of additional annual runoff, 11.7 thousand water towers of groundwater recharge as the annual loss, 13.7 large dump trucks of TN and 1.5 large dump trucks of TP as the average annual increase in nutrient load in the entire Taunton River watershed.

Table 5-6. Summary of change in major land use area distribution between 2016 baseline and 2060 future conditions in the Taunton River watershed

Major Land Use Classification	Land Cover	2016 Baseline (acre)	2060 Future (acre)	Change (%)
Paved Forest	Impervious	9	9	0%
Paved Agriculture	Impervious	128	158	23%
Paved Commercial	Impervious	4,858	6,873	41%
Paved Industrial	Impervious	2,745	3,892	42%
Paved Low Density Residential	Impervious	9,951	20,717	108%
Paved Medium Density Residential	Impervious	489	1,133	132%
Paved High Density Residential	Impervious	2,856	4,041	42%
Paved Transportation	Impervious	11,852	21,709	83%
Paved Open Land	Impervious	4,138	8,377	102%
Developed OpenSpace	Pervious	40,955	76,120	86%
Forested Wetland	Pervious	66,463	66,463	0%
Non-Forested Wetland	Pervious	9,734	9,734	0%
Forest	Pervious	144,393	78,832	-45%
Agriculture	Pervious	25,255	25,768	2%

Table 5-7. Summary of changes between baseline land use and historical climate model results and the future land use and climate scenarios for annual average runoff volume, groundwater (GW) recharge, evapotranspiration (ET), total nitrogen (TN) load, and total phosphorus (TP) load by major land use in Taunton River watershed

Major Land Use Classification	Runoff (MG/yr)				GW Recharge (MG/yr)				ET (MG/yr)				TN (lb/yr)				TP (lb/yr)			
	2060 FLULC	Ecodef. 8.5 Dry	Ecodef. 8.5 Med.	Ecodef. 8.5 Wet	2060 FLULC	Ecodef. 8.5 Dry	Ecodef. 8.5 Med.	Ecodef. 8.5 Wet	2060 FLULC	Ecodef. 8.5 Dry	Ecodef. 8.5 Med.	Ecodef. 8.5 Wet	2060 FLULC	Ecodef. 8.5 Dry	Ecodef. 8.5 Med.	Ecodef. 8.5 Wet	2060 FLULC	Ecodef. 8.5 Dry	Ecodef. 8.5 Med.	Ecodef. 8.5 Wet
Paved Forest	0	0	0	1	0	0	0	0	0	0	0	0	0	-6	-3	3	0	-1	0	0
Paved Agriculture	36	38	39	53	0	0	0	0	4	3	4	3	339	233	287	384	44	32	40	52
Paved Commercial	2,486	2,559	2,601	3,185	0	0	0	0	254	212	256	202	30,707	24,599	27,714	33,340	3,615	2,494	2,905	3,495
Paved Industrial	1,416	1,457	1,480	1,811	0	0	0	0	145	121	146	115	17,484	14,025	15,789	18,975	2,058	1,424	1,656	1,990
Paved Low Density Residential	13,285	13,503	13,630	15,390	0	0	0	0	1,357	1,230	1,364	1,201	153,634	136,222	145,011	160,824	16,182	13,352	14,390	15,878
Paved Medium Density Residential	795	807	814	910	0	0	0	0	81	74	82	73	9,192	8,239	8,720	9,585	1,269	1,122	1,196	1,367
Paved High Density Residential	1,463	1,505	1,530	1,874	0	0	0	0	149	125	151	119	16,905	13,528	15,241	18,335	2,823	1,992	2,311	2,807
Paved Transportation	12,164	12,392	12,525	14,369	0	0	0	0	1,242	1,110	1,250	1,079	101,133	88,134	94,758	106,720	15,101	12,042	13,152	14,720
Paved Open Land	5,231	5,319	5,370	6,080	0	0	0	0	534	483	537	471	48,661	43,020	45,875	51,011	6,646	5,447	5,884	6,506
Developed OpenSpace	14,083	8,832	10,186	13,169	17,380	16,647	17,524	21,417	16,308	21,417	19,698	18,925	59,202	44,899	45,999	51,368	5,516	4,203	4,309	4,801
Forested Wetland	0	-4,420	-2,529	2,444	0	-3,463	-2,631	-767	0	7,816	5,554	4,199	0	-6,797	-5,163	3,631	0	-1,459	-1,118	715
Non-Forested Wetland	0	-683	-403	330	0	-540	-418	-141	0	1,145	810	602	0	-1,027	-785	511	0	-220	-170	100
Forest	-15,491	-19,672	-18,225	-14,457	-29,320	-33,833	-32,054	-28,694	-44,636	-36,120	-38,835	-39,411	-56,406	-70,920	-68,137	-58,062	-11,193	-14,100	-13,549	-11,522
Agriculture	174	-1,287	-785	416	220	-707	-355	891	304	2,402	1,738	1,374	2,916	-14,091	-10,533	-301	485	-2,386	-1,791	-58
TOTAL	**35,642**	**20,349**	**26,233**	**45,576**	**-11,720**	**-21,895**	**-17,933**	**-7,295**	**-24,259**	**18**	**-7,245**	**-11,046**	**383,765**	**280,057**	**314,774**	**396,321**	**42,545**	**23,943**	**29,216**	**40,850**

Units: MG – million gallons, lb – pounds, yr – year

6. IMPACTS OF FUTURE LAND USE AND CLIMATE ON THE UPPER HODGES BROOK SUBWATERSHED

The preceding sections described projections of future land use and climate for the Taunton River watershed as a whole; much of the remainder of this report focuses on the impact of next-generation SCMs on second and third-order headwater stream segments and finer scales. The Upper Hodges Brook subwatershed, which is a tributary to the Wading River within the Taunton River watershed, was used as a pilot for this purpose. Table 6-1 shows a 34% increase in impervious cover and a 55% increase in developed pervious cover resulting from a 67% decrease in the forested land cover for 2060 future land use/land cover in the pilot subwatershed. As such, the impacts of future land use, climate, and IC disconnection were evaluated for Upper Hodges Brook and are presented in this section.

Table 6-1. Summary of changes in the land cover area between baseline land cover and the future land cover in Upper Hodges Brook sub-watershed

Land Cover Class	2016 Existing Area		2060 Future Area		Change in Area	
	Acres	%	Acres	%	Acres	%
Impervious	424.1	32%	567.6	42%	143.5	34%
Developed Pervious	273.7	20%	422.9	32%	149.2	55%
Forest	461.5	35%	153.8	11%	-307.7	-67%
Agriculture	17.8	1%	32.8	2%	15.0	84%
Water/Wetland	160.2	12%	160.2	12%	0.0	0%
Total	1,337.3	100%	1,337.3	100%	--	--

When future land use is simulated in the Upper Hodges Brook subwatershed with historical climate conditions, there is a moderate increase in flow across the entire FDC (Figure 6-1). When future IC is fully connected (100% unmanaged), high flows are increased and low flows are decreased compared to the existing IC and predevelopment conditions. This is because of increase in IC generates more runoff causing an increase in the high flows and loss of vegetated cover causes less infiltration and evapotranspiration resulting in a decrease in low flows. Conversely, when IC is fully disconnected (100% managed), the highest 10% of flows are less than existing conditions, and moderate to low flows are greater. This is because capturing all runoff from IC under a 100% managed scenario brings down the high flows but due to loss in vegetated areas the ET is significantly reduced and higher infiltrated water causes an increase in the baseflow.

Impacts from the combination of future land use and future climate scenarios on the Upper Hodges Brook are generally consistent with those for the larger Taunton River watershed. These are key points for comparing baseline scenarios against future land use scenarios under various climatic conditions.

- The historical climate scenario for future land use conditions generates more flow across the entire FDC by comparing against the baseline scenario. This reflects the increased IC at the expense of natural vegetated cover, which increases runoff primarily by decreasing evapotranspiration and creates an ecosurplus of 90 MG/yr (Figure 6-2).
- The dry future climate scenario for future land use conditions creates ecodeficit across all but the highest 10% of flows. It creates an ecosurplus of 66.9 MG/yr and an ecodeficit of 90.5 MG/yr (Figure 6-3).
- The median future climate scenario for future land use conditions shows slightly higher ecosurplus (79.9 MG/yr) and lower ecodeficit (68.2 MG/yr) patterns as compared to the dry future climate scenario (Figure 6-4).

- The wet future climate scenario for future land use conditions shows similar trends with higher ecosurplus (182.4 MG/yr) and lower ecodeficit (55.9 MG/yr) patterns as compared to the median future climate scenario (Figure 6-5).

Figure 6-6 shows the impacts of various climatic conditions on hydrology and water quality between the baseline scenario and future land use scenario in the pilot sub-watershed. The trend is consistent across three future climate conditions. There is an increasing trend in runoff and nutrient loads for the dry, median, and wet future climate conditions, respectively.

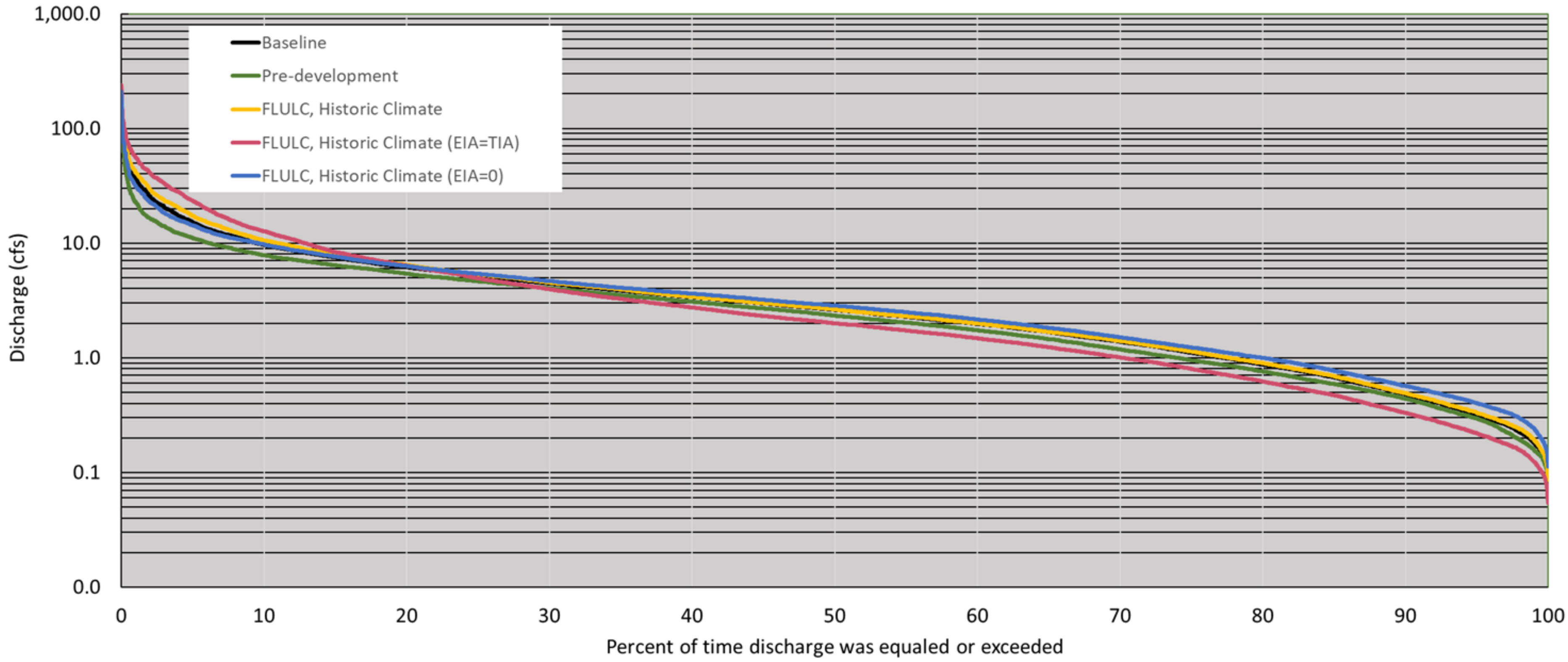


Figure 6-1. Flow duration curves for the Upper Hodges Brook for predevelopment, baseline (2016 existing conditions), and future land use/land cover (FLULC) with varying amounts of IC disconnection (existing condition, fully connected (Effective Impervious Area [EIA] = Total Impervious Area [TIA]), and fully disconnected (EIA=0)). All scenarios use historical climate data.

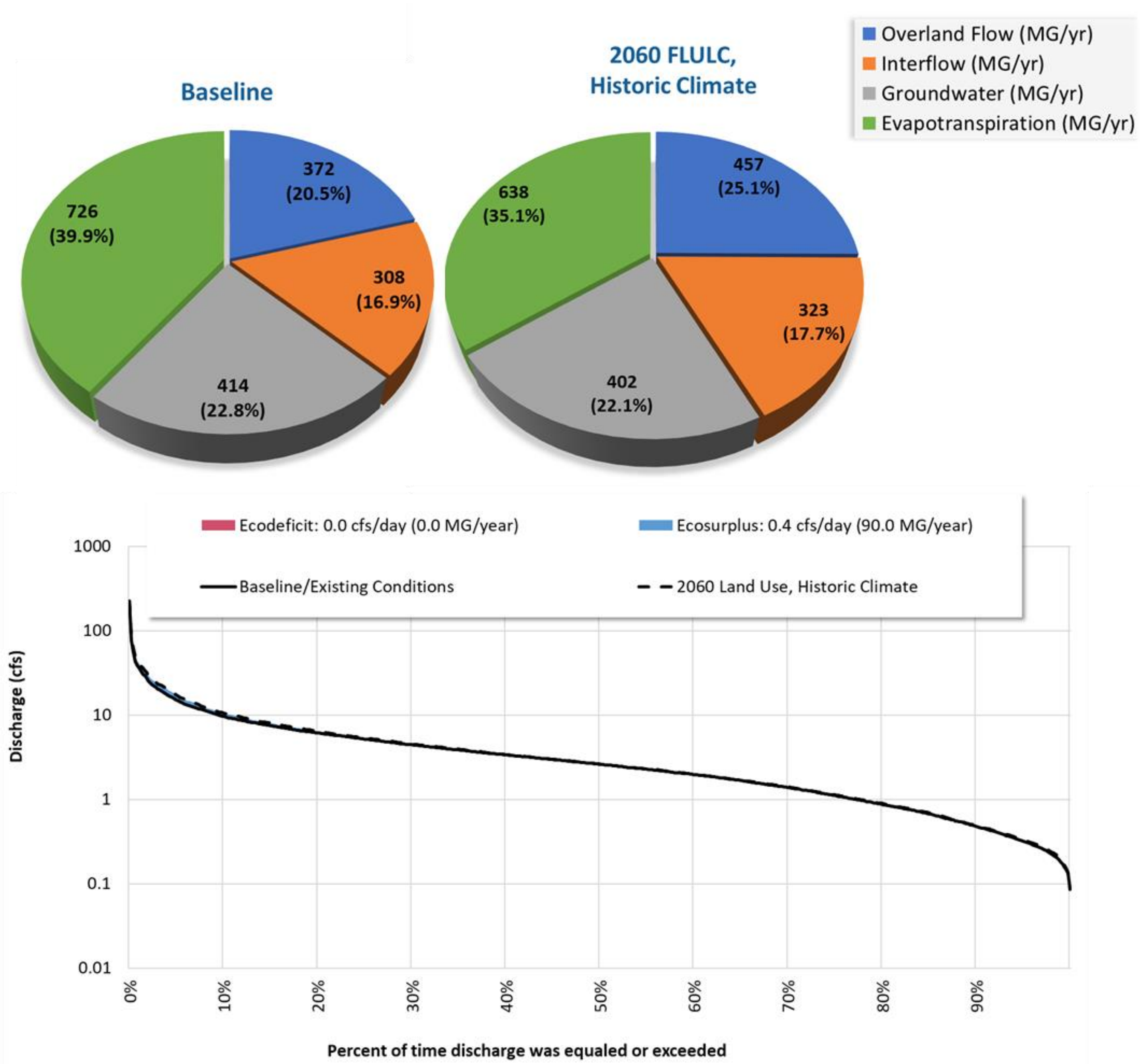


Figure 6-2. Water balance (pie charts) and FDC comparisons for existing baseline conditions and future land use with the historical climate scenario for the Upper Hodges Brook subwatershed.

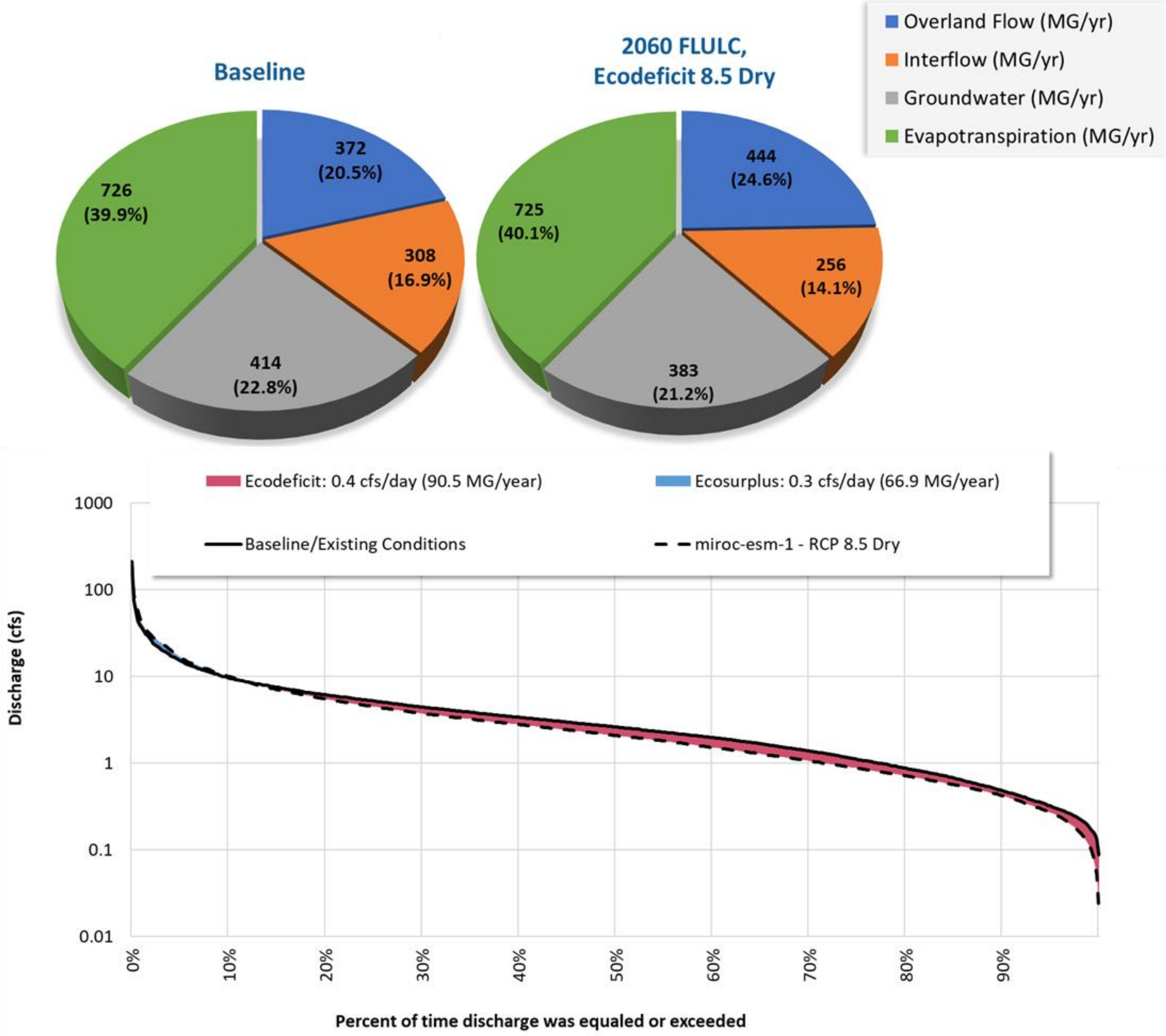


Figure 6-3. Water balance (pie charts) and FDC comparisons for existing baseline conditions and future land use with the dry future climate scenario for the Upper Hodges Brook subwatershed.

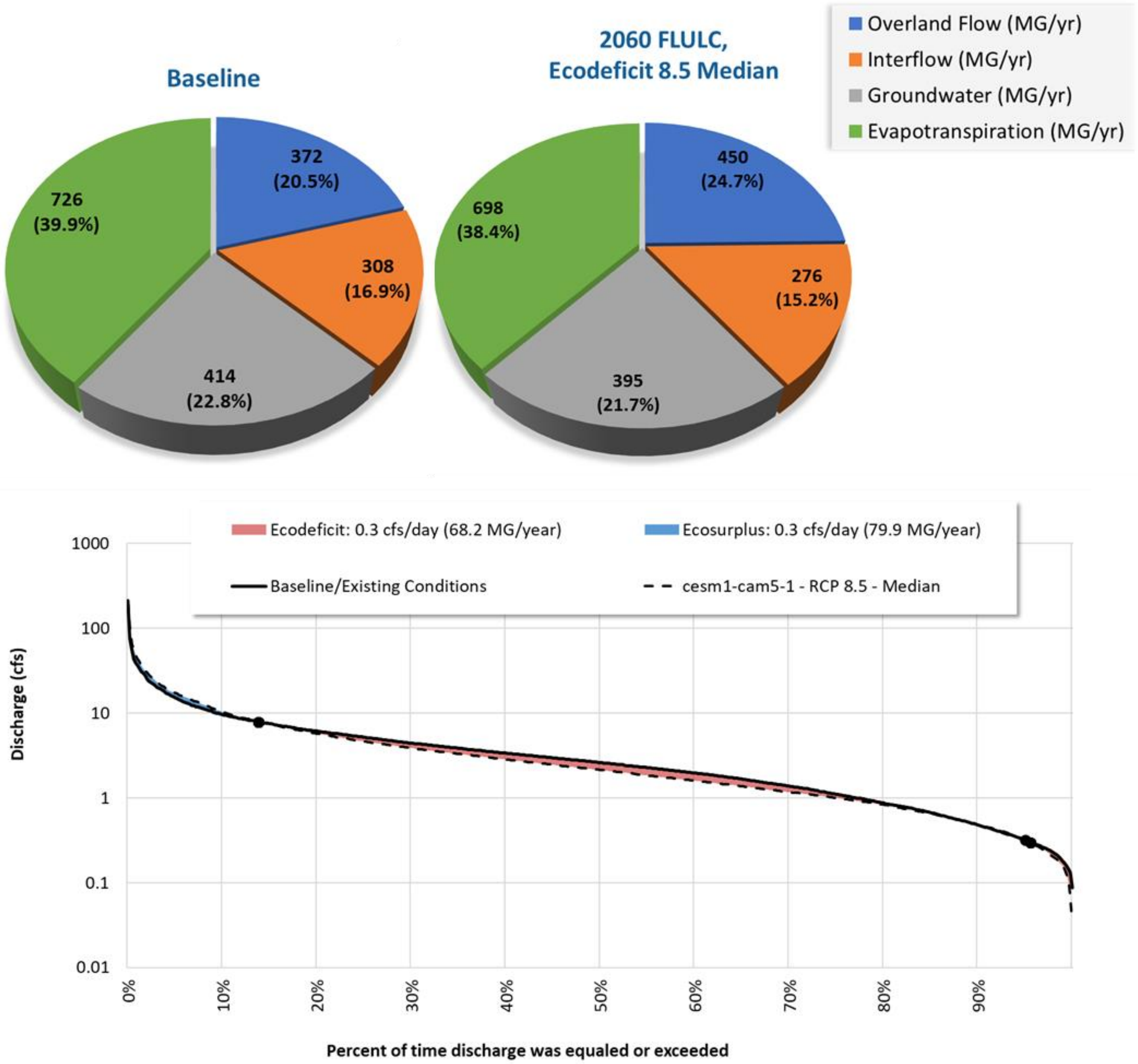


Figure 6-4. Water balance (pie charts) and FDC comparisons for existing baseline conditions and future land use with the median future climate scenario for the Upper Hodges Brook subwatershed.

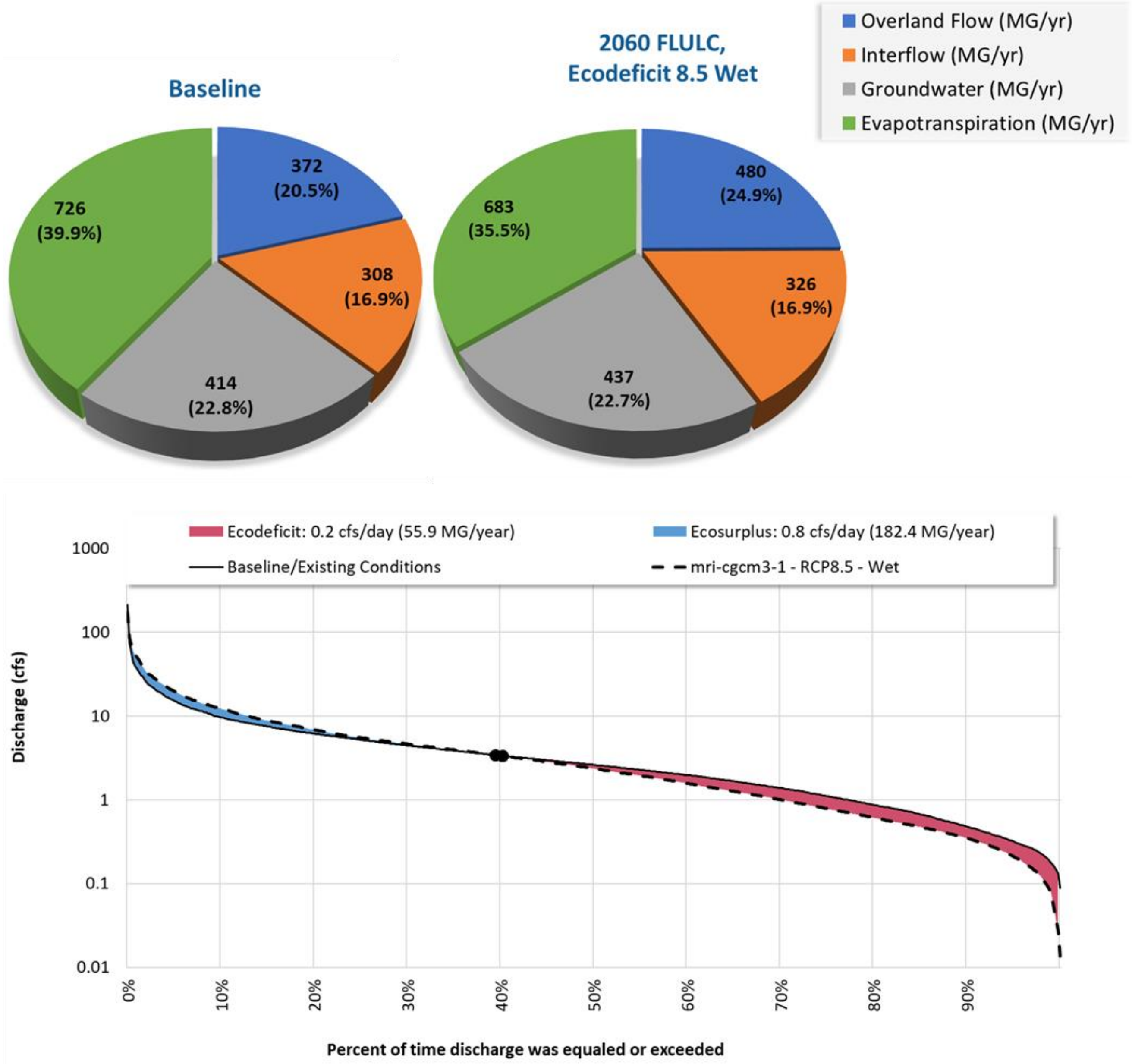


Figure 6-5. Water balance (pie charts) and FDC comparisons for existing baseline conditions and future land use with the wet future climate scenario for the Upper Hodges Brook subwatershed.

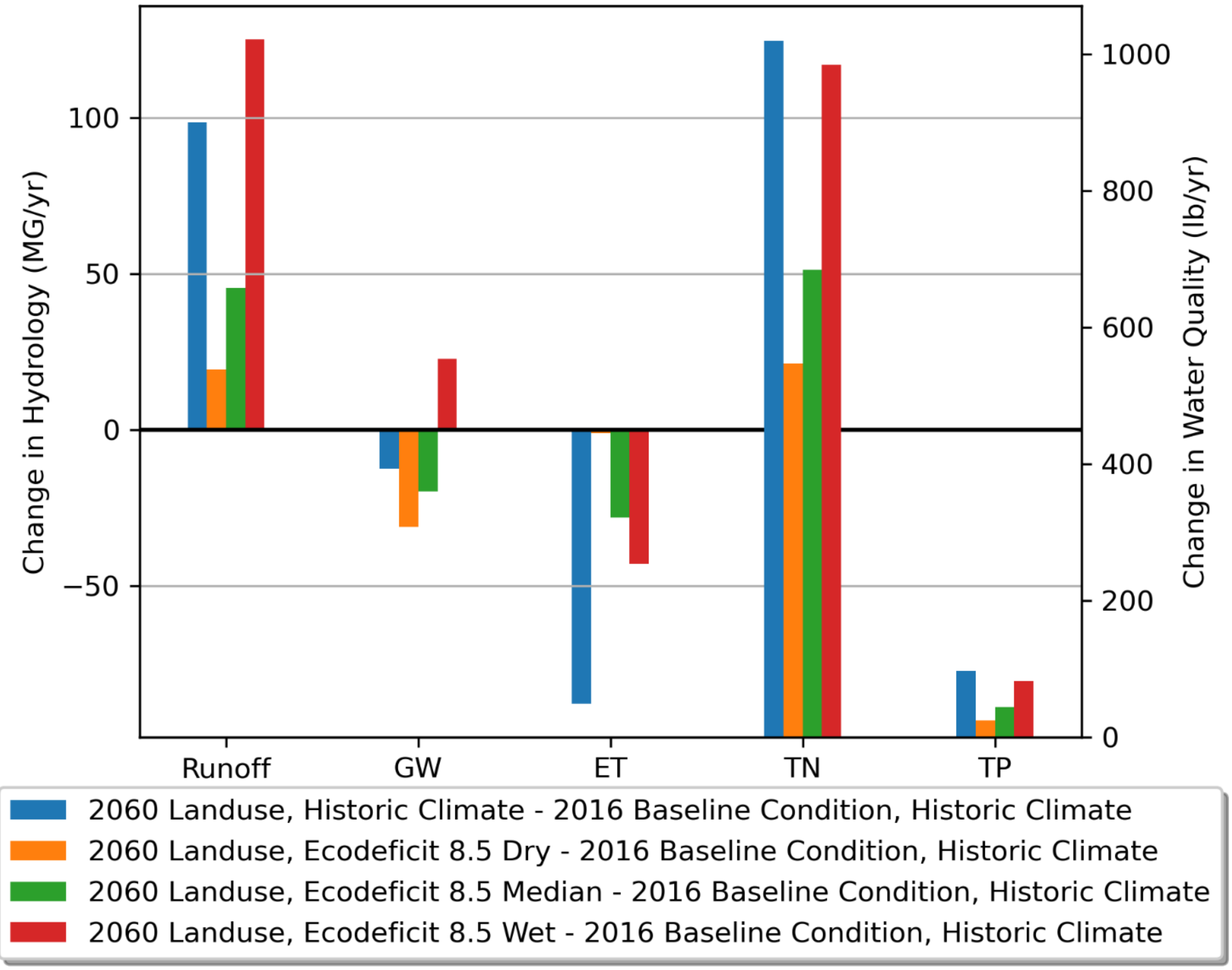


Figure 6-6. Comparison of changes in hydrology (runoff, groundwater recharge GW, and evapotranspiration ET) and water quality parameters (total nitrogen TN and total phosphorous TP) between the baseline and future land use/climate conditions for the Upper Hodges Brook subwatershed.

7. SITE SCALE MODELING ANALYSES

This section shows the modeling analysis of 12 scenarios for 3 site-scale concept designs which were taken from the real-world site plans to demonstrate the effectiveness of green infrastructure stormwater control measures (GI SCMs) that meet the existing standard of the Massachusetts Department of Environmental Protection (MassDEP) and also include a more protective high level of controls that nearly return the predevelopment hydrology. These site-scale conceptual designs were created for nD/rD scenarios. Each of these scenarios was configured in the Opti-Tool and the results are analyzed under the following sub-sections. Some of the CD practices were added to the Opti-Tool to simulate those GI SCMs under the site-scale and watershed-scale modeling scenarios. Appendix B outlines four new GI SCM, incorporated into the Opti-Tool to support management alternative analyses involving disconnection of impervious cover.

7.1. Site Scale Modeling Scenarios

Table 7-1 lists the site scale modeling scenarios; these are further distinguished by the level of stormwater control. Scenarios 1.2, 2.2, and 3.2 are developed sites with no SCMs. Scenarios 1.3, 2.3, and 3.3 represent current MassDEP and MS4 standards with peak flow control. Scenarios 1.4, 2.4, and 3.4 represent next-generation SCMs that promote resilient hydrology similar to predevelopment conditions with no net increase in nutrient loads. These scenarios were tested with both historical and future climate conditions.

Table 7-1. Conceptual design scenarios

Concept Design	Site Type	HSG	Scenario	Control Level
1	High Density Residential	B	1.1	Predevelopment
			1.2	No Controls
			1.3	Conventional
			1.4	GI and CD Practices
2	High Density Commercial	A	2.1	Predevelopment
			2.2	No Controls
			2.3	Conventional
			2.4	GI and CD Practices
3	Low Density Residential	B	3.1	Predevelopment
			3.2	No Controls
			3.3	Conventional
			3.4	GI and CD Practices

Conceptual Design 1 represents the new development of a high-density residential site. In Scenario 1.3, each single-family home has a rain garden that treats driveway runoff and an infiltration trench that treats rooftop runoff (Figure 7-1). These SCMs, and road runoff, all drain into a detention pond. In comparison, Scenario 1.4 treats road and roof runoff with infiltration trenches sized for enhanced capture; rooftop infiltration trenches drain into the roadway infiltration system (Figure 7-2). This eliminates the need for a detention pond and allows an additional house to be built.

The new development of a high-density commercial site is represented in Conceptual Design 2. In Scenario 2.3, infiltration trenches treat rooftop runoff from one building and drain to subsurface detention (pipe storage) below a parking lot (Figure 7-3). Runoff from another rooftop is treated by permeable pavement. In Scenario 2.4, the subsurface detention is replaced with permeable pavement for the entire parking lot (Figure 7-4).

Conceptual Design 3 represents the new development of a low-density residential area with dispersed housing units and large meadow and forest buffers. Runoff from rooftops, driveways, and roads is treated by routing it via sheet flow over buffer areas (i.e., IC disconnection) (Figure 7-5). This allows for runoff reduction by infiltration and evapotranspiration, sediment capture based on the vegetated land cover, and nutrient uptake by vegetation. Scenario 3.4 provides enhanced treatment by first treating runoff from impervious surfaces through infiltration trenches that infiltrate and act as level spreaders to pervious areas when their capacity is exceeded (Figure 7-6).

7.2. Site Scale Opti-Tool Setup

The setup of site scale conceptual designs began by transferring site information (e.g., land use, soil type) and SCM information (e.g., type, sizing, drainage area) into the Opti-Tool. One Opti-Tool model was created for each conceptual design and scenario; Figure 7-1 to Figure 7-6 show the Opti-Tool watershed sketch for Scenarios 1.3, 1.4, 2.3, 2.4, 3.3, and 3.4, respectively. The drainage area and footprints for SCMs used in each scenario are shown in Table 7-2 and Table 7-3, respectively. SCM specifications used in concept designs 1, 2, and 3 are given in Table 7-4, Table 7-5, and Table 7-6, respectively.

Number of Subwatersheds: 1
Number of Landuses: 36
Number of BMPs: 13
Number of Pollutants: 5
Number of Aquifers: 1

Figure 7-1. Opti-Tool watershed sketch for Scenario 1.3 with conceptual SCM diagrams.

Number of Subwatersheds: 1
Number of Landuses: 36
Number of BMPs: 8
Number of Pollutants: 5
Number of Aquifers: 1

Figure 7-2. Opti-Tool watershed sketch for Scenario 1.4 with conceptual SCM diagrams.

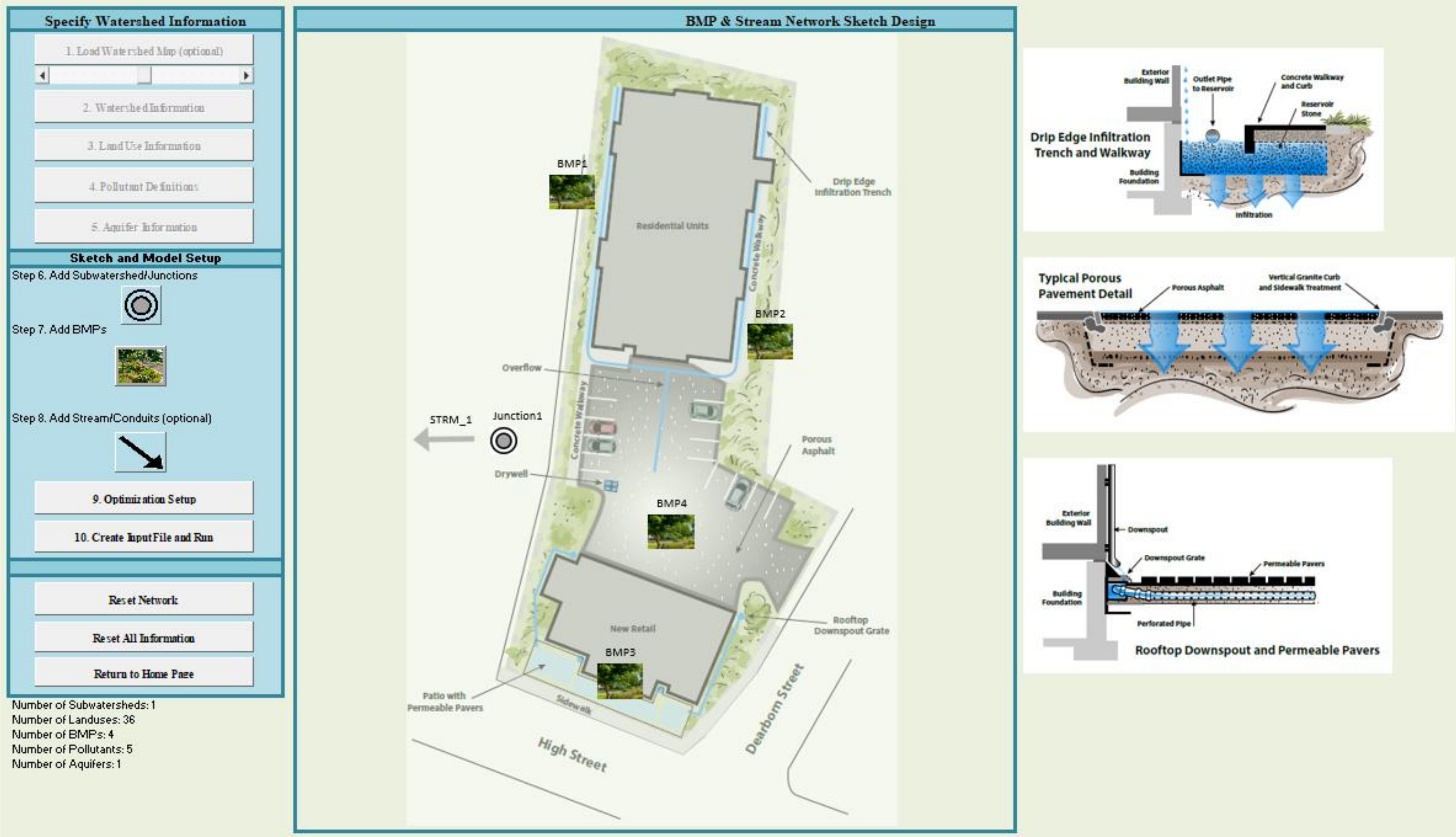
Step 6. Add Subwatershed/Junctions

Step 7. Add BMPs

Step 8. Add Stream/Conduits (optional)

Number of Subwatersheds: 1
Number of Landuses: 36
Number of BMPs: 4
Number of Pollutants: 5
Number of Aquifers: 1

Figure 7-3. Opti-Tool watershed sketch for Scenario 2.3 with conceptual SCM diagrams.

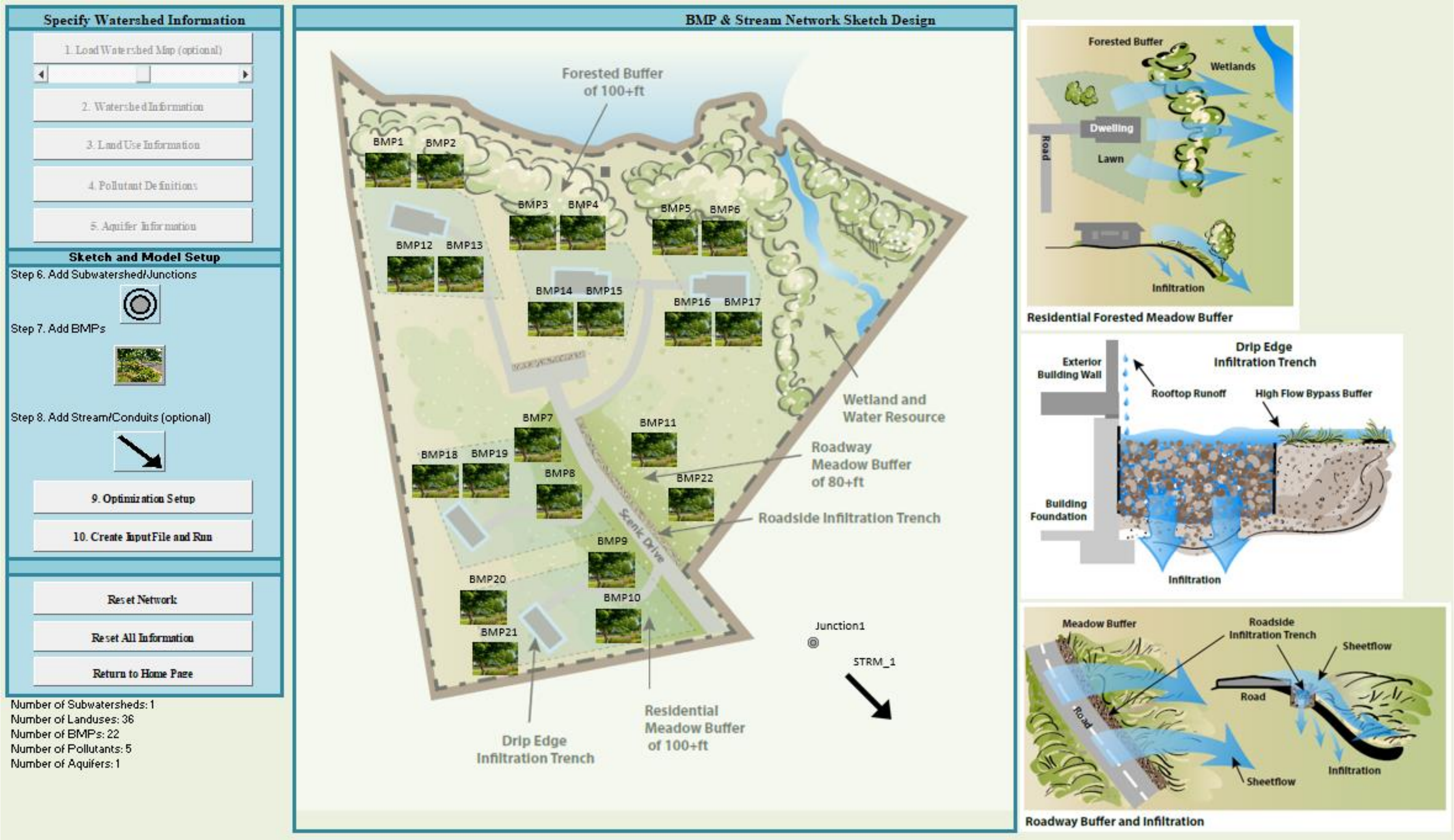


Number of Subwatersheds: 1
Number of Landuses: 36
Number of BMPs: 4
Number of Pollutants: 5
Number of Aquifers: 1

Figure 7-4. Opti-Tool watershed sketch for Scenario 2.4 with conceptual SCM diagrams.

Number of Subwatersheds: 1
Number of Landuses: 36
Number of BMPs: 11
Number of Pollutants: 5
Number of Aquifers: 1

Figure 7-5. Opti-Tool watershed sketch for Scenario 3.3 with conceptual SCM diagrams.



Step 6. Add Subwatershed/Junctions

Step 7. Add BMPs

Step 8. Add Stream/Conduits (optional)

Number of Subwatersheds: 1
Number of Landuses: 36
Number of BMPs: 22
Number of Pollutants: 5
Number of Aquifers: 1

Figure 7-6. Opti-Tool watershed sketch for Scenario 3.4 with conceptual SCM diagrams.

Table 7-2. SCM drainage areas (acres) for the concept designs 1, 2, and 3

Land Use Group	Disconnection Type	SCM Type	HSG	1.3	1.4	2.3	2.4	3.3	3.4
Commercial	Rooftop	Infiltration Trench	A			0.17	0.17		
		Porous Pavement	A			0.10	0.06		
	Other IC	Porous Pavement	A				0.22		
		Bioretention	A			0.18			
Low Density Residential	Rooftop	Infiltration Trench	B						0.92
		IC Disconnection	B					0.92	
High Density Residential	Rooftop	Infiltration Trench	B	0.36	0.41				
		Bioretention	B	0.12					
	Other IC	Infiltration trench	B		0.14				
Transportation	Other IC	Infiltration trench	B		0.12				0.24
		Bioretention	C	0.12					
		IC Disconnection	B					0.24	
Open Land	Other IC	Infiltration trench	B		0.66				
		Bioretention	B	0.97					
Developed Open Space	NA	IC Disconnection	B					7.15	7.15

Table 7-3. SCM capacity (ft^3) for the concept designs 1, 2, and 3

Land Use Group	Disconnection Type	SCM Type	HSG	1.3	1.4	2.3	2.4	3.3	3.4
Commercial	Rooftop	Infiltration Trench	A			1,245	1,423		
		Porous Pavement	A			1,244	566		
	Other IC	Porous Pavement	A				12,019		
		Bioretention	A			1,698			
Low Density Residential	Rooftop	Infiltration Trench	B						34,911
		IC Disconnection	B						
High Density Residential	Rooftop	Infiltration Trench	B	1,508	1,471				
		Bioretention	B	840					
	Other IC	Infiltration trench	B		4,689				
Transportation	Other IC	Infiltration trench	B		4,004				
		Bioretention	B	429					
		IC Disconnection	B						
Open Land	Other IC	Infiltration trench	B		2,008				
		Bioretention	C						
Developed Open Space	NA	IC Disconnection	B					47,021	47,021

Table 7-4. SCM design specifications for conceptual design 1

General Information	SCM Parameters	Infiltration Trench HSG – B	Bioretention (Rain Garden) HSG – B	Bioretention (Detention Pond) HSG –B	Infiltration Trench (Roadway Subsurface) HSG B
Surface Storage Configuration	Orifice Height (ft)	0	0	0	0
	Orifice Diameter (in.)	0	0	0.75	0
	Rectangular or Triangular Weir	Rectangular	Rectangular	Rectangular	Rectangular
	Weir Height (ft)/Ponding Depth (ft)	0	0.5	4	0
	Crest Width (ft)	30	30	30	30
Soil Properties	Depth of Soil (ft)	3	2	0	3
	Soil Porosity (0-1)	0.4	0.25	0.4	0.4
	Vegetative Parameter A	0.9	0.9	0	0.9
	Soil Infiltration (in/hr)	2.5	2.5	2.5	2.5
Underdrain Properties	Consider Underdrain Structure?	No	No	No	No
	Storage Depth (ft)	0	0	0	0
	Media Void Fraction (0-1)	0	0	0	0
	Background Infiltration (in/hr)	N/A	N/A	N/A	N/A
Cost Parameters (CD1.4)	Storage Volume Cost ($/ft^3)	$12.82 ($10.53)	$6.35	$6.98	$5.51
Cost Function Adjustment (CD1.4)	SCM Development Type	New SCM in Undeveloped Area	New SCM in Undeveloped Area	New SCM in Undeveloped Area	New SCM in Undeveloped Area
	Cost Adjustment Factor	1 (0.8215)	0.4	0.44	0.43
Decay Rates	TSS (1/hr)	0.74	0.79	0.79	0.74

General Information	SCM Parameters	Infiltration Trench HSG – B	Bioretention (Rain Garden) HSG – B	Bioretention (Detention Pond) HSG –B	Infiltration Trench (Roadway Subsurface) HSG B
	TN (1/hr)	0.42	0.01	0.01	0.42
	TP (1/hr)	0.03	0.01	0.01	0.03
	ZN (1/hr)	0.45	0.49	0.49	0.45
Underdrain Removal Rates	TSS (%, 0-1)	N/A	N/A	N/A	N/A
	TN (%, 0-1)	N/A	N/A	N/A	N/A
	TP (%, 0-1)	N/A	N/A	N/A	N/A
	ZN (%, 0-1)	N/A	N/A	N/A	N/A

Table 7-5. SCM design specifications for conceptual design 2

General Information	SCM Parameters	Infiltration Trench HSG – A	Porous Pavement (Concrete) HSG A	Porous Pavement (Asphalt) HSG A	Bioretention (Subsurface Detention) HSG A
Surface Storage Configuration	Orifice Height (ft)	0	0	0	0
	Orifice Diameter (in.)	0	0	0	1
	Rectangular or Triangular Weir	Rectangular	Rectangular	Rectangular	Rectangular
	Weir Height (ft)/Ponding Depth (ft)	0	0	0	3.5
	Crest Width (ft)	30	30	30	30
Soil Properties (CD2.4)	Depth of Soil (ft)	1.75 (2)	1.1 (0.5)	1.75	0
	Soil Porosity (0-1)	0.4	0.4	0.4	0.4
	Vegetative Parameter A	0.9	0.1	0.1	0.9
	Soil Infiltration (in/hr)	2.41	2.41	2.41	0
Underdrain Properties	Consider Underdrain Structure?	No	No	No	No
	Storage Depth (ft)	0	0	0	0
	Media Void Fraction (0-1)	0	0	0	0

General Information	SCM Parameters	Infiltration Trench HSG – A	Porous Pavement (Concrete) HSG A	Porous Pavement (Asphalt) HSG A	Bioretention (Subsurface Detention) HSG A
	Background Infiltration (in/hr)	N/A	N/A	N/A	N/A
Cost Parameters	Storage Volume Cost ($/ft^3)	$12.82	$18.07	$5.46	$15.87
Cost Function Adjustment	SCM Development Type	New SCM in Undeveloped Area	New SCM in Undeveloped Area	New SCM in Undeveloped Area	New SCM in Undeveloped Area
	Cost Adjustment Factor	1	1	1	1
Decay Rates	TSS (1/hr)	0.74	0.22	0.22	0.79
	TN (1/hr)	0.42	0.26	0.26	0.01
	TP (1/hr)	0.03	0.0051	0.0051	0.01
	ZN (1/hr)	0.45	0.14	0.14	0.49
Underdrain Removal Rates	TSS (%, 0-1)	N/A	N/A	N/A	N/A
	TN (%, 0-1)	N/A	N/A	N/A	N/A
	TP (%, 0-1)	N/A	N/A	N/A	N/A
	ZN (%, 0-1)	N/A	N/A	N/A	N/A

Table 7-6. SCM design specifications for conceptual design 3

General Information	SCM Parameters	Infiltration Trench HSG – B	IC Disconnection HSG – B
Surface Storage Configuration	Orifice Height (ft)	0	0
	Orifice Diameter (in.)	0	0
	Rectangular or Triangular Weir	Rectangular	Rectangular
	Weir Height (ft)/Ponding Depth (ft)	0.5	0.15
	Crest Width (ft)	30	0
Pervious Area Properties	Depression Storage (in.)	N/A	0.15
	Slope	N/A	0.19
	Mannings n	N/A	0.12 (meadow), 0.05 (forest)
Soil Properties	Depth of Soil (ft)	2	0

General Information	SCM Parameters	Infiltration Trench HSG – B	IC Disconnection HSG – B
	Soil Porosity (0-1)	0.4	0.3
	Vegetative Parameter A	0.9	0.9
	Soil Infiltration (in/hr)	1.5	0.1
Underdrain Properties	Consider Underdrain Structure?	No	No
	Storage Depth (ft)	0	0
	Media Void Fraction (0-1)	0	0
	Background Infiltration (in/hr)	N/A	N/A
Cost Parameters	Storage Volume Cost ($/ft^3)	$10.53	$0.00
Cost Function Adjustment	SCM Development Type	New SCM in Undeveloped Area	New SCM in Undeveloped Area
	Cost Adjustment Factor	0.8214	1
Decay Rates	TSS (1/hr)	0.74	0.2
	TN (1/hr)	0.42	0.2
	TP (1/hr)	0.03	0.2
	ZN (1/hr)	0.45	0.2
Underdrain Removal Rates	TSS (%, 0-1)	N/A	N/A
	TN (%, 0-1)	N/A	N/A
	TP (%, 0-1)	N/A	N/A
	ZN (%, 0-1)	N/A	N/A

7.3. Site Scale Modeling Results

Runoff duration curves (RDCs), which account for storm runoff only, are conceptually similar to FDCs and provide a powerful tool to illustrate the differences between the control levels for each conceptual design. Each of the RDCs in Figure 7-7 to Figure 7-12 shows predevelopment hydrology ("Pre-Dev"), no controls developed under historical climate conditions ("Post-Dev, no BMPs"), the controlled developed under historical climate conditions ("Post-Dev, with BMPs"), and the controlled developed under future climate conditions ("Future Climate, with BMPs"). Comparing scenarios 1.3 and 1.4, it is clear that the SCMs in scenario 1.4 are a much better match to predevelopment hydrology for the high density residential site. Similarly, scenario 2.4 achieves near-predevelopment hydrology across the entire runoff duration curve. An example of what a large event on the upper end of the RDC looks like is shown in Figure 7-14 and Figure 7-15. For this 10-year, 24-hour storm event (totaling 4.9 in of rainfall in 24 hours) from the historical precipitation record, the GI and CD practices eliminated peak flow and attenuated the entire event.

The RDCs for the median future climate ("Future Climate, with BMPs") as compared to the RDCs for historical precipitation ("Post-Dev, with BMPs"), show all flows are shifted somewhat higher, reflecting the increase in precipitation. Even with the increased precipitation, the GI and CD practices like those used in scenario 2.4 are effective at approaching predevelopment hydrology.

Annualized runoff, Total Suspended Solids (TSS), and TP loads for each conceptual design are shown in Figure 7-16 to Figure 7-18 for both historical and median future climate conditions. For each conceptual design, the GI and CD practices outperform conventional and no control scenarios. The capital cost and the cost per acre IC treated for each scenario are shown in Table 7-7. Further, while pollutant loads from the GI and CD practices are greatly reduced for the high-density residential site compared to conventional practices, they are almost eliminated for the commercial site. IC disconnection for the low-density residential site is a particularly effective SCM, with or without the infiltration trenches used in scenario 3.4. Infiltration trenches would be needed to meet the peak flow standard as shown in Figure 7-15.

Table 7-7. Summary of total cost and cost of unit-acre IC treated for each scenario at site-scale concept plans

Concept Design	Site Type	HSG	Scenario	Control Level	Total Cost ($)	Cost/Acre IC Treated ($/ac)
1	High Density Residential	B	1.1	Predevelopment	--	--
			1.2	No Controls	--	--
			1.3	Conventional	$37,804	$63,536
			1.4	GI and CD Practices	$33,843	$50,815
2	High Density Commercial	A	2.1	Predevelopment	--	--
			2.2	No Controls	--	--
			2.3	Conventional	$42,337	$93,459
			2.4	GI and CD Practices	$37,678	$83,173
3	Low Density Residential	B	3.1	Predevelopment	--	--
			3.2	No Controls	--	--
			3.3	Conventional	$0*	$0*
			3.4	GI and CD Practices	$106,203	$91,554

*The cost of disconnecting the IC and level spreader to route the flow to the buffer area is not considered.

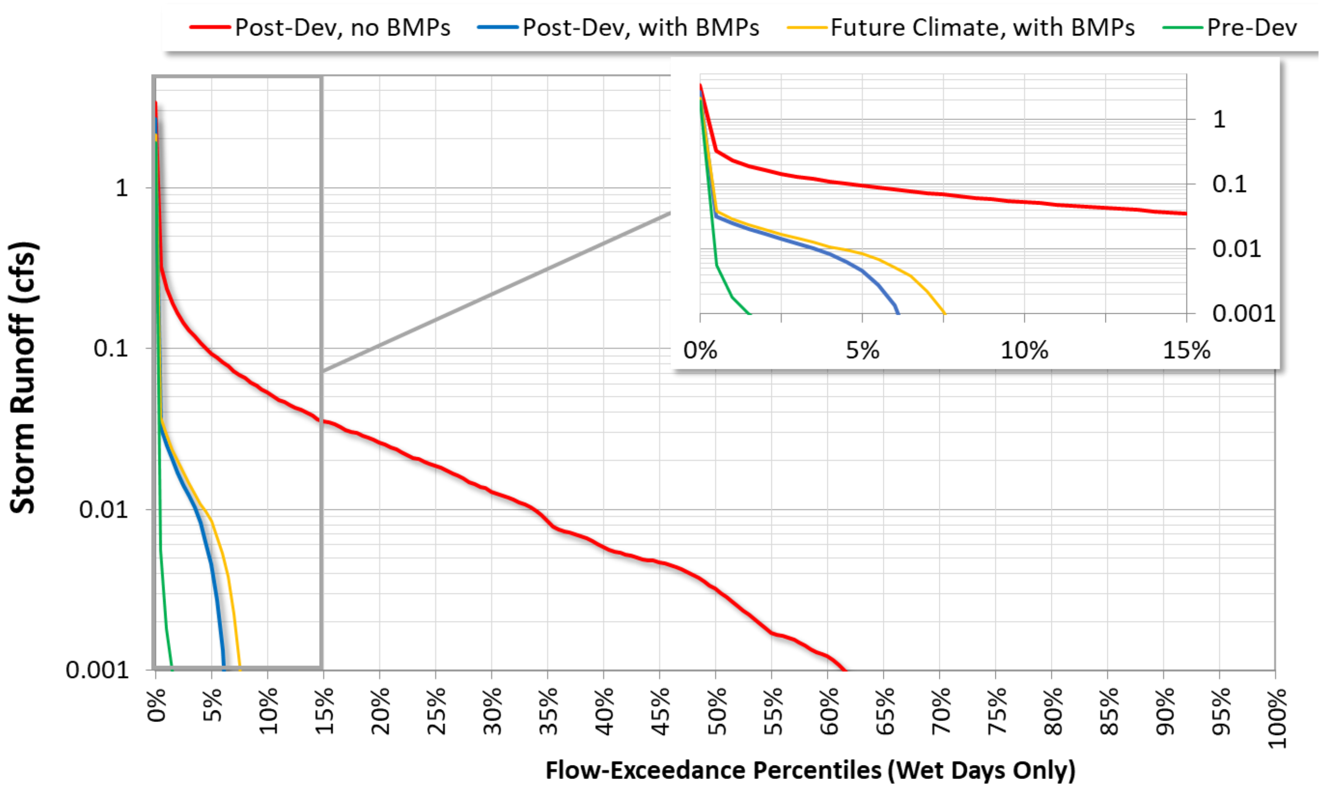


Figure 7-7. Runoff duration curve for Scenario 1.3 with historical and future climate.

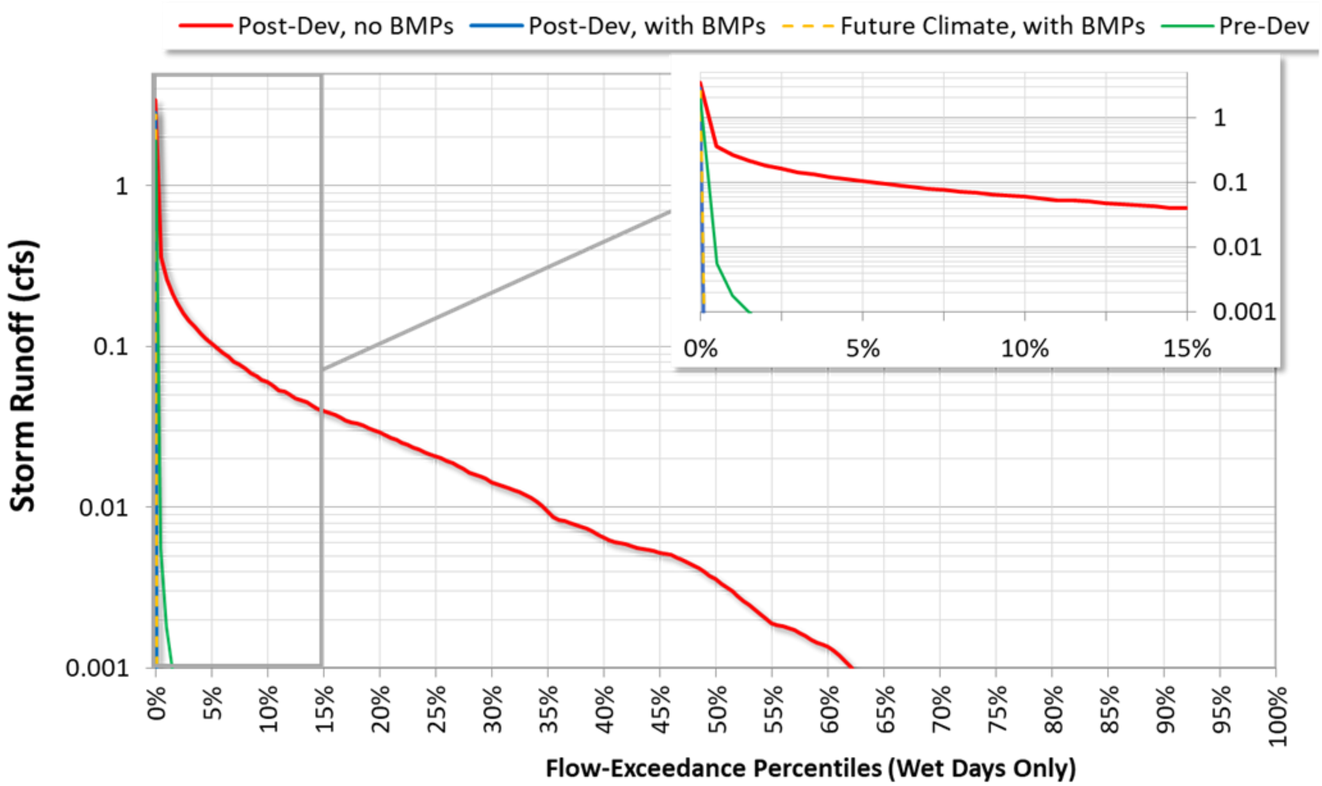


Figure 7-8. Runoff duration curve for Scenario 1.4 with historical and future climate.

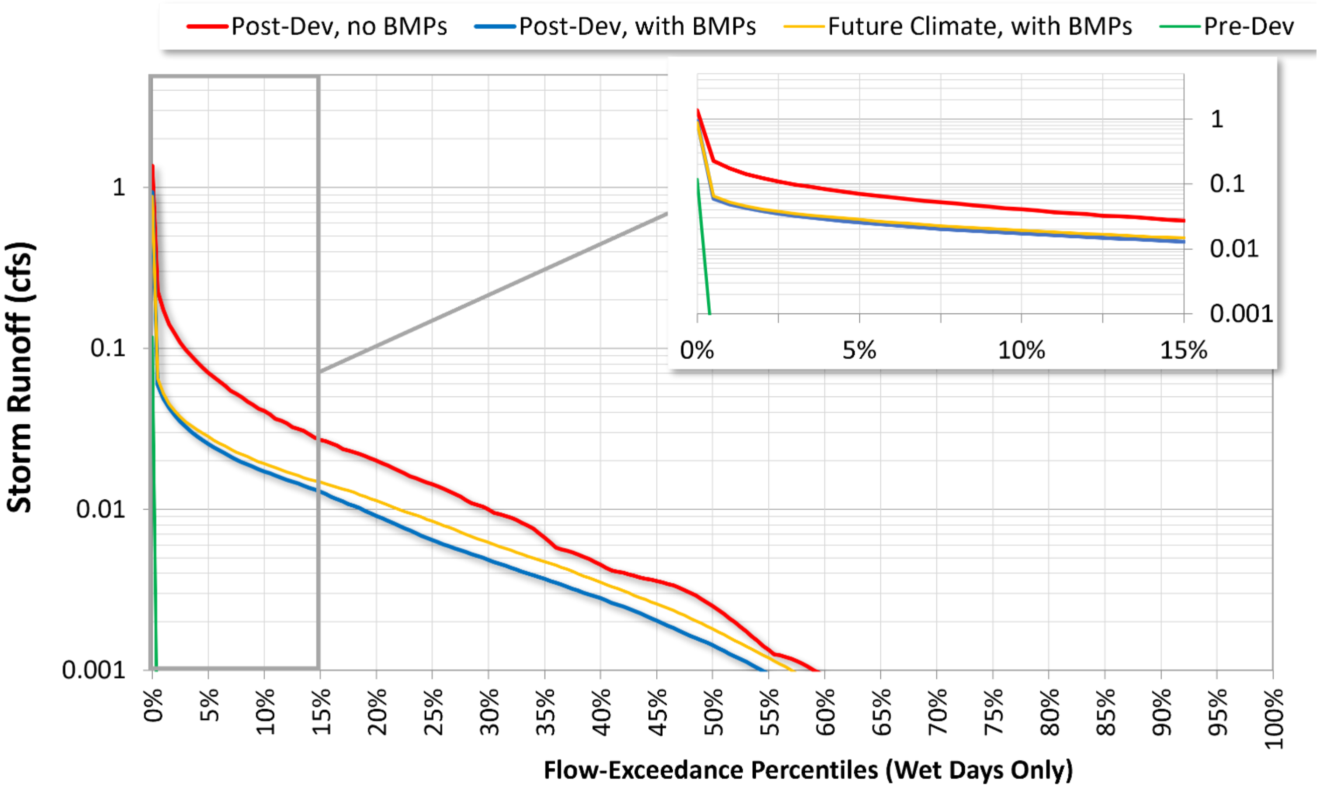


Figure 7-9. Runoff duration curve for Scenario 2.3 with historical and future climate.

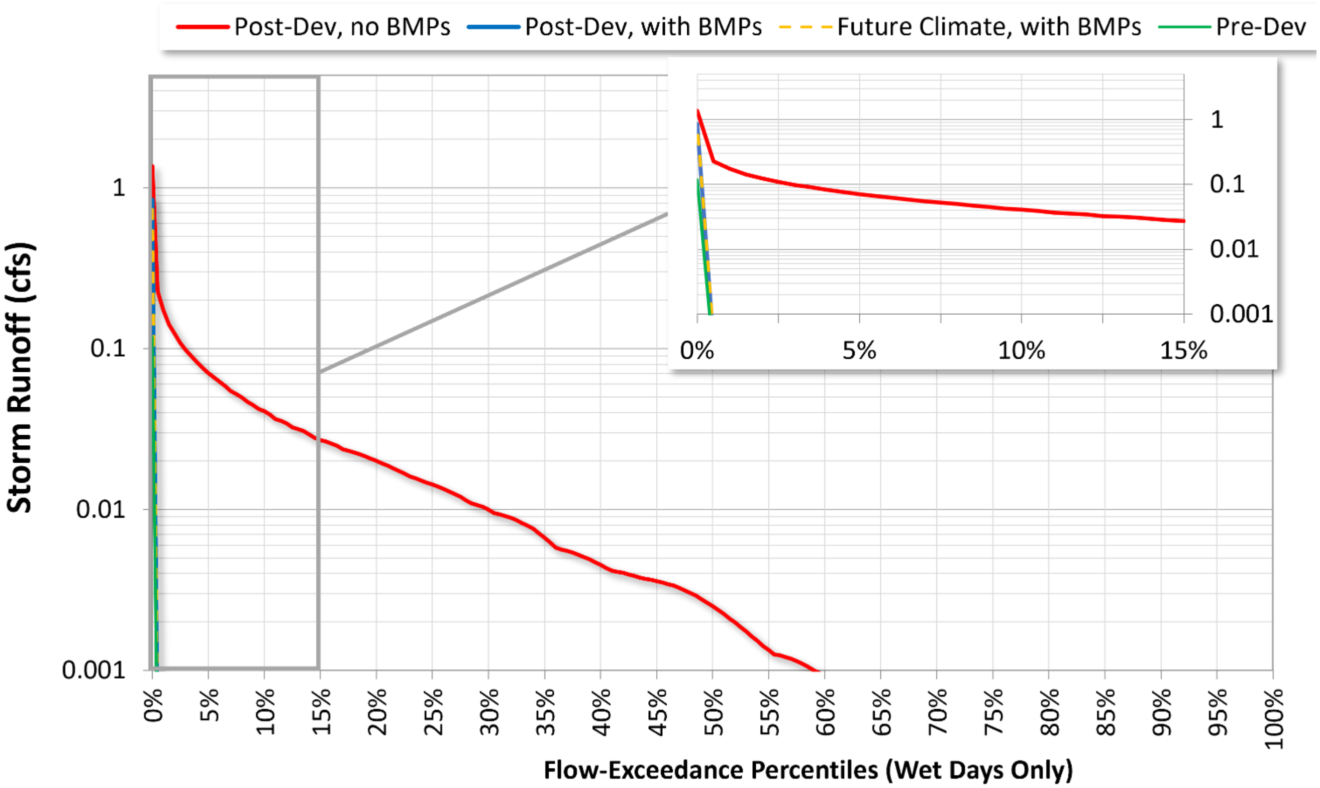


Figure 7-10. Runoff duration curve for Scenario 2.4 with historical and future climate.

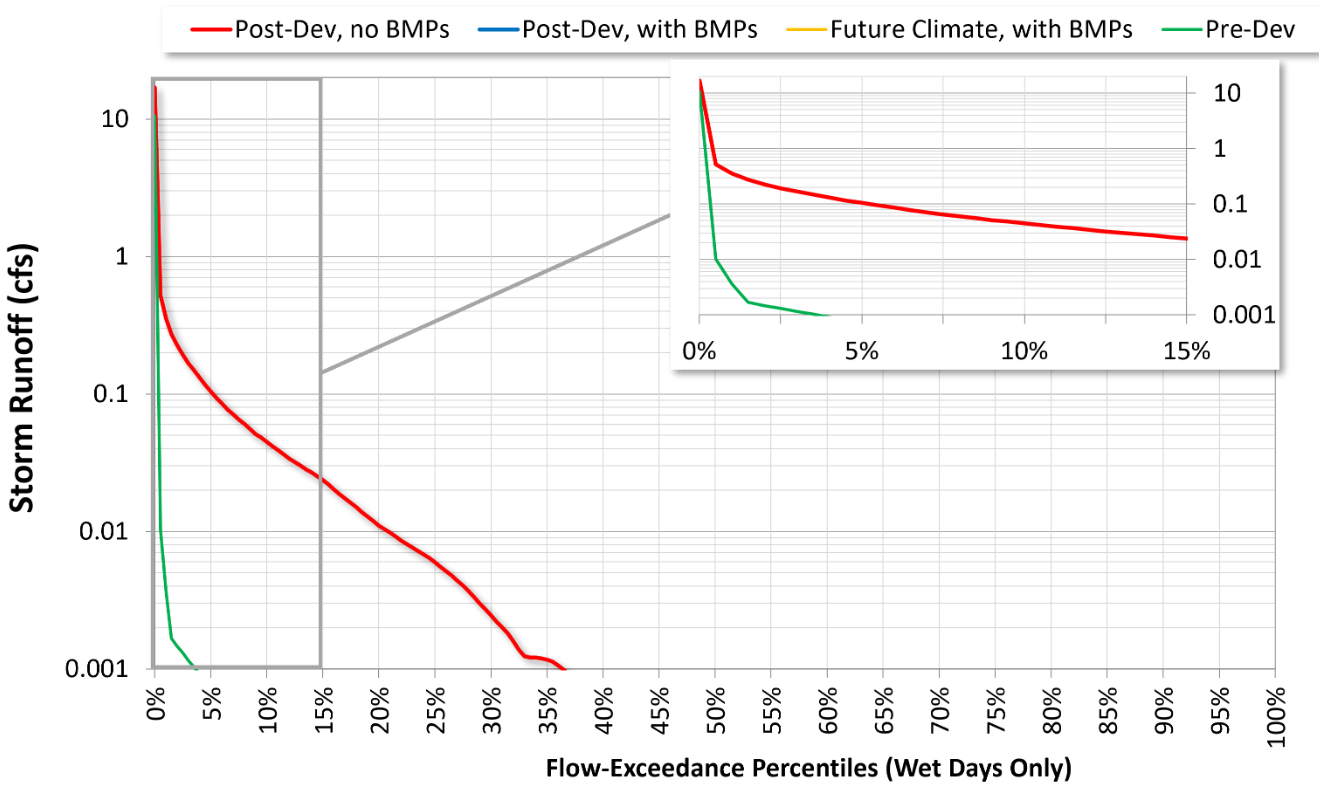


Figure 7-11. Runoff duration curve for Scenario 3.3 with historical and future climate.

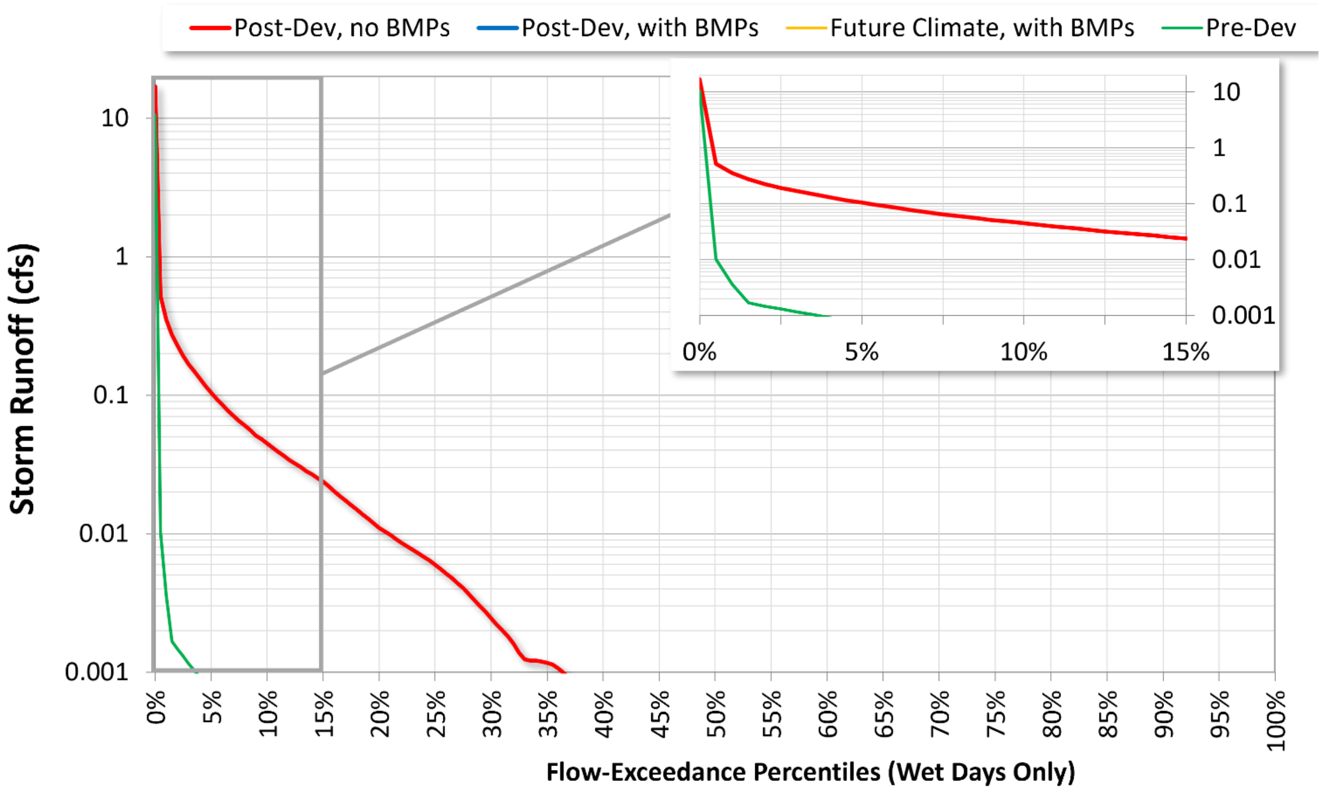


Figure 7-12. Runoff duration curve for Scenario 3.4 with historical and future climate.

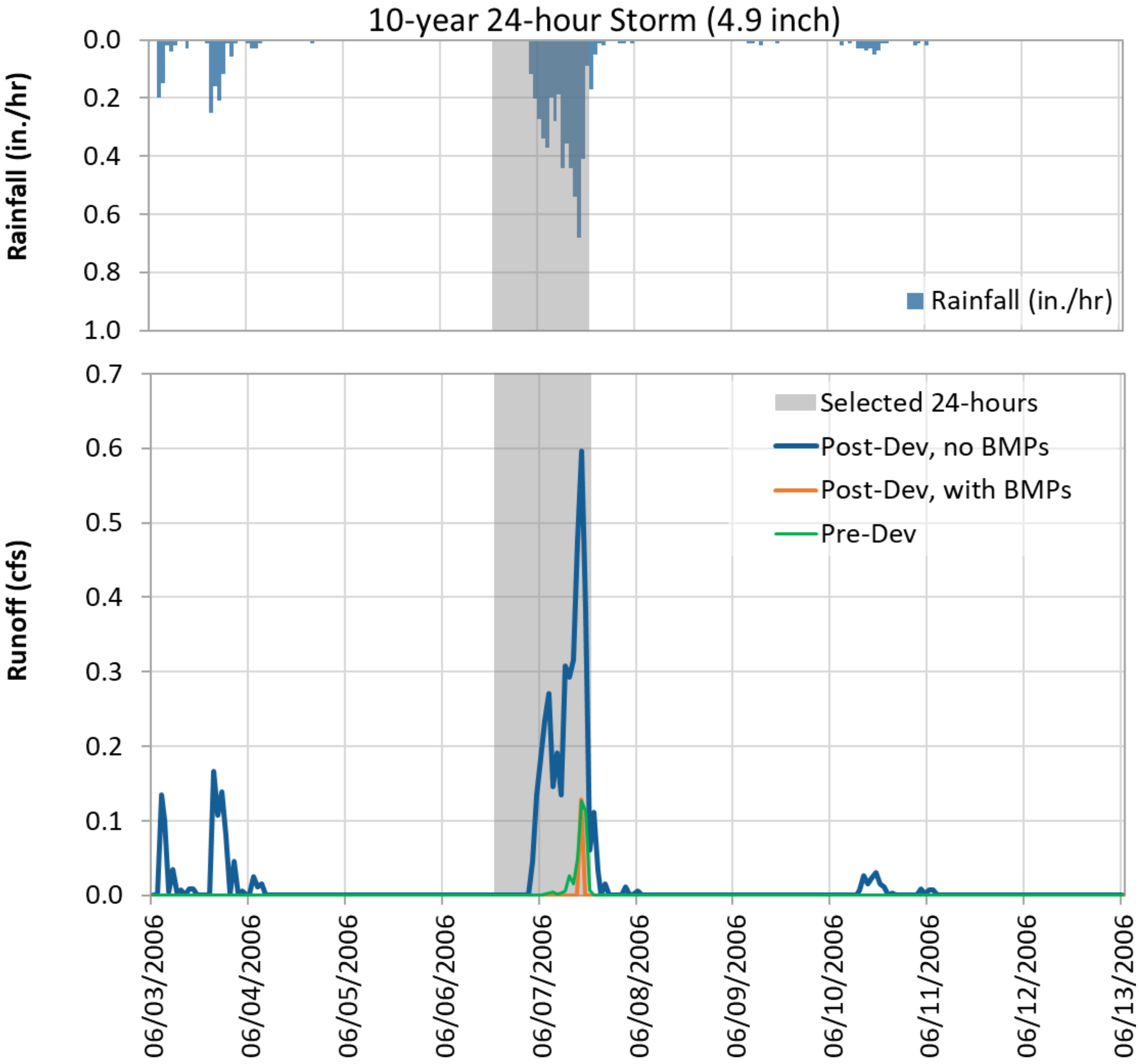


Figure 7-13. Hyetograph (top) and hydrograph (bottom) for a 10yr-24hr storm event for Scenario 1.4 illustrating peak runoff capture of the GI and CD practices that is similar to the predeveloped condition.

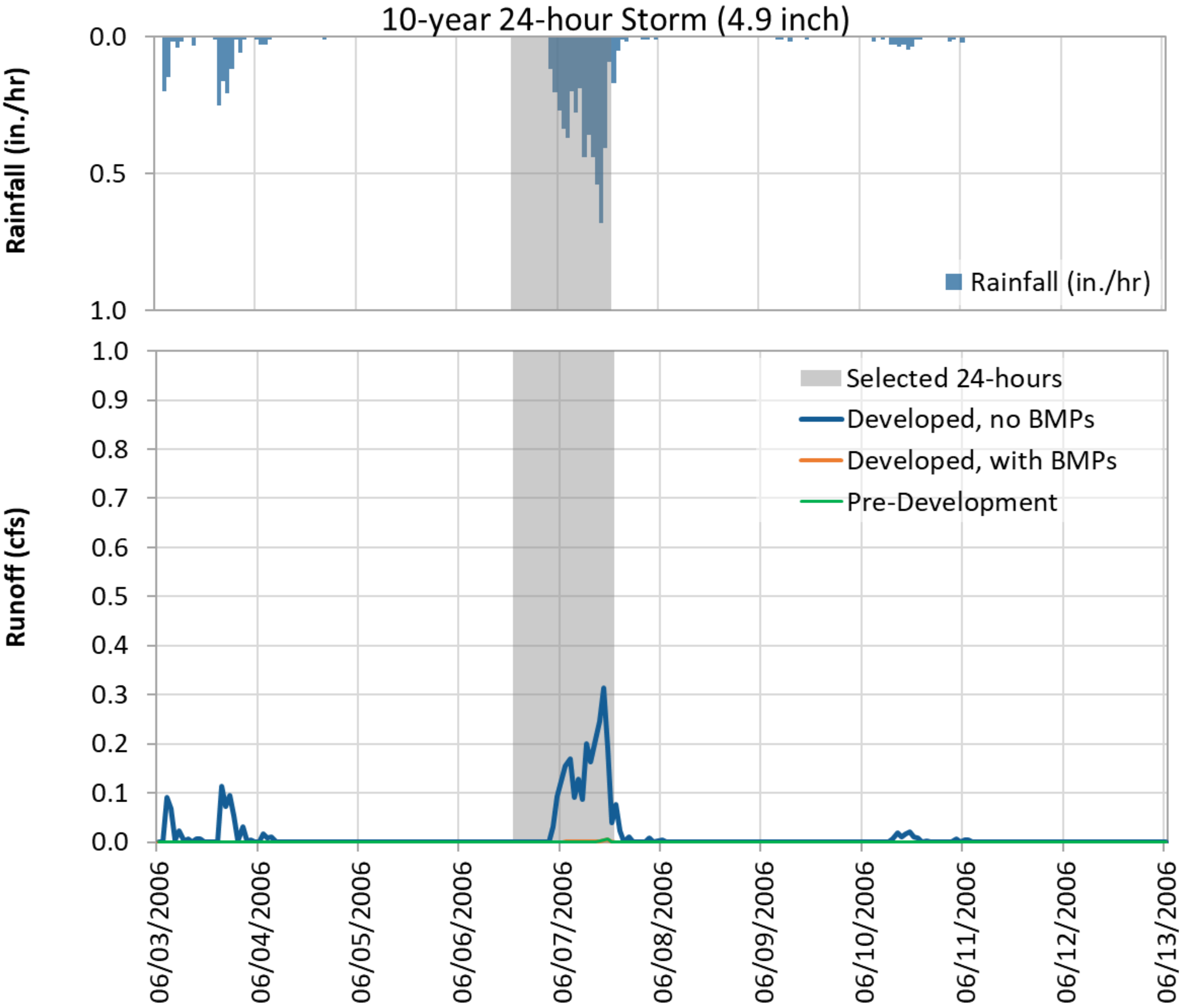


Figure 7-14. Hyetograph (top) and hydrograph (bottom) for a 10yr-24hr storm event for Scenario 2.4 illustrating peak runoff capture of the GI and CD practices that is similar to the predeveloped condition.

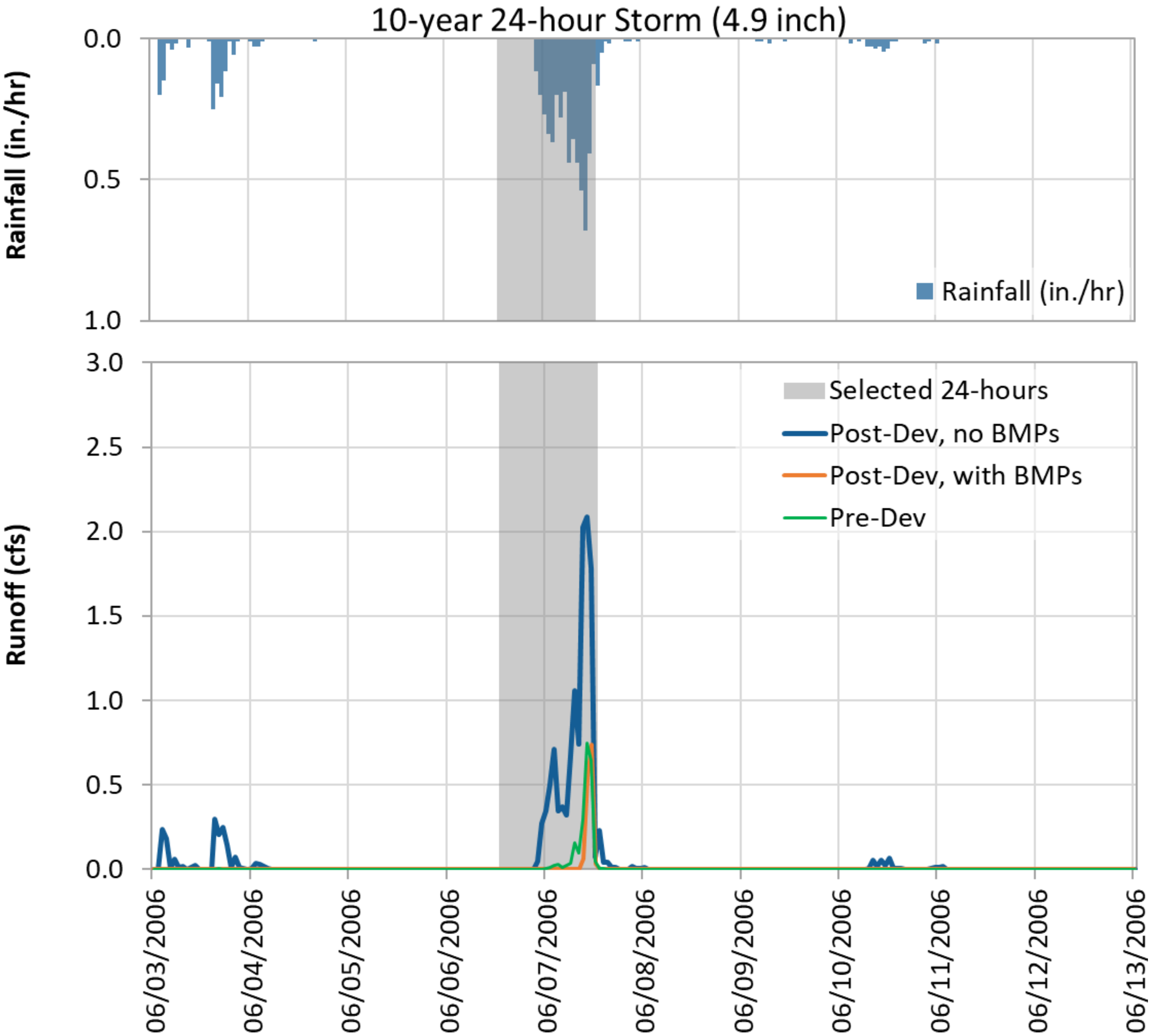


Figure 7-15. Hyetograph (top) and hydrograph (bottom) for a 10yr-24hr storm event for Scenario 3.4 illustrating peak runoff capture of the GI and CD practices that is similar to the predeveloped condition.

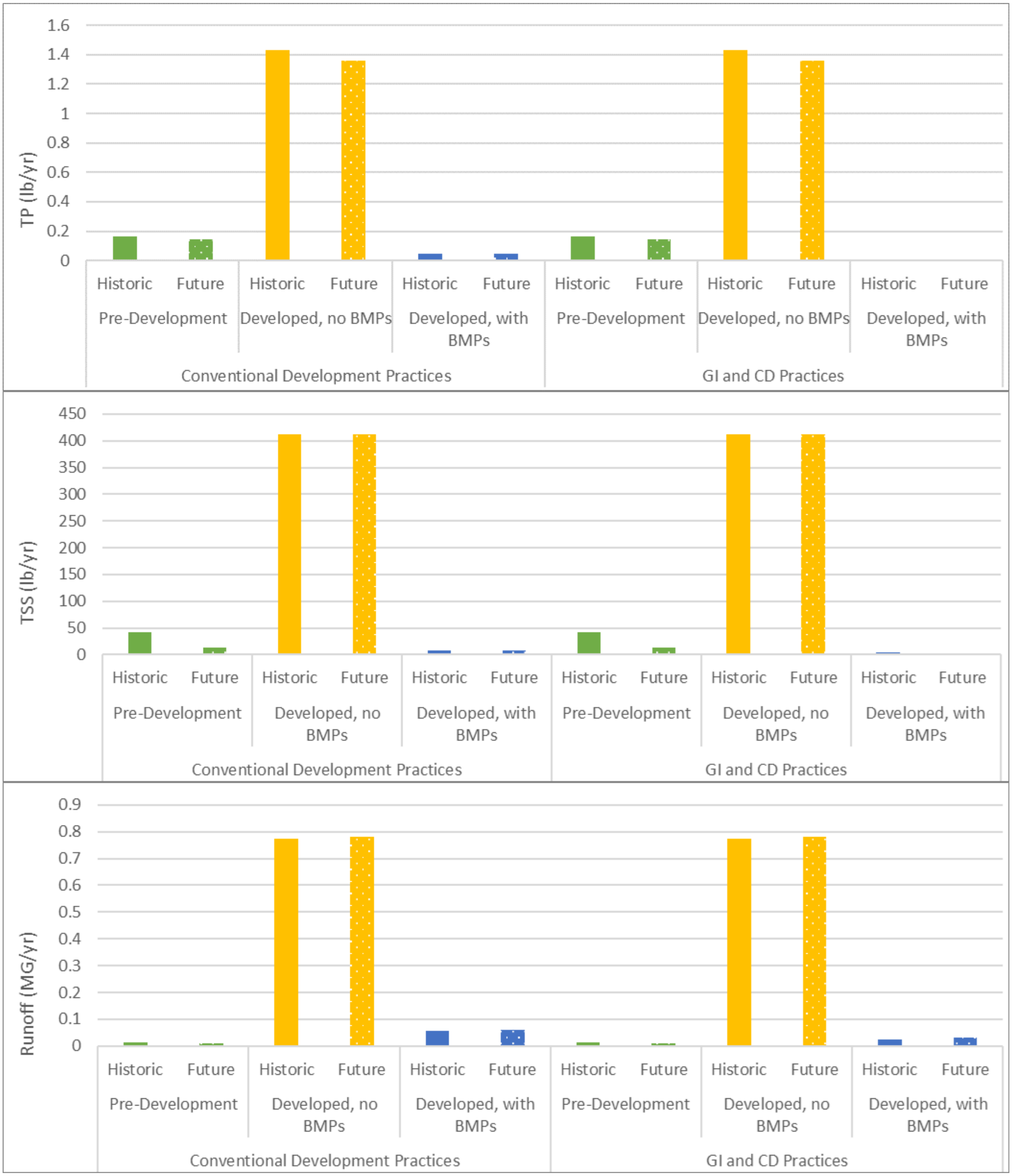


Figure 7-16. Annualized TP, TSS, and Runoff load and removal cost for High Density Residential (HSG-B) conceptual design 1 for conventional development practices and GI and conservation design practices with historical climate.

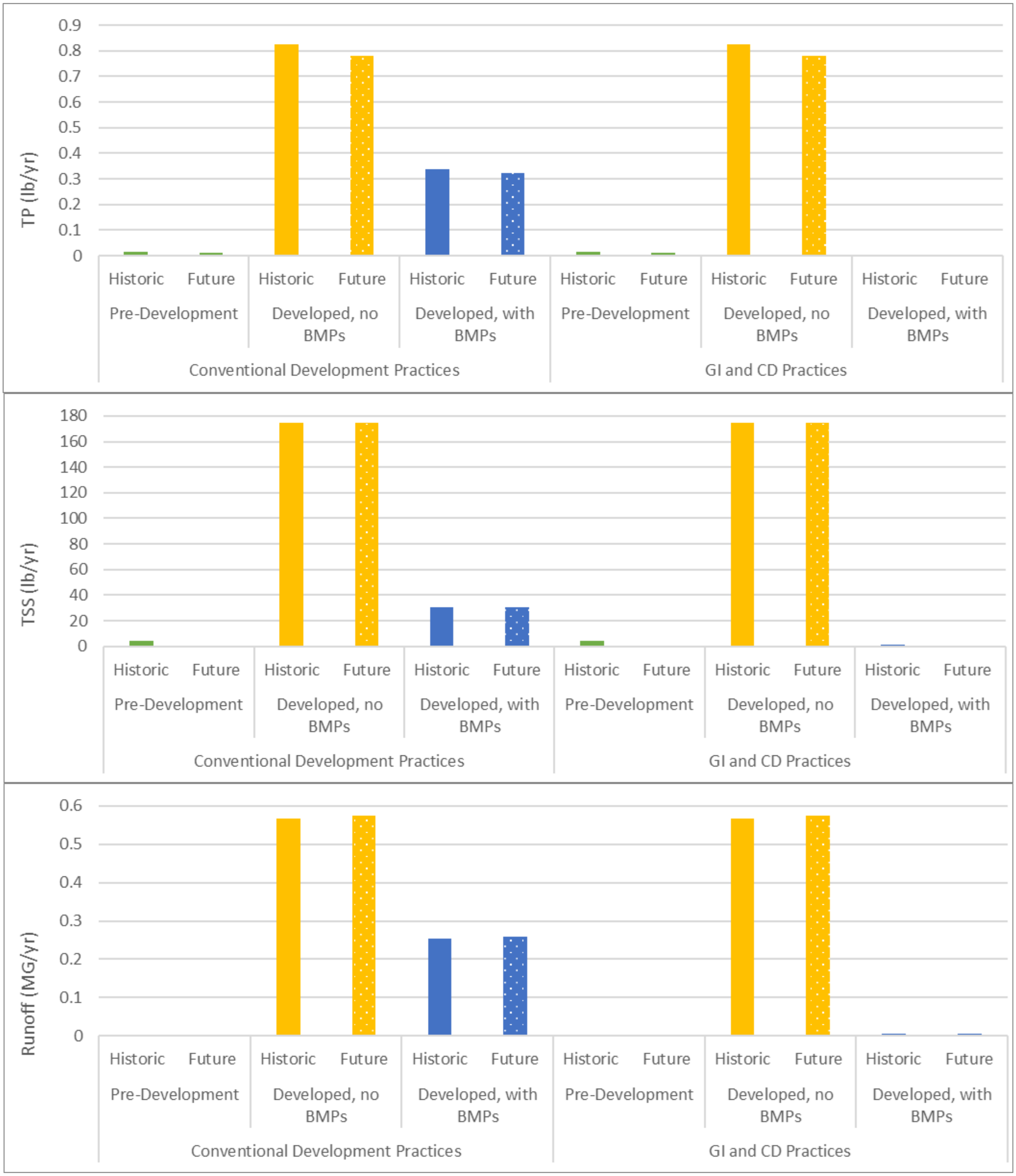


Figure 7-17. Annualized TP, TSS, and Runoff load and removal cost for High Density Commercial (HSG-A) conceptual design 2 for conventional development practices and GI and conservation design practices with historical climate.

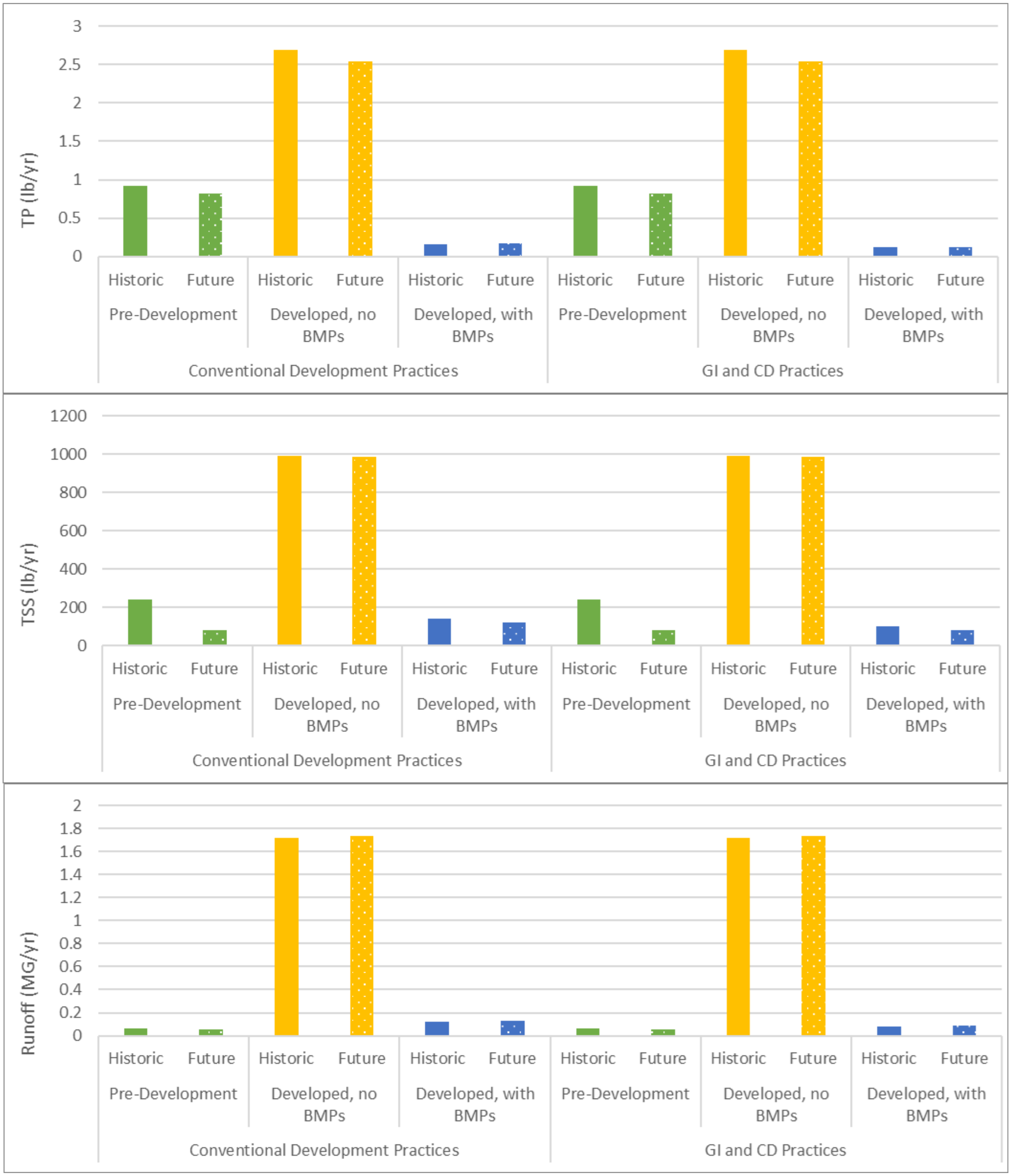


Figure 7-18. Annualized TP, TSS, and Runoff load and removal cost for Low Density Residential (HSG-B) conceptual design 3 for conventional development practices and GI and conservation design practices with historical climate.

8. HRU SCALE MODELING ANALYSES

The surface and subsurface infiltration SCMs are the most efficient stormwater (SW) practices to meet small-scale site control targets under current MassDEP (2008) and MS4 regulations. These regulations require SW controls to be implemented if a project is above a certain regulatory threshold area of disturbance or impervious cover. For example, MassDEP requires a threshold of 1 acre IC (approximately 30% of total IC treated at the watershed scale) and a more stringent regulation requires a threshold of 1/8th of an acre IC (approximately 80% of total IC treated at the watershed scale). In practice, these requirements may not provide enough treatment to protect water quality with continued future development and climate change. The next generation of SCMs could provide greater water quality to maintain predevelopment groundwater recharge and nutrient export.

8.1. HRU Scale Modeling Scenarios

To evaluate the performance of current and next-generation individual SCMs, they were simulated in the Opti-Tool using a unit-area HRU approach. In the following sections, the current MassDEP and MS4 control SCMs are referred to as MS4 control SCMs and the next generation SCMs are referred to as High control SCMs. Each control level is evaluated for surface and subsurface SCMs for HSGs A-D, with a high and low infiltration rate for each HSG. For each combination of SCM category, HSG, and infiltration rate, a design storage volume (DSV) necessary to reach the desired treatment efficiency and/or groundwater recharge volume was calculated using the GI SCM performance curves. These performance curves were developed for the infiltration basins and infiltration trenches for different soil types (HSG) using the long-term continuous hourly rainfall data collected at Boston Logan airport. The regionally calibrated EPA SWMM model was used to generate the runoff and pollutant loads and the regionally calibrated EPA Opti-Tool was used to simulate the GI SCM to evaluate the performance under different DSV and native HSG combinations.

MassDEP and MS4 Control

MassDEP (2008) requires capture depths of IC runoff no less than 0.6, 0.35, 0.25, and 0.1 inches for predevelopment HSGs A, B, C, and D, respectively. Using a simple dynamic sizing method provided by MassDEP, these depths translate into the DSVs shown in column “Recharge” of Table 8-1. The performance curves for TSS do not include pretreatment for SCM. Therefore, a 10% additional reduction in annual TTS load has been added to performance curves for determining DSVs shown in column “90% TSS Reduction” of Table 8-1. The DSV for 60% TP reductions were derived directly from the performance curves. The maximum required DSV was selected as the controlling size for the 16 GI SCM scenarios as shown in Table 8-1.

To test the resilience of MS4 control SCMs under future climate conditions, eight additional scenarios were run using the median RCP 8.5 ecodeficit future climate as a boundary condition. These scenarios were for infiltration basin and trench with HSG A, B, C, and D (infiltration rates of 2.41 in/hr, 0.52 in/hr, 0.17 in/hr, and 0.05 in/hr, respectively).

Table 8-1. Impervious Cover HRU SCM Design Storage Volume (DSV) Sizing for MassDEP (2008) & MS4 level of Control (MS4 Control)

SCM Category	SCM Examples	HSG	Infiltration Rate (in/hr)	Design Storage Volume (in)			
				Controlling	Recharge	60% TP Reduction	90% TSS Reduction
Surface Infiltration	Basin, swale, raingarden (i.e., bioretention), permeable pavement	A	8.27	**0.36**	0.36	0.10	0.20
		A	2.41	**0.50**	0.50	0.14	0.20
		B	1.02	**0.32**	0.32	0.19	0.21

SCM Category	SCM Examples	HSG	Infiltration Rate (in/hr)	Design Storage Volume (in)			
				Controlling	Recharge	60% TP Reduction	90% TSS Reduction
		B	0.52	**0.34**	0.34	0.22	0.22
		C	0.27	**0.27**	0.24	0.27	0.20
		C	0.17	**0.29**	0.25	0.29	0.20
		D	0.1	**0.30**	0.10	0.30	0.20
		D	0.05	**0.42**	0.10	0.42	0.20
Subsurface Infiltration	Trench, Chambers, drywell, tree filter retention	A	8.27	**0.36**	0.36	0.12	0.30
		A	2.41	**0.50**	0.50	0.20	0.40
		B	1.02	**0.32**	0.32	0.30	0.32
		B	0.52	**0.34**	0.34	0.31	0.34
		C	0.27	**0.36**	0.24	0.36	0.36
		C	0.17	**0.40**	0.25	0.40	0.40
		D	0.1	**0.42**	0.10	0.42	0.42
		D	0.05	**0.59**	0.10	0.59	0.59

High Control

The predevelopment recharge was based on a Water Balance method for Boston MA using average annual runoff yields from long-term continuous SWMM HRU models (1992-2020) of meadow and forested lands for HSGs A, B, C, and D. Predevelopment recharge conditions were met when infiltration practices are sized (via the DSVs) to capture 66%, 63%, 51% and 40% of average annual IC runoff volumes for HSGs A, B, C, and D, respectively.

Predevelopment nutrient export is considered to be the nutrient load delivered in surface runoff from natural wooded and meadow lands according to HSG. Required percent reductions to IC runoff TP export are 98%, 93%, 86%, and 77%, for predevelopment HSGs A, B, C, and D. Required percent reductions to IC runoff TN export are 98%, 91%, 82%, and 71%, for predevelopment HSGs A, B, C, and D. The DSVs for High control SCMs were estimated using the performance curves to meet the above-mentioned required percent reductions for TN, TP, and runoff volume as shown in Table 8-2. The maximum required DSV was considered as the controlling size for each GI SCM scenario.

To test the resilience of High control SCMs under future climate conditions, eight additional scenarios were run using the median RCP 8.5 ecodeficit future climate as a boundary condition. These scenarios were for infiltration basin and trench with HSG A, B, C, and D (infiltration rates of 2.41 in/hr, 0.52 in/hr, 0.17 in/hr, and 0.05 in/hr, respectively).

Table 8-2. Impervious Cover HRU SCM Design Storage Volume (DSV) Sizing for Predevelopment Average Annual Recharge and Nutrient Export Level of Control (High Control)

SCM Category	SCM Examples	HSG	Infiltration Rate (in/hr)	Design Storage Volume (in)			
				Controlling	Predev Recharge	Predev TP Export	Predev TN Export
Surface Infiltration	Basin, swale, raingarden (i.e., bioretention), permeable pavement	A	8.27	**0.39**	0.15	0.39	0.39
		A	2.41	**0.67**	0.36	0.67	0.60
		B	1.02	**0.59**	0.37	0.59	0.39
		B	0.52	**0.73**	0.46	0.73	0.42
		C	0.27	**0.60**	0.40	0.60	0.33
		C	0.17	**0.69**	0.50	0.69	0.35
		D	0.1	**0.60**	0.50	0.60	0.25
		D	0.05	**0.86**	0.86	0.80	0.30
Subsurface Infiltration	Trench, Chambers, drywell, tree filter retention	A	8.27	**0.60**	0.20	0.60	0.60
		A	2.41	**1.00**	0.56	1.00	0.80
		B	1.02	**0.86**	0.51	0.86	0.53
		B	0.52	**0.99**	0.60	0.99	0.53
		C	0.27	**0.81**	0.55	0.81	0.38
		C	0.17	**0.93**	0.68	0.93	0.39
		D	0.1	**0.79**	0.72	0.79	0.25
		D	0.05	**1.25**	1.25	1.00	0.22

8.2. HRU Scale Opti–Tool Setup

Opti-Tool models were configured for each of the 32 combinations of control level, SCM, HSG, and infiltration rate. Each SCM was sized using the DSV to treat runoff from 1 acre of commercial IC. Boundary conditions for these models represent historical LULC and climate within the Upper Hodges Brook subwatershed. The SCM parameters used in Opti-Tool are shown in Table 8-3. No optimization was performed because SCMs were sized according to their required DSV which meets the MassDEP and MS4 standards. The predeveloped condition for each scenario was set as forested land cover with the corresponding HSG.

Table 8-3. SCM specifications for HRU level models

General Information	SCM Parameters	Infiltration Trench	Infiltration Basin
Surface Storage Configuration	Orifice Height (ft)	0	0
	Orifice Diameter (in.)	0	0
	Rectangular or Triangular Weir	Rectangular	Rectangular

General Information	SCM Parameters	Infiltration Trench	Infiltration Basin
	Weir Height (ft)/Ponding Depth (ft)	0.5	2
	Crest Width (ft)	30	30
Soil Properties	Depth of Soil (ft)	6	0
	Soil Porosity (0-1)	0.6	0.4
	Vegetative Parameter A	0.9	0.9
	Soil Infiltration (in/hr)	Table 8-1 & Table 8-2	Table 8-1 & Table 8-2
Underdrain Properties	Consider Underdrain Structure?	No	No
	Storage Depth (ft)	0	0
	Media Void Fraction (0-1)	0	0
	Background Infiltration (in/hr)	N/A	N/A
Cost Parameters	Storage Volume Cost ($/ft^3)	$12.82	$6.41
Cost Function Adjustment	SCM Development Type	New SCM in Undeveloped Area	New SCM in Undeveloped Area
	Cost Adjustment Factor	1	1
Decay Rates	TSS (1/hr)	0.74	1.9
	TN (1/hr)	0.42	0.42
	TP (1/hr)	0.03	0.07
	ZN (1/hr)	0.45	1.7
Underdrain Removal Rates	TSS (%, 0-1)	N/A	N/A
	TN (%, 0-1)	N/A	N/A
	TP (%, 0-1)	N/A	N/A
	ZN (%, 0-1)	N/A	N/A

8.3. HRU Scale Modeling Results

The HRU scale modeling results were evaluated by comparison of annual average percent load reductions and runoff duration curves. The cost per acre IC treated for each scenario is shown in Table 8-4. Annual average percent reductions for the HRU scale models are shown in Table 8-5. For the same combination of SCM, HSG, and infiltration rate, the High control SCMs achieve greater reductions than the MS4 control SCM. Similarly, when only the infiltration rate is varied, the higher infiltration rate achieves slightly greater reductions than the lower infiltration rate. One exception to this result was for HSG-D. The increase in SCM capacity with the lower infiltration rate on these soils outweighed the benefit of the slightly higher infiltration rate. Under the median future climate condition, the selected SCMs show only a minor decrease in performance, indicating these High control SCMs still operate effectively (Table 8-6).

Runoff duration curves, which account for storm runoff only, were also created for each scenario (all RDCs are presented in Appendix C). Figure 8-1 and Figure 8-2 provide example RDCs for MS4 control and high control infiltration basins on HSG-A and HSG-D with infiltration rates of 2.41 in/hr and 0.05 in/hr, respectively. Examining these curves shows that the High control SCM, while not matching the predeveloped condition, does provide reduced flows over a greater percentage of the time, even on soils with a low infiltration rate. HSG-B and HSG-C show similar trends between MS4 and High control levels and their RDCs fall between those of HSG-A (Figure 8-1) and HSG-D (Figure 8-2).

When the High control SCMs are evaluated with the median future climate conditions (holding all other parameters including SCM capacity constant), there is an increase in flow across the entire runoff duration curve that corresponds to the increased future precipitation. The impact on each RDC from future climate varied by HSG. For example, infiltration basins and trenches on HSG A had only a slight increase in flow (Figure 8-3 and Figure 8-7, respectively). SCMs on HSG B and HSG C had larger increases in flow compared to the historical climate condition (Figure 8-4, Figure 8-5, Figure 8-8, Figure 8-9). HSG D has the lowest infiltration rate and the highest flows across the RDC compared to the other HSGs. However, the increase in flows for HSG D with the future climate condition was not as great as those for HSG B and HSG C (Figure 8-6 and Figure 8-10).

Table 8-4. Summary of cost of unit-acre IC treated for HRU level SCM scenarios

SCM Category	HSG	Design Storage Volume (in.)	Infiltration Rate (in./hr)	Cost/Acre IC Treated ($/ac)	
				MS4	High
Infiltration Basin	A	0.36	8.27	$8,378	$9,077
		0.5	2.41	$11,636	$15,594
	B	0.32	1.02	$7,447	$13,732
		0.34	0.52	$7,913	$16,990
	C	0.27	0.27	$6,284	$13,964
		0.29	0.17	$6,750	$16,059
	D	0.3	0.1	$6,982	$13,964
		0.42	0.05	$9,775	$20,015
Infiltration Trench	A	0.36	8.27	$23,684	$39,474
		0.5	2.41	$32,899	$65,792
	B	0.32	1.02	$21,056	$56,583
		0.34	0.52	$22,370	$65,135
	C	0.36	0.27	$23,684	$53,293
		0.4	0.17	$26,318	$61,187
	D	0.42	0.1	$27,632	$51,979
		0.59	0.05	$38,817	$82,244

Table 8-5. Annual average percent reductions for HRU level SCM scenarios

SCM Category	HSG	Infiltration Rate (in/hr)	SCM Volume (ft^3)		Flow Volume		TSS		TN		TP		Zn	
			MS4	High	MS4	High	MS4	High	MS4	High	MS4	High	MS4	High
Infiltration Basin	A	8.27	1,307	1,417	89%	91%	99%	99%	97%	98%	98%	99%	99%	99%
		2.41	1,816	2,433	82%	89%	99%	100%	97%	98%	96%	98%	99%	100%
	B	1.02	1,162	2,143	56%	76%	99%	100%	88%	96%	84%	94%	97%	99%
		0.52	1,235	2,651	49%	76%	99%	100%	87%	96%	81%	94%	97%	99%
	C	0.27	981	2,179	34%	61%	98%	100%	81%	93%	70%	88%	96%	99%
		0.17	1,053	2,506	29%	58%	98%	100%	81%	93%	69%	87%	96%	99%
	D	0.1	1,090	2,179	22%	41%	99%	100%	79%	90%	65%	81%	95%	98%
		0.05	1,525	3,123	18%	36%	99%	100%	82%	92%	68%	83%	97%	99%
Infiltration Trench	A	8.27	2,929	4,882	79%	91%	98%	99%	95%	98%	94%	98%	96%	99%
		2.41	4,068	8,136	71%	90%	98%	100%	94%	99%	91%	98%	95%	99%
	B	1.02	2,604	6,997	46%	78%	95%	99%	86%	97%	76%	94%	89%	98%
		0.52	2,766	8,055	40%	76%	95%	99%	86%	97%	72%	93%	88%	98%
	C	0.27	2,929	6,590	33%	61%	96%	99%	85%	95%	69%	87%	87%	96%
		0.17	3,255	7,567	29%	57%	96%	99%	85%	95%	68%	87%	88%	96%
	D	0.1	3,417	6,428	22%	38%	96%	99%	85%	92%	66%	80%	87%	94%
		0.05	4,800	10,171	17%	35%	97%	99%	87%	95%	69%	84%	89%	96%

Table 8-6. Change in annual average percent reduction for selected HRU-level SCM scenarios with a future climate

SCM Category	HSG	Infiltration Rate (in/hr)	Flow Volume		TSS		TN		TP		Zn	
			MS4	High	MS4	High	MS4	High	MS4	High	MS4	High
Infiltration Basin	A	2.41	-1.5%	-1.1%	0.1%	-0.1%	-0.5%	-0.3%	-0.7%	-0.4%	-0.3%	-0.1%
	B	0.52	-6.5%	-6.0%	0.3%	-0.1%	-1.4%	-0.9%	-3.3%	-2.2%	-0.4%	-0.2%
	C	0.17	-3.7%	-7.4%	0.4%	0.0%	-0.9%	-1.2%	-2.5%	-2.9%	-0.4%	-0.3%
	D	0.05	-0.9%	-2.2%	0.2%	0.0%	-0.3%	-0.4%	-1.6%	-1.7%	-0.2%	-0.1%
Infiltration Trench	A	2.41	-3.0%	-1.5%	0.5%	0.1%	-0.6%	-0.2%	-1.6%	-0.5%	-0.6%	-0.2%
	B	0.52	-5.6%	-6.6%	1.0%	0.2%	-0.8%	-0.6%	-3.3%	-2.6%	-0.9%	-0.6%
	C	0.17	-3.2%	-6.7%	1.3%	0.3%	-0.3%	-0.6%	-2.5%	-3.2%	-0.5%	-0.6%
	D	0.05	-0.6%	-1.8%	0.9%	0.2%	-0.1%	-0.2%	-2.1%	-2.3%	-0.3%	-0.2%

Table 8-7. Summary of runoff volume captured for HRU-level SCMs

SCM Category	HSG	Infiltration Rate (in/hr)	Design Storage Volume (in)		Captured Volume (gal/ac/yr)				Captured Volume (%)			
					MS4		High		MS4		High	
			MS4	High	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate
Infiltration Basin	A	8.27	0.36	0.39	55847	--	56812	--	89%	--	91%	--
		2.41	0.5	0.67	51155	50868	55739	55776	82%	80%	89%	88%
	B	1.02	0.32	0.59	35017	--	47574	--	56%	--	76%	--
		0.52	0.34	0.73	30847	27160	47326	44167	49%	43%	76%	70%
	C	0.27	0.27	0.6	21080	--	37899	--	34%	--	61%	--
		0.17	0.29	0.69	18307	16173	36202	31991	29%	26%	58%	51%
	D	0.1	0.3	0.6	13877	--	25592	--	22%	--	41%	--
		0.05	0.42	0.86	11182	10787	22223	21132	18%	17%	36%	33%
Infiltration Trench	A	8.27	0.36	0.6	49336	--	56584	--	79%	--	91%	--
		2.41	0.5	1	44223	42897	55961	55741	71%	68%	90%	88%
	B	1.02	0.32	0.86	28817	--	48771	--	46%	--	78%	--
		0.52	0.34	0.99	25095	21862	47717	44175	40%	35%	76%	70%
	C	0.27	0.36	0.81	20758	--	37949	--	33%	--	61%	--
		0.17	0.4	0.93	18122	16346	35764	32014	29%	26%	57%	51%
	D	0.1	0.42	0.79	13507	--	23979	--	22%	--	38%	--
		0.05	0.59	1.25	10715	10446	22061	21240	17%	16%	35%	34%

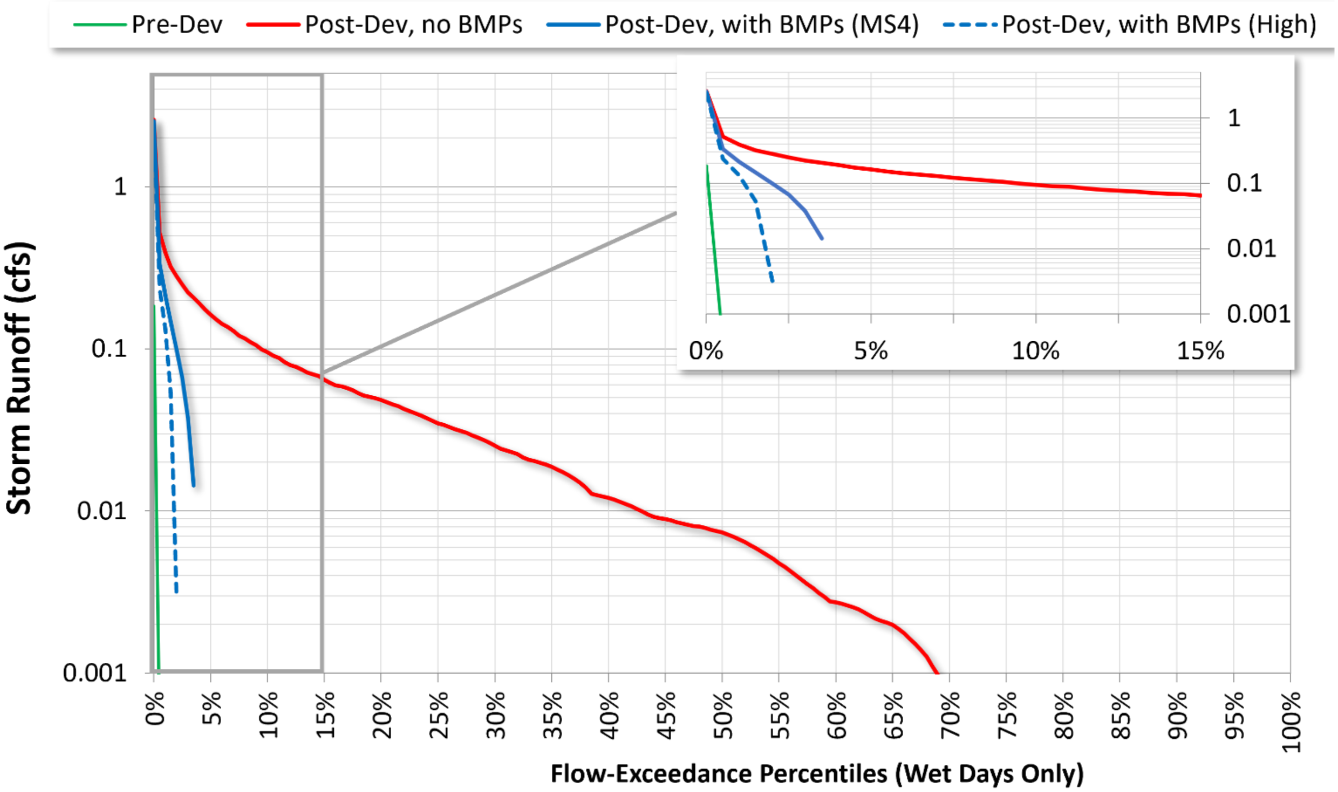


Figure 8-1. Runoff duration curve for MS4 and High control level infiltration basin on HSG A with an infiltration rate of 2.41 in/hr.

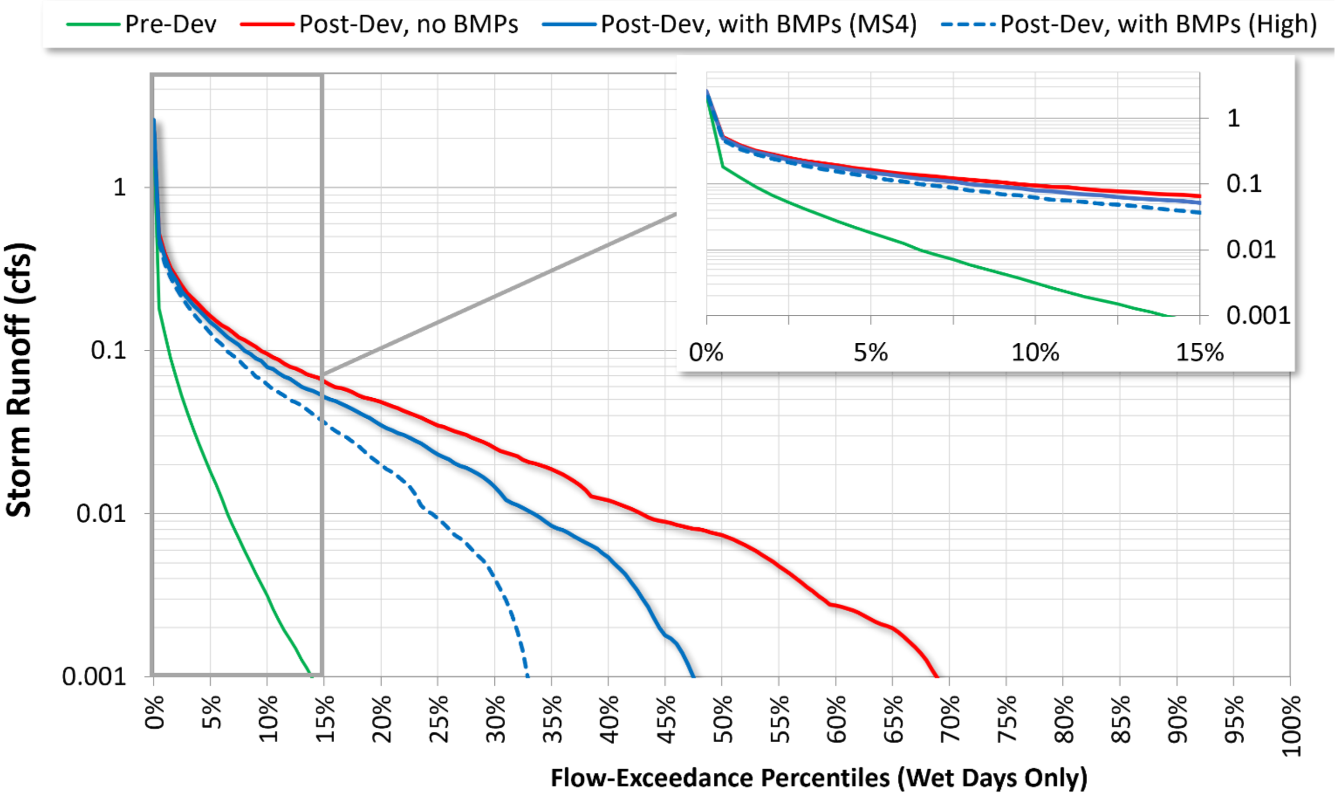


Figure 8-2. Runoff duration curve for MS4 and High control level infiltration basin on HSG D with an infiltration rate of 0.05 in/hr.

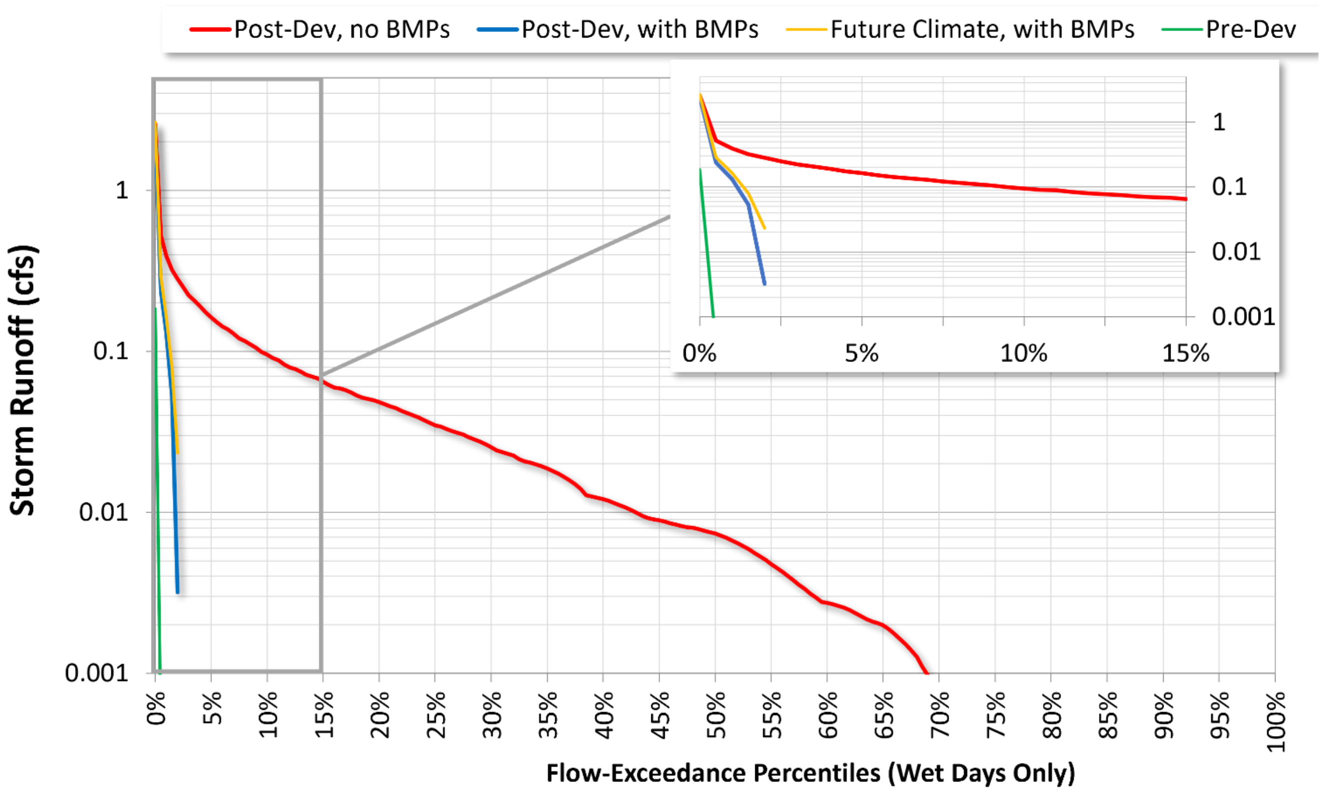


Figure 8-3. Runoff duration curve for High control level infiltration basin on HSG A with an infiltration rate of 2.41 in/hr with historical and future climate.

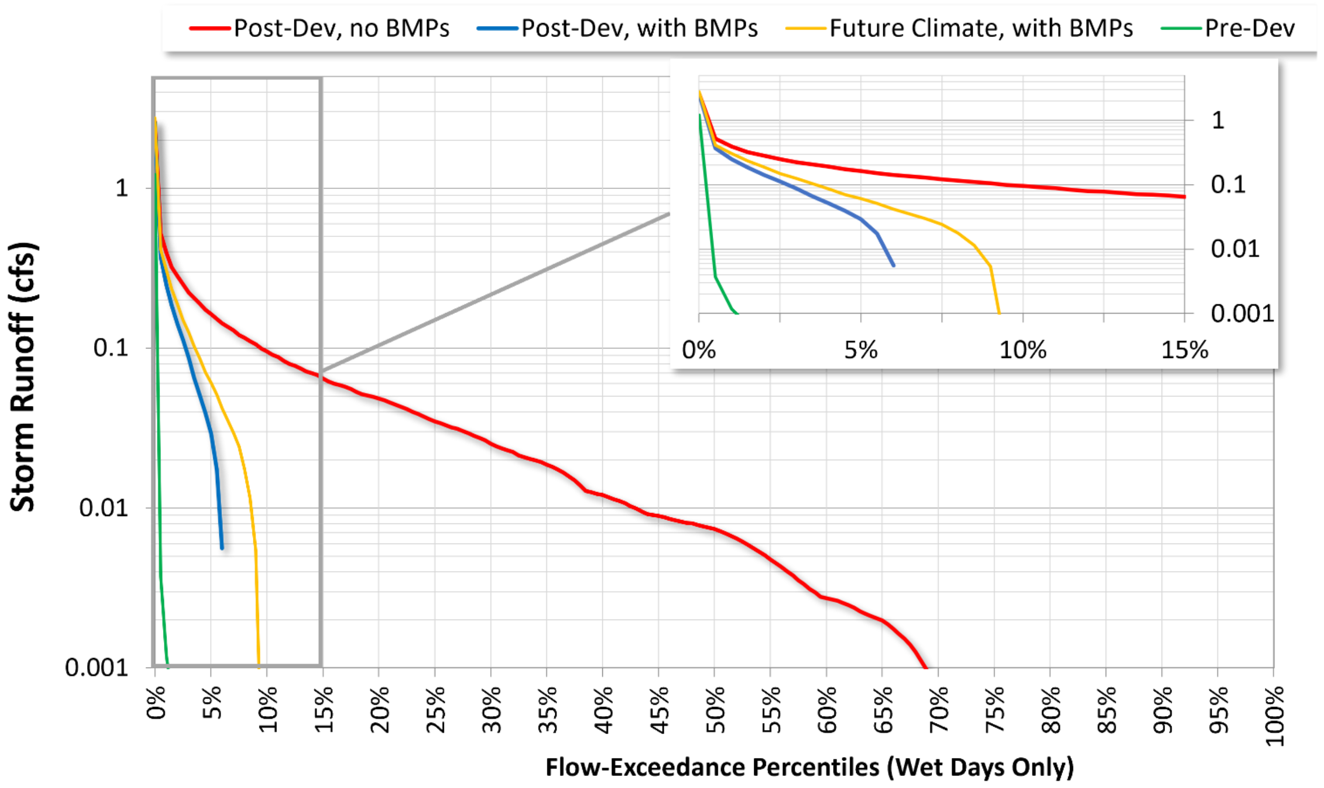


Figure 8-4. Runoff duration curve for High control level infiltration basin on HSG B with an infiltration rate of 0.52 in/hr with historical and future climate.

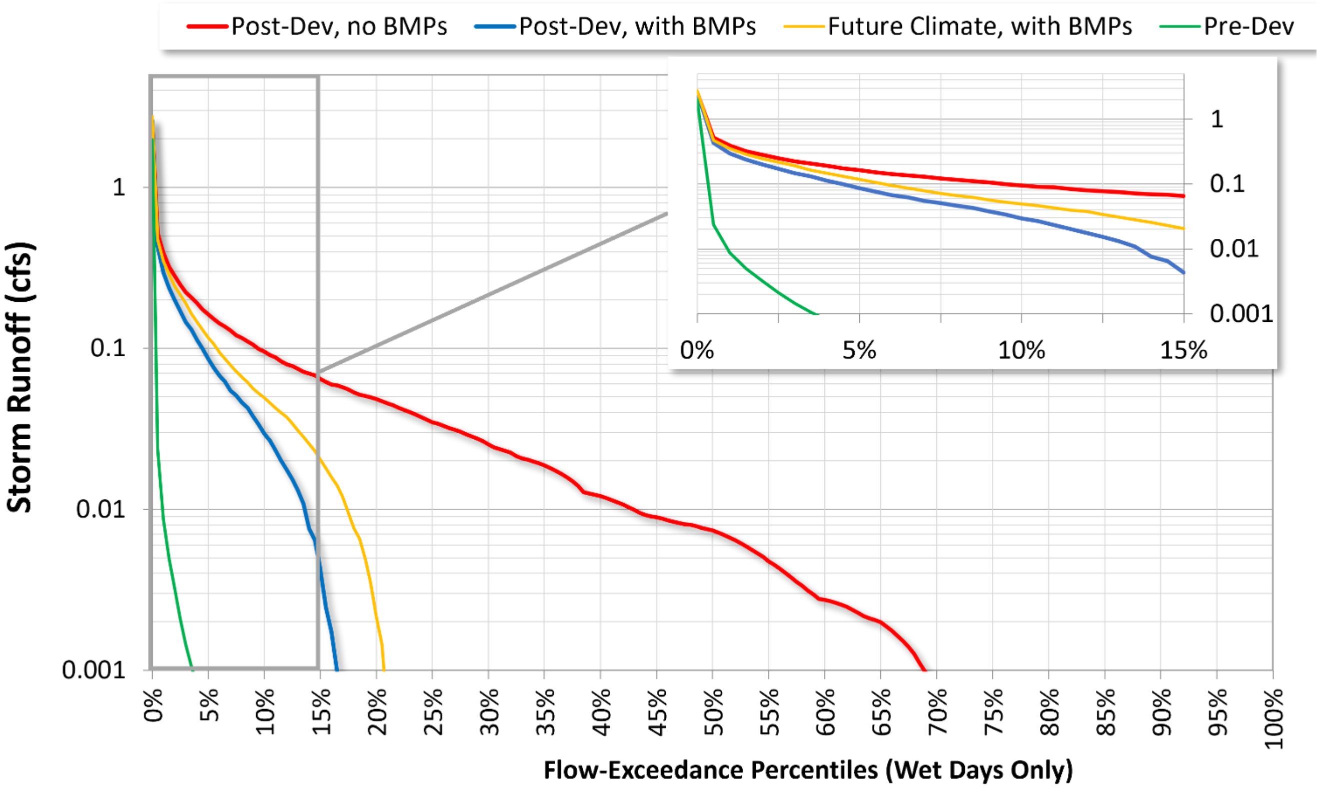


Figure 8-5. Runoff duration curve for High control level infiltration basin on HSG C with an infiltration rate of 0.17 in/hr with historical and future climate.

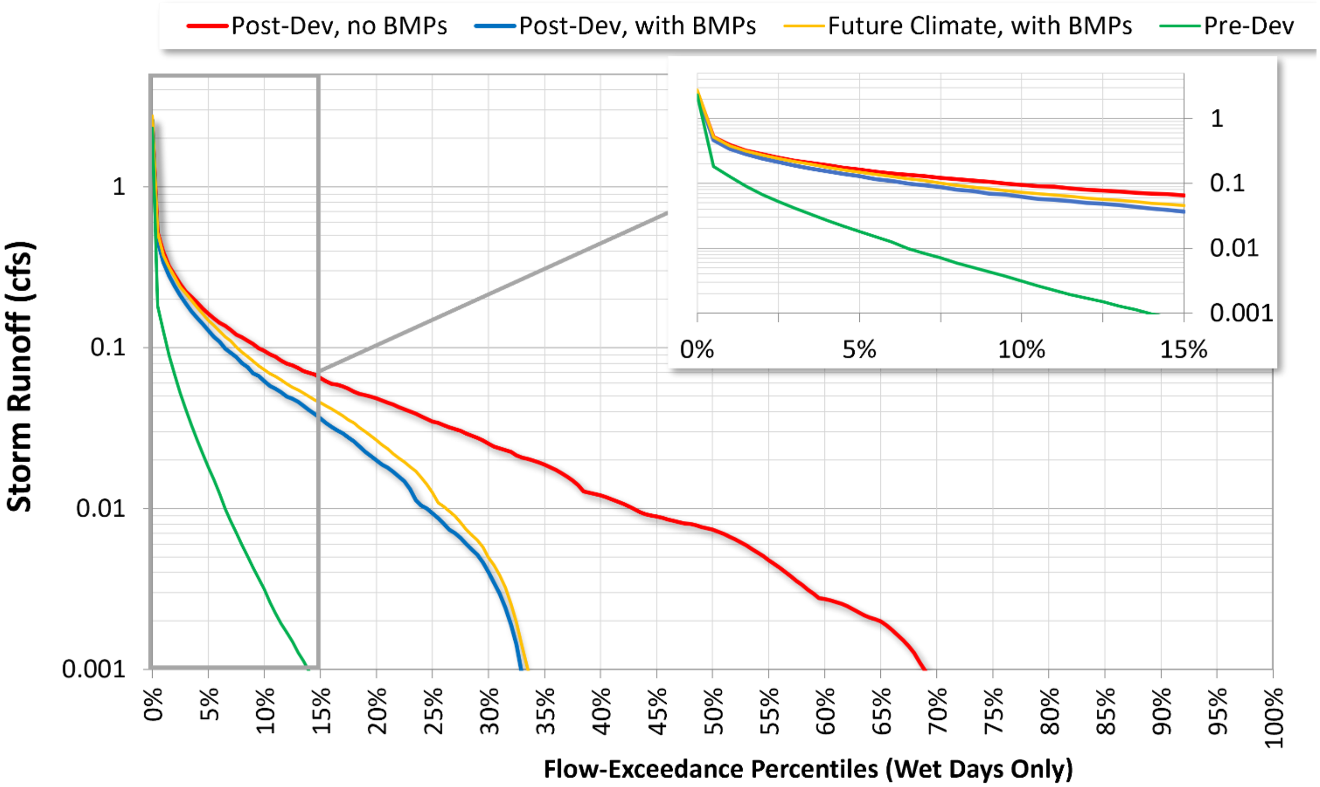


Figure 8-6. Runoff duration curve for High control level infiltration basin on HSG D with an infiltration rate of 0.05 in/hr with future climate.

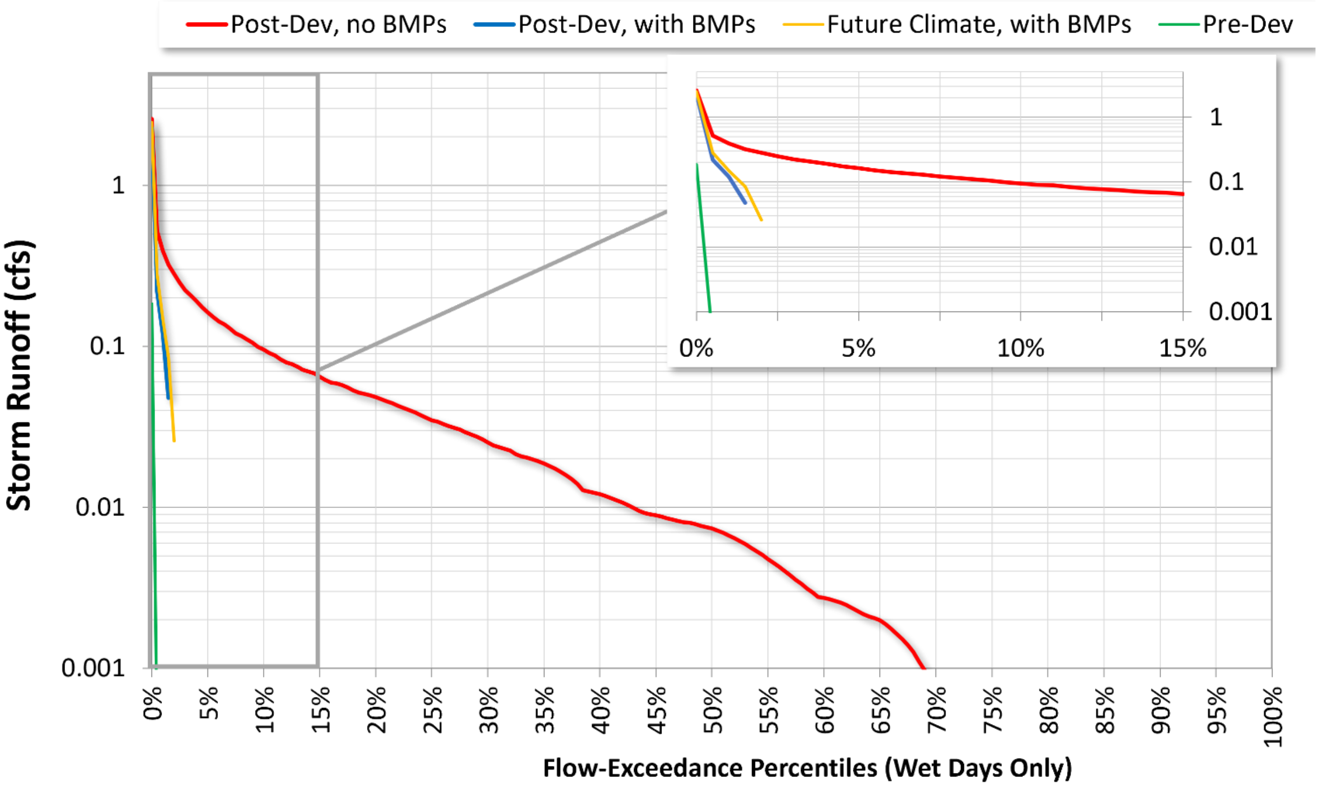


Figure 8-7. Runoff duration curve for High control level infiltration trench on HSG A with an infiltration rate of 2.41 in/hr with future climate.

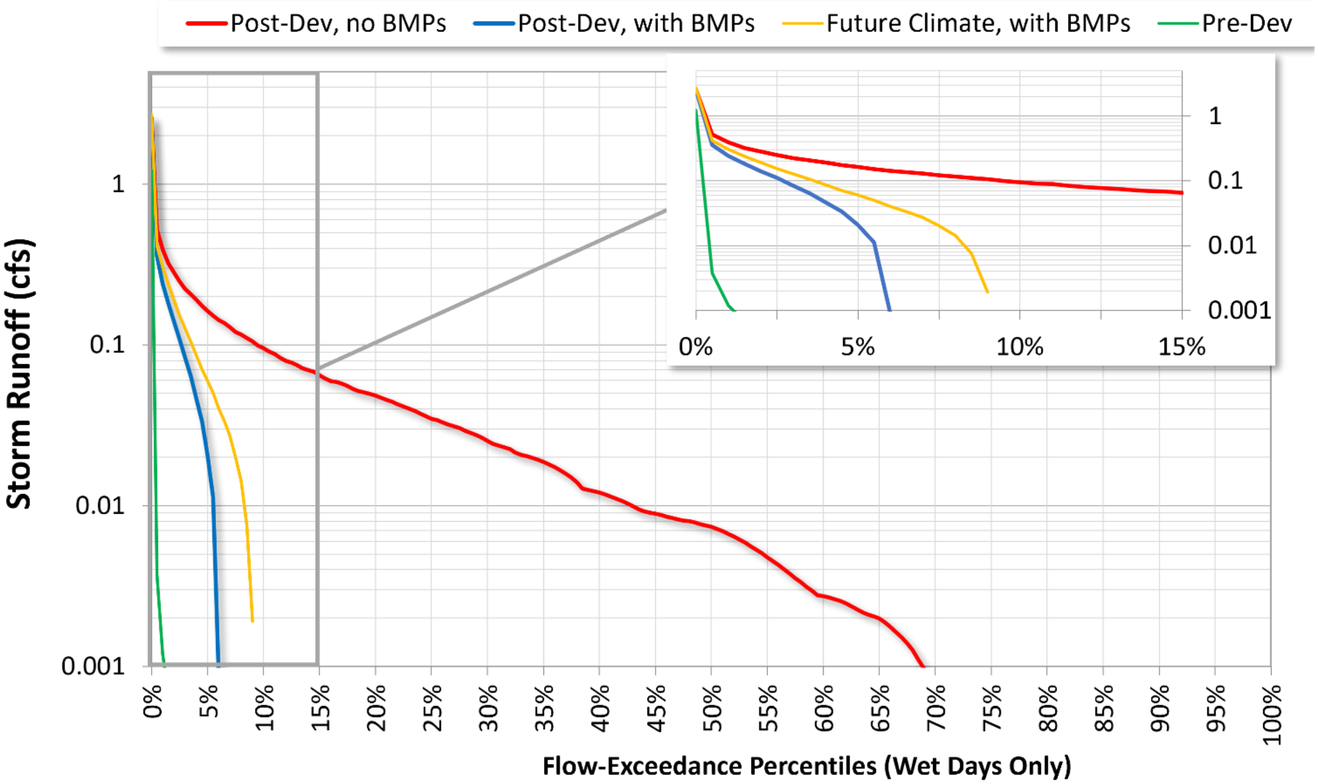


Figure 8-8. Runoff duration curve for High control level infiltration trench on HSG B with an infiltration rate of 0.52 in/hr with future climate.

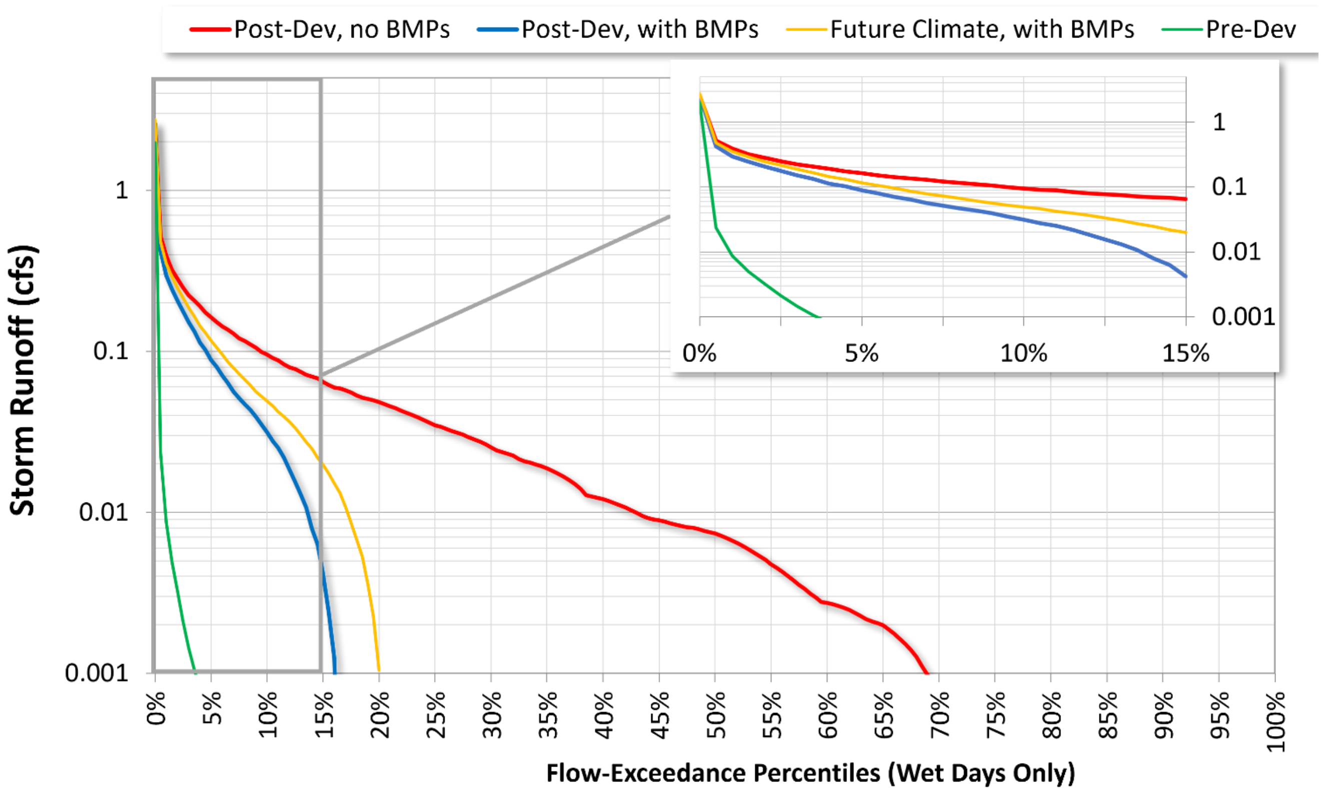


Figure 8-9. Runoff duration curve for High control level infiltration trench on HSG C with an infiltration rate of 0.17 in/hr with future climate.

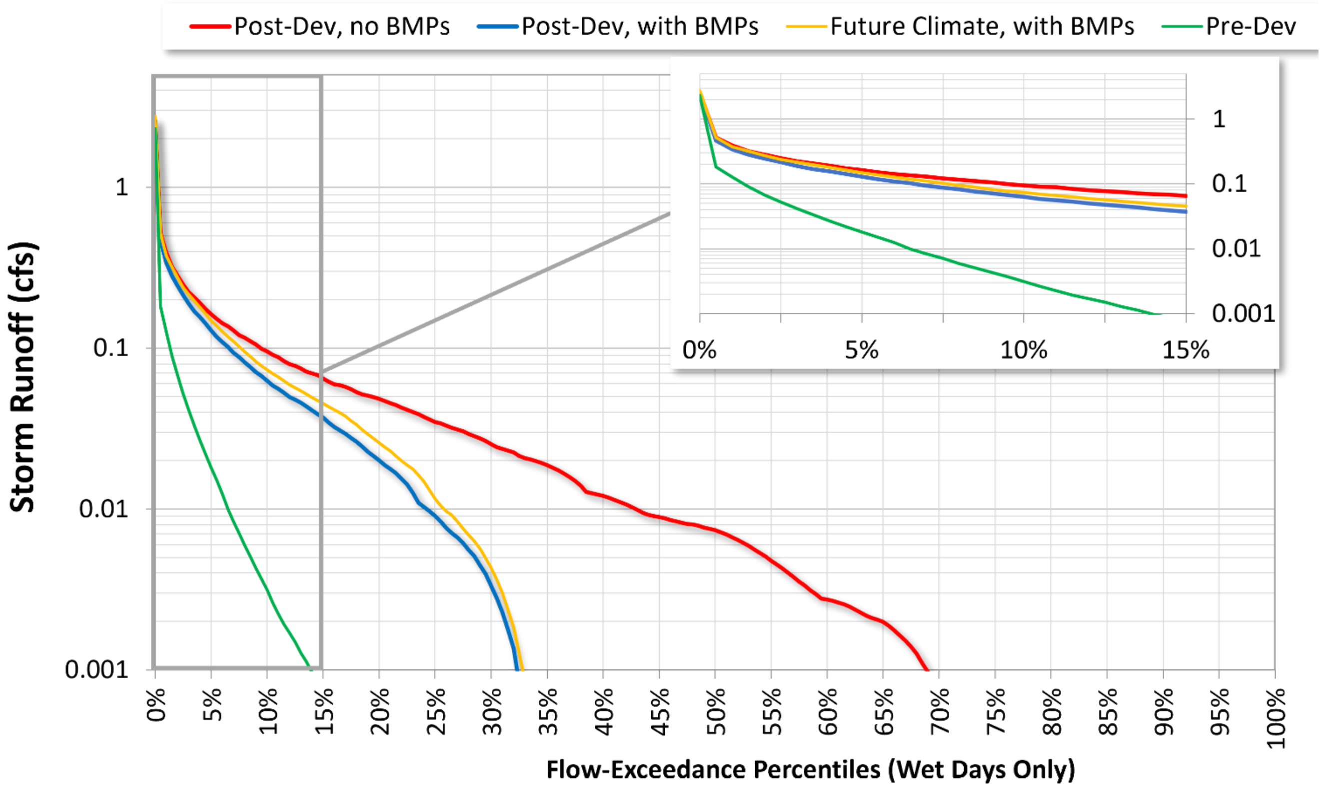


Figure 8-10 Runoff duration curve for High control level infiltration trench on HSG D with an infiltration rate of 0.05 in/hr with future climate.

9. WATERSHED SCALE MODELING ANALYSES

This section demonstrates the impact of GI SCM designed to meet MassDEP and MS4 stormwater standards as well as high-level controls that provide groundwater recharge similar to the predevelopment hydrology in the Upper Hodges Brook watershed. The DSVs for GI SCM and HSG combinations used in the HRU scale modeling were scaled to the impervious area being treated by different GI SCM from different land use and HSG combinations at the watershed scale. The following sub-sections provide the detail of all modeling scenarios with existing and predicted future land use/land cover under historical and future predicted climate conditions in the Upper Hodges Brook watershed.

9.1. Watershed Scale Next-Generation SCM Modeling Scenarios

Watershed scale Opti-Tool models were run for scenarios including historical and future land use-land cover, historical and median RCP 8.5 future climate, and varying percentages of IC treatment. These scenarios evaluate the MS4 and High control HRU level SCMs and are shown in Table 9-1. These fourteen scenarios are repeated for 100% IC treatment, 80% IC treatment, and 30% IC treatment for a total of 42 scenarios.

Table 9-1. Table of watershed-scale modeling scenarios using HRU level SCMs

Scenario Number	Control Level	Land use / Land cover	Weather
1	MassDEP and MS4 (existing standard for recharge and load reduction)	2016 Baseline IC (treated)	Historical
2		2016 Baseline IC (treated)	Future Median
3		Scenario 1 + 2060 increase in IC (untreated)	Historical
4		Scenario 2 + 2060 increase in IC (untreated)	Future Median
5		Scenario 1 + 2060 increase in IC (treated)	Historical
6		Scenario 2 + 2060 increase in IC (treated)	Future Median
7	High (PreDev Recharge and no net increase in load)	2016 Baseline IC (treated)	Historical
8		2016 Baseline IC (treated)	Future Median
9		Scenario 7 + 2060 increase in IC (untreated)	Historical
10		Scenario 8 + 2060 increase in IC (untreated)	Future Median
11		Scenario 7 + 2060 increase in IC (treated)	Historical
12		Scenario 8 + 2060 increase in IC (treated)	Future Median
13	1 inch retention	Scenario 7 + 2060 increase in IC (treated)	Historical
14		Scenario 8 + 2060 increase in IC (treated)	Future Median

9.2. Watershed Scale Opti-Tool Setup

Configuration of Opti-Tool models for the watershed scale scenarios used the same number and type of SCMs by land use and soil combinations as in the FDC1 (Phase 1) project. Specifically, runoff from non-roof IC for a given land use type was treated by infiltration basins for HSG A, B, and C and by biofiltration for HSG-D. Rooftop runoff was treated by infiltration trenches on HSG A, B, and C. The SCM drainage areas and footprints are given in Table 9-2 and Table 9-3 respectively; SCM parameters are shown in Table 9-4. Infiltration rates were the lower rate for each HSG used in the HRU scale modeling. No optimization was performed as SCM sizes were determined based on the drainage area and unit-area DSV.

Opti-Tool cost estimates are based on regional unit cost information for the SCM type (University of New Hampshire Stormwater Center, 2020). Also included in the cost estimate are a 35% add-on for engineering and contingencies and a site factor multiplier to account for anticipated difficulties associated with BMP installation in already developed areas. Opti-Tool cost estimates are for capital and design costs only; operations and maintenance costs are not included.

Table 9-2. SCM drainage areas (ac) for watershed scale scenarios by the percentage of IC treated

Landuse Group	Disconnection Type	SCM Type	HSG	IC Treated (%) and LULC Type					
				30%		80%		100%	
				Historic	Future	Historic	Future	Historic	Future
Commercial	Rooftop	Infiltration Trench	A	2.57	3.70	6.84	9.88	8.55	12.35
			B	0.03	0.04	0.08	0.12	0.10	0.15
			C	1.72	2.48	4.59	6.62	5.73	8.28
	Other IC	Infiltration basin	A	3.81	5.51	10.17	14.69	12.72	18.36
			B	0.15	0.21	0.39	0.56	0.49	0.70
			C	2.45	3.54	6.54	9.45	8.18	11.81
			D	2.95	4.26	7.87	11.36	9.84	14.20
Industrial	Rooftop	Infiltration Trench	A	1.74	1.90	4.63	5.06	5.79	6.32
			B	0.19	0.21	0.50	0.55	0.63	0.69
			C	29.20	31.88	77.86	85.01	97.32	106.26
	Other IC	Infiltration basin	A	1.27	1.38	3.38	3.69	4.22	4.61
			B	0.45	0.49	1.20	1.31	1.50	1.64
			C	16.36	17.87	43.64	47.65	54.55	59.56
			D	17.86	19.50	47.63	52.01	59.54	65.01
Low Density Residential	Rooftop	Infiltration Trench	A	1.15	3.96	3.08	10.55	3.85	13.19
			B	0.38	1.31	1.02	3.49	1.27	4.36
			C	0.99	3.41	2.65	9.08	3.31	11.35
	Other IC	Infiltration basin	A	0.64	2.19	1.70	5.84	2.13	7.29
			B	0.24	0.81	0.63	2.16	0.79	2.69
			C	0.56	1.90	1.48	5.07	1.85	6.34
			D	1.36	4.66	3.63	12.43	4.53	15.54
Medium Density Residential	Rooftop	Infiltration Trench	A	0.00	0.00	0.00	0.00	0.00	0.00
			B	0.08	0.08	0.21	0.21	0.26	0.26
			C	0.05	0.05	0.13	0.13	0.16	0.16
	Other IC	Infiltration basin	A	0.00	0.00	0.00	0.00	0.00	0.00
			B	0.11	0.11	0.29	0.29	0.36	0.36
			C	0.10	0.10	0.28	0.28	0.35	0.35
			D	0.23	0.23	0.61	0.61	0.76	0.76
High Density Residential	Rooftop	Infiltration Trench	A	0.00	0.00	0.00	0.00	0.00	0.00
			B	0.73	1.40	1.94	3.74	2.42	4.68
			C	0.13	0.26	0.36	0.69	0.45	0.87
	Other IC	Infiltration basin	A	0.00	0.01	0.01	0.02	0.02	0.03
			B	0.57	1.11	1.53	2.95	1.91	3.69

Landuse Group	Disconnection Type	SCM Type	HSG	IC Treated (%) and LULC Type					
				30%		80%		100%	
				Historic	Future	Historic	Future	Historic	Future
			C	0.17	0.33	0.46	0.88	0.57	1.10
			D	0.87	1.68	2.32	4.47	2.90	5.59
Transportation	Rooftop	Infiltration Trench	A	0.00	0.00	0.00	0.00	0.00	0.00
			B	0.00	0.00	0.00	0.00	0.00	0.00
			C	0.00	0.00	0.00	0.00	0.00	0.01
	Other IC	Infiltration basin	A	8.54	11.92	22.77	31.79	28.46	39.74
			B	2.91	4.07	7.77	10.84	9.71	13.56
			C	13.45	18.78	35.87	50.08	44.83	62.61
			D	10.20	14.25	27.21	38.00	34.02	47.50
Open Land	Rooftop	Infiltration Trench	A	0.09	0.14	0.24	0.37	0.30	0.46
			B	0.03	0.05	0.08	0.12	0.10	0.15
			C	0.25	0.39	0.67	1.04	0.84	1.30
	Other IC	Infiltration basin	A	0.36	0.56	0.95	1.49	1.19	1.86
			B	0.19	0.29	0.50	0.78	0.63	0.97
			C	0.89	1.39	2.38	3.70	2.97	4.63
			D	1.20	1.87	3.21	5.00	4.01	6.24

Table 9-3. SCM footprints (ft²) for watershed scale scenarios by the percentage of IC treated and LULC and climate boundary conditions

Landuse Group	Disconnection Type	SCM Type	HSG	IC Treated (%), LULC Type, and Climate Type											
				30%				80%				100%			
				Historical LULC		Future LULC		Historical LULC		Future LULC		Historical LULC		Future LULC	
				Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate
Commercial	Rooftop	Inf. Trench	A	2,018.7	2,018.7	2,018.7	2,018.7	5,383.2	5,383.2	5,383.2	5,383.2	6,729.0	6,729.0	6,729.0	6,729.0
			B	23.7	23.7	23.7	23.7	63.2	63.2	63.2	63.2	79.0	79.0	79.0	79.0
			C	1,353.1	1,353.1	1,353.1	1,353.1	3,608.1	3,608.1	3,608.1	3,608.1	4,510.2	4,510.2	4,510.2	4,510.2
	Other IC	Inf. Basin	A	4,352.0	4,352.0	4,352.0	4,352.0	11,605.2	11,605.2	11,605.2	11,605.2	14,506.6	14,506.6	14,506.6	14,506.6
			B	167.1	167.1	167.1	167.1	445.6	445.6	445.6	445.6	557.0	557.0	557.0	557.0
			C	2,800.0	2,800.0	2,800.0	2,800.0	7,466.6	7,466.6	7,466.6	7,466.6	9,333.2	9,333.2	9,333.2	9,333.2
			D	4,810.5	4,810.5	4,810.5	4,810.5	12,828.0	12,828.0	12,828.0	12,828.0	16,034.9	16,034.9	16,034.9	16,034.9
Industrial	Rooftop	Inf. Trench	A	1,368.1	1,368.1	1,368.1	1,368.1	3,648.3	3,648.3	3,648.3	3,648.3	4,560.4	4,560.4	4,560.4	4,560.4
			B	148.8	148.8	148.8	148.8	396.9	396.9	396.9	396.9	496.1	496.1	496.1	496.1
			C	22,986.8	22,986.8	22,986.8	22,986.8	61,298.1	61,298.1	61,298.1	61,298.1	76,622.6	76,622.6	76,622.6	76,622.6
	Other IC	Inf. Basin	A	1,446.9	1,446.9	1,446.9	1,446.9	3,858.4	3,858.4	3,858.4	3,858.4	4,823.0	4,823.0	4,823.0	4,823.0
			B	513.0	513.0	513.0	513.0	1,368.1	1,368.1	1,368.1	1,368.1	1,710.1	1,710.1	1,710.1	1,710.1
			C	18,681.9	18,681.9	18,681.9	18,681.9	49,818.4	49,818.4	49,818.4	49,818.4	62,273.0	62,273.0	62,273.0	62,273.0
			D	29,128.8	29,128.8	29,128.8	29,128.8	77,676.8	77,676.8	77,676.8	77,676.8	97,096.1	97,096.1	97,096.1	97,096.1
Low Density Residential	Rooftop	Inf. Trench	A	552.0	552.0	552.0	552.0	1,471.9	1,471.9	1,471.9	1,471.9	1,839.9	1,839.9	1,839.9	1,839.9
			B	182.7	182.7	182.7	182.7	487.1	487.1	487.1	487.1	608.9	608.9	608.9	608.9
			C	475.2	475.2	475.2	475.2	1,267.2	1,267.2	1,267.2	1,267.2	1,584.0	1,584.0	1,584.0	1,584.0
	Other IC	Inf. Basin	A	442.7	442.7	442.7	442.7	1,180.5	1,180.5	1,180.5	1,180.5	1,475.6	1,475.6	1,475.6	1,475.6
			B	163.5	163.5	163.5	163.5	436.0	436.0	436.0	436.0	545.0	545.0	545.0	545.0
			C	384.9	384.9	384.9	384.9	1,026.5	1,026.5	1,026.5	1,026.5	1,283.1	1,283.1	1,283.1	1,283.1
			D	1,347.3	1,347.3	1,347.3	1,347.3	3,592.8	3,592.8	3,592.8	3,592.8	4,490.9	4,490.9	4,490.9	4,490.9
Mediu	Ro		A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Landuse Group	Disconnection Type	SCM Type	HSG	IC Treated (%), LULC Type, and Climate Type											
				30%				80%				100%			
				Historical LULC		Future LULC		Historical LULC		Future LULC		Historical LULC		Future LULC	
				Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate
			B	61.7	61.7	61.7	61.7	164.5	164.5	164.5	164.5	205.7	205.7	205.7	205.7
			C	38.9	38.9	38.9	38.9	103.6	103.6	103.6	103.6	129.5	129.5	129.5	129.5
	Other IC	Inf. Basin	A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			B	122.2	122.2	122.2	122.2	325.9	325.9	325.9	325.9	407.4	407.4	407.4	407.4
			C	118.6	118.6	118.6	118.6	316.2	316.2	316.2	316.2	395.3	395.3	395.3	395.3
			D	370.2	370.2	370.2	370.2	987.3	987.3	987.3	987.3	1,234.1	1,234.1	1,234.1	1,234.1
High Density Residential	Rooftop	Inf. Trench	A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			B	1,499.3	1,499.3	1,499.3	1,499.3	3,998.1	3,998.1	3,998.1	3,998.1	4,997.6	4,997.6	4,997.6	4,997.6
			C	277.7	277.7	277.7	277.7	740.6	740.6	740.6	740.6	925.8	925.8	925.8	925.8
	Other IC	Inf. Basin	A	14.1	14.1	14.1	14.1	37.5	37.5	37.5	37.5	46.9	46.9	46.9	46.9
			B	1,713.6	1,713.6	1,713.6	1,713.6	4,569.7	4,569.7	4,569.7	4,569.7	5,712.1	5,712.1	5,712.1	5,712.1
			C	511.8	511.8	511.8	511.8	1,364.9	1,364.9	1,364.9	1,364.9	1,706.2	1,706.2	1,706.2	1,706.2
			D	3,711.1	3,711.1	3,711.1	3,711.1	9,896.1	9,896.1	9,896.1	9,896.1	12,370.2	12,370.2	12,370.2	12,370.2
Transportation	Rooftop	Inf. Trench	A	1.0	1.0	1.0	1.0	2.6	2.6	2.6	2.6	3.3	3.3	3.3	3.3
			B	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
			C	2.3	2.3	2.3	2.3	6.1	6.1	6.1	6.1	7.7	7.7	7.7	7.7
	Other IC	Inf. Basin	A	25,520.4	25,520.4	25,520.4	25,520.4	68,054.3	68,054.3	68,054.3	68,054.3	85,067.9	85,067.9	85,067.9	85,067.9
			B	8,704.5	8,704.5	8,704.5	8,704.5	23,212.0	23,212.0	23,212.0	23,212.0	29,015.0	29,015.0	29,015.0	29,015.0
			C	40,201.7	40,201.7	40,201.7	40,201.7	107,204.7	107,204.7	107,204.7	107,204.7	134,005.8	134,005.8	134,005.8	134,005.8
			D	43,573.9	43,573.9	43,573.9	43,573.9	116,197.0	116,197.0	116,197.0	116,197.0	145,246.2	145,246.2	145,246.2	145,246.2
Open Land	Rooftop	Inf. Trench	A	70.4	70.4	70.4	70.4	187.6	187.6	187.6	187.6	234.5	234.5	234.5	234.5
			B	23.0	23.0	23.0	23.0	61.2	61.2	61.2	61.2	76.6	76.6	76.6	76.6
			C	197.2	197.2	197.2	197.2	525.8	525.8	525.8	525.8	657.3	657.3	657.3	657.3

Landuse Group	Disconnection Type	SCM Type	HSG	IC Treated (%), LULC Type, and Climate Type											
				30%				80%				100%			
				Historical LULC		Future LULC		Historical LULC		Future LULC		Historical LULC		Future LULC	
				Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate	Historical Climate	Future Climate
	Other IC	Inf. Basin	A	407.7	407.7	407.7	407.7	1,087.2	1,087.2	1,087.2	1,087.2	1,359.0	1,359.0	1,359.0	1,359.0
			B	213.9	213.9	213.9	213.9	570.5	570.5	570.5	570.5	713.1	713.1	713.1	713.1
			C	1,015.7	1,015.7	1,015.7	1,015.7	2,708.4	2,708.4	2,708.4	2,708.4	3,385.5	3,385.5	3,385.5	3,385.5
			D	1,958.2	1,958.2	1,958.2	1,958.2	5,221.9	5,221.9	5,221.9	5,221.9	6,527.3	6,527.3	6,527.3	6,527.3

Table 9-4. SCM specifications for watershed scale scenarios

General Information	SCM Parameters	Infiltration Trench	Infiltration Basin
Surface Storage Configuration	Orifice Height (ft)	0	0
	Orifice Diameter (in.)	0	0
	Rectangular or Triangular Weir	Rectangular	Rectangular
	Weir Height (ft)/Ponding Depth (ft)	0.5	2
	Crest Width (ft)	30	30
Soil Properties	Depth of Soil (ft)	6	0
	Soil Porosity (0-1)	0.4	0.4
	Vegetative Parameter A	0.9	0.9
	Soil Infiltration (in/hr)	Table 8-1 & Table 8-2, Lower value for HSG A-C, higher value for HSG D	Table 8-1 & Table 8-2, Lower value for HSG A-C, higher value for HSG D
Underdrain Properties	Consider Underdrain Structure?	No	No
	Storage Depth (ft)	0	0
	Media Void Fraction (0-1)	0	0
	Background Infiltration (in/hr)	N/A	N/A
Cost Parameters	Storage Volume Cost ($/ft^3)	$12.82	$6.41
Cost Function Adjustment	SCM Development Type	New SCM in Undeveloped Area	New SCM in Undeveloped Area
	Cost Adjustment Factor	1	1
Decay Rates	TSS (1/hr)	0.74	1.9
	TN (1/hr)	0.42	0.42
	TP (1/hr)	0.03	0.07
	ZN (1/hr)	0.45	1.7
Underdrain Removal Rates	TSS (%, 0-1)	N/A	N/A
	TN (%, 0-1)	N/A	N/A
	TP (%, 0-1)	N/A	N/A
	ZN (%, 0-1)	N/A	N/A

9.3. Watershed Scale Modeling Results

The watershed-scale modeling results were evaluated by comparison of annual average percent load reductions, ecodeficit/ecosurplus, and flow duration curves. The capital cost and the cost per acre IC treated for each scenario are shown in Table 9-5. The runoff volume captured by SCMs for each scenario, which primarily infiltrates and becomes groundwater recharge, is shown in Table 9-6. All FDCs from the watershed scale modeling are presented in Appendix D.

Table 9-5. Summary of total cost and cost of unit-acre IC treated for each scenario at the watershed-scale

Scenario	Control Level	IC Area Treated (ac)			Total Cost ($)			Cost/IC Area Treated ($/ac)
		30%	80%	100%	30%	80%	100%	
1	MS4	127.2	339.3	424.1	$1,432,046	$3,818,787	$4,773,483	$11,256
2		127.2	339.3	424.1	$1,432,046	$3,818,787	$4,773,483	$11,256
3		127.2	339.3	424.1	$1,432,046	$3,818,787	$4,773,483	$11,256
4		127.2	339.3	424.1	$1,432,046	$3,818,787	$4,773,483	$11,256
5		170.3	454.1	567.6	$1,918,350	$5,115,601	$6,394,500	$11,266
6		170.3	454.1	567.6	$1,918,350	$5,115,601	$6,394,500	$11,266
7	High	127.2	339.3	424.1	$3,060,582	$8,161,551	$10,201,940	$24,056
8		127.2	339.3	424.1	$3,060,582	$8,161,551	$10,201,940	$24,056
9		127.2	339.3	424.1	$3,060,582	$8,161,551	$10,201,940	$24,056
10		127.2	339.3	424.1	$3,060,582	$8,161,551	$10,201,940	$24,056
11		170.3	454.1	567.6	$4,068,984	$10,850,623	$13,563,281	$23,896
12		170.3	454.1	567.6	$4,068,984	$10,850,623	$13,563,281	$23,896
13	1-inch Retention	170.3	454.1	567.6	$5,155,181	$13,747,150	$17,183,939	$30,276
14		170.3	454.1	567.6	$5,155,181	$13,747,150	$17,183,939	$30,276

There are several ways to compare the watershed scale scenarios. First, annual average load reductions can be compared between the same scenario but with varying percentages of IC treated. Annual average percent reductions, as evaluated at the watershed outlet, are shown in Table 9-7; Table 9-8 presents these metrics but for the load from IC only since no pervious areas were treated by any of the modeled scenarios. The 30% IC treated represents an estimate of the amount of IC treated at the watershed scale when the projects fall under a regulatory threshold area of 1-acre disturbance or impervious cover, while 80% IC treated represents a more stringent regulation that requires a threshold of 1/8th of an acre IC. Treatment of 100% of the IC is included as a theoretical maximum. Increasing the percentage of IC treated understandably leads to greater treatment and lower loads to receiving waters.

A second way to compare the results of the watershed scale modeling is with the same boundary conditions, but for different control levels. Figure 9-1 visualizes this for Scenario 5 (MS4 Control), Scenario 11 (High Control), Scenario 13 (1in. Retention) using future land use and historical climate conditions. This figure shows that the 1-acre of land disturbance threshold (30% IC treated) will not meet the 60% TP load reduction target at the subwatershed scale. The 1/8th–acre of land disturbance threshold (80% IC treated) may also not meet the TP reduction target if the pervious nutrient load at the time of development is not offset by management actions. The trend in these TP reductions is similar when considering future climate, but slightly reduced.

As another example, Scenarios 1 and 7 both have historical boundary conditions but use the MS4 and High control SCMs, respectively. High control under these conditions, and with 80% IC treated, achieves an 11%

greater TP reduction than the MS4 control level (Table 9-7 and Table 9-8). This comparison can be extended to the FDCs (Figure 9-2 and Figure 9-5) and ecosurplus/ecodeficit (Figure 9-9). Visual differences in the FDCs can be subtle, however, their cumulative impact is seen in the ecosurplus and ecodeficit values. In this example, the High control SCMs have a slightly lower ecosurplus (by 1.9 MG/yr).

Table 9-6. Summary of runoff volume captured by SCMs for each watershed -scale scenario

Scenario	Control Level	IC Area Treated (ac)			Captured Volume (gal/ac/yr)			Captured Volume (%)		
		30%	80%	100%	30%	80%	100%	30%	80%	100%
1	MS4	127.2	339.3	424.1	6,407	17,086	21,357	10%	27%	34%
2		127.2	339.3	424.1	5,925	15,801	19,751	9%	25%	31%
3		127.2	339.3	424.1	6,407	17,086	21,357	8%	20%	26%
4		127.2	339.3	424.1	5,925	15,801	19,751	7%	19%	23%
5		170.3	454.1	567.6	6,657	17,752	22,190	11%	28%	35%
6		170.3	454.1	567.6	6,179	16,478	20,598	10%	26%	33%
7	High	127.2	339.3	424.1	10,509	28,025	35,031	17%	45%	56%
8		127.2	339.3	424.1	9,651	25,735	32,169	15%	41%	51%
9		127.2	339.3	424.1	10,509	28,025	35,031	13%	33%	42%
10		127.2	339.3	424.1	9,651	25,735	32,169	11%	30%	38%
11		170.3	454.1	567.6	10,722	28,591	35,739	17%	46%	57%
12		170.3	454.1	567.6	9,893	26,380	32,976	16%	42%	52%
13	1-inch Retention	170.3	454.1	567.6	12,831	34,215	42,769	21%	55%	68%
14		170.3	454.1	567.6	11,869	31,652	39,565	19%	50%	63%

The third comparison of results can be made between the same control level, but with varying boundary conditions. Each FDC in Figure 9-2 to Figure 9-8 shows the same control level and land use boundary conditions, but with historical or future climate. Results can also be compared in this way across land use conditions. Figure 9-5 and Figure 9-7 show an example of this between High control SCMs with historical LULC and climate (Scenario 7) compared to High control SCMs with future LULC and climate (Scenario 12). Between these scenarios, there is an increase in ecodeficit and ecosurplus which demonstrates the impact of increased IC coupled with increased precipitation and temperature on the flow duration curve. While these scenarios both treat 80% of the IC, the area treated and SCM capacity is greater under the future LULC condition.

Table 9-7. Watershed total annual average percent reductions for watershed level scenarios with 30%, 80%, and 100% IC treated

Scenario	Control Level	TSS			TN			TP			Zn		
		30%	80%	100%	30%	80%	100%	30%	80%	100%	30%	80%	100%
1	MS4	25.1%	66.9%	83.6%	20.1%	52.4%	65.5%	16.2%	41.2%	51.2%	25.2%	66.8%	83.6%
2		25.4%	67.8%	84.7%	20.2%	52.4%	65.3%	15.8%	39.8%	49.5%	25.2%	66.8%	83.5%
3		19.4%	51.7%	64.7%	15.8%	41.3%	51.6%	13.2%	33.6%	41.9%	20.4%	54.0%	67.5%
4		19.5%	52.0%	65.0%	15.8%	41.0%	51.2%	12.9%	32.3%	40.2%	20.3%	53.8%	67.2%
5		26.7%	71.2%	89.0%	21.0%	55.1%	68.9%	17.7%	45.4%	56.6%	26.5%	70.4%	88.0%
6		26.8%	71.5%	89.4%	21.0%	54.8%	68.4%	17.2%	43.7%	54.4%	26.4%	70.1%	87.6%
7	High	25.6%	68.3%	85.4%	22.5%	60.1%	75.3%	19.7%	52.4%	65.5%	26.5%	70.7%	88.4%
8		25.8%	68.9%	86.1%	22.6%	60.2%	75.3%	19.2%	50.9%	63.6%	26.5%	70.9%	88.7%
9		19.8%	52.8%	66.1%	17.7%	47.4%	59.3%	16.1%	42.8%	53.5%	21.4%	57.2%	71.5%
10		19.8%	52.9%	66.1%	17.7%	47.2%	59.0%	15.6%	41.3%	51.7%	21.4%	57.1%	71.4%
11		27.2%	72.6%	90.8%	23.6%	62.9%	78.7%	21.5%	57.1%	71.4%	27.8%	74.3%	92.9%
12		27.2%	72.7%	90.8%	23.5%	62.7%	78.4%	20.8%	55.3%	69.1%	27.8%	74.1%	92.7%
13	1-inch Retention	27.3%	72.8%	90.9%	24.4%	65.1%	81.4%	22.9%	61.0%	76.3%	28.0%	74.8%	93.5%
14		27.3%	72.8%	91.0%	24.3%	65.0%	81.2%	22.3%	59.4%	74.2%	28.0%	74.8%	93.5%

Table 9-8. Impervious cover annual average percent reductions for watershed level scenarios with 30%, 80%, and 100% IC treated

Scenario	Control Level	TSS			TN			TP			Zn		
		30%	80%	100%	30%	80%	100%	30%	80%	100%	30%	80%	100%
1	MS4	29.2%	78.0%	97.5%	24.5%	64.0%	79.9%	20.4%	52.1%	64.8%	27.7%	73.4%	91.8%
2		29.4%	78.3%	97.9%	24.3%	63.0%	78.6%	19.8%	49.8%	61.8%	27.5%	72.9%	91.1%
3		21.3%	56.7%	70.9%	18.5%	48.3%	60.3%	15.4%	39.3%	48.9%	21.4%	56.7%	70.8%
4		21.4%	57.0%	71.3%	18.3%	47.6%	59.4%	15.0%	37.6%	46.7%	21.2%	56.2%	70.3%
5		29.3%	78.0%	97.6%	24.6%	64.5%	80.6%	20.7%	53.1%	66.2%	27.8%	73.8%	92.3%
6		29.4%	78.4%	98.0%	24.4%	63.6%	79.4%	20.0%	50.8%	63.3%	27.6%	73.3%	91.6%
7	High	29.8%	79.6%	99.6%	27.5%	73.4%	91.8%	24.9%	66.3%	82.8%	29.1%	77.7%	97.2%
8		29.9%	79.6%	99.6%	27.2%	72.5%	90.7%	24.0%	63.6%	79.6%	28.9%	77.3%	96.7%
9		21.7%	57.9%	72.4%	20.8%	55.4%	69.4%	18.8%	50.0%	62.5%	22.5%	60.0%	75.0%
10		21.7%	57.9%	72.4%	20.5%	54.7%	68.5%	18.1%	48.1%	60.1%	22.3%	59.6%	74.6%
11		29.8%	79.6%	99.6%	27.6%	73.6%	92.1%	25.1%	66.8%	83.4%	29.2%	77.9%	97.4%
12		29.9%	79.7%	99.6%	27.3%	72.7%	91.0%	24.2%	64.3%	80.3%	29.0%	77.5%	96.9%
13	1-inch Retention	29.9%	79.8%	99.7%	28.5%	76.2%	95.2%	26.8%	71.3%	89.1%	29.4%	78.4%	98.1%
14		29.9%	79.8%	99.8%	28.2%	75.4%	94.3%	25.9%	69.0%	86.3%	29.3%	78.1%	97.7%

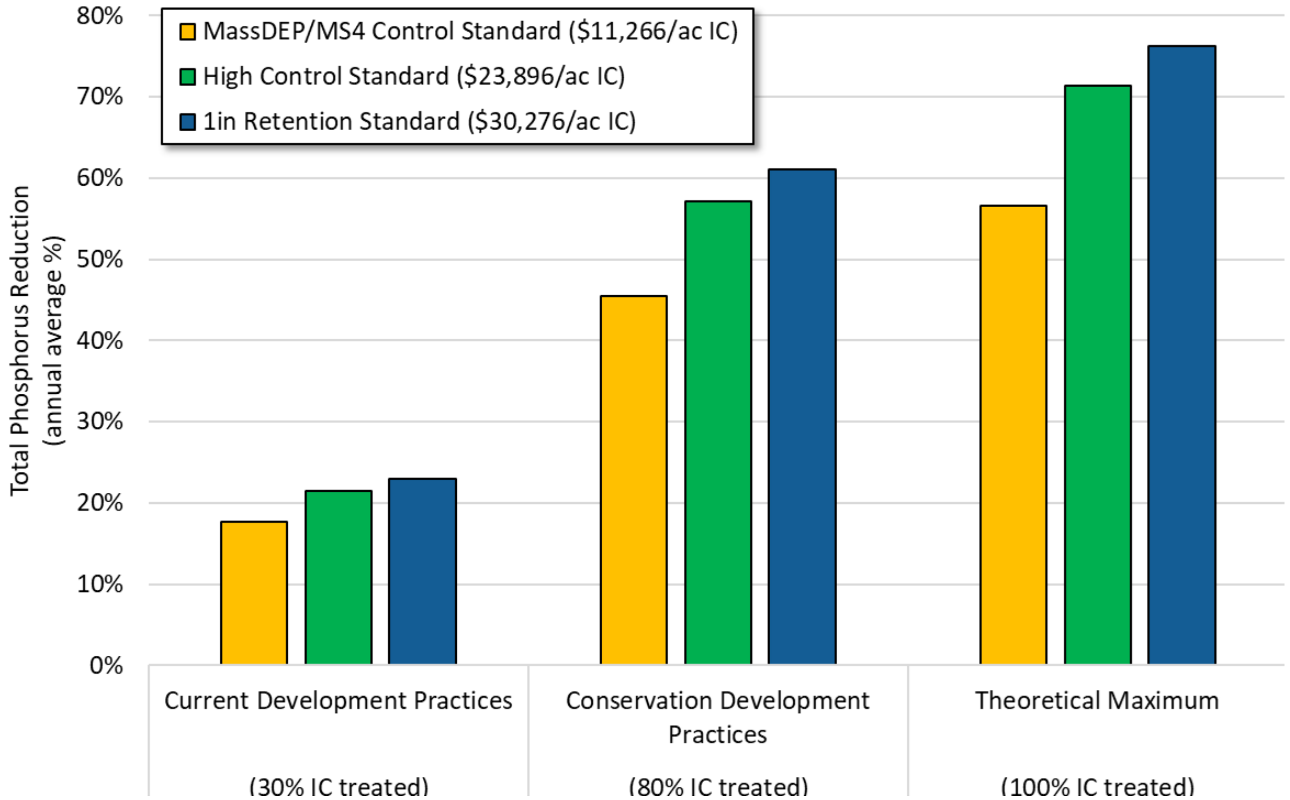


Figure 9-1. Comparison of annual average TP reduction for MassDEP/MS4 (Scenario 5), High (Scenario 11), and 1in. Retention (Scenario 13) control levels using future land use and historical climate conditions.

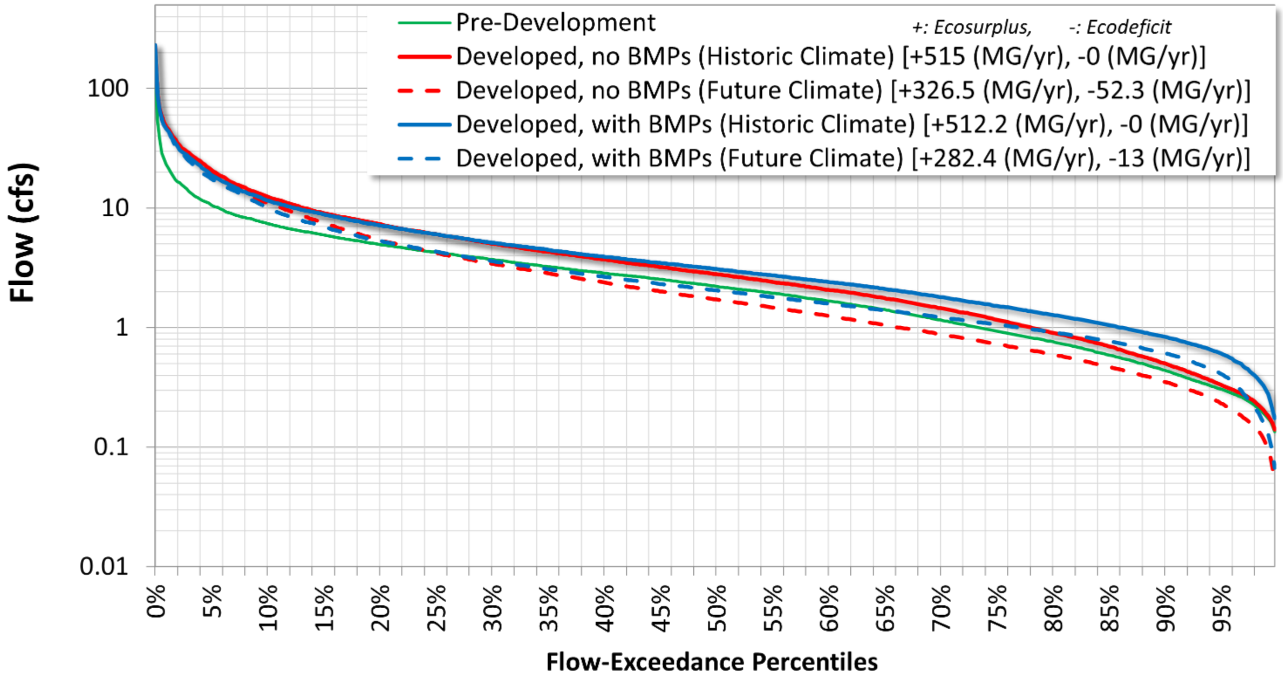


Figure 9-2 Flow duration curve with MS4 control of 80% of the Upper Hodges Brook subwatershed's impervious cover under historical LULC with both historical and future climate conditions (Scenarios 1 and 2).

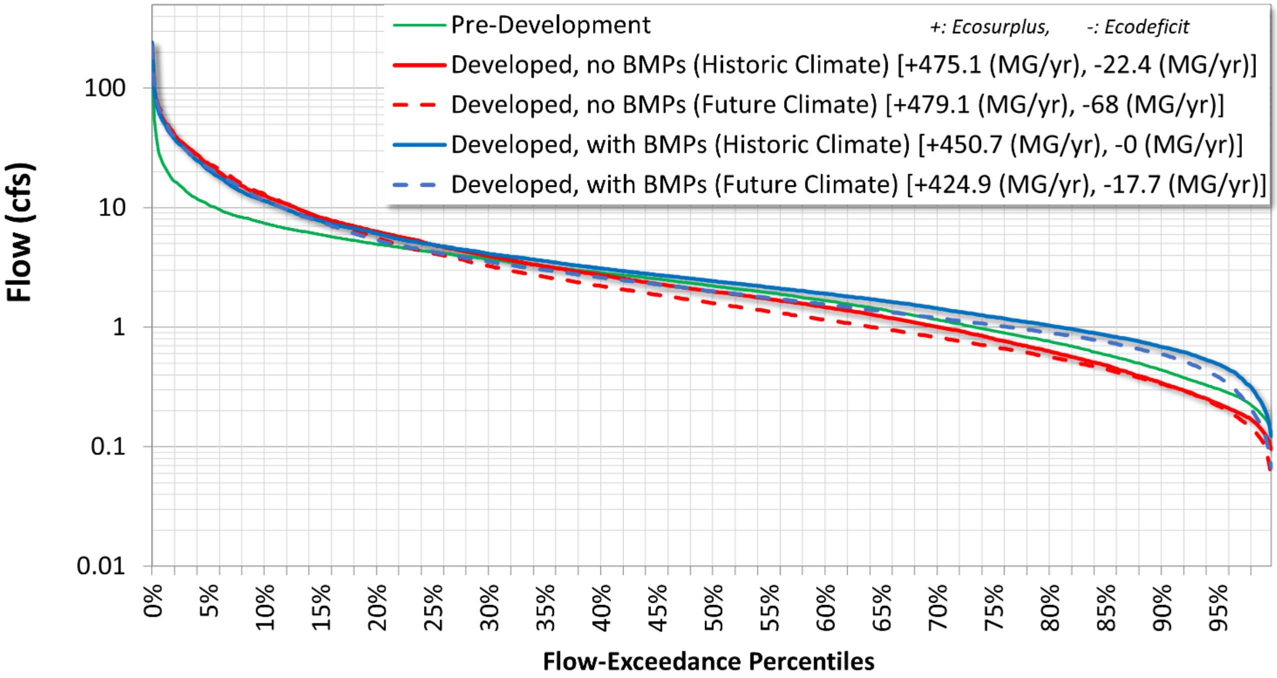


Figure 9-3. Flow duration curve with MS4 control of 80% of the Upper Hodges Brook subwatershed's impervious cover under future LULC with both historical and future climate conditions (Scenarios 3 and 4). Future IC beyond the historical amount is untreated.

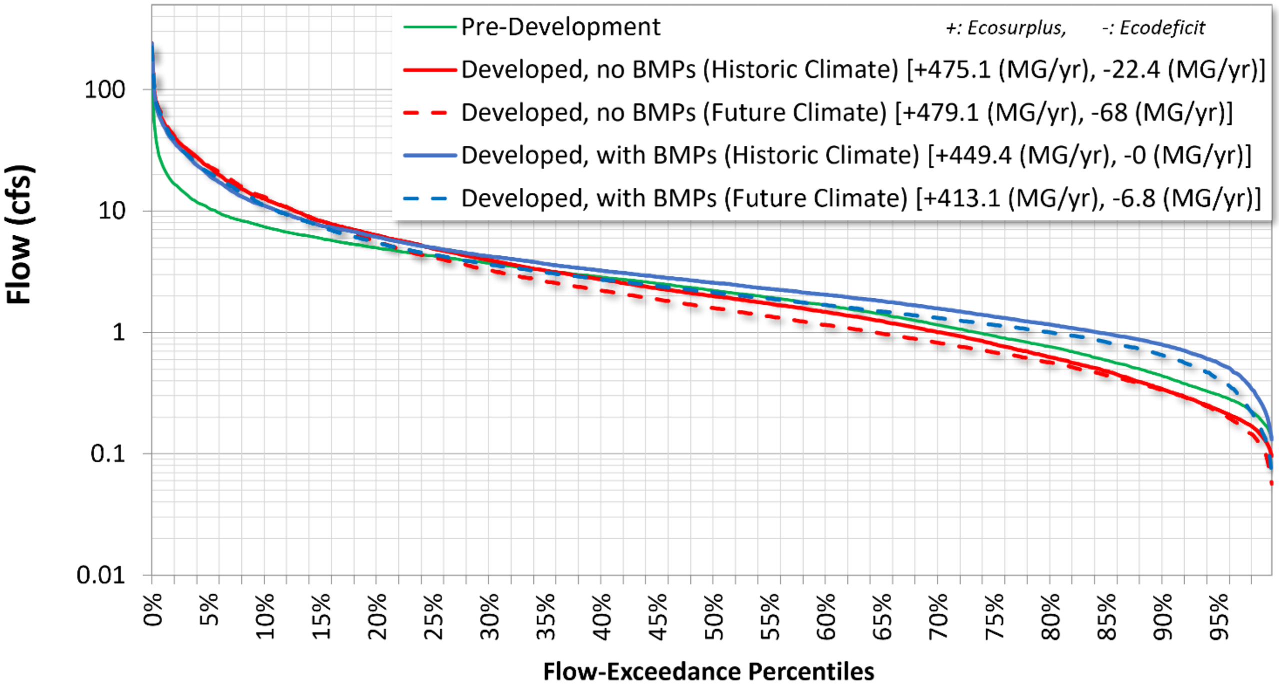


Figure 9-4. Flow duration curve with MS4 control of 80% of the Upper Hodges Brook subwatershed's impervious cover under future LULC with both historical and future climate conditions (Scenarios 5 and 6).

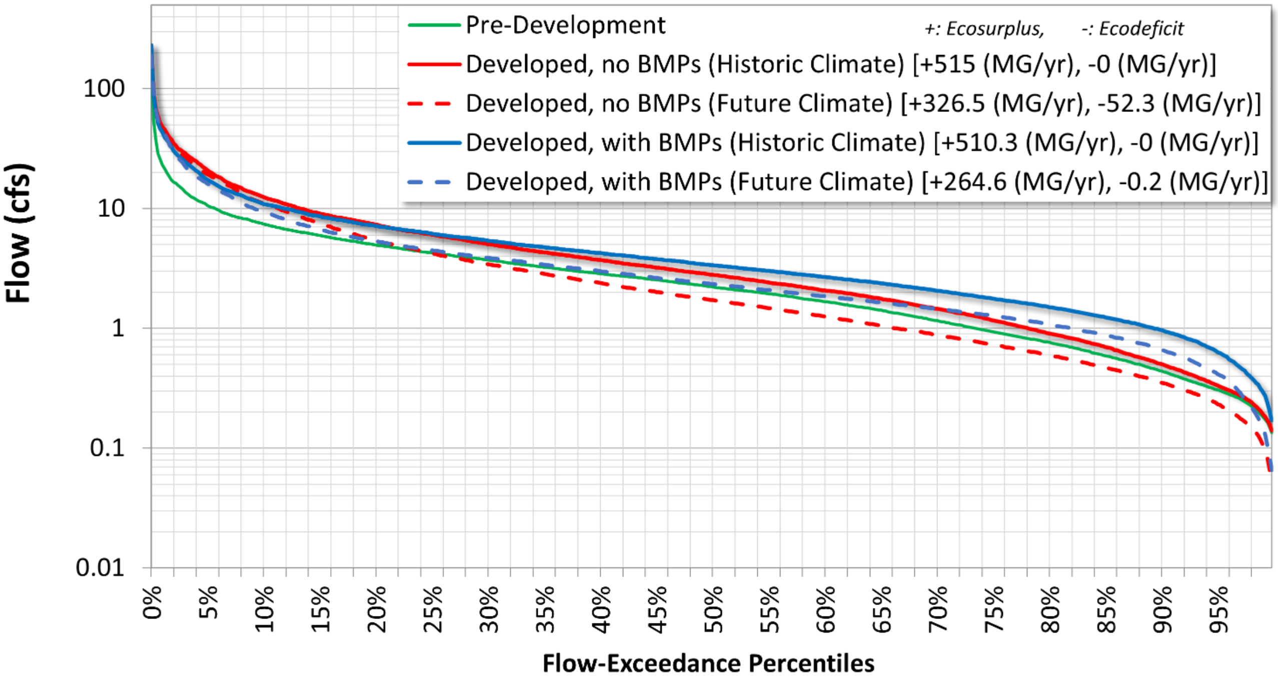


Figure 9-5. Flow duration curve with High control of 80% of the Upper Hodges Brook subwatershed's impervious cover under historical LULC with both historical and future climate conditions (Scenarios 7 and 8).

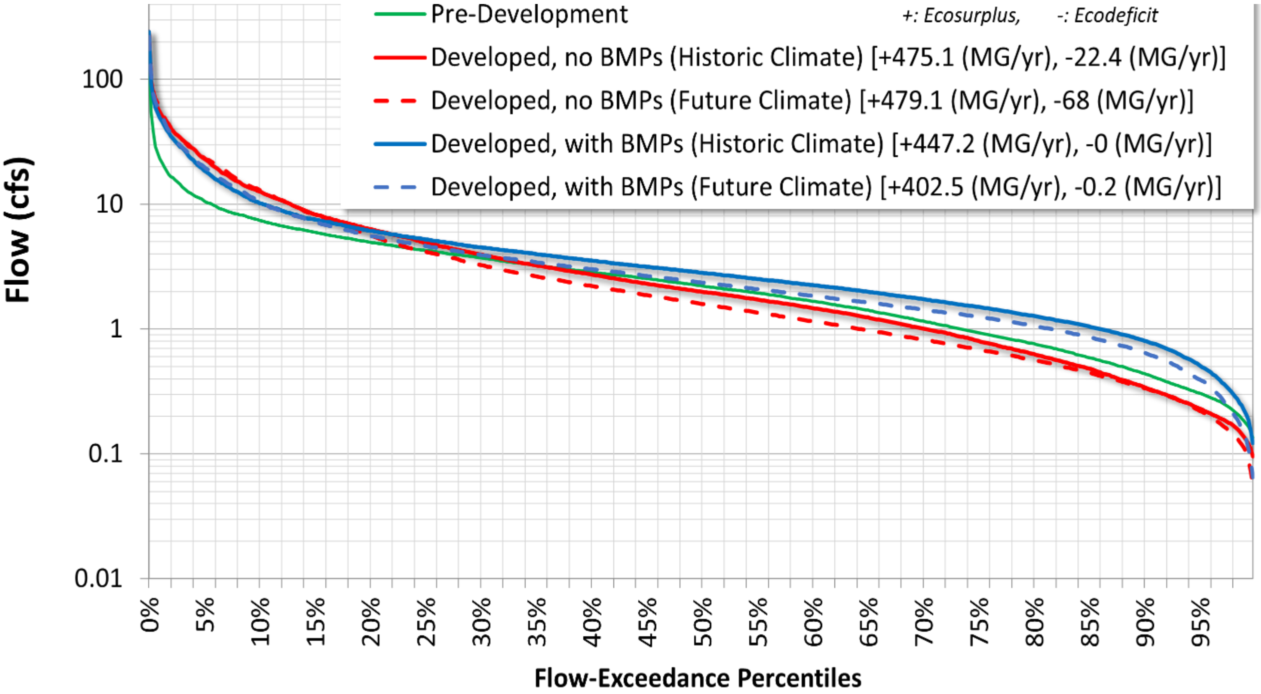


Figure 9-6. Flow duration curve with High control of 80% of the Upper Hodges Brook subwatershed's impervious cover under future LULC with both historical and future climate conditions (Scenarios 9 and 10). Future IC beyond the historical amount is untreated.

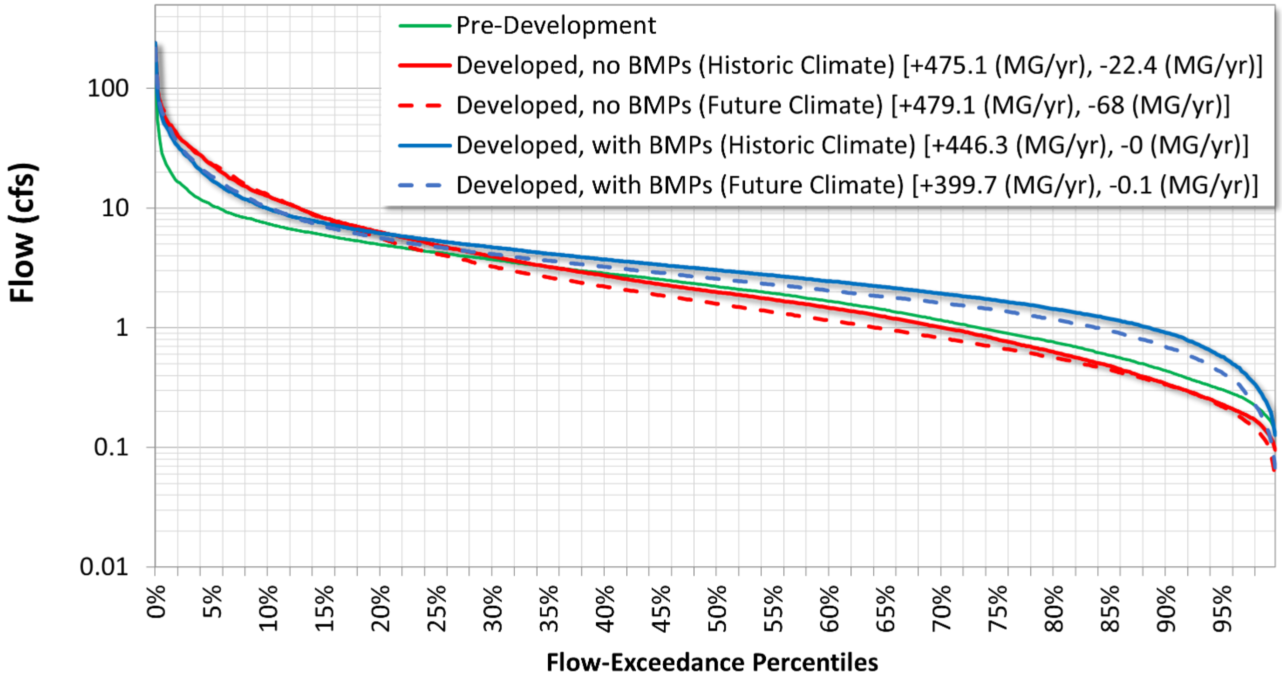


Figure 9-7 Flow duration curve with High control of 80% of the Upper Hodges Brook subwatershed's impervious cover under future LULC with both historical and future climate conditions (Scenarios 11 and 12).

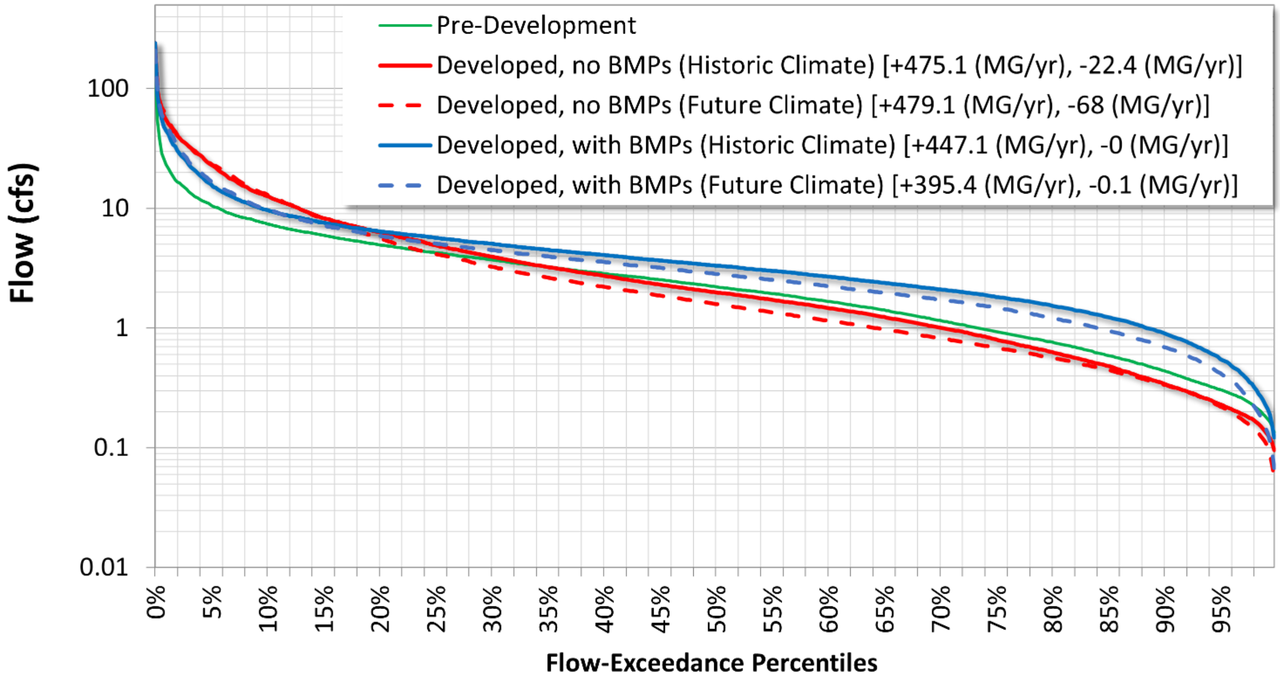


Figure 9-8. Flow duration curve with 1in Retention control of 80% of the Upper Hodges Brook subwatershed's impervious cover under future LULC with both historical and future climate conditions (Scenarios 13 and 14).

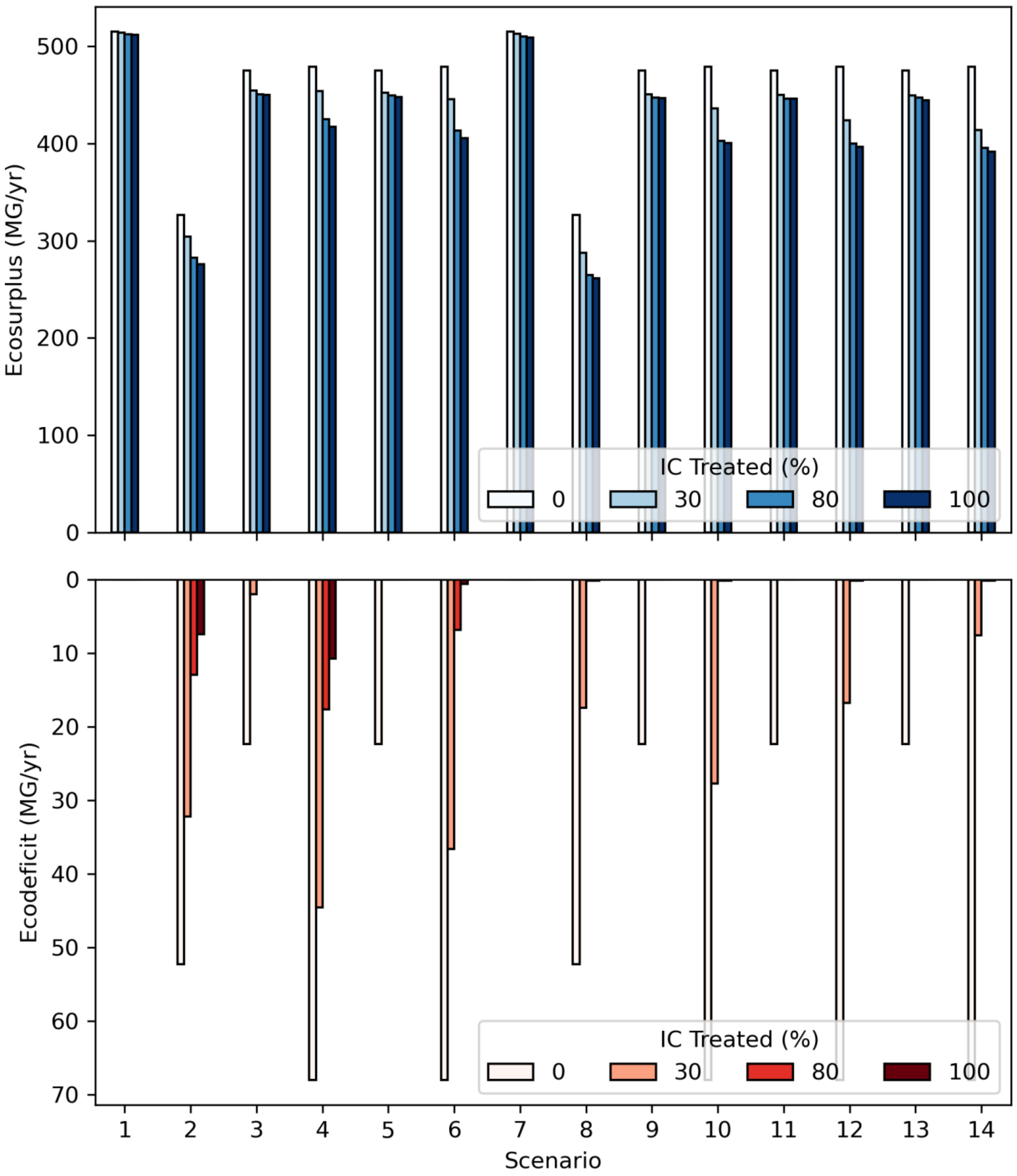


Figure 9-9. Comparison of ecosurpluses and deficits for each watershed scale scenario and percentage of IC treated.

10. CONCLUSIONS AND RECOMMENDATIONS

This report presents a quantitative analysis of FDCs and other associated metrics for understanding the impact of land use decision-making on freshwater flow regimes and ecosystem health. These analyses were based on long-term continuous hydrologic models previously developed under Phase 1 of this project for the Taunton River Basin in eastern Massachusetts using the LSPC and EPA's Opti-Tool models. This report (Phase 2A) conceptualized, evaluated, and communicated the benefits of next-generation conservation-focused development and stormwater management practices.

In this report, a wide range of scenarios were evaluated for individual SCMs, for conservation-focused conceptual new and redevelopment sites, and for a small urbanized watershed using both historical and future projections of land use and climate. Results presented in this report indicate that individual conservation-focused SCMs, when sized to maintain predevelopment hydrologic conditions, can achieve 95% and 90% reductions in annual average Total Nitrogen (TN) and Total Phosphorous (TP) load, respectively. These High control SCMs outperform conventional (MS4) control SCMs by 8% for TN and by 13% for TP. When individual High control SCMs are combined within a new or redevelopment site, they can be configured as a system to achieve goals such as maintaining resilient, predevelopment hydrology with little to no net increase in nutrient loads. This was demonstrated for a high-density residential site and a high-density commercial site in this report.

Recommendations from the findings in this report include the following:

- The SCMs evaluated in this report represent structural controls for treating runoff from impervious surfaces. However, there is a need to look at the impact of treating pervious areas i to meet watershed load reduction targets. Source control (e.g., fertilizer reduction, leaf pickup, pet waste removal, etc.) should be added to the modeling to reflect more holistic stormwater management.
- A conceptual design for a low-density residential site in this report used IC disconnection as an SCM. IC disconnection, with and without temporary storage as well as GI-like green roofs, should be further evaluated and their secondary or co-benefits should be included to the extent possible.

This report adds to a body of work that envisions the next generation of stormwater management practices. Stormwater management requires multifaceted approaches including structural controls like those evaluated here, as well as source control from developed pervious areas and locally driven conservation-focused regulations and ordinances to be most effective. Evaluating the impact of structural and source controls in combination at the watershed level in future work would provide valuable insights for next-generation conservation development and stormwater management.

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