EPA/600/R-17/469F | May 2018 | www.epa.gov/research

United States
Environmental Protection
Agency

Improving the Resilience of Best Management Practices in a Changing Environment:
Urban Stormwater Modeling Studies




Office of Research and Development
Washington, D.C.

EPA/600/R-17/469F
May, 2018
www.epa.gov/research

Improving the Resilience of Best Management Practices in a Changing Environment: Urban Stormwater Modeling Studies

National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

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ABSTRACT

The United States Environmental Protection Agency (U.S. EPA) identified a need for improved understanding of the potential impacts of changes in long term weather conditions on the occurrence and management of stormwater runoff (U.S. EPA, 2008; 2010; 2012). Accordingly, we conducted continuous simulation modeling of the hydrology, hydraulics, and water quality discharged from a series of conceptual development sites using a variety of conventional (or “gray”) and green infrastructure (GI) practices consistent with local stormwater and site design regulations. We assessed the performance of green and gray stormwater controls under current conditions and a range of potential changes in precipitation and temperature, and examined how designs could be adapted accordingly. The stormwater management scenarios covered five types of developed land use in five geographic locations representing different hydroclimatic regimes throughout the United States. The results and conclusions of the study are applicable to both new development, redevelopment, and stormwater retrofits.

Preferred citation:

U.S. EPA (Environmental Protection Agency). 2018. Improving the resilience of BMPs in a changing environment: urban stormwater modeling studies. Office of Research and Development, Washington, DC; EPA/600/R-17/469F. Available online at http://www.epa.gov/research.

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LIST OF ABBREVIATIONS

ACE	Air, Climate and Energy
ACF	Apalachicola•Chattahoochee•Flint
BCSD	bias•correction spatial disaggregation
BMP	best management practice
C	coefficients
CCSM	Community Climate System Mode
CF	cubic feet
CMIP	Coupled Model Intercomparison Project
CNT	Center for Neighborhood Technology
Cp	pervious coefficient runoff value
CPv	channel protection volume
ET	evapotransporation
FDC	flow duration curve
GCM	general circulation model
GFDL	Geophysical Fluid Dynamics Laboratory
GI	green infrastructure
GIS	geographic information system
HADCM3	Hadley Centre Coupled Model, Version 3
HSG	hydrologic soil group
HSPF	Hydrologic Simulation Program• Fortran
HUC	hydrologic unit code
Hw/D	headwater/pipe diameter ratio
LF	linear feet
LID	low impact development
MPCA	Minnesota Pollution Control Agency
NARCCAP	North American Regional Climate Change Assessment Program
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEA	National Center for Environmental Assessment
NOAA	National Oceanic and Atmospheric Administration
O&M	operation and maintenance
Qp	overbank flood protection
PET	potential evapotranspiration
PFDS	Precipitation Frequency Data Server
PV	present value
RCM	regional climate models
Rev	recharge volume
ROW	right•of•way
SF	square feet
SRES	Special Report on Emissions Scenarios
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	stormwater management model
Tc	timing variable
TN	total nitrogen
TP	total phosphorous
TSS	total suspended solids
WMO	watershed management organizations
WQv	water quality volume

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EPA's Office of Research and Development was responsible for producing this report. The report was prepared by Tetra Tech, Inc. under EPA Contract No. EP-C-12-060. Susan Julius served as the Task Order Project Officer, providing overall direction and technical assistance, and was a contributing author. We would like to thank the internal and external reviewers for their valuable comments and insights.

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EXECUTIVE SUMMARY

The EPA Office of Water has identified a need for improved understanding of the potential impacts of future changes in extreme precipitation events on the occurrence and management of stormwater runoff (U.S. EPA, 2008; 2010; 2012). Accordingly, the EPA National Center for Environmental Assessment (NCEA) conducted a technical analysis of the performance of conventional ("gray") and natural or semi-natural ("green") stormwater controls under precipitation and temperature scenarios to examine how those controls could be re-engineered to control stormwater. This report presents the results of these modeling studies.

Using continuous simulation modeling of the hydrology, hydraulics, and water quality discharged from a series of conceptual development sites with a variety of gray and green infrastructure (GI) practices, we addressed the following questions:

1. How might extreme precipitation events affect the performance of conventional stormwater infrastructure and GI,
2. How can conventional designs and GI designs be adapted so that a site experiencing extreme precipitation conditions in the future provides the same performance as the site under current conditions, and
3. What do the results suggest regarding the adaptation potential of gray and green infrastructure for increases in extreme precipitation events?

We used the modeling framework shown in *Figure* ES-1 to address the three questions above. The Hydrologic Simulation Program• Fortran (HSPF) model (Bicknell et al., 2004) was used to simulate hourly unit-area time series of runoff and pollutant loads (total suspended solids [TSS], total nitrogen [TN], and total phosphorous [TP]) from pervious and impervious land. Future scenarios of extreme precipitation were developed from the current time series using downscaled general circulation models (GCMs) as well as percent changes in precipitation. The conceptual sites and associated stormwater management infrastructure were simulated using the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model, a decision support system and modeling tool. Hourly output is provided by SUSTAIN for each individual best management practice (BMP) and at the site outlet.

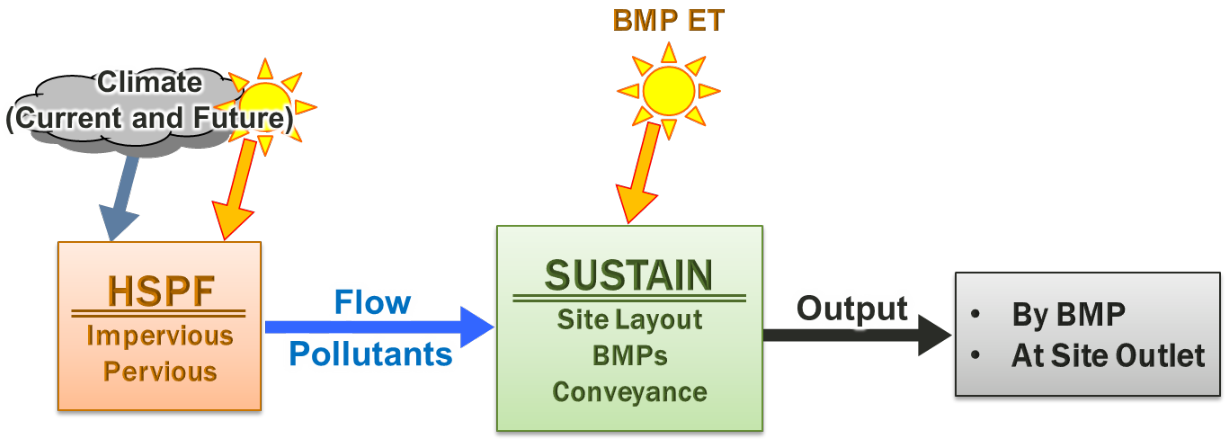

Figure ES-1. Modeling framework for study.

APPROACH

The stormwater management scenarios covered five types of developed land use in five geographic locations representing different hydroclimatic regimes throughout the United States. The developed land use types included residential, commercial, mixed-use, ultra-urban, and green street areas. HSPF models developed for a previous project (U.S. EPA, 2013; Johnson et al., 2015) were used as input for the SUSTAIN simulation. Each land use type was paired with a geographic location (i.e., a single development type was modeled at a single location as shown in *Table* ES-1). A variety of stormwater BMPs were represented, ranging from gray infrastructure to GI designs. The stormwater management BMP configurations were consistent with local design standards, requirements, and guidance. For each land use type, one, two, or three stormwater management approaches were used to illustrate different ways to address site stormwater. Most of the land use types had at least one conventional stormwater management approach and one approach incorporating GI elements. In some cases, the GI approach also included gray infrastructure practices to address peak flow control requirements for large storm events (i.e., 10-year through 100-year design storms). In other cases, a GI approach with no gray infrastructure met local stormwater requirements. Best professional judgment was used to select the BMPs used for modeling, informed by local and state design guidance.

Each stormwater management approach was modeled under current and a selected set of projected future precipitation scenarios for the mid-21st century, and the water quantity and quality performance of the site practices were calculated from modeling results. In an additional model run, the site's practices were modified under projected future precipitation conditions to achieve the same or better performance as under the current conditions using SUSTAIN's optimization function. Modifications targeted resizing the water quality treatment and peak flow control BMPs, which are the primary drivers controlling site performance. The adaptation scenario that was selected as optimal was the one that was both lowest cost and provided the same or better performance as current baseline conditions.

Table ES-1. Matrix of regions, locations, land uses, future precipitation scenarios, and stormwater management approaches

Region	Location	Type	Scenarios	Stormwater management approach
Mid-Atlantic	Harford County, MD	Mixed use	GCM high intensity Minus 10% Plus 10% Plus 20%	Conventional (Gray) Infrastructure
				GI with Gray Infrastructure
				Conventional (Gray) Infrastructure with distributed GI
Midwest	Scott County, MN	Residential	GCM low intensity GCM medium intensity GCM high intensity Minus 10% Plus 10%t Plus 20%	Conventional (Gray) Infrastructure
				GI with Gray Infrastructure
				GI Only
				Conventional (Gray) Infrastructure with Distributed GI
Arid Southwest	Maricopa County, AZ	Commercial	GCM high intensity	Conventional (Gray) Infrastructure
				GI Only
Southeast	Atlanta, GA	Ultra-urban	GCM high intensity	Conventional (Gray) Infrastructure
				GI with Gray Infrastructure
Pacific Northwest	Portland, OR	Transportation corridor	GCM high intensity	GI Only

At two of the geographic locations, additional scenarios were developed that kept the current conventional BMP configuration intact but added distributed GI practices to provide treatment equivalent to the current conditions.

For each site location, a "base-case" future precipitation scenario was selected from a pool of ten downscaled scenarios EPA developed previously (U.S. EPA, 2013; Johnson et al., 2015) to model the impact of changes in precipitation on hydrology and water quality in 20 watersheds throughout the United States (referred to in this report as the "20 Watersheds" project). The base-case was chosen as the scenario with the largest increase in the intensity of large storm events to represent the upper range of potential impacts. In addition, two types of sensitivity analyses were conducted as part of the study. First, 2 additional downscaled GCM scenarios were selected from the pool of 10 for the Midwestern site• scenarios representing the lowest change and a medium change in large storm event intensity. Finally, a sensitivity analysis was conducted at the Midwestern site and the Mid-Atlantic site evaluating the effects of set percent changes in all precipitation events• minus 10, plus 10, and plus 20% changes in precipitation volume. *Table* ES-1 provides a summary of components of the analyses.

The study sites and stormwater management approaches are outlined below in *Table* ES-2. The sites, approaches, and applicable regulations are discussed in detail in each of the five site sections in the report (see *Sections 3.* to *7.*). Each detailed site representation developed included both the local requirements as well as the local or state guidance for BMP footprint, volume, and configuration. TR-55 and other tools were used to develop scoping-level designs for the practices, including details of outlet structures with orifices and weirs set to meet stormwater requirements. Soil properties of media in filtering BMPs such as bioretention and sand filters were represented using properties from design guidance as well as values from BMP research.

To address impacts to water resources due to changes in precipitation events, each stormwater management approach was modified by increasing the size (area, or footprint) of the structural stormwater BMPs to provide treatment equivalent to current conditions. The performance metrics were defined as follows:

- *Annual outflow volume* to address stormwater volume treatment requirements,
- *Flow duration curve* (FDC) to address channel erosion risk and flooding risk, and
- *Pollutant mass export* (nitrogen, phosphorus, and sediment) to address water quality performance.

Annual runoff volume, pollutant loads, and the flow duration curve were tabulated for each site under current conditions in an initial SUSTAIN model run. Under projected future precipitation conditions, annual runoff volume, pollutant loads, and the magnitude of flows in the upper portion of the flow duration curve generally increased. To find a new configuration that met all of the current condition metrics, an optimization was performed in SUSTAIN with numerous model runs that incrementally changed practice sizes. For the flow duration curve, the difference between the current conditions and future precipitation curves was used to assess increases in peak flows across a range of storms. Optimization sought to minimize the area between the curves, thus, mimicking the current conditions hydraulic response. The SUSTAIN optimization included scoping-level estimates of unit-area practice costs, so the optimal solution was the configuration that was both lowest cost and met all of the target values of the metrics. As an example, for the Scott County GI with Gray stormwater management approach, the footprints of the bioretention cells and the dry detention basin were increased under future precipitation conditions. This increase provided additional hydrologic control and pollutant removal so that the revised configuration performed as well or better than the site under current precipitation conditions.

For the Harford County, MD and Scott County, MN stormwater management approaches, the designs were modified using two different management strategies•   increasing the size of the structural practices (as done for the other locations) and addressing the performance gap by incorporating additional distributed GI practices into the site. In the latter approach, the current Conventional Infrastructure configuration was unchanged and distributed infiltration trenches (Harford County, MD) and bioretention (Scott County, MN) were added to provide treatment equivalent to the current conditions.

Table ES-2. Stormwater management approach summary

Location	Characteristics	Stormwater requirements	Stormwater management approach	Practices
Harford County, MD	Mixed use 20 acres 65% impervious	Completely infiltrate recharge volume Treat water quality volume for TSS/TP Channel protection volume (24-h detention of 1-yr 24-h storm) Match predeveloped peak for 10-yr 24-h storm	Conventional (Gray) Infrastructure	Surface sand filters, extended dry detention basin
			GI with Gray Infrastructure	Infiltration trenches, infiltration basins, permeable pavement, and dry detention basin
			Conventional (Gray) Infrastructure with Distributed GI	Surface sand filters, extended dry detention basin, distributed infiltration trenches
Scott County, MN	Residential 30 acres 48% impervious	Treat water quality volume for TSS Match predeveloped peak for 2-yr 24-h storm and 100-yr 24-h storm	Conventional (Gray) Infrastructure	Wet pond
			GI with Gray Infrastructure	Distributed bioretention and dry detention basin
			GI Only	Distributed bioretention, permeable pavement, and impervious surface disconnection
			Conventional (Gray) Infrastructure with Distributed GI	Wet pond, distributed bioretention
Maricopa County, AZ	Commercial 10 acres 80% impervious	100% retention of the 100-yr 2-h storm event	Conventional (Gray) Infrastructure	Detention/infiltration basin
			GI Only	Permeable pavement, cistern, bioretention, and stormwater harvesting basin
Atlanta, GA	Ultra-urban 2 acres 90% impervious	Treat water quality volume for TSS Channel protection volume (24-h detention of 1-yr 24-h storm) Match predeveloped peak for 2-yr, 5-yr, 10-yr, 25-yr, and 100-yr 24-h storm	Conventional (Gray) Infrastructure	Underground sand filter, underground dry detention basin
			GI with Gray Infrastructure	Green roof, permeable pavement, bioretention, and underground dry detention basin
Portland, OR	Transportation corridor 0.35 acres 89% impervious	70% TSS reduction Infiltration of 10-yr 24-h storm event as practicable Match predeveloped peak for 2-yr, 5-yr, 10-yr 24-h storm	GI Only	Bioretention swales, permeable pavement

TSS = total suspended solids.

This study was not exhaustive and considers only a limited number of developed land use types, practice configurations, and projected future precipitation scenarios. In addition, while the five geographic regions selected for modeling represent a range of ecoregions and climate types, they do not cover all of the precipitation conditions found in the United States. Results are also dependent on the representations of the complex physical processes governing stormwater hydrology and pollutant loading that are incorporated into the HSPF and SUSTAIN model codes. Like all simulation models, these tools are simplified approximations of the real world. For most of the sites, the precipitation change scenarios were selected to represent the upper range of potential impacts. The analysis does provide insights into the potential impacts of changes in precipitation events on stormwater infrastructure performance, and allows comparison of how the responses may differ between conventional and GI practices.

RESULTS

Model simulations in five study locations suggest some ranges for the increase in pretreatment total urban runoff and pollutant loads that may result from changes in precipitation events by midcentury. For overall post-treatment site-scale performance, simulations using both conventional and GI BMP scenarios generally remove more runoff volume and pollutant mass under future increases in precipitation and runoff compared to current conditions. However, overall site export rates of runoff volume and pollutant mass still increase (i.e., BMP does not remove 100% of the additional runoff/pollutant load resulting from increased precipitation) despite better volume/mass removal. Changes in large storm event runoff (as indicated by comparison of FDCs) show that BMPs designed for current conditions will not mitigate increases in stormwater runoff and associated downstream channel erosion and flooding impacts under projected future conditions. Thus, there may be a need for adapting site stormwater infrastructure to future precipitation conditions to protect downstream water resources. Sites may also need to be configured to be adaptable in the first place to allow for placement of additional stormwater treatment if needed in the future.

When considering the adaptation of BMPs under future precipitation conditions to achieve the same or better performance as seen under current conditions, the most difficult performance measure to mitigate was usually control of large flooding event outflows. Given that control of flooding events is a ubiquitous requirement throughout the United States, this indicates that current practices will need greater temporary volume storage and/or reconfiguration of outlet structures to mitigate flooding and channel erosion risk in locations where the magnitude of extreme events is expected to increase. GI practices that rely on treatment without volume storage will be at a disadvantage for adaptation to increased precipitation, but approaches that rely only on adapting conventional practices may not have the flexibility to address multiple performance objectives.

When comparing the current cost of stormwater management for new development between conventional and GI-based approaches, the conventional approaches tended to be more cost-effective than their GI counterparts. However, when precipitation scenarios with smaller increases in large storm event intensities are considered, the additional cost of adapting sites using GI approaches tended to be less than adapting conventional-only approaches. Overall, approaches to stormwater management that combined both conventional and GI elements tended to have the best combined cost resiliency.

1. INTRODUCTION AND OVERVIEW

The technical analysis described in this report was performed to quantify potential impacts of climate change on stormwater infrastructure performance. The foundation of the technical analysis is continuous simulation modeling of the hydrology, hydraulics, and water quality discharged from a series of conceptual study sites using a variety of conventional (or “gray”) and green infrastructure (GI) practices consistent with local stormwater and site design regulations. The report assesses the performance of green and gray stormwater controls under current and future climate and offers insights into how designs could be adapted in the future in response to a changing climate. The results and conclusions of the study are applicable to both new development, redevelopment, and stormwater retrofits.

The principal questions addressed by the study include:

1. How might extreme precipitation events affect the performance of conventional stormwater infrastructure and GI,
2. How can conventional designs and GI designs be adapted so that a site experiencing extreme precipitation conditions in the future provides the same performance as the site under current conditions, and
3. What do the results suggest regarding the adaptation potential of gray and green infrastructure for increases in extreme precipitation events?

This report describes the modeling approach and the results of the continuous simulation modeling.

Figure 1-1 summarizes the modeling framework. First, the Hydrologic Simulation Program• Fortran (HSPF; Bicknell et al., 2004) was used to simulate hourly unit-area time series of runoff and pollutant loads (total suspended solids [TSS], total nitrogen [TN], and total phosphorous [TP]) from pervious and impervious land surfaces for 30 years of input meteorology obtained from National Weather Service monitoring stations. Future climate scenarios were developed from the current time series using downscaled general circulation model (GCM) output, augmented by percentage change climate sensitivity analyses. The conceptual urban sites and associated stormwater management infrastructure were simulated by inputting the HSPF unit-area time series into the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN, U.S. EPA, 2009) decision support system and modeling tool. Hourly output was provided by the model for each individual best management practice (BMP) and at the site outlet. Note that only surface runoff and associated loads are considered in the analysis because the purpose of this analysis is to assess climate change impacts on stormwater. It is possible for site BMPs to increase groundwater outflow and associated pollutants, but the impact on the results would have been minimal compared to the magnitude of surface runoff and pollutants. For simplicity, high water table impacts are not considered in this analysis.

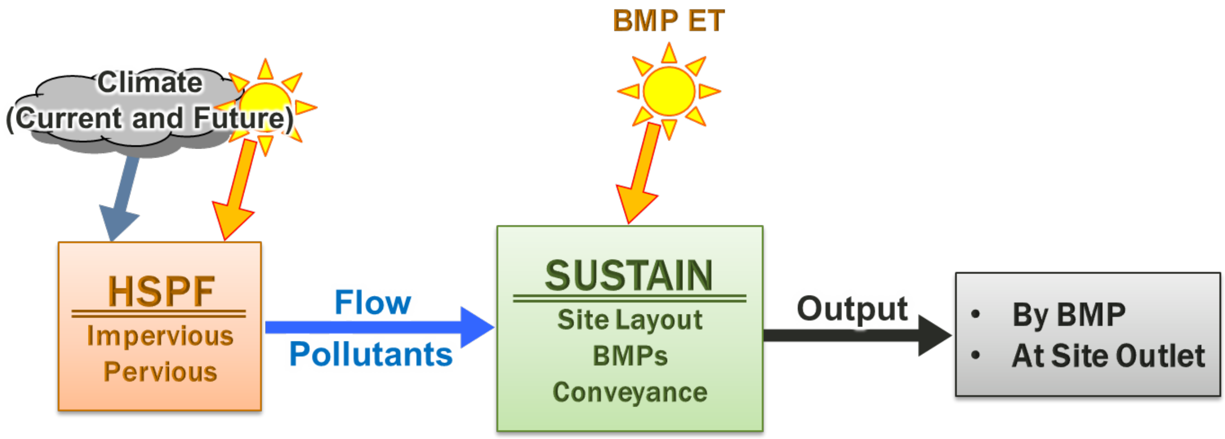

Figure 1-1. Modeling framework for study.

The stormwater management scenarios cover five types of developed land use in five specific geographic locations representing different hydroclimatic regimes throughout the United States. The developed land use types include residential, commercial, mixed-use, ultra-urban, and green street areas. Five regions were chosen because they leverage existing EPA climate change research. Each of these regions was modeled as part of an EPA project to simulate the impact of climate change on hydrology and water quality in 20 watersheds throughout the United States (U.S. EPA, 2013; Johnson et al., 2015). That study is referenced frequently in this report by the shorthand name of the "20 Watersheds" project. HSPF models developed for the "20 Watersheds" project were used as input for the SUSTAIN simulations. Each land use type was paired with a geographic location, and a variety of stormwater BMPs were represented, ranging from conventional gray infrastructure to GI designs. The stormwater management BMP configurations were consistent with local design standards and guidance. One, two, or three stormwater management approaches were used for each land use type to illustrate different ways to address site stormwater. Most of the land use types had one conventional stormwater management approach and one approach incorporating GI elements. In some cases, the GI approach also included gray infrastructure practices to address peak flow control requirements for large storm events (i.e., 10-year through 100-year design storms). In other cases, a GI approach with no gray infrastructure met local stormwater requirements. An example layout is shown in Figure 1-2.

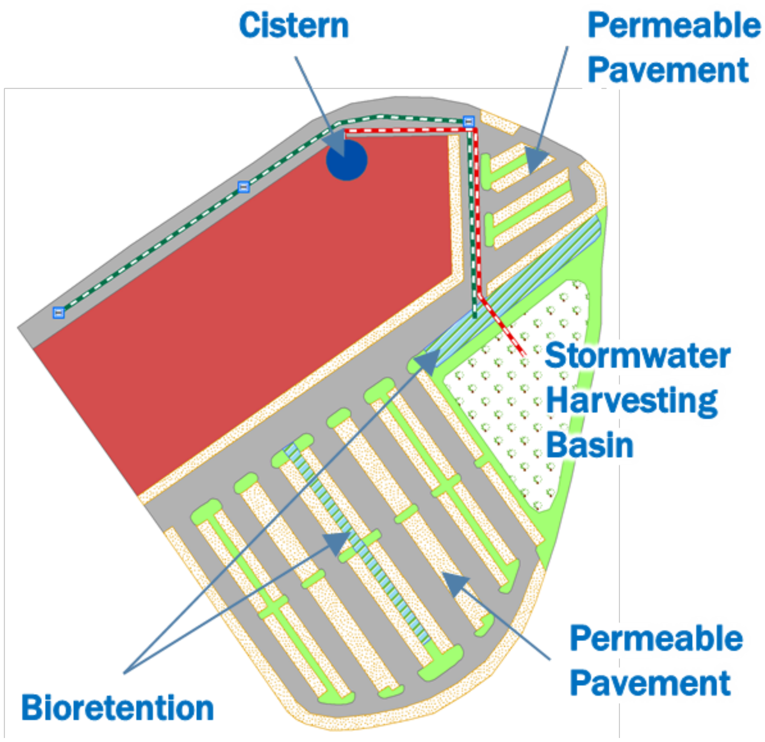

Figure 1-2. Example site layout with green infrastructure (GI) stormwater management approach.

Each stormwater management approach was modeled under current and a selected set of projected future climate conditions for the mid-21st century, and the water quantity and quality performance of the site practices were calculated from modeling results. In an additional model run, the site's practices were adapted under future climate conditions to achieve the same or better performance as under the current climate scenario using SUSTAIN's optimization function. Modifications targeted resizing the water quality treatment and peak flow control BMPs, which are the primary drivers controlling site performance (see Figure 1-3). When optimization is performed, SUSTAIN is configured to execute numerous runs (usually in the hundreds to over a thousand) making incremental changes in the BMP configuration to achieve specified targets (in this case, the targets were equal to the current hydrology and water quality performance of the site). The optimization scenario with the least cost was selected as the best solution because there were multiple "solutions" that achieved the goals of the simulation.

At two of the geographic locations, additional scenarios were developed that kept the current conventional BMP configuration intact but added distributed GI practices to provide treatment equivalent to the current conditions climate scenario (see Figure 1-4).

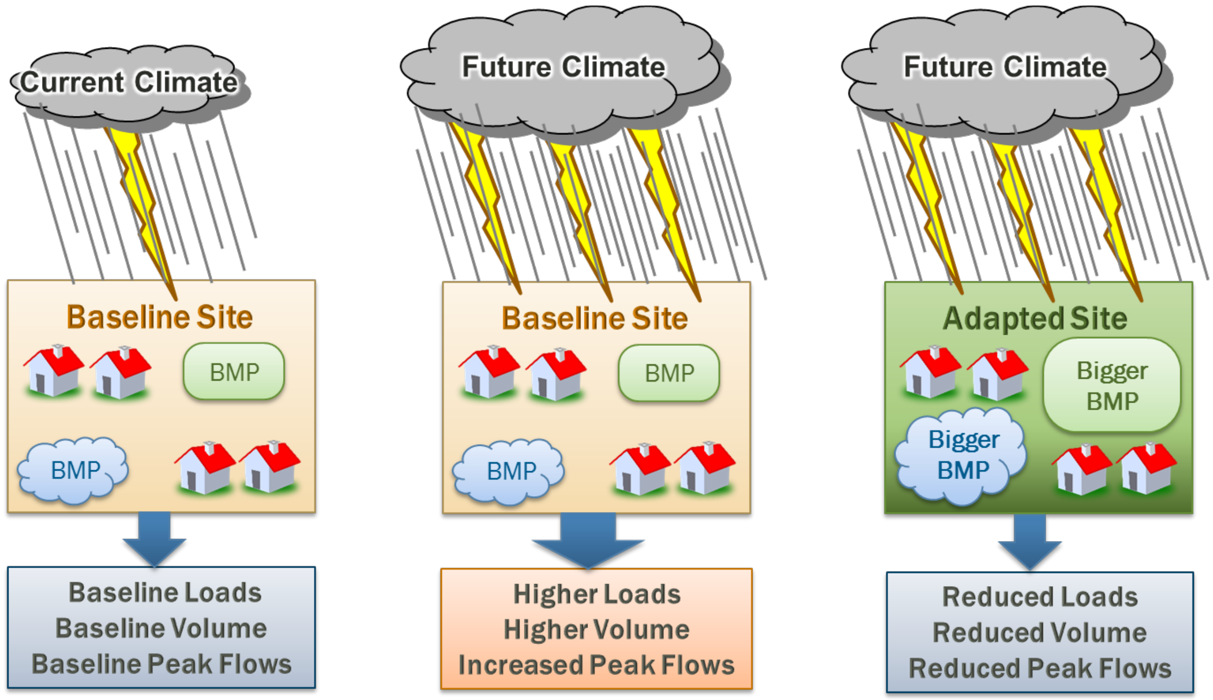

Figure 1-3. Climate scenarios, with adaptation using larger best management practices (BMPs).

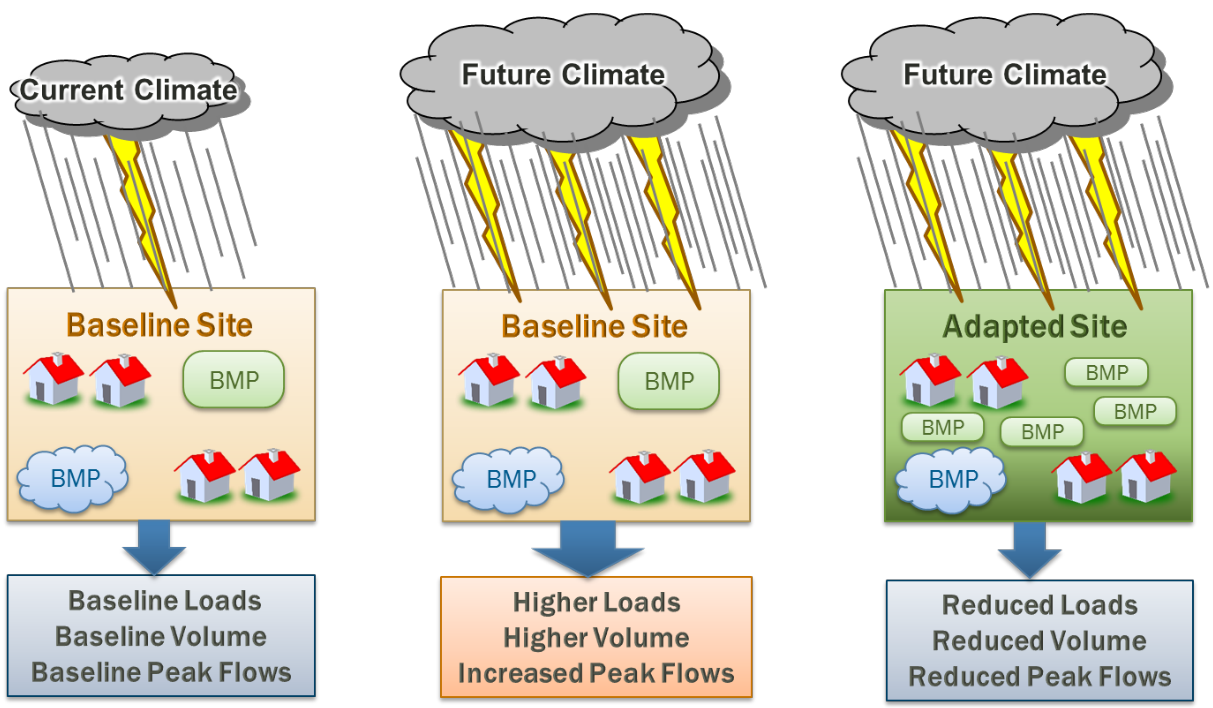

Figure 1-4. Climate scenarios, with adaptation using additional best management practices (BMPs).

A “base-case” future climate scenario was selected for each site location from a pool of ten potential downscaled GCM climate scenarios developed for the “20 Watersheds” project. The base-case was chosen as the scenario with the largest increase in the intensity of large storm events in order to estimate the potential impact of climate change at the upper end of the range of potential climate futures. In addition, two types of climate sensitivity analysis were conducted as part of the study. First, two additional downscaled GCM scenarios were selected from the “20 Watersheds” project for the Midwestern site• scenarios representing the lowest change and a medium change in large storm event intensity. Finally, a sensitivity analysis was conducted at the Midwestern site and the Mid-Atlantic site evaluating the effects of set percentage changes in all precipitation events• minus 10, plus 10, and plus 20% changes in hourly precipitation volume. *Table* 1-1 provides a summary of the components of the analysis.

Table 1-1. Matrix of regions, locations, land uses, management approaches, and future climate scenarios

Region	State	Land use	Management approach			Future climate scenarios
			Gray	Mixed	GI only	
Mid-Atlantic	Maryland	Mixed use	X	X		4
Midwest	Minnesota	Residential	X	X	X	6
Arid southwest	Arizona	Commercial	X		X	1
Southeast	Georgia	Ultra-urban	X	X		1
Pacific northwest	Oregon	Green street			X	1

This report is organized into eight sections beginning with the introduction, followed by details of the modeling approach, a separate section for each of the five sites, and finally results and discussion to address the principle study questions.

2. STUDY APPROACH

2.1. REGIONS AND LAND USES

The five geographic regions selected for simulation are listed in *Table* 2-1 and shown in Figure 2-1. These regions were chosen because they leverage existing EPA climate change research: each of these was modeled as part of the EPA “20 Watersheds” project, which examined the impact of climate change on water quality (represented using sediment, TN, and TP) in 20 large (4-digit hydrologic unit code [HUC] scale) watersheds located throughout the United States, and included several future climate scenarios representing a range of projected meteorological conditions. Output from this modeling is available down to an approximately 12-digit HUC scale and for individual unit-area upland land use/land cover types within each model subbasin. As a result, watershed response model simulations for future climate scenarios have already been produced for the forcing meteorological data for these regions, which represent a diversity of geographic settings and climate conditions. The “20 Watersheds” project included five watersheds that were modeled with HSPF using an hourly time step, which is needed for the continuous simulation SUSTAIN modeling; No other regions had HSPF models available to use in this study (the full set of 20 watersheds was modeled using the Soil and Water Assessment Tool [Neitsch et al., 2011], which runs on a daily time step and, therefore, did not meet our requirements). The corresponding HSPF model river basins are shown in Figure 2-1.

For each geographic location, a specific municipality or county was selected within or near the river basin. Following selection of a municipality/county, a specific land use type was chosen for each location. The decision regarding which municipality/county and land use type to select within each region was informed by several factors, including presence of an urbanized area, types of development taking place, and applicable stormwater requirements. For instance, Maricopa County, AZ has stormwater requirements and performs design review for the greater Phoenix area. The City of Minneapolis, MN is more or less built-out and limited new residential development is taking place within city limits, so Scott County on the southern outskirts of the Minneapolis metropolitan area was chosen because active residential development is taking place in some of the county’s communities. Municipality/county and land use types are shown in *Table* 2-1.

Table 2-1. Summary of geographic locations and land use types

Geographic region	River basin	Municipality/county	Land use type
Mid-Atlantic	Susquehanna River	Harford County, MD	Mixed use
Midwest	Minnesota River	Scott County, MN (near Minneapolis)	Ultra-urban
Arid southwest	Salt River	Maricopa County, AZ (surrounds Phoenix)	Commercial
Southeast	ACF rivers	Atlanta, GA	Residential
Pacific northwest	Willamette River	Portland, OR	Transportation corridor/green street

ACF = Apalachicola-Chattahoochee-Flint.

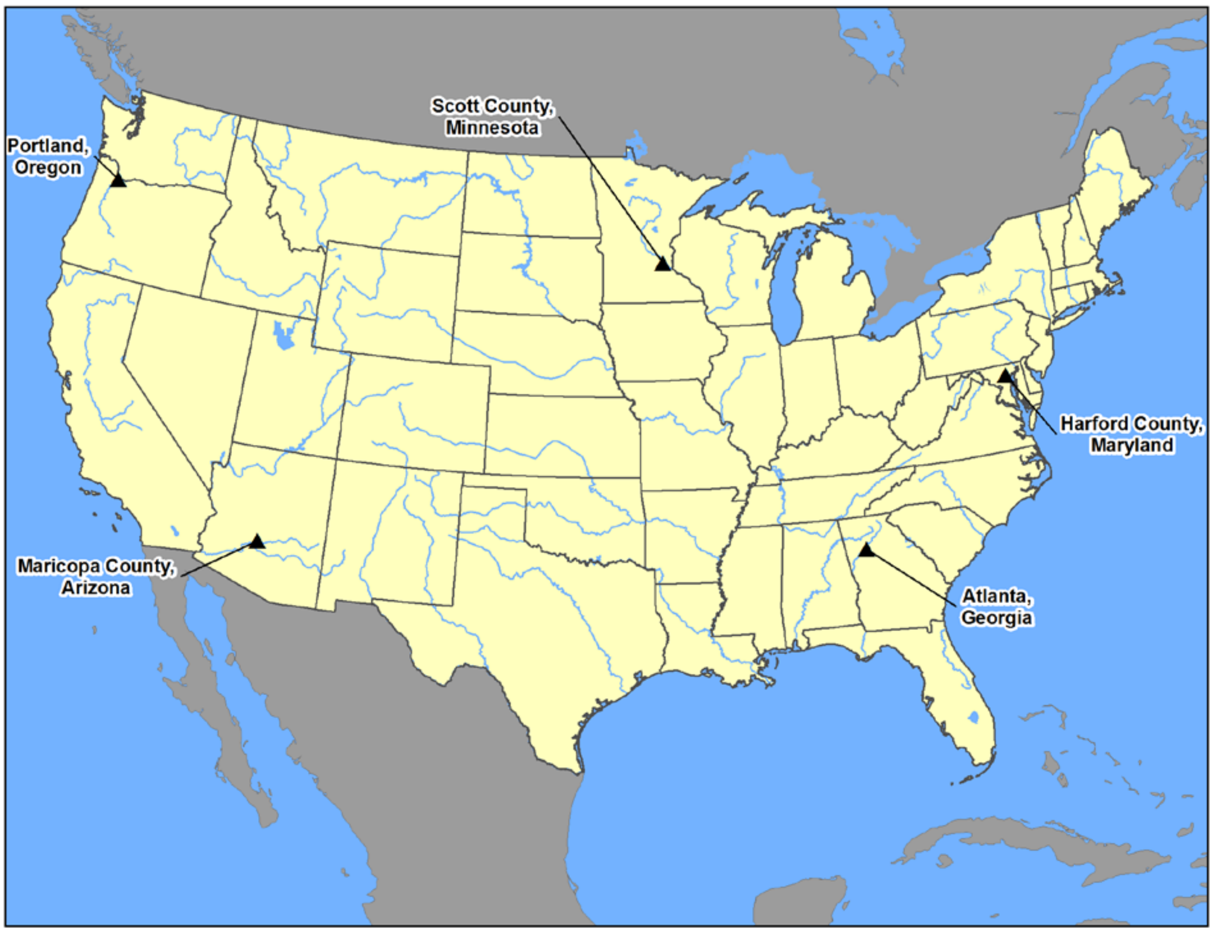

Figure 2-1. Locations of sites selected for analysis.

2.2. STORMWATER MANAGEMENT APPROACHES

The study sites and stormwater management approaches are outlined below in *Table* 2-2. The sites, approaches, and applicable regulations are summarized in detail in each of the five site sections in the report. To address impacts of increased stormwater volume, large storm event peak flow, and pollutant loading due to climate change, each stormwater management approach was modified by increasing the size (area, or footprint) of the structural stormwater BMPs to provide treatment equivalent to the current conditions climate scenario. For the Harford County, MD and Scott County, MN stormwater management approaches, the designs were modified using two different management strategies: increasing the size of the structural practices (as done for the other locations) and addressing the performance gap by incorporating additional distributed GI practices into the site. In the latter approach, the current conventional BMP configuration was unchanged, and distributed infiltration trenches (Harford County, MD) and bioretention (Scott County, MN) were added to provide treatment equivalent to the current conditions climate scenario.

Table 2-2. Stormwater management approach summary

Region	Location	Type	Characteristics	Stormwater management approach	Practices
Mid-Atlantic	Harford County, MD	Mixed use	20 acres 65% impervious	Conventional (Gray) Infrastructure	Surface sand filters, extended dry detention basin
				GI with Gray Infrastructure	Infiltration trenches, infiltration basins, permeable pavement, and dry detention basin
				Conventional (Gray) Infrastructure with Distributed GI	Surface sand filters, extended dry detention basin, distributed infiltration trenches
Midwest	Scott County, MN	Residential	30 acres 48% impervious	Conventional (Gray) Infrastructure	Wet pond
				GI with Gray Infrastructure	Distributed bioretention and dry detention basin
				GI Only	Distributed bioretention, permeable pavement, and impervious surface disconnection
				Conventional (Gray) Infrastructure with Distributed GI	Wet pond, distributed bioretention
Arid southwest	Maricopa County, AZ	Commercial	10 acres 80% impervious	Conventional (Gray) Infrastructure	Detention/infiltration basin
				GI Only	Permeable pavement, cistern, bioretention, and stormwater harvesting basin
Southeast	Atlanta, GA	Ultra-urban	2 acres 90% impervious	Conventional (Gray) Infrastructure	Underground sand filter, underground dry detention basin
				GI with Gray Infrastructure	Green roof, permeable pavement, bioretention, and underground dry detention basin
Pacific northwest	Portland, OR	Transportation corridor	0.35 acres 89% impervious	GI Only	Bioretention swales, permeable pavement

2.3. ADAPTATION SIMULATION

2.3.1. Analytical Design

The objectives of this study are to understand:

1. How might extreme precipitation events affect the performance of conventional stormwater infrastructure and GI,

2. How can conventional designs and GI designs be adapted so that a site experiencing extreme precipitation conditions in the future provides the same performance as the site under current conditions, and

   What do the results suggest regarding the adaptation potential of gray and green infrastructure for increases in extreme precipitation events?

To answer the first question, each stormwater management scenario was modeled under current climate conditions, and the performance of the site practices was calculated from the modeling results. Next, each management scenario was modeled under future climate conditions and the change in performance metrics tabulated. Performance metrics used for the analyses are shown in the next subsection.

For the second and third questions, the ultimate objective of the simulation is to answer the question: "*How would the current stormwater management practice(s) need to be adapted in order to maintain current performance under future climate conditions?*" For all sites, performance is evaluated at the site "outlet," defined as the point to which all areas, BMPs, and conveyances ultimately drain. Therefore, the objective is to evaluate a site's performance as a whole at meeting performance targets, rather than the performance of individual BMPs. For sites with multiple BMPs, the goal of the adaptation simulation is then to determine an optimal combination of BMP areas that result in the site as a whole meeting performance objectives, or "targets." In the final model run, the site's practices were modified under future climate conditions to achieve the same or better performance as the current climate scenario. Modifications targeted resizing the water quality treatment and peak flow control BMPs, which are the primary drivers controlling site performance. For the Midwest and Mid-Atlantic sites, additional runs were performed where distributed GI practices were added to the sites rather than increasing the size of the existing BMPs.

The primary tool for analyzing BMP performance is SUSTAIN, a decision support system and modeling tool developed by EPA to facilitate selection and placement of BMPs and low-impact development practices in urban watersheds (U.S. EPA, 2009). SUSTAIN was selected because it is able to do the following:

- Support continuous simulations.

- Use unit-area runoff and pollutant time series from the continuous simulation watershed models HSPF or Loading Simulation Program in C++ (LSPC) (Tetra Tech, 2009). When series are available from a calibrated watershed model, there is no need to parameterize soil properties to support a long-term simulation.

- Simulate the hydrologic and hydraulic conditions of both conventional and GI practices.
- Represent pollutant reduction mechanisms for both conventional and GI practices.
- Run optimizations (i.e., can be used to develop optimal design addressing future projected climate).

The EPA stormwater management model (SWMM 5) (Rossman, 2010) was also considered for simulating BMP performance in this project. It is similar to SUSTAIN (indeed, much of SUSTAIN is based on SWMM 5), and it can be driven by external runoff and pollutograph time series. SWMM has a fairly well-developed module for representing GI hydrology. SUSTAIN was chosen over SWMM because one cannot specify variable pollutant removal mechanisms for multiple outflow paths in SWMM. It is also not designed for running optimizations. HSPF is used to provide unit-area input time series to SUSTAIN, but was not selected for the BMP simulation because it does not include an optimization component to perform the adaptation scenarios.

To investigate the adaptation of stormwater practices under future climate conditions, the SUSTAIN model was executed in its “optimization” mode. When SUSTAIN performs an optimization, the site model is executed hundreds (or even thousands) of times with incremental variations in the sizes and/or configurations of the stormwater BMPs. Model results are automatically compared to performance targets set by the user, and the increase in cost associated with the change in practice dimensions is calculated using user cost inputs. SUSTAIN uses algorithms to guide the selection of subsequent incremental variations in practice configuration, using both performance relative to the targets and cost differential. After numerous model runs are complete, the user can select the best solution• one that achieves all of the performance targets at the lowest cost. During optimization, practices can be reconfigured using a number of options available in SUSTAIN. However, increasing practice size (as opposed to adding volume by changing the stage of an outlet) was used for all the optimizations because many of the BMP cost metrics used in the analysis are based on area alone. Note that practice costs in the optimization reflected Present Value Life Cycle Cost (as discussed in *Section 2.5.2.*); the opportunity cost of land area was not included.

2.3.2. Best Management Practice (BMP) Performance Measures

Site performance is summarized in terms of typical stormwater BMP performance metrics from the SUSTAIN model output and includes the following:

- *Annual outflow volume* to address stormwater volume treatment requirements,
- *Flow duration curve* (FDC) to address hydromodification associated with channel erosion risk and flooding risk, and
- *Pollutant mass export* (nitrogen, phosphorus, and sediment) to address water quality performance.

The measures work together to assess impacts to site hydrology and water quality. These performance measures are discussed in detail below.

2.3.2.1. Annual Average Runoff Volume

Stormwater BMPs can be designed to serve numerous functions, with one of the most critical functions being their ability to reduce the volume of stormwater leaving a site. The primary mechanisms of volume reduction by BMPs include infiltration, evapotranspiration (ET), and storage for reuse. Their relative importance varies across the numerous BMP types, land uses, site locations, and climate scenarios investigated.

All of the sites included in this investigation are subject to varying degrees of local regulations for stormwater volume retention. Annual runoff volume is also a better indicator for changes in long-term hydrology than a measure related to large storm events. To address the impacts of increased stormwater volume due to climate change, the annual average flow volume (ft^3/year) measure is included in the adaptation simulation procedure to ensure that a site's performance for stormwater volume reduction under current climate is maintained under future climate conditions. The objective is for the annual average flow volume leaving each site under current climate conditions to remain the same (or decrease) under future climate conditions.

2.3.2.2. Flow Duration Curve

The FDC is a cumulative frequency curve that shows the percentage of time discharges are equaled or exceeded during a given period (see *APPENDIX* A. for a detailed discussion of the FDC and its relevance for this project). For the purposes of this investigation, the flows resulting from the largest storm events during the 30-year simulation period were investigated. These are the storms associated with large infrequent flooding events (e.g., a 10-year frequency event), as well as more frequent events associated with the highest cumulative risk of downstream bank erosion (often called bankfull events, which typically occur every 1 to 2 years). Using the FDC allows a comparison of current versus future climate conditions across a *range* of flows that have the potential to physically alter the channel. For these reasons, matching the FDC was selected as a performance measure rather than the single largest peak discharge flow during the 30-year simulation. While the use of the largest peak discharge flow as a performance measure would help ensure that BMPs provide adequate control of the highest magnitude flows under future climate conditions, matching the FDC as a performance measure is designed to maintain BMP performance for multiple flooding events. Many of the locations represented in this study have peak flow and/or channel protection requirements for stormwater management, so the FDC analysis is used to address these.

The FDC performance factor is computed by SUSTAIN as the area between two flow duration curves representing two different hydrologic conditions, within specified lower and upper bounds. For this study, the two hydrologic conditions evaluated are (1) the FDC under current climate conditions and (2) the FDC under future climate conditions. The modeler defines upper and lower flow limits (thresholds) that bound the FDC comparison. Figure 2-2 illustrates an example of how the FDC performance factor is calculated as the area between the two curves between the lower and upper flow boundaries. In this example, the lower flow boundary is 13.5 cfs, where the 2-year hourly flow crosses the current conditions FDC.[1] The upper flow boundary is set to the highest flow from either FDC in the simulation.

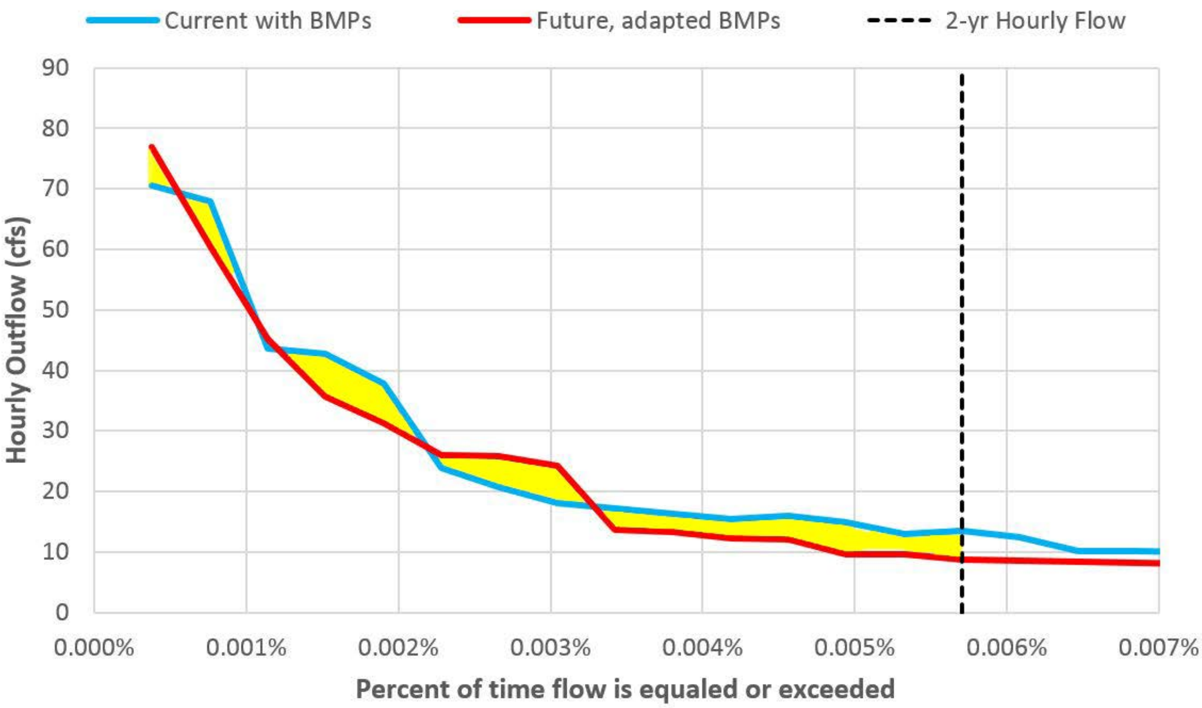

Figure 2-2. Flow duration curve (FDC) performance factor.

For this investigation, the high flow limit was defined as the highest flow encountered during the simulation among the climate scenarios, and the low flow limit was varied according to site location. For Portland, the hourly flow with a 1-year recurrence from the 30-year simulation was used for the low flow limit due to limited outflow below this frequency. For Atlanta, the hourly flow with a 0.5-year recurrence was used to capture a range of flows including bankfull events. For Harford County and Scott County, the hourly flow with a 2-year recurrence was used as the lower limit to allow the FDC optimization to better fit large events associated with local peak flow requirements, For Maricopa County, no outflow from the BMP is predicted under current climate conditions, so FDC optimization was not needed. The SUSTAIN optimization process tracks the area between the current and future climate curves bounded by the lower and upper flow limits, and attempts to minimize the area over the course of hundreds of model runs. The future climate FDC varies according to changed precipitation record and the size and configuration of all the site practices; surface conditions, practice volume, and runoff timing are contributing factors controlling the shape of the FDC. When the simulation is complete, the user selects the best FDC

[1]Flow recurrence is calculated as the reciprocal of the product of flow percentile (from hourly output over the course of the 30-year simulation) and the number of hours in a year. In the example shown, the 2-year flow recurrence occurs at flow percentile 5.7×10^{-3}. The ranked flow at this percentile is 13.5 cfs.

performance (lowest value) with the corresponding lowest cost as the adapted solution. It is important to note that the lower flow limits used in the analysis are not the same as design storm event peak flows. The values are derived from the hourly outflows from the 30-year simulation, and represent recurrence frequencies (i.e., the 2-year hourly recurrence flow is the 15th highest hourly flow during the 30-year simulation).

2.3.2.3. Annual Average Pollutant Load

Another principal design function of stormwater BMPs is pollutant load reduction. Across the United States, local stormwater and water quality regulations mandate specific pollutant reduction goals (typically driven by total maximum daily loads and/or local water quality management plans). BMPs may be used to help address these requirements. The primary pollutant removal mechanisms of stormwater BMPs vary widely by practice type, and include filtration, infiltration, and settling. For some BMP types, biological uptake and soil adsorption may also be significant pollutant removal pathways.

Under future climate conditions, changes in the depth, intensity, and duration of rainfall are expected to have a significant impact on the delivery of pollutant loads, affecting both the timing and magnitude. In most of the climate scenarios used in this project, pollutant loads increase under future climate conditions (although this is not always the case). To address the impacts of increased pollutant loading due to climate change, the annual average pollutant load (pound/year) measure is included in the adaptation simulation procedure to ensure that BMP performance for pollutant load reduction under the current climate is maintained under future climate conditions. The objective is for the loading of nitrogen, phosphorus, and sediment (referred to as total suspended solids, or TSS) under current climate conditions to remain the same, or decrease, under future climate conditions. The HSPF models developed for the “20 Watersheds” project included these three pollutants, so the water quality simulation in SUSTAIN was limited to these constituents.

2.4. HIGH PRECIPITATION SCENARIO

Three groups of future climate scenarios were chosen for this study:

1. Downscaled GCMs with high intensity change for largest storm events, used for all sites, stormwater management approaches, and adaptation approaches.

2. Downscaled GCMs with low, medium, and high intensity changes for largest storm events for first climate sensitivity analysis. Applied to Midwest site only.

3. Precipitation volume percentage change scenarios for second climate sensitivity analysis. Applied to Mid-Atlantic and Midwest sites.

2.4.1. High Intensity Change Scenarios

This analysis drew from a pool of 10 future climate change scenarios from the EPA “20 Watersheds” study. Six future climate scenarios are from the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP scenarios were developed by driving a number of different regional climate models (RCMs) at a resolution of 50 × 50 km with results from four GCMs from Phase 3 of the

Coupled Model Intercomparison Project (CMIP3), (Mearns et al., 2009, 2013).[1] All scenarios assume the Special Report on Emissions Scenarios (SRES) A2 greenhouse gas emissions trajectory (Nakicenovic et al., 2000). Differences among SRES emissions scenarios, however, are not substantial for the mid-century time period considered here. The NARCCAP scenarios were selected because they provide higher spatial and temporal resolution climate change information for the entire contiguous United States and, unlike the archived data from the parent GCMs, provide the full suite of meteorological variables needed to implement HSPF simulations that use an energy balance approach to estimate evapotranspiration. In addition, four scenarios were developed based on statistically downscaled output from the same set of GCMs used by NARCCAP from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive at http://gdo-dcp.ucllnl,org/downscaled_cmip_projections commonly referred to as bias-correction spatial disaggregation (BCSD) data but more formally developed using BCSD and bias-correction constructed analogs temporal disaggregation (Maurer et al., 2007).[2] This data set provides temperature and precipitation on a 1/8-degree (approximately 14 × 10 km at 45°N) horizontal grid and at a daily time step.

All climate change scenarios were implemented using a change-factor approach (Anandhi et al., 2011) to modify 30 years of observed local hourly weather data to ensure realistic patterns in time series. Projected monthly change statistics (change factors) at each weather station were calculated for total precipitation (%), precipitation above/below the 70th percentile (%), air temperature (°C), relative humidity (°C), surface downwelling shortwave radiation (%), and wind speed (%). Projected changes in the proportion of precipitation volume occurring in larger events (i.e., event intensity) were represented by applying different change factors to events above and below the 70th percentile event (based on daily depth). For further details, see EPA (2013) and Johnson et al. (2015).

The climate scenario representing the *largest increase in precipitation intensity* among the 10 scenarios was selected for modeling climate change impacts to stormwater infrastructure (see *Table* 2-3). The scenario with the largest intensity increase was selected to allow the study to characterize an upper bound for climate change impacts. Intensity was assessed at the National Climatic Data Center (NCDC) meteorological monitoring station closest to the municipality/county. An important aspect of future climate is the potential for increases in high intensity precipitation. This is expected for physical reasons because increased air temperature increases the capacity of the air to hold moisture and potential energy. For each of the 10 climate scenarios, we calculated both the change in monthly precipitation depth and the fraction of precipitation contained within events greater than the 70th percentile daily event by comparing runs of the same GCM for future and historic 30-year time periods. Future climate time series are created from observed historic time series by applying a multiplicative change factor approach to adjust total volume and redistributing the fraction of this volume to events above and below the 70th percentile event.

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[1]Seth McGinnis of the National Center for Atmospheric Research (NCAR) processed the North American Regional Climate Change Assessment Program (NARCCAP) output into change statistics for use in the watershed modeling. NCAR is supported by the National Science Foundation.
[2]We acknowledge the modeling groups and the Program for Climate Model Diagnosis and Intercomparison and the WCRP's Working Group on Coupled Modeling for their roles in making available the WCRP Coupled Model Intercomparison Project Phase 3 multimodel data set. Support of this data set is provided by the Office of Science, U.S. Department of Energy.

The scenario with the month with the highest predicted volume of events above the 70th percentile was chosen as approximating the highest storm event volume among the available scenarios. Because the same monthly multiplicative factors were used throughout a given scenario, it follows that the scenario will contain the series of highest storm event volumes, and thus, serve as a proxy for the scenario with the greatest change in large storm event intensity. Note that this selection is constrained by the available climate scenarios and other scenarios not contained in the “20 Watersheds” data set are likely to show an even greater range of storm volumes and intensities at these sites.

Table 2-3. Climate scenarios for each geographic location

Geographic region	River basin	NCDC station[a]	Climate scenario
Mid-Atlantic	Susquehanna River	PA 366289 (New Park)	BCSD HADCM3
Midwest	Minnesota River	MN 215435 (Minneapolis/St. Paul Airport)	Low: NARCCAP GFDL High Res GFDL Medium: NARCCAP RCM3 GFDL High: BCSD CCSM
Arid southwest	Salt River	AZ 026840 (Punkin Center)	BCSD GFDL
Southeast	ACF Rivers	GA 096407 (Atlanta Hartsfield Intl. Airport)	NARCCAP RCM3 GFDL
Pacific northwest	Willamette River	OR 356749 (Portland KGW TV)	BCSD GFDL

CCSM = Community Climate System Model, GFDL = Geophysical Fluid Dynamics Laboratory, HADCM3 = Hadley Centre Coupled Model, Version 3.

[a]State and cooperative summary of the day identification number.

In terms of the analysis, future climate inputs have been prepared that are representative of local meteorology by virtue of using local NCDC stations. In addition, the redistribution of precipitation changes between smaller (<70th percentile) versus larger (>70th percentile) events helps account for not only changes in volume but also changes in intensity. (Potential changes in frequency or duration of events independent of volume were not investigated.) The approach is appropriate for the goal of providing examples of potential impacts of projected climate change on the performance of stormwater BMPs in urban watersheds distributed across the United States; however, the specific results for each geographic location are in part dependent on the characteristics of the individual meteorological station.

In this project, SUSTAIN used external time series to represent surface runoff and pollutant loads from land surfaces. These external runoff and pollutant time series were derived from output from the HSPF watershed model. The HSPF models were modified to generate unit-area time series on an hourly basis using meteorological inputs corresponding to the station shown in *Table* 2-3. Separate unit-area time series were produced for developed pervious and impervious land, representing a continuous simulation of approximately 30 years of input meteorology derived from weather monitoring stations. The representation of sediment-associated loading of TP from pervious land in the Susquehanna River HSPF model was corrected from the representation in the previous model version.

The meteorological inputs to HSPF include precipitation, air temperature, and potential evapotranspiration (PET). All of the meteorological inputs were modified for the future climate scenarios, including calculation of PET using the Penman-Monteith energy balance method. Therefore, the impact of changing temperature and PET were included in HSPF's generation of runoff and pollutant concentrations, which are the inputs to SUSTAIN as stated above.

It is important to note that only surface runoff modeled by HSPF is used as an input to SUSTAIN. Infiltration and ET from site land surfaces are modeled by HSPF, but are not tracked in this project. Nevertheless, SUSTAIN simulates infiltration into the underlying soil via BMPs, and also calculates ET loss directly from BMPs. Daily minimum and maximum air temperature time series from HSPF were used as inputs to SUSTAIN, which then calculated evaporation and transpiration losses from BMPs using the Hamon method (Hamon,1961).

2.4.2. Low, Medium, and High Intensity Change Scenarios Used for Sensitivity Analysis

The Midwest location uses the *range* of intensity changes to explore the extent of projected impacts (smallest, average, and largest). The previous section describes how the climate scenario with the highest change in large storm event intensity was selected from the pool of 10 future climate scenarios. The same approach was taken here, but in this case, scenarios were selected from the pool of 10 to represent the lowest, medium, and highest changes in intensity. The highest intensity change scenario was the same as previously selected, as discussed in the preceding section.

2.4.3. Percentage Difference Scenarios Used for Sensitivity Analysis

The climate scenarios discussed up to this point were derived from a variety of GCM outputs and spatial downscaling approaches. The future projected precipitation patterns show a great deal of variability with respect to degree of intensity change by rainfall depth, monthly volume increases and decreases, and interannual volume changes. While GCM/downscaling approaches provide detailed representations of possible future conditions, a simpler structured approach assessing system sensitivity to percentage change in different climatic drivers is also informative. When a series of percentage changes is explored (e.g., +5, +10, +15%), the resulting responses are more comparable because sources of variation in the future precipitation are minimized. Other meteorological parameters may also be modified in a similar manner. Air temperature is often modified using a fixed delta (e.g., +3°F) applied to each observation.

For Harford County, MD and Scott County, MN, graduated precipitation and temperature changes were applied to the historic records for each site. The graduated climate scenarios were applied to all of the stormwater management scenarios for both locations. The current precipitation record was modified to represent potential future climate conditions by applying a graduated set of percentage changes to the entire precipitation record (across the entire range of hourly precipitation values from a trace to the largest rainfall value, in other words); therefore, the number of events and event durations remained unchanged. The percentage change factors were −10 (a decrease in intensity), +10, and +20%(both increases in intensity). Air temperature was adjusted as well using the Clausius-Clapeyron relationship (Clausius, 1850; Clapeyron, 1834), such that a 10% change in precipitation intensity was paired with a 2.6°F change in air temperature. PET was then recalculated from the modified air temperature and precipitation time series using the same method employed for the "20 Watersheds" project. The unit-area runoff HSPF models were executed with the new meteorological inputs, and the resulting surface runoff time series used for the climate sensitivity analysis.

2.5. SITE ASSUMPTIONS

There were two elements of design assumptions that were developed generically for all of the locations/practice scenarios: those related to piped stormwater conveyance and those related to stormwater infrastructure cost. Site-specific assumptions are detailed in the individual site *Sections 3.* through *7.* .

2.5.1. Stormwater Conveyance Representation

A simplified pipe-sizing methodology was used to estimate appropriate conveyance capacity for each site's design storm runoff. For the smaller sites (Atlanta, GA and Maricopa County, AZ), peak flow rates and pipe sizes were calculated for each delineated subwatershed area. For the larger sites (Scott County, MN and Harford County, MD), a generic sizing table was developed that matched drainage area threshold size with adequate pipe diameter. The Portland, OR site was less than one acre and did not include any piped conveyance. For all sites, the conveyance infrastructure was designed according to the 10-year, 24-hour storm event (typical for municipal storm sewers), unless noted otherwise.

The two primary methods for estimating peak flow and culvert sizes are described below. The different approaches used between the smaller sites and larger sites are also explained in further detail.

2.5.1.1. Peak Flow Estimation

For smaller watersheds, the Rational method is appropriate for estimating peak discharges for specified design storms. Although it is considered a crude but efficient method, its level of precision is justified by the need to select among standard pipe sizes available. The Rational equation is defined as follows:

$$Q = CIA \qquad (2\text{-}1)$$

In which

Q = peak discharge (cfs)

C = composite runoff coefficient for the watershed (dimensionless)

I = average rainfall intensity (inch/hour) for storm frequency, duration (equal to time of concentration), and geographic area

A = watershed area (acre)

Although runoff coefficients (C) are provided for a large range of land use/cover types and hydrologic soil group (HSG) conditions, composite C values can also be calculated from a site's total impervious percentage using the following equation:

$$C = 0.9(\%\ impervious) + Cp(1 - \%\ impervious) \tag{2-2}$$

Where Cp represents the pervious coefficient runoff value, which is defined according to the watershed HSG (see *Table* 2-4).

Table 2-4. Maryland Stormwater Manual pervious runoff coefficients

HSG	*Cp*
A	0.20
B	0.25
C	0.30
D	0.35

Rainfall intensities were calculated using statistical rainfall depth-duration tables from the National Oceanic and Atmospheric Administration's (NOAA's) Precipitation Frequency Data Server (PFDS). For the 10-year frequency storm, rainfall depths were selected for a storm duration equal to the time of concentration for each drainage area. Rainfall intensity was then calculated by dividing the 10-year precipitation depth (inch) by the time of concentration (hour).

The timing variable, also referred to as the time of concentration variable (Tc) was assumed to equal 5 minutes for all of the drainage areas in the Atlanta and Maricopa County scenarios. Although actual Tc values are likely less the 5 minutes, the Rational method uses a minimum Tc value of 5 minutes to estimate peak discharge. For the larger site scenarios (i.e., MD and MN), time of concentration values were calculated using the Kirpich equation, formulated as:

$$Tc = \left[\frac{K}{128}\right]\left[\frac{L^3}{H}\right]^{0.385}$$

(2-3)

In which

Tc = time of concentration (minute)

L = hydraulic length of watershed (feet)

H = height (feet) of highest elevation point in watershed above the outlet (elevation difference)

K = multiplier (dimensionless) associated with the nature of flow path (1.0 for flow in mixed urban settings)

2.5.1.2. Culvert Sizing

In lieu of Federal Highway Administration culvert capacity charts, an analytical model was used to determine culvert sizes for the various stormwater management scenarios. For circular pipes operating under inlet-control conditions, the orifice equation can be expressed as follows:

$$Q = 0.0437 C_{\mathrm{d}} D^2 \sqrt{Z - \frac{D}{24}} \tag{2-4}$$

In which

Q = discharge (cfs)

D = pipe diameter (inch)

Z = depth of water above the centerline of pipe entrance (feet)

C_d = coefficient of discharge (dimensionless)

Headwater/pipe diameter ratio (Hw/D) is the headwater depth (height above pipe centerline) divided by the pipe diameter. For all scenarios, the Hw/D ratio was set to 2, assuming that new developments will be able to minimize culvert depths for most upland drainage areas. C_d was assumed to equal the default value, 0.6. Hydraulic Condition was assumed to be under inlet control. For new developments, the downstream discharge location (e.g., open ephemeral channel or floodplain) will likely yield greater conveyance capacity than the 10-year peak flow rate.

For each drainage area in the Atlanta and Maricopa County scenarios, the 10-year peak discharge was calculated using the Rational method and aforementioned input assumptions. Culvert sizes were then selected using an iterative approach. Using the orifice equation to determine pipe discharge, the pipe diameter was varied by the standard available pipe sizes to find the minimum pipe size that can convey the 10-year peak flow.

For the Scott County and Harford County scenarios, the site areas were too large and complex to calculate culvert sizes for each subwatershed area. Instead, a threshold table was developed to automatically assign a culvert size based on total drainage area. To develop the threshold table, the Rational equation was ultimately rearranged to calculate a drainage area size for each culvert size and associated peak discharge capacity. Because the *Tc* and average rainfall intensity (based on the *Tc* value) changes with watershed size, a separate table was first created that matched time of concentration, rainfall intensity, and drainage area size. The resolution of this “Rational input table” were based on 1-minute *Tc* intervals between the minimum assumed *Tc* (i.e., 5 minutes) and the maximum calculated *Tc* for the largest drainage area in the scenario site. Precipitation values were interpolated from NOAA PFDS tables between reported values (e.g., 5, 10, 15-minute duration intervals). Finally, drainage area thresholds were assumed for each pipe diameter by iteratively back-calculating the drainage area from the Rational equation, using each pipe's peak discharge (orifice equation) and the associated rainfall intensity (extracted from the "Rational input table").

2.5.2. Infrastructure Cost Estimates

Cost estimates were developed for adapting gray and GI practices using a cost/tradeoff analysis. Life cycle costs were estimated for a 20-year project operation period, assuming that design-build (capital) costs will occur in the year before the first year of operation and BMP operation and maintenance (O&M) will occur annually for 20 years. While individual BMPs and BMP types vary in life span, the 20-year period allows for ease of comparison across the scenarios and reflects a typical planning period for stormwater management.

BMP life-cycle costs were estimated using literature sources and best professional judgment based on Tetra Tech project experience. The primary sources were King and Hagan (2011) and the Green Values Calculator (CNT, 2014). The King and Hagan (2011) model, produced by the University of Maryland Center for Environmental Science, incorporates BMP cost information into Maryland's Assessment and Scenario Tool. Their study is a summary of previous regional studies, which were verified or modified based on interviews with stormwater experts. The Green Values Calculator was developed by the Center for Neighborhood Technology (CNT), a nonprofit organization with a national scope, in collaboration with the EPA Office of Wetlands, Oceans, and Watersheds•   assessment and Watershed Protection Division. Similar to King and Hagan (2011), the purpose of the tool is to evaluate performance, costs, and benefits of GI practices when compared to conventional treatment. Costs were compiled on a national scale from literature reviews along with information from municipalities, public utilities, and research institutions. The King and Hagan (2011) model provides cost data on capital as well as operation and maintenance expenditures on a cost per impervious drainage area basis. The Green Values Calculator provides cost data based on a whole BMP measure (e.g., cost per square foot of permeable pavement). Both sources provide sufficient data for approximate life-cycle cost estimates, including capital and O&M costs.

These sources covered most of the BMPs implemented but were supplemented with other cost data. RS Means (2016), a construction industry cost database, was used to adjust BMP costs and estimate the cost of additional infrastructure (e.g., culverts). The cost estimates were developed to reflect national averages. Insufficient data were available to estimate local or regional differences in costs.

Some adjustments to the cost data methods were necessary in a few cases. For instance, changes to BMP storage volumes, not drainage areas, are likely to occur between the current and future scenarios. For BMP costs based on impervious surface drainage area, a unit cost by BMP volume (e.g., cost per cubic foot) was calculated by dividing the current scenario BMP cost by the current scenario BMP volume. That unit cost by volume was then applied to the future scenario volume to estimate the BMP cost for the future scenarios. BMP volume was assumed to be treatment volume, not total excavation volume.

Table 2-5 presents the unit costs assumed for the infrastructure costs estimates, indicating the data sources by type infrastructure. Note that costs are a function of BMP size, not BMP treatment area. Capital costs reflect both preconstruction (planning, design, and engineering) and construction costs. To estimate the present value (PV) of annual costs over a BMP's lifetime, the annual O&M costs were discounted at a rate of 3%. The PV life-cycle costs reflect the sum of the capital and 20-year PV O&M costs.

Stormwater infrastructure costs vary widely and are often site-specific. These unit cost estimates reflect the best available information and professional judgment on average costs for a comparative analysis at a national-scale. These costs are not appropriate for use in site-level budget estimates.

Table 2-5. Unit cost estimates for modeled practices

Practice	Unit[a]	Capital cost ($)	Annual O&M ($)	20-Year present value O&M ($)	Present value life-cycle cost ($)	Reference(s)
Compost amended soils	SF	4	0.40	7	11	RS Means (2016)
Impervious surface disconnection	SF roof area	0.10	0.0002	3	3	CNT (2014)
Stormwater harvesting basin	SF	21	2.00	30	51	RS Means (2016)
Bioretention	SF	25	2.00	30	55	RS Means (2016); King and Hagan (2011)
Bioretention with underdrain	SF	60	2.00	30	90	King and Hagan (2011); MPCA (2016)
Bioretention swales• infiltration trench hybrid	SF	126	2.00	30	156	RS Means (2016); King and Hagan (2011)
Green roof	SF	19	1.00	8	27	CNT (2014)
Permeable pavement	SF	5	0.20	3	8	CNT (2014); King and Hagan (2011)
Permeable pavement with underdrain	SF	36	0.20	3	39	CNT (2014); King and Hagan (2011); MPCA (2016)
Dry detention basin	CF	8	0.20	3	11	King and Hagan (2011)
Extended dry detention basin	CF	8	0.20	3	11	King and Hagan (2011)
Underground dry detention basin	CF	19	0.20	1	20	CNT (2014)
Wet pond	CF	8	0.20	3	11	King and Hagan (2011)
Infiltration basin	CF	22	0.20	4	26	King and Hagan (2011)
Infiltration trench	CF	22	0.20	4	26	King and Hagan (2011)
Cistern	CF	13	1.00	14	27	CNT (2014), Impact Infrastructure and Stantec (2014), and LIDC (2005)
Sand filter	CF	41	0.90	13	54	King and Hagan (2011)
Underground sand filter	CF	47	1.00	15	62	King and Hagan (2011)

Table 2 5. Unit cost estimates for modeled practices (Continued)

Practice	Unit*	Capital cost ($)	Annual O&M ($)	20-Year present value O&M ($)	Present value life cycle cost ($)	Reference(s)
Concrete drain pipe, 12" diameter	LF	52	0.50	7	59	RS Means (2016)
Concrete drain pipe, 15" diameter	LF	58	0.50	7	65	RS Means (2016)
Concrete drain pipe, 18" diameter	LF	70	0.50	7	77	RS Means (2016)
Concrete drain pipe, 21" diameter	LF	80	0.50	7	88	RS Means (2016)
Concrete drain pipe, 24" diameter	LF	96	0.50	7	103	RS Means (2016)
Concrete drain pipe, 27" diameter	LF	127	0.50	7	134	RS Means (2016)
Concrete drain pipe, 30" diameter	LF	139	0.50	7	146	RS Means (2016)
Concrete drain pipe, 33" diameter	LF	158	0.50	7	166	RS Means (2016)
Concrete drain pipe, 36" diameter	LF	178	0.50	7	185	RS Means (2016)
Concrete drain pipe, 42" diameter	LF	232	0.50	7	239	RS Means (2016)
Concrete drain pipe, 48" diameter	LF	269	0.50	7	276	RS Means (2016)
Concrete drain pipe, 54" diameter	LF	329	0.50	7	336	RS Means (2016)

SF = square feet, CF = cubic feet, LF = linear feet.
[a]Units reflect BMP size, not BMP treatment area.

3. MID-ATLANTIC SITE: MIXED USE

3.1. REGULATORY REQUIREMENTS AFFECTING STORMWATER MANAGEMENT

Harford County defers its stormwater requirements to the State of Maryland, which are published in the Maryland Stormwater Manual (Center for Watershed Protection and Maryland Department of Environment, 2000). The Maryland Stormwater Manual uses a tiered approach for managing stormwater at different scales and for different purposes. Requirements are discussed below.

- Rev: The recharge volume addresses impacts to groundwater resulting from development. The volume must be completely infiltrated on the site. Rev is equal to the product of an area-weighted value based on HSG, a coefficient based on percentage impervious area, and site area. A volume-based criterion using a volumetric runoff coefficient is used for structural BMPs and an area-based criterion is used for nonstructural practices. A variety of structural and nonstructural practices can be used to meet the Rev requirement.

- WQv: In the region of Harford County, the water quality volume is equal to 1 inch times the site area times a coefficient based on percentage impervious area. The detention time for treatment is 24 hours. Treatment must achieve 80% TSS removal and 40% TP removal. Rev can be subtracted from the WQv.

- Cpv: The channel protection criterion requires 24-hour extended detention of the postdevelopment 1-year 24-hour storm.

- Qp: The overbank flood protection criterion requires peak matching to predeveloped conditions for the 10-year 24-hour storm event. The Manual notes it is optional and depends on the review authority. Harford County requires it.

- Credits are given for various forms of impervious surface disconnection. There are specific minimum flow path length requirements for the credits.

3.2. STORMWATER MANAGEMENT SCENARIOS

The 20-acre mixed-use site (see Figure 3-1) is assumed to have the following characteristics in each of the scenarios:

- The site is 65% impervious, distributed as follows:
    - 41% road, parking, and sidewalk area.
    - 24% building area.
- The remaining pervious area (35%) is comprised of lawn/landscaping.
- The HSG percent distribution is based on a regional geographic information system (GIS) analysis (the portion of Harford County within the Susquehanna River Basin). The HSG composition is used for design storm event routing calculations to size practices for peak flow

control. Predevelopment land cover is assumed to be woods in good condition. It is likely that a small site would have at most two HSG types of course, but the HSG distribution was used to be representative of average conditions in the region.

- HSG A: 1%
- HSG B: 71%
- HSG C: 20%
- HSG D: 8%

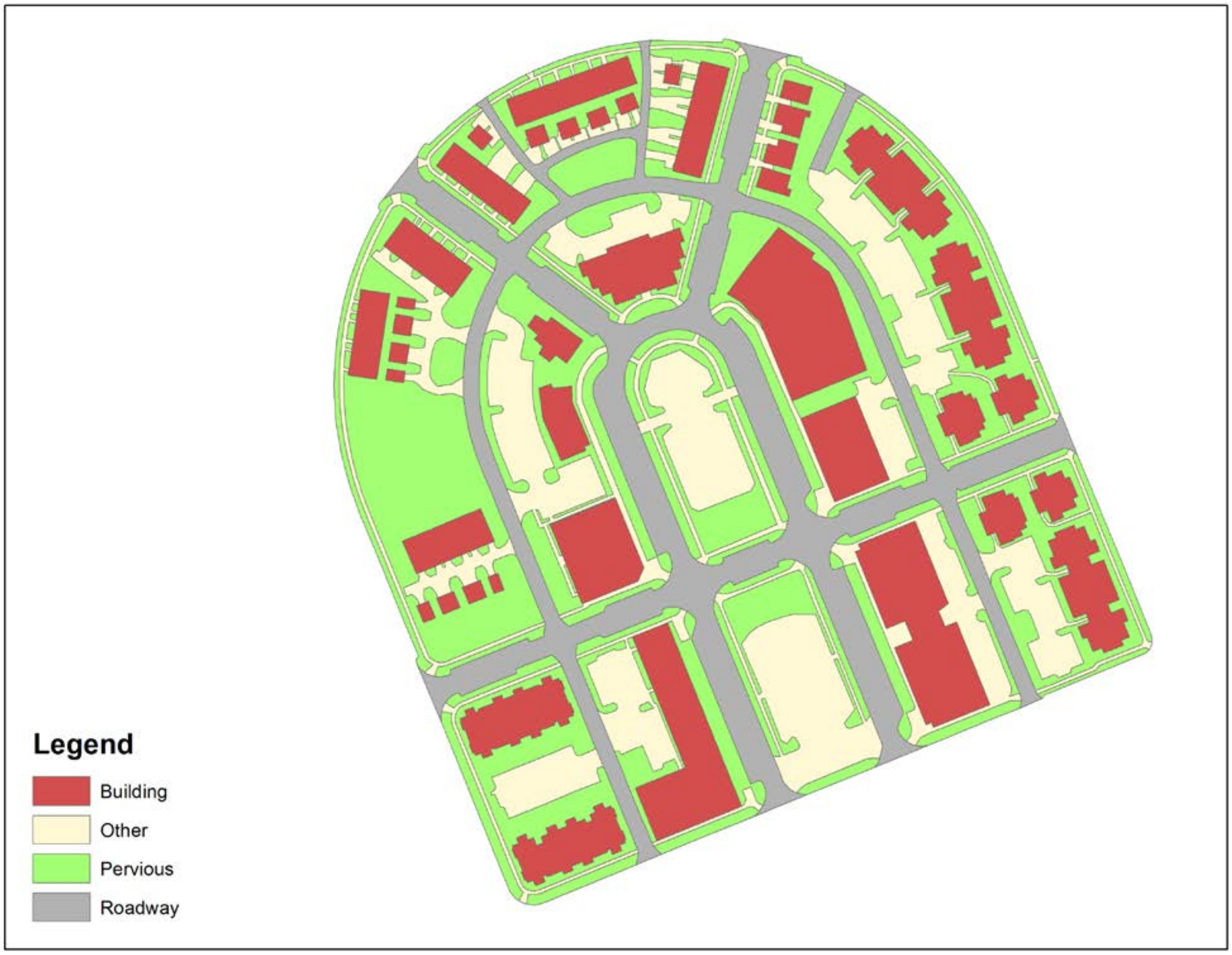

Figure 3-1. Mixed-use site layout (Harford County, MD).

Two scenarios have been developed representing different approaches to stormwater management: a conventional scenario using gray practices and a GI scenario using a combination of green and gray practices. As noted in *Section 5.* , the conventional scenario was used as the basis for a fourth scenario in which distributed GI practices were added to achieve current performance under future climate conditions. The site's percentage impervious area is sufficiently high that it is not feasible to use only GI practices to meet the regulatory requirements. The scenarios are described in the following subsections.

3.2.1. Conventional (Gray) Infrastructure

The key design elements in the Conventional (Gray) Infrastructure scenario are as follows:

- Surface sand filters address the Rev and WQv requirements. A portion of the volume is infiltrated into the soil, meeting the Rev. The remainder of the volume is treated by the sand filter and discharged via underdrain, meeting the WQv requirement.
- An extended dry detention basin treats the entire site to address the CPv and Qp requirements.
    - 24-hour drawdown of CPv is provided via a low flow orifice.
    - Peak matching for 10-year 24-hour storms (Qp requirement) is addressed using a weir.

As seen in Figure 3-2 for the Conventional scenario, runoff reaches surface sand filters distributed throughout the site via overland flow. Underdrain flow and larger storm event overflow from the sand filters is then conveyed to the extended dry detention basin, which then discharges flow offsite. To simplify the representation in SUSTAIN, the site sand filters were lumped into six representative sand filters, one for each drainage area.

Figure 3-2. Mixed-use Conventional (Gray) Infrastructure stormwater management scenario (Harford County, MD).

For the SUSTAIN simulation, the surface sand filters were sized according to design standards published in the Maryland Stormwater Manual, taking into account the contributing drainage areas and percentage impervious area. The design specifications for "perimeter sand filter" (a type of surface sand filter) were used to represent the configuration. An underlying soil infiltration rate of 0.52 inches/hour was assumed for the site, reflecting the minimum infiltration rate needed to use infiltrating practices (an analysis of soils data for the northern portion of Harford County in the Susquehanna River Basin indicates that even higher infiltration rates are typical in this region). The sand filter media was assumed to achieve pollutant removal rates of 86% for TSS, 30% for TN, and 60% for TP using published performance values from the Center for Watershed Protection (2007) and Hirschman et al. (2008).[1] Removal was modeled in SUSTAIN for only the volume that filtered through the sand media and was subsequently discharged via

[1]The 2014 BMP Performance Summaries published by the International Stormwater BMP Database (Geosyntec Consultants and Wright Water Engineers, 2014) became available around the time we developed assumptions for BMP pollutant removal performance. However, for the most part our values are within the 95% confidence intervals of the percentage reductions relative to influent-effluent concentrations shown by their performance summaries.

the underdrain. Any pollutants carried by runoff infiltrating into the underlying soil were assumed to be removed completely from the system. While dissolved pollutants may be transported via groundwater and eventually be exported from the site, this study is focused on stormwater and surface runoff only.

The dry extended detention basin was sized and configured for SUSTAIN using a two-step process:

- The CPv was calculated using design criteria in the Maryland Stormwater Manual.
- A routing spreadsheet was created simulating design storm runoff using a 1-minute time step. Inflow hydrographs were produced using TR-55 methods (USDA, 1972, 1986) for undeveloped (forest) and developed conditions. Detention basin outflow was represented using basin dimension, stage, and outlet characteristics (orifice/weir size and stage). The detention basin size and outlet characteristics were optimized to allow for release of the CPv over a 24-hour period via an orifice; then, a weir was used to match the developed site peak outflow from the 10-year 24-hour storm to the predeveloped condition.

The basin was assumed to be earthen and a background infiltration of 0.52 inches/hour was included in SUSTAIN, allowing for infiltration and removal of runoff and pollutants. ET was modeled in SUSTAIN for both the sand filters and the detention basin.

3.2.2. Green Infrastructure (GI) with Gray Infrastructure

The key design elements in the Green with Gray Infrastructure scenario are as follows:

- Permeable pavement is used for the parking areas and sidewalks throughout the site.
- Infiltration Basins (aboveground) and infiltration trenches (below ground) address the Rev, WQv, and CPv. The roads drain to infiltration basins, while the rooftops drain to the infiltration trenches. The entire capture volume is infiltrated into the underlying soil.
- A dry detention basin addresses the Qp only.

Figure 3-3 provides the BMP locations and site conveyance for the GI with Gray scenario. Road runoff is conveyed to the infiltration basins either via curb flow or by culvert. Rooftops drain to adjacent infiltration trenches. Overflow from large storm events is then conveyed from the infiltration practices via a separate drainage network to the dry detention basin. Flow is then discharged offsite.

Figure 3-3. **Mixed-use Green Infrastructure (GI) with Gray Infrastructure stormwater management scenario (Harford County, MD).**

The process for developing the SUSTAIN simulation representation was similar to the approach used for the conventional site scenario. The permeable pavement was configured to be consistent with Maryland Stormwater Manual. No external runoff was directed to the permeable pavement, and the subbase provided sufficient storage to address the CPv. The infiltration basins and infiltration trenches were sized to capture the CPv using the Manual’s procedures for applying an alternative stormwater management strategy called “Environmental Site Design,” which incorporates low impact development (LID) principles. Volume in excess of the CPv were routed to a conventional earthen dry detention basin designed to match postdeveloped peak flow to predeveloped conditions for the 10-year 24-hour storm, as well as pass larger storm events with a spillway. The detention basin dimensions and outlet configuration were estimated using a stage-storage-discharge spreadsheet as was done for the conventional site. All of the practices were assumed to have infiltration rates of 0.52 inches per hour. The only pollutant removal mechanism is via infiltration from the BMPs. ET was simulated to occur from the detention basin and from the infiltration basins, but not from the infiltration trenches (which store runoff for infiltration below the ground surface). A small amount of ET from permeable pavement was assumed, equal to 10% of ET that would normally take place, based on best professional judgment.

3.2.3. Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI)

The objective of this scenario is to address the performance gap between current and future climate by incorporating additional distributed GI practices into the site. The current conventional BMP (extended detention basin and surface sand filters) configurations are unchanged and distributed GI practices are added during the adaptation SUSTAIN run to provide treatment equivalent to the current conditions climate scenario.

For the Conventional with Distributed GI scenario, infiltration trenches are distributed throughout the 20-acre study site (represented as one aggregate infiltration trench per drainage area). The same basic design used for the GI with Gray Infrastructure was incorporated, but practices were not sized for a specific design criterion. Rather, SUSTAIN was allowed to dynamically size the individual trenches until the site's performance met or exceeded all of the performance measures defined for current conditions as discussed in *Section 2.3.2.* .

3.3. ADAPTATION SIMULATION

The objective of the adaptation simulation is to determine the increases in BMP footprint (surface area) that would be required to maintain current levels of performance under future climate conditions for each stormwater management scenario. *Table* 3-1 summarizes the key components of the modeling procedure for each scenario. In the GI with Gray scenario, all practice types were resized except for permeable pavement because no additional area was considered to be available for permeable pavement. As discussed in *Section 3.2.3.* , the Conventional with Distributed GI scenario consisted of adding distributed green practices (infiltration trenches) to the site; the conventional practices were not resized.

Table 3-1. Features of adaptation simulation for Harford County, MD

Location	Stormwater management scenario	Future adaptation	Affected practices
Harford County, MD	Conventional (Gray) Infrastructure	Resize practices	Surface sand filters, extended dry detention basin
	GI with Gray Infrastructure	Resize practices	Infiltration trenches, infiltration basins, dry detention basin
	Conventional (Gray) Infrastructure with Distributed GI	Add distributed GI to site	Distributed infiltration trenches

3.4. CURRENT AND FUTURE CHANGES IN PRECIPITATION

Water-year annual precipitation ranked by current climate totals is shown in Figure 3-4. Annual precipitation volume is projected to increase for each year of the simulation period; however, the increase varies from a few inches per year to over 10 inches per year. The overall annual averages are 44.3 inches for current conditions, and 50.0 inches for future conditions, reflecting a 12.8% increase in volume. A comparison of current and projected future monthly average precipitation is provided in Figure 3-5. Precipitation depth increases for some months and decreases in other months. The largest change is seen in September, where projected average depth increases from about 4 to 7 inches. In addition, daily sums of precipitation depth were calculated and were used to determine percentiles of 24-hour depth of interest to stormwater managers (see *Table* 3-2). While daily sums do not provide a true measure of storm event depth (storms have variable lengths and may span more than 1 day), they do provide useful information about expected depths over a 24-hour period. As seen in the table, the change in depth between current and future ranges from 0.09inches for the 85th percentile to 0.43 inches for the 99th percentile.

While the first two figures provide an indication of changes in overall precipitation volume, they do not speak to changes in storm event volume and intensity, which was used as the basis for the selection of the future climate scenario among 10 candidate scenarios. Figure 3-6 shows the highest hourly precipitation volumes in the current and future precipitation time series, plotted by recurrence interval in years in the 30-year simulation period. It is important to note that the depths shown (1) are not storm event depths but rather hourly precipitation values and (2) may not reflect the true distribution of hourly depths due to the use of only 30 years of meteorological history. However, the figure provides a useful way to visualize volume/intensity changes for the largest events resulting from projected climate change. There is an approximately 1.5-fold increase in hourly precipitation depth across the recurrence range. The figure also provides an indication in the change in frequency for a given depth. The depth corresponding to 10-year recurrence under current conditions is projected to take place at a 2-year recurrence under future climatic conditions.

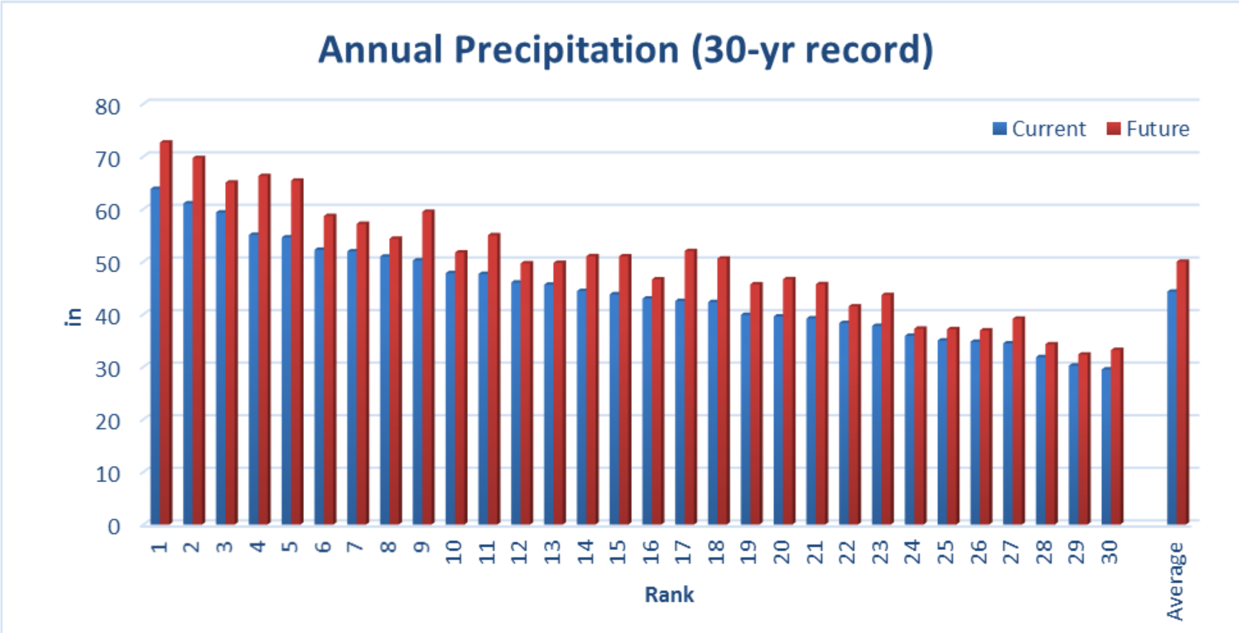

Figure 3-4. **Ranked annual precipitation for current and high intensity future climate at Harford County, MD.**

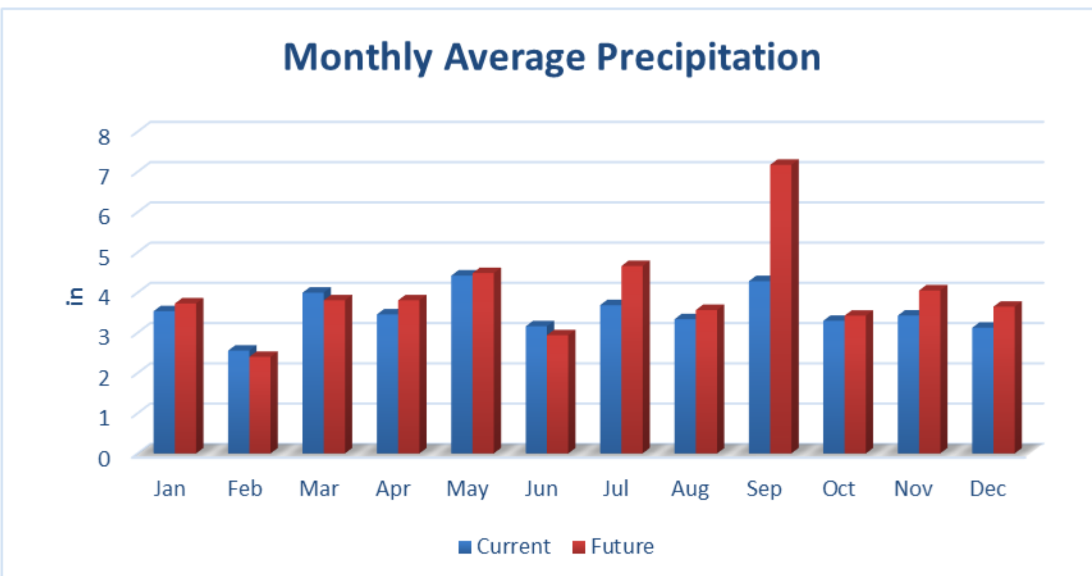

Figure 3-5. **Monthly average precipitation for current conditions and high intensity future climate scenario at Harford County, MD**

Table 3-2. 24-hour precipitation depth percentiles for current conditions and high intensity future climate scenario at Harford County, MD

Percentile	Current conditions 24-h depth (in)	Future climate 24-h depth (in)	Change (+/−in)
85th	0.81	0.90	+0.09
90th	1.03	1.15	+0.12
95th	1.39	1.58	+0.19
99th	2.33	2.76	+0.43

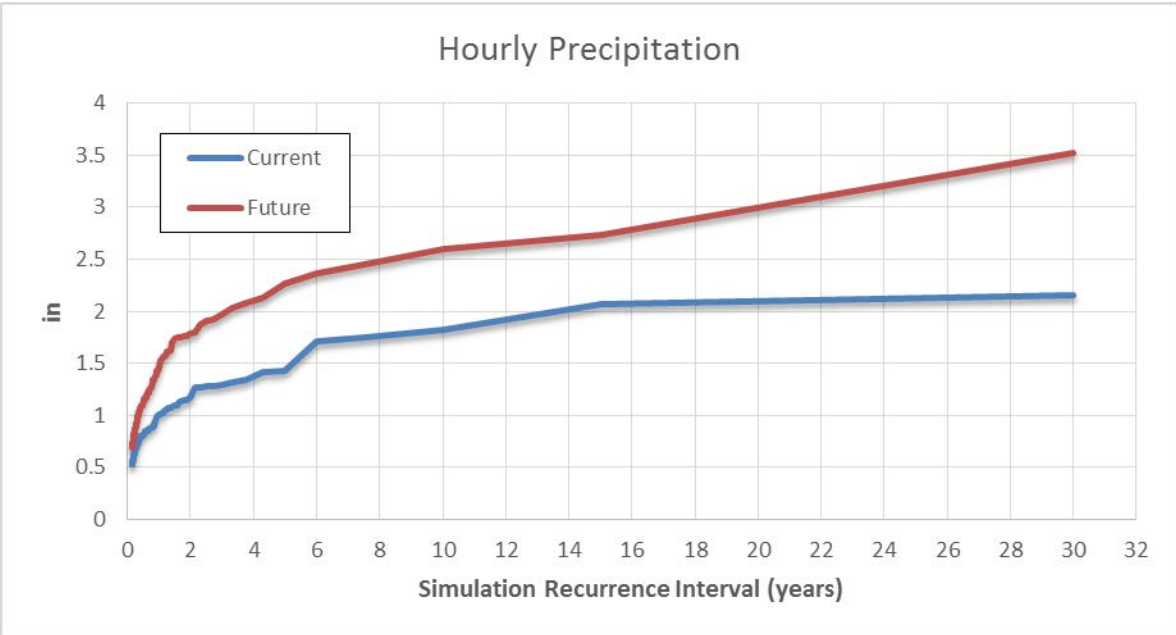

Figure 3-6. Hourly precipitation recurrence interval for current conditions and high intensity future climate scenario at Harford County, MD.

3.5. RESULTS

SUSTAIN was run under the following conditions for each stormwater management scenario:

- Current climate, site without stormwater management/BMPs
- Future climate, site without stormwater management/BMPs
- Current climate, site with stormwater management/BMPs
- Future climate, site with stormwater management/BMPs
- Future climate, site with BMPs adapted to meet current hydrology and water quality performance

As shown in *Table* 3-3, 11 sets of SUSTAIN runs were performed for a combination of three stormwater management approaches and four climate scenarios. The Conventional with Distributed GI approach is a variation of the Conventional approach, where the adaptation to meet current performance used addition of GI components to the site, rather than resizing practices already in place as was done for the Conventional approach. Because the minus 10% change climate scenario resulted in a reduction to all performance measures, there was no need to perform an adaptation run because current performance was already met. As a result, no SUSTAIN run was needed for the Conventional with Distributed GI approach because it is identical to the Conventional approach prior to adaptation.

Table 3-3. Stormwater management and climate scenarios for Harford County, MD

Stormwater management approach	GCM high intensity	Minus 10%	Plus 10%	Plus 20%
Conventional	X	X	X	X
GI + Gray	X	X	X	X
Conventional with Distributed GI	X		X	X

A full presentation of the results of all the runs is provided in *APPENDIX* B. . For brevity, the results in this section focus on a few topics of interest to stormwater managers: (1) a comparison of the site performance with BMPs between current and future climate conditions, (2) the increases in BMP footprints needed to offset impacts of climate change when BMPs are adapted using SUSTAIN optimization, and (3) a comparison of current stormwater infrastructure costs to future costs when BMPs are adapted to offset impacts of climate change.

For the comparison of the site performance with BMPs between current and future climate conditions, the downscaled future GCM (high intensity change) scenario was selected for the comparison. A discussion of other topics of interest are provided in the general conclusions *Section 8.* , including changes in pretreatment site performance, changes in post-treatment site performance, climate scenario sensitivity analysis, and adapting BMPs under future climate to meet current performance.

Rather than comparing the performance of the stormwater management approaches independent of climate change (i.e., how much better does one perform than the other under current conditions), this study focuses on how the stormwater management approaches compare *relative to climate change. Table* 3-4 provides current and future performance for the stormwater management approaches, normalized to area. Note that there is no numeric measure of change in the FDC between current and future climate, so the highest hourly peak flow during the simulation is presented as a proxy for large storm event response.

Figure 3-7 through Figure 3-11 present each metric graphically from *Table* 3-4. For annual average site runoff, the increase in runoff for the Conventional approach at 3.92 inches is more than double the runoff increase for GI + Gray at 1.88 inches. This indicates the GI + Gray approach was better at disposing of additional runoff due to changes in future precipitation volume than the Conventional approach, suggesting that the GI + Gray approach is more resilient to climate change for this measure. The same is not true for the maximum hourly peak flow, where both approaches gained 0.67 cfs/acre, as well as for the sediment loading rate, where both sites increased by a bit less than 0.1 ton/acre/year. The GI + Gray approach does appear to be somewhat more resilient for the nutrient loading rates, with increases somewhat less than for the Conventional approach.

Table 3-4. Current and future performance of Harford County, MD site by stormwater management approach

Stormwater management approach	Current	Future	Change
Runoff (inch/yr)			
Conventional	7.04	10.96	+3.92
GI + Gray	1.52	3.40	+1.88
Maximum hourly peak flow (cfs/ac)			
Conventional	1.12	1.80	+0.67
GI + Gray	0.85	1.52	+0.67
Sediment (ton/ac/yr)			
Conventional	0.12	0.20	+0.09
GI + Gray	0.04	0.11	+0.08
TN (lb/ac/yr)			
Conventional	2.74	4.34	+1.60
GI + Gray	0.64	1.58	+0.94
TP (lb/ac/yr)			
Conventional	0.32	0.51	+0.18
GI + Gray	0.07	0.18	+0.11

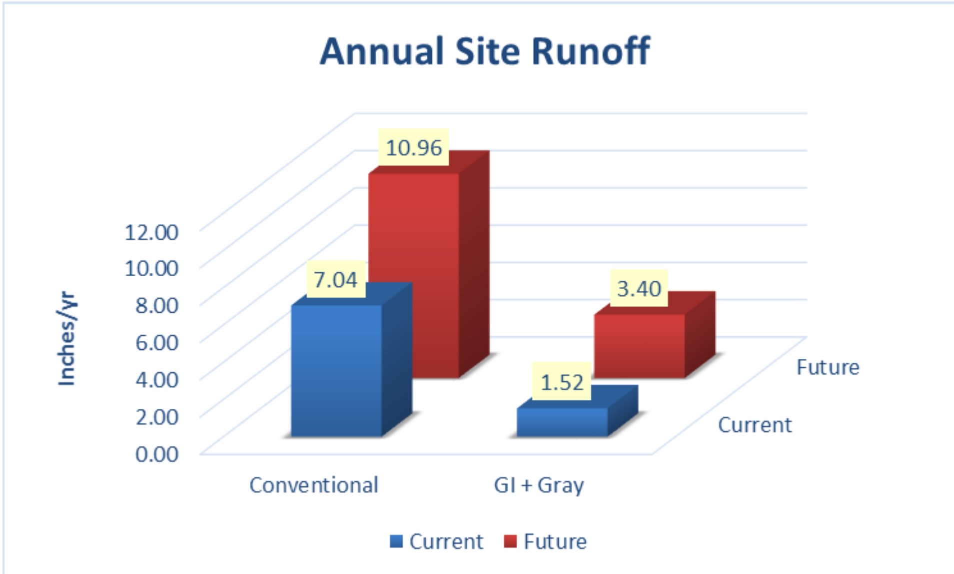

Figure 3-7. Annual site runoff under current climate and future general circulation model (GCM) scenario by stormwater management approach for Harford County, MD.

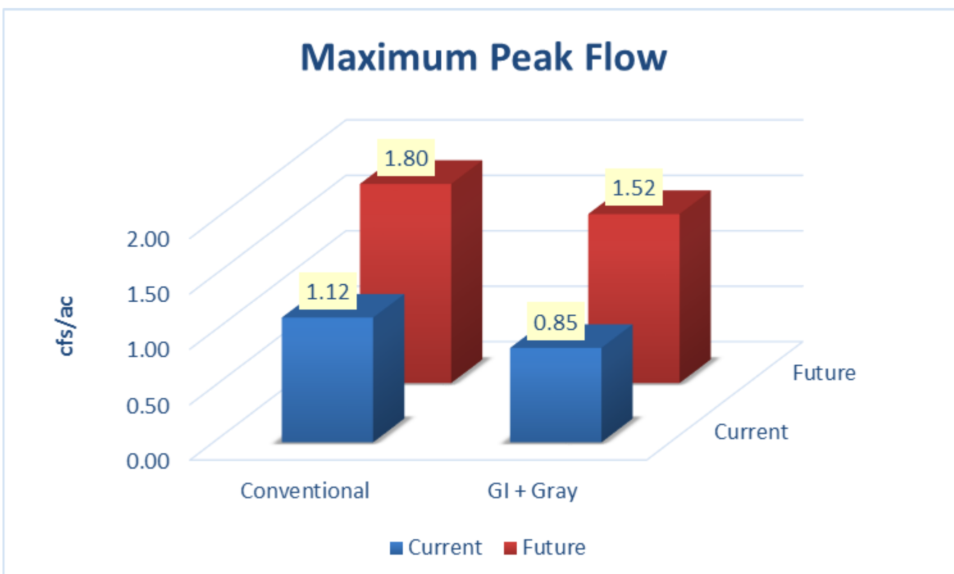

Figure 3-8. Maximum hourly peak flow under current climate and future general circulation model (GCM) scenario by stormwater management approach for Harford County, MD.

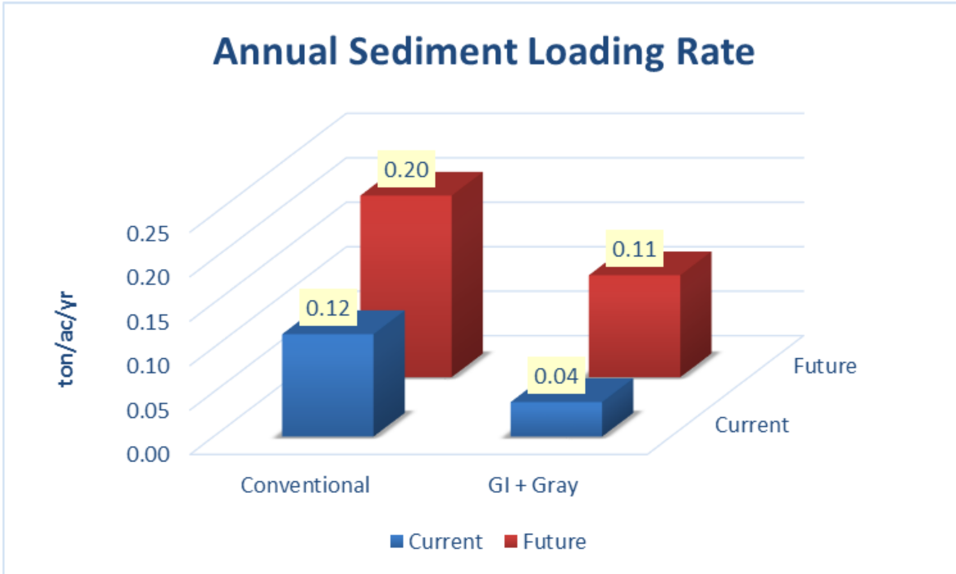

Figure 3-9. Annual sediment loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Harford County, MD.

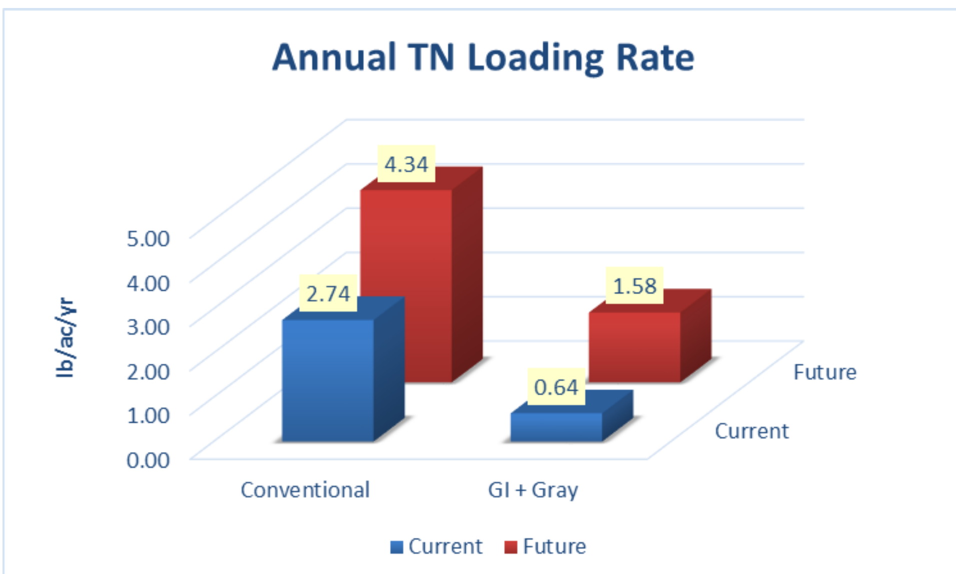

Figure 3-10. Annual TN loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Harford County, MD.

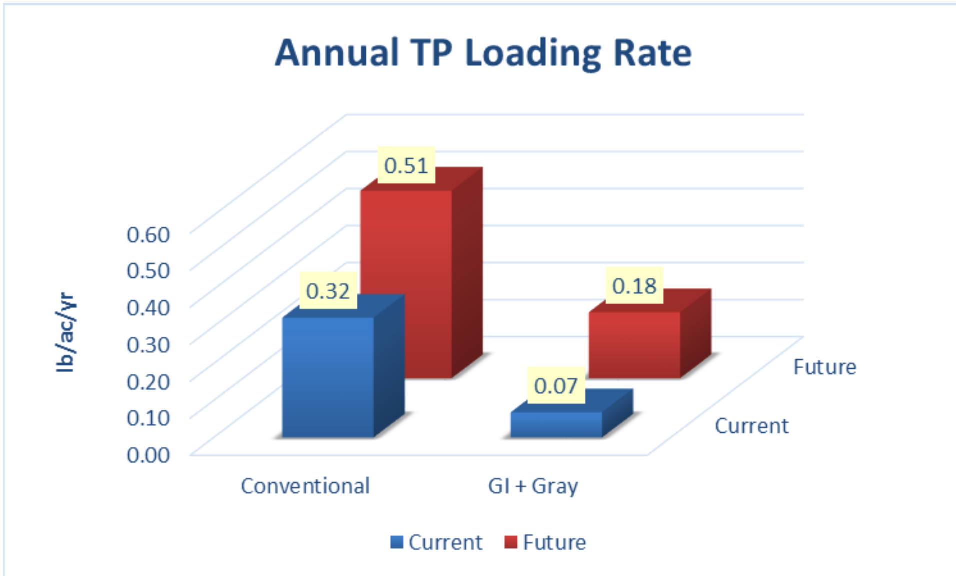

Figure 3-11. Annual TP loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Harford County, MD.

Design Results - General Circulation Model (GCM) High Intensity

For the Conventional (Gray) Infrastructure scenario, the optimal solution resulted in an increase in size for both the extended dry detention basin and the surface sand filters. The detention basin needs to be more than triple its original size, while the sand filters show an increase of nearly 50%. The combined increase in BMP footprint is equal to about 7% of the site area, about 1.4 acres.

The GI with Gray Infrastructure scenario uses a smaller detention basin for large flooding event mitigation and transfers much of the stormwater control to infiltration practices. For this adaptation, SUSTAIN favored the infiltration practices for resizing, with infiltration basins quadrupling in size, and the infiltration basins more than tripling in size. On the other hand, the detention basin has a 130% increase, more than double the size under current climate conditions. The combined increase in BMP footprint amounts to nearly 10% of the site area, over 2 acres. Note that permeable pavement was not included as an adaptation practice because it was already implemented to the maximum practical extent.

The Conventional Infrastructure with Distributed GI scenario differs from the previous ones in that GI practices are added to the site rather than resizing the practices already present. To offset the impacts of climate change, nearly 100,000 square feet (over 2 acres) of infiltration trenches must be added to the site to mitigate future climate change impacts under the GCM high intensity future climate scenario.

Design Results - Intensity Change Plus 10%

In the Conventional (Gray) Infrastructure scenario, the SUSTAIN optimization selected the extended dry detention basin only for adaptation. This outcome is somewhat surprising and follows a different pattern than the adaptations to the GCM high intensity future climate scenario, where both sand filters and the detention basin were selected for resizing during the optimization as being the most cost-effective solution. The required basin footprint for future climate adaptation reflects a near doubling of size.

In the GI with Gray Infrastructure scenario, the SUSTAIN optimization targeted resizing only the infiltration basins and infiltration trenches, the opposite outcome as seen for the Conventional scenario. This difference is likely due in part to sediment and TP loads being the limiting factor, resulting in the selection of practices with the best infiltration capacity and load reduction. The required infiltration basin footprint reflects nearly a 50% increase, and nearly a 40% increase is required in the infiltration trench footprint.

For the Conventional (Gray) Infrastructure with Distributed GI scenario, the addition of 15,351 square feet of distributed infiltration trenches would be required to maintain current BMP performance. This footprint represents approximately 1.8% of the total site area.

Design Results - Intensity Change Plus 20%

In the Conventional (Gray) Infrastructure scenario, the extended dry detention basin footprint must increase by a factor of 2.8 for future climate adaptation. In the GI with Gray Infrastructure scenario, the required infiltration basin footprint reflects a more than doubling in size, and nearly a 60% increase is required in the infiltration trench footprint. For the Conventional (Gray) Infrastructure with Distributed GI scenario, the addition of 32,514 square feet of distributed infiltration trenches would be required to maintain current performance. This footprint represents approximately 3.7% of the total site area.

Table 3-5 summarizes the increases in BMP footprints for the Harford County stormwater management scenarios that would be required to maintain current performance under future climate conditions. The current and adapted footprints are presented in terms of both actual square feet of practice as well as percentage of overall site area. The latter is provided as a means of comparing the current and future adapted sizes relative to the site area (20 acres) for this particular development type (mixed use). Results are discussed separately for each of the future climate scenarios modeled for the Harford County site.

Table 3-5. Comparison of current and future adapted best management practice (BMP) footprints for Harford County, MD stormwater management scenarios

Future climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% Increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GCM high intensity	Conventional (Gray) Infrastructure	Extended dry detention basin	25,000	2.9	81,250	9.3	225
		Surface sand filters	10,119	1.2	14,840	1.7	47
	GI with Gray Infrastructure	Dry detention basin	10,000	1.1	23,000	2.6	130
		Infiltration basin	12,858	1.5	52,155	6.0	306
		Infiltration trench	14,800	1.7	47,954	5.5	224
		Permeable pavement	201,242	23.1	201,242	23.1	0
	Conventional (Gray) Infrastructure with Distributed GI	Extended dry detention basin	25,000	2.9	25,000	2.9	0
		Surface sand filters	10,119	1.2	10,119	1.2	0
		Distributed infiltration trenches	0	0	95,869	11.0	--
Percentage difference plus 10%	Conventional (Gray) Infrastructure	Extended dry detention basin	25,000	2.9	25,000	2.9	0
		Surface sand filters	10,119	1.2	20,023	2.3	98
	GI with Gray Infrastructure	Dry detention basin	10,000	1.1	10,000	1.1	0
		Infiltration basin	12,858	1.5	18,943	2.2	47
		Infiltration trench	14,800	1.7	20,435	2.3	38
		Permeable pavement	201,242	23.1	201,242	23.1	0
	Conventional (Gray) Infrastructure with Distributed GI	Extended dry detention basin	25,000	2.9	25,000	2.9	0
		Surface sand filters	10,119	1.2	10,119	1.2	0
		Distributed infiltration trench	0	0.0	15,351	1.8	--

Table 3-5. Comparison of current and future adapted best management practice (BMP) footprints for Harford County, MD stormwater management scenarios (Continued)

Future climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% Increase in footprint
			Footprint SF	**Footprint as % of site area**	**Footprint** SF	**Footprint as % of site area**	
Percentage difference plus 20%	Conventional (Gray) Infrastructure	Extended dry detention basin	25,000	2.9	25,000	2.9	0
		Surface sand filters	10,119	1.2	28,043	3.2	177
	GI with Gray Infrastructure	Dry detention basin	10,000	1.1	10,000	1.1	0
		Infiltration basin	12,858	1.5	27,846	3.2	117
		Infiltration trench	14,800	1.7	23,350	2.7	58
		Permeable pavement	201,242	23.1	201,242	23.1	0
	Conventional (Gray) Infrastructure with Distributed GI	Extended dry detention basin	25,000	2.9	25,000	2.9	0
		Surface sand filters	10,119	1.2	10,119	1.2	0
		Distributed infiltration trench	0	0.0	32,514	3.7	--

Cost Results - General Circulation Model (GCM) High Intensity

For the Conventional (Gray) scenario, the cost of adaptation (based on 20-year present value) is estimated to increase by $6.47 million, or 122%, compared with the current cost. This is equivalent to a cost of adaptation of $0.32 million per acre of site area.

The cost of adaptation for the GI with Gray scenario is estimated to increase by $6.99 million, or 136%. On a cost per site-acre basis, the estimated cost of adaptation is $0.35 million per acre of site area.

Implementing distributed green practices (infiltration trenches) to address the performance gap between current and future climate comes at an estimated cost increase of $10.56 million, an increase of 199%. The increase in cost per acre of site is estimated to be $0.53 million for the Conventional with Distributed GI scenario.

Cost Results - Intensity Change Plus 10%

The cost of adaptation for the Conventional (Gray) scenario is estimated to be an increase of $2.69 million, which reflects a 51% increase in cost. This is equivalent to a cost of adaptation of $0.13 million per acre of site area.

For the GI with Gray scenario, the estimated cost of adaptation is a $1.09 million increase compared to the current cost, or an increase in cost of 21%. The increase in cost per acre of site is estimated to be $0.05 million.

Implementing distributed green practices (infiltration trenches) to address the performance gap between current and future climate comes at an estimated cost increase of $1.62 million, an increase of 30%. On a cost per site acre basis, the estimated cost of adaptation is $0.08 million per acre of site area.

For all three stormwater management scenarios, the cost of adaptation for the percentage change plus 10% scenario is significantly less than the cost for the GCM high intensity change scenario. The reason adaptation costs are so high for the GCM high intensity change scenario is due to the large increase in storm event volume for the largest storm events, as seen in Figure 3-6. The largest hourly rainfall depth increases from about 2 to 3.5 inches, an increase of 75%.

Cost Results - Intensity Change Plus 20%

For the Conventional (Gray) scenario, the estimated cost of adaptation is a $4.89 million increase compared to the current cost, or an increase in cost of 92%. The increase in cost per acre of site is estimated to be $0.24 million.

The cost of adaptation for the GI with Gray scenario is estimated to be an increase of $2.13 million, which reflects a 41% increase in cost. This is equivalent to a cost of adaptation of $0.11 million per acre of site area.

Implementing distributed green practices (infiltration trenches) to address the performance gap between current and future climate comes at an estimated cost increase of $3.55 million, an increase of 67%. On a cost per site acre basis, the estimated cost of adaptation is $0.18 million per acre of site area.

For all three stormwater management scenarios, the cost of adaptation for the percentage change plus 20% scenario is less than the cost for the GCM high intensity change scenario, but more than for the percentage change plus 10% scenario.

Table 3-6 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all of the Harford County stormwater management scenarios. Refer to *Section 2.5.2.* of the report for a discussion on how the infrastructure cost estimates were developed. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site. These three metrics represent three alternative methods for evaluating the cost of adaptation, which is effectively the increase in cost between the current and future adapted climate scenarios.

Table 3-6. Comparison of current and future adapted 20-year present value costs for the Harford County, MD stormwater management scenarios

Future climate scenario	Stormwater management scenario	Current cost (20-Year present value, $millions)	Future adapted cost (20-Year present value, $millions)	Increase in cost (20-Year present value, $millions)	% Increase in cost	Increase per acre of site ($millions)
GCM high intensity	Conventional (Gray) Infrastructure	5.31	11.78	6.47	122	0.32
	GI with Gray Infrastructure	5.15	12.15	6.99	136	0.35
	Conventional (Gray) Infrastructure with Distributed GI	5.31	15.87	10.56	199	0.53
Percentage difference plus 10%	Conventional (Gray) Infrastructure	5.31	8.00	2.69	51	0.13
	GI with Gray Infrastructure	5.15	6.24	1.09	21	0.05
	Conventional (Gray) Infrastructure with Distributed GI	5.31	6.93	1.62	30	0.08
Percentage difference plus 20%	Conventional (Gray) Infrastructure	5.31	10.17	4.86	92	0.24
	GI with Gray Infrastructure	5.15	7.29	2.13	41	0.11
	Conventional (Gray) Infrastructure with Distributed GI	5.31	8.86	3.55	67	0.18

4. MIDWEST SITE: RESIDENTIAL

4.1. REGULATORY REQUIREMENTS AFFECTING STORMWATER MANAGEMENT

At the highest level, development is regulated under the Minnesota Pollution Control Agency's (MPCA) statewide stormwater permit. Local requirements are also common and highly variable, with many locations falling under the jurisdiction of local watershed management organizations (WMOs). The Scott County WMO has requirements in addition to the state permit requirements.

Relevant MPCA stormwater requirements include:

- Retention of 1 inch of runoff from impervious surfaces is required (the WQv). The volume shall be infiltrated, evaporated, or reused on site.
- If retention is not possible (e.g., clay soils with low infiltration rates), then treatment BMPs must be used to remove 80% of TSS from the WQv. The WQv must be discharged within 48 hours.
- Wet ponds qualify for meeting the TSS removal requirement without need for another treatment BMP. If wet ponds are used, the design requirements are as follows:
  - Permanent pool of 1,800 ft^3 per acre of drainage
  - Maximum discharge d5.66 cfs per acre of pond surface area
  - Depth 3 to 10 feet
- Stormwater credits are given for various GI practices. The WQv can be reduced, and in some cases, an adjusted runoff curve number can be used for large storm event peak flow calculations. There are a number of restrictions on using the credit based on contributing impervious area, receiving pervious area, HSG, etc.

Relevant Scott County WMO stormwater requirements include:

- If detention is not possible, treatment BMPs must be used to remove 80% of TSS.
- Predevelopment peak matching is required for the 2-year, 10-year, and 100-year 24-hour events. Predevelopment conditions are defined as "woods in good condition" for purposes of performing stormwater routing calculations.

4.2. STORMWATER MANAGEMENT SCENARIOS

The 30-acre Residential site (see Figure 4-1) is assumed to have the following characteristics in each of the scenarios:

- A combination of single-family homes and townhomes occupy the site. The density is about 6.5 units per acre.

- The site is 48% impervious, distributed as follows:
    - 16% road area
    - 22% house area
    - 7% driveway area
    - 3% sidewalk area
- The remaining pervious area (52%) is comprised of lawn/landscaping.
- The entire site is assumed to be composed of HSG D soils; this was done to allow one of the modeled geographic locations to have poor infiltration rates. In addition, D soils are common in this region due to poorly drained soils of glacial origin. Due to limited infiltration capacity, the infiltration requirement is assumed to be waived. This assumption was made to allow for a conventional scenario that did not incorporate GI practices. The HSG composition is also used for design storm event routing calculations to size practices for peak flow control. Predevelopment land cover is assumed to be woods in good condition.
- The site must meet the more restrictive MPCA requirements for WQv and the discharge time period.
- The effects of frozen conditions on BMP performance are not modeled specifically in SUSTAIN. However, the input runoff time series from HSPF do account for snowfall, development of snowpack, and snow melt timing.

Figure 4-1. **Residential site layout (Scott County, MN).**

Three stormwater management scenarios have been developed representing different approaches to stormwater management: a conventional scenario using gray practices, a scenario using a combination of green and gray practices, and a scenario using only GI practices. As noted in *Section 2.2.* , the conventional scenario was used as the basis for a fourth scenario in which distributed GI practices were added to achieve current or better performance under future climate conditions. The scenarios are described in the following subsections.

4.2.1. Conventional (Gray) Infrastructure

The key design elements represented in the Conventional (Gray) Infrastructure scenario are as follows:

- The entire site drains to one point and is treated by a wet pond.
- The WQv is discharged from a low-flow orifice over a period of approximately 48 hours.
- The predevelopment peak-matching requirements are met for 2-year, 10-year, and 100-year 24-hour storms using a weir in the wet pond with extra volume storage above the WQv storage.

As shown in Figure 4-2 for the Conventional scenario, site drainage is directed to a storm drain sewer system that conveys flow to the wet pond. Flow is then discharged from the wet pond off the site.

For the SUSTAIN simulation, a routing spreadsheet was created simulating design storm runoff using the same approach as for the Harford County detention basins. The wet pond dimension and permanent pool volume were set-based MPCA design requirements. A low-flow orifice was configured to discharge the WQv within 48 hours. For the Scott County WMO peak matching requirements, a weir was added and optimization used to size the weir so that design storm event peak flows matched predeveloped conditions. The entire design configuration was transferred to SUSTAIN. Infiltration from the pond was set to zero, but ET was configured to occur from the pond water surface. For wet ponds, pollutant removal can be modeled using decay rates, which reduce the ambient concentration in the permanent pool. Decay rates were identified through successive model runs that mimicked published percentage removal values of 80% for TSS, 30% for TN, 50% for TP (Center for Watershed Protection, 2007; Hirschman et al., 2008).

Figure 4-2. **Residential Conventional (Gray) Infrastructure stormwater management scenario (Scott County, MN).**

4.2.2. Green Infrastructure (GI) with Gray Infrastructure

The key design elements represented in the GI with Gray Infrastructure scenario are as follows:

- Distributed bioretention treats the WQv.
- Bioretention is designed as follows:
    - 18-inch ponding depth
    - 48-hour drawdown time
    - 3 feet of media
    - An underdrain is used because the soils have a low infiltration capacity.
- A dry detention basin is used for peak matching for 2-year, 10-year, and 100-year 24-hour storms.

Figure 4-3 shows the BMP locations and stormwater conveyance for the GI with Gray Scenario. Site runoff is directed to five bioretention cells either by the storm drain sewer system or via grass channels (swales) where drainage patterns allow. Flow discharged from the bioretention cells (either via the underdrain or bypass flow during larger events) is then routed to a single centralized dry detention basin serving the entire site for large event peak flow reduction. Any overflow is discharged offsite from the dry detention basin.

For the SUSTAIN configuration, the bioretention cells were configured to store and treat the WQv associated with each contributing drainage area according to MPCA guidelines. A nominal infiltration rate of 0.06 inches per hour was used to represent infiltration from a 3-inch rock layer below the underdrain. The bioretention media was assumed to achieve pollutant removal rates of 78% for TSS, 57% for TN, and 63% for TP, using published performance values from Center for Watershed Protection (2007) and Tetra Tech (2014). Removal was modeled in SUSTAIN for only the volume that filtered through the bioretention media and was subsequently discharged via the underdrain. The detention basin configuration was determined using the same approach as for the conventional site, except there was no permanent pool nor WQv orifice. The 0.06 inches/hour infiltration rate was used also for the detention basin. ET was modeled in SUSTAIN for both the bioretention and the dry detention basin.

Figure 4-3. Residential Green Infrastructure (GI) with Gray Infrastructure stormwater management scenario (Scott County, MN).

4.2.3. Green Infrastructure (GI) Only

The key design elements represented in the GI Only scenario are as follows:

- Permeable pavement is used for the sidewalks. No adjacent areas drain to the sidewalks. Driveways were assumed to use conventional paving surfaces.
- Rooftop downspout disconnection is used in select areas where there is sufficient pervious surface to meet the design criteria.
- Bioretention is used with a modified design to address the peak flow matching requirements:
    - Additional storage in the bioretention performs peak matching for 2-year, 10-year, and 100-year 24-hour storms using a weir.
    - 12-inch ponding depth (modification to allow for peak matching using additional storage above ponding depth).

- 48-hour drawdown time.
- 3 feet of media.
- An underdrain is used because the soils have a low infiltration capacity.

The GI Only scenario differs from the previous two scenarios, each of which provided centralized control of large storm event peak flows. In the GI Only scenario, peak flow and flood control management are addressed in a distributed fashion. Each of the bioretention cells includes additional storage and a control structure to capture and release large storm event volumes closer to the source. As shown in Figure 4-4, many rooftops are configured to discharge to adjacent pervious areas. Because the site is composed of D soils, the pervious areas receiving the roof runoff must have their soils amended by compost to improve infiltration capacity (as required by MPCA). Minor grading may also be needed to ensure that runoff is well dispersed and overland flow maintained. The sidewalks are comprised of pervious concrete and have sufficient storage in an underlying stone layer to store the 100-year storm event volume. As shown in the figure, street culverts or grass channels are still needed to convey flow to the bioretention cells. Flow from the bioretention cells is then conveyed offsite via a separate drainage system.

For the SUSTAIN simulation, the following assumptions were used to develop the model configuration:

- Each bioretention cell was configured to capture and treat the WQv from its drainage area. The same configuration as was used for the GI with Gray Infrastructure site, including the use of underdrains and percentage removal of treated pollutants.

- Additional storage was added to each bioretention cell above the WQv to address peak flow reduction requirements. The stage-storage-discharge routing spreadsheet, as discussed previously, was reconfigured for each individual drainage area. Flows in excess of the WQv were discharged gradually from weirs to perform the peak matching to undeveloped conditions.

- Permeable pavement areas were not assumed to have underdrains. While underdrains are typically used when infiltration rates are very low, the use of permeable pavement was restricted to sidewalks, which would likely have lateral infiltration as well as vertical infiltration. A small amount of ET was assumed, equal to 10% of ET that would normally take place.

- The areas receiving disconnected roof runoff were sized at an approximate 1:1 ratio (i.e., 1,000 ft^2 of impervious surface drained to 1,000 ft^2 of pervious surface). The receiving pervious areas were assumed to have compost-amended soils. The infiltration rate was increased from 0.06 inches/hour to 0.15 inches/hour (a 2.5× increase) based on a literature review of infiltration rate changes in compost amended soils (Harrison et al., 1997; Carmen, 2015; Brown and Cotton, 2011; Eusufzai and Fujii, 2012).

Figure 4-4. Residential Green Infrastructure (GI) Only stormwater management scenario (Scott County, MN).

4.2.4. Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI)

The objective of this scenario is to address the performance gap between current and future climate by incorporating additional distributed GI practices into the site. The current conventional BMP (wet pond) configuration is unchanged and distributed GI practices are added to provide treatment equivalent to the current conditions climate scenario. The Scott County, MN location is unique in that three distinct future climate scenarios representing low, medium, and high intensity changes (as discussed in *Section 2.4.2.*) are evaluated.

For the Conventional with Distributed GI scenario, bioretention areas are distributed throughout the 30-acre study site. The bioretention design is the same configuration used in the GI with Gray scenario:

- 18-inch ponding depth.
- 48-hour drawdown time.
- 3 feet of media.
- An underdrain is used because the soils have a low infiltration capacity.

4.3. ADAPTATION SIMULATION

The objective of the adaptation simulation is to determine the increases in BMP footprint (surface area) that would be required to maintain or exceed current performance under future climate conditions for each stormwater management scenario. *Table* 4-1 summarizes the key components of the modeling procedure for each scenario. Although the GI Only scenario includes permeable pavement and impervious surface disconnection, only the distributed bioretention practices were resized in the adaptation simulation because (1) permeable pavement is already implemented in 100% of sidewalk areas, and its expansion to include residential driveways and streets was ruled impractical due primarily to maintenance concerns, and (2) impervious surface disconnection is already implemented to the maximum extent practicable in this scenario for residential rooftops and disconnection of additional impervious surface is not considered feasible.

Table 4-1. Features of adaptation simulation for Scott County, MN

Location	Stormwater management scenario	Future adaptation	Affected practices
Scott County, MN	Conventional (Gray) Infrastructure	Resize practices	Wet pond
	GI with Gray Infrastructure	Resize practices	Distributed bioretention and dry detention basin
	GI Only	Resize practices	Distributed bioretention
	Conventional (Gray) Infrastructure with Distributed GI	Add distributed GI to site	Distributed bioretention

4.4. CURRENT AND FUTURE CHANGES IN PRECIPITATION

As discussed in *Section 4.1.* , three future climate scenarios were selected for simulation reflecting a range in changes in intensity• the lowest intensity change, a medium intensity change, and the highest intensity change (note that the highest intensity change was used for all the other locations). Figure 4-5, Figure 4-6, and Figure 4-7 provide the ranked projected annual precipitation totals for the low, medium, and high intensity future scenario compared to current climate conditions. Under the low intensity scenario, projected annual precipitation volume decreases during nearly all the years. The medium and high intensity scenarios show a somewhat variable increase across all years. Average annual precipitation is 30.1 inches for current climate and is projected to be 28.7 inches for future low, 33.3 inches for future medium, and 33.6 inches for future high, corresponding to changes of −4.4, 10.7, and 11.6% respectively.

For monthly average precipitation depth (see Figure 4-8), the changes across future scenarios are highly variable by month, notably in July. In addition, daily sums of precipitation depth were calculated and used to determine percentiles of 24-hour depth of interest to stormwater managers (see *Table* 4-2). While daily sums do not provide a true measure of storm event depth (storms have variable lengths and may span more than 1 day), they do provide useful information about expected depths over a 24-hour period. For the future low intensity scenario, there is a decrease across the board for all percentiles. The future medium intensity and future high intensity scenarios have comparable depth increases across the percentiles, with the future high showing a larger increase for the 99th percentile.

Figure 4-9 provides a comparison of the highest hourly precipitation volumes. The low intensity scenario projects a decrease in intensity compared with current climate for all hours except the single largest precipitation depth in the 30-year time series. The medium intensity scenario is only slightly higher than current conditions, while the high intensity scenario has a projected increase of about 1.25 to 1.4 times that of the current conditions.

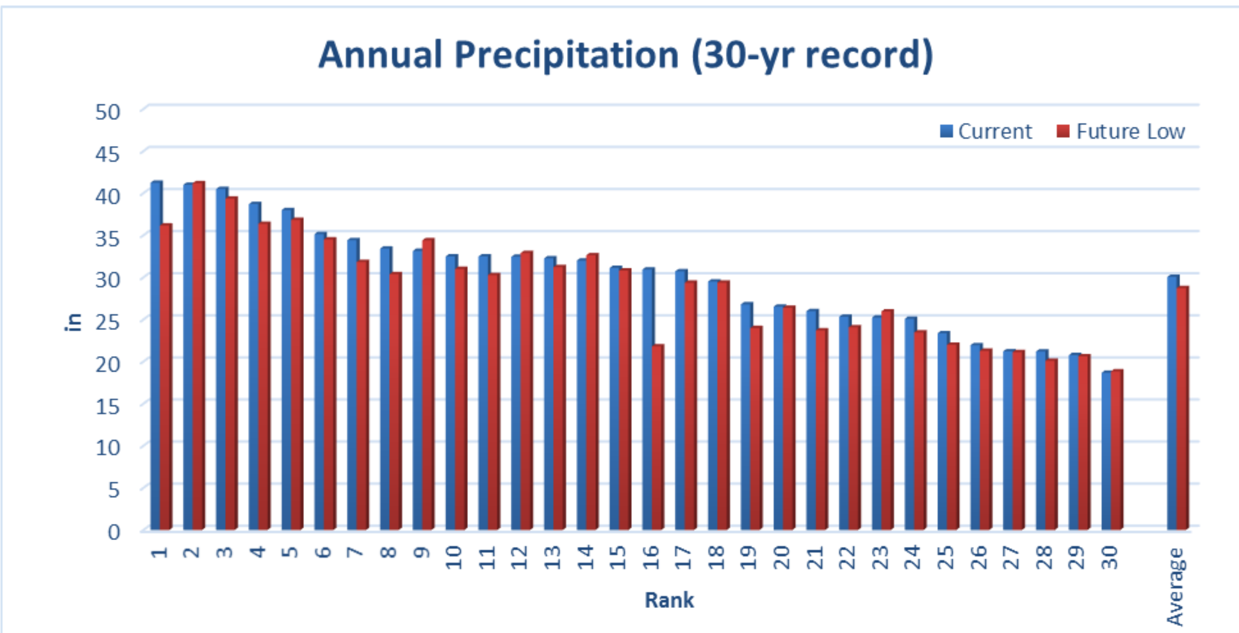

Figure 4-5. **Ranked annual precipitation for current conditions and low intensity future climate scenario at Scott County, MN.**

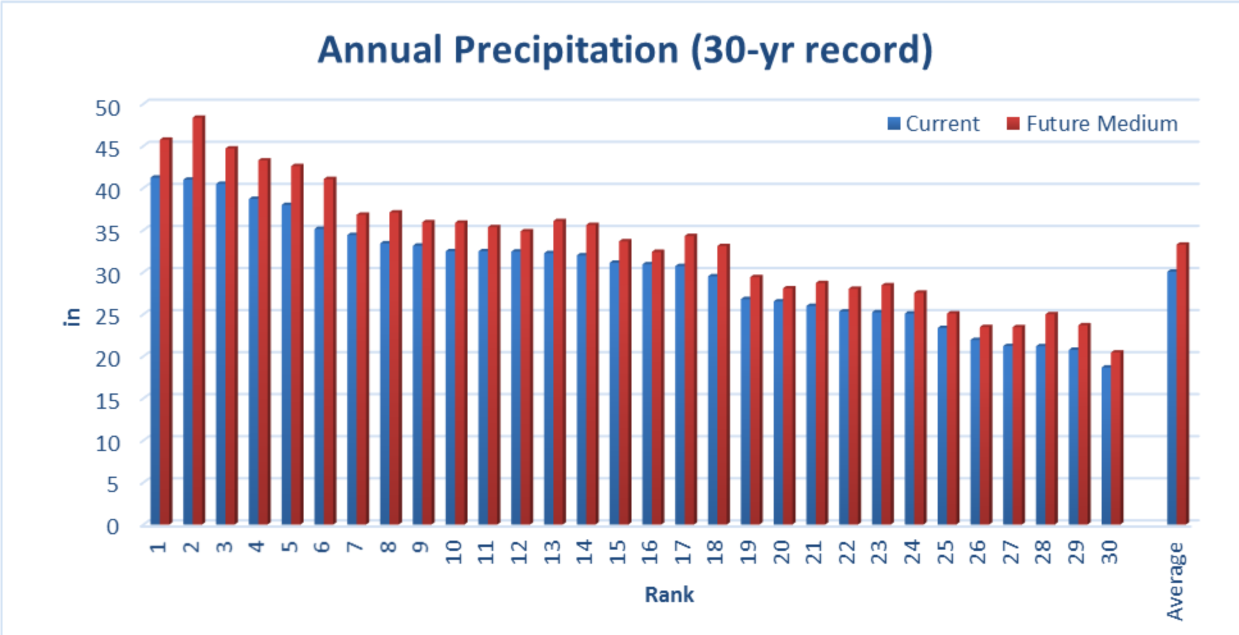

Figure 4-6. **Ranked annual precipitation for current conditions and medium intensity future climate scenario at Scott County, MN.**

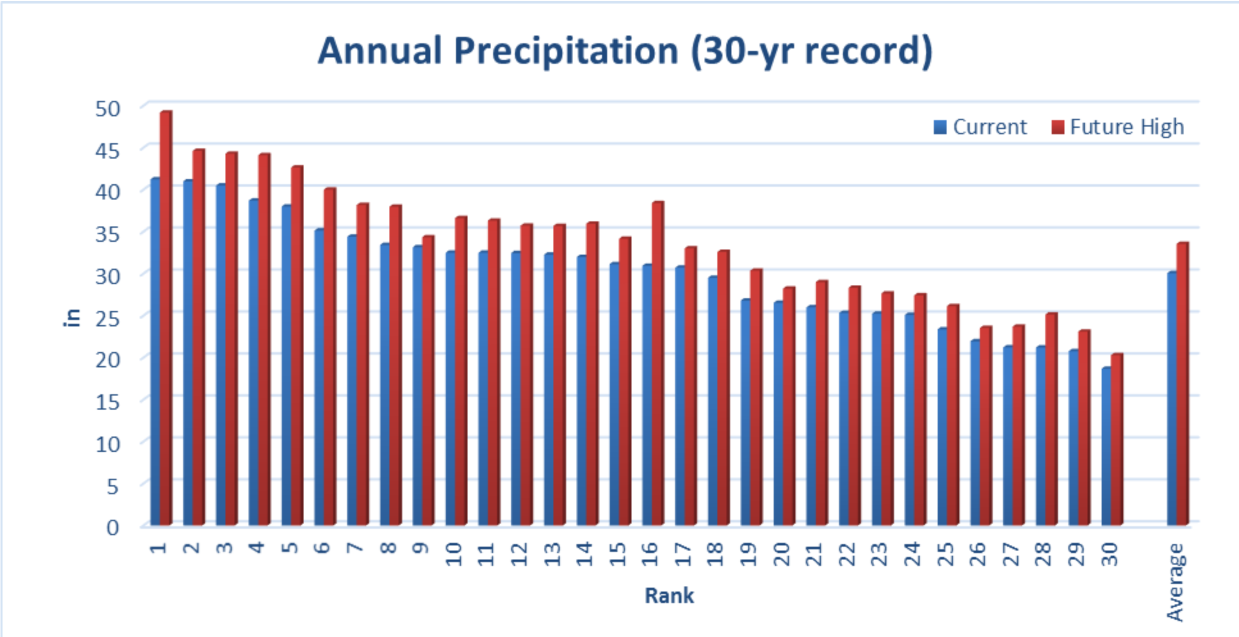

Figure 4-7. **Ranked annual precipitation for current conditions and high intensity future climate scenario at Scott County, MN.**

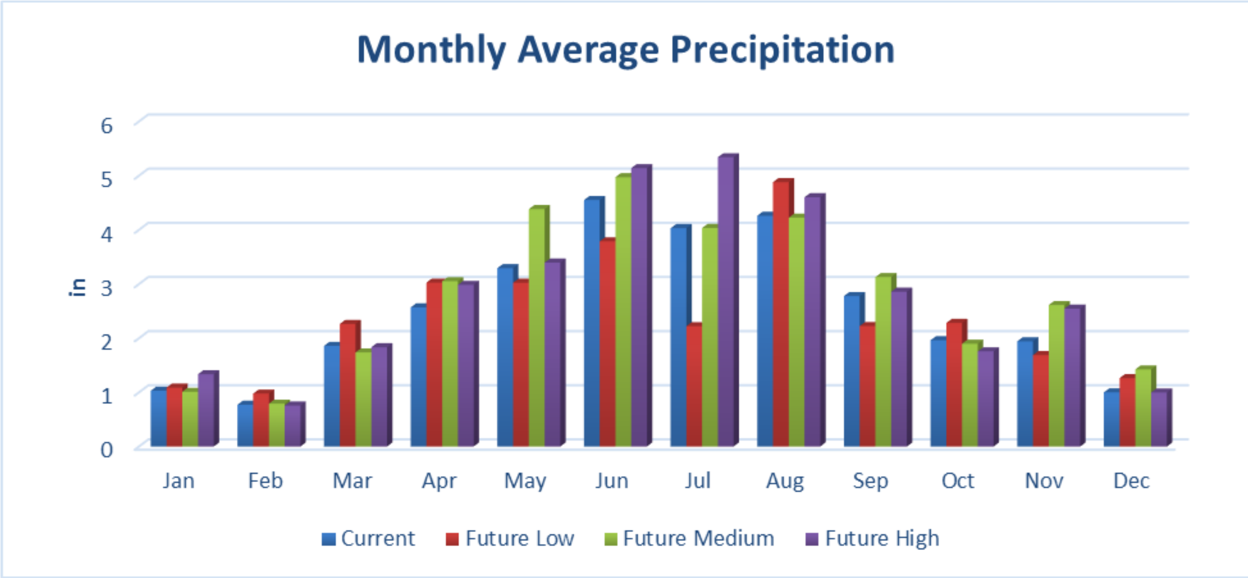

Figure 4-8. **Monthly average precipitation for current conditions and low/medium/high intensity future climate scenarios at Scott County, MN.**

Table 4-2. 24-hour precipitation depth percentiles for current conditions and low, medium, and high intensity future climate scenario at Scott County, MN

Percentile	Current conditions 24-h depth in	Future low 24-h depth in	Future low change +/−in	Future medium 24-h depth in	Future medium change +/−in	Future high 24-h depth in	Future high change +/−in
85th	0.50	0.48	−0.02	0.56	+0.06	0.55	+0.05
90th	0.67	0.65	−0.02	0.75	+0.08	0.76	+0.09
95th	1.01	0.96	−0.05	1.17	+0.16	1.12	+0.11
99th	1.94	1.77	−0.17	2.27	+0.33	2.33	+0.40

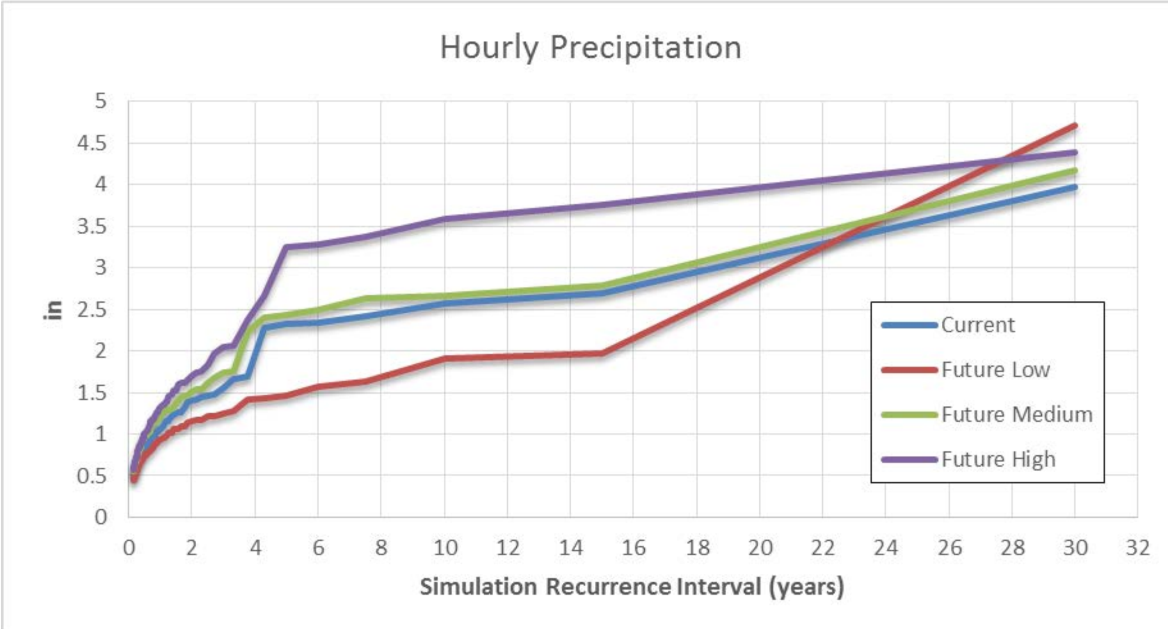

Figure 4-9. **Hourly precipitation recurrence interval for current conditions and low/medium/high intensity future climate scenarios at Scott County, MN.**

4.5. RESULTS

SUSTAIN was run for the following conditions for each stormwater management scenario:

- Current climate, site without stormwater management/BMPs
- Future climate, site without stormwater management/BMPs
- Current climate, site with stormwater management/BMPs
- Future climate, site with stormwater management/BMPs
- Future climate, site with BMPs adapted to meet current hydrology and water quality performance

As shown in *Table* 4-3, 22 sets of SUSTAIN runs were performed for a combination of four stormwater management approaches and six climate scenarios. The Conventional with Distributed GI approach is a variation of the Conventional approach, where the adaptation to meet or exceed current performance used the addition of GI components to the site, rather than resizing practices already in place as was done for the Conventional approach. Because the downscaled GCM low intensity and minus 10% change climate scenarios both resulted in a reduction in all performance measures, there was no need to perform adaptation runs; the current performance was already met. As a result, no SUSTAIN run was needed for the Conventional with Distributed GI approach for these two climate scenarios because it is identical to the Conventional approach prior to adaptation.

Table 4-3. Stormwater management and climate scenarios for Scott County, MN

Stormwater management approach	GCM low intensity	GCM medium intensity	GCM high intensity	Minus 10%	Plus 10%	Plus 20%
Conventional	X	X	X	X	X	X
GI + Gray	X	X	X	X	X	X
GI Only	X	X	X	X	X	X
Conventional with Distributed GI		X	X		X	X

A full presentation of the results of all the runs is provided in *APPENDIX B.* . For brevity, the results in this section focus on a few topics of interest to stormwater managers: (1) a comparison of the site performance with BMPs between current and future climate conditions, (2) the increases in BMP footprints needed to offset impacts of climate change when BMPs are adapted using SUSTAIN optimization, and (3) a comparison of current stormwater infrastructure costs to future costs when BMPs are adapted to offset impacts of climate change.

For the comparison of the site performance with BMPs between current and future climate conditions, the downscaled future GCM (high intensity change) scenario was selected for the comparison. A discussion of other topics of interest are provided in the general conclusions *Section 8.* , including changes in pretreatment site performance, changes in post-treatment site performance, climate scenario sensitivity analysis, and adapting BMPs under future climate to meet current performance.

Rather than comparing the performance of the stormwater management approaches independent of climate change (i.e., how much better does one perform than the other under current conditions), this study focuses on how the stormwater management approaches compare *relative to climate change. Table* 4-4 provides current and future performance for the stormwater management approaches, normalized to area. Note that there is no numeric measure of change in the FDC between current and future climate, so the highest hourly peak flow during the simulation is presented as a proxy for large storm event response. Figure 4-10 through Figure 4-14 present each metric graphically from *Table* 4-4.

Table 4-4. Current and future performance of Scott County, MN site by stormwater management approach for general circulation model (GCM) high intensity scenario

Stormwater management approach	Current	Future	Change
Runoff (inch/yr)			
Conventional	13.04	14.61	+1.57
GI + Gray	10.36	12.03	+1.67
GI Only	7.71	9.23	+1.52
Maximum hourly peak flow (cfs/ac)			
Conventional	2.40	3.45	+1.05
GI + Gray	2.38	3.43	+1.05
GI Only	2.35	3.41	+1.06
Sediment (ton/ac/yr)			
Conventional	0.123	0.193	+0.070
GI + Gray	0.248	0.360	+0.112
GI Only	0.199	0.300	+0.102
TN (lb/ac/yr)			
Conventional	6.95	7.44	+0.49
GI + Gray	3.64	4.07	+0.44
GI Only	2.39	2.77	+0.38
TP (lb/ac/yr)			
Conventional	0.69	0.79	+0.10
GI + Gray	0.49	0.59	+0.10
GI Only	0.36	0.46	+0.10

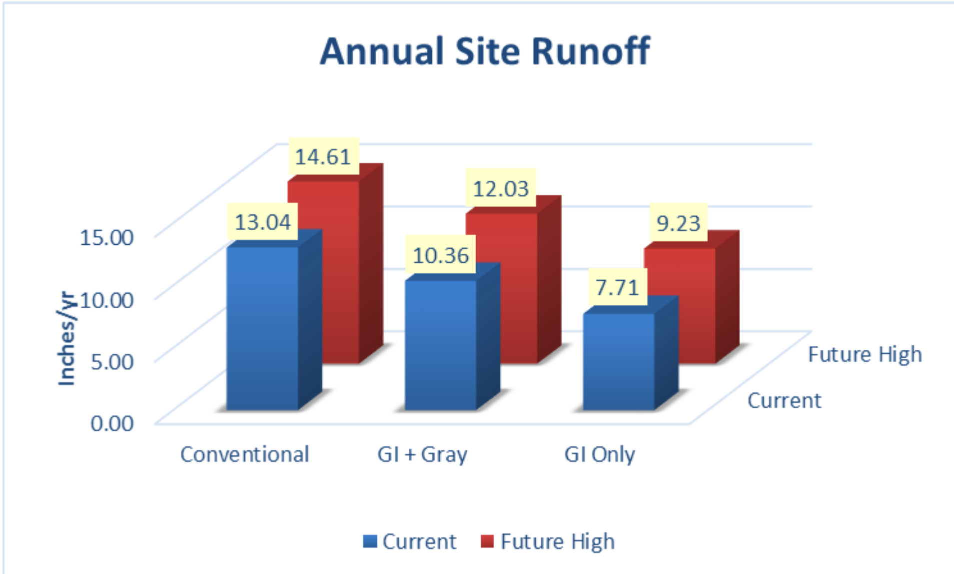

Figure 4-10. Annual site runoff under current climate and future general circulation model (GCM) high intensity scenario by stormwater management approach for Scott County, MN.

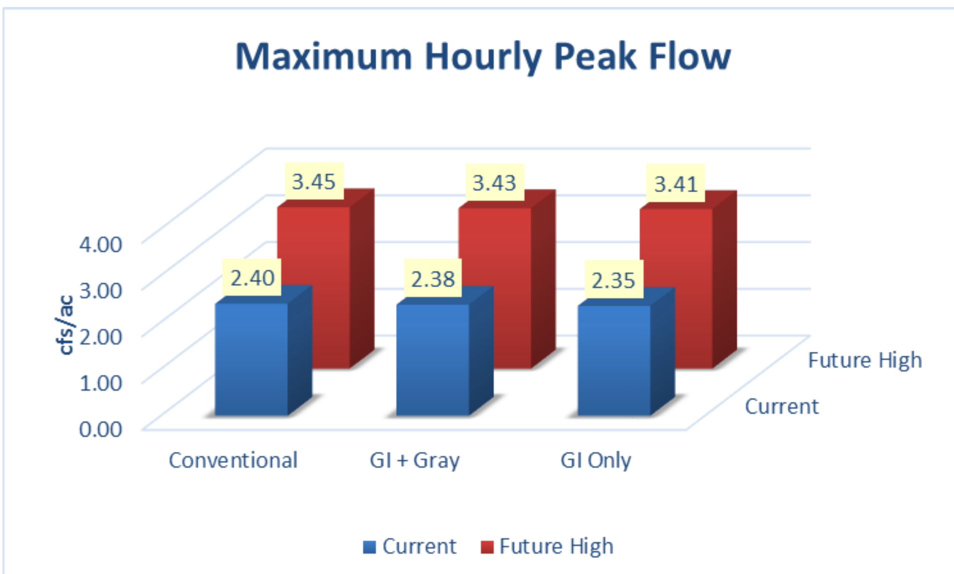

Figure 4-11. Maximum hourly peak flow under current climate and future general circulation model (GCM) high intensity scenario by stormwater management approach for Scott County, MN.

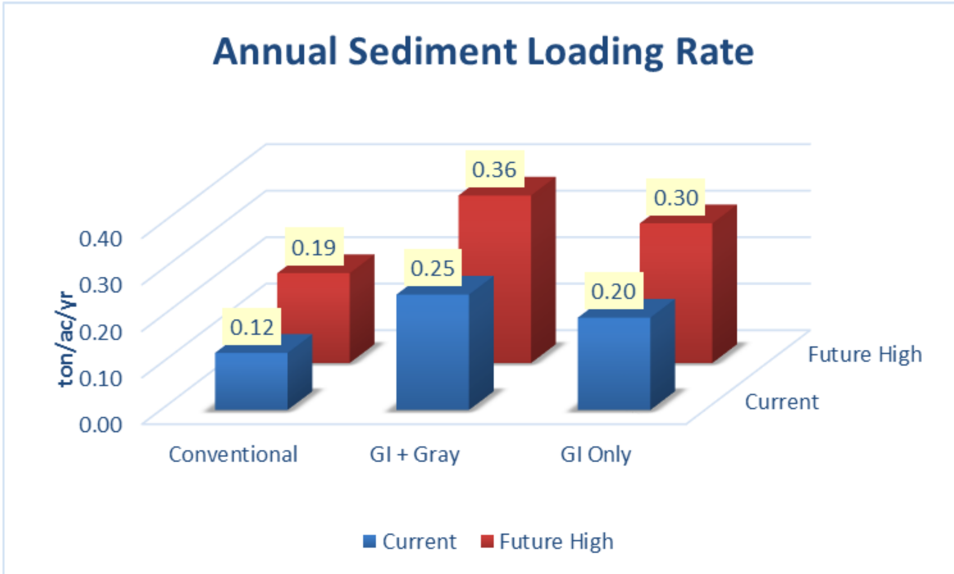

Figure 4-12. Annual sediment loading rate under current climate and future general circulation model (GCM) high intensity scenario by stormwater management approach for Scott County, MN.

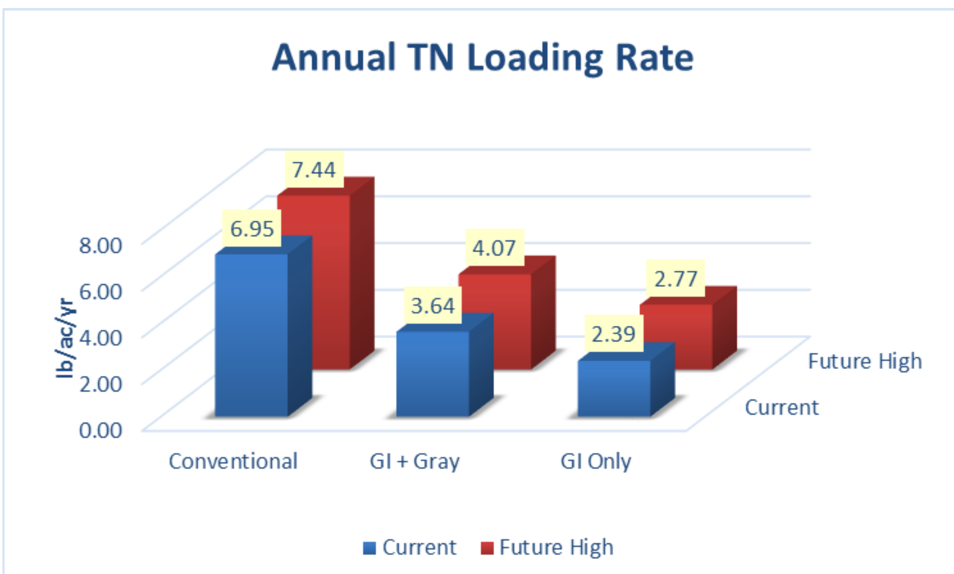

Figure 4-13. Annual total nitrogen (TN) loading rate under current climate and future general circulation model (GCM) high intensity scenario by stormwater management approach for Scott County, MN.

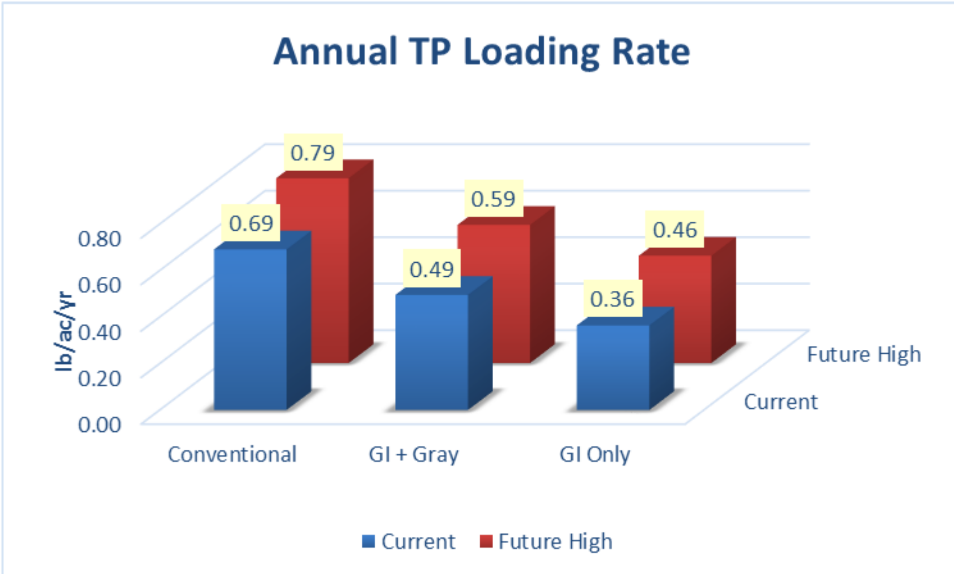

Figure 4-14. Annual total phosphorous (TP) loading rate under current climate and future general circulation model (GCM) high intensity scenario by stormwater management approach for Scott County, MN.

As discussed in *Section 3.5.* , for Harford County the GI + Gray stormwater management approach appeared to be more resilient to climate change in terms of raw increase in annual stormwater runoff and nutrient load export. An examination of the results of the three stormwater management approaches for Scott County does not reveal a similar trend. The increases in annual runoff, highest hourly peak flow, sediment loads, and nutrient loads are all similar. In other words, the stormwater management approach had little effect on changes in site runoff and pollutant loading. The reason for the difference between Harford County and Scott County is not known, but may be related to the low permeability of the soils for the Scott County site.

Table 4-5 summarizes the increases in BMP footprints for the Scott County stormwater management scenarios that would be required in order to maintain or exceed current performance under future climate conditions. The current and adapted footprints are presented both in terms of actual square feet of practice as well as percentage of overall site area. The latter is provided as a means of comparing the current and future adapted sizes relative to the site area (30 acres) for this particular development type (residential). Results are discussed separately for each of the future climate scenarios modeled for the Scott County site.

Table 4-5. Comparison of current and future adapted best management practice (BMP) footprints for Scott County, MN stormwater management scenarios

Future climate scenario	Stormwater management scenario	Practice	Current: Footprint SF	Current: Footprint as % of site area	Future adapted: Footprint SF	Future adapted: Footprint as % of site area	% increase in footprint
GCM medium intensity	Conventional (Gray) Infrastructure	Wet pond	32,670	2.5	107,811	8.3	230
	GI with Gray Infrastructure	Bioretention	34,848	2.7	58,848	4.5	69
		Dry detention basin	26,136	2.0	32,336	2.5	24
	GI Only	Bioretention (modified)	43,275	3.3	71,675	5.5	66
		Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
		Permeable pavement	39,390	3.0	39,390	3.0	0
	Conventional (Gray) Infrastructure with Distributed GI	Wet pond	32,670	2.5	32,670	2.5	0
		Distributed bioretention	0	0.0	18,280	1.4	--
GCM high intensity	Conventional (Gray) Infrastructure	Wet pond	32,670	2.5	128,066	9.8	292
	GI with Gray Infrastructure	Bioretention	34,848	2.7	93,286	7.1	168
		Dry detention basin	26,136	2.0	123,136	9.4	371
	GI Only	Bioretention (modified)	43,275	3.3	111,735	8.6	158
		Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
		Permeable pavement	39,390	3.0	39,390	3.0	0
	Conventional (Gray) Infrastructure with Distributed GI	Wet pond	32,670	2.5	32,670	2.5	0
		Distributed bioretention	0	0.0	56,770	4.3	--
Percentage difference plus 10%	Conventional (Gray) Infrastructure	Wet pond	32,670	2.5	107,484	8.2	229
	GI with Gray Infrastructure	Bioretention	34,848	2.7	70,348	5.4	102
		Dry detention basin	26,136	2.0	26,136	2.0	0
	GI Only	Bioretention (modified)	43,275	3.3	80,405	6.2	86
		Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
		Permeable pavement	39,390	3.0	39,390	3.0	0
	Conventional (Gray) Infrastructure with Distributed GI	Wet pond	32,670	2.5	32,670	2.5	0
		Distributed bioretention	0	0.0	17,500	1.3	--

Table 4 5. Comparison of current and future adapted best management practice (BMP) footprints for Scott County, MN stormwater management scenarios (Continued)

Future climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Percentage difference plus 20%	Conventional (Gray) Infrastructure	Wet pond	32,670	2.5	172,171	13.2	427
	GI with Gray Infrastructure	Bioretention	34,848	2.7	83,348	6.4	139
		Dry detention basin	26,136	2.0	68,636	5.3	163
	GI Only	Bioretention (modified)	43,275	3.3	117,601	9.0	172
		Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
		Permeable pavement	39,390	3.0	39,390	3.0	0
	Conventional (Gray) Infrastructure with Distributed GI	Wet pond	32,670	2.5	32,670	2.5	0
		Distributed bioretention	0	0.0	30,500	2.3	--

Design Results - General Circulation Model (GCM) Medium Intensity

The Conventional (Gray) Infrastructure scenario uses an adapted wet pond that is 3.3 times larger than the wet pond under current climate conditions. Due to the presence of D soils at the site, the wet pond infiltration rate is negligible. As a result, a large size is needed under future climate conditions to increase ET to allow the adapted wet pond to meet the runoff volume criterion.

For the GI with Gray Infrastructure scenario, the adapted site would need a 69% increase in bioretention area and a 24% increase in the dry detention basin area, equivalent to 2.3% of the site area.

For the GI Only Infrastructure scenario, only bioretention was modified for future climate adaptation. Permeable pavement and rooftop downspout disconnection were not modified for two reasons:
(1) permeable pavement is already implemented in 100% of sidewalk areas, and its expansion to include residential driveways and streets was considered impractical due primarily to maintenance concerns, and
(2) impervious surface disconnection is already implemented to the maximum extent practicable in this scenario for residential rooftops, and disconnection of additional impervious surface is not considered feasible. The increase in size for the adapted bioretention was 66%, or 2.2% of the site area.

The Conventional + Distributed GI Infrastructure scenario adaptation would require the addition of 18,280 square feet of bioretention (roughly 1.4% of the total site area).

Design Results - General Circulation Model (GCM) High Intensity

For the Conventional (Gray) Infrastructure scenario, the adapted wet pond is nearly four times larger than the current wet pond. The adapted size is larger for this climate scenario than for the GCM medium intensity change scenario due to greater precipitation volume. The GI with Gray Infrastructure scenario resulted in an adapted bioretention footprint that was approximately 2.7 times larger than the current footprint, and the adapted dry detention basin footprint that was approximately 4.7 times larger than the current footprint. For the GI Only Infrastructure scenario, the adapted bioretention footprint was 158% of the size under current conditions, or 5.3% of the site area. The Conventional + Distributed GI Infrastructure scenario adaptation would require the addition of 56,770 square feet of bioretention (roughly 4.3% of the total site area).

Design Results - Intensity Change Plus 10%

Adaptation for the Conventional (Gray) Infrastructure scenario would require the wet pond footprint to increase by nearly 3.3 times, which is analogous to the GGM medium intensity change scenario. For the GI with Gray Infrastructure scenario, no increase in the dry detention basin footprint was required, but the bioretention footprint would need to more than double in size. Adaptation for the GI Only scenario would require an 86% increase in bioretention footprint. When distributed GI is added to the Conventional (Gray) Infrastructure scenario for adaptation, the required bioretention footprint of 17,500 square feet would comprise approximately 1.3% of the total site area.

Design Results - Intensity Change Plus 20%

Adaptation for the Conventional (Gray) Infrastructure scenario would require the wet pond footprint to increase by nearly 4.3 times, greater even that for the GCM high intensity change scenario. For the GI with Gray Infrastructure scenario, the dry detention basin footprint would need to increase by 163%, and the bioretention footprint would need to increase by 139%. Adaptation for the GI Only scenario would require a 172% increase in bioretention footprint. When distributed GI is added to the Conventional (Gray) Infrastructure scenario for adaptation, the required bioretention footprint of 30,500 square feet would comprise approximately 2.3% of the total site area.

Table 4-6 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all of the Scott County stormwater management scenarios. Refer to *Section 2.5.2.* of the report for a discussion on how the infrastructure cost estimates were developed. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site. These three metrics represent three alternative methods for evaluating the cost of adaptation, which is effectively the increase in cost between the current and future adapted climate scenarios.

Table 4-6. Comparison of current and future adapted 20-year present value costs for the Scott County, MN stormwater management scenarios

Future climate scenario	Stormwater management scenario	Current cost (20-yr present value, $millions)	Future adapted cost (20-yr present value, $millions)	Increase in cost (20-yr present value, $millions)	% Increase in cost	Increase per acre of site ($millions)
GCM medium intensity	Conventional (Gray) Infrastructure	3.05	8.99	5.94	195	0.30
	GI with Gray Infrastructure	4.92	7.37	2.46	50	0.12
	GI Only	8.51	11.80	3.29	39	0.16
	Conventional (Gray) Infrastructure with Distributed GI	3.05	4.69	1.65	54	0.08
GCM high intensity	Conventional (Gray) Infrastructure	3.05	10.59	7.54	248	0.38
	GI with Gray Infrastructure	4.92	14.82	9.90	201	0.50
	GI Only	8.51	16.44	7.93	93	0.40
	Conventional (Gray) Infrastructure with Distributed GI	3.05	8.16	5.11	168	0.26
Percentage difference plus 10%	Conventional (Gray) Infrastructure	3.05	8.96	5.92	194	0.30
	GI with Gray Infrastructure	4.92	8.11	3.20	65	0.16
	GI Only	8.51	12.76	4.25	50	0.21
	Conventional (Gray) Infrastructure with Distributed GI	3.05	4.62	1.58	52	0.08
Percentage difference plus 20%	Conventional (Gray) Infrastructure	3.05	14.08	11.03	362	0.55
	GI with Gray Infrastructure	4.92	11.31	6.40	130	0.32
	GI Only	8.51	17.12	8.61	101	0.43
	Conventional (Gray) Infrastructure with Distributed GI	3.05	5.79	2.75	90	0.14

Cost Results - General Circulation Model (GCM) Medium Intensity

For the Conventional (Gray) scenario, the cost of adaptation is estimated to increase by $5.94 million, or 195%, compared with the current cost. This is equivalent to a cost of adaptation of $0.30 million per acre of site area.

For the GI with Gray scenario, the cost of adaptation is estimated to increase by $2.46 million, or 50% compared to the current cost. The increase in cost per acre of site is estimated to be $0.12 million.

The GI Only scenario adaptation to future climate resulted in a $3.29 million increase in cost, a 39% increase. When normalized to site area, the increase is estimated to be $0.16 million per acre.

Implementing distributed green practices (bioretention) to address the performance gap between current and future climate comes at an estimated cost increase of $1.65 million, an increase of 54%. On a cost per site acre basis, the estimated cost of adaptation is $0.08 million per acre of site area.

Cost Results - General Circulation Model (GCM) High Intensity

For the Conventional (Gray) scenario, the cost of adaptation is estimated to increase by $7.54 million, or 248% compared to the current cost. This is equivalent to a cost of adaptation of $0.38 million per acre of site area.

For the GI with Gray scenario, the cost of adaptation is estimated increase by $9.90 million, or 201% compared to the current cost. On a cost per site acre basis, the estimated cost of adaptation is $0.50 million per acre of site area.

For the GI Only scenario, the cost of adaptation was estimated as a $7.93 million increase over the current cost, or an increase of 93%. This is equivalent to an increase of $0.40 million per acre of site area.

Implementing distributed green practices (bioretention) to address the performance gap between current and future climate comes at an estimated cost increase of $5.11 million, an increase of 168%. The increase in cost per acre of site is estimated to be $0.26 million for the Conventional with Distributed GI scenario.

Cost Results - Intensity Change Plus 10%

For the Conventional (Gray) scenario the cost of adaptation is estimated to increase by $5.92 million, or 194% compared to the current cost. This is equivalent to a cost of adaptation of $0.30 million per acre of site area.

For the GI with Gray scenario, the cost of adaptation is estimated to increase by $3.20 million increase, or 65% compared to the current cost. The increase in cost per acre of site is estimated to be $0.16 million.

For the GI Only scenario, the cost of adaptation was estimated as a $4.25 million increase over the current cost, or an increase of 50%. This is equivalent to an increase of $0.21 million per acre of site acre.

Implementing distributed green practices (infiltration trenches) to address the performance gap between current and future climate comes at an estimated cost increase of $1.58 million, an increase of 52%. On a cost per site acre basis, the estimated cost of adaptation is $0.08 million per site area.

Cost Results – Intensity Change Plus 20%

For the Conventional (Gray) scenario, the cost of adaptation is estimated to increase by $11.03 million, or 362% compared to the current cost. The increase in cost per acre of site is estimated to be $0.55 million.

The cost of adaptation for the GI with Gray scenario is estimated to increase by $6.40 million, or 130% compared to the current cost. This is equivalent to a cost of adaptation of $0.32 million per acre of site area.

For the GI Only scenario, the cost of adaptation is estimated to increase by $8.61 million, or 101% compared to the current cost. This is equivalent to an increase of $0.43 million per acre of site area.

Implementing distributed green practices (infiltration trenches) to address the performance gap between current and future climate costs an additional $2.75 million, or a 90% increase compared to current costs. On a cost per site acre basis, the estimated cost of adaptation is $0.14 million per acre of site area.

5. ARID SOUTHWEST SITE: COMMERCIAL

5.1. REGULATORY REQUIREMENTS AFFECTING STORMWATER MANAGEMENT

Maricopa County has design requirements for new development:

- Retention of runoff from the 100-year 2-hour storm event (as shown in the Maricopa County Hydrology Manual) is required. Volume shall be infiltrated, evaporated, or reused on site. The 100-year 2-hour storm event depth varies widely across Maricopa County; a value of 2.8 inches was selected from the Maricopa County Hydrology Design Manual as being typical for the portion of Maricopa County close to the selected weather station.

- If retention is not possible, then the following requirements apply:

  - The first flush volume must be treated. The volume is defined as 0.5 inch of uniform runoff from site.

  - Predevelopment peak matching is required for the 2-, 10-, 50-, and 100-year storm events. The ordinance does not state the duration, so a 2-hour event was assumed based on the storm event duration for the retention standard.

5.2. STORMWATER MANAGEMENT SCENARIOS

The 10-acre Commercial shopping center site (see Figure 5-1) is assumed to have the following characteristics in each of the scenarios:

- The site is 80% impervious, distributed as follows:

  - 30% building

  - 50% pavement

- The remaining pervious area (20%) is comprised of native vegetation/landscaping.

- The HSG percentage distribution is based on a GIS analysis of soils in Maricopa County. The HSG composition is used for sizing practices to meet the retention requirement.

  - HSG A: 1%

  - HSG B: 79%

  - HSG C: 8%

  - HSG D: 12 %

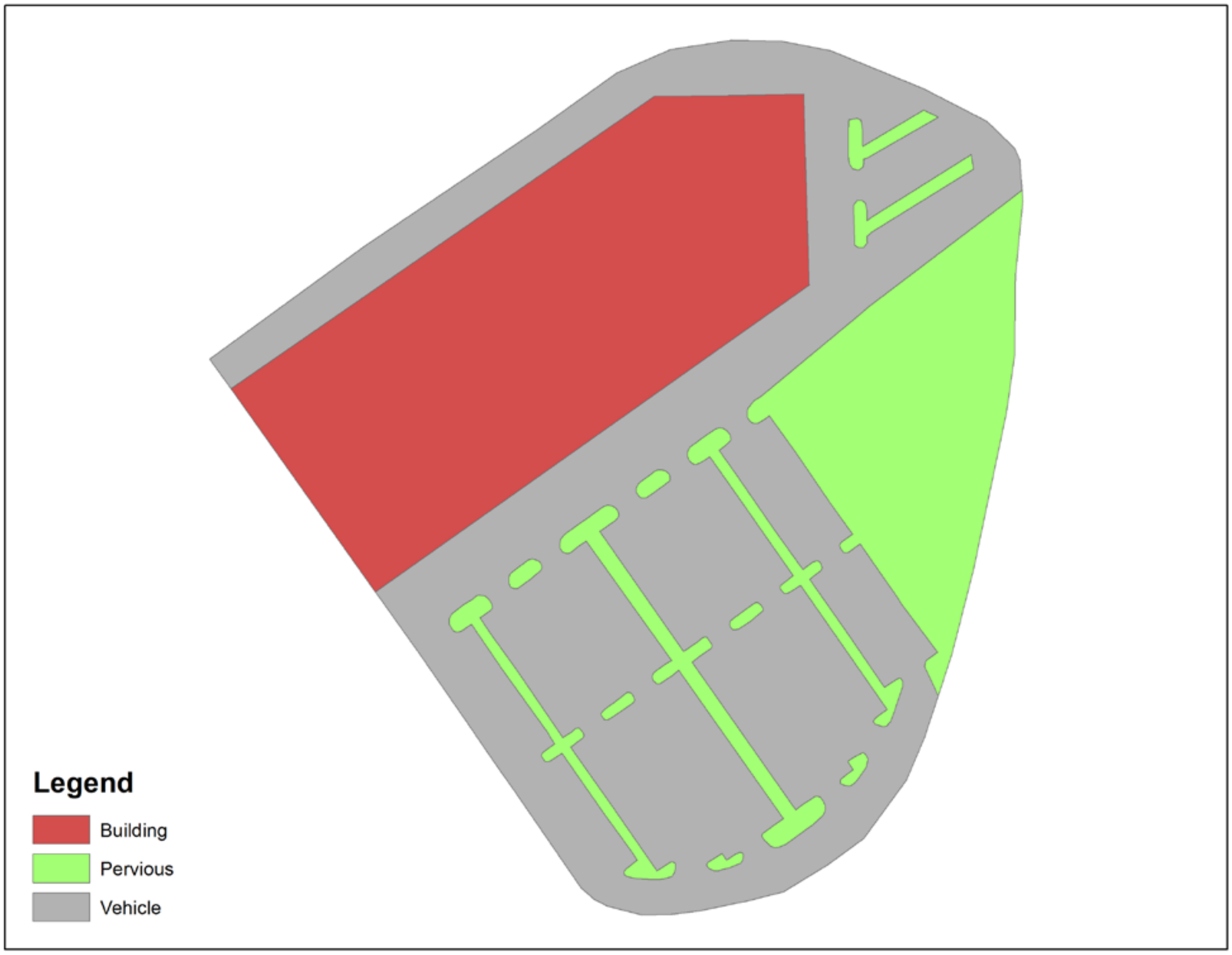

Figure 5-1. **Commercial site layout (Maricopa County, AZ).**

Two scenarios have been developed representing different approaches to stormwater management• a conventional scenario using a retention basin and a GI scenario using alternative green practices. (Note that “retention basin” is the nomenclature used by Maricopa County; it is more commonly called an infiltration basin.) The scenarios are described in the following subsections.

5.2.1. Conventional (Gray) Infrastructure

The key design elements in the Conventional (Gray) Infrastructure scenario are as follows:

- Entire site is treated by a retention basin. The basin provides full infiltration of the required volume.
- The peak-matching requirement is automatically met by meeting the retention requirement.

As shown in Figure 5-2 for the Conventional scenario, site runoff is conveyed to a single infiltration basin. The basin has a relatively large surface area to minimize the depth stored during the 100-year event, thus allowing the entire volume to infiltrate within 36 hours per design requirements. An emergency spillway provides discharge for events exceeding the 100-year design event.

Figure 5-2. Commercial Conventional (Gray) Infrastructure stormwater management scenario (Maricopa County, AZ).

For SUSTAIN, the retention basin was sized using design guidance from Maricopa County. Because the basin was designed to fully infiltrate the design storm (100-year 2-hour event), no additional routing calculations were needed. A large spillway was included for volumes exceeding the design capacity. An infiltration rate of 0.7 inches/hour was used, based on the rate needed to fully infiltrate the design volume within 36 hours. An investigation into GIS soil survey properties in the portion of Maricopa County associated with the selected meteorological station showed that infiltration rates in excess of 0.7 inches/hour are common. ET was also modeled in SUSTAIN from the retention basin.

5.2.2. Green Infrastructure (GI) Only

The key design elements in the GI Only scenario are as follows:

- The GI practices are configured to meet the retention requirement.
- The Pima County (Tucson, AZ) LID Manual is used to provide design guidance for the GI practices because Maricopa County does not currently have design guidance for GI.
- In the parking areas, approximately 50% of the pavement is permeable. Runoff from adjacent conventional pavement and pervious areas flows onto the permeable pavement.
- The remaining paved area drains to bioretention.
- The entire roof drains to a large cistern.
- It is not possible to guarantee that the cistern will be completely empty prior to the 100-year 2-hour storm event, so cistern overflow is routed to a stormwater harvesting basin. A stormwater harvesting basin is a shallow vegetated basin with storage that provides for infiltration. The stormwater harvesting basin is assumed to have one-half the storage capacity of the cistern.
- Runoff captured and stored by the cistern is used to irrigate landscaping in the stormwater harvesting basin. Water is released at a slow constant rate; the entire cistern, if full, would take about 60 days to empty completely. The application rate is based on applying approximately 1.3 inches/week of irrigation to the stormwater harvesting basin.

Figure 5-3 provides the BMP locations and drainage network for the GI Only scenario. Permeable pavement (using pervious concrete or asphalt) is used for site parking areas; the permeable pavement fully addresses the 100-year storm event capture volume using a stone storage layer below the pavement matrix. The pavement surrounding the building is of conventional design, and its drainage is conveyed to the two bioretention cells either via culvert or sheet flow. The bioretention cells are configured to fully store the required 100-year storm event volume. The rooftop drains to a large cistern, which is also configured to store the entire 100-year event volume. Overflow from the cistern is routed to the stormwater harvesting basin. If the cistern whose water can be used to irrigate the stormwater harvesting basin at a low, constant rate is completely full, a pump is assumed to fully drain it within about 6 days.

For the SUSTAIN configuration, the Pima County LID Manual provided the primary source for design guidelines. Due to the high underlying infiltration rates, underdrains were not used for any of the GI components. Infiltration rates were set to 0.7 inches/hour for all practices except the cistern. ET was also modeled for bioretention and the stormwater harvesting basin. A small amount of ET from permeable pavement was assumed, equal to 10% of ET that would normally take place. No ET was assumed to take place for the water stored in the cistern.

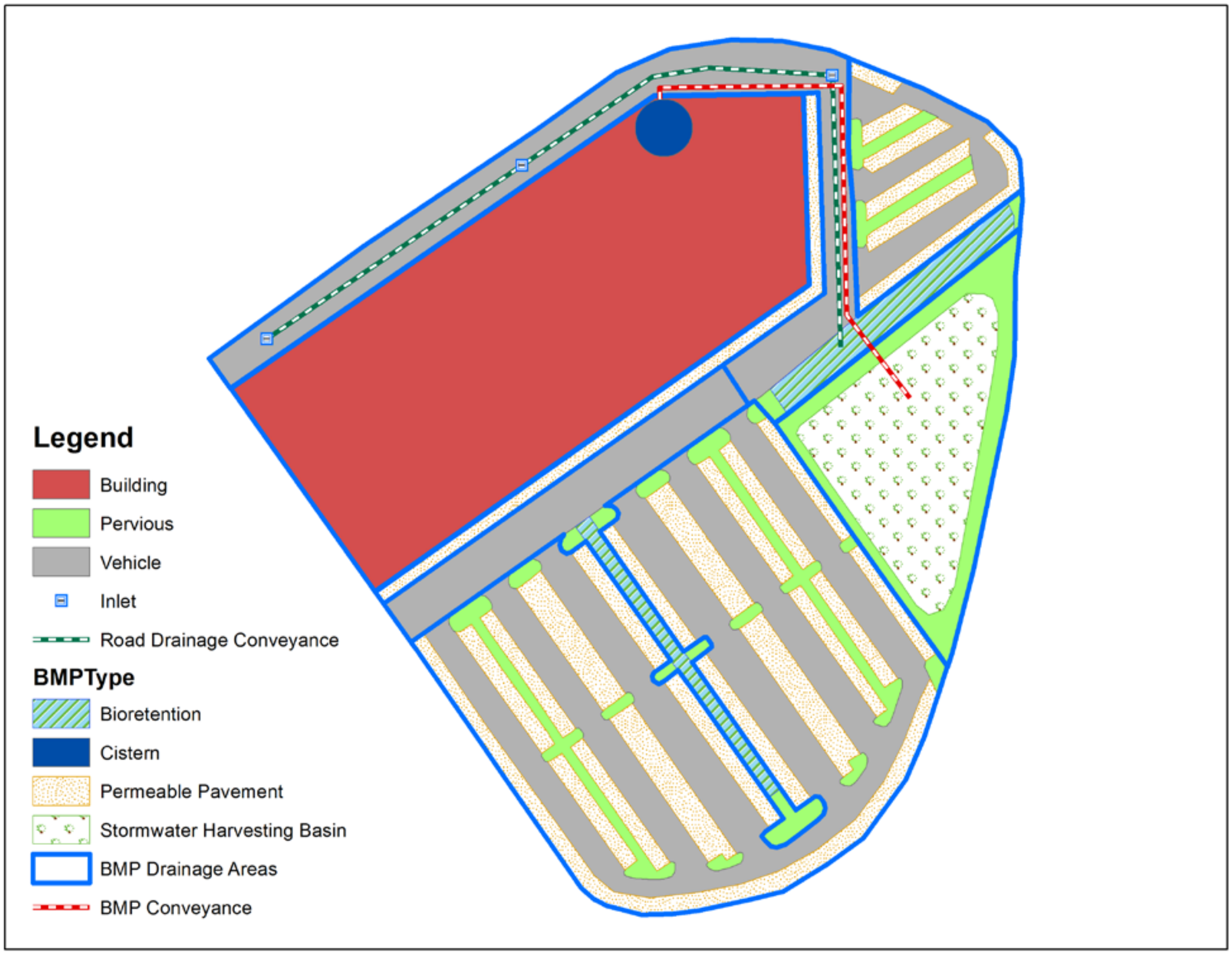

Figure 5-3. Commercial Green Infrastructure (GI) Only stormwater management scenario (Maricopa County, AZ).

5.3. ADAPTATION SIMULATION

The objective of the adaptation simulation is to determine the increases in BMP footprint (surface area) that would be required to maintain or exceed current performance under future climate conditions for each stormwater management scenario. *Table* 5-1 summarizes the key components of the modeling procedure for each scenario.

Table 5-1. Features of adaptation simulation for Maricopa County, AZ

Location	Stormwater management scenario	Future adaptation	Affected practices
Maricopa County, AZ	Conventional (Gray) Infrastructure	Resize practices	Infiltration basin
	GI Only	Resize practices	Permeable pavement, bioretention, cistern, stormwater harvesting basin

5.4. CURRENT AND FUTURE CHANGES IN PRECIPITATION

Maricopa County is located in the arid Southwest, where annual precipitation volume is much lower than at the other locations in the study. The climate station selected for the modeling is a short distance outside Maricopa County to the northeast. The Salt River watershed selected for the "20 Watersheds" project borders Maricopa County, and the climate station was the closest available. Annual precipitation across Maricopa County is highly variable, ranging from less than 5 to over 20 inches per year.[1] Annual average precipitation at the climate station used in this analysis is over 18 inches per year, which is at the high end of the range for the county.

The annual precipitation comparison shown in Figure 5-4 reveals that projected future conditions are highly variable, with increases seen in some years and decreases in other years. (Note that 29 years were used in the Maricopa County SUSTAIN simulations rather than the 30 years used for the other locations.) Average annual totals are 18.4 inches for current conditions and 19.6 inches for future conditions, reflecting a change of 6.5%. Monthly changes are somewhat variable, with the largest changes in January (see Figure 5-5). In addition, daily sums of precipitation depth were calculated and were used to determine percentiles of 24-hour depth of interest to stormwater managers (see *Table* 5-2). While daily sums do not provide a true measure of storm event depth (storms have variable lengths and may span more than 1 day), they do provide useful information about expected depths over a 24-hour period. The change in depth between current and future ranges from no change for the 85th percentile to 0.80 inches for the 99th percentile. Note that 0.80 inches is the single largest change for the 99th percentile across all of the geographic locations.

The comparison of the highest hourly precipitation volumes shown in Figure 5-6 indicates a steadily increasing gap between current and future intensity, ranging from 1.2× at the 1-year recurrence interval to as much as 1.8× at the highest recurrence interval.

[1]http://www.fcd.maricopa.gov/Weather/Rainfall/raininfo.aspx.

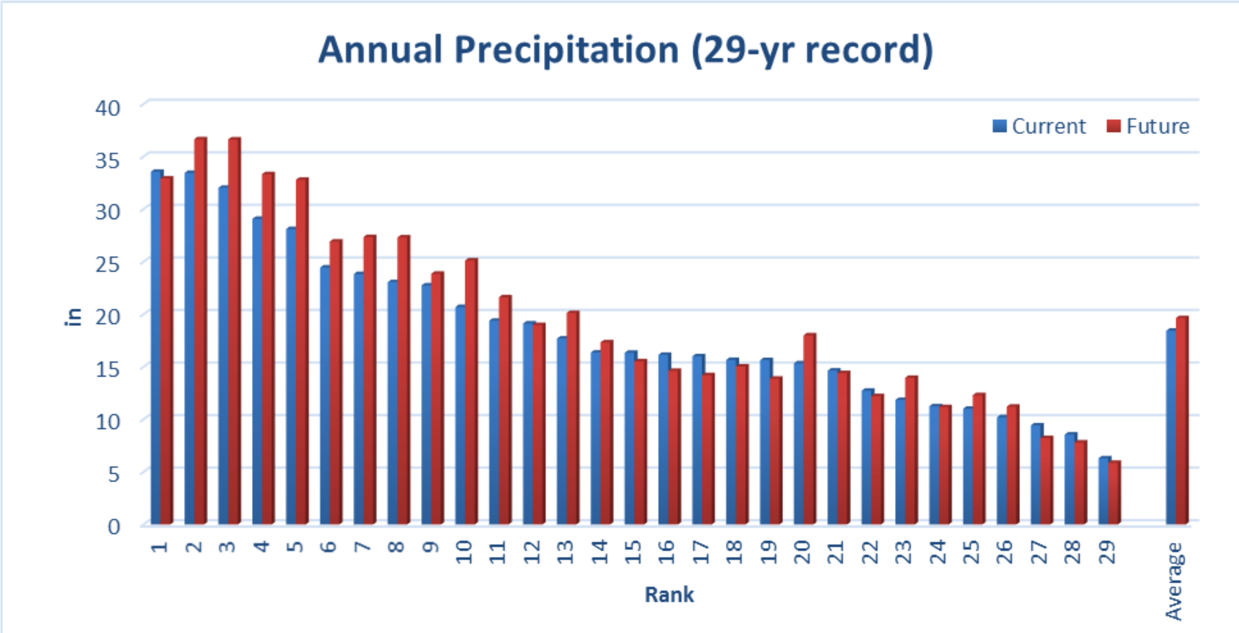

Figure 5-4. **Ranked annual precipitation for current conditions and high intensity future climate scenario at Maricopa County, AZ.**

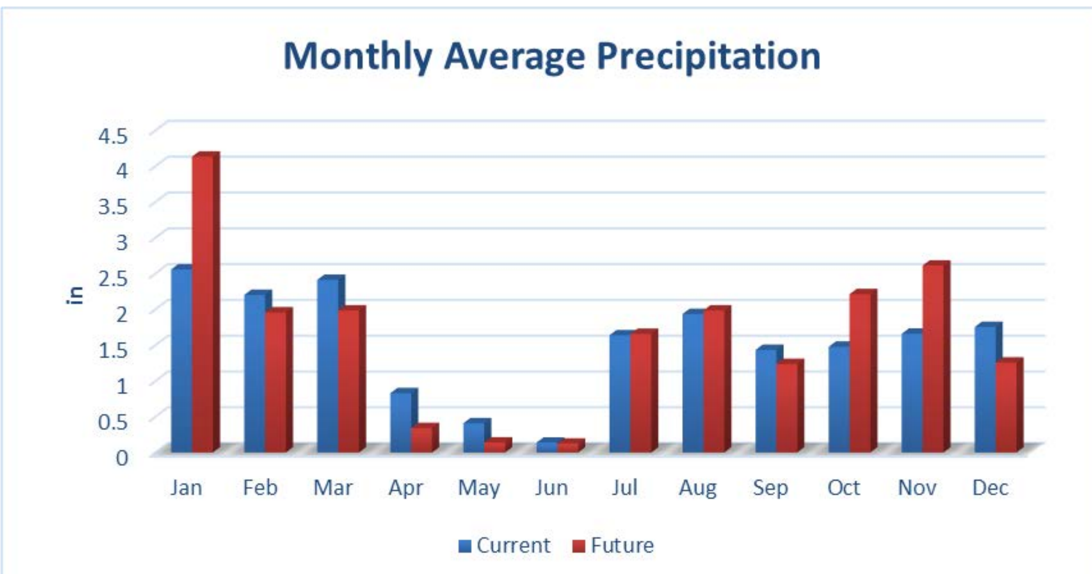

Figure 5-5. **Monthly average precipitation for current conditions and high intensity future climate scenario at Maricopa County, AZ.**

Table 5-2. 24-hour precipitation depth percentiles for current conditions and high intensity future climate scenario at Maricopa County, AZ

Percentile	Current conditions 24-h depth (in)	Future climate 24-h depth (in)	Change (+/−in)
85th	0.71	0.71	0.00
90th	0.91	0.94	+0.02
95th	1.16	1.57	+0.41
99th	1.99	2.79	+0.80

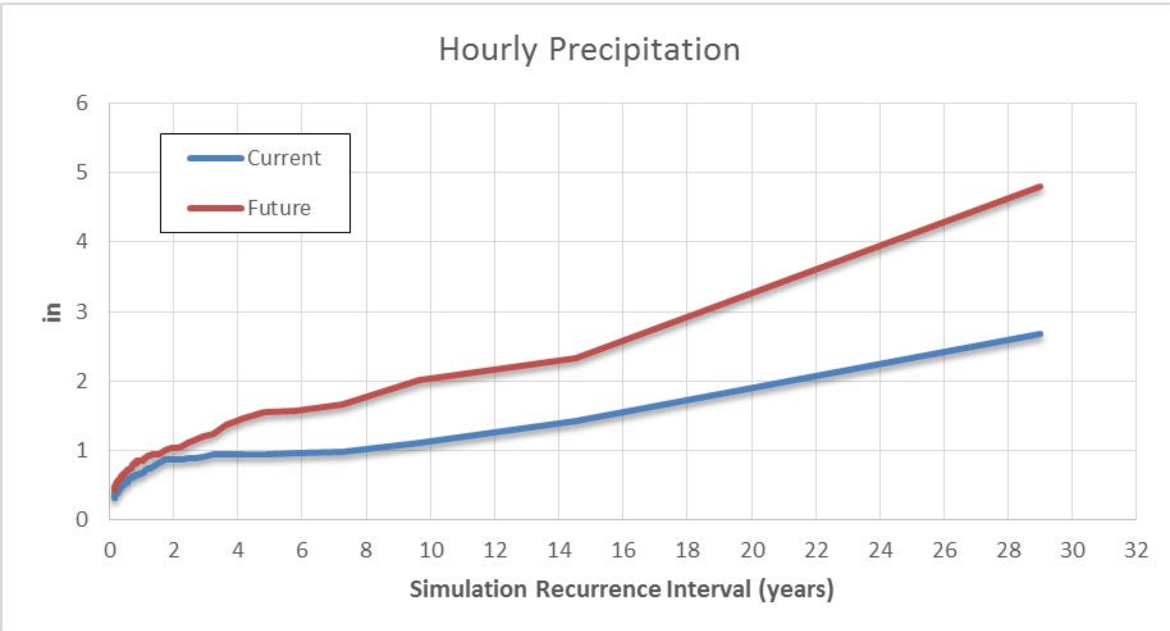

Figure 5-6. Hourly precipitation recurrence interval for current conditions and high intensity future climate scenario at Maricopa County, AZ.

5.5. RESULTS

SUSTAIN was run for the following conditions for each stormwater management scenario:

- Current climate, site without stormwater management/BMPs
- Future climate, site without stormwater management/BMPs
- Current climate, site with stormwater management/BMPs
- Future climate, site with stormwater management/BMPs
- Future climate, site with BMPs adapted to meet current hydrology and water quality performance

As shown in *Table* 5-3, two sets of SUSTAIN runs were performed for a combination of two stormwater management approaches and one climate scenario.

Table 5-3. Stormwater management and climate scenarios for of Maricopa County, AZ

Stormwater management approach	GCM high intensity
Conventional	X
GI + Gray	X

A full presentation of the results of all the runs is provided in *APPENDIX B.* . For brevity, the results in this section focus on a few topics of interest to stormwater managers: (1) a comparison of the site performance with BMPs between current and future climate conditions, (2) the increases in BMP footprints needed to offset impacts of climate change when BMPs are adapted using SUSTAIN optimization, and (3) a comparison of current stormwater infrastructure costs to future costs when BMPs are adapted to offset impacts of climate change.

For the comparison of the site performance with BMPs between current and future climate conditions, the downscaled Future GCM (high intensity change) scenario was selected for the comparison. A discussion of other topics of interest are provided in the general conclusions *Section 8.* , including changes in pretreatment site performance, changes in post-treatment site performance, climate scenario sensitivity analysis, and adapting BMPs under future climate to meet current performance.

Rather than comparing the performance of the stormwater management approaches independent of climate change (i.e., how much better does one perform than the other under current conditions), this study focuses on how the stormwater management approaches compare *relative to climate change. Table* 5-4 provides current and future performance for the stormwater management approaches, normalized to area. Note that there is no numeric measure of change in the FDC between current and future climate, so the highest hourly peak flow during the simulation is presented as a proxy for large storm event response. Figure 5-7 through Figure 5-11 present each metric graphically from *Table* 5-4.

Table 5-4. Current and future performance of Maricopa County, AZ site by stormwater management approach

Stormwater management approach	Current	Future	Change
Runoff (inch/yr)			
Conventional	0.000	0.075	+0.075
GI Only	0.000	0.065	+0.065
Maximum hourly peak flow (cfs/ac)			
Conventional	0.000	0.673	+0.673
GI Only	0.001	0.640	+0.638
Sediment (ton/ac/yr)			
Conventional	0.000	0.018	+0.018
GI Only	0.000	0.049	+0.049
TN (lb/ac/yr)			
Conventional	0.000	0.013	+0.013
GI Only	0.000	0.012	+0.011
TP (lb/ac/yr)			
Conventional	0.0000	0.0005	+0.0005
GI Only	0.0000	0.0057	+0.0057

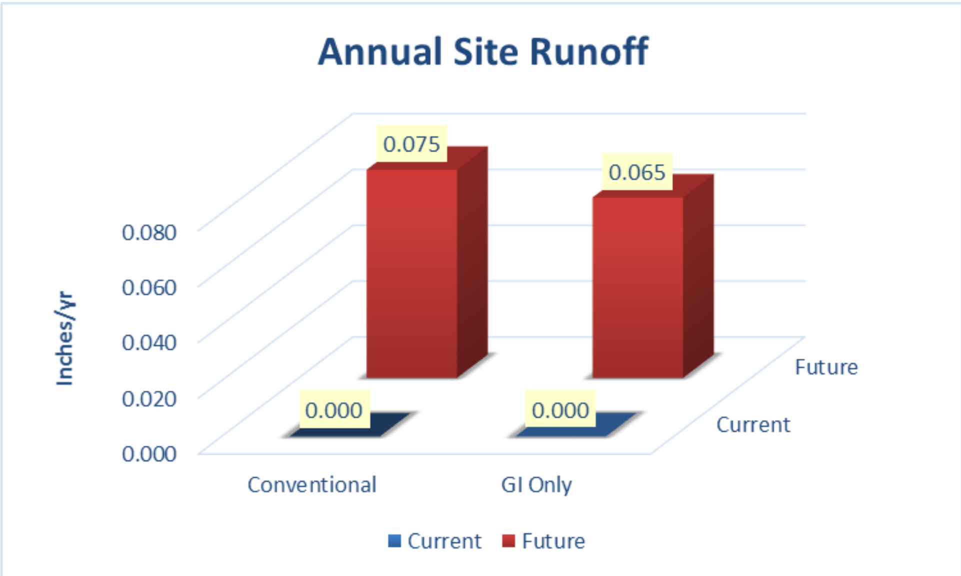

Figure 5-7. Annual site runoff under current climate and future general circulation model (GCM) scenario by stormwater management approach for Maricopa County, AZ.

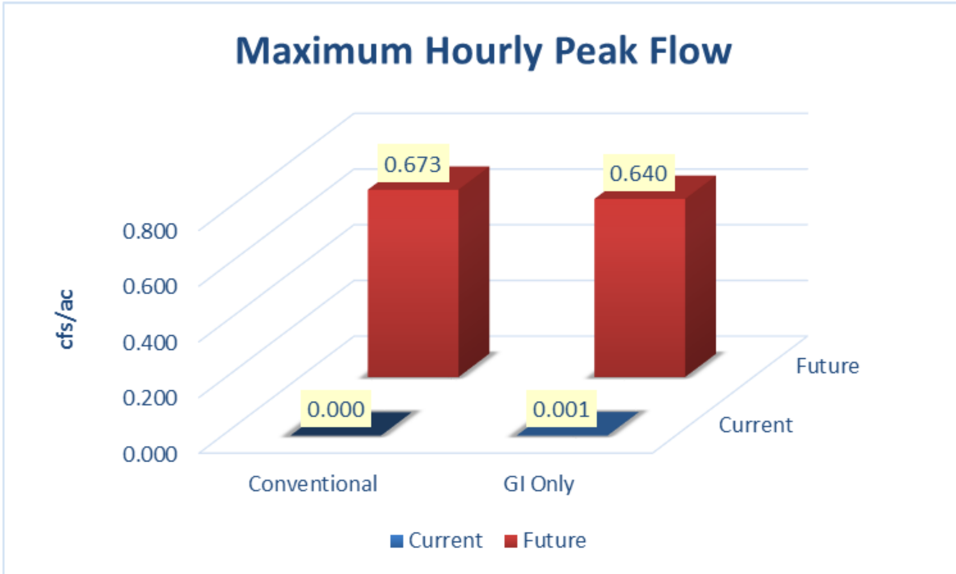

Figure 5-8. Maximum hourly peak flow under current climate and future general circulation model (GCM) scenario by stormwater management approach for Maricopa County, AZ.

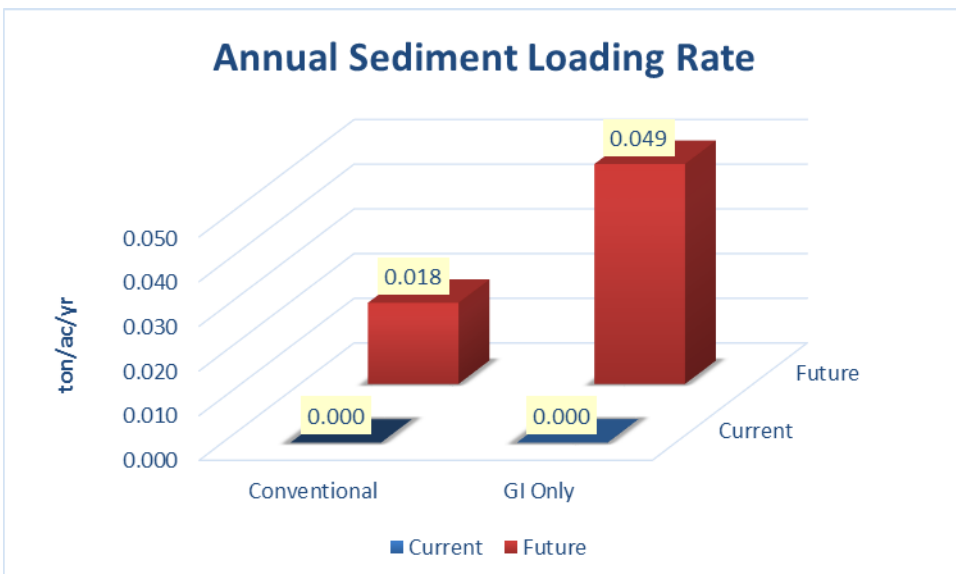

Figure 5-9. Annual sediment loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Maricopa County, AZ.

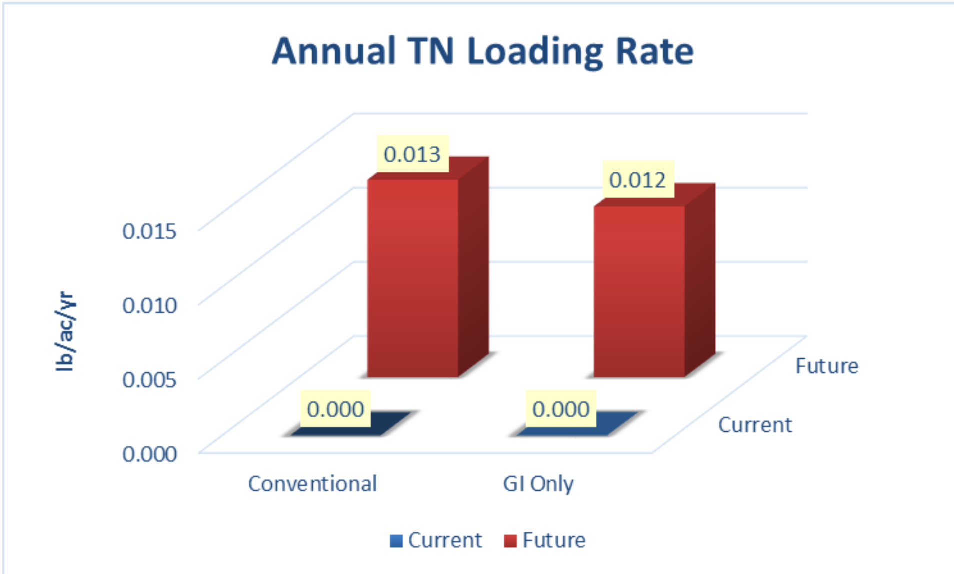

Figure 5-10. Annual TN loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Maricopa County, AZ.

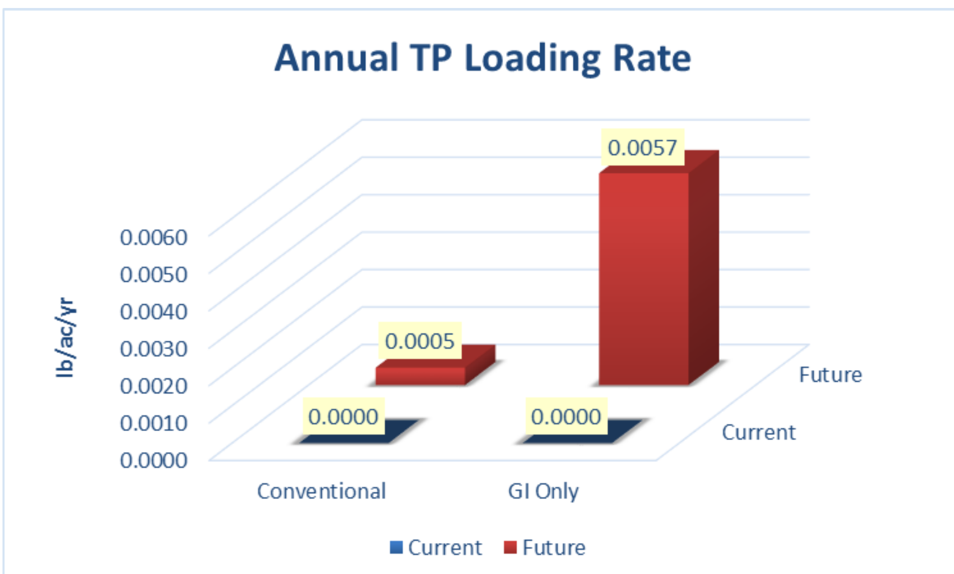

Figure 5-11. Annual TP loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Maricopa County, AZ.

As discussed in the Results sections for Harford County, MD and Scott County, MN, the resiliency of the stormwater management approaches relative to each other can be assessed by analyzing the increase in runoff, peak flow, and pollutant loading due to projected climate change. The first thing apparent when looking at the Maricopa County results is that there is practically no runoff from either stormwater management approach under current conditions. This is not surprising because the design standard calls for zero discharge up to the 100-year storm event, and there are only 30 years of meteorology in the HSPF and SUSTAIN simulations. Nevertheless, as a result of climate change there is a small amount of discharge• less that one tenth of an inch per year on average. The amount of runoff is comparable for the Conventional and GI Only approaches, as is the maximum hourly peak flow and TN loading rate. There is, however, a substantially larger increase in the sediment and TP loading rates for the GI Only scenario. The future climate simulation for Maricopa County contains an especially intense precipitation event resulting in a short period of high sediment erosion. TP is represented as sediment-associated, so both were elevated in runoff during the storm event. The reason that the GI Only approach captures less of the sediment and phosphorus load increases is not known. It is important to note that while the GI + Gray approach has a much higher increase in the two loading rates, the changes are still very small.

Table 5-5 summarizes the increases in BMP footprints for the Maricopa County stormwater management scenarios that would be required to maintain or exceed current performance under future climate conditions. The current and adapted footprints are presented both in terms of actual square feet of practice as well as percentage of overall site area. The latter is provided as a means of comparing the current and future adapted sizes relative to the site area (10 acres) for this particular development type (commercial).

The Conventional (Gray) Infrastructure scenario showed a 44% increase in infiltration basin size (the sole practice) to address future climate change impacts under the GCM high intensity change climate scenario. This represents an increase of 5.0% of the site area, or 0.5 acres. On the other hand, the combined increase in area for the four practices modeled under the GI Only stormwater management scenario is 16.2%, or 1.62 acres.

Table 5-6 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all of the Maricopa County stormwater management scenarios. Refer to *Section 2.5.2.* of the report for a discussion on how the infrastructure cost estimates were developed. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site. These three metrics represent three alternative methods for evaluating the cost of adaptation, which is effectively the increase in cost between the current and future adapted climate scenarios.

For the Conventional (Gray) scenario, the cost of adaptation is estimated to increase by $2.04 million, or 43% compared to the current cost. This is equivalent to a cost of adaptation of $0.20 million per acre of site area.

The cost of adaptation for the GI Only scenario is estimated to increase by $2.35 million, or 59% compared to the current cost. On a cost per site acre basis, the estimated cost of adaptation is $0.23 million per acre of site area. Interestingly, while the area increase for the GI Only scenario is nearly three times that of the Conventional scenario, the cost increases are nearly equivalent.

Table 5-5. Comparison of current and future adapted best management practice (BMP) footprints for Maricopa County, AZ stormwater management scenarios

Future climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% Increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GCM high intensity	Conventional (Gray) Infrastructure	Infiltration basin	49,997	11.5	71,776	16.5	44
	GI Only	Permeable pavement	86,382	19.8	124,482	28.6	44
		Bioretention	13,405	3.1	24,125	5.5	80
		Cistern	2,495	0.6	3,564	0.8	43
		Stormwater harvesting basin	32,034	7.4	53,034	12.2	66

Table 5-6. Comparison of current and future adapted 20-year present value costs for the Maricopa County, AZ stormwater management scenarios

Future climate scenario	Stormwater management scenario	Current cost (20-yr present value, $millions)	Future adapted cost (20-yr present value, $millions)	Increase in cost (20-yr present value, $millions)	% Increase in cost	Increase per acre of site ($millions)
GCM high intensity	Conventional (Gray) Infrastructure	4.79	6.83	2.04	43	0.20
	GI Only	3.98	6.33	2.35	59	0.23

6. SOUTHEAST SITE: ULTRA-URBAN

6.1. REGULATORY REQUIREMENTS AFFECTING STORMWATER MANAGEMENT

Atlanta has recently enacted a progressive stormwater ordinance that promotes use of GI practices, and it includes a substantial retention requirement. There is, however, a WQ treatment alternative if a site cannot meet the retention requirement. The Atlanta ordinance retains the focus on tiered volume and control requirements used in the Georgia Stormwater Manual.

- Retention of runoff from the first inch of rainfall is required (WQv). The calculation of runoff incorporates a volumetric runoff coefficient based on site impervious area. The volume must be infiltrated, evaporated, or reused on site.
- If retention is not possible, then the site practices must provide treatment to remove 80% of TSS for the WQv.
- A CPv is required as well. The CPv is equal to the runoff from 1-year 24-hour storm event, and must be discharged over a 24-hour period.
- Overbank flood protection and extreme flood protection• predevelopment peak matching is required for the 2-, 5-, 10-, 25-, and 100-year 24-hour storm events.

6.2. STORMWATER MANAGEMENT SCENARIOS

The 2-acre ultra-urban site (see Figure 6-1) is assumed to have the following characteristics in each of the scenarios:

- The site is 90% impervious, distributed as follows:
    - 45% building
    - 40% driving surfaces (parking, entry road, loading dock)
    - 5% sidewalk
- The remaining pervious area (10%) is comprised of lawn/landscaping.
- The HSG percent distribution is based on a GIS analysis of soils within Atlanta. The HSG composition is used for design storm event routing calculations to size practices for peak flow control. Predevelopment land cover is assumed to be woods in good condition.
    - HSG A: 0%
    - HSG B: 77%
    - HSG C: 8%
    - HSG D: 15%

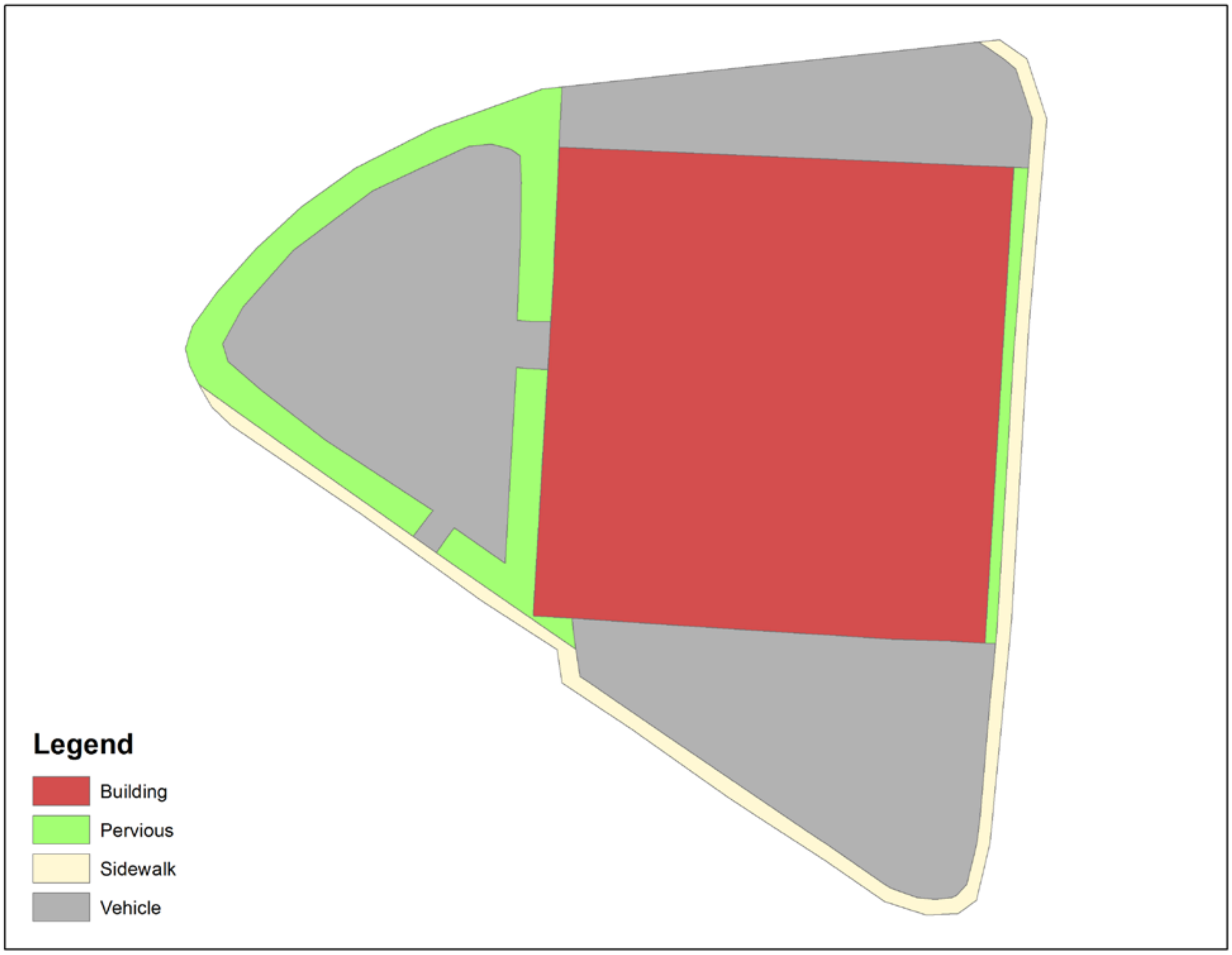

Figure 6-1. **Ultra-urban site layout (Atlanta, GA).**

Two scenarios have been developed representing different approaches to stormwater management• a conventional scenario using gray practices and a GI scenario using a combination of green and gray practices. The site's percentage impervious area is sufficiently high that it is not feasible to use only GI practices to meet the regulatory requirements. The scenarios are described in the following subsections.

6.2.1. Conventional (Gray) Infrastructure

The ultra-urban nature of the site means that pervious area is extremely limited for BMP placement. As a result, the BMP components are assumed to be located underground. The key design elements in the Conventional (Gray) Infrastructure scenario are as follows:

- The entire site is treated by an underground sand filter that meets the WQv requirement. The underground sand filter is assumed to be constructed as an enclosed vault with no contact with the underlying soil. The sand filter is located underneath a parking lot, so the design is not amenable to infiltration into the underlying soil. As a result, it is assumed that the infiltration requirement is waived.

- Underground detention is used to address the CPv and flooding requirements:
    - The CPv is discharged using a low flow orifice.
    - A weir is used for peak-matching requirements (2-, 5-, 10-, 25-, and 100-year 24-hour storms).

As shown in Figure 6-2 for the Conventional scenario, site runoff is routed to the underground sand filter via culverts. Drainage and overflow from the sand filter are routed to the underground detention basin. Runoff is then discharged off the site.

For the SUSTAIN configuration, design guidance in the Georgia Stormwater Manual was used. The sand filter was sized to capture and treat the WQv (calculated from site impervious area), with excess runoff discharged from a spillway to the detention basin. Underdrain outflow was also routed to the detention basin. The sand filter media was assumed to achieve pollutant removal rates of 86% for TSS, 30% for TN, and 60% for TP using published performance values from Center for Watershed Protection (2007) and Hirschman et al. (2008). Removal was modeled in SUSTAIN for only the volume that filtered through the sand media. For the detention basin, the CPv was estimated using procedures from the Georgia Stormwater Manual. A routing spreadsheet was used to configure a weir to achieve predevelopment peak flow matching. No pollutant removal was assigned to the detention basin. Both the sand filter and the detention basin were assumed to be enclosed in concrete vaults, so no infiltration or ET was modeled.

Figure 6-2. Ultra-urban Conventional (Gray) Infrastructure stormwater management scenario (Atlanta, GA).

6.2.2. Green Infrastructure (GI) with Gray Infrastructure

The key design elements in the GI with Gray Infrastructure scenario are as follows:

- The site GI practices meet the retention requirement.
- The building has an extensive green roof that covers about 78% of the roof area (35% of the total site area).
- Bioretention is incorporated into the site pervious area, and is configured to treat the WQv.
- Permeable pavement is used for 62.5% of the driving surface (25% of the total site area).
- Permeable pavement is used for the entire sidewalk area.
- Underground detention is used to address the remaining CPv and flood protection requirements.

The GI with Gray scenario BMPs and conveyance are shown in Figure 6-3. Pervious concrete or asphalt is used in the parking areas, and the storage layer fully captures the 100-year design storm depth. The green roof captures the water quality volume within its soil media, and excess runoff is discharged with the runoff from the remainder of the rooftop. Runoff from the roof and from the conventional pavement is conveyed to the bioretention cells north and south of the building. Overflow from the bioretention cells is routed to the underground detention basin, and then offsite.

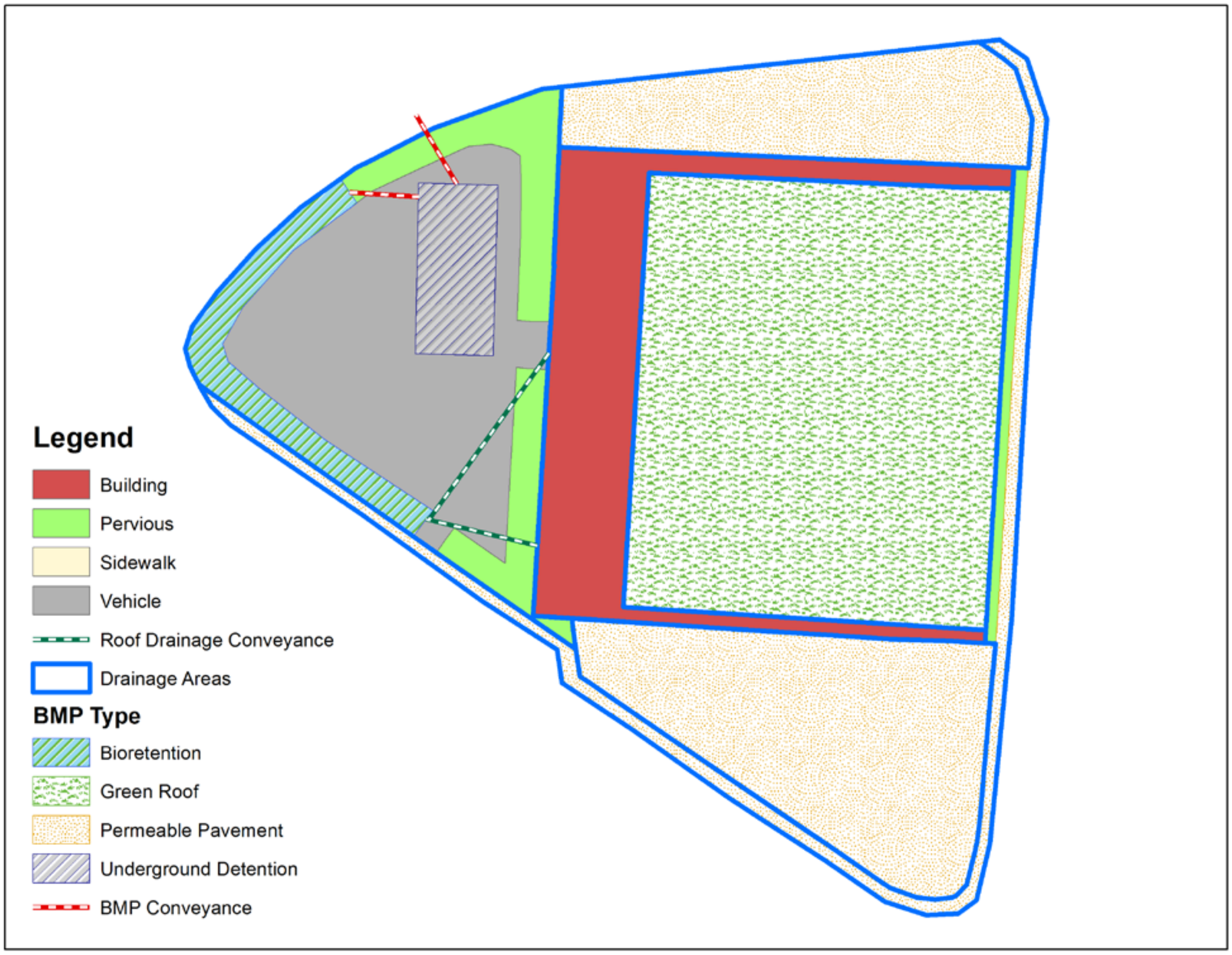

Figure 6-3. **Ultra-urban Green Infrastructure (GI) with Gray Infrastructure stormwater management scenario (Atlanta, GA).**

For the SUSTAIN configuration, practice dimensions and properties were based on design criteria and guidance from the Georgia Stormwater Manual. The green roof soil media depth was assumed to be 6 inches, with soil moisture holding properties based on Palla et al. (2008), Schneider (2011), and Latshaw et al. (2009). Both the permeable pavement and bioretention were assumed to have underdrains. For both the bioretention and the permeable pavement, 4 inches of stone base were assumed to lie below the underdrain, which allowed for a fraction of the site runoff to be infiltrated. Infiltration rates for bioretention and permeable pavement were assumed to be 0.1 inches/hour, consistent with compacted

B soils. ET was assumed for bioretention. A small amount of ET from permeable pavement was assumed, equal to 10% of ET that would normally take place. The bioretention media was assumed to achieve percentage pollutant removal rates of 78% for TSS, 57% for TN, and 63% for TP using published performance values from Center for Watershed Protection (2007) and Tetra Tech (2014). Removal was modeled in SUSTAIN for only the volume that filtered through the bioretention media and was subsequently discharged via the underdrain. A routing spreadsheet was used as described for previous site scenarios to develop the configuration for the underground detention basin to address the remaining CPv and to meet peak flow matching requirements.

6.3. ADAPTATION SIMULATION

The objective of the adaptation simulation is to determine the increases in BMP footprint (surface area) that would be required to maintain or exceed current performance under future climate conditions for each stormwater management scenario. *Table* 6-1 summarizes the key components of the modeling procedure for each scenario. In the GI with Gray Infrastructure scenario, permeable pavement is modeled but was not modified in the adaptation simulation because the ultra-urban site layout does not allow for expansion of this practice.

Table 6-1. Features of adaptation simulation for Atlanta, GA

Location	Stormwater management scenario	Future adaptation	Affected practices
Atlanta, GA	Conventional (Gray) Infrastructure	Resize practices	Underground sand filter, underground dry detention basin
	GI with Gray Infrastructure	Resize practices	Bioretention, underground dry detention basin, green roof

6.4. CURRENT AND FUTURE CHANGES IN PRECIPITATION

For the Atlanta, GA climate scenarios, the changes in average annual precipitation show an increase for all years with a low degree of variability (see Figure 6-4). Projected average annual depth increases from 55.7 to 59.4 inches, or by 6.6%. As seen in Figure 6-5, projected monthly precipitation increases in some months and decreases in other months. In addition, daily sums of precipitation depth were calculated and were used to determine percentiles of 24-hour depth of interest to stormwater managers (see *Table* 6-2). While daily sums do not provide a true measure of storm event depth (storms have variable lengths and may span more than 1 day), they do provide useful information about expected depths over a 24-hour period. As seen in the table, the change in depth between current and future ranges from 0.10 inches for the 85th percentile to 0.41 inches for the 99th percentile.

The plot of highest hourly precipitation volumes (see Figure 6-6) shows an increase of about 1.2× between the 1-year and 10-year recurrence intervals; for the two highest hourly values (15-year and 30-year recurrence), the increase is about 1.5×.

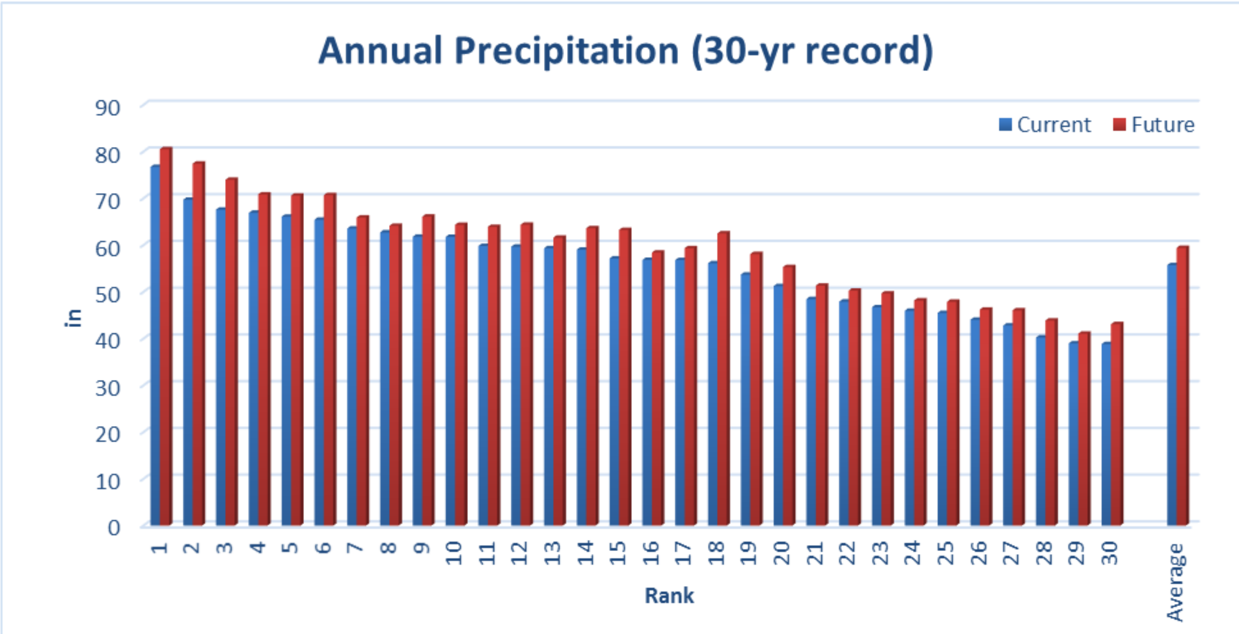

Figure 6-4. Ranked annual precipitation for current conditions and high intensity future climate scenario at Atlanta, GA.

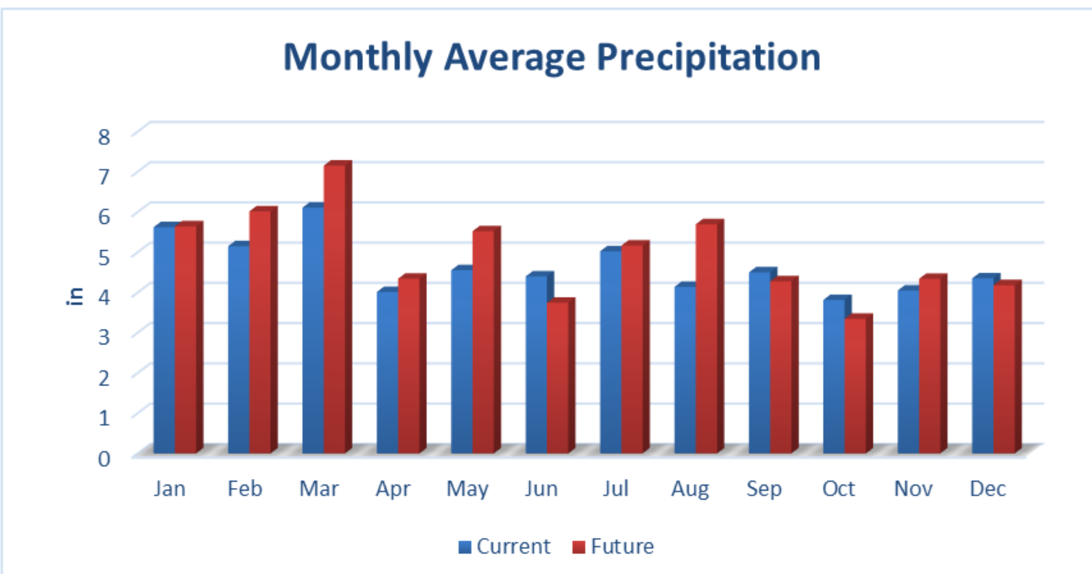

Figure 6-5. Monthly average precipitation for current conditions and high intensity future climate scenario at Atlanta, GA.

Table 6-2. 24-hour precipitation depth percentiles for current conditions and high intensity future climate scenario at Atlanta, GA

Percentile	Current conditions 24-h depth (in)	Future climate 24-h depth (in)	Change (+/−in)
85th	1.04	1.14	+0.10
90th	1.28	1.40	+0.12
95th	1.71	1.87	+0.17
99th	2.66	3.07	+0.41

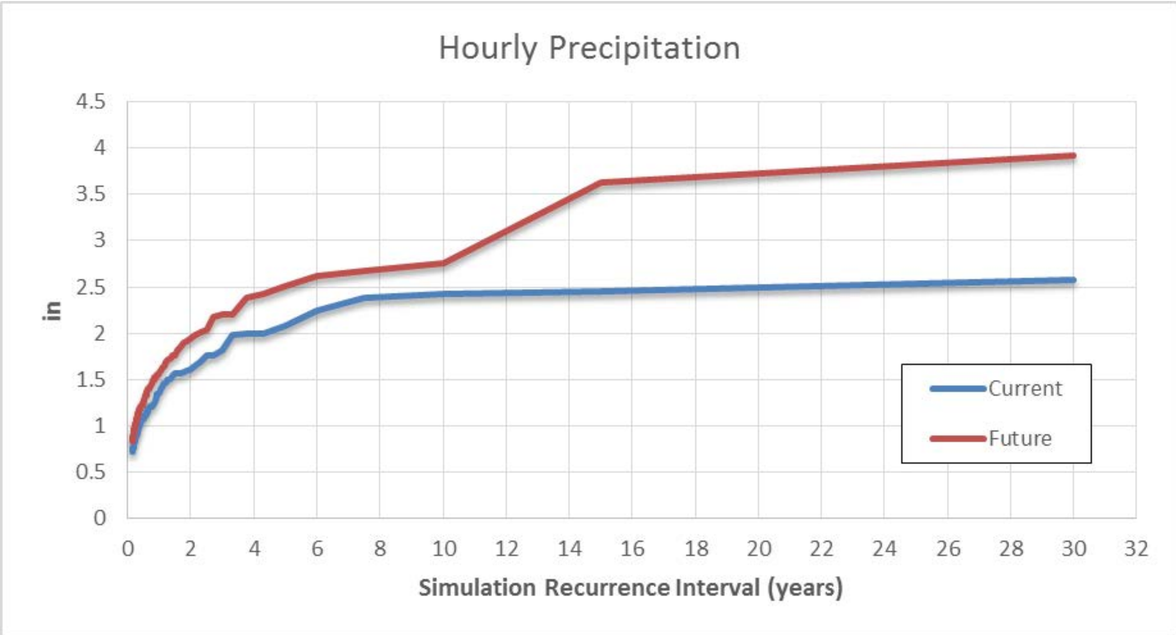

Figure 6-6. Hourly precipitation recurrence interval for current conditions and high intensity future climate scenario at Atlanta, GA.

6.5. RESULTS

SUSTAIN was run for the following conditions for each stormwater management scenario:

- Current climate, site without stormwater management/BMPs
- Future climate, site without stormwater management/BMPs
- Current climate, site with stormwater management/BMPs
- Future climate, site with stormwater management/BMPs
- Future climate, site with BMPs adapted to meet current hydrology and water quality performance

As shown in *Table* 6-3, two sets of SUSTAIN runs were performed for a combination of two stormwater management approaches and one climate scenario.

Table 6-3. Stormwater management and climate scenarios for Atlanta, GA

Stormwater management approach	GCM high intensity
Conventional	X
GI Only	X

A full presentation of the results of all the runs is provided in *APPENDIX B.* . For brevity, the results in this section focus on a few topics of interest to stormwater managers: (1) a comparison of the site performance with BMPs between current and future climate conditions, (2) the increases in BMP footprints needed to offset impacts of climate change when BMPs are adapted using SUSTAIN optimization, and (3) a comparison of current stormwater infrastructure costs to future costs when BMPs are adapted to offset impacts of climate change.

For the comparison of the site performance with BMPs between current and future climate conditions, the downscaled future GCM (high intensity change) scenario was selected for the comparison. A discussion of other topics of interest are provided in the general conclusions *Section 8.* , including changes in pretreatment site performance, changes in post-treatment site performance, climate scenario sensitivity analysis, and adapting BMPs under future climate to meet current performance.

Rather than comparing the performance of the stormwater management approaches independent of climate change (i.e., how much better does one perform than the other under current conditions), this study focuses on how the stormwater management approaches compare *relative to climate change. Table* 6-4 provides current and future performance for the stormwater management approaches, normalized to area. Note that there is no numeric measure of change in the FDC between the current and future climate, so the highest hourly peak flow during the simulation is presented as a proxy for large storm event response. Figure 6-7 through Figure 6-11 present each metric graphically from *Table* 6-4.

Table 6-4. Current and future performance of Atlanta, GA Site by stormwater management approach

Stormwater management approach	Current	Future	Change
Runoff (inch/yr)			
Conventional	43.97	47.28	+3.31
GI + Gray	15.14	16.98	+1.84
Maximum hourly peak flow (cfs/ac)			
Conventional	0.24	0.51	+0.26
GI + Gray	0.92	1.50	+0.59
Sediment (ton/ac/yr)			
Conventional	0.45	0.56	+0.11
GI + Gray	0.55	0.70	+0.16
TN (lb/ac/yr)			
Conventional	18.61	19.20	+0.59
GI + Gray	7.07	8.00	+0.93
TP (lb/ac/yr)			
Conventional	1.05	1.09	+0.03
GI + Gray	0.63	0.72	+0.09

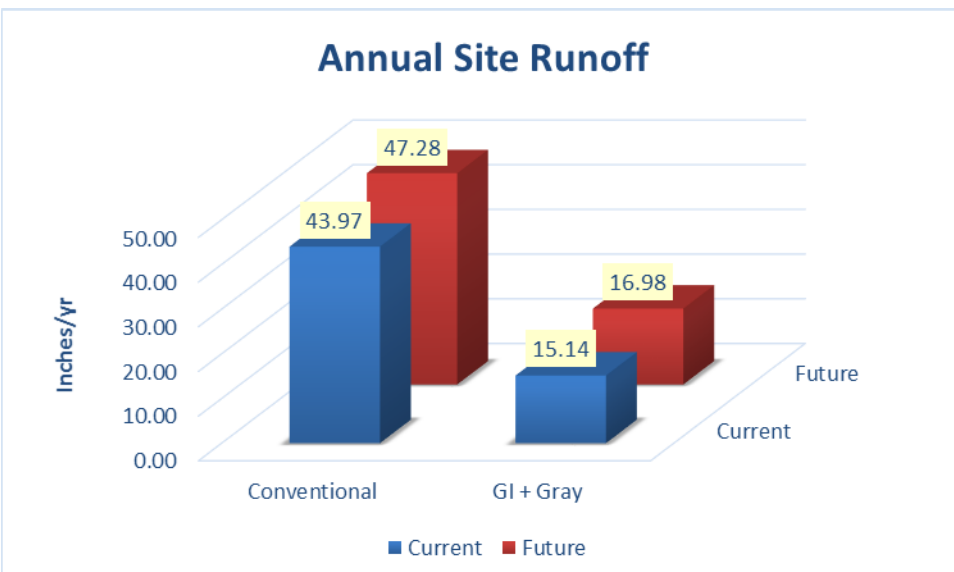

Figure 6-7. Annual site runoff under current climate and future general circulation model (GCM) scenario by stormwater management approach for Atlanta, GA.

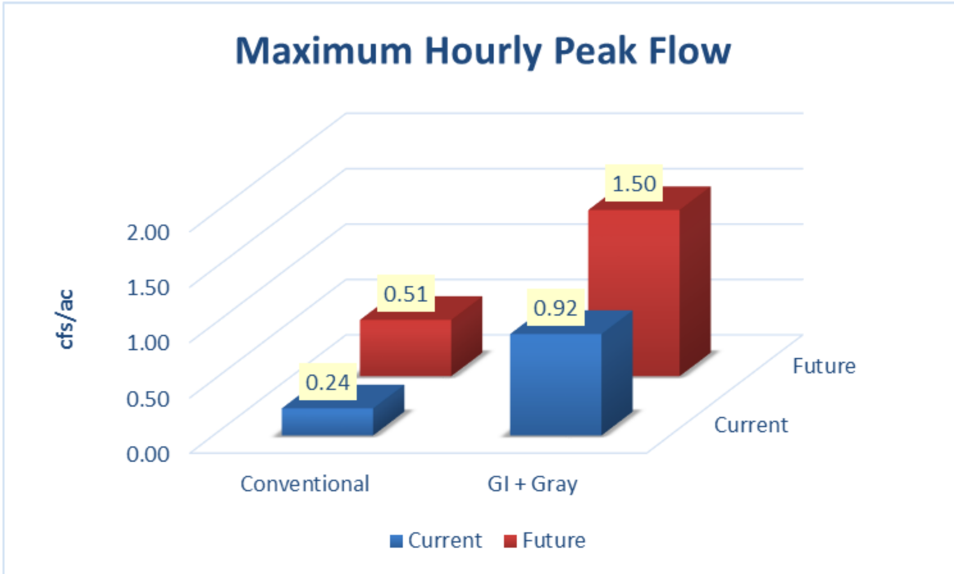

Figure 6-8. Maximum hourly peak flow under current climate and future general circulation model (GCM) scenario by stormwater management approach for Atlanta, GA.

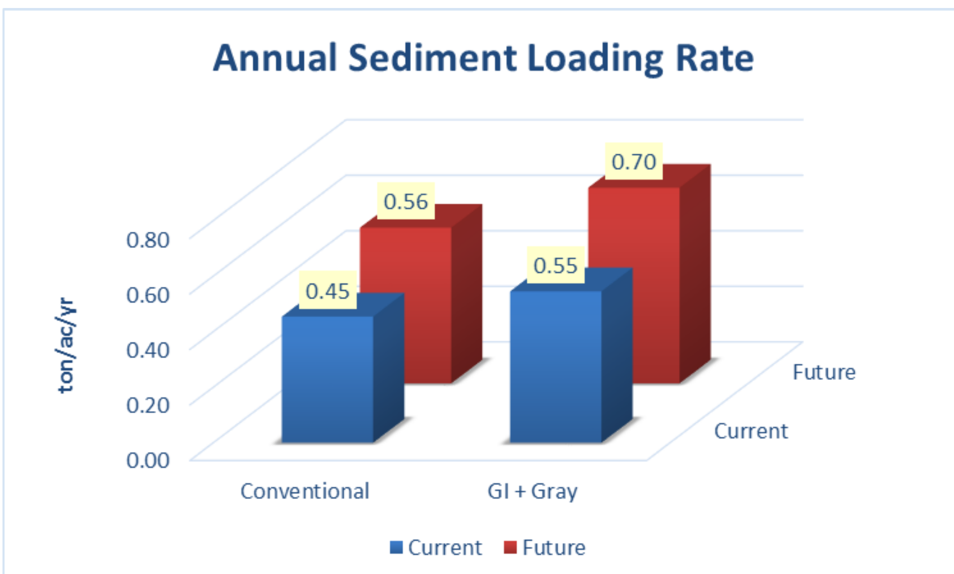

Figure 6-9. Annual sediment loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Atlanta, GA.

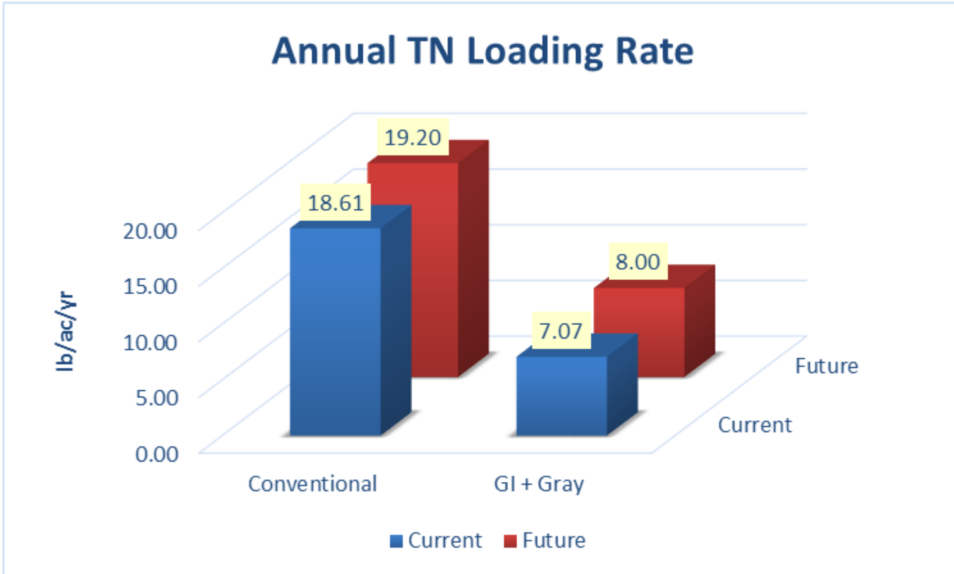

Figure 6-10. Annual total nitrogen (TN) loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Atlanta, GA.

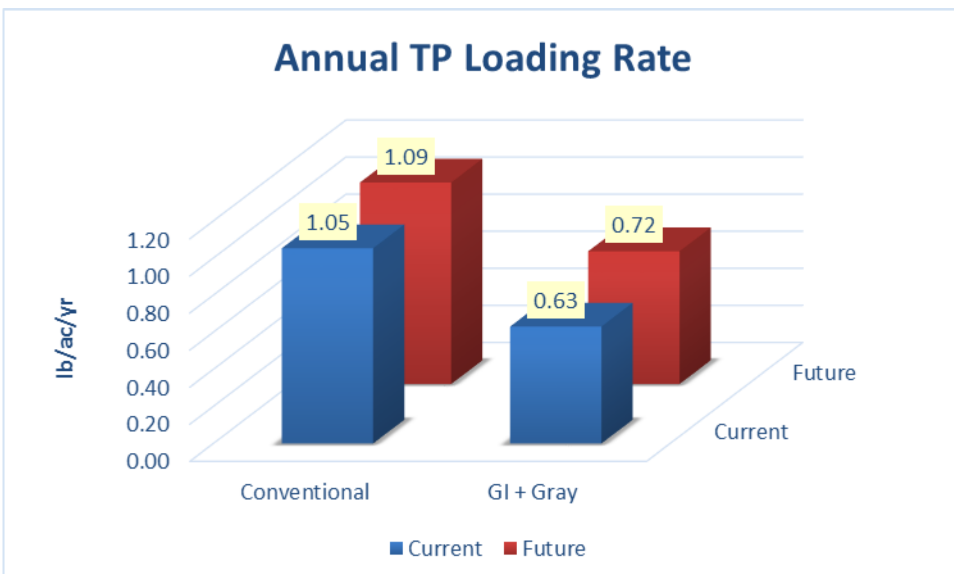

Figure 6-11. Annual total phosphorous (TP) loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Atlanta, GA.

As discussed in the previous Results sections for the individual sites, the resiliency of the stormwater management approaches relative to each other can be assessed by an analysis of the increase in runoff, peak flow, and pollutant loading due to projected climate change. For annual average site runoff, the increase in runoff for the Conventional approach at 3.31 inches is nearly double the runoff increase for

GI + Gray, at 1.84 inches. This indicates the GI + Gray approach was better at disposing of additional runoff due to changes in future precipitation volume than the Conventional approach, suggesting that the GI + Gray approach is more resilient to climate change for this measure. The same is not true for the other measures, where the GI + Gray has a larger increase in maximum hourly peak flow, as well as a larger increase in all of the pollutant loading rates.

Table 6-5 summarizes the increases in BMP footprints for the Atlanta, GA stormwater management scenarios that would be required to maintain or exceed current performance under future climate conditions. The current and adapted footprints are presented both in terms of actual square feet of practice as well as percentage of overall site area. The latter is provided as a means of comparing the current and future adapted sizes relative to the site area (2 acres) for this particular development type (ultra-urban).

Table 6-5. Comparison of current and future adapted best management practice (BMP) footprints for Atlanta, GA stormwater management scenarios

Future climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% Increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GCM high intensity	Conventional (Gray) Infrastructure	Underground sand filter	2,500	2.9	4,600	5.3	84
		Underground dry detention basin	5,000	5.7	6,200	7.1	24
	GI with Gray Infrastructure	Bioretention with underdrain	2,810	3.2	3,934	4.5	40
		Underground dry detention basin	2,500	2.9	3,300	3.8	32
		Green roof	30,492	35.0	35,184	40.4	15
		Permeable pavement	26,136	30.0	26,136	30.0	0

For the Conventional (Gray) Infrastructure scenario, the optimal solution resulted in an increase in size for both the underground dry detention basin and the underground sand filter. The combined increase in BMP footprint is equal to about 3.8% of the site area, or about 3,300 square feet. One outcome of the optimization was that increases in runoff volume and TN under the GCM high intensity future climate scenario could not be fully mitigated by increasing BMP footprints. For runoff volume, this is not surprising because both practices are underground and concrete-lined, so there is no mechanism to reduce runoff volume. However, the outcome is surprising for TN because increasing the area (and thus the treatment volume) of the sand filter does improve TN mass removal. The reason is that the increase in TN mass under the future climate scenario is greater than the ability of the sand filter to remove TN mass even at full treatment capacity. This may be an artifact of how TN removal is represented in the SUSTAIN model (fixed percentage reduction of mass), but it does suggest that gray practices with limited pollutant removal mechanisms may be at a disadvantage for mitigating climate change impacts.

The GI with Gray Infrastructure scenario uses a different approach for meeting regulatory stormwater requirements, and the adapted site under future climate conditions is able to meet all of the targets, including runoff and TN reduction. The combined increase in BMP footprint is equal to 7.6% of the site area, about 6,600 square feet. Most of the increase is due to a larger green roof footprint. Note that permeable pavement was considered to be implemented at the maximum practical footprint, so it was not included in the adaptation optimization.

Table 6-6 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all of the Atlanta, GA stormwater management scenarios. Refer to *Section 2.5.2.* of the report for a discussion on how the infrastructure cost estimates were developed. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site. These three metrics represent three alternative methods for evaluating the cost of adaptation, which is effectively the increase in cost between the current and future adapted climate scenarios.

Table 6-6. Comparison of current and future adapted 20-year present value costs for the Atlanta, GA stormwater management scenarios

Future climate scenario	Stormwater management scenario	Current cost (20-yr present value, $millions)	Future adapted cost (20-yr present value, $millions)	Increase in cost (20-yr present value, $millions)	% Increase in cost	Increase per acre of site $millions
GCM high intensity	Conventional (Gray) Infrastructure	1.38	2.27	0.89	64	0.09
	GI with Gray Infrastructure	2.31	2.60	0.29	13	0.03

For the Conventional (Gray) scenario, the estimated cost of adaptation is a $0.89 million increase compared to the current cost, or an increase in cost of 64%. This is equivalent to a cost of adaptation of $0.09 million per acre of site area.

The cost of adaptation for the GI with Gray scenario is estimated to be an increase of $0.29 million, which reflects a 13% increase in cost. On a cost per site acre basis, the estimated cost of adaptation is $0.03 million per acre of site area. While the adaptation cost increase for the GI with Gray scenario is significantly less than the cost for the Conventional scenario, the cost of GI with Gray under current climate is significantly more to start with than the cost of the Conventional stormwater management.

7. PACIFIC NORTHWEST SITE: TRANSPORTATION CORRIDOR/GREEN STREET

7.1. REGULATORY REQUIREMENTS AFFECTING STORMWATER MANAGEMENT

Portland has a stormwater ordinance that emphasizes use of retention and GI practices. The ordinance requires infiltration of the 10-year 24-hour storm event to the maximum extent practicable. There is a 70% TSS reduction required for discharging systems (where the infiltration requirement cannot be met). There is also a predevelopment peak matching requirement for the 2-, 5-, and 10-year 24-hour storm events, depending on where the site discharges.

7.2. STORMWATER MANAGEMENT SCENARIOS

The approach for the Portland scenario differs from the other locations; the stormwater management scenario reflects a specific style of stormwater management for which Portland has gained recognition in the stormwater management profession• the green street. Practitioners use land adjacent to roads as an opportunity to retrofit practices into the urban landscape. GI elements placed in medians and along rights-of-way (ROWs) are used to address water quality treatment and stormwater volume reduction goals. Green street projects in Portland tend not to fall under the city's requirements because the city is implementing them in road rights-of-way that are exempt from postconstruction stormwater requirements. The city does attempt to meet the requirements, but it is not always possible due to site limitations.

There are numerous green street case studies and master plans the city has published. One of the master plans is for a district encompassing several city blocks called the Gateway Urban Renewal Area (City of Portland, 2008). Rather than providing street-by-street designs, the report presents several "typologies" based on the ROW width. After reviewing the typologies, the 68-foot ROW Stormwater Curb Extension typology was selected for modeling representation. This typology lies in the middle of the range of ROW widths, and it comes the closest to fully meeting the infiltration requirement among the typologies.

The 68' ROW Stormwater Curb Extension typology is shown in Figure 7-1. For the SUSTAIN modeling, one side of the street was modeled because each street side is a mirror image of the other. Based on design parameters in the master plan, the green street site has the following characteristics:

- Site area:
    - 30,800 ft^2
    - 1.1% street trees
    - 2.2% permeable pavement
    - 8.1 bioretention/infiltration trench surface area
    - 88.6% impervious surface area

- Bioretention/infiltration trench configuration:
    - 6 inches of storage above the soil media
    - Soil media depth 6 inches
    - Drain rock depth 5 feet

The master plan discusses soil characteristics, stating that the area is composed of well-drained loams and silt loams with infiltration rates exceeding 6 inches per hour below 4 feet. Tests by local staff confirmed infiltration rates of 2 inches per hour or greater below the top compacted soil layer.

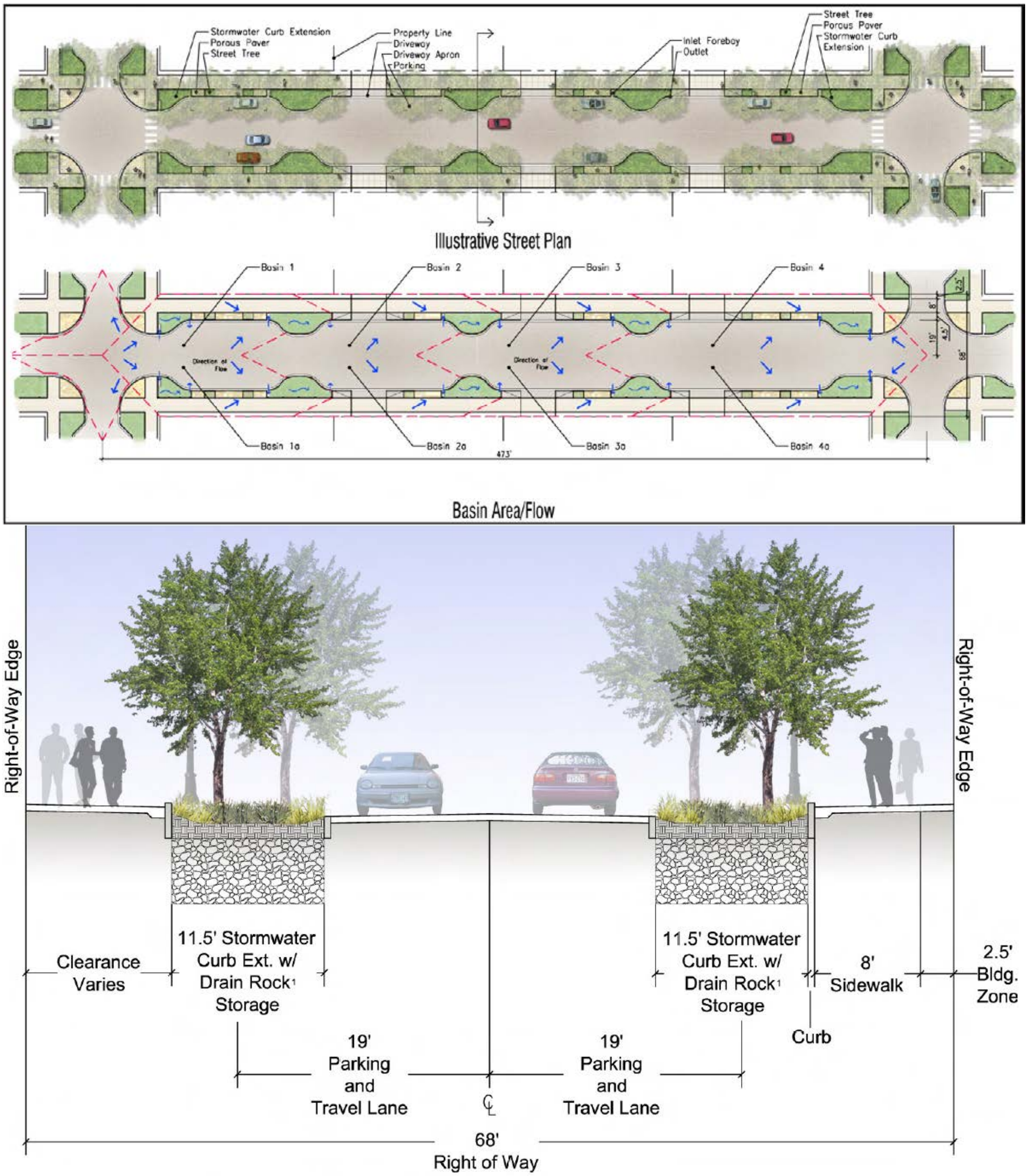

Figure 7-1. **Green street site layout (City of Portland, 2008).**

7.2.1. Green Infrastructure (GI) Only

The key design elements in the GI Only (green street) scenario are as follows:

- Each side of the street is a mirror image, and the assumed flow direction shown in Figure 7-1 is away from the centerline of the road. For simplicity, the SUSTAIN scenario is built using one side of the street. As a result, the site area is 15,400 ft2 (about 0.35 acre).

- Bioretention occupies 1,247 ft2, located in bump-outs along the street. The stored runoff infiltrates completely into the soil; no underdrain is used.

- Permeable pavement occupies 339 ft^2, and is located between street parking and the sidewalk.

The site is modeled as a series of adjacent connected drainage areas as shown in Figure 7-1. Within each drainage area, flow is routed proportionately to the street trees, permeable pavement, and bioretention. Overflow from the street trees and permeable pavement is routed to bioretention in the same drainage area. When the capacity of bioretention is exceeded, flow is routed to the downstream bioretention. Overflow from the most downstream bioretention is routed off the site.

For the SUSTAIN configuration, the areas and depths (storage, soil, and drain rock) were specified as given in the site plan dimension shown above. Infiltration into the underlying soil from all of the practices was assumed to be 2 inches per hour. Infiltration was assumed to be the primary removal mechanism, so no additional pollutant removal was modeled. ET was assumed for the bioretention. A small amount of ET from permeable pavement was assumed, equal to 10% of ET that would normally take place.

7.3. ADAPTATION SIMULATION

The objective of the adaptation simulation is to determine the increases in BMP footprint (surface area) that would be required to maintain or exceed current performance under future climate conditions for each stormwater management scenario. *Table* 7-1 summarizes the key components of the modeling procedure for the Portland GI Only scenario. Note that permeable pavement was also modeled as part of the GI Only (green street) scenario for Portland. However, this practice was not modified in the adaptation simulation because expansion of the permeable pavement footprint is not feasible given the current site layout. Further, permeable pavement areas only account for approximately 2% of the area of the green street and do not receive significant runoff. Rather, they serve more of an aesthetic function.

Table 7-1. **Features of adaptation simulation for Portland, OR**

Location	Stormwater management scenario	Future adaptation	Affected practices
Portland, OR	GI Only	Resize practices	Bioretention

7.4. CURRENT AND FUTURE CHANGES IN PRECIPITATION

The Portland, OR future climate scenario reflects a deviation from the previous locations, where the scenarios with the highest increase in intensity also showed an overall volume increase. For Portland (see Figure 7-2), the precipitation volume is actually projected to decrease, from 42.0 to 39.7 inches (−5.5% drop). As seen in Figure 7-3, monthly precipitation volume decreases in most months from current to future conditions, although increases are seen during two of the winter months. In addition, daily sums of precipitation depth were calculated and used to determine percentiles of 24-hour depth of interest to stormwater managers (see *Table* 7-2). While daily sums do not provide a true measure of storm event depth (storms have variable lengths and may span more than 1 day), they do provide useful information about expected depths over a 24-hour period. For the 85th through 95th percentiles, the change in 24-hour depth actually decreases. However, there is an increase of 0.14 inches for the 99th percentile, indicating a modest increase in intensity for the very largest events.

In terms of highest hourly precipitation volumes (see Figure 7-4), projected future intensity more or less tracks current intensity, with the highest increase about 1.16×.

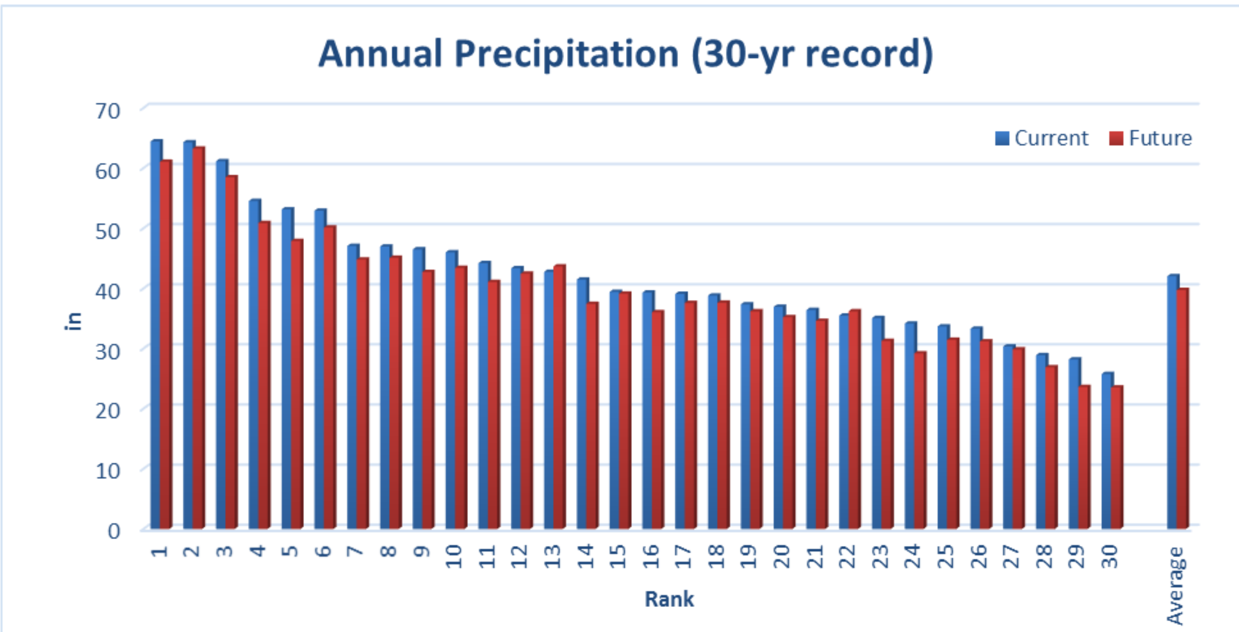

Figure 7-2. Ranked annual precipitation for current conditions and high intensity future climate scenario at Portland, OR.

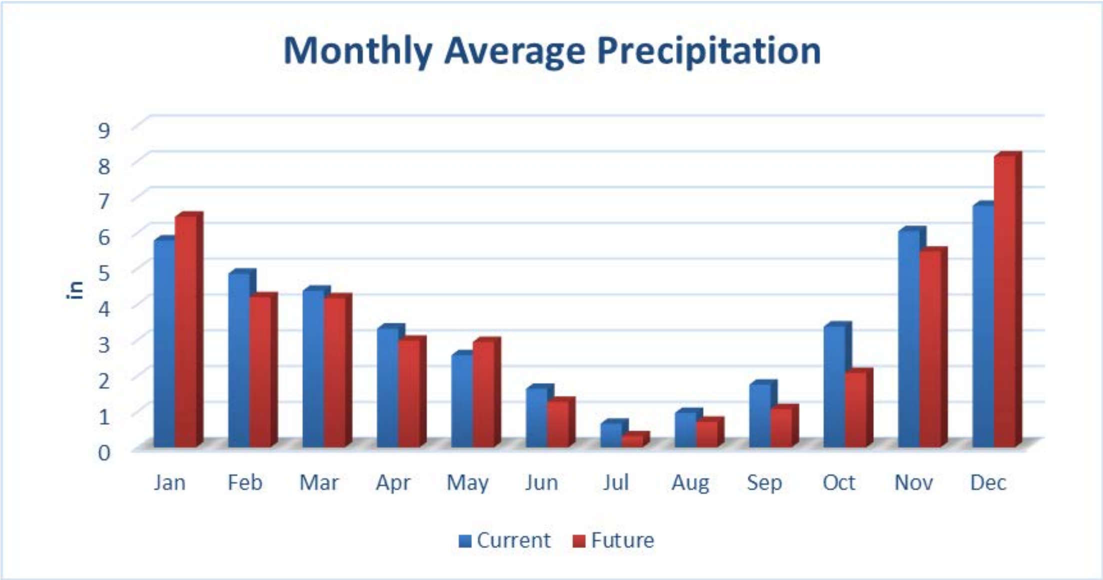

Figure 7-3. **Monthly average precipitation for current conditions and high intensity future climate scenario at Portland, OR.**

Table 7-2. 24-hour precipitation depth percentiles for current conditions and high intensity future climate scenario at Portland, OR

Percentile	Current conditions 24-h depth (in)	Future climate 24-h depth (in)	Change (+/−in)
85th	0.53	0.49	−0.04
90th	0.67	0.62	−0.05
95th	0.91	0.90	−0.01
99th	1.51	1.65	+0.14

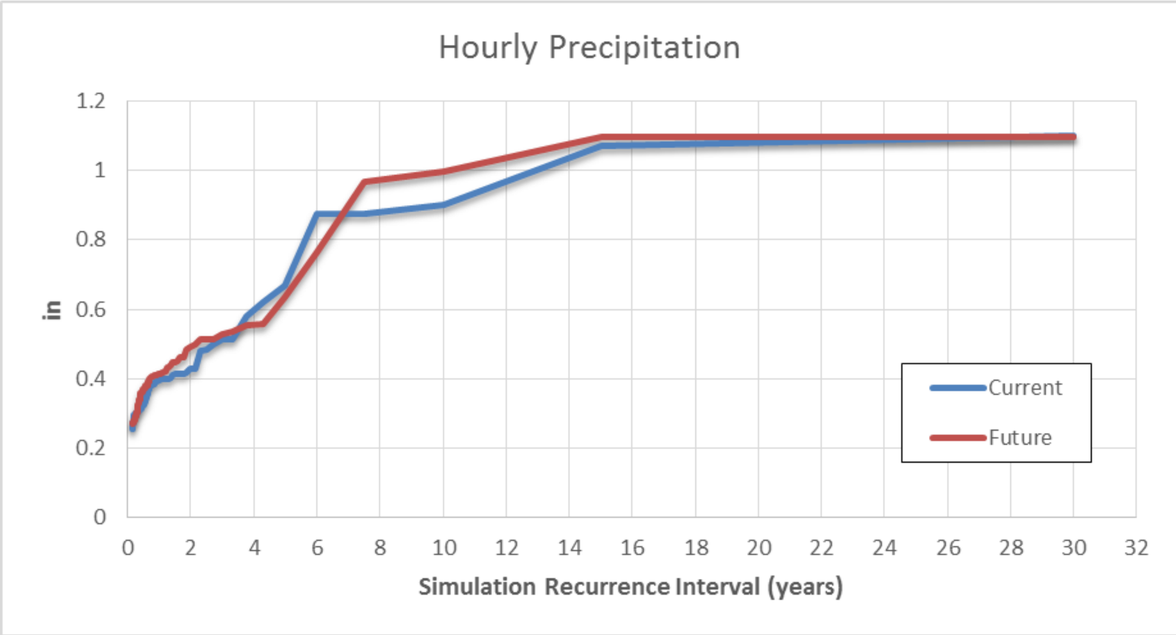

Figure 7-4. Hourly precipitation recurrence interval for current conditions and high intensity future climate scenario at Portland, OR.

7.5. RESULTS

SUSTAIN was run for the following conditions for each stormwater management scenario:

- Current climate, site without stormwater management/BMPs
- Future climate, site without stormwater management/BMPs
- Current climate, site with stormwater management/BMPs
- Future climate, site with stormwater management/BMPs
- Future climate, site with BMPs adapted to meet current hydrology and water quality performance

As shown in *Table* 7-3, one set of SUSTAIN runs was performed for a combination of one stormwater management approach and one climate scenario.

Table 7-3. Stormwater management and climate scenario for Portland, OR

Stormwater management approach	GCM high intensity
GI Only	X

A full presentation of the results of all the runs is provided in *APPENDIX B.* . For brevity, the results in this section focus on a few topics of interest to stormwater managers: (1) a comparison of the site performance with BMPs between current and future climate conditions, (2) the increases in BMP footprints needed to offset impacts of climate change when BMPs are adapted using SUSTAIN optimization, and (3) a comparison of current stormwater infrastructure costs to future costs when BMPs are adapted to offset impacts of climate change.

For the comparison of the site performance with BMPs between current and future climate conditions, the downscaled future GCM (high intensity change) scenario was selected for the comparison. A discussion of other topics of interest are provided in the general conclusions *Section 8.* , including changes in pretreatment site performance, changes in post-treatment site performance, climate scenario sensitivity analysis, and adapting BMPs under future climate to meet current performance.

Rather than comparing the performance of the stormwater management approaches independent of climate change (i.e., how much better does one perform than the other under current conditions), this study focuses on how the stormwater management approaches compare *relative to climate change. Table* 7-4 provides current and future performance for the stormwater management approaches, normalized to area. Note that there is no numeric measure of change in the FDC between current and future climate, so the highest hourly peak flow during the simulation is presented as a proxy for large storm event response. Figure 7-5 through Figure 7-9 present each metric graphically from *Table* 7-4.

The Northwest site has one stormwater management approach, so multiple approaches are not available for comparison. What stands out from the results is the small increase in measures between current and future climate conditions• much smaller, for the most part, than the increases reported for the other sites. This is not due to the lower site area used for this site because all of the measures are normalized to area. The reason the changes are small is likely that climate models generally predict lower changes in precipitation intensity relative to most other locations in the United States. The future climate scenario selected for this geographic location had the highest large storm event intensity change among ten candidate future climate scenarios. As shown in *Table* 7-2, the increase in the 99th percentile daily rainfall volume is only 0.14 inches, considerably less than the 99th percentile values shown for the other sites corresponding to the future climate scenario with the highest large storm event intensity change.

Table 7-4. Current and future performance of Portland, OR site by stormwater management approach

Stormwater management approach	Current	Future	Change
Runoff (inch/yr)			
GI Only	0.052	0.088	+0.036
Maximum hourly peak flow (cfs/ac)			
GI Only	0.26	0.49	+0.22
Sediment (ton/ac/yr)			
GI Only	0.0014	0.0015	+0.0002
TN (lb/ac/yr)			
GI Only	0.027	0.039	+0.012
TP (lb/ac/yr)			
GI Only	0.0034	0.0042	+0.0008

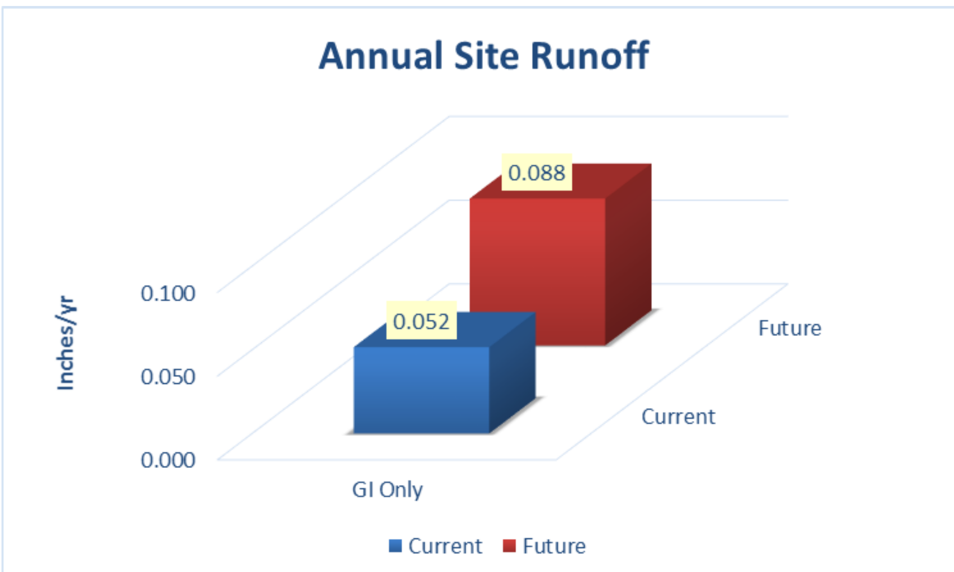

Figure 7-5. Annual site runoff under current climate and future general circulation model (GCM) scenario by stormwater management approach for Portland, OR.

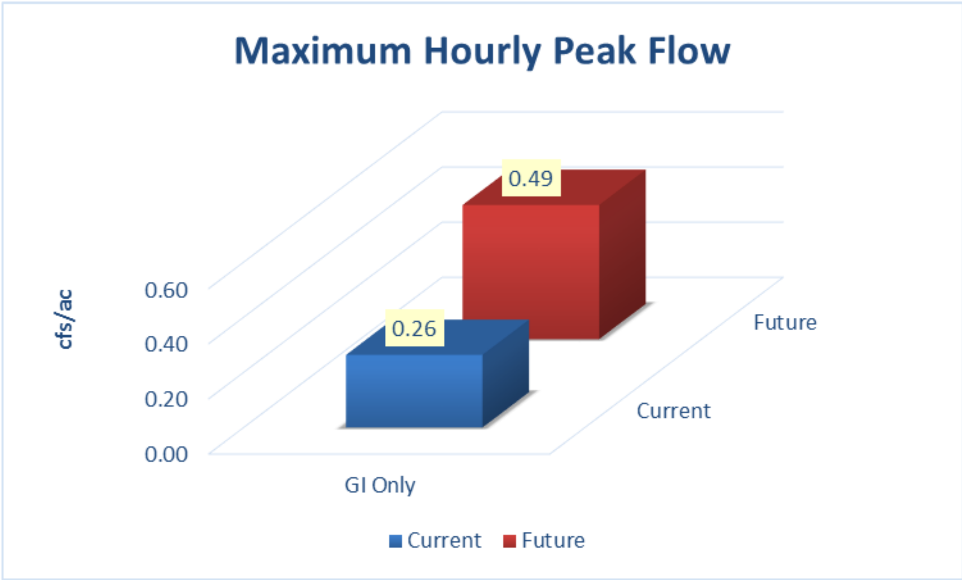

Figure 7-6. Maximum hourly peak flow under current climate and future general circulation model (GCM) scenario by stormwater management approach for Portland, OR.

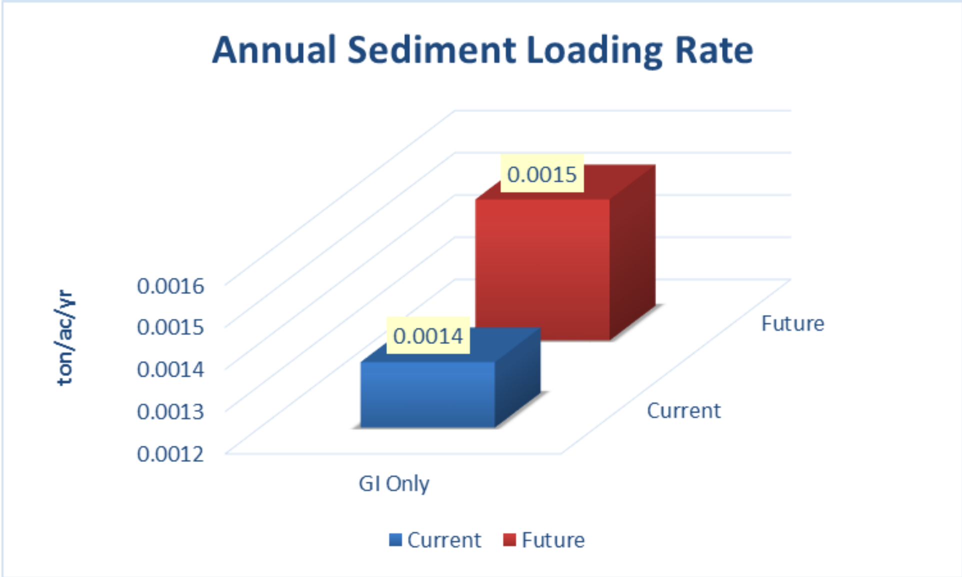

Figure 7-7. Annual sediment loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Portland, OR.

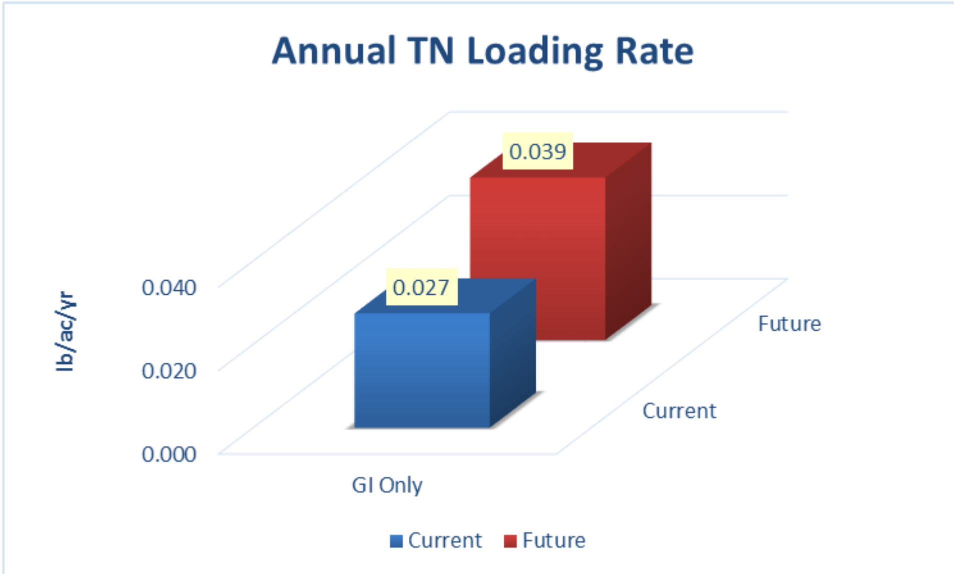

Figure 7-8. Annual total nitrogen (TN) loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Portland, OR.

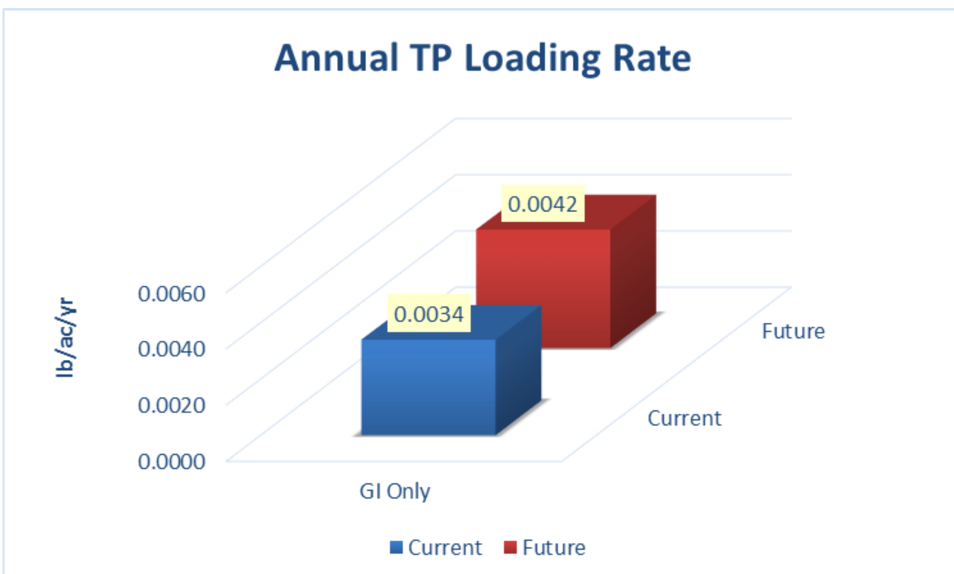

Figure 7-9. Annual total phosphorous (TP) loading rate under current climate and future general circulation model (GCM) scenario by stormwater management approach for Portland, OR.

Table 7-5 summarizes the increases in BMP footprints for the Portland, OR stormwater management scenarios that would be required to maintain or exceed current performance under future climate conditions. The current and adapted footprints are presented both in terms of actual square feet of practice as well as percentage of overall site area. The latter is provided as a means of comparing the current and future adapted sizes relative to the site area for this particular development type (transportation corridor). Permeable pavement was not resized as part of the adaptation. Bioretention provides almost all of the water quantity and quality treatment for the site due to their large storage volumes and high infiltration capacity. The increase in bioretention footprint is 36%, or 2.9% of the site area. Interestingly, total runoff volume under the GCM high intensity change climate scenario actually decreases compared to current climate conditions. However, the volume discharged from the BMPs increases under future climate compared to current climate. The reason is that the site is designed to capture the equivalent of a 10-year 24-hour storm event, so runoff only occurs during the largest of storm events. While overall future runoff decreases, the intensify of the largest events increases, leading to an increase in discharge, nutrient loads, and large event peak flows.

Table 7-5. Comparison of current and future adapted best management practice (BMP) footprints for Atlanta, GA stormwater management scenarios

Future climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% Increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of Site area	
GCM high intensity	GI Only	Bioretention swale	1,239	8.0	1,681	10.9	36
		Permeable pavement	345	2.2	345	2.2	0

Table 7-6 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all of the Portland, OR stormwater management scenarios. Refer to *Section 2.5.2.* of the report for a discussion on how the infrastructure cost estimates were developed. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site. These three metrics represent three alternative methods for evaluating the cost of adaptation, which is effectively the increase in cost between the current and future adapted climate scenarios.

Table 7-6. Comparison of current and future adapted 20-year present value costs for the Maricopa County, AZ stormwater management scenarios

Future climate scenario	Stormwater management scenario	Current cost (20-yr present value, $millions)	Future adapted cost (20-yr present value, $millions)	Increase in cost (20-Yr present value, $millions)	% Increase in cost	Increase per acre of site ($millions)
GCM high intensity	GI Only	0.20	0.27	0.07	35	0.20

The cost of adaptation for the GI Only scenario is estimated to be an increase of $0.07 million, which reflects a 35% increase in cost. On a cost per site acre basis, the estimated cost of adaptation is $0.20 million per acre of site area.

8. DISCUSSION AND CONCLUSIONS

Each of the individual site sections concluded with a discussion of results centered on a comparison of site performance under current and projected future climate conditions. This section takes a broader view and looks at results across all of the sites to interpret what can be learned about climate change impacts to stormwater management. The discussion is organized around the central study questions provided in the Introduction and repeated below, and concludes with a summary of results and some additional insights:

1. How might extreme precipitation events affect the performance of conventional stormwater infrastructure and GI,
2. How can conventional designs and GI designs be adapted so that a site experiencing extreme precipitation conditions in the future provides the same performance as the site under current conditions, and
3. What do the results suggest regarding the adaptation potential of gray and green infrastructure for increases in extreme precipitation events?

For reference, *Table* 8-1 lists each site analyzed in this study, along with the site's characteristics, stormwater management requirements, and stormwater management approaches and practices.

Table 8-1. Stormwater management approach summary

Region	Location	Characteristics	Stormwater requirements	Stormwater management approach	Practices
Mid-Atlantic	Harford County, MD	Mixed use 20 acres 65% impervious	Completely infiltrate recharge volume Treat water quality volume for TSS/TP Channel protection volume (24-h detention of 1-yr 24-h storm) Match predeveloped peak for 10-yr 24-h storm	Conventional (Gray) Infrastructure	Surface sand filters, extended dry detention basin
				GI with Gray Infrastructure	Infiltration trenches, infiltration basins, permeable pavement, and dry detention basin
				Conventional (Gray) Infrastructure with Distributed GI	Surface sand filters, extended dry detention basin, distributed infiltration trenches
Midwest	Scott County, MN	Residential 30 acres 48% impervious	Treat water quality volume for TSS Match predeveloped peak for 2-yr 24-h storm and 100-yr 24-h storm	Conventional (Gray) Infrastructure	Wet pond
				GI with Gray Infrastructure	Distributed bioretention and dry detention basin
				GI Only	Distributed bioretention, permeable pavement, and impervious surface disconnection
				Conventional (Gray) Infrastructure with Distributed GI	Wet pond, distributed bioretention
Arid southwest	Maricopa County, AZ	Commercial 10 acres 80% impervious	100% retention of the 100-yr 2-h storm event	Conventional (Gray) Infrastructure	Detention/infiltration basin
				GI Only	Permeable pavement, cistern, bioretention, and stormwater harvesting basin
Southeast	Atlanta, GA	Ultra-urban 2 acres 90% impervious	Treat water quality volume for TSS Channel protection volume (24-h detention of 1-yr 24-h storm) Match predeveloped peak for 2-yr, 5-yr, 10-yr, 25-yr, and 100-yr 24-h storm	Conventional (Gray) Infrastructure	Underground sand filter, underground dry detention basin
				GI with Gray Infrastructure	Green roof, permeable pavement, bioretention, and underground dry detention basin

Table 8 1. Stormwater management approach summary (Continued)

Region	Location	Characteristics	Stormwater requirements	Stormwater management approach	Practices
Pacific northwest	Portland, OR	Transportation corridor 0.35 acres 89% impervious	70% TSS reduction infiltration of 10-yr 24-h storm event as practicable Match predeveloped peak for 2-yr, 5-yr, 10-yr 24-h storm	GI Only	Bioretention swales, permeable pavement

8.1. STUDY QUESTION #1

How might extreme precipitation events affect the performance of conventional stormwater infrastructure and green infrastructure (GI)?

To answer the first question, each stormwater management scenario was modeled under current climate conditions, and the performance of the site practices was calculated from modeling results. Next, each scenario was modeled under future climate conditions and the change in performance tabulated. Performance is presented first for the downscaled high intensity GCM climate scenarios. Next, results of the future climate sensitivity analysis are provided.

8.1.1. Performance Comparison for Stormwater Management Scenarios Under Current and Future Precipitation Conditions

This subsection presents results showing projected changes to site performance due to climate change. The future climate scenarios presented here are limited to the downscaled GCM scenarios representing the largest increase in precipitation intensity (i.e., the low and medium intensity scenarios for Scott County are not included). The reason for focusing on the high intensity climate scenarios is to allow for a more equivalent comparison between locations and stormwater management–stormwater treatment scenarios. It is important to note that these results represent *potential* conditions under future climate, notably using climate scenarios with the largest storm intensity change among a population of ten climate scenarios. Future climate impacts could be less, or more extreme. In the end, the results are intended to show sensitivity to plausible future conditions that will stress these stormwater systems.

Site performance measures used in this analysis include annual runoff, maximum peak outflow during the 30-year simulation, and pollutant loads for sediment, TN, and TP. Results are first presented for each site without the impact of BMPs• in other words, how climate change could affect the site as a whole. Next, site performance is explored taking the benefits of BMPs into account.

8.1.1.1. Changes in Pretreatment Site Performance

The analysis focuses on changes in runoff volume, maximum peak flow, and pollutant mass loading from the site land surfaces prior to any reductions due to BMPs. Percentage change in runoff ranges from −6.7

to 12.5% (see Figure 8-1). The change is negative for Portland due to lower precipitation and higher summer ET under the future downscaled GCM climate scenario. For maximum hourly peak outflow during the 30-year simulations, the percentage change ranges from 6.3 to 90.8% (see Figure 8-2). While the change in peak flow at Portland is the lowest among the locations, it is positive rather than negative; this indicates that while overall precipitation volume decreased under the future climate scenario, the intensity of the largest storm events did increase.

Percentage changes in loads range from 1.5 to 26.7% in most cases, except for Portland where the percentage changes are negative (see Figure 8-3**,** Figure 8-4, and Figure 8-5). A major exception is Maricopa County, where sediment more than doubles and TP more than triples. There is one storm event with wet antecedent conditions where precipitation doubles under future climate, and a large increase in pervious runoff depth results. Surface and rill erosion have a nonlinear increase with runoff depth, so a large mass of sediment and bound phosphorus are exported. It is possible that the model prediction represents an extremely rare occurrence. If the storm is omitted from the analysis, the percentage increase drops to 58.4% for sediment and 32.0% for TP. Note that percentage changes in loads reflect the entire 30-year simulation, whereas the percentage changes in maximum outflow are calculated from the single highest hour from the 30-year simulation and, therefore, tend to be larger than the load increases.

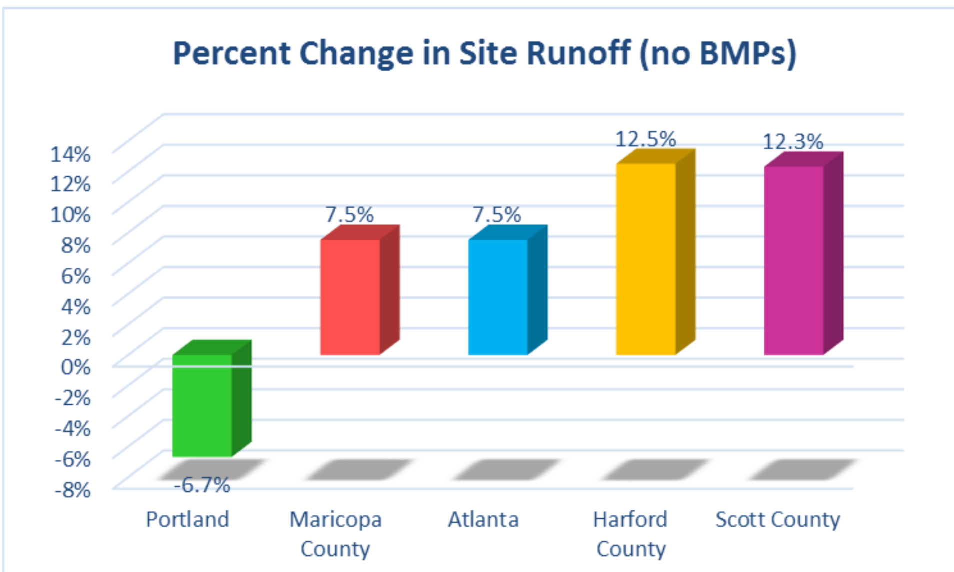

Figure 8-1. Percentage change in site runoff (no best management practices [BMPs]) between current and future climate conditions.

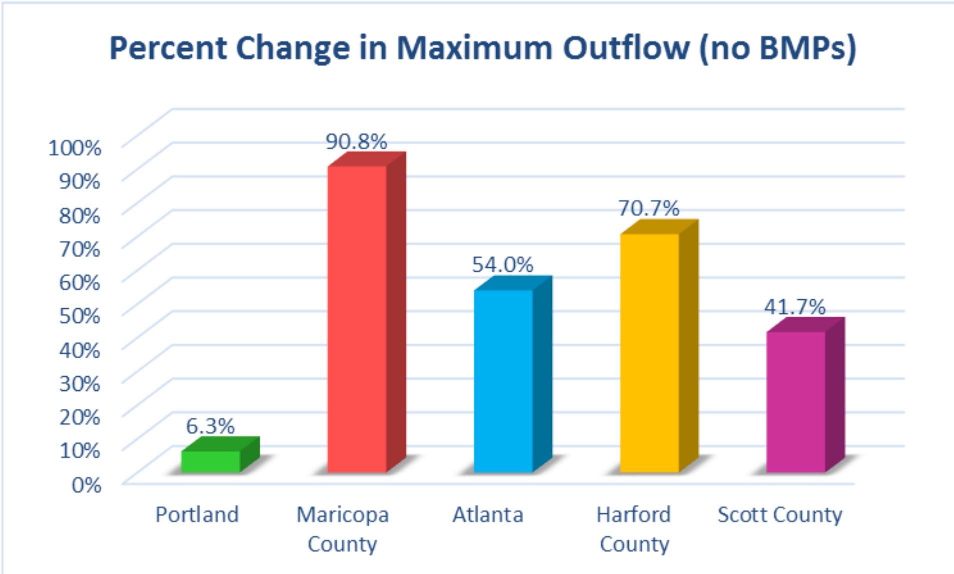

Figure 8-2. Percentage change in site maximum hourly peak outflow (no best management practices [BMPs]) between current and future climate conditions.

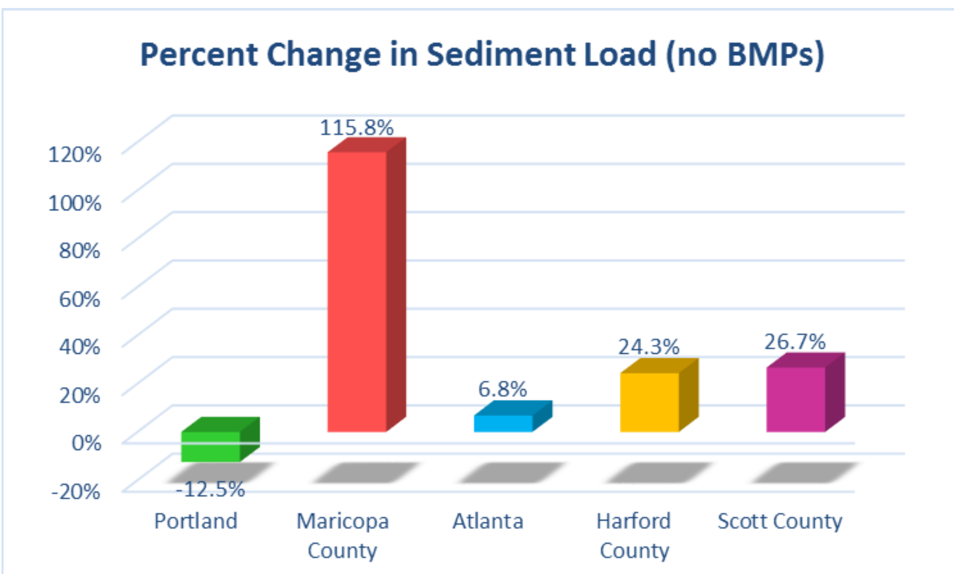

Figure 8-3. Percentage change in site sediment load (no best management practices [BMPs]) between current and future climate conditions.

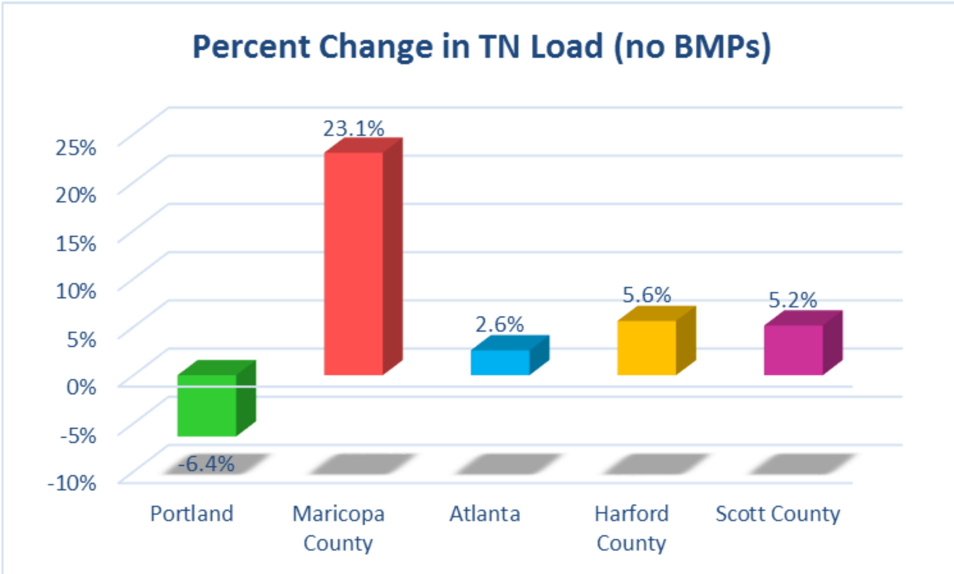

Figure 8-4. Percentage change in site TN load (no best management practices [BMPs]) between current and future climate conditions.

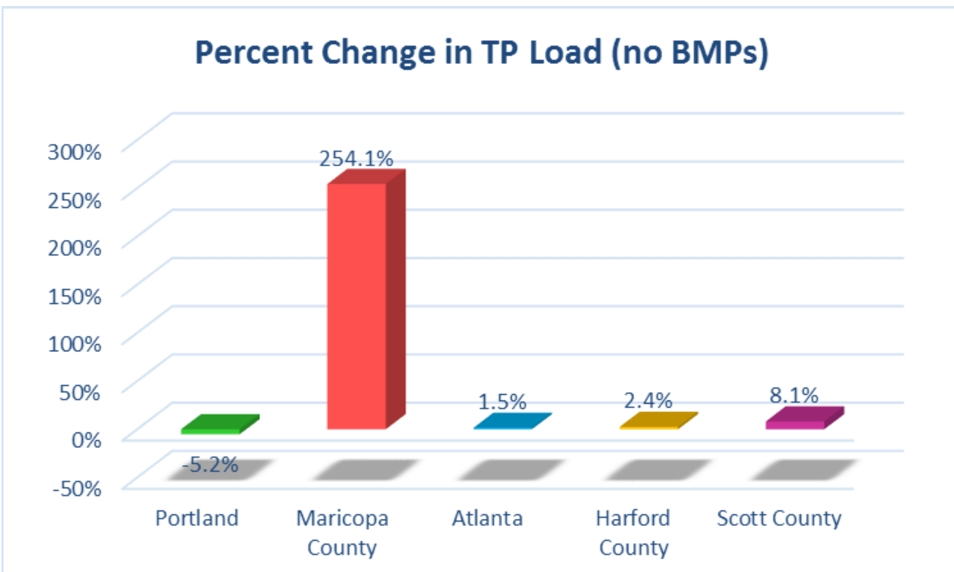

Figure 8-5. Percentage change in site total phosphorous (TP) load (no best management practices [BMPs]) between current and future climate conditions.

The load simulated in HSPF from the land surface is largely a function of runoff depth, although load buildup may be exhausted on impervious land. Thus, the sediment and TP loads tend to be strongly sensitive to changes in intensity. It is really the intensity of runoff, not precipitation that matters• the difference being especially important in northern sites where there is a change in the snow accumulation/melt regime.

8.1.1.2. Changes in Post-treatment Site Performance

A series of charts is presented in this subsection showing performance of BMPs and overall site export, accounting for BMP treatment. The focus of the analysis is on comparing performance for currently implemented BMPs under current versus future climate conditions. Both conventional and GI site-based scenarios are shown. Performance for the adaptation scenarios (where BMPs are resized or distributed GI is added to a site to reduce runoff volume, loads, and the highest runoff rates to match current performance) is not discussed because performance with adapted BMPs is the same or better than current performance and does not provide insight into how climate change affects BMP performance.

Three sets of analyses are shown:

- BMP percentage reductions in volume and mass
- Unit-area volume and mass reductions from BMPs
- Unit-area post-treatment site export

It is important to note that these results reflect an exploration of the range of climate impacts on BMP performance. While five different geographic regions are presented, the design of the study does not lend itself to making inferences about regional variation in BMP response to climate change. Each location represents a different type of land use, climate conditions, soils and infiltration rates, as well as other factors. BMP selection is driven largely by local and state design requirements. However, some trends are evident.

The first set of figures shows percentage reductions in volume (see Figure 8-6) and mass (see Figure 8-7, Figure 8-8, and Figure 8-9) due to the combined effects of all the BMPs at each site. Percentage reduction of runoff volume and pollutant mass tends to decrease under future climate conditions. Bypass increases under future climate conditions with high projected changes in large storm event intensity, while the BMP footprints and configurations are unchanged. As a result, overall percentage effectiveness decreases. Portland and Maricopa County are an exception to the trend seen at other locations. In many cases there is near 100% reduction under both current and future conditions due to the design criteria/goals for these site-based scenarios.

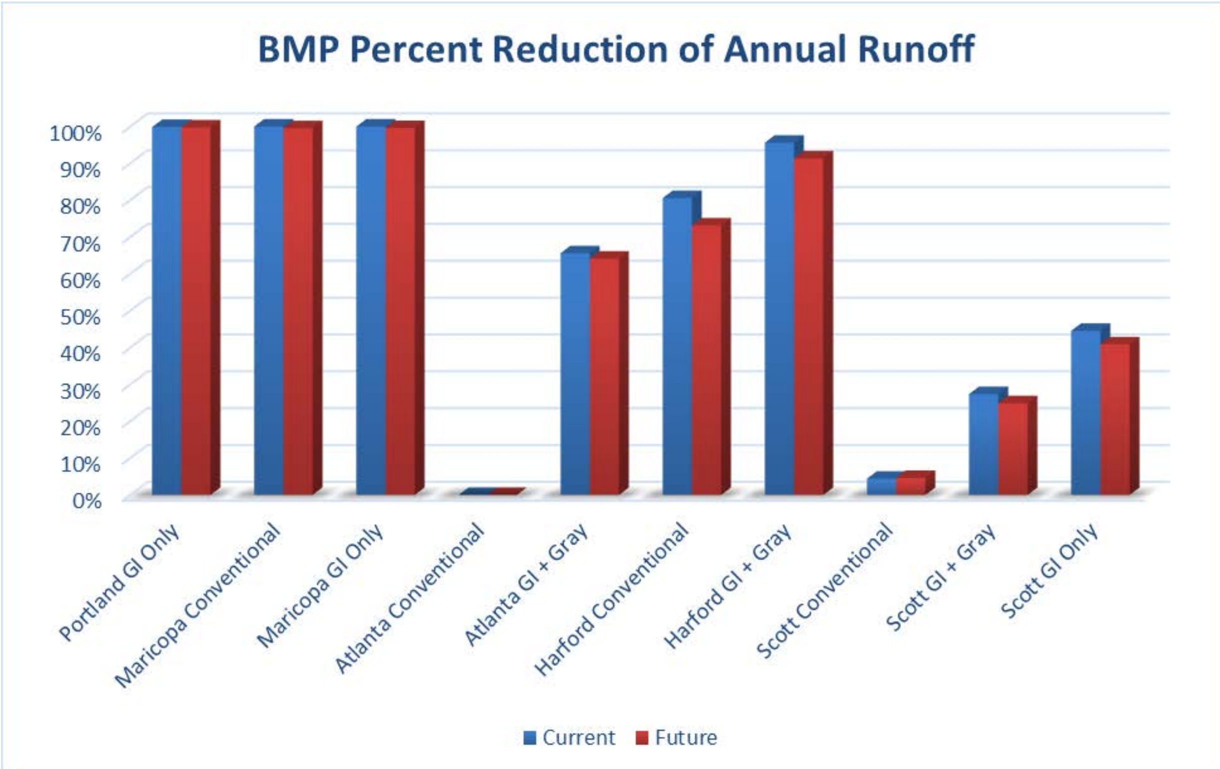

Figure 8-6. Best management practice (BMP) percentage reduction of annual runoff under current and future climate conditions.

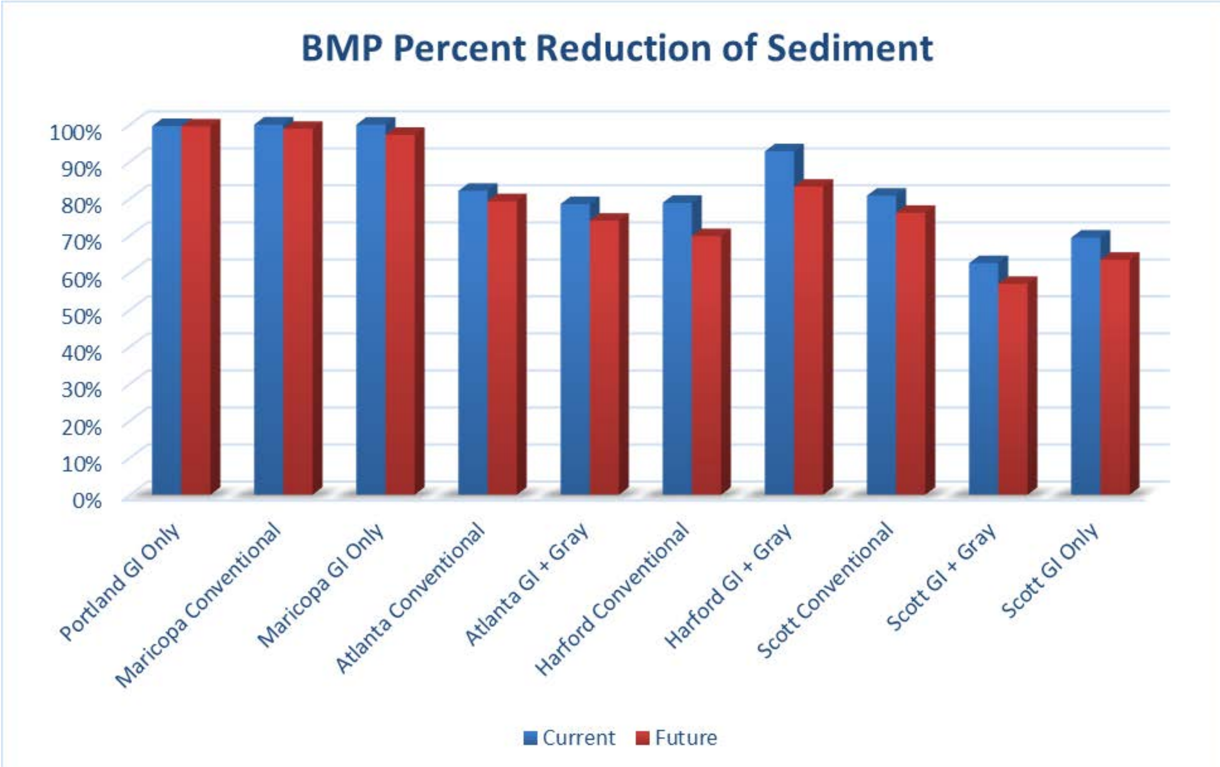

Figure 8-7. Best management practice (BMP) percentage reduction of sediment load under current and future climate conditions.

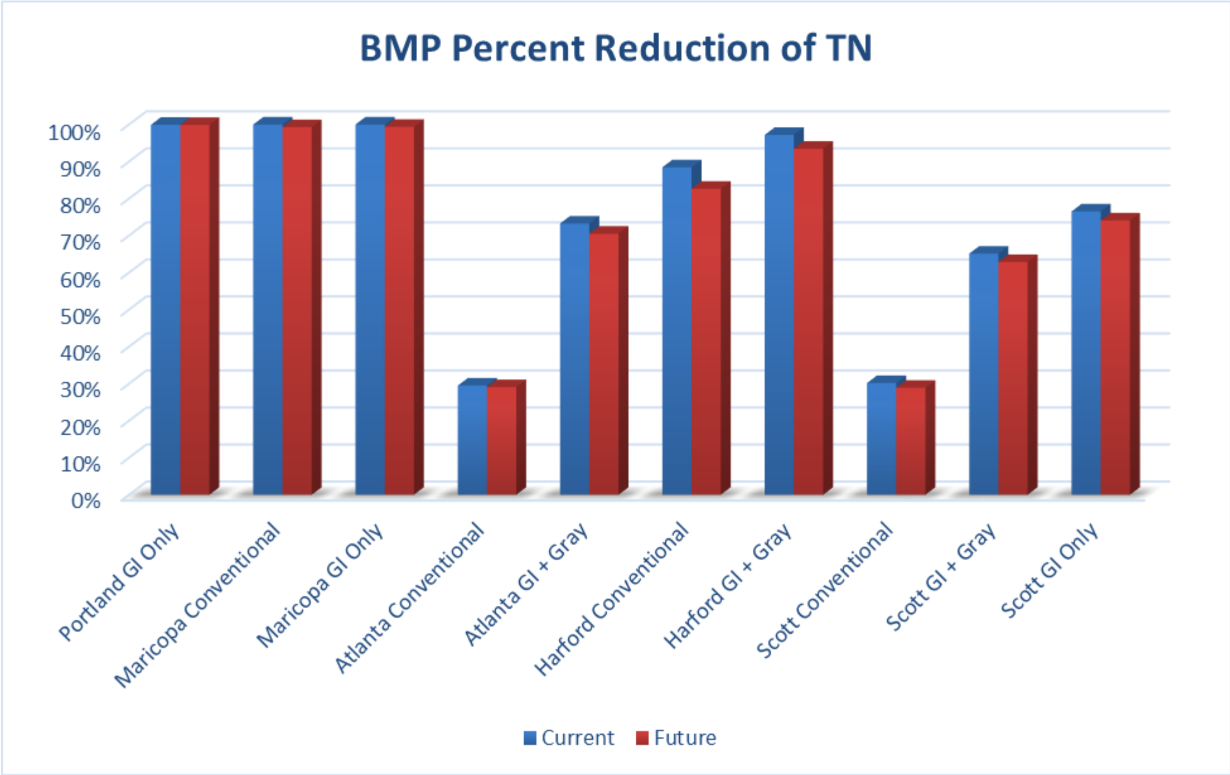

Figure 8-8. Best management practice (BMP) percentage reduction of total nitrogen (TN) load under current and future climate conditions.

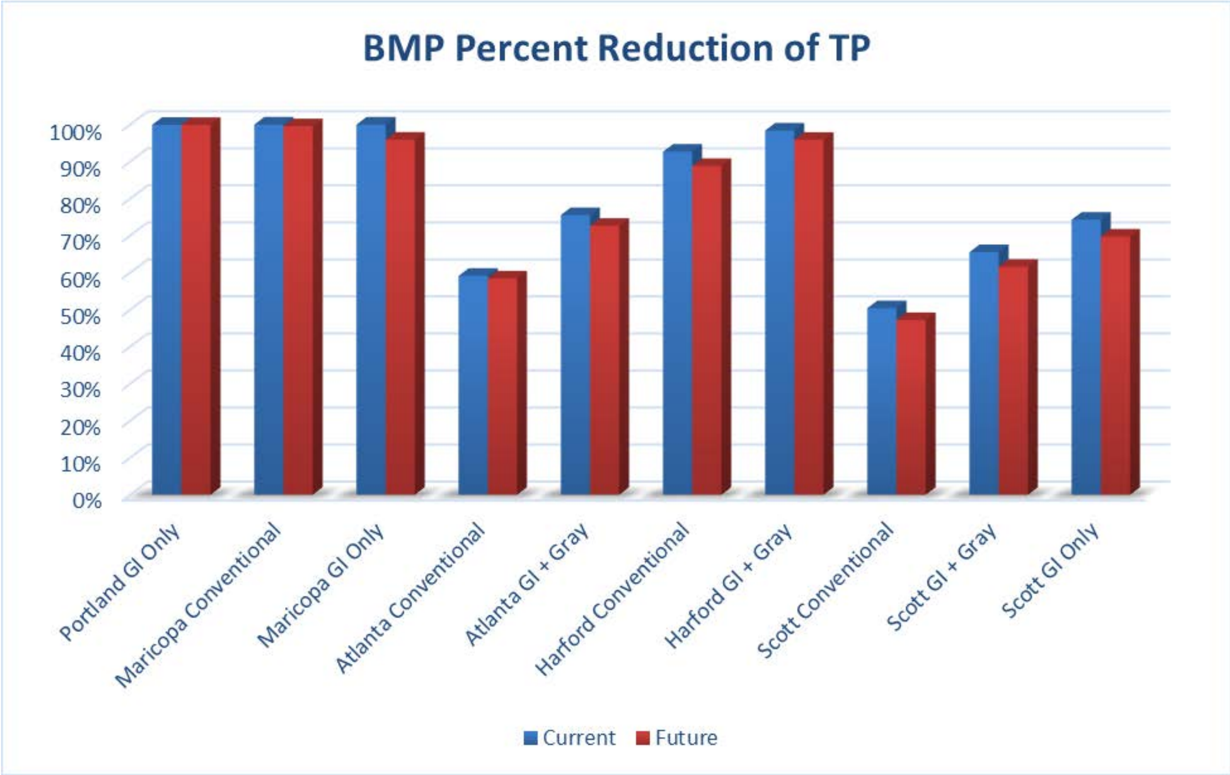

Figure 8-9. Best management practice (BMP) percentage reduction of total phosphorous (TP) load under current and future climate conditions.

The difference in current to future percentage reduction ranges are shown in the bullets that follow. The ranges suggest that site-scale future percentage reduction performance typically declines but not by a large margin.

- 0.2 to −7.4% for annual runoff
- −0.1 to −9.6% for sediment
- 0 to −5.8% for TN
- 0 to −4.5 % for TP

The second set of figures shows unit-area volume (see Figure 8-10) and mass reductions (see Figure 8-11, Figure 8-12, and Figure 8-13) from BMPs, in terms of feet/year and pounds/acre/year. The results were normalized to site area to facilitate comparison between sites and regions. While overall percentage reduction tends to decrease under future climate conditions (as seen in the previous set of figures), the magnitude of the volume and sediment mass removal tends to increase. This means that while the BMPs are removing a lower percentage of volume/mass, they do remove a greater quantity of volume/mass. This is largely due to the increased volume/mass input, but also depends on assumptions about how BMPs remove mass in the SUSTAIN configurations. The effect is less pronounced for TN and TP, and not surprisingly volume and mass removal decreases at Portland where future runoff decreases.

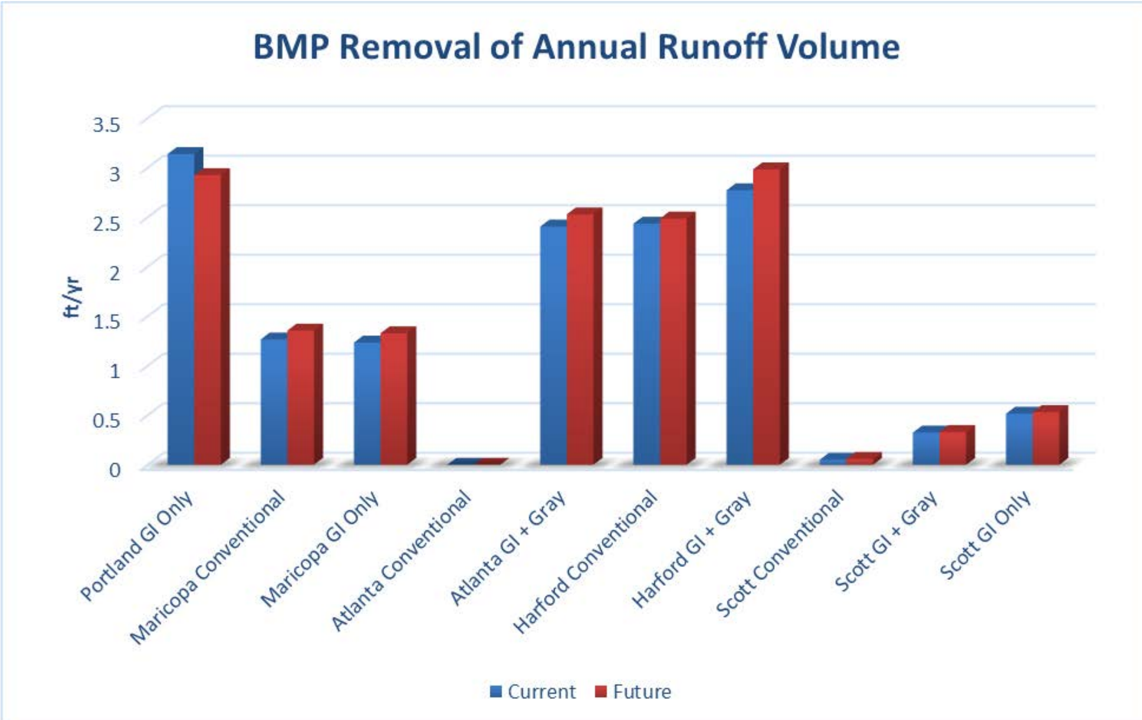

Figure 8-10. Normalized site-scale best management practice (BMP) removal of annual runoff under current and future climate conditions.

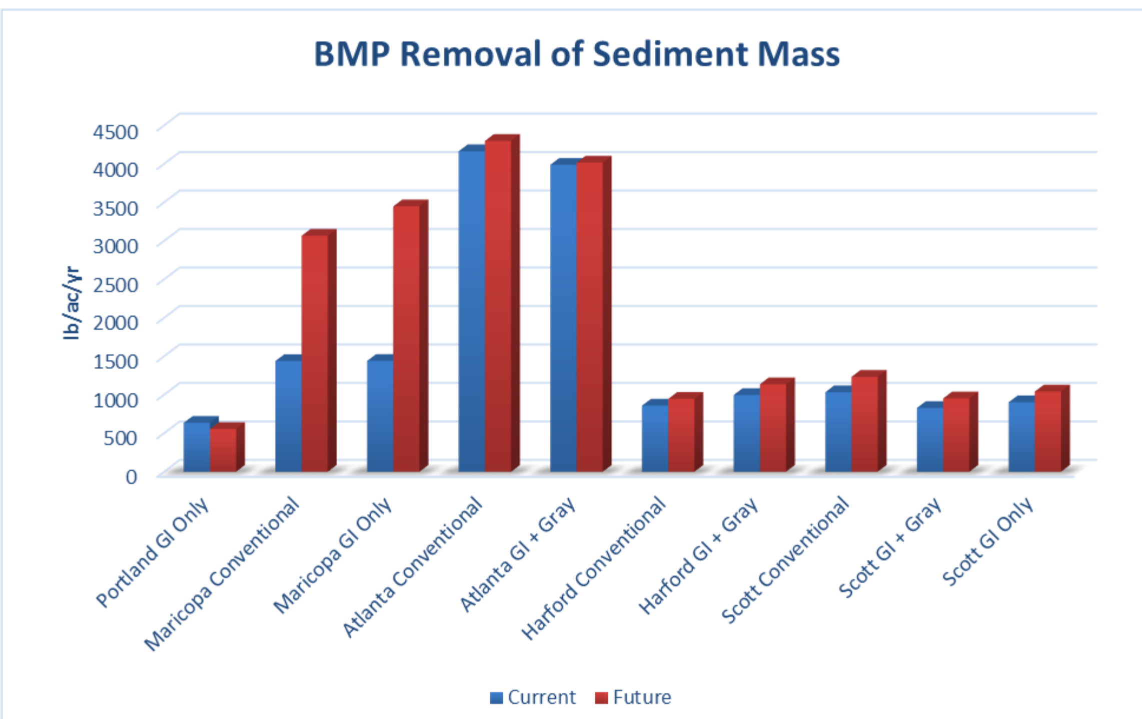

Figure 8-11. Normalized site-scale best management practice (BMP) removal of sediment load under current and future climate conditions.

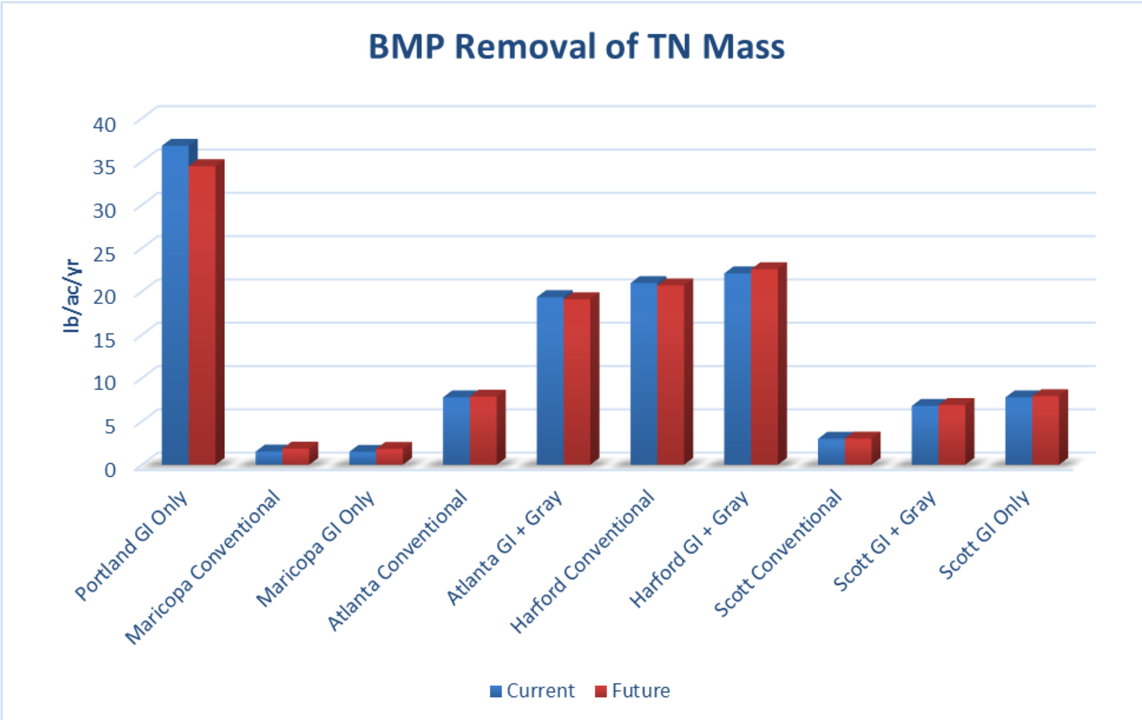

Figure 8-12. Normalized site-scale best management practice (BMP) removal of total nitrogen (TN) load under current and future climate conditions.

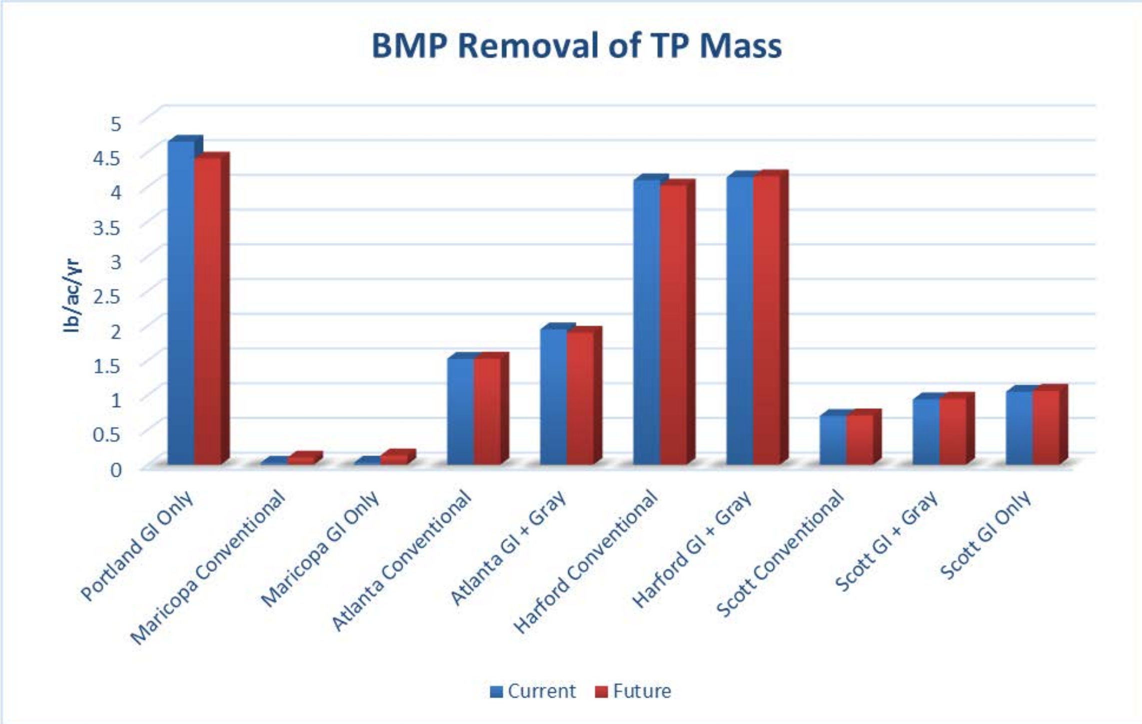

Figure 8-13. Normalized site-scale best management practice (BMP) removal of total phosphorous (TP) load under current and future climate conditions.

The difference in volume/mass removal from current to future climate conditions is relatively small, but the difference in unit-area rates varies widely between regions/locations. This discrepancy is due to regional differences in developed site loading rates and large storm event precipitation depths, as well as variation in BMP performance for various types of practices.

The third set of figures shows unit-area post-treatment site export of runoff (see Figure 8-14) and pollutant mass (see Figure 8-15, Figure 8-16, and Figure 8-17). The results were normalized to site area to facilitate comparison between sites and regions. Even though site practices remove more mass under future conditions, the overall site export rates of volume/mass increases under future conditions. The percentage increase in export load is very high for some scenarios (e.g., sediment mass export for Harford County GI plus Gray nearly triples), but the absolute increase (future minus current) is fairly stable.

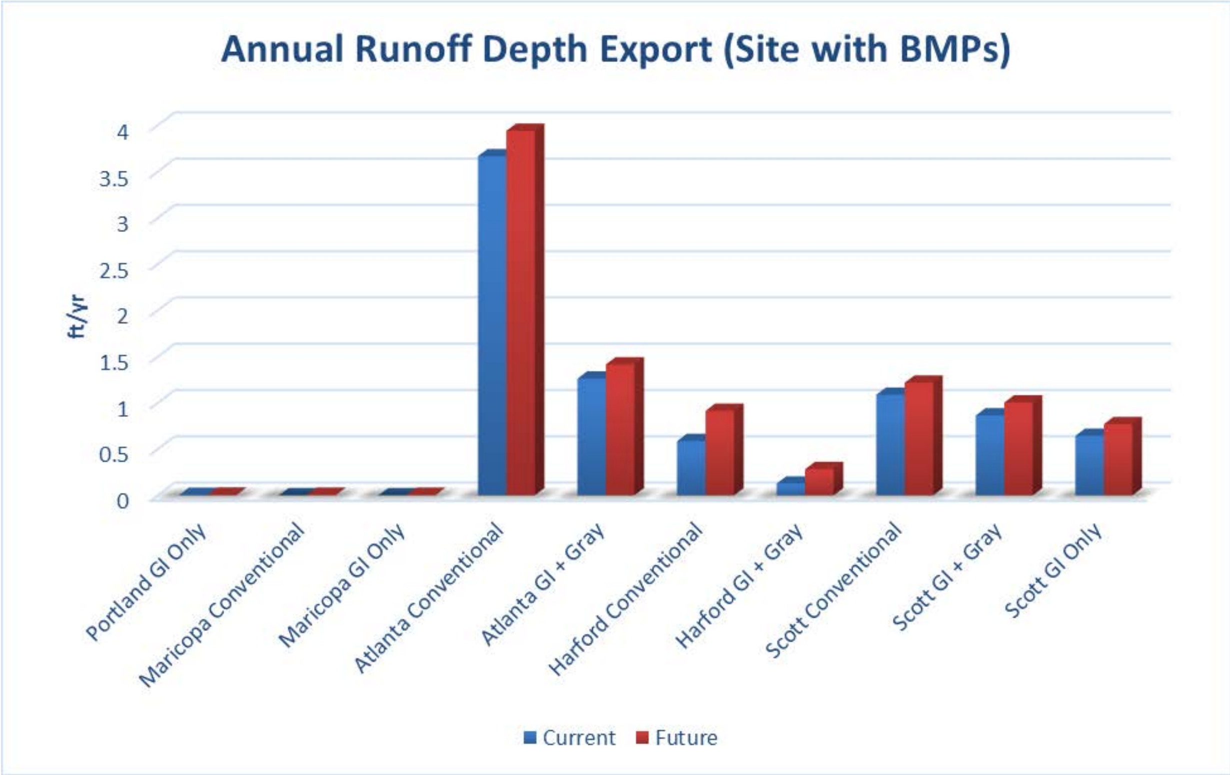

Figure 8-14. Normalized site-runoff export under current and future climate conditions.

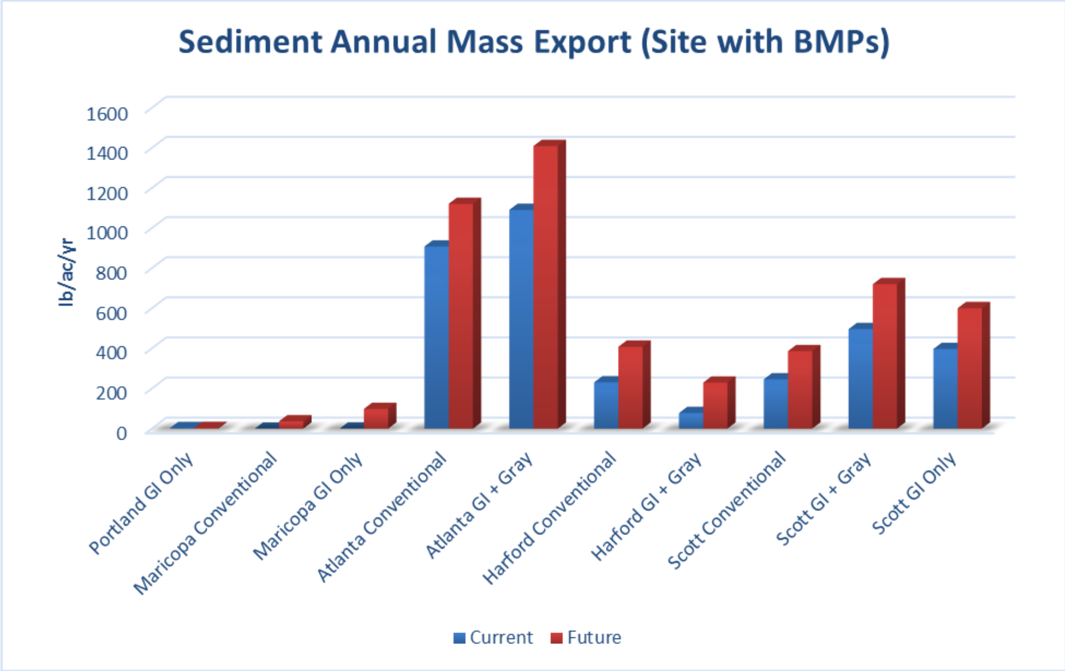

Figure 8-15. Normalized site-sediment mass export under current and future climate conditions.

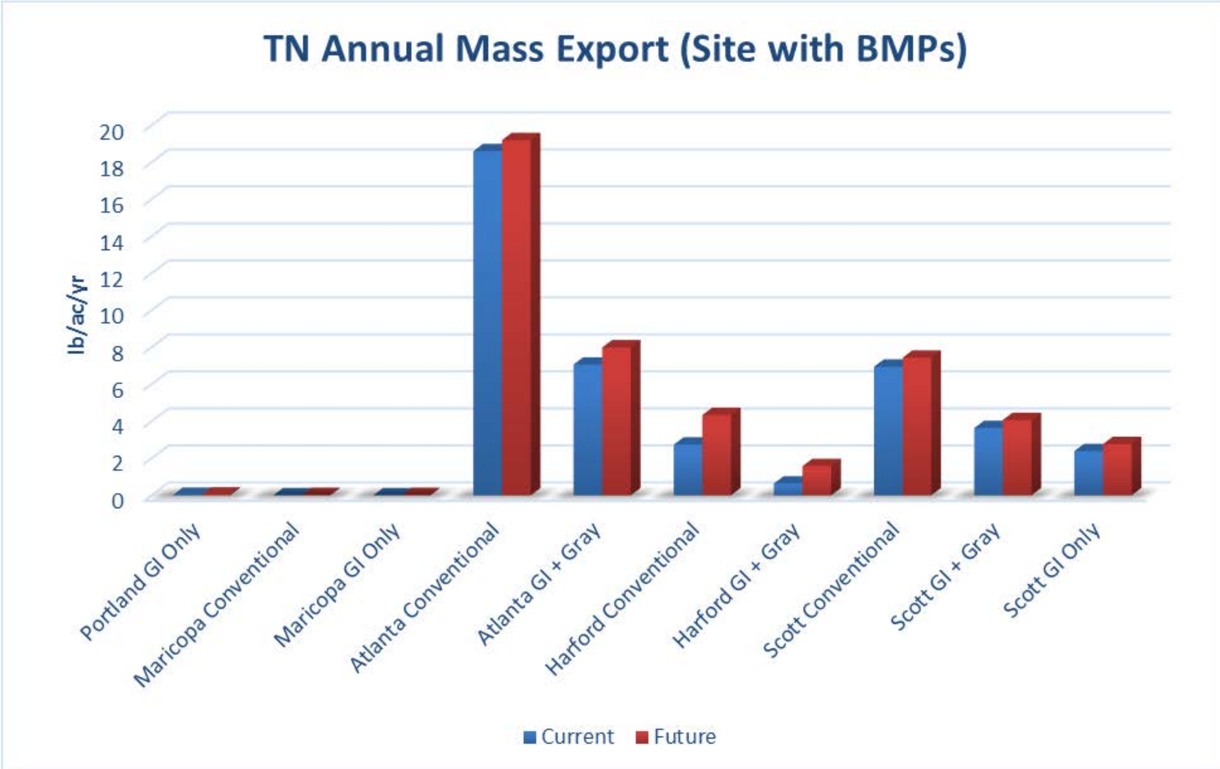

Figure 8-16. Normalized site-total nitrogen (TN) mass export under current and future climate conditions.

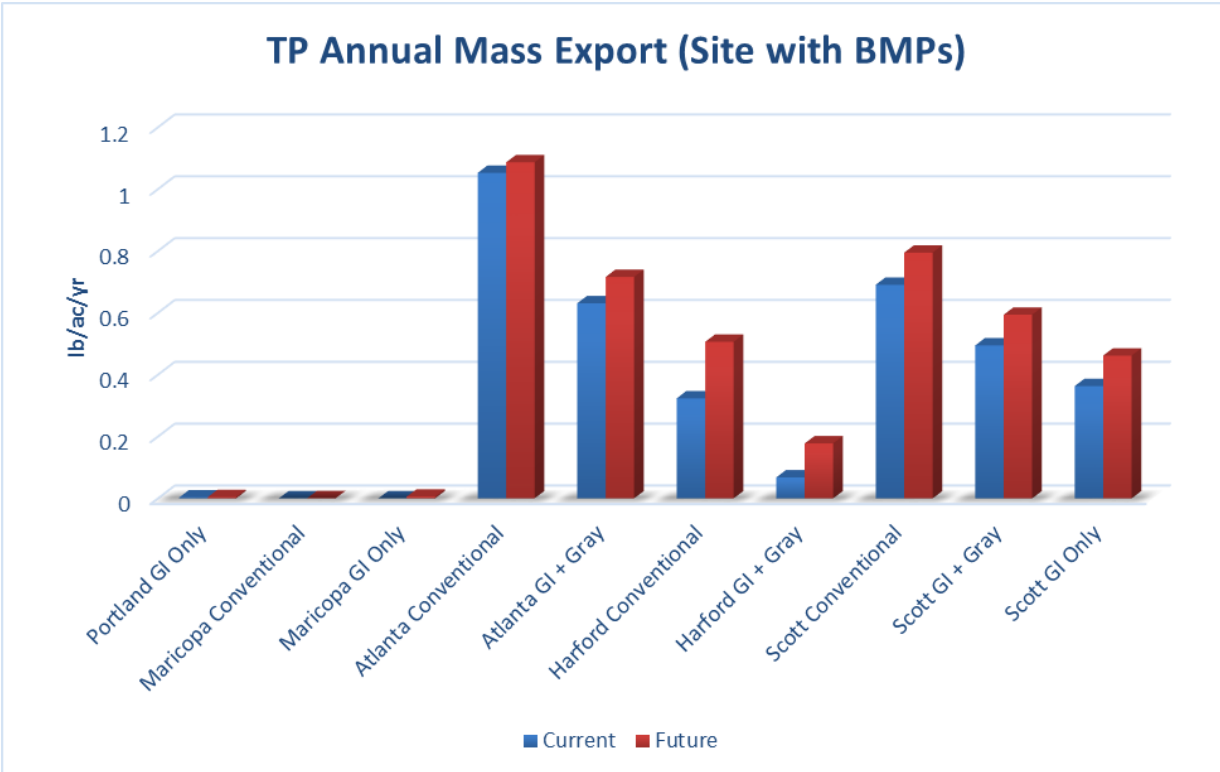

Figure 8-17. Normalized site-total phosphorous (TP) mass export under current and future climate conditions.

8.1.2. Sensitivity Analyses to Precipitation Events

The sensitivity analyses focus on the most critical measure of site performance• overall volume and mass export from the site. Sensitivity analyses were conducted using two different sets of variable future climate conditions. The first set used a range of three large storm event intensity changes (low, medium, and high) selected from 10 of the downscaled GCM climate scenarios used in the "20 Watersheds" project, as discussed in *Section 2.4.2.* . SUSTAIN runs were performed for the Scott County stormwater management scenarios and are shown below in *Section 8.1.2.1.* . The second set used a range of three percentage changes in precipitation depths (−10, +10, and +20%) relative to current precipitation, as discussed in *Section 2.4.3.* . SUSTAIN runs were performed for the Harford County and Scott County stormwater management scenarios, and are shown below in *Section 0*.

For all of the results, the change in volume and mass between current and future climate conditions, which provides a measure of resilience, is shown for each stormwater management scenario (rather than showing current next to future as was done in *Section 8.1.1.2.*). Results are grouped in the figures by different approaches to stormwater management (i.e., Conventional vs. GI-based) to facilitate comparison. All of the results were normalized to site area to facilitate comparison between sites and regions.

Note that these results focus on how future climate conditions hypothetically affect performance of currently implemented BMPs, and how resilient those BMPs are to changes in volume and intensity. SUSTAIN optimizations for adapting practices to meet current measures were also performed for all of the future climate scenarios in the sensitivity analyses and those results are presented in *Section 8.2.* .

8.1.2.1. Sensitivity Analysis• Modeled Scenarios

For change in runoff volume export, (see Figure 8-18) there is not much difference between the scenarios. Change in sediment load export response (see Figure 8-19) is variable; the GI plus Gray stormwater management scenario has the highest change across the three GCM intensities. For TN (see Figure 8-20), the GI plus Gray and GI Only scenarios appear to be progressively more resilient, while for TP (see Figure 8-21), the pattern varies between the low, medium, and high intensity scenarios. These results suggest there is no overall discernible pattern in degree of resiliency between the Conventional, GI plus Gray, and GI Only scenarios when examining changes in site export across a range of intensity changes in future precipitation using the downscaled GCM climate scenarios.

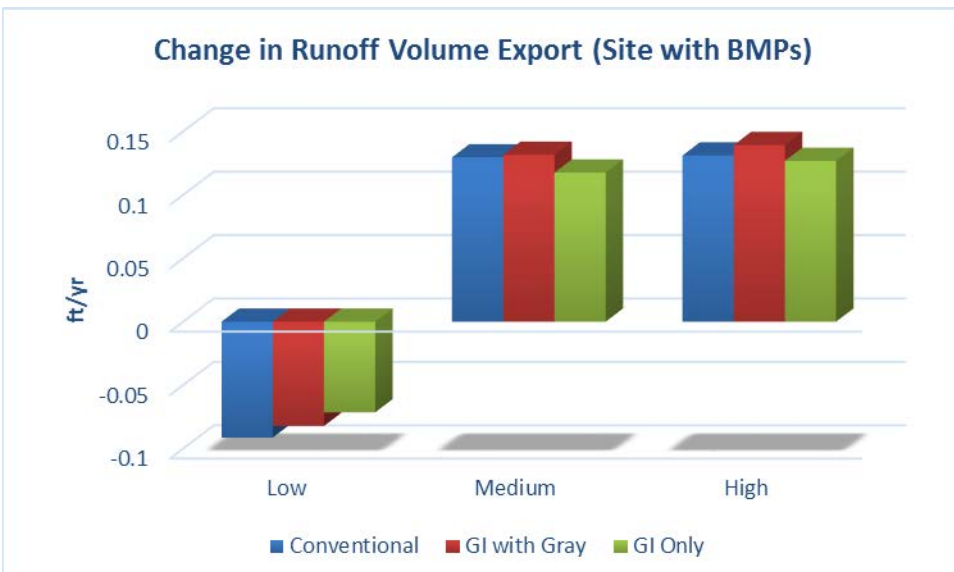

Figure 8-18. Change in runoff volume export for Scott County between current and future downscaled general circulation model (GCM) climate scenarios.

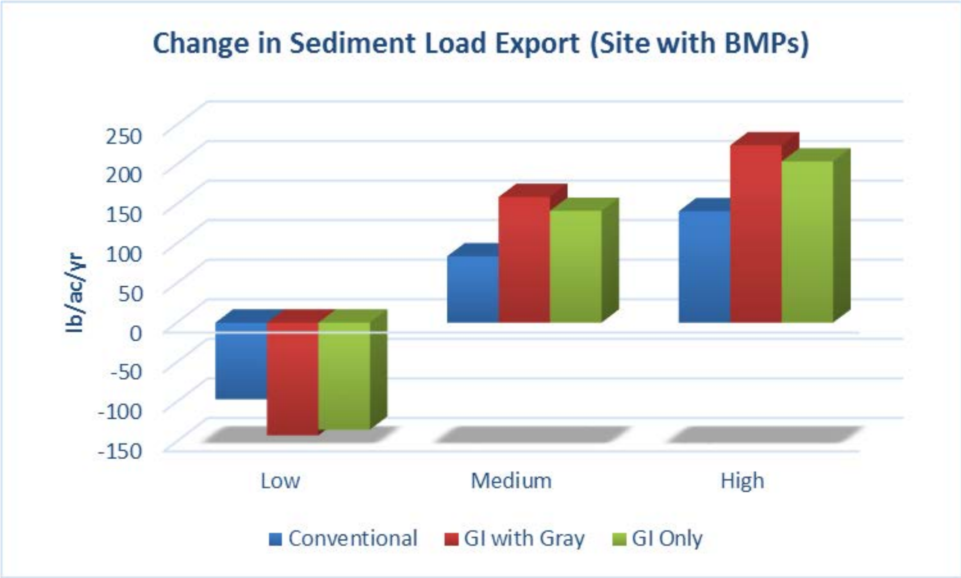

Figure 8-19. Change in sediment load export for Scott County between current and future downscaled general circulation model (GCM) climate scenarios.

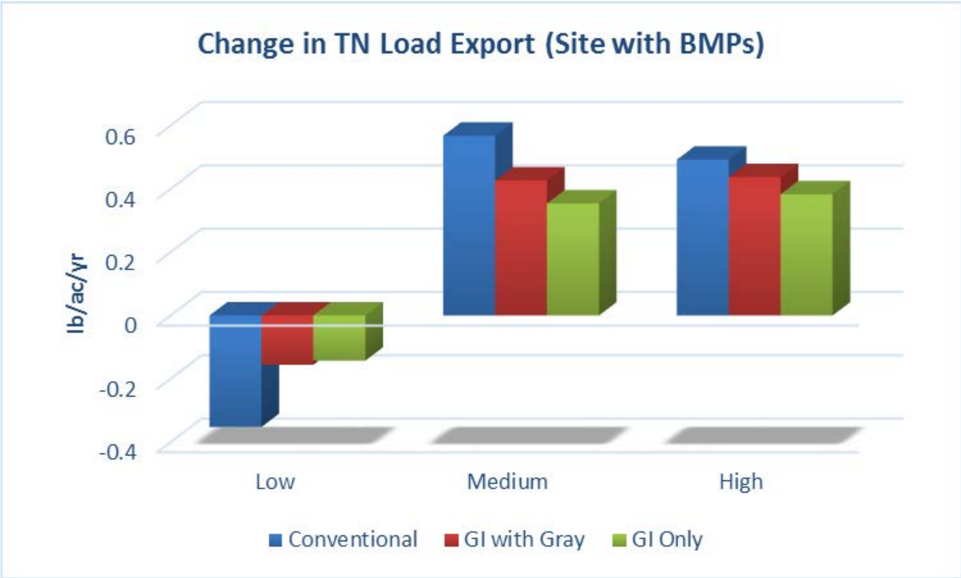

Figure 8-20. Change in total nitrogen (TN) load export for Scott County between current and future downscaled general circulation model (GCM) climate scenarios.

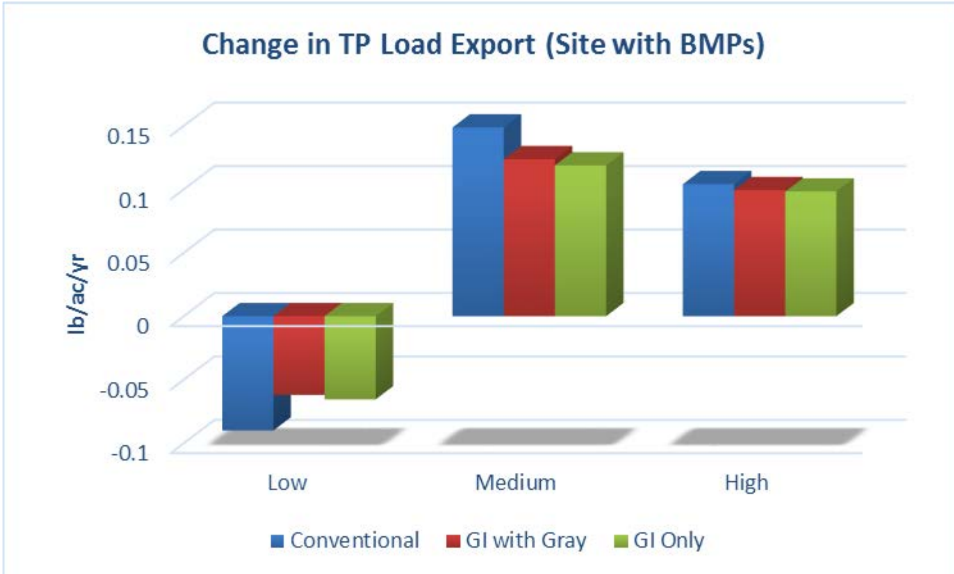

Figure 8-21. Change in total phosphorous (TP) load export for Scott County between current and future downscaled general circulation model (GCM) climate scenarios.

8.1.2.2. Sensitivity Analysis• Percentage Change Scenarios

As noted previously, the sensitivity analysis using percentage change in precipitation was conducted for stormwater management scenarios for Harford County and Scott County. Harford County results are shown in Figure 8-22 (runoff volume), Figure 8-23 (sediment), Figure 8-24 (TN), and Figure 8-25 (TP). For Harford County, the GI plus Gray scenario has a smaller change in export than the Conventional scenario across the board for all parameters across the range of future climate percentage changes. This suggests that the GI plus Gray stormwater management scenario is more resilient to changes in future climate conditions than the Conventional scenario, at least when percentage-change future conditions are modeled. Scott County results are shown in Figure 8-26 (runoff volume), Figure 8-27 (sediment), Figure 8-28 (TN), and Figure 8-29 (TP). For Scott County, the difference between the site-based approaches is smaller than for Harford County, but the Conventional scenario tends to have the highest change in export, the GI plus Gray scenario tends to be in the middle, and the GI Only scenario tends to be lowest. An exception is sediment where GI plus Gray is the highest. Interestingly, the patterns for both locations and all the parameters are carried through to the −10% future climate scenario. In other words, the negative degree of change tends to be less for approaches using elements of GI. While the Conventional scenarios have a greater decrease in runoff and loads (suggesting better performance), the GI-based scenarios show less change (i.e., greater resilience), which may actually be a benefit in cases where downstream baseflow needs to be maintained.

The results of the analysis for the percentage change climate scenarios at both sites suggest that GI is more resilient in terms of mitigating increases in runoff and loads. However, the same conclusion was not reached for the Scott County analysis using a range of intensity changes among downscaled GCM climate models. This difference suggests that results regarding resilience are sensitive to the assumptions used to generate future climate scenarios. It is important to note that these results reflect a limited set of locations and site/BMP characteristics.

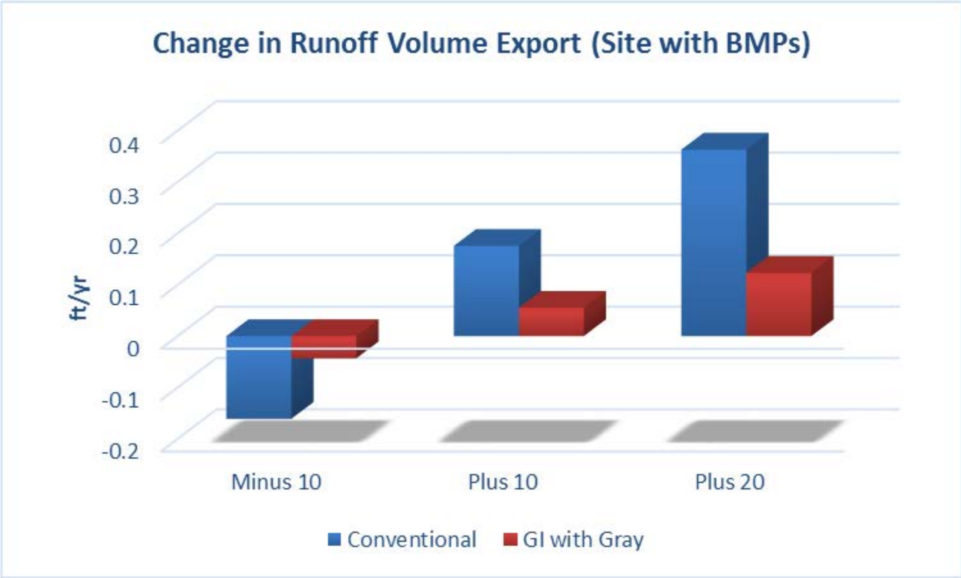

Figure 8-22. Change in runoff volume export for Harford County between current and future percentage change climate scenarios.

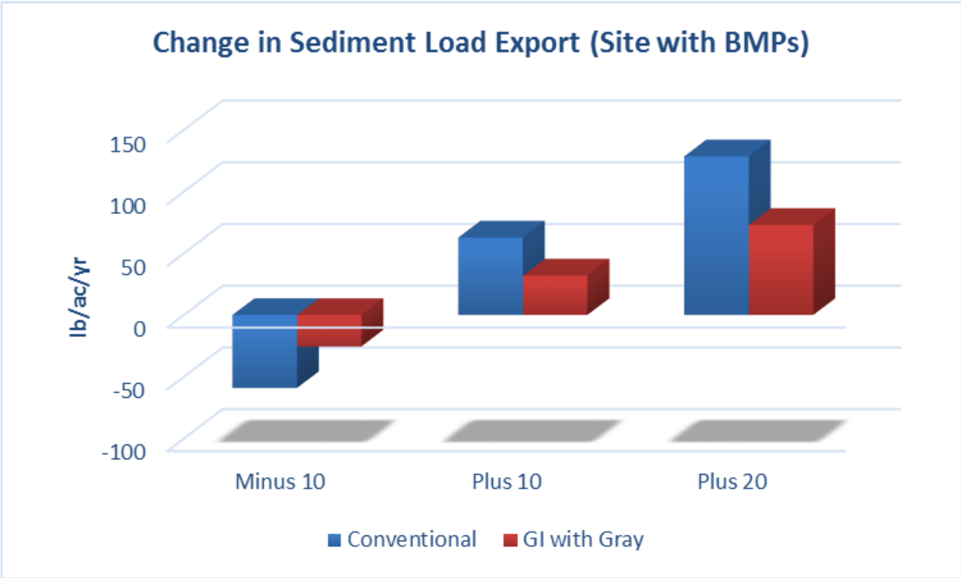

Figure 8-23. Change in sediment load export for Harford County between current and future percentage change climate scenarios.

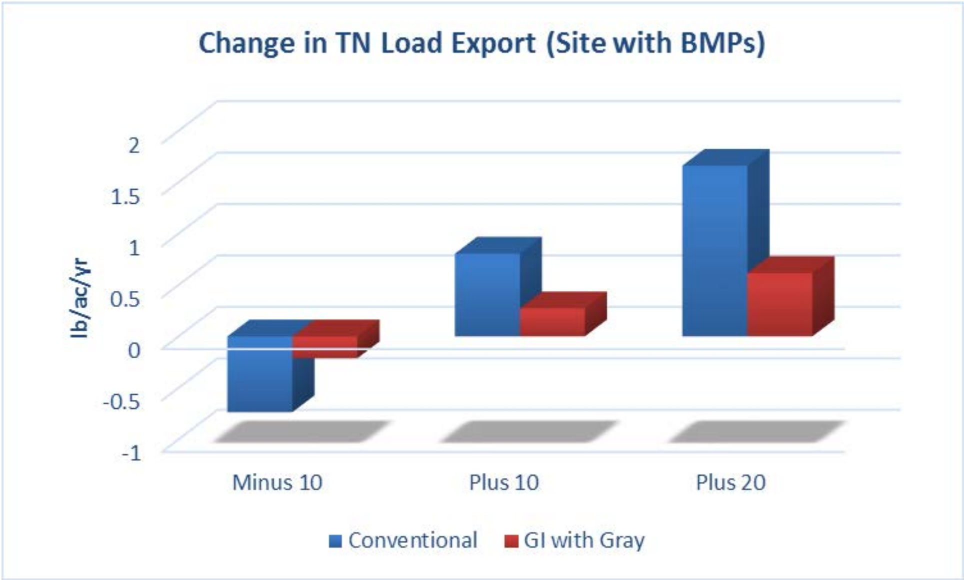

Figure 8-24. Change in total nitrogen (TN) load export for Harford County between current and future percentage change climate scenarios.

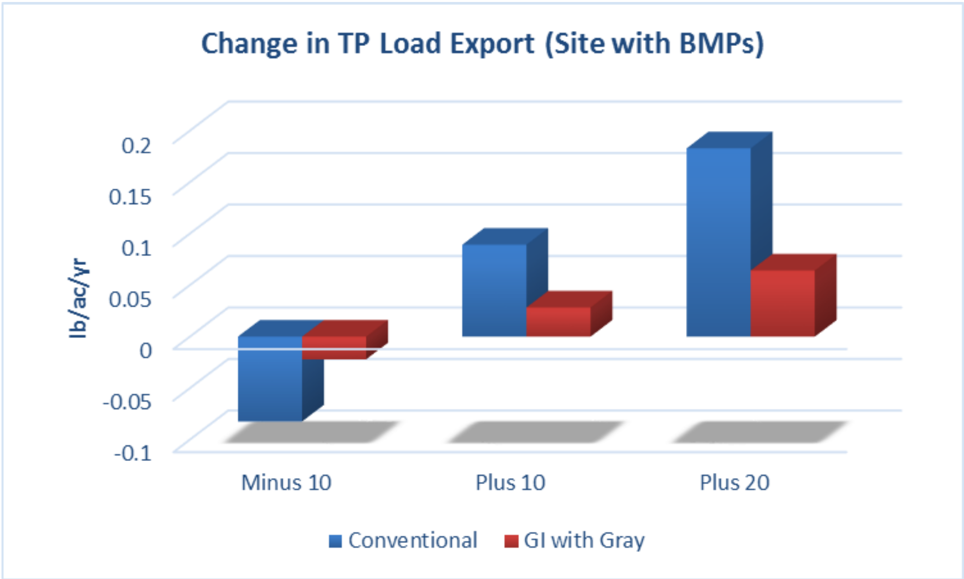

Figure 8-25. Change in total phosphorous (TP) load export for Harford County between current and future percentage change climate scenarios.

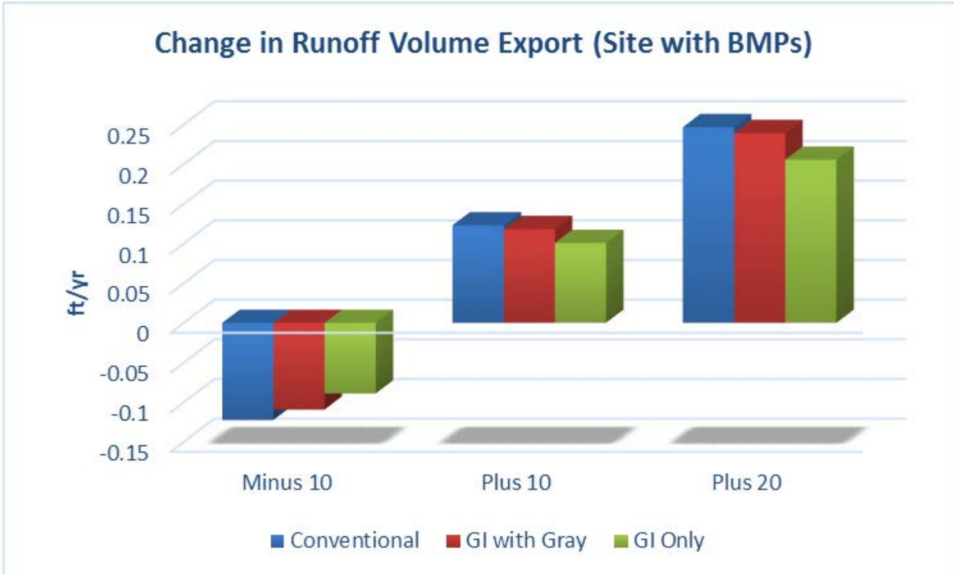

Figure 8-26. Change in runoff volume export for Scott County between current and future percentage change climate scenarios.

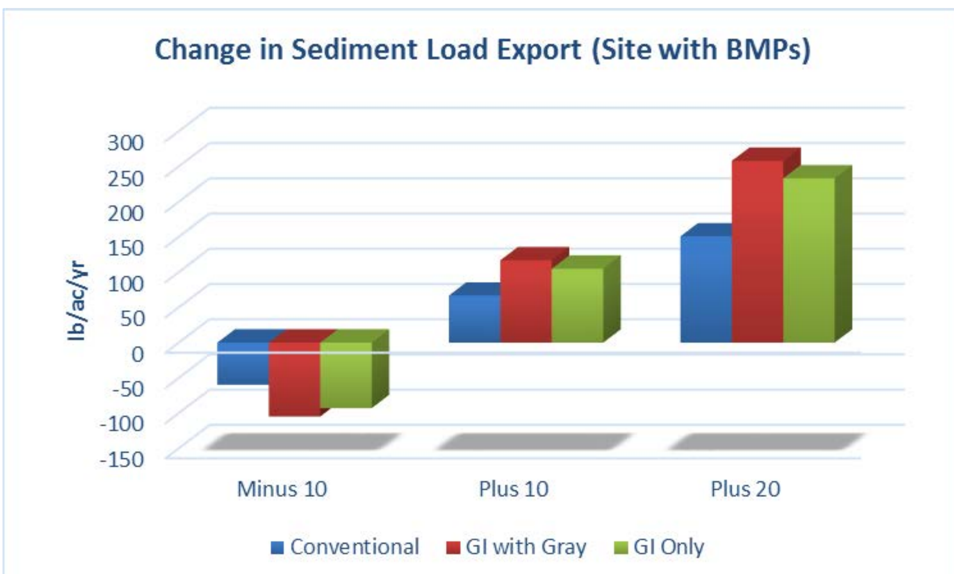

Figure 8-27. Change in sediment load export for Scott County between current and future percentage change climate scenarios.

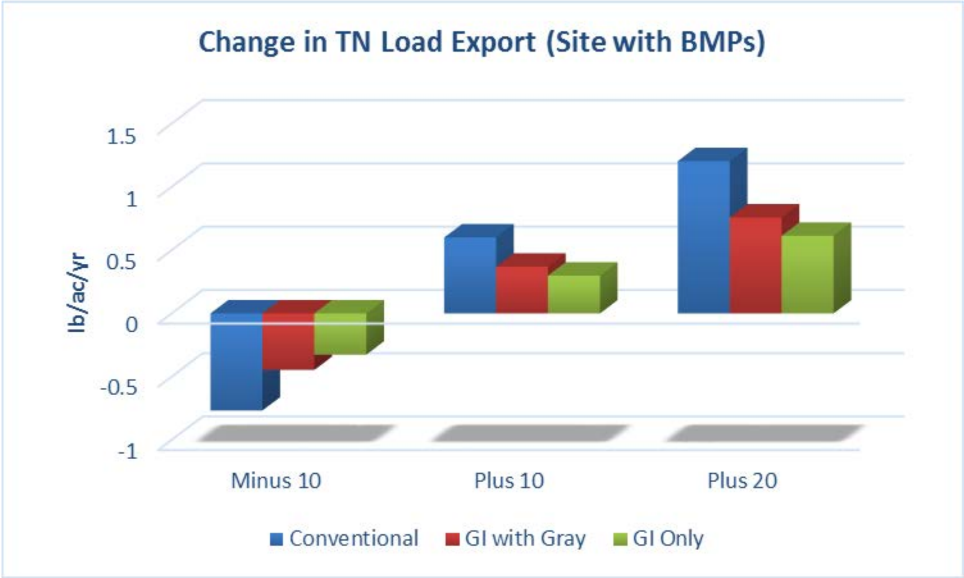

Figure 8-28. Change in total nitrogen (TN) load export for Scott County between current and future percentage change climate scenarios.

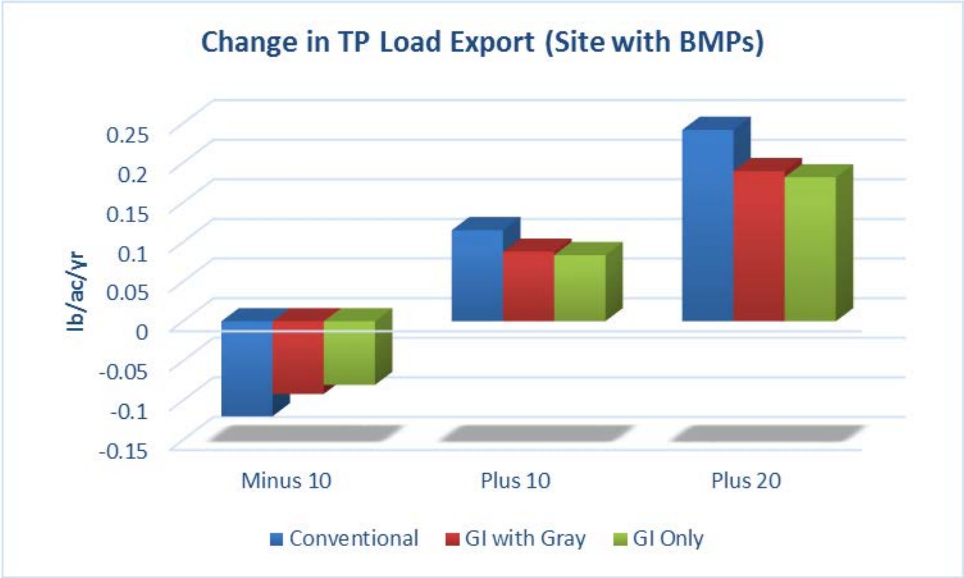

Figure 8-29. Change in total phosphorous (TP) load export for Scott County between current and future percentage change climate scenarios

8.2. STUDY QUESTION #2

> ***How can conventional designs and GI designs be adapted so that a site experiencing extreme precipitation conditions in the future provides the same performance as the site under current conditions?***

For all sites, performance is evaluated at the site "outlet," defined as the point to which all areas, BMPs, and conveyances ultimately drain. Therefore, the objective is to evaluate a site's performance as a whole at meeting performance targets, rather than the performance of individual BMPs. For sites with multiple BMPs, the goal of the adaptation simulation is then to determine the optimal combination of BMP areas that result in the site as a whole meeting performance objectives, or "targets." Within the SUSTAIN optimization framework, the site practices were modified under future climate conditions to achieve the same or better performance as the current climate scenario. Modifications targeted resizing the water quality treatment and peak flow control BMPs, which are the primary drivers controlling site performance. The SUSTAIN model performed hundreds of, and in some cases over 1,000, separate simulations with unique resized BMP configurations to find the optimum solution, which was defined as a configuration meeting or exceeding all of the performance objectives simultaneously at the least cost.

First, results are provided showing the cost of adapting BMPs under future climate conditions to meet or exceed performance metrics under current climate conditions. Next, limiting factors for the adaptation runs are discussed.

8.2.1. Adapting Best Management Practices (BMPs) for Heavy Precipitation

Results of the adaptation model runs are summarized in *Table* 8-2 for all combinations of sites, stormwater management approaches, and climate scenarios. Note that climate scenarios resulting in a reduction in all performance metrics are not presented because they already meet all of the objectives: Current cost of stormwater infrastructure reflects the 20-year present value of the capital cost and O&M for new development. Following the adaptation simulations under future climate conditions, the 20-year present value was recalculated for resized/adapted BMPs. Note that the adapted cost reflects new development cost (i.e., the cost for new construction of the adapted BMPs) rather than retrofit costs of changing BMP configurations on an already developed site. The reason for using the same basis for calculating costs is twofold; first, it allows the results to be more comparable, and second, retrofit cost data tend to be highly variable and difficult to generalize from literature values. The current cost was subtracted from the adapted total cost to obtain the adaptation cost increase. Both metrics were normalized to contributing impervious area. The last column shows the percentage increase in cost for adaptation relative to current cost.

Table 8-2. Cost metrics for future climate and stormwater management scenarios

Location	Climate scenario	Stormwater management scenario	Cost metric: Current cost ($/impervious acre)	Cost metric: Adaptation cost increase ($/impervious acre)	Cost metric: % increase in cost
Downscaled GCM high intensity climate scenarios					
Maricopa County, AZ	Downscaled GCM (high intensity)	Conventional	599,248	255,095	43
		GI Only	497,924	293,403	59
Atlanta, GA		Conventional	767,699	494,727	64
		GI with Gray	1,281,819	162,050	13
Portland, OR		GI Only	623,934	219,453	35
Harford County, MD		Conventional	408,415	497,355	122
		GI with Gray	396,483	537,965	136
Scott County, MN		Conventional	211,546	523,833	248
		GI with Gray	341,375	687,650	201
		GI Only	590,973	550,952	93
Sensitivity analysis climate scenarios					
Harford County, MD	Plus 10%	Conventional	408,415	206,662	51
		GI with Gray	396,483	83,849	21
	Plus 20%	Conventional	408,415	373,822	92
		GI with Gray	396,483	163,940	41
Scott County, MN	Downscaled GCM (medium intensity)	Conventional	211,546	412,610	195
		GI with Gray	341,375	170,608	50
		GI Only	590,973	228,319	39
	Plus 10%	Conventional	211,546	410,815	194
		GI with Gray	341,375	221,875	65
		GI Only	590,973	294,965	50
	Plus 20%	Conventional	211,546	766,021	362
		GI with Gray	341,375	444,388	130
		GI Only	590,973	597,650	101

Table 8 2. Cost metrics for future climate and stormwater management scenarios (Continued)

Location	Climate scenario	Stormwater management scenario	Cost metric		
			Current cost ($/impervious acre)	Adaptation cost increase ($/impervious acre)	% increase in cost
Conventional with distributed GI stormwater management scenarios					
Harford County, MD	Downscaled GCM (high intensity)	Conventional with distributed GI	408,415	812,054	199
	Plus 10%		408,415	124,540	30
	Plus 20%		408,415	273,255	67
Scott County, MN	Downscaled GCM (medium intensity)		211,546	114,250	54
	Downscaled GCM (high intensity)		211,546	354,813	168
	Plus 10%		211,546	109,375	52
	Plus 20%		211,546	190,625	90

8.2.2. Limiting Factors for Adaptation Optimizations

During the SUSTAIN optimizations, which of the five performance measures were the most limiting (i.e., hardest to achieve)? What does this suggest about adapting practices to future climate conditions? As discussed in *Section 2.2.* , each stormwater management scenario was modified (via increase in current practice sizes or addition of GI practices) so that the overall site stormwater performance was the same or better under future climate than under current conditions. At most locations, annual runoff volume and pollutant loads increased under future climate conditions, so SUSTAIN optimization found the most cost-effective way to modify BMPs to return the site to current annual runoff volume and pollutant load export values. In addition, the flow regime changed for the largest runoff values (corresponding to flooding and downstream bankfull flows) between current and future conditions, so the SUSTAIN optimization sought to minimize the difference across a range of flows between current and future conditions as exhibited by FDCs. The goal of the optimizations was to meet all five metrics simultaneously; the result is that the performance improvement "overshot" some of the metrics while seeking to meet *all* of the metrics. When reviewing optimization, it became clear that certain metrics were the most limiting (i.e., costliest to achieve). *Table* 8-3 provides a listing of the limiting metrics for each location, stormwater management approach, and climate scenario (note that the minus 10% climate scenarios and the low intensity downscaled GCM scenario for Scott County resulting in improvements in all metrics, so those climate scenarios were not included in the BMP adaptation runs). In many cases, only one metric was the limiting factor, while in other cases, multiple metrics were limiting factors. Some interesting findings are:

1. Meeting the FDC metric was the limiting or colimiting factor in over 80% of the optimization runs. This indicates that control of flood event runoff volumes is generally the most difficult objective to meet when adapting site BMPs to future climate conditions. Practices that can address flood event volume control are, therefore, a critical component of adaptation to climate change, assuming there is a substantial increase in large storm event intensity.

2. The Scott County Conventional stormwater management scenarios that focused on resizing current practices were always limited by reduction of annual runoff volume. The reason is that the site used a single practice• a wet detention pond• to meet all of the regulatory stormwater requirements. Due to an assumption of poorly infiltrating soils (plus the need to maintain a permanent pool), there was essentially no modeling of infiltration from the bottom of the pond. The only mechanism for the pond to decrease annual runoff under future climate conditions was evaporation from the pond surface. This required a large increase in pond surface area.

3. The Atlanta Conventional stormwater management scenario used two practices that were assumed to be located underground and encased in concrete. As a result, no infiltration or evaporation was modeled from the practices. This meant that there was no mechanism to address increase in runoff volume. As a result, the runoff volume metric was excluded from the adaptation analysis.

4. Optimization runs for the Atlanta Conventional stormwater management scenario resulted in another interesting outcome• it was not possible (at least in the simulation as modeled) for the practices to be resized to reduce TN export to the current metric. As a result, TN was also excluded from the adaptation analysis. TN removal was modeled as a fixed percentage of runoff filtering through an underground sand filter. Because the removal rate did not change because of resizing the practice, the only way to increase removal was to limit large event bypass from the sand filter• in other words, convert untreated bypass runoff to treated filtered runoff. A simulation was performed in which the sand filter was tripled in size, leading to zero bypass and 100% treatment of the future runoff. Even so, the treated mass under future conditions exceeded the sum of treated and bypass current mass.

Table 8-3. Adaptation optimization limiting factors

Location	Climate scenario	Stormwater management scenario	Adaptation optimization limiting factor				
			Annual runoff	FDC	Sediment	TN	TP
Maricopa County, AZ	Downscaled GCM (high intensity)	Conventional[1]	X				
		GI Only[1]	X				
Atlanta, GA	Downscaled GCM (high intensity)	Conventional[2]		X			X
		GI with Gray		X			
Portland, OR	Downscaled GCM (high intensity)	GI Only	X	X			
Harford County, MD	Downscaled GCM (high intensity)	Conventional		X			
		GI with Gray		X			
		Conventional with Distributed GI		X			
	Plus 10%	Conventional		X			
		GI with Gray		X			
		Conventional with Distributed GI		X			
	Plus 20%	Conventional		X			
		GI with Gray		X			
		Conventional with Distributed GI	X	X		X	

Table 8 3. Adaptation optimization limiting factors (Continued)

Location	Climate scenario	Stormwater management scenario	Adaptation optimization limiting factor				
			Annual	FDC	Sediment	TN	TP
Scott County, MN	Downscaled GCM (medium intensity)	Conventional	X				
		GI with Gray		X			X
		GI Only		X			X
		Conventional with Distributed GI	X				X
	Downscaled GCM (high intensity)	Conventional	X	X			
		GI with Gray		X	X		
		GI Only		X	X		
		Conventional with Distributed GI	X	X			
	Plus 10%	Conventional	X				
		GI with Gray		X	X		
		GI Only		X	X		
		Conventional with Distributed GI	X	X			
	Plus 20%	Conventional	X				
		GI with Gray		X	X		
		GI Only		X	X		
		Conventional with Distributed GI	X	X			

Objective was to achieve zero outflow.
Annual runoff and TN targets not met.

8.3. STUDY QUESTION #3

What do the results suggest regarding the adaptation potential of gray and green infrastructure for increases in extreme precipitation events?

This question asks what bigger picture conclusions can be made regarding how adapting BMPs to climate change differs between green and gray stormwater management approaches. Does one tend to cost more than the other? Is one approach more adept at addressing particular performance metrics? These and other questions are addressed in the sections that follow.

8.3.1. Stormwater Infrastructure Cost

How do current stormwater infrastructure costs and additional costs for adaption compare between Conventional versus GI-based stormwater management scenarios? What does this say about various approaches to stormwater management? In the graphs that follow, stormwater infrastructure costs for meeting current regulatory requirements are shown, along with the cost of adapting site BMPs to meet current performance metrics. The two costs (current cost and additional cost of adaptation) are shown in different colors and stacked to provide *total* infrastructure cost. All of the stormwater management scenarios where current practices were resized to adapt to future conditions are shown, including results for the climate sensitivity analyses. (Results comparing resizing practices vs. adding distributed GI are explored in the next subsection.) Figure 8-30 provides results for Portland, Maricopa County, Atlanta, and Harford County, and Figure 8-31 shows all the results for Scott County.

In general, the original (current) cost of stormwater infrastructure using GI practices is more expensive on a per impervious acre basis than the equivalent scenario using only conventional practices. The cost for the GI Only scenario for Maricopa County is less, but that may be due in part to limited cost data for representing an infiltration basin (used in the Conventional scenario) in an arid environment leading to an overestimation of the current cost.

However, the cost of adaptation is frequently less for approaches using GI compared to the Conventional-only approaches. For Maricopa County, the GI Only adaption cost is higher than for Conventional, but the net cost (current plus adaptation) is less for the GI Only scenario than for the Conventional scenario. For Atlanta, the adaptation cost is much less for the GI plus Gray approach, although the combined cost is somewhat higher than the Conventional cost. For Harford County, the adaptation and combined costs of GI plus Gray are lower than Conventional for the percentage change future climate scenarios, but slightly higher for the downscaled GCM scenario using high storm event intensity change. For Scott County, the GI plus Gray scenario has both the lower adaptation and combined cost (compared to Conventional and GI Only) for the percentage change and medium intensity downscaled GCM scenarios, but the trend is not held for the high intensity downscaled GCM scenario. Combined costs are highest for the GI Only approach.

These results suggest two trends:

1. Approaches that use a combination of conventional and GI components tend to have greater cost resiliency compared to approaches relying on only conventional or only GI practices• in other words, the increase in cost of maintaining current performance under future climate is less than for conventional-only or GI Only approaches, which indicates combined conventional/GI approaches are better equipped (i.e., more resilient) for adaptation. This greater resilience likely reflects the combined advantages of having practices that better address large flooding events (such as wet ponds and detention basins) with GI practices that provide most holistic treatment of volume and pollutants.

2. However, GI practices appear to be at a disadvantage in some cases when there is a large projected increase in the most extreme precipitation events. The adaptation optimization forced GI components (which tend to be more expensive on a unit basis) to be larger to provide sufficient volume control for the highest runoff events to meet the FDC metric. Given the importance of flood control for stormwater management, this outcome is realistic.

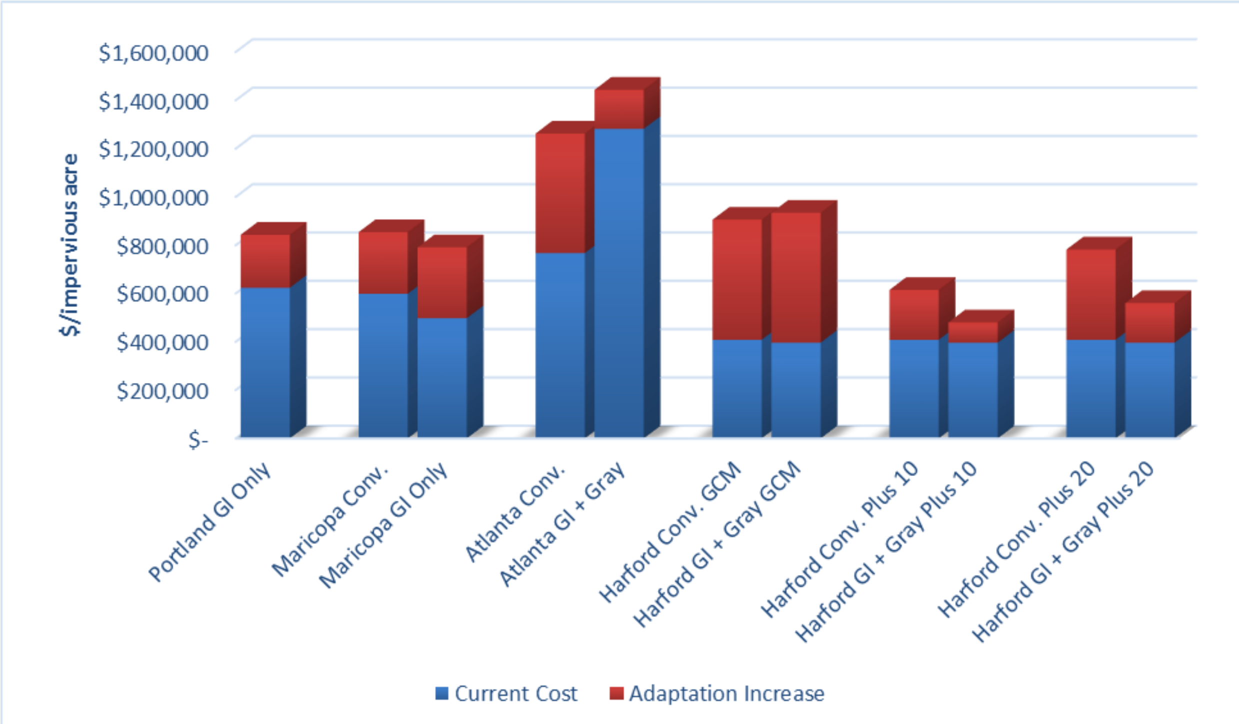

Figure 8-30. Current cost and best management practice (BMP) adaptation cost for Portland, Maricopa County, Atlanta, and Harford County stormwater management scenarios.

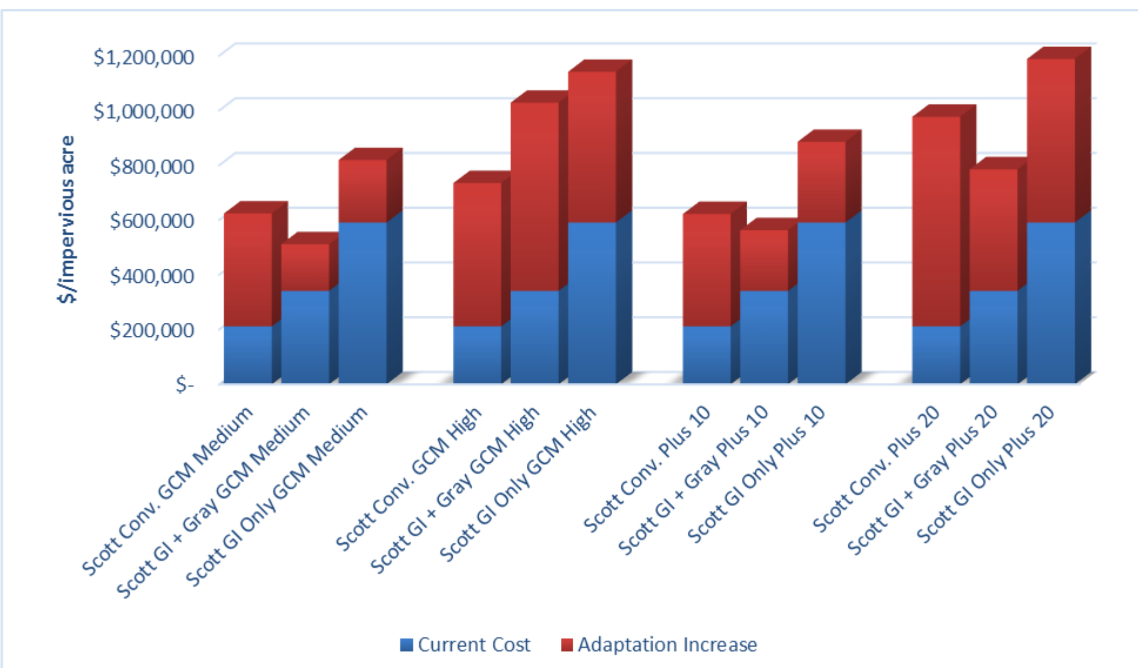

Figure 8-31. Current cost and best management practice (BMP) Adaptation cost for Scott County stormwater management scenarios.

8.3.2. Resizing Current Practices versus Adding Green Infrastructure (GI) to Site

Two different approaches to adapting a site under future climate to address increase in performance measures were modeled for Harford County and Scott County Conventional stormwater management scenarios: resizing currently implemented practices versus adding distributed GI to the site. How do the results compare, and what do they say about the two different approaches? Adaptation optimizations were performed for all the Harford County and Scott County stormwater management and climate scenarios. A comparison of performance improvement is not relevant; the adaptation optimizations ensure that current performance levels will be achieved regardless of the approach. What is more interesting is a comparison of the adaptation costs.

Figure 8-32 provides the results using the same stacked-cost format from the previous subsection. The trends shown in the results are consistent with those seen before. Adding distributed GI to a site to adapt to climate change is generally less expensive than resizing conventional practices• again, the approach that combines conventional and GI practices has the greatest resiliency. However, this is not the case for Harford County for the high intensity downscaled GCM climate scenario. In this case, so much additional volume control is needed that the higher cost of GI outstrips a simple resizing of the less expensive extended detention basin. For Scott County, the distributed GI approach remains less expensive for the high intensity downscaled GCM climate scenario, but this is driven in part by the large footprint needed by the wet pond to provide sufficient evaporation to control the runoff volume increase. In addition, the GI adaptation cost is highest among the future climate scenarios for the high intensity downscaled GCM.

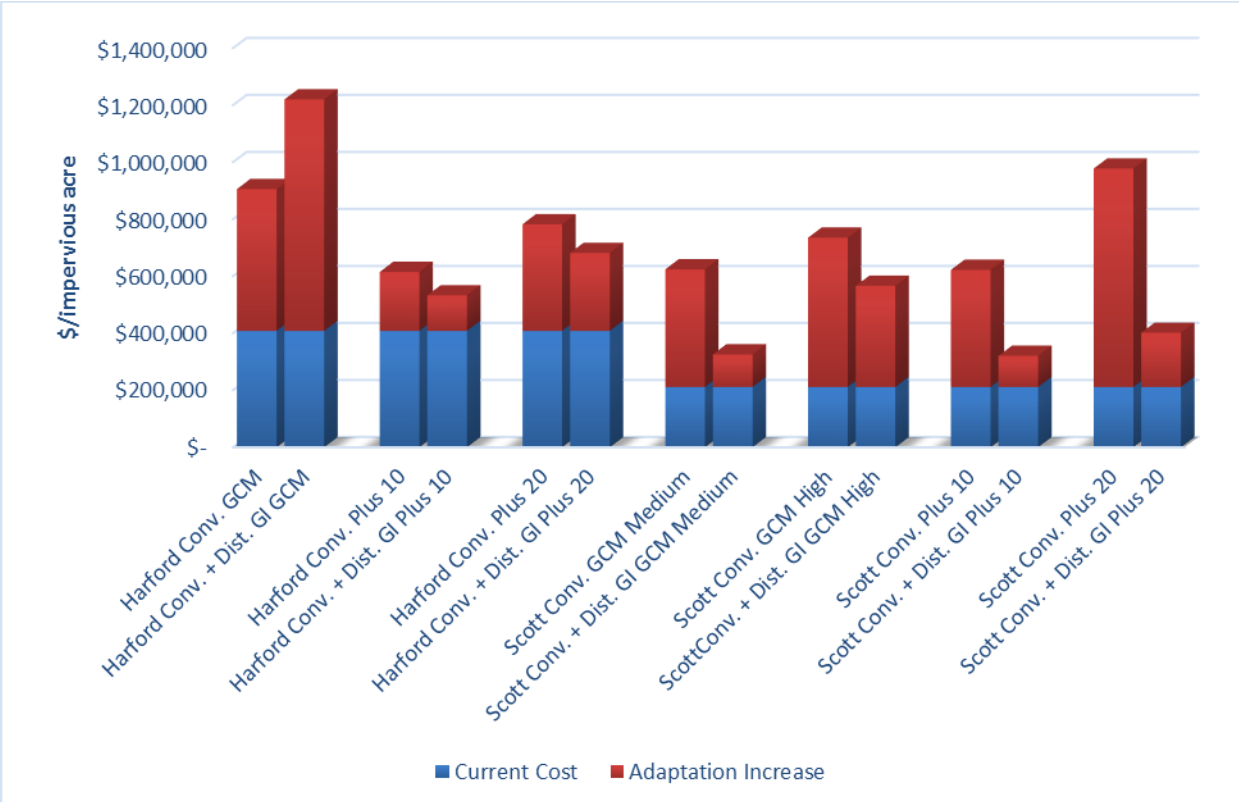

Figure 8-32. Current cost and best management practice (BMP) adaptation cost for Harford County and Scott County conventional stormwater management scenarios, using different adaptation approaches.

8.3.3. Increase in Best Management Practice (BMP) Footprint and Implications

To adapt stormwater BMPs to address climate impacts, practices were either resized or distributed GI was added to the sites. BMPs take up physical space, and the SUSTAIN optimizations provided future practice dimensions. How do changes in BMP footprints (relative to the entire site) compare between scenarios and locations? Are the increases realistic? BMP footprints as a percentage of overall site area are shown below for current and future adapted stormwater management scenarios. All climate scenarios are shown, and adaptation results using distributed GI are provided as well. Due to the number of stormwater management scenarios, the figures are broken into four groups: Portland, Maricopa County, and Atlanta (see Figure 8-33); Harford County (see Figure 8-34); Scott County Conventional and GI plus Gray (see Figure 8-35); and Scott County GI Only and Conventional plus Distributed GI (see Figure 8-36).

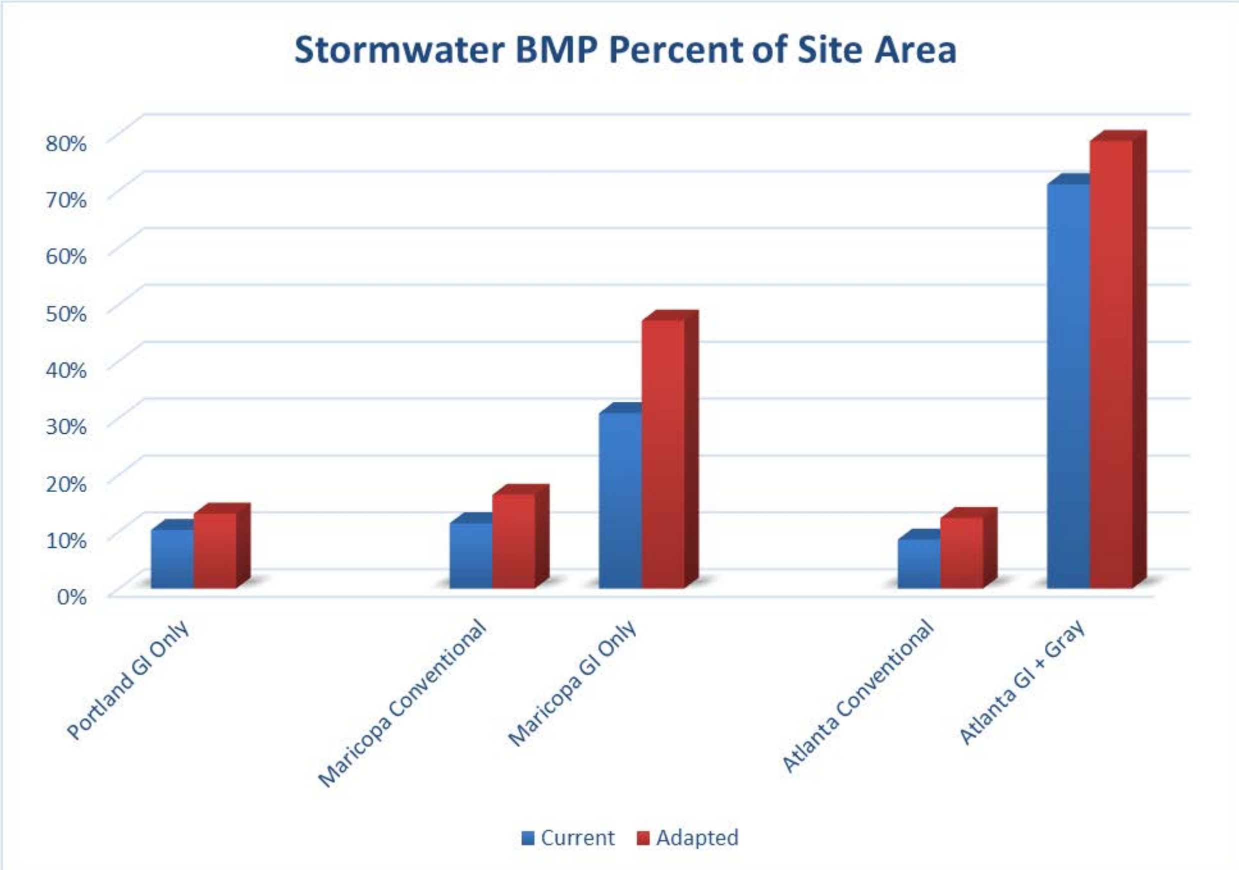

Figure 8-33. Percentage change in best management practice (BMP) footprint between current and adapted future climate for Portland, Maricopa County, and Atlanta stormwater management scenarios.

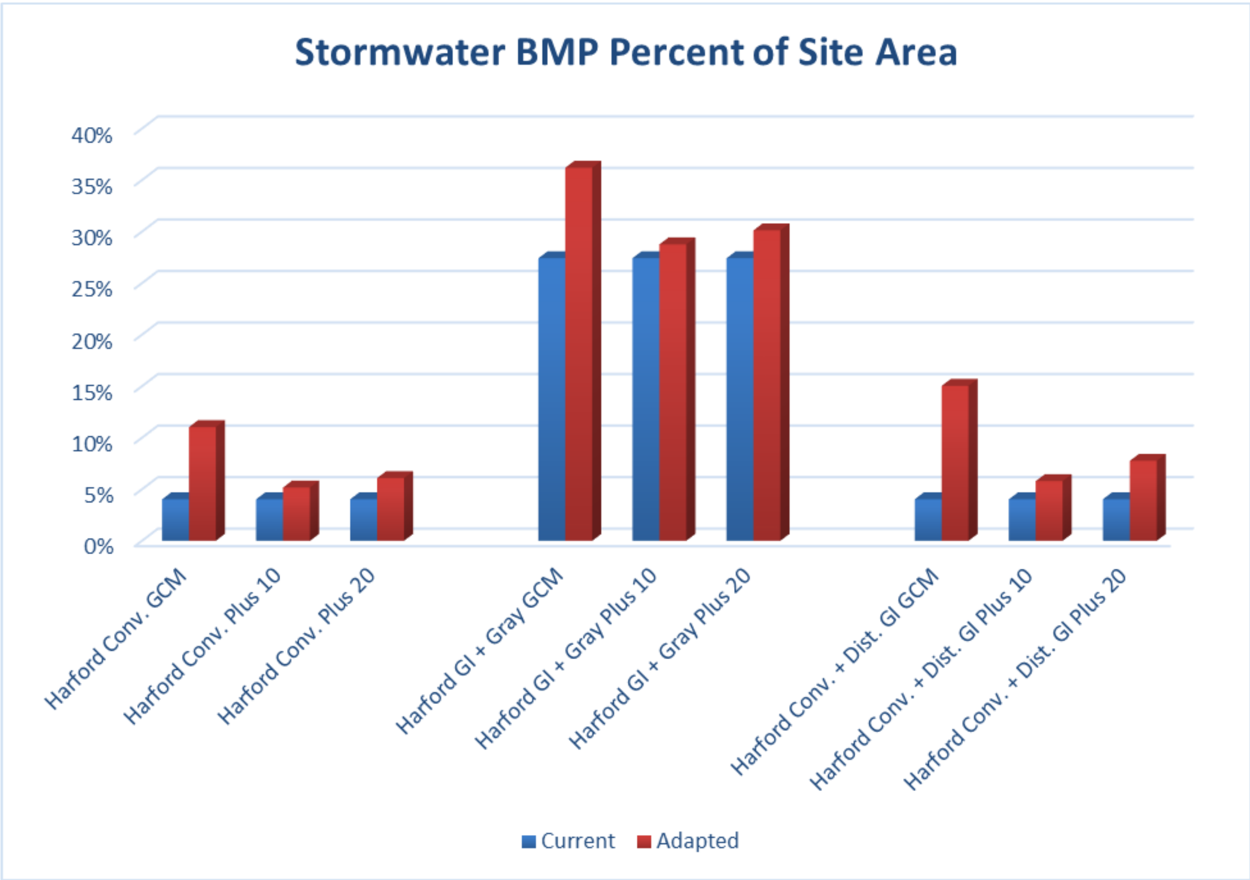

Figure 8-34. Percentage change in best management practice (BMP) footprint between current and adapted future climate for Harford County stormwater management scenarios.

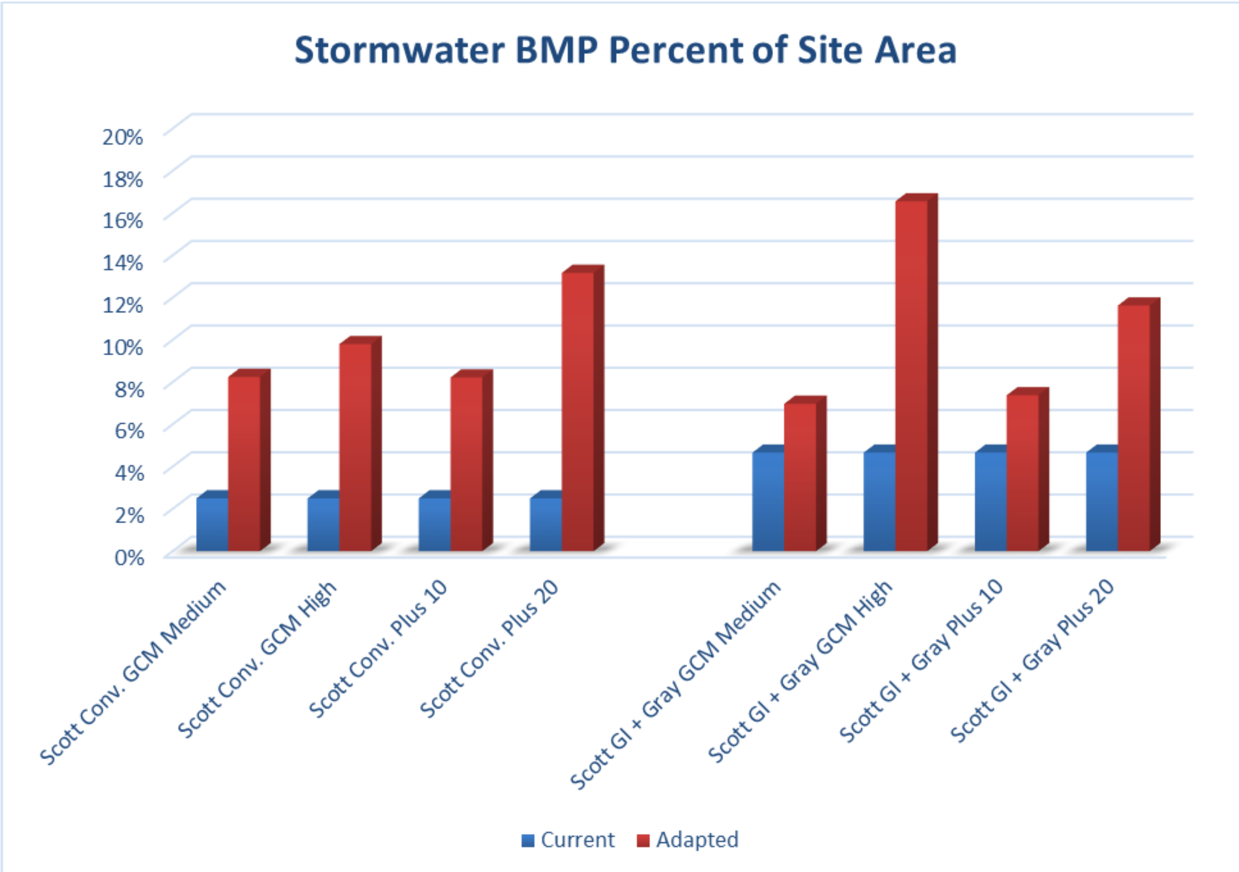

Figure 8-35. Percentage change in best management practice (BMP) footprint between current and adapted future climate for Scott County Conventional and Green Infrastructure (GI) + Gray stormwater management scenarios.

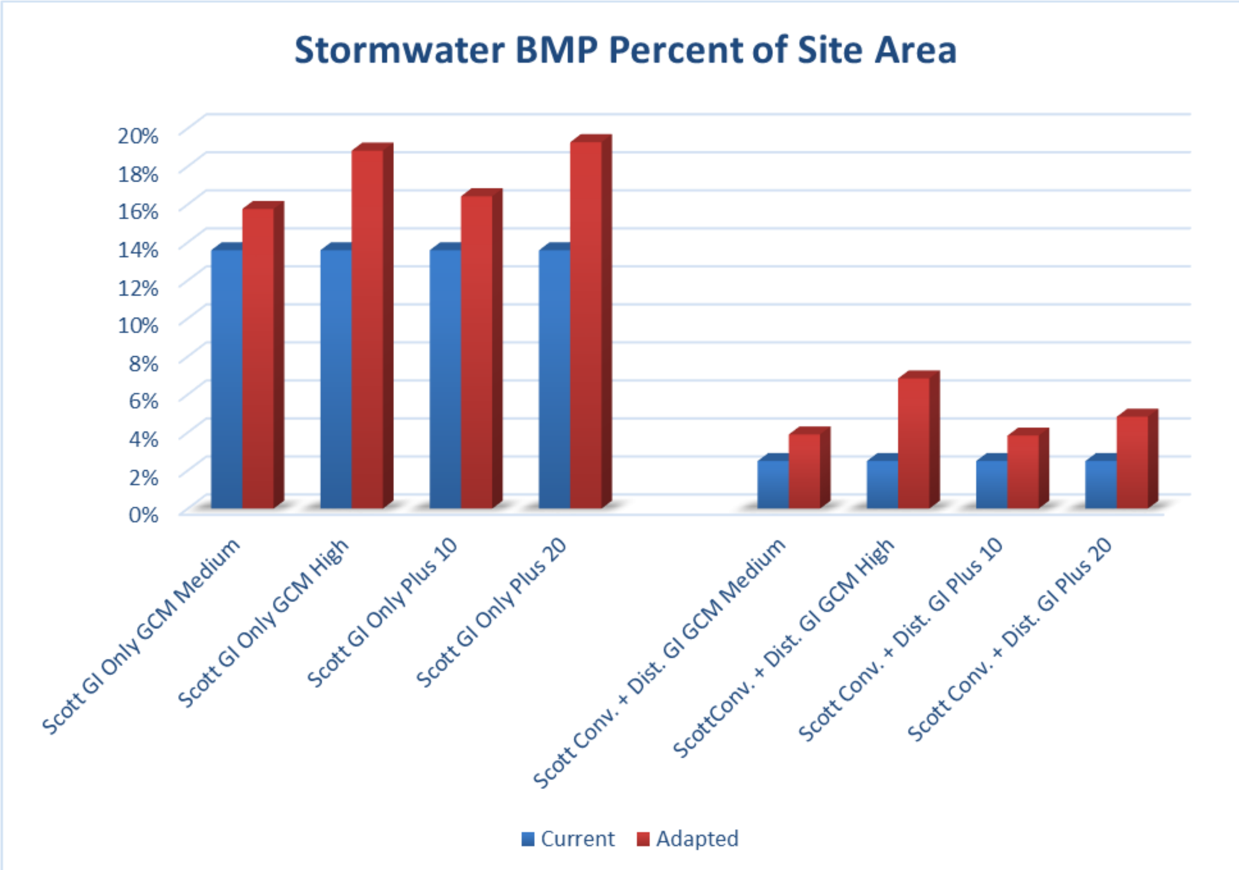

Figure 8-36. Percentage change in best management practice (BMP) footprint between current and adapted future climate for Scott County Green Infrastructure (GI) Only and Conventional + Distributed GI stormwater management scenarios.

The importance of the change in BMP physical footprint depends largely on whether space is readily available for BMP expansion. While the figures show total practice area as a percent of the total site area, it is important to note where the increase in practice footprint is occupying pervious versus impervious areas. This is important because practices that increase coverage of impervious surfaces are simply replacing existing impervious surfaces (i.e., expansion of green roof area and increased use of permeable pavement) versus taking up current site pervious area, which was previously used as landscaping, open space, or even private yard area. The Maricopa GI Only, Atlanta GI plus Gray, Harford GI plus Gray, and Scott County GI Only stormwater management scenarios make use of permeable pavement, so the initial footprints are higher than their counterparts; permeable pavement is allowed to expand for adaptation for Maricopa County GI Only. In addition, the Atlanta GI plus Gray scenario has a large portion of the impervious area devoted to a green roof, which is also allowed to expand somewhat for adaptation. For both Atlanta scenarios, the underground BMPs are resized for adaptation. The remaining increase in site footprint represents the conversion of pervious surfaces to BMP area.

Trends are most evident for Harford County and Scott County where multiple climate scenarios were modeled. For Harford County, the biggest increase in footprint across the stormwater management approaches is always associated with the high intensity downscaled GCM climate scenario. This corresponds to the previous conclusion that large increases in the most intense rainfall leads to a larger practice footprint to provide sufficient storm event volume control. This trend is less evident for Scott County, where both the high intensity downscaled GCM and the plus 20% change climate scenarios show the largest footprint increase.

Consideration should be given to how realistic it is to implement some of the adaptation scenarios. For instance, the wet pond in the Scott County Conventional scenario must be tripled or even quadrupled in size to provide sufficient control of runoff volume. While sufficient pervious surface is technically available for expansion, it would be difficult if not impossible in practice to achieve this expansion given the site layout. This suggests that distributed solutions are a better option when the alternative is to tear out roads and properties. However, were there a large increase in high intensity storm events, as noted previously, GI alone might not be suitable for peak flow volume control. In the Harford County adaptation scenario using distributed GI, the infiltration trenches occupy nearly half of the available remaining pervious area on the site.

Another factor to consider is how site design and stormwater management are typically conducted. Development often maximizes the site footprint to meet the goals of the project, which are to make a profit, or at least to use the available space. Stormwater management is generally minimized to just comply with current regulation, and little if any thought is given to setting aside space for climate change resiliency. As a result, if a site is to be adapted to future climate, other site uses (e.g., parking, amenities) may need to be converted to stormwater management.

8.4. CONCLUSIONS

Model simulations in five study locations suggest potential ranges for altered total urban runoff and pollutant loads under mid-century climate. Using climate scenarios with larger increases in storm event precipitation intensity, the percentage increases in volumes and loads were generally between 1.5 and 26.7%.

For overall post-treatment site-scale performance, simulations using both conventional and GI BMP scenarios generally remove more runoff volume and pollutant mass under future climate conditions (increased precipitation and runoff) compared to current conditions. However, overall site export rates of runoff volume and pollutant mass still increase (i.e., BMP does not remove 100% of the additional runoff/pollutant load due to climate change) despite better volume/mass removal. Changes in large storm event runoff (as indicated by comparison of FDCs) indicate that BMPs designed for current conditions will likely fail to mitigate downstream increases in stormwater runoff and associated downstream channel erosion and flooding impacts under projected future conditions. Thus, there is likely a need to adapt site stormwater infrastructure to future climate conditions to protect downstream water resources.

Considering the adaptation of BMPs under future climate conditions to achieve the same or better performance as seen under current climate, the model simulations show that the most difficult performance measure to mitigate was usually control of large flooding event outflows. Because control of flooding events is a ubiquitous requirement throughout the United States, currently built practices will need greater temporary volume storage and/or reconfiguration of outlet structures to mitigate flooding and channel erosion risk in locations where the magnitude of extreme events is likely to increase. GI practices that rely on treatment without volume storage will be at a disadvantage for climate change adaptation, but approaches that rely only on adaptation of conventional practices may not have the flexibility to address multiple performance objectives. For instance, the conventional practices for the Atlanta ultra-urban site could not be adapted to address runoff volume increase or fully mitigate the increase in TN load. Likewise, the stormwater wet pond for the Scott County residential site provided poor annual volume reduction and thus was resized excessively in the adaptation scenarios to address annual runoff increases.

Comparing the current cost of stormwater management for new development between conventional and GI-based approaches, the conventional approaches tended to be more cost effective than their GI counterparts. However, when climate scenarios with smaller increases in large storm event intensities are considered, the additional cost of adapting sites using GI approaches tended to be less than adapting the conventional-only approaches. Overall, approaches to stormwater management that combined both conventional and GI elements tended to have the best combined cost resiliency. This was further reflected in the stormwater management scenarios that added distributed GI to a conventional approach site versus resizing the conventional practices. Again, the combination of conventional and GI practices had better cost resiliency; however, the trend did not hold up for many of the climate scenarios with the highest projected changes in intensities for large storm events. In these cases, GI was at a disadvantage for providing temporary detention storage needed to mitigate flooding risk.

Projections of future seasonal average increases in air temperature are relatively consistent between various climate models, but changes in precipitation regime are much more uncertain. There would be a “regret cost” if practices were dramatically up-sized in anticipation of climate changes that did not actually occur. GI may have an advantage in flexibility because it typically has a shorter design life before rehabilitation is required, so it would be possible to commit less in the present and use a more incremental approach as climate evolves.

An important issue to consider is the flexibility of different types of practices, regardless of whether gray or green. On an already-developed site, it will likely be difficult to add more area or types of practices, especially if all of the developable area is occupied. Adding dispersed GI may be considerably easier at a later date than resizing hard structures. However, it may be possible to use the existing footprint of BMPs and excavate them to provide more storage and treatment• something that is not explored in this study. This option is less likely on sites with a low elevation gradient. Another option is to build flexibility into site design, setting aside space for potential future BMP addition and/or expansion. Regardless of how it is addressed, flexibility is a key factor to consider, especially because changing climates may result in changes to the environment downstream of development sites, which could then lead to changes in policy and management decisions.

9. REFERENCES

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APPENDIX A. FLOW DURATION CURVES

Flow duration curves analyze the cumulative frequency of historic flow data over a specified period. These curves relate flow values to the percentage of time a flow rate is equal to or exceeded by all the values in the record. The use of “percentage of time” provides a uniform scale ranging between 0 and 100. Thus, the full range of flows is considered. Low flows are usually exceeded, while flood flows are exceeded infrequently. Sometimes flow duration curve analyses consider a subset of the entire curve between lower and upper bounds (as this study does).

A basic flow duration curve runs from high to low along the *x*-axis, as illustrated in Figure A-1. The *x*-axis represents the duration amount, or “percentage of time,” as in a cumulative frequency distribution. The *y*-axis represents the flow value (e.g., cubic feet per second [cfs]) associated with that “percentage of time” (or duration). The *y*-axis is generally shown on a log scale.

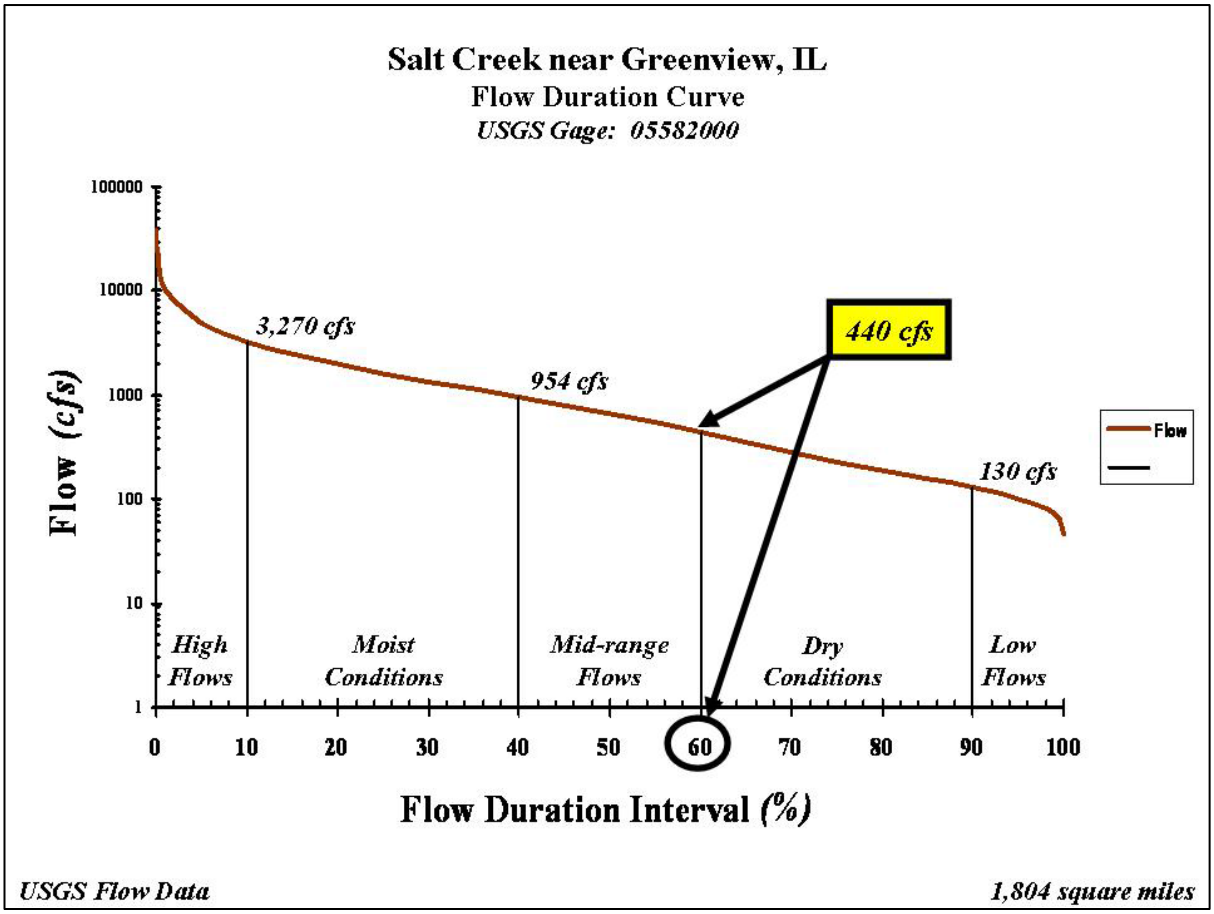


Figure A-1. Example flow duration curve for a perennial stream using daily average flow.

Flow duration curves are sorted from the highest value to the lowest (see Figure A-2). Using this convention, flow duration intervals are expressed as a percentage, with zero corresponding to the highest stream discharge in the record (i.e., flood conditions) and 100 to the lowest (i.e., drought conditions). Thus, a flow duration interval of 60 associated with a stream discharge of 440 cfs implies that 60% of all observed daily average stream discharge values equal or exceed 440 cfs. The generalized formula for a flow duration curve is as follows:

$$p = 100 \times (M \div [n + 1]) \quad \text{(A-1)}$$

p = the probability that a given flow will be equaled or exceeded (percentage of time)
M = the ranked position of the observation (dimensionless)
n = the number of events for the period of record (dimensionless)

While flow duration curves shown in the example represents a perennial water body, they can be used for any type of drainage with outflow. When applied to a development site, the flow is generally comprised of surface runoff during storm events (assuming the site is small enough that there is no baseflow emerging in the site drainage ways). An example of a flow duration curve representative of a development site is shown in Figure A-2. The flow data were taken from one of the Harford County site simulations discussed in the main report. Note that flow drops to the minimum on the scale below the 20th percentile (zero flow cannot be plotted on a log scale), which indicates that during the majority of the time, there is no outflow from the site.

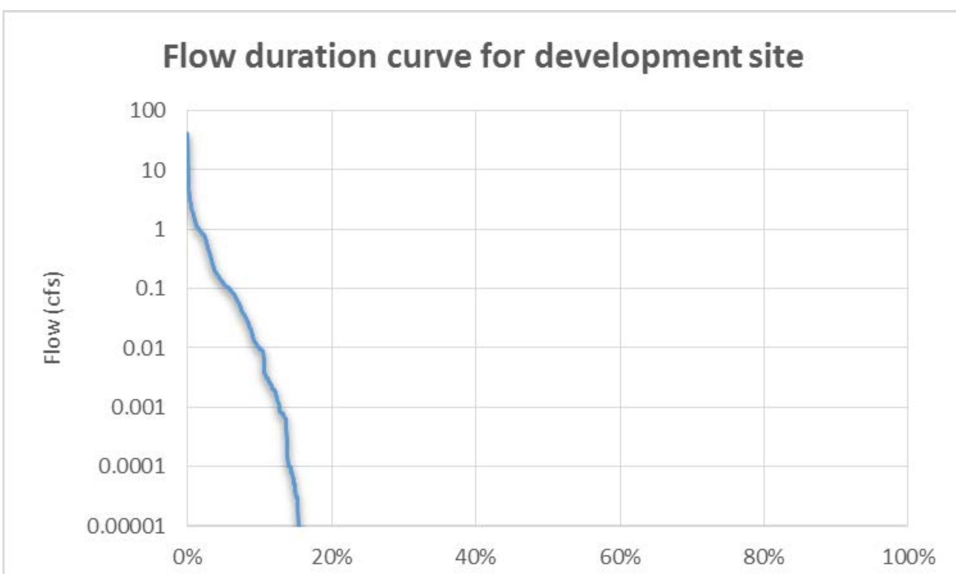


Figure A-2. Flow duration curve for development site.

As discussed in the main document, the analysis makes extensive use of flow duration curves for the very highest site outflows corresponding to flooding storm events. As a result, the flow duration curves shown in the report and in *APPENDIX* B. focus on the very highest flows of interest at the far left side of the curve. An example is shown in Figure A-3. Note the extremely small percentages on the *x*-axis of the plot. The *y*-axis uses a standard scale rather than a log scale to facilitate comparison of flow duration curves from the various simulation scenarios.

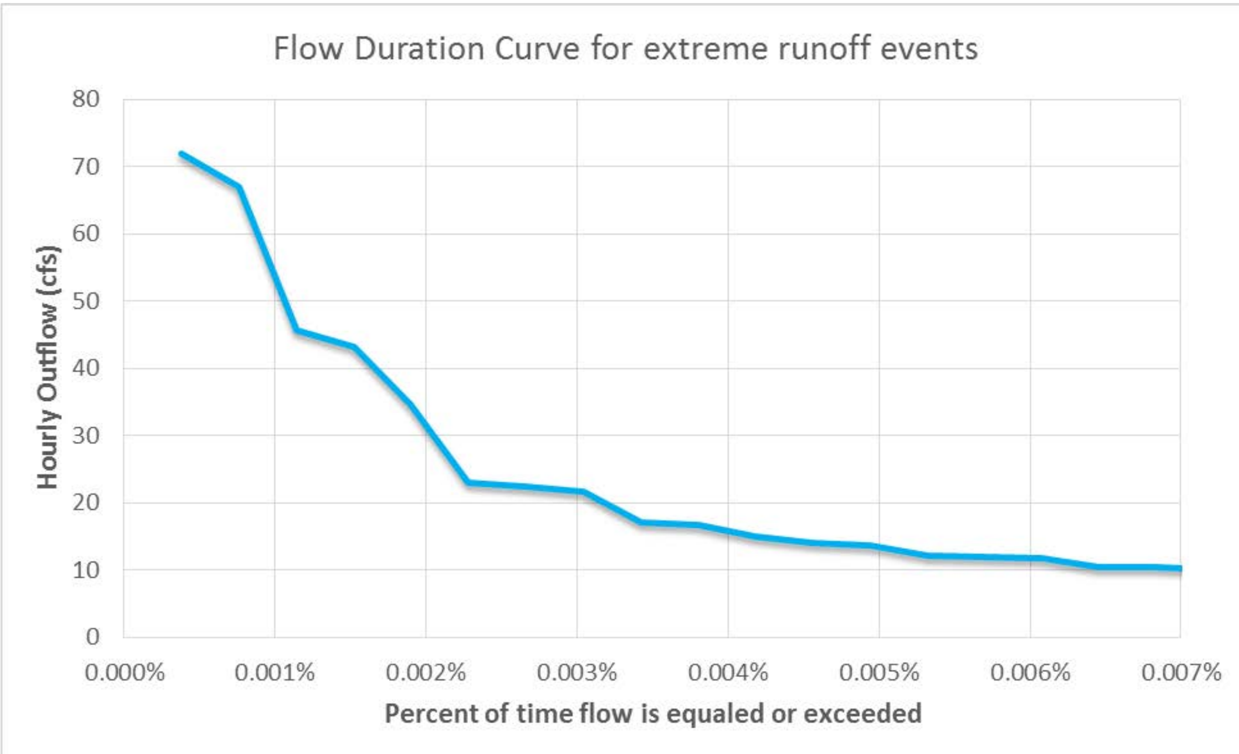


Figure A-3. Example flow duration curve showing only the most extreme runoff values.

APPENDIX B. DETAILED RESULTS

This section provides detailed results of the simulation modeling. First, simulation results by site are presented and focus on current versus future performance within each green or gray scenario. This information is followed by sensitivity analysis results at two sites.

For all results presented below, the "current with BMPs" label reflects current climate conditions with current best management practice (BMP) configurations. The "future with BMPs" label represents future climate conditions with current BMP configurations. Finally, the "future, adapted BMPs" label reflects future climate conditions with practices resized ("adapted," according to the results of the System for Urban Stormwater Treatment and Analysis Integration [SUSTAIN] optimization) to maintain current performance.

B.1. SIMULATION RESULTS BY SITE

B.1.1. Harford County, MD

B.1.1.1. Conventional (Gray) Infrastructure

As discussed in *Section 4.2.* of the report, the selected future climate scenario for Harford County, MD resulted in an across the board increase in precipitation depth and intensity, with the largest storm events having the largest increase in hourly precipitation depth. This trend translates into the increase in annual runoff volume between the current and future climate scenarios seen in Figure B-1. This figure presents the partitioning of runoff volume among the three runoff fate pathways: infiltration, evapotranspiration (ET), and outflow for the Harford County Conventional (Gray) Infrastructure stormwater management scenario under the simulated current and future climate conditions.

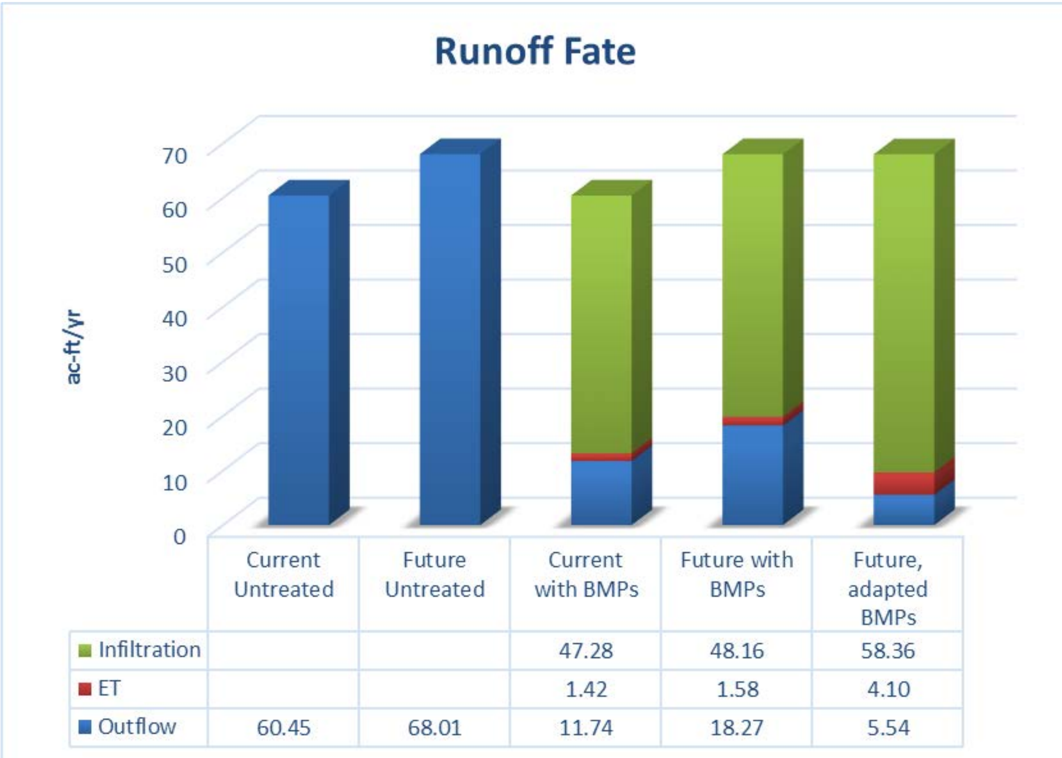


Figure B-1. Current and future partitioning of runoff fate for the Harford County, MD Conventional (Gray) Infrastructure scenario.

Under current climate with BMPs (third bar in Figure B-1), approximately 78% of annual runoff is lost to infiltration and 2% to ET with the remaining 19% discharging from the site as outflow. Under future climate with BMPs (fourth bar in Figure B-1), about 71% of runoff is lost to infiltration and 2% to ET. A greater fraction of runoff volume (27%) is lost to outflow. Increases in rainfall volume and large storm event intensity associated with projected climate change result in a greater runoff volume overall, leading to a larger fraction of runoff being discharged rather than infiltrated. When the surface sand filter and extended dry detention basin footprints are increased to adapt to future climate conditions (last bar in Figure B-1), the increase in BMP surface area results in an increased fraction of runoff portioning to infiltration (86%) as well as ET (6%). Only 8% of annual runoff is converted to outflow when BMPs are adapted for future climate.

Annual average sediment loads for current and future climate conditions (see Figure B-2) exhibit similar behavior to annual runoff volumes. This is not surprising because sediment load is closely tied to rainfall intensity such that an increase in intensity, as is predicted for Harford County, will promote greater sediment wash-off. Increased sediment concentrations combined with increased runoff volumes result in increased sediment loads in future climate. In the current climate conditions, the combined influence of the conventional site practices results in a 79% reduction in annual sediment load. In the future without any modification, the reduction declines to 70%. The surface sand filters and extended dry detention basin have been sized according to performance criteria that are based on current climate conditions, and the reduction in performance demonstrates that the current sizing is not adequate to maintain performance in future climate. When the BMP footprints are increased for future climate adaptation, the annual sediment load reduction improves to 90%.

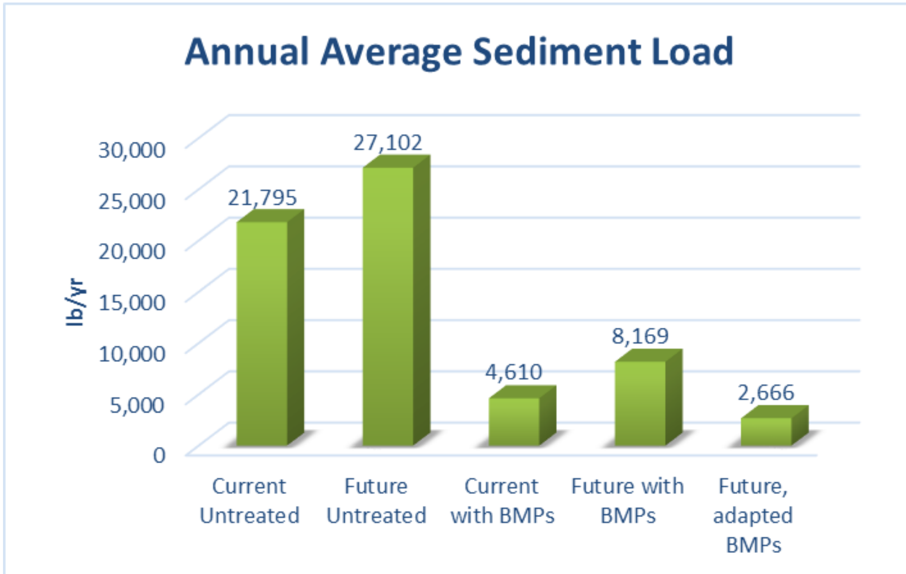


Figure B-2. Current and future performance for annual average sediment load, Harford County, MD Conventional (Gray) Infrastructure scenario.

Because nitrogen fate and transport in the environment is complex, a direct connection between annual average total nitrogen (TN) load (pounds/year) and runoff volume cannot readily be made. However, the key observations from Figure B-3 are that (1) annual average TN loads are predicted to increase under future climate and (2) the Harford County conventional practices are highly effective at managing TN. In the current climate conditions, the combination of the surface sand filters and extended dry detention basin achieves an overall 88% load reduction for TN on an annual basis. Under future climate conditions, TN load reduction decreases to 83%. With the future adapted BMP footprints, the annual TN load reduction increases to nearly 95%.

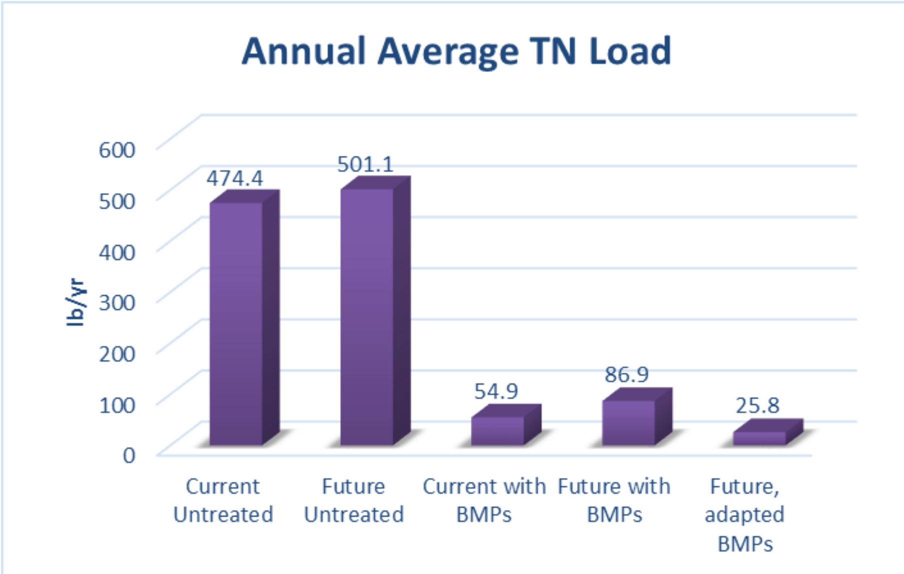


Figure B-3. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Conventional (Gray) Infrastructure scenario.

Figure B-4 shows that a small increase in annual average total phosphorous (TP) load (pounds/year) is predicted under future climate compared to the current climate for the untreated Conventional (Gray) site. The conventional practices are highly effective at reducing annual average TP load. Their combined TP load reduction is greater than 93% in the current climate. In future climate without any resizing, the TP load reduction decreases to 89%. With the increased adapted BMP footprints, the annual average TP load reduction is improved to 97%.

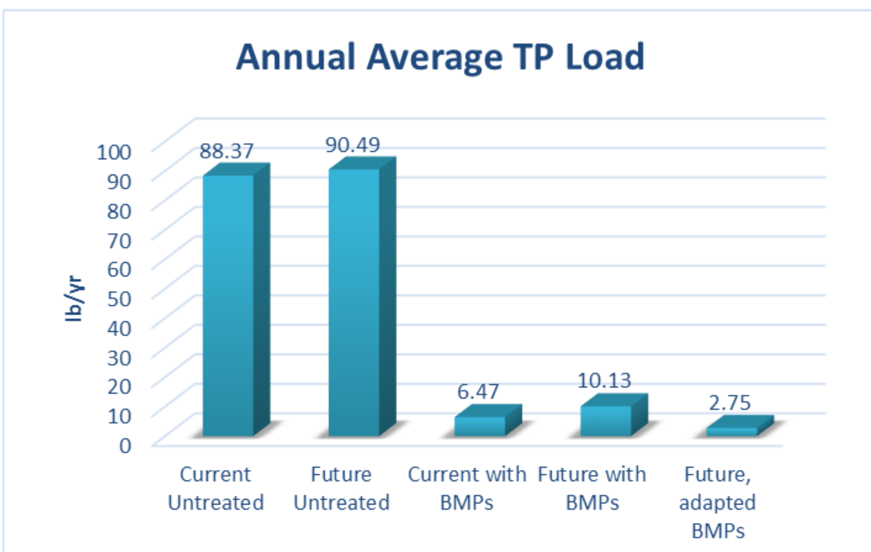


Figure B-4. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Conventional (Gray) Infrastructure scenario.

As discussed in *Section 5.2.2.* of the report, the approximate 2-year hourly flow based on the 30-year hourly outflow record for the Harford County Conventional (Gray) Infrastructure scenario was used to bound the flow duration curve (FDC) analysis. This is represented by the dashed vertical line in Figure B-5. This figure presents the FDC results for the current and future BMP scenarios. The objective of the BMP adaptation was to resize the surface sand filters and extended dry detention basin to minimize the difference between the "current with BMPs" (blue line) and "future with BMPs" (gray line) FDCs from the approximate 2-year hourly flow (lower bound) to the highest hourly peak flow. The future adapted FDC (dashed red line) reflects the resulting increased (adapted) conventional BMP footprints. Comparison of the current and future adapted FDCs suggests that the adapted BMPs are effective at reducing the highest peak flows (upper end of the curve) and flows in the vicinity of the 2-year hourly flow, with variable performance in between. Overall, the future adapted BMPs produce a flow duration response that reasonably reproduces the current BMP performance.

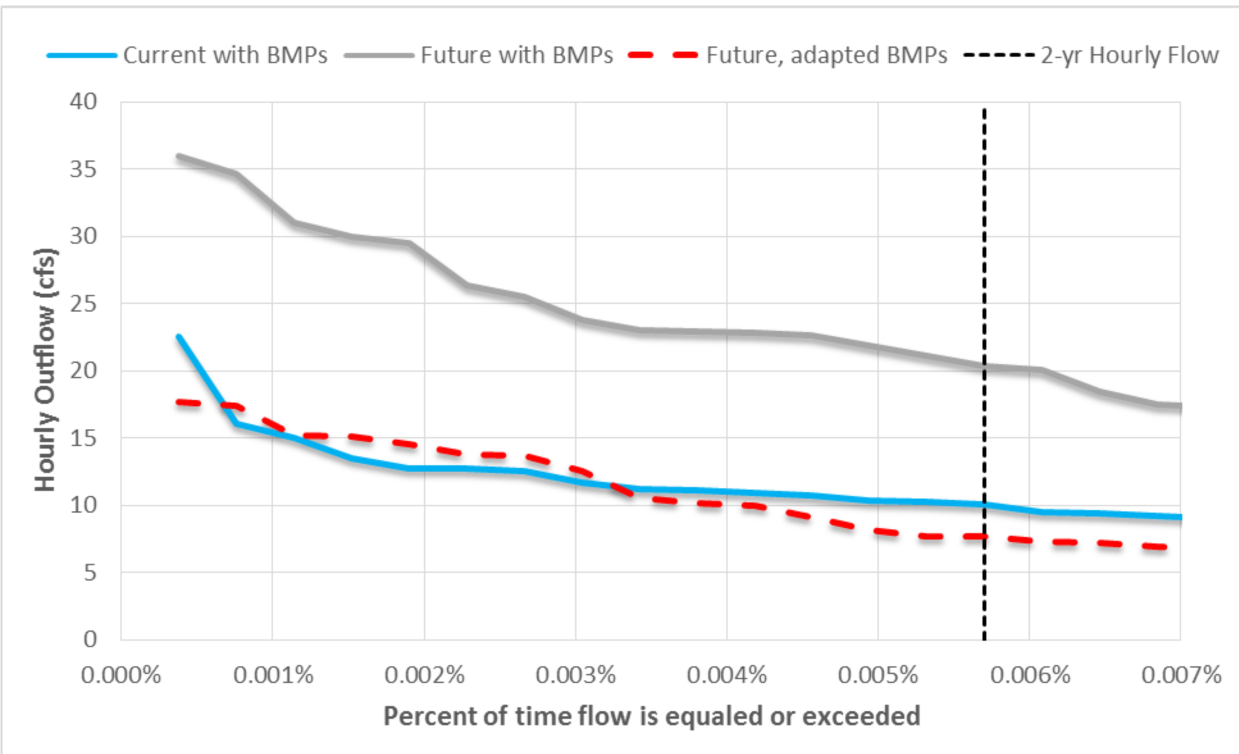


Figure B-5. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Conventional (Gray) Infrastructure scenario.

Maximum hourly peak flow (see Figure B-6) was not a performance measure for the adaptation exercise, but results are provided for discussion. These results also provide additional insight into the FDC evaluation in Figure B-5. The observed increase in maximum hourly peak flow between the current and future untreated scenarios aligns well with expectations based on the current and future climate comparisons provided in *Section 4.* of the report for Harford County. Projected increases in precipitation intensity and depth translate into increases in the maximum peak flow leaving the site. In the

Conventional (Gray) Infrastructure scenario, peak flow reduction is primarily provided by the extended dry detention basin. Comparison of the “current with BMPs” and “future with BMPs” scenarios demonstrates that without resizing, the BMPs are unable to mitigate the increase in peak flow between the current and future climate. When the footprints are increased for future climate adaptation, the maximum hourly peak flow is reduced below the “current with BMPs” scenario (17.70 cfs versus 22.50 cfs, respectively). This impact is observed in Figure B-5 where the “current with BMPs” and “future, adapted BMPs” curves diverge at the highest hourly outflow value (peak flow).

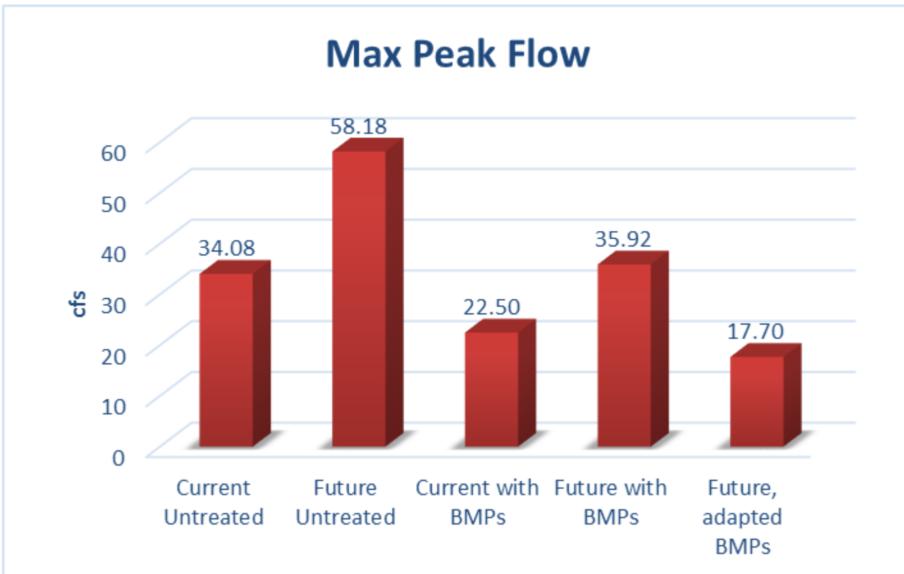


Figure B-6. Current and future performance for maximum hourly peak flow, Harford County, MD Conventional (Gray) Infrastructure scenario.

Figure B-7 provides an alternate means of comparing the performance of the current and future adapted BMPs with respect to outflow volume. Examining these results on a monthly basis provides additional insight into BMP behavior, and helps verify that they align with expectations given the climate scenario comparisons provided in *Section 4.2.* of the report. The current and future monthly average precipitation comparison for Harford County demonstrated that the increase in future precipitation compared to current is greatest in July, September, November, and December, with September exhibiting overwhelmingly the greatest increase of all months. These predicted increases in monthly precipitation result in the corresponding increases in monthly outflow volume seen in Figure B-7. Comparison of the “current with BMPs” and “future with BMPs” graphs suggests that prior to adaptation, the conventional BMPs are not highly effective at mitigating increased runoff volumes under future climate conditions; in almost all months, the future (not adapted) outflow volumes are higher than the current outflow volumes, indicating a decrease in volume reduction effectiveness. With the adapted BMP sizes, monthly outflows are well below the future baseline, and lower than the “current with BMPs” monthly outflows in every month but September. The increased footprints of the adapted surface sand filters and extended detention basin provide increased surface area for infiltration and ET as well as greater storage volume to mitigate the increase in future outflow volume.

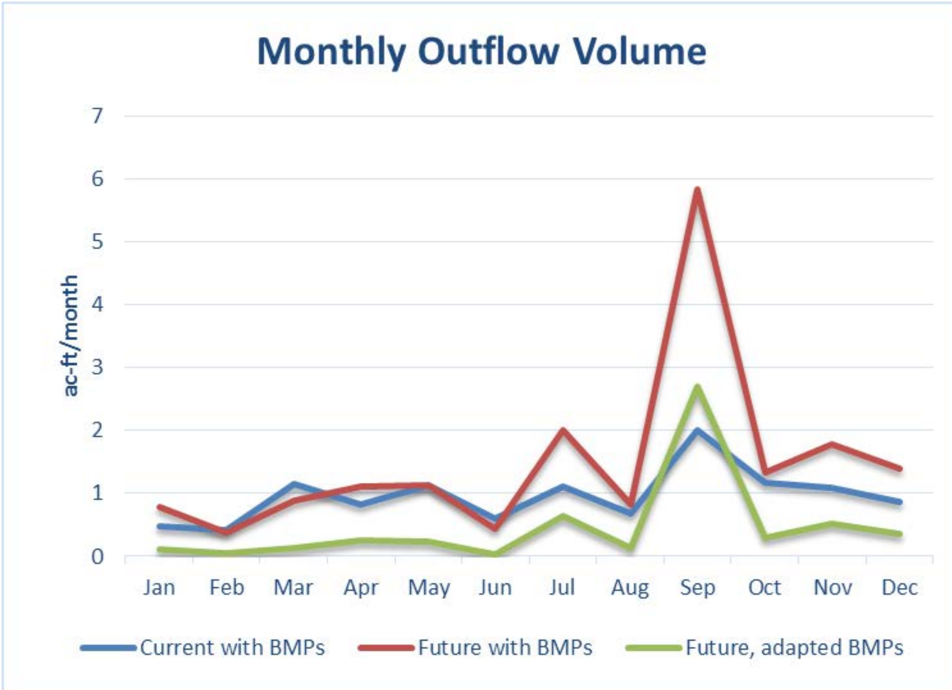


Figure B-7. Current and future performance for monthly outflow volume, Harford County, MD Conventional (Gray) Infrastructure scenario.

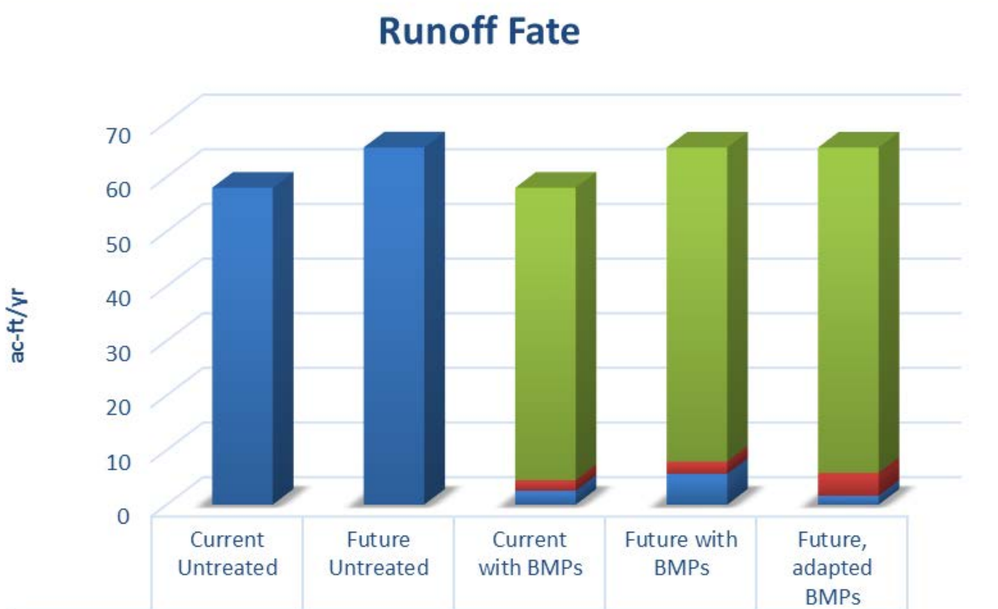
Table B-1 summarizes the increases in BMP footprints for the Harford County Conventional (Gray) Infrastructure scenario that would be required to maintain current performance under future climate conditions. The current and adapted footprints are presented both in terms of actual square feet of practice as well as a percentage of overall site area. The latter is provided as a means of comparing the current and future adapted sizes relative to the site area (20 acres) for this particular development type (mixed use).

Table B-1. Comparison of current and future adapted best management practice (BMP) footprints, Harford County, MD Conventional (Gray) Infrastructure scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure	Extended dry detention basin	25,000	2.9%	81,250	9.3%	225%
	Surface sand filters	10,119	1.2%	14,840	1.7%	47%

B.1.1.2. Green Infrastructure (GI) with Gray Infrastructure

In the Green Infrastructure (GI) with Gray Infrastructure stormwater management scenario, the combination of green (infiltration basins, infiltration trenches, and permeable pavement) and gray (dry detention basin) practices is highly effective at managing site runoff. Over 92% of annual runoff is infiltrated, 3% is converted to ET, and the remaining fraction (4%) is converted to outflow under current climate conditions. Under future climate, the effectiveness of the Green and Gray practices decreases, with 88% of annual runoff being infiltrated, 3% converted to ET, and approximately 9% leaving the site as outflow. With the increased BMP footprints in the future adapted scenario, the infiltration fraction is increased to greater than 91% and ET to over 6%. Less than 3% of annual runoff volume is converted to outflow.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			53.52	57.49	59.54
ET			1.93	2.19	4.19
Outflow	57.99	65.36	2.54	5.67	1.62

Figure B-8. Current and future partitioning of runoff fate for the Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario.

The practices in the GI with Gray Infrastructure scenario are highly effective at managing sediment. On an annual basis, the sediment load reduction for the site in the current climate is nearly 93%. Under future climate prior to adaptation, annual sediment load reduction decreases to 83%. With the adapted BMP footprints, future sediment load reduction improves to nearly 95%.

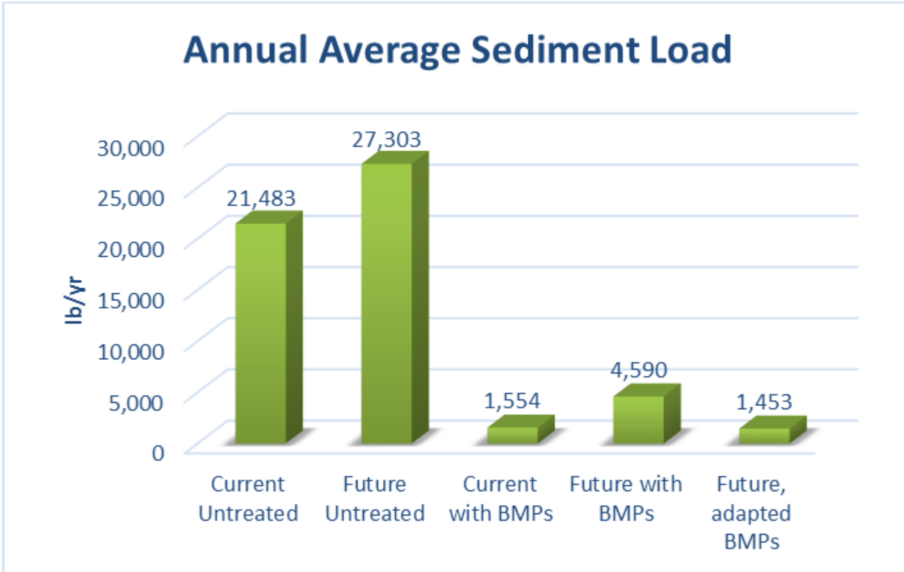


Figure B-9. Current and future performance for annual average sediment load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario.

The future adapted practices in the GI with Gray Infrastructure scenario are highly effective at treating TN and mitigating the increased annual average TN load under future climate conditions. The current climate TN load reduction for the site is approximately 97%, which decreases to 93% under future climate. The adapted BMP footprints achieve an annual average TN load reduction of 98%.

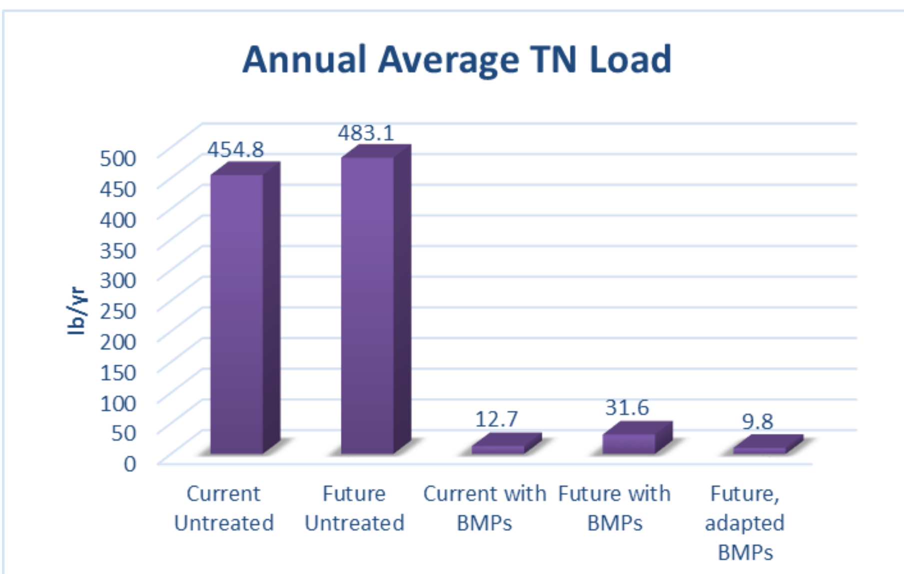


Figure B-10. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario.

The combination of Green and Gray practices is very effective at reducing annual average TP load. Current performance achieves a reduction of 99% for the site, which decreases slightly to 98% before adaptation in future climate conditions. Increasing the practice footprints for future adaptation improves the site's annual average TP load reduction to nearly 99%.

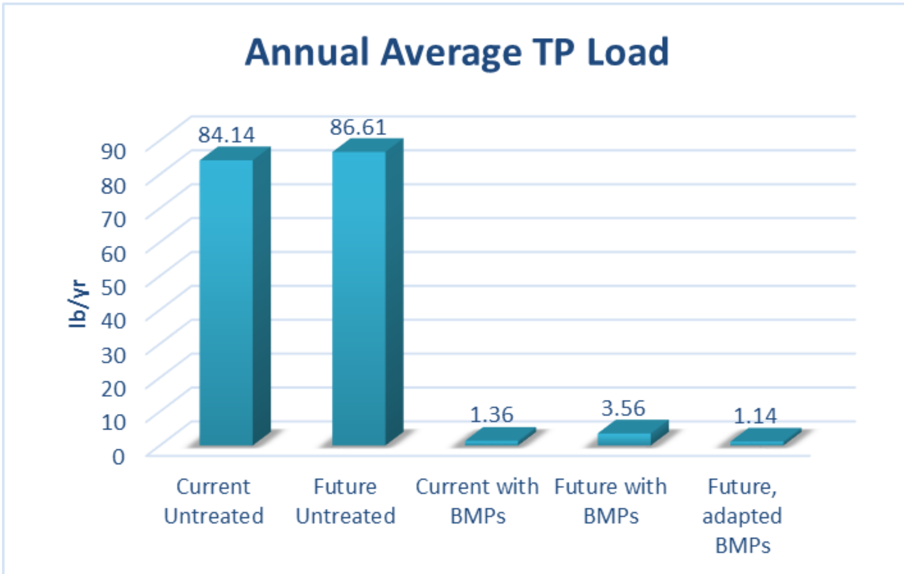


Figure B-11. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario.

Figure B-12 presents the flow duration curves for the current, future, and future adapted BMP scenarios, and demonstrates that the increased BMP footprints adapted for future climate achieve a very similar flow duration response to the current climate BMP configurations in the evaluated range of flows.

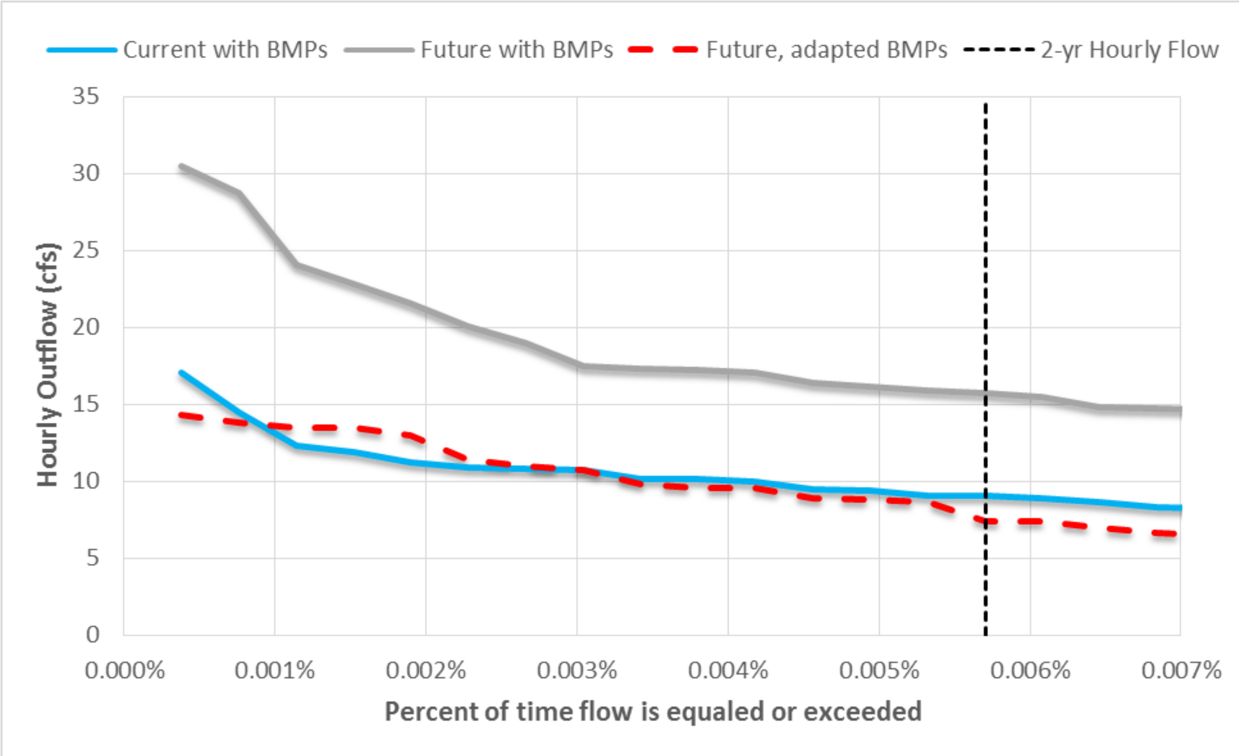


Figure B-12. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario.

In the Harford County GI with Gray Infrastructure scenario, peak flow reduction functions are primarily provided by the dry detention basin. Under the current climate, the conventional practices reduce the maximum hourly peak flow for the site by nearly 50% (from 34 to 17 cfs). Under future climate conditions, without any practice resizing, the maximum hourly peak flow reduction is 46%, with a maximum hourly peak flow of 30.5 cfs. With adaptation, the practices are able to reduce the future hourly peak flow to 14.3 cfs, which is lower than the current hourly peak flow of 17 cfs.

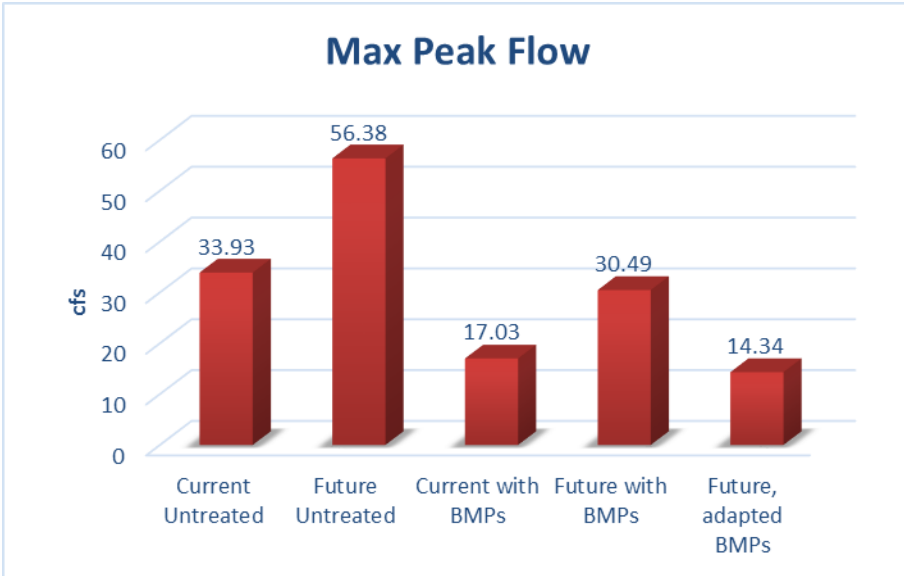


Figure B-13. Current and future performance for maximum hourly peak flow, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario.

Comparison of the annual monthly outflow volumes for the GI with Gray Infrastructure stormwater management scenario shows that the future adapted BMPs are highly effective at reducing monthly outfall volumes from the site; volumes are lower in the "future, adapted BMPs" scenario than the "current with BMPs" scenario for all months except September, which is the month in which the greatest increase in future runoff volumes is predicted to occur.

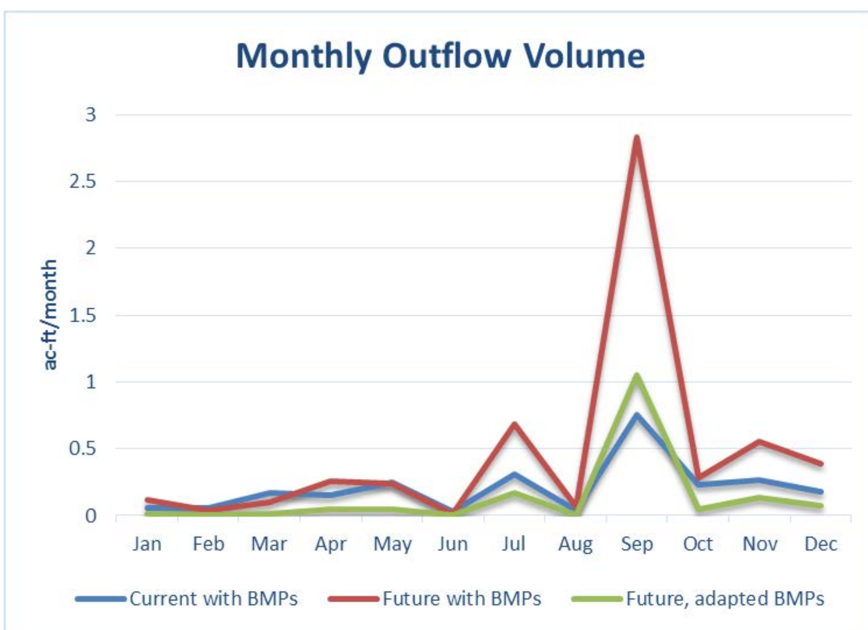


Figure B-14. Current and future performance for monthly outflow volume, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario.

Table B-2 summarizes the increases in BMP footprints for the Harford County GI with Gray Infrastructure scenario that would be required to maintain current performance under future climate conditions.

Table B-2. Comparison of current and future adapted best management practice (BMP) footprints, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI with Gray Infrastructure	Dry detention basin	10,000	1.1%	23,000	2.6%	130%
	Infiltration basin	12,858	1.5%	52,155	6.0%	306%
	Infiltration trench	14,800	1.7%	47,954	5.5%	224%
	Permeable pavement	201,242	23.1%	201,242	23.1%	0%

B.1.1.3. Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI)

The partitioning of runoff rate for the Conventional (Gray) Infrastructure with Distributed GI scenario is identical to the Conventional (Gray) Infrastructure scenario for all climate scenarios except for "future, adapted BMPs" (fifth bar in Figure B-15). This is the case for all results presented in this subsection. Figure B-15 demonstrates that when distributed infiltration trenches are added to the site, without any resizing of the conventional practices, over 95% of annual runoff volume is infiltrated. About 2% of runoff volume is converted to ET, and the remaining fraction (3%) is outflow.

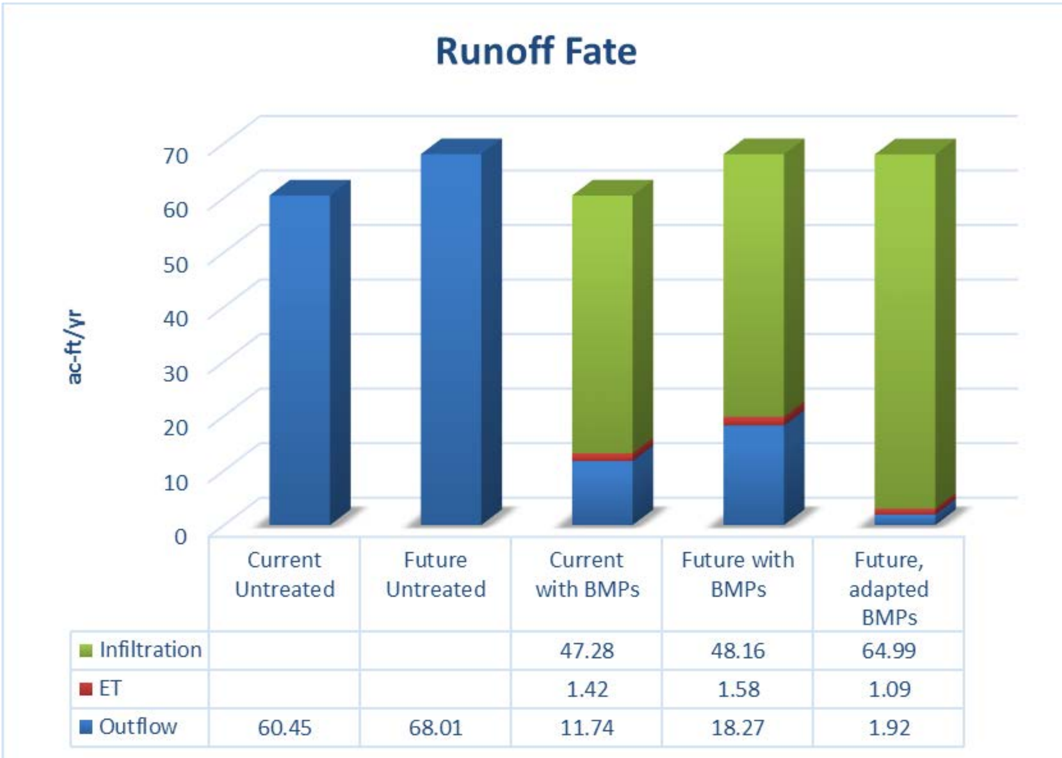


Figure B-15. Current and future partitioning of runoff fate for the Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario.

The addition of distributed infiltration trenches to the site results in an annual average sediment load reduction that is greater than the "current with BMPs" scenario. With adaptation, the practices reduce the annual average sediment load by greater than 96%. Comparatively, the load reduction for the "current with BMPs" scenario is approximately 79%, and approximately 70% for the "future with BMPs" (not adapted) scenario.

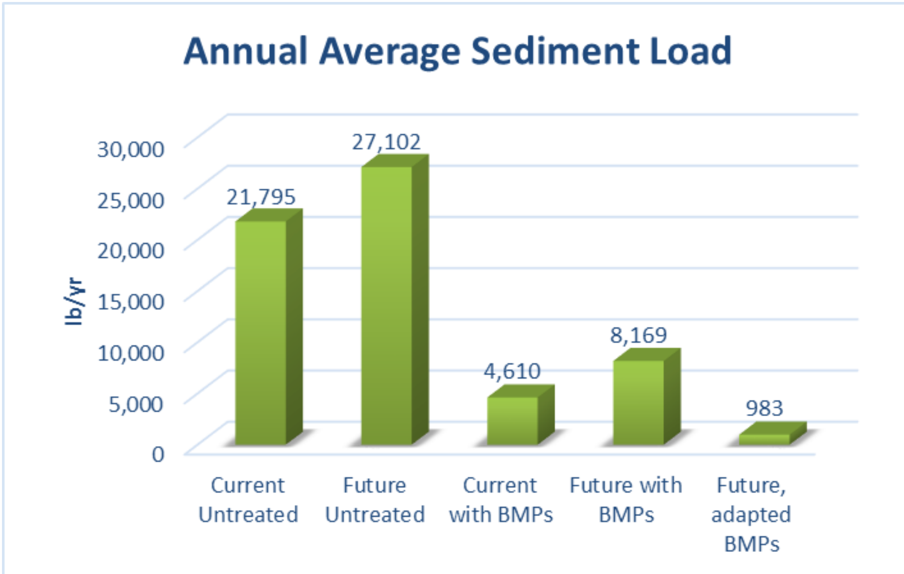


Figure B-16. Current and future performance for annual average sediment load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario.

As noted in the Conventional (Gray) Infrastructure scenario discussion, future climate conditions result in a decrease in performance ("future with BMPs") for both annual average TN and TP load reduction compared to current performance. The adaptation simulation results suggest that implementing distributed infiltration trenches achieves a very high TN and TP load reduction on an annual basis. The "future, adapted BMPs" TN load reduction is greater than 98%, and the TP load reduction is nearly 99%.

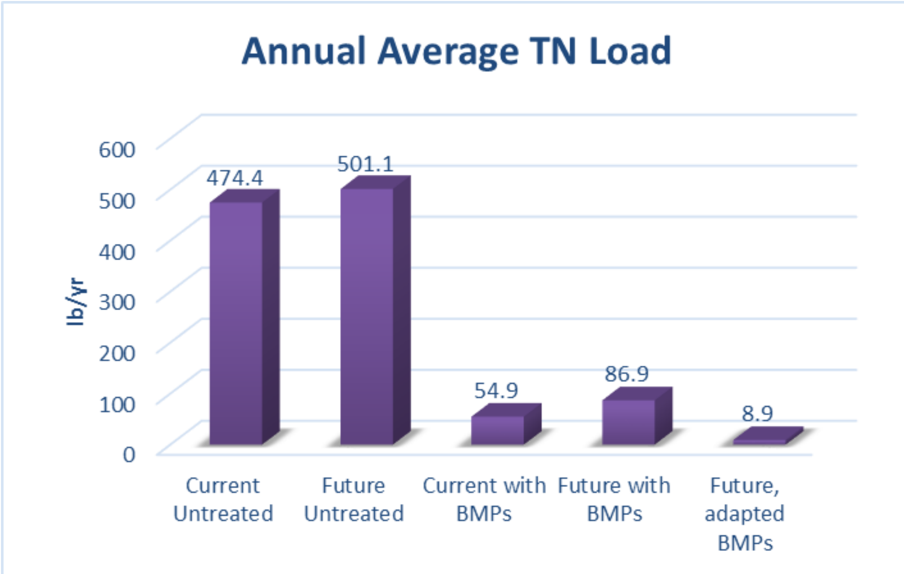


Figure B-17. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario.

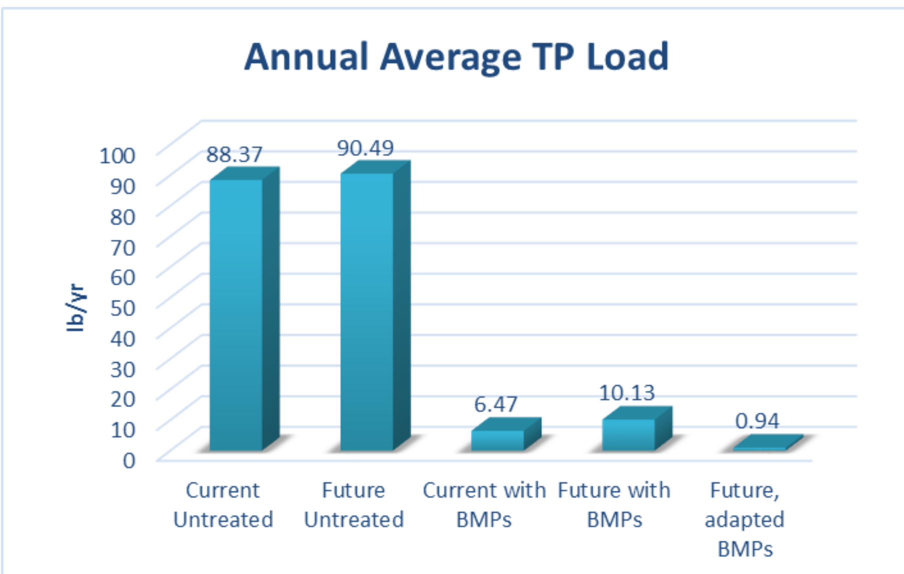


Figure B-18. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario.

The addition of distributed infiltration trenches (“future, adapted BMPs”) results in a reasonably similar flow duration response to the “current with BMPs” scenario within the evaluated range of flows. The observed divergence between the two curves in the uppermost range of flows is most likely a result of seasonal difference in storm event patterns between the current and future climate scenarios.

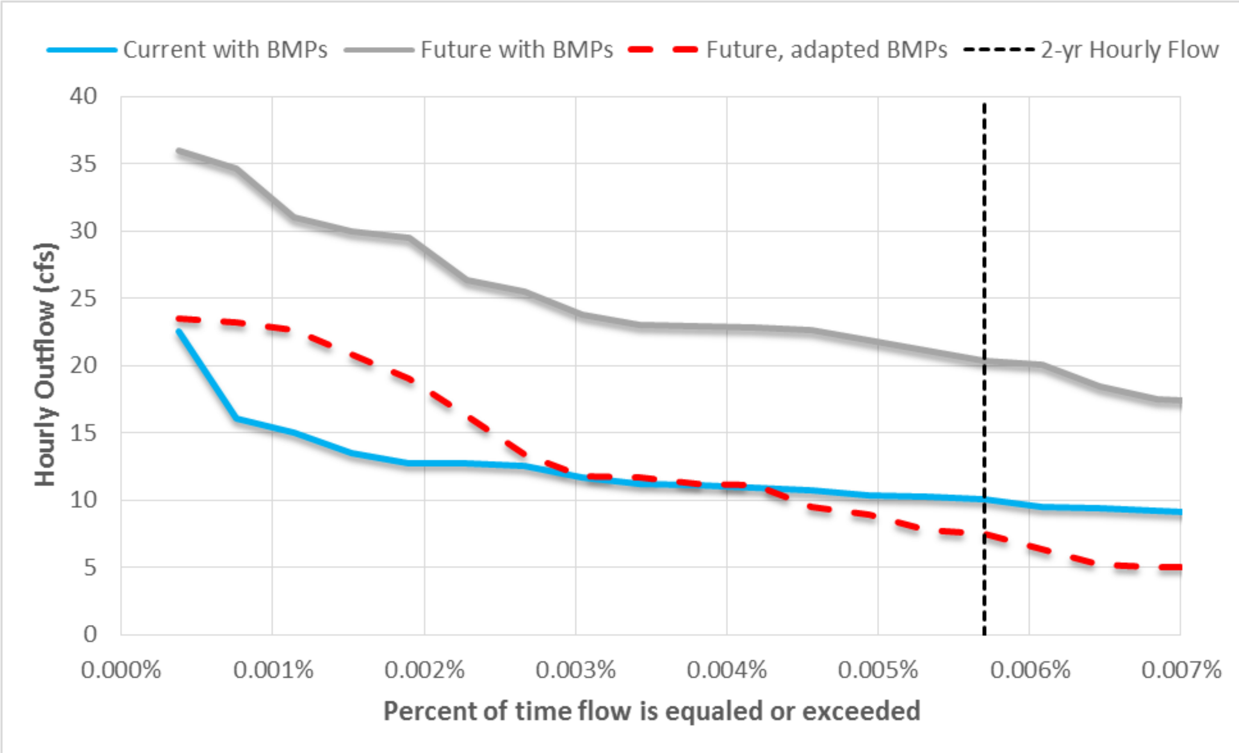


Figure B-19. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario.

Figure B-20 demonstrates that the addition of distributed green practices (infiltration trenches) enables the site to almost completely mitigate the increase in peak flow predicted under future climate. Maximum hourly peak flow is reduced from approximately 36.0 cfs ("future with BMPs") to approximately 23.5 cfs ("future, adapted BMPs") when infiltration trenches are added to the site. The "future, adapted BMPs" hourly peak flow is approximately 1 cfs higher than the "current with BMPs" hourly peak flow.

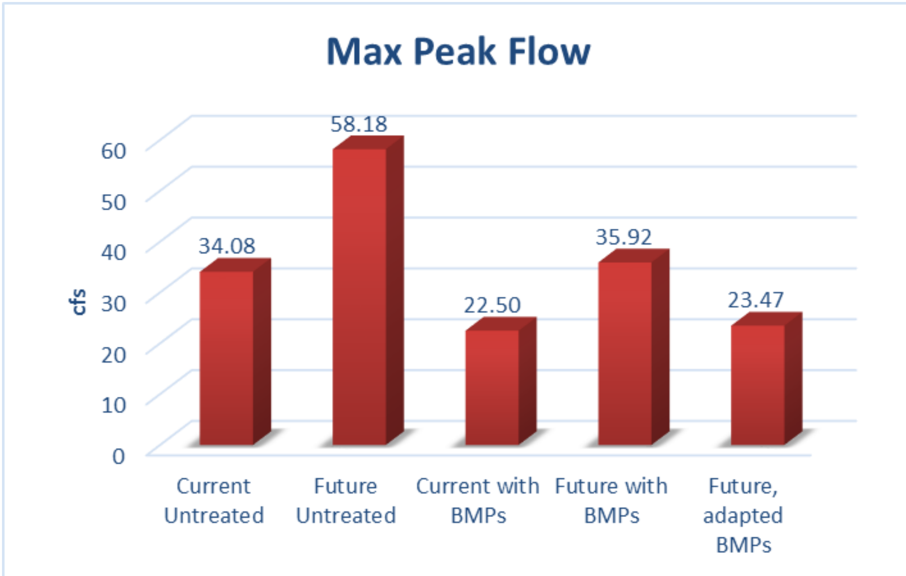


Figure B-20. Current and future performance for maximum hourly peak flow, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario.

Monthly outflow volumes are presented for the Conventional (Gray) Infrastructure with Distributed GI stormwater management scenario in Figure B-21. These results demonstrate that there is almost no outflow from the site when distributed green practices are added. With the addition of the infiltration trenches, monthly outflow volume is lower for all months in the future adapted scenario compared to the "current with BMPs" scenario, even in September, when the greatest increase in future outflow volume is likely to occur.

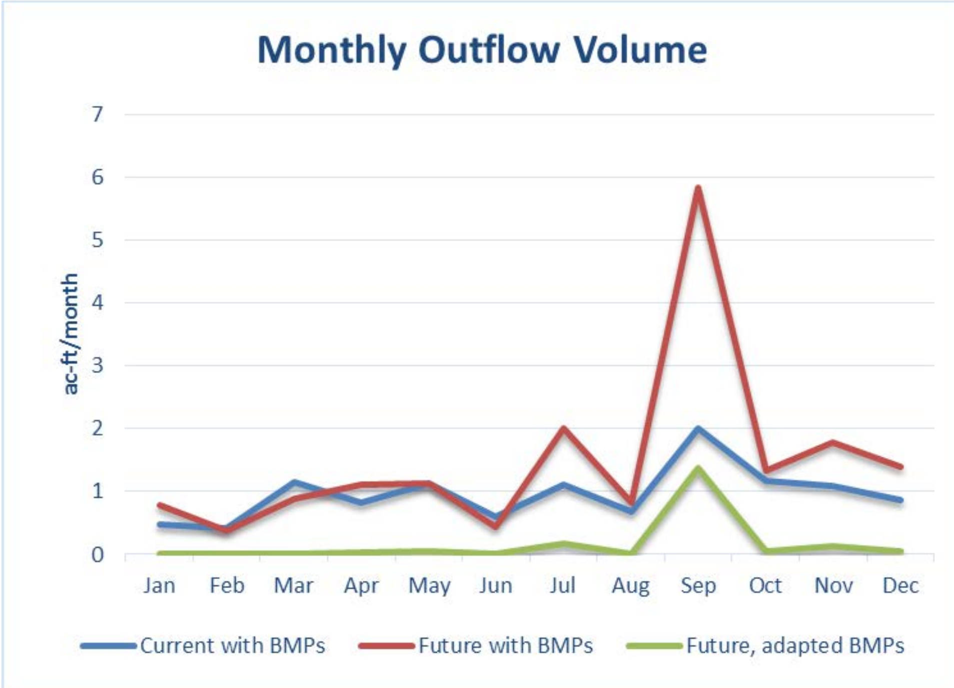


Figure B-21. Current and future performance for monthly outflow volume, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario.

Table B-3 summarizes the increases in BMP footprints for the Harford County Conventional (Gray) Infrastructure with Distributed GI scenario that would be required to maintain current performance under future climate conditions. The footprint of infiltration trenches required for adaptation would comprise approximately 11% of the total site area.

Table B-3. Comparison of current and future adapted best management practice (BMP) footprints, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF.	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure with Distributed GI	Extended dry detention basin	25,000	2.9%	25,000	2.9%	0%
	Surface sand filters	10,119	1.2%	10,119	1.2%	0%
	Distributed infiltration trenches	0	0%	95,869	11.0%	--

B.1.1.4. Cost Estimation

Table B-4 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all three Harford County stormwater management scenarios. Refer to Section 6.5 of the report for a discussion of how the infrastructure cost estimates were developed. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site. These three metrics represent three alternative methods for evaluating the cost of adaptation, which is effectively the increase in cost between the current and future adapted climate scenarios.

Table B-4. Comparison of the current and future estimated 20-year present value costs for the Harford County, MD stormwater management scenarios

Location	Stormwater management scenario	Current cost 20-yr present value, $millions	Future adapted cost 20-yr present value, $millions	Increase in cost 20-yr present value, $millions	% increase in cost	Increase per acre of site $millions
Harford County, MD	Conventional (Gray) Infrastructure	5.31	11.78	6.47	122	0.32
	GI with Gray Infrastructure	5.15	12.15	6.99	136	0.35
	Conventional (Gray) Infrastructure with Distributed GI	5.31	15.8	10.56	199	0.53

For the Conventional (Gray) scenario, the cost of adaptation (based on 20-year present value) is estimated to increase by $6.47 million, or 122% compared to the current cost. This is equivalent to a cost of adaptation of $0.32 million per acre of site area.

The cost of adaptation for the GI with Gray scenario is estimated to be an increase of $6.99 million, which reflects a 136% increase in cost. On a cost per site acre basis, the estimated cost of adaptation is $0.35 million per acre of site area.

Implementing distributed green practices (infiltration trenches) to address the performance gap between the current and future climate comes at an estimated cost increase of $10.56 million, an increase of 199%. The increase in cost per acre of site is estimated to be $0.53 million for the Conventional with Distributed GI scenario.

B.1.2. Scott County, MN

B.1.2.1. Conventional (Gray) Infrastructure

Future Low Intensity

The precipitation analysis for the Scott County, MN future low intensity climate scenario predicted an overall decrease in annual precipitation depth across the 30-year simulation. The monthly average precipitation depth across the simulation period is predicted to increase in some months compared to the current climate; however, on an annual basis, this is offset by the decreases in precipitation depth in other months. Precipitation intensity is predicted to decrease throughout the entire 30-year assessment period, except in the single highest hour of precipitation, resulting in a maximum hourly peak flow in the future low intensity climate scenario that is higher than in the current climate (see Figure B-26). Comparison of the monthly outflow volumes for the current climate and future low intensity climate scenarios (see Figure B-27) shows higher monthly outflow volumes in the future for some months and lower for others. The discrepancy is within ±1 acre-feet/month except in June and July, in which the future outflow volumes decrease by approximately 1.1 acre-feet/month and 2.7 acre-feet/month, respectively. On an annual basis, outflow is lower under the future low intensity climate scenario compared to the current climate.

Due to the predicted decrease in precipitation depth and intensity, the overall runoff volume and outflow volume also decrease between the current and future low intensity climate conditions (see Figure B-22). The decrease in site outflow in the future low intensity climate scenario results in decreased sediment, TN, and TP loads compared to current climate conditions (seeFigure B-23, Figure B-24, and Figure B-25, respectively). Because there was no decrease in the performance of the conventional (gray) practice (wet pond) between the current and future climate, this scenario was not investigated for adaptation.

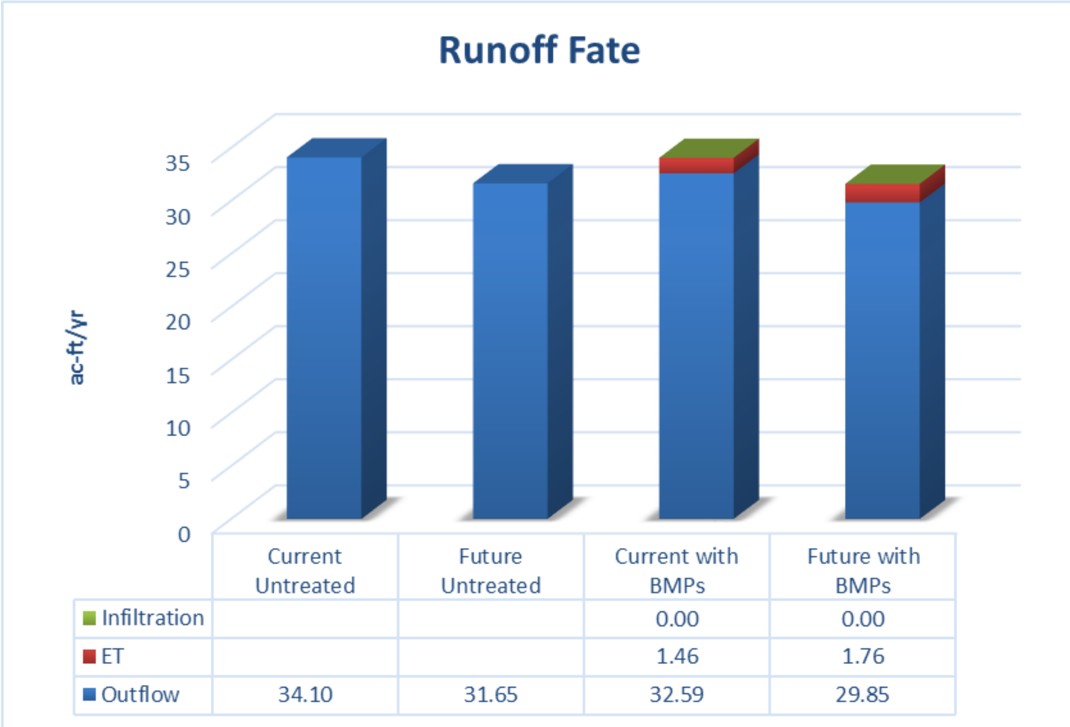


Figure B-22. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure (low intensity) scenario.

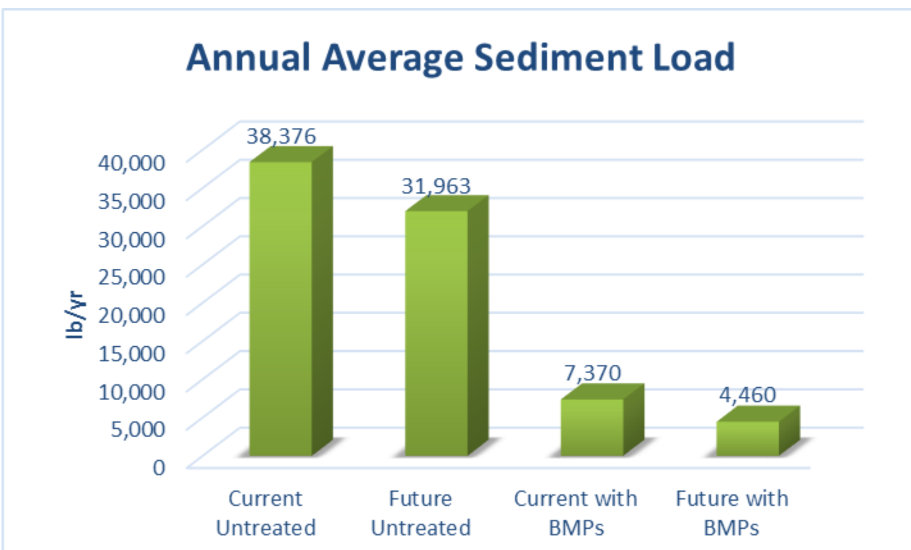


Figure B-23. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure (low intensity) scenario.

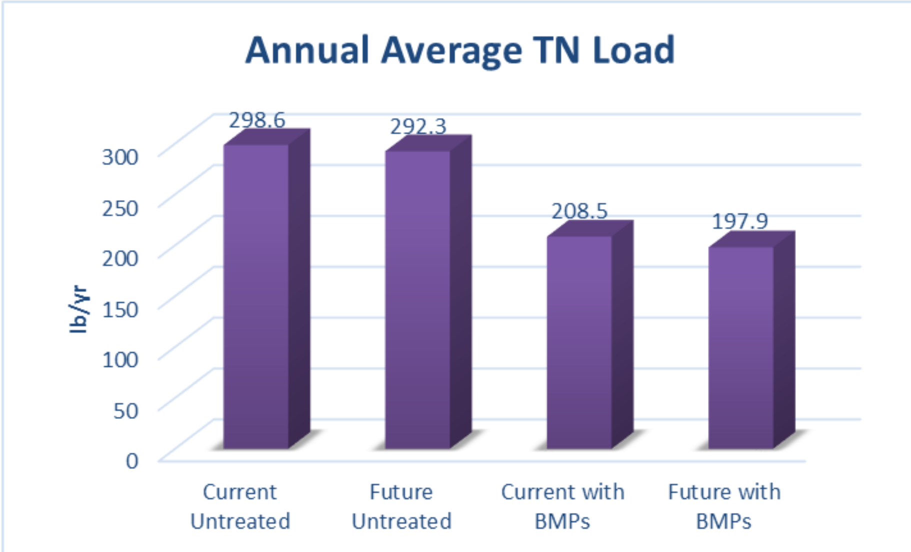


Figure B-24. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure (low intensity) scenario.

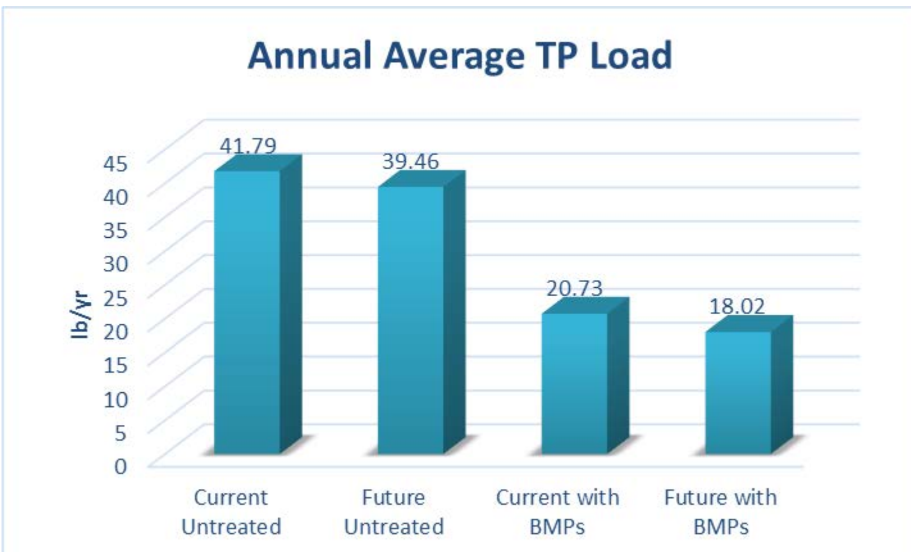


Figure B-25. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure (low intensity) scenario.

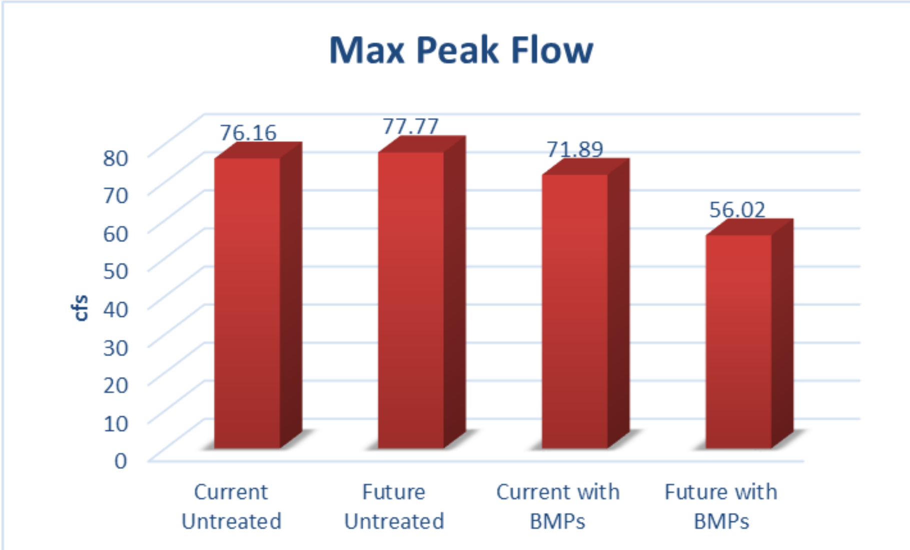


Figure B-26. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure (low intensity) scenario.

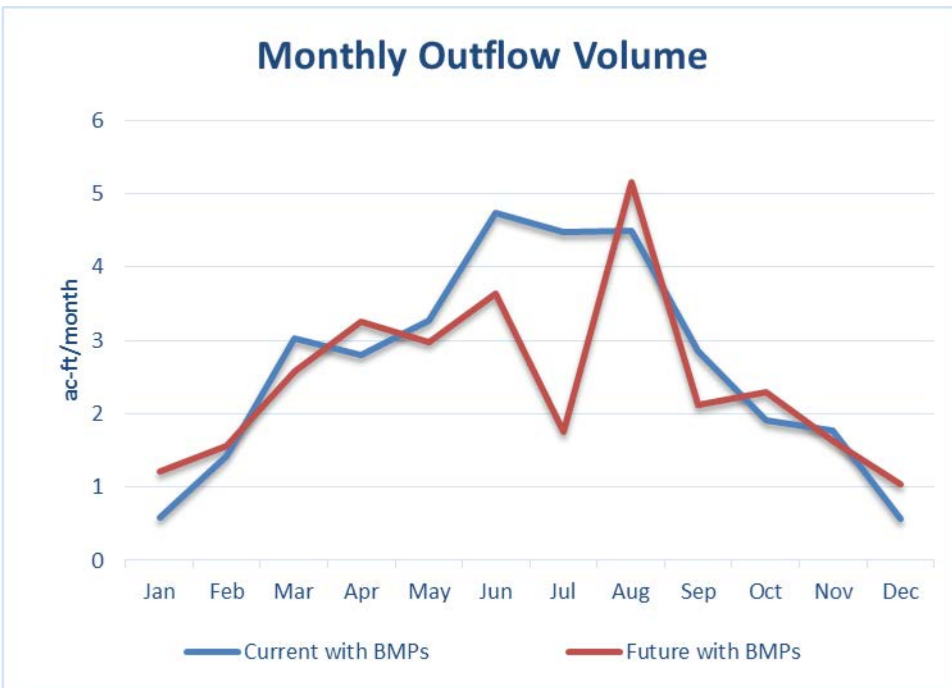


Figure B-27. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure (low intensity) scenario.

Future Medium Intensity

In the Scott County, MN future medium intensity climate scenario, annual precipitation depth is predicted to increase in all 30 years of the simulation period compared to the current climate. Monthly average precipitation is predicted to increase or remain approximately the same for all months, and the intensity of precipitation is predicted to increase slightly compared to the current climate. Figure B-28 indicates an increase in outflow (32.59 cfs to 36.48 cfs) if the current conventional practice (wet pond) is not resized.

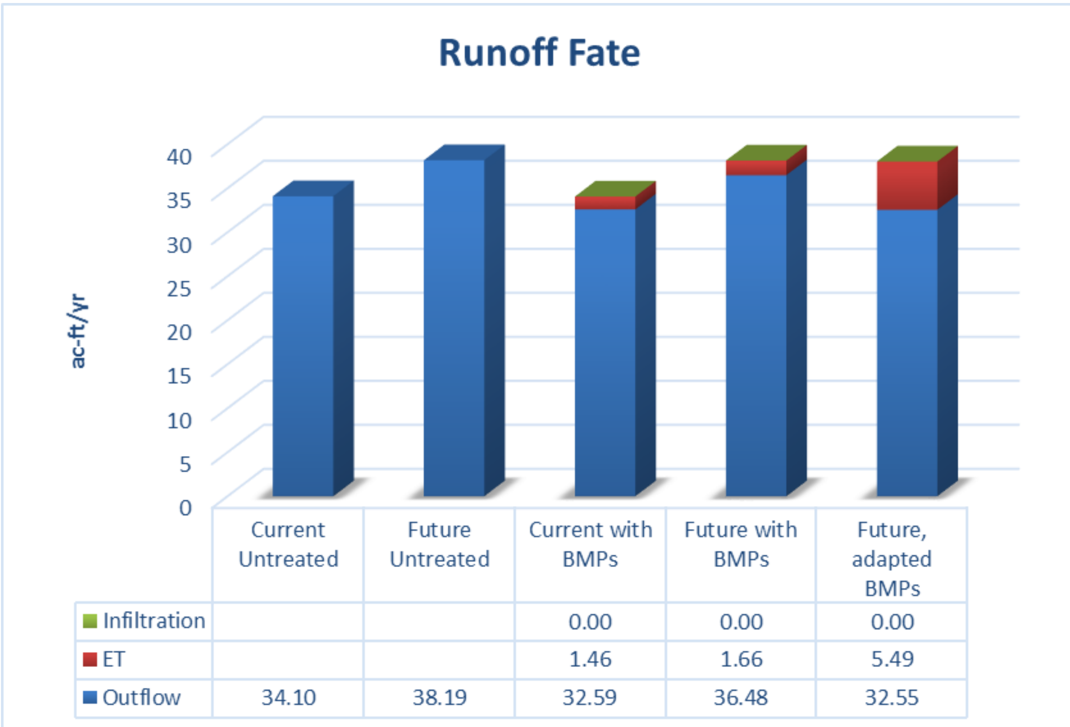


Figure B-28. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario.

The adaptation simulation targeted increasing the wet pond footprint until future outflow was the same or less than the current outflow. With future adaptation, the increased wet pond footprint enables outflow to be reduced below the “current with BMPs” outflow due to a larger proportioning of runoff to ET. Infiltration is not a runoff fate pathway for the wet pond in the Scott County Conventional (Gray) Infrastructure scenario due to poorly infiltrating soils, as discussed in Chapter 4 of the report.

The current conventional practice (wet pond) achieves an annual average sediment load reduction of nearly 81%. Without resizing, the performance under the future medium intensity climate scenario declines slightly, with a 79% sediment load reduction. The future adapted wet pond footprint increases the load reduction to 95% and maintains the future (medium intensity) annual sediment load (2,296 pound/year) below the current climate load (7,370 pound/year). Because the practice resizing for the future medium intensity climate was driven by the required reduction in outflow volume (see Figure

B-28), the future adapted BMP annual average loads for sediment (see Figure B-29), TP (see Figure B-30), and TN (see Figure B-31) are all well below the “current with BMPs” loads.

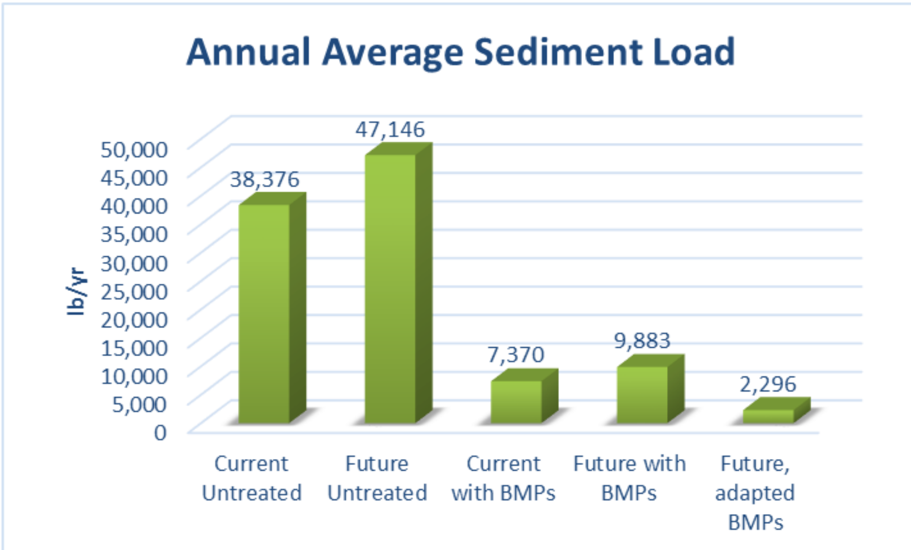


Figure B-29. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario.

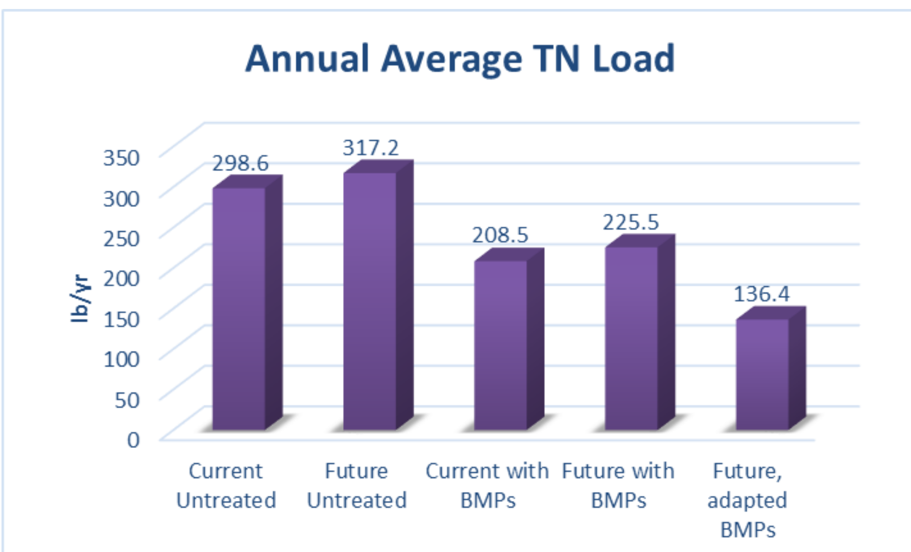


Figure B-30. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario.

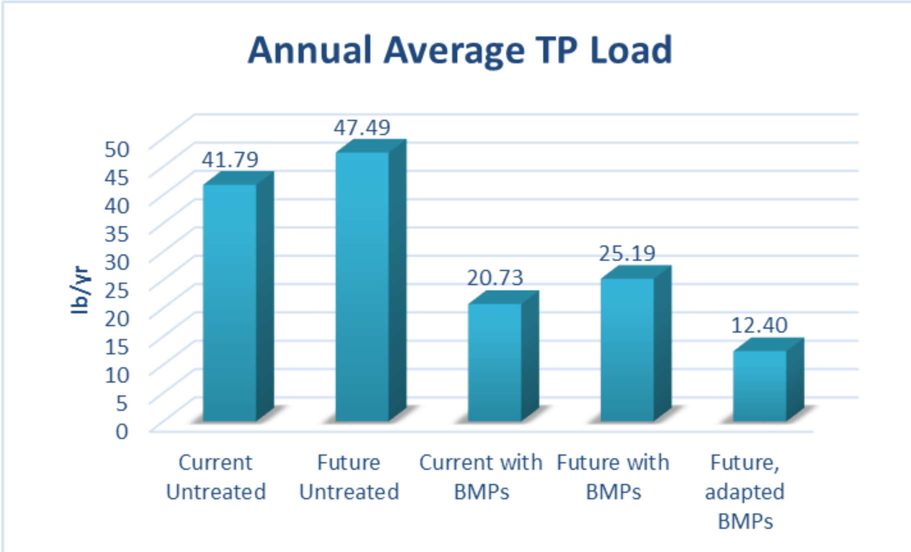


Figure B-31. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario.

The TN load reductions achieved by the current, future (not adapted), and future adapted conventional practice (wet pond) in the medium intensity climate scenario are 30, 29, and 57%, respectively.

The TP load reductions achieved by the current, future (not adapted), and future adapted conventional practice (wet pond) in the medium intensity climate scenario are 50, 47, and 74%, respectively.

As discussed above, the increase in footprint of the wet pond for adaptation in the future medium intensity climate scenario was primarily driven by the required reduction in outflow volume that would be necessary to maintain the current climate outflow. As a result, the increased wet pond size produces a "future, adapted BMPs" flow duration curve that is reduced well below the "current with BMPs" curve for almost the entire range of flows evaluated. Although good for peak flow reduction, decreasing the outflow to this extent could have implications for stream baseflow or other ecological considerations.

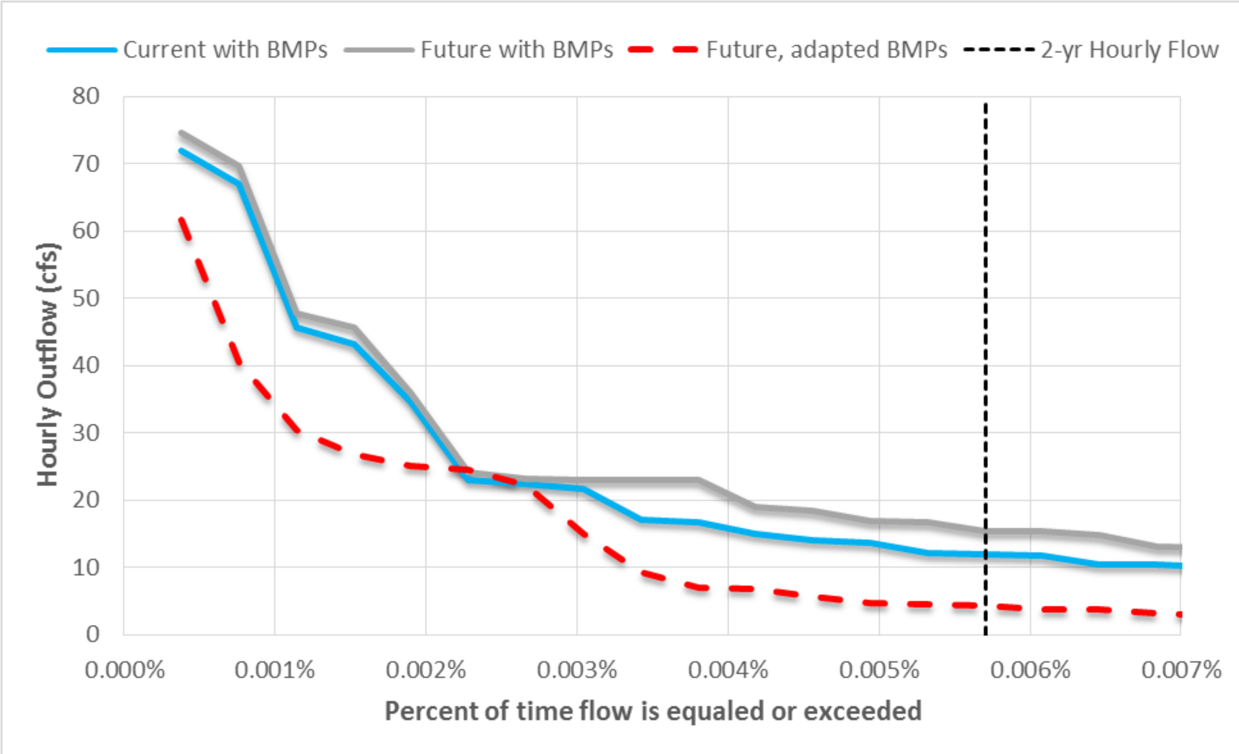


Figure B-32. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario.

Figure B-33 indicates that the future adapted wet pond results in a reduction in maximum hourly peak flow due to the increased sizing of the practice to maintain current performance for outflow.

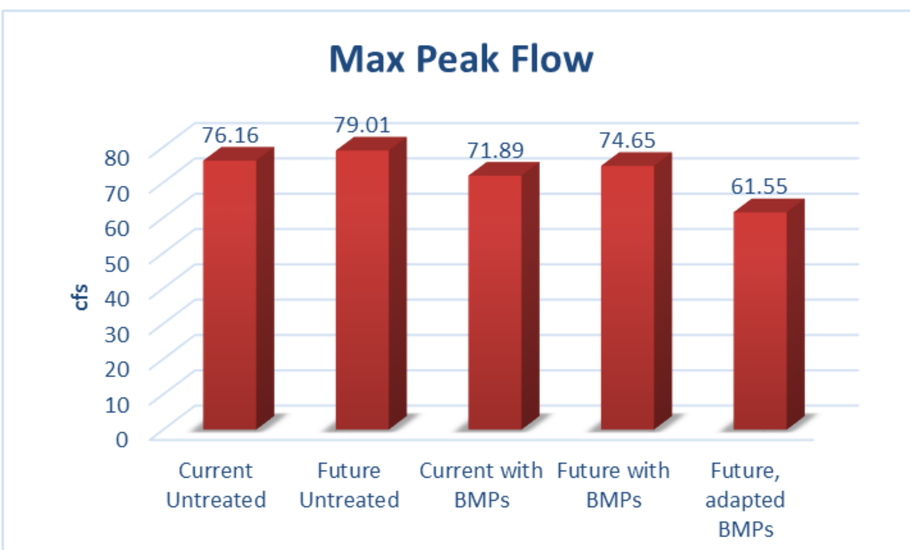


Figure B-33. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario.

The simulated future medium intensity climate condition is predicted to alter both the timing and magnitude of outflow throughout the year. To some extent, the adapted conventional practice (wet pond) is able to more closely reproduce monthly outflow volumes under the current climate. However, monthly outflow volumes in 6 months (January, April, May, September, November, and December) are still higher than in the current climate. On an annual basis, the future adapted practice produces a lower outflow volume overall compared to the current practice.

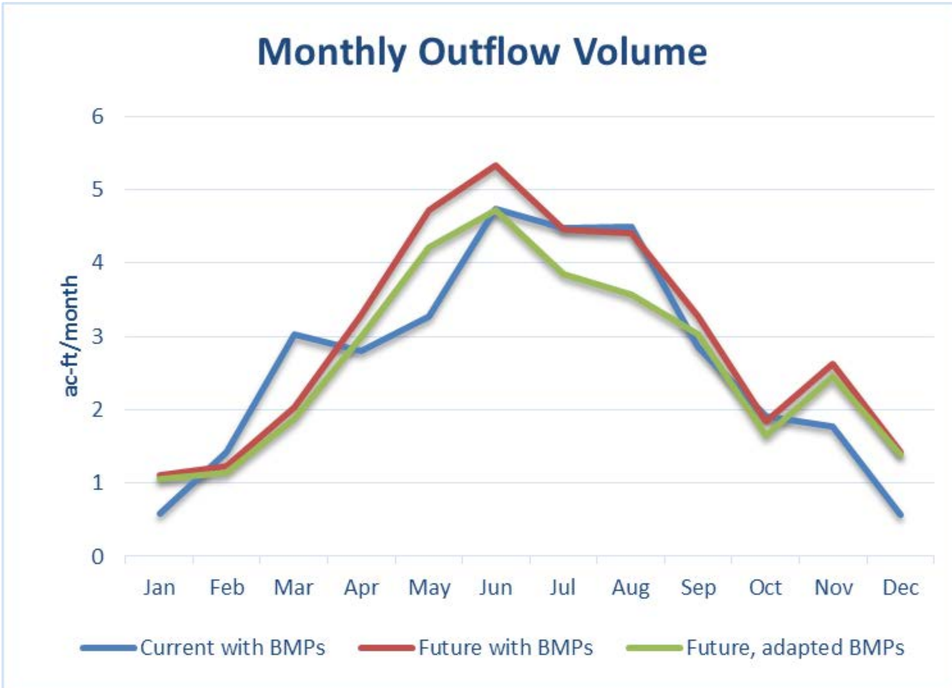


Figure B-34. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario.

Table B-5 summarizes the increases in BMP footprints for the Scott County Conventional (Gray) Infrastructure (medium intensity) scenario that would be required to maintain current performance under future climate conditions. The adapted wet pond is 3.3 times larger than the current wet pond.

Table B-5. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Conventional (Gray) Infrastructure (medium intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure	Future medium intensity	Wet pond	32,670	2.5%	107,811	8.3%	230%

Future High Intensity

In the future high intensity climate scenario, annual precipitation depth is predicted to increase in all years across the 30-year simulation period. Monthly average precipitation is predicted to increase or remain approximately the same as in the current climate, with the greatest increase concentrated in the summer months (June, July, and August), in which most of the annual precipitation occurs due to summer storms with relatively high intensity and depth. These trends result in the increase in runoff, and consequently outflow, between the current and future high intensity scenarios. Increasing the wet pond footprint increases the proportioning of runoff to ET, allowing the conventional site to maintain the current climate outflow performance under future high intensity climate conditions.

Similar to the Conventional (Gray) Infrastructure medium intensity scenario, the adaptation simulation targeted increasing the wet pond footprint until future outflow was the same or less than the current outflow (see Table B-6). The increase in wet pond footprint required to maintain the current outflow in future high intensity climate resulted in a BMP that is larger than would be required to maintain current performance for the other measures (annual average load for sediment, TP, and TN), as seen in the figures below. The adapted wet pond footprint reduces simulated pollutant loads (see Figure B-36, Figure B-37, and Figure B-38) well below current performance.

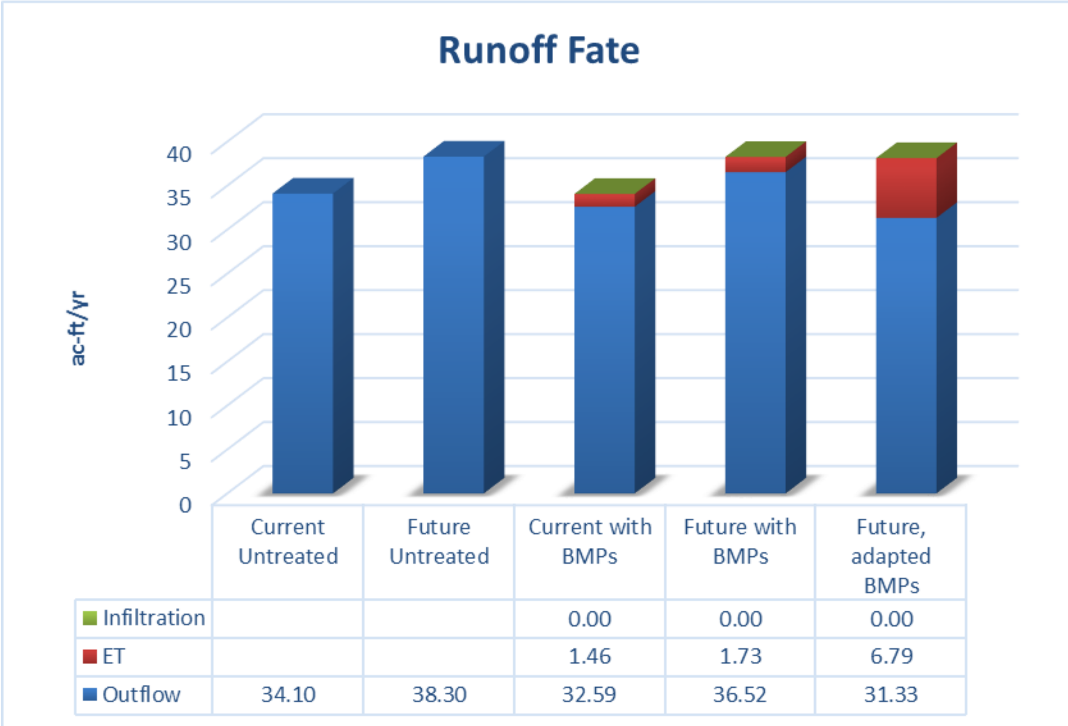


Figure B-35. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario.

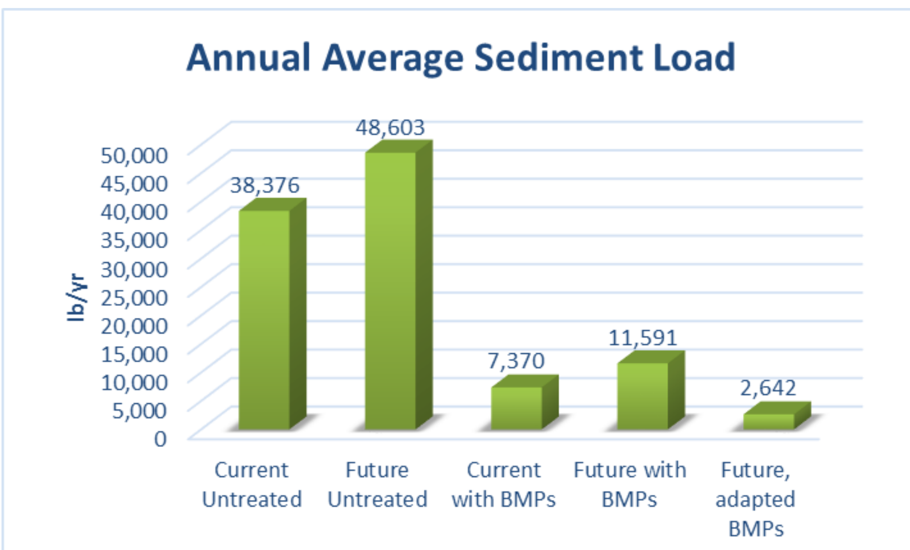


Figure B-36. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario.

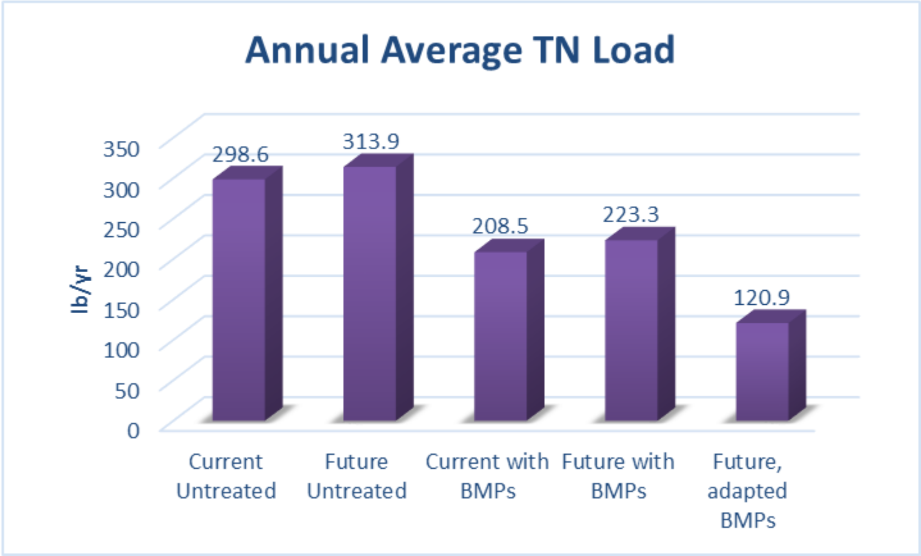


Figure B-37. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario.

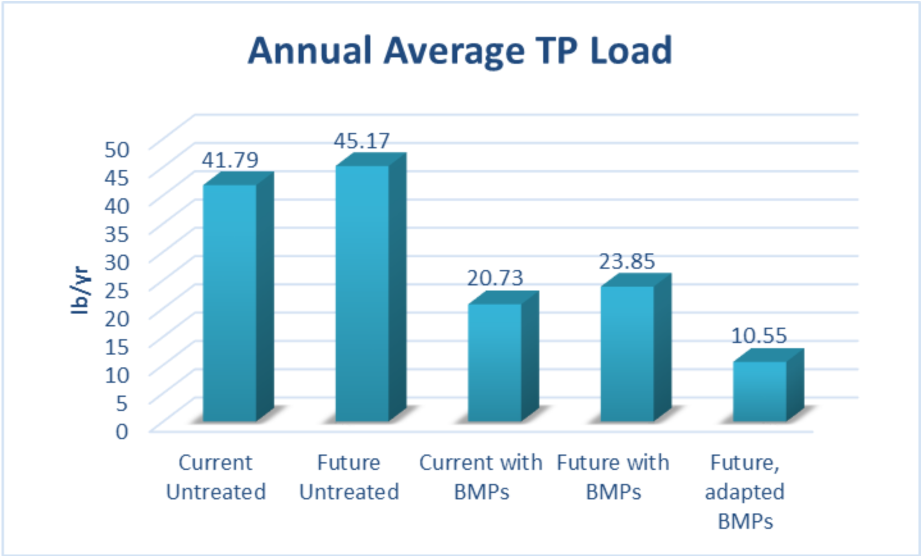


Figure B-38. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario.

The flow duration curve analysis (see Figure B-39) suggests that the adapted wet pond is able to reasonably match the outflow response of the current wet pond, with some deviation at the upper end due to the practice’s inability to fully mitigate the increase in maximum hourly peak flow (see Figure B-40) under future high intensity climate conditions.

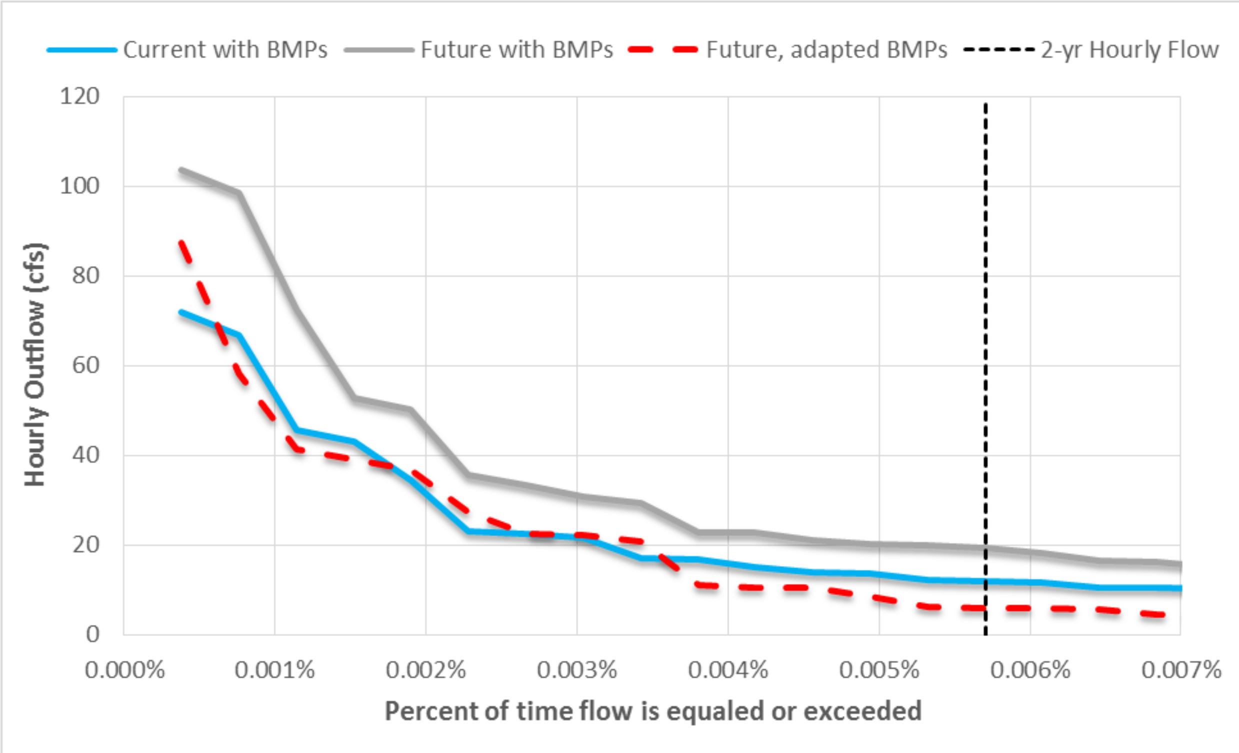


Figure B-39. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario.

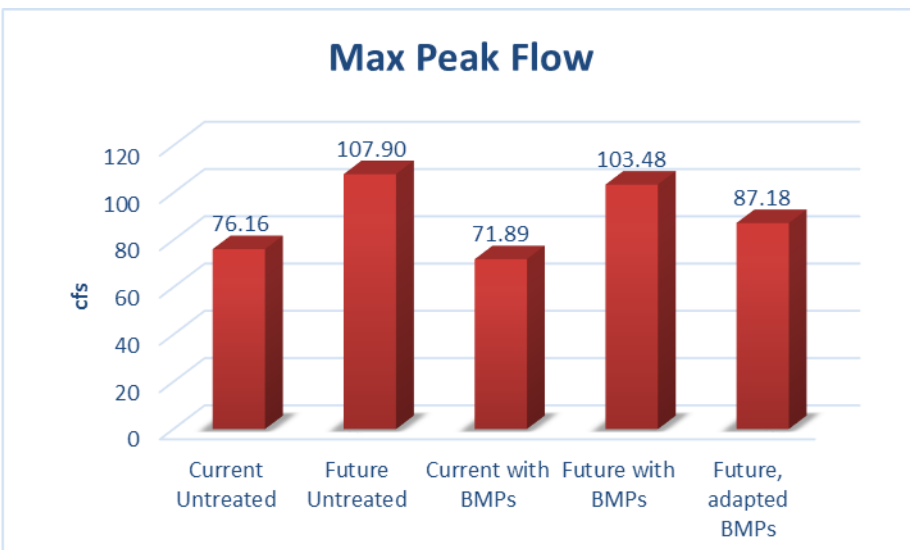


Figure B-40. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario.

To some extent, the adapted conventional practice (wet pond) is able to more closely reproduce monthly outflow volumes under the current climate. However, monthly outflow volumes are still higher in several months under the future adapted scenario compared to the current performance. On an annual basis, the increases are outweighed by the months in which there are decreases in outflow volume.

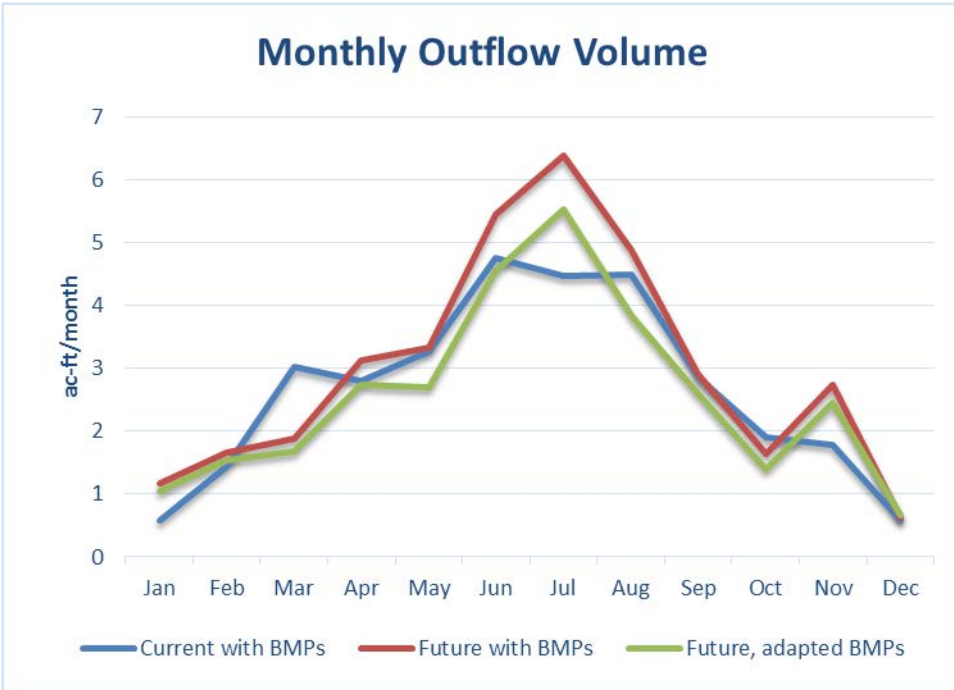


Figure B-41. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario.

Table B-6 summarizes the increases in BMP footprints for the Scott County Conventional (Gray) Infrastructure (high intensity) scenario that would be required to maintain current performance under future climate conditions. The adapted wet pond is nearly four times larger than the current wet pond.

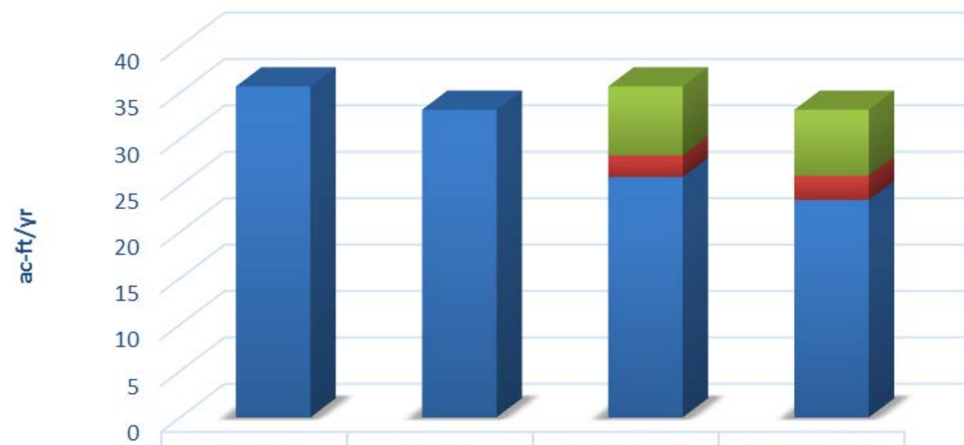
Table B-6. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Conventional (Gray) Infrastructure (high intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure	Future high intensity	Wet pond	32,670	2.5%	128,066	9.8%	292%

B.1.2.2. Green Infrastructure (GI) with Gray Infrastructure

Future Low Intensity

Due to the predicted decrease in precipitation depth and intensity in the future low intensity climate scenario, the overall runoff volume and outflow volume decrease compared to the current climate conditions (see Figure B-42). The decrease in site outflow in the future low intensity climate scenario results in decreased sediment load, TN load, and TP load compared to the current climate conditions (see Figure B-43, Figure B-44, and Figure B-45, respectively). Because there was no decrease in the performance of the green (bioretention) and gray (dry detention basin) practices between the current and future low intensity climate, this scenario was not investigated for adaptation.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs
Infiltration			7.45	7.13
ET			2.32	2.60
Outflow	35.68	33.16	25.90	23.44

Figure B-42. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (low intensity) scenario.

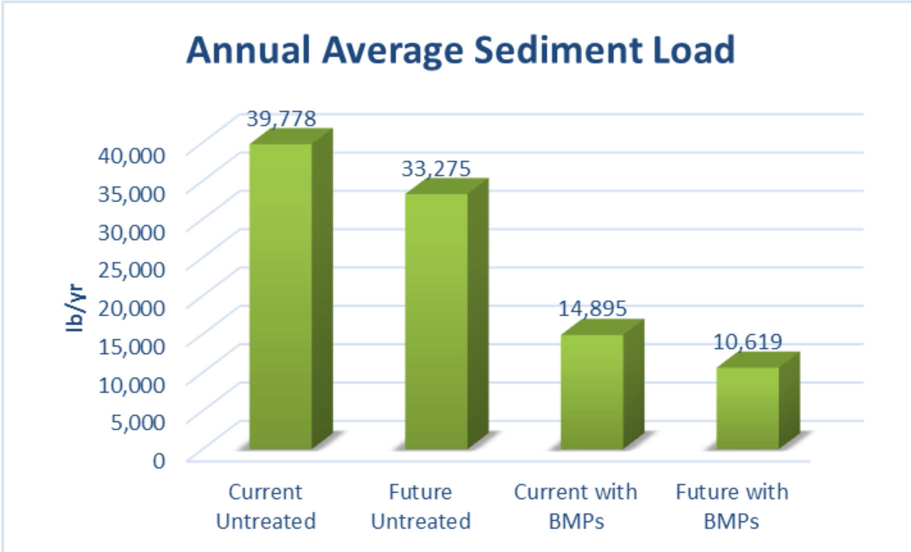


Figure B-43. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (low intensity) scenario.

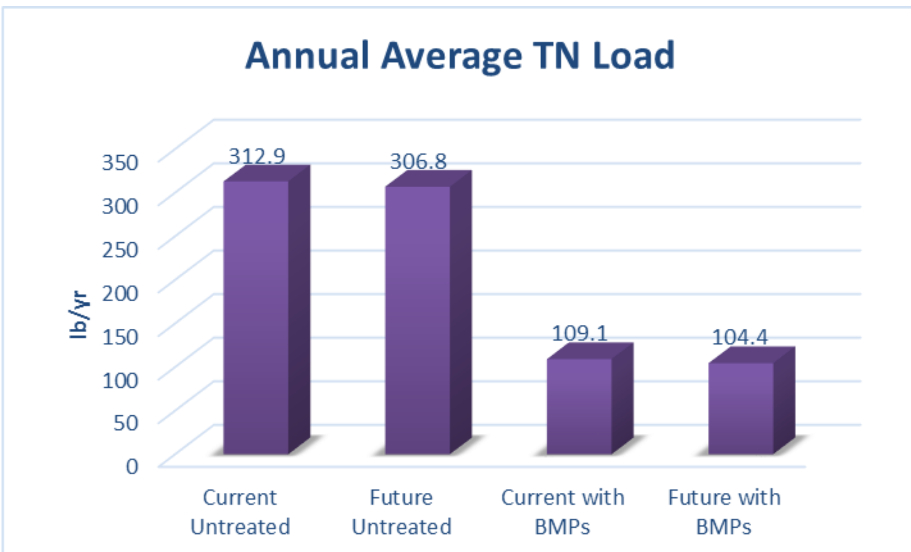


Figure B-44. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (low intensity) scenario.

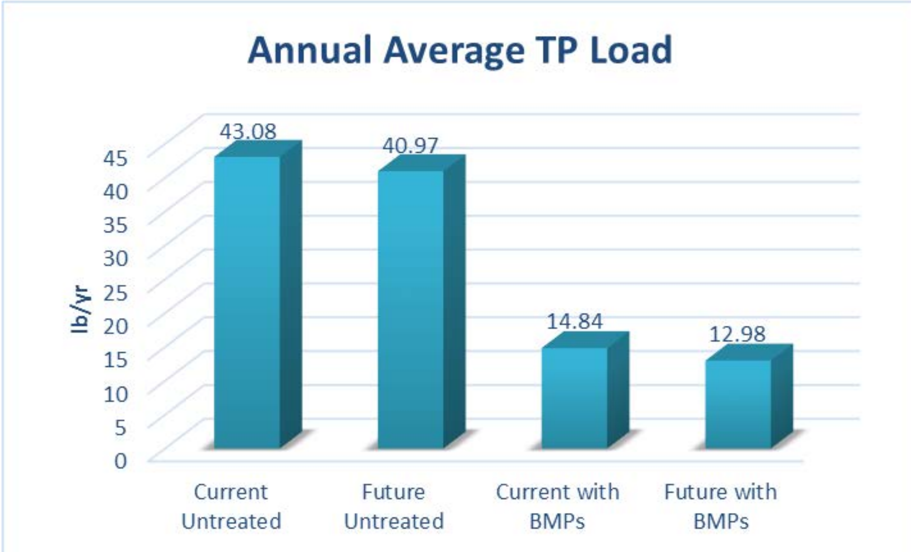


Figure B-45. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (low intensity) scenario.

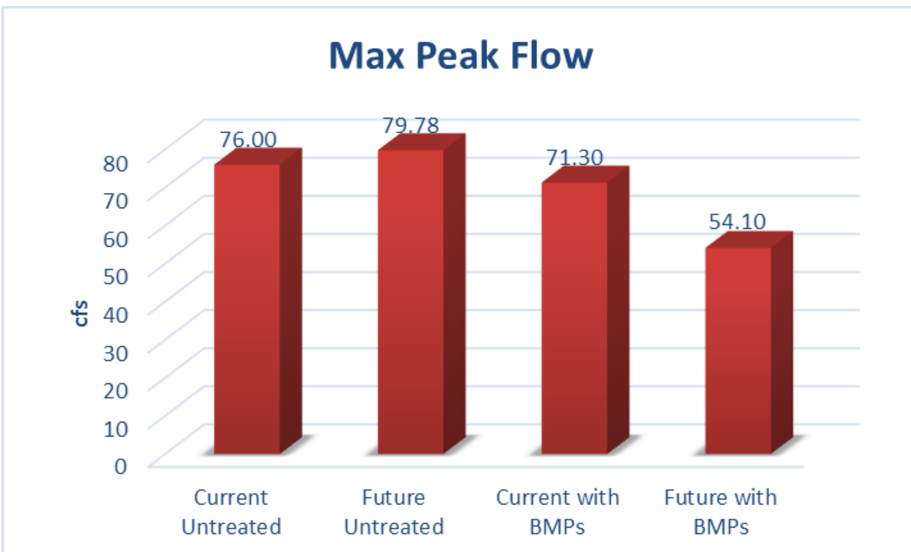


Figure B-46. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (low intensity) scenario.

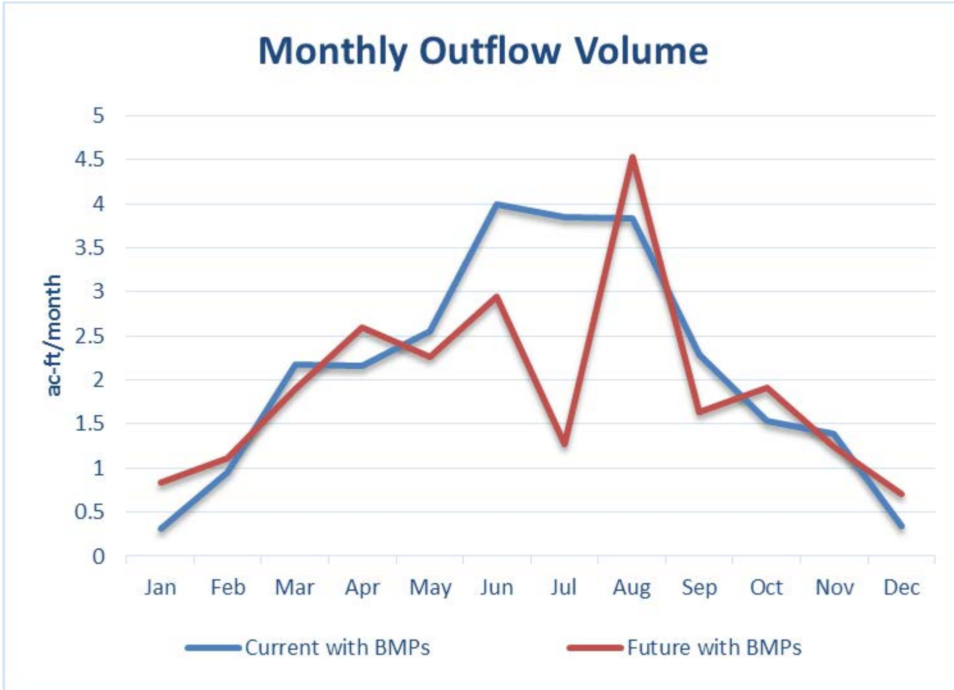
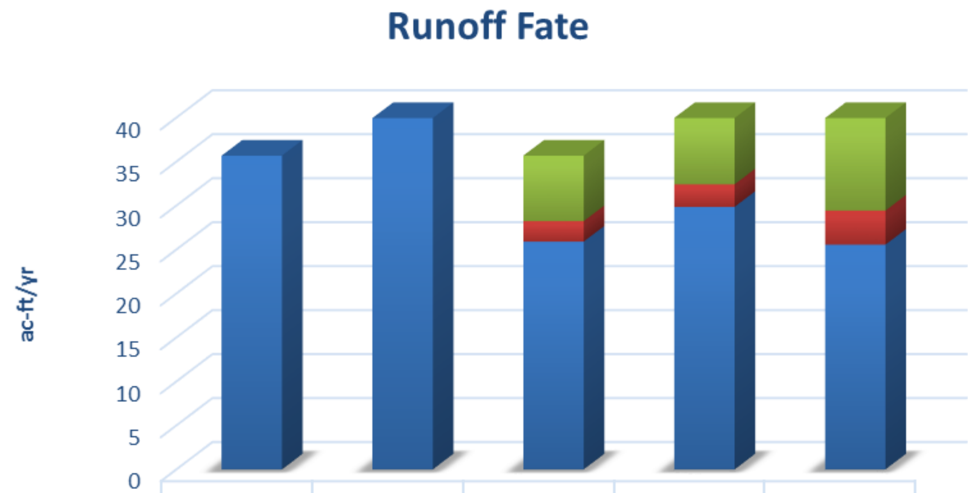


Figure B-47. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (low intensity) scenario.

Future Medium Intensity

The predicted increase in annual precipitation depth and intensity in the Scott County future medium intensity climate scenario results in an increase in outflow between the current climate (25.90 cfs) and future climate (29.85 cfs) when the Green and Gray practices are not resized for adaptation.

With future adaptation, the increased green (bioretention) and gray (dry detention basin) practice footprints reduce the volume of outflow below the "current with BMPs" scenario due to a larger proportioning of runoff to ET and infiltration. As discussed in Chapter 4 of the report, the soils in the Scott County study site have low infiltration capacity, so outflow remains the dominant runoff pathway, even when practice sizes are increased.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			7.45	7.54	10.53
ET			2.32	2.57	3.87
Outflow	35.68	39.95	25.90	29.85	25.56

Figure B-48. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario.

The future adapted Green and Gray practices achieve an annual average sediment load that is lower than the current climate load. The corresponding sediment load reductions for the current, future, and future adapted BMP scenarios are 63, 60, and 70%, respectively.

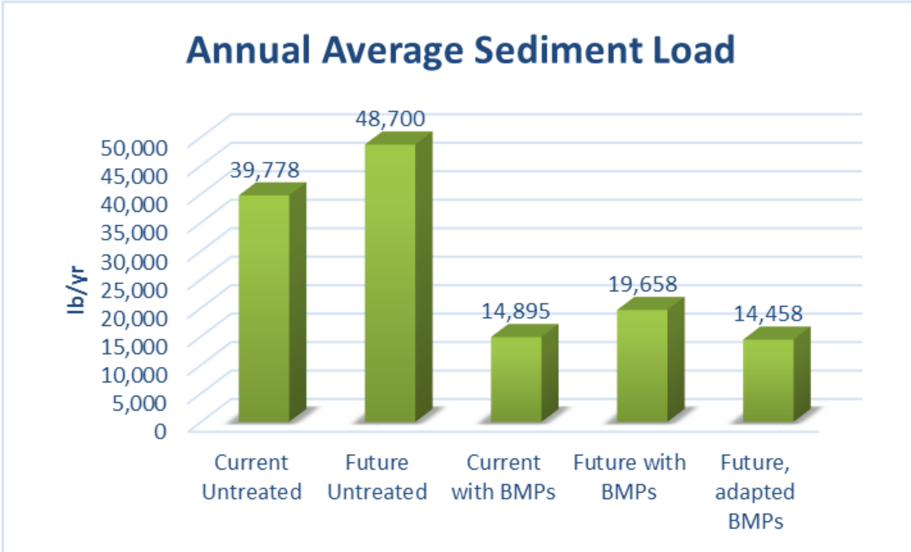


Figure B-49. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario.

The future adapted bioretention and dry detention basin combine to reduce annual average TN load by 70%. This is greater than the current and future (not adapted) reductions of 65 and 63%, respectively.

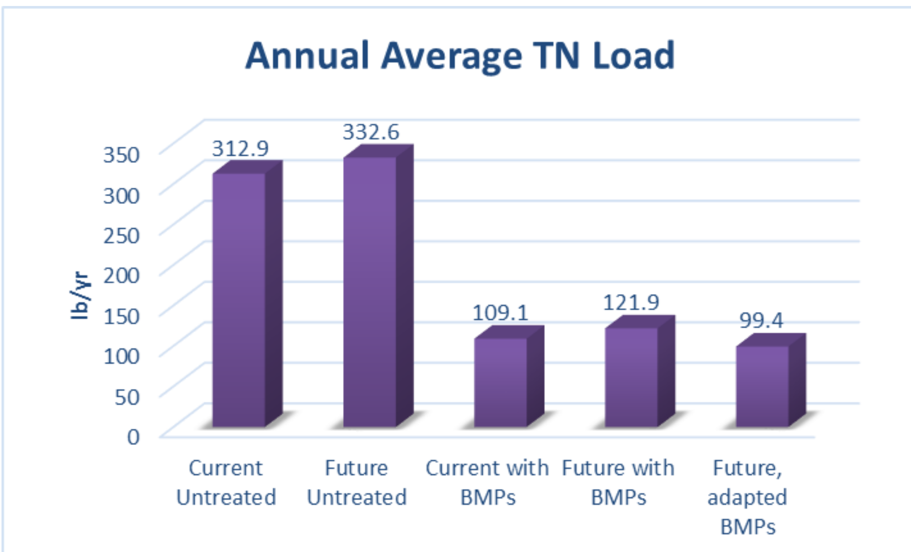


Figure B-50. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario.

The future adapted Green and Gray practices achieve an annual average TP load that is lower than the current climate load. The corresponding TP load reductions for the current, future, and future adapted BMP scenarios are 66, 62, and 70%, respectively.

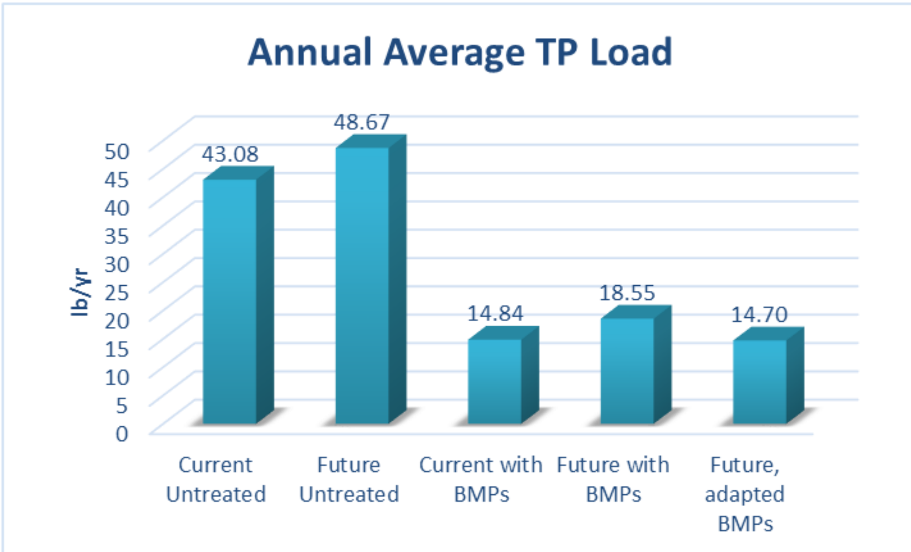


Figure B-51. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario.

The flow duration curve analysis (see Figure B-52) for the Scott County GI with Gray Infrastructure (medium intensity) scenario suggests that the adapted practices are able to reasonably match the outflow response of the current practices within the evaluated range of flows.

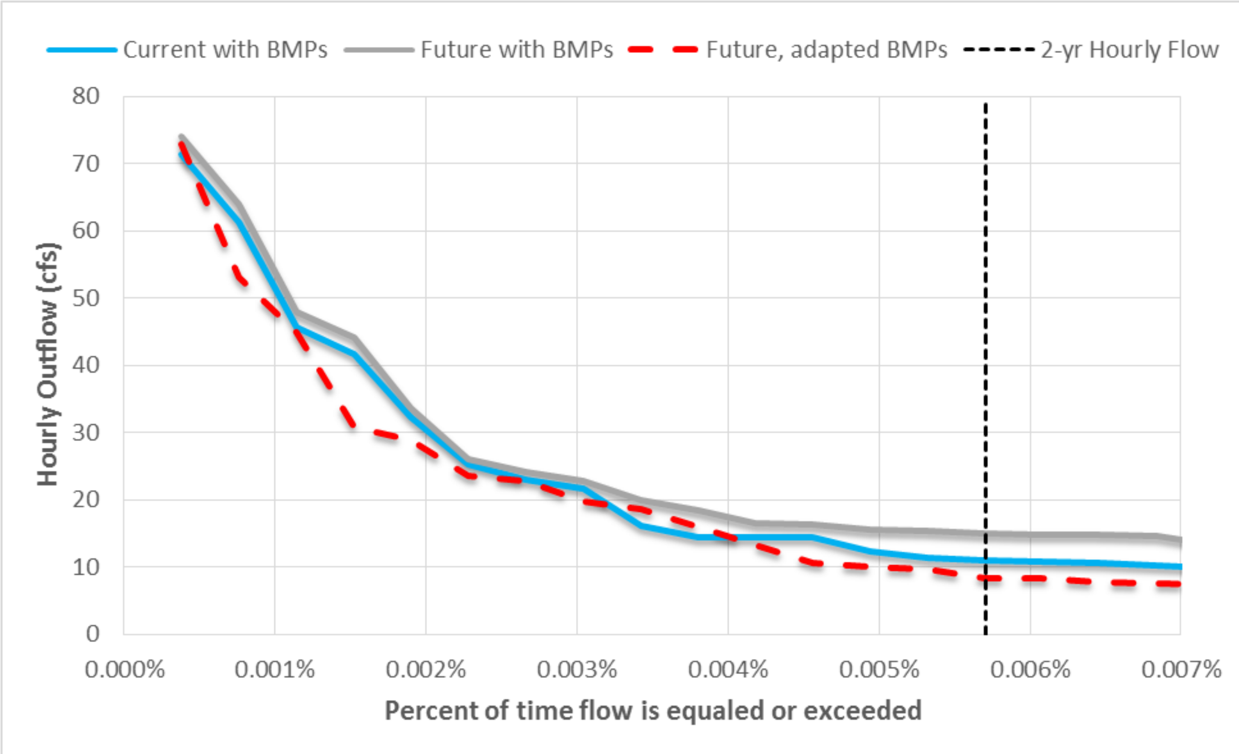


Figure B-52. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario.

Although maintaining maximum hourly peak flow at current performance is not an objective of the adaptation simulation, Figure B-53 indicates that the adapted Green and Gray practices are able to reduce hourly peak flow somewhat compared to the future (not adapted) practice sizing.

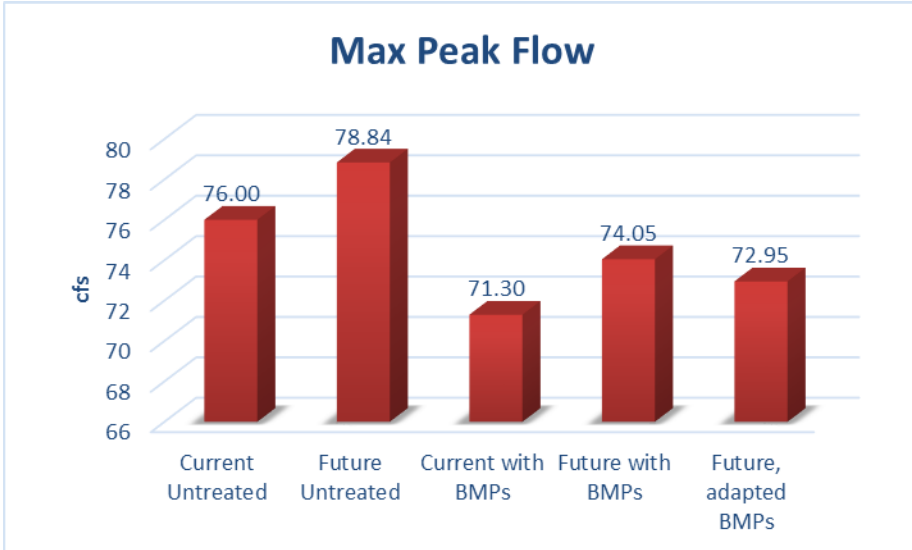


Figure B-53. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario.

Figure B-54 suggests that the adapted bioretention and dry detention basin practices are able to more closely match the monthly outflow volumes under the current climate, although outflow is greater in several months, particularly in May, November, and December.

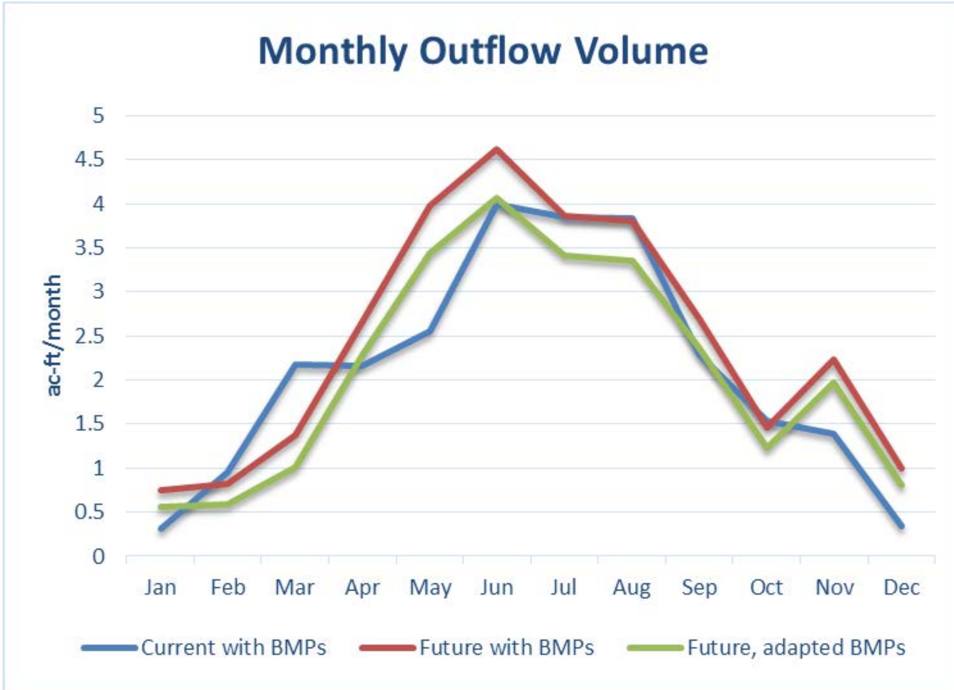


Figure B-54. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario.

Table B-7 summarizes the increases in BMP footprints for the Scott County GI with Gray Infrastructure (medium intensity) scenario that would be required to maintain current performance under future climate conditions.

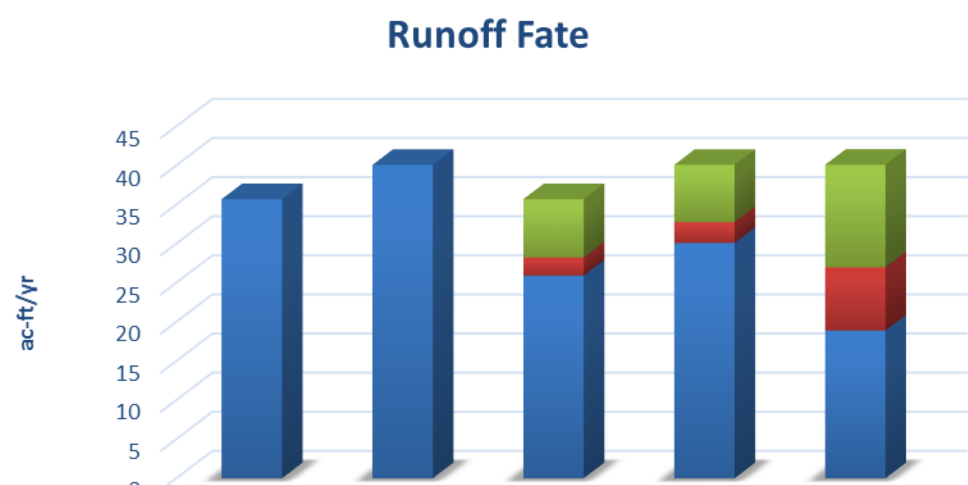
Table B-7. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (medium intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI with Gray Infrastructure	Future medium intensity	Bioretention	34,848	2.7%	58,848	4.5%	69%
		Dry detention basin	26,136	2.0%	32,336	2.5%	24%

Future High Intensity

The increase in precipitation depth and intensity in the Scott County future high intensity climate scenario results in the observed increase in runoff, and consequently outflow, compared to the current climate. The comparison of the “current with BMPs” and “future with BMPs” runoff fates indicates that the current practice sizing in the GI with Gray Infrastructure scenario is not sufficient to mitigate the increase in runoff volume, with a greater fraction of runoff partitioning to outflow.

Increasing the green (bioretention) and gray (dry detention basin) practice footprints increases the proportioning of runoff to infiltration and ET, allowing the site to maintain the current climate outflow performance under future high intensity climate conditions. However, as discussed above, due to the poor infiltration capacity of the soils in the Scott County study site, outflow remains the dominant runoff fate pathway.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			7.45	7.31	13.11
ET			2.32	2.67	8.08
Outflow	35.68	40.06	25.90	30.08	18.89

Figure B-55. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario.

The following figures demonstrate that the adapted green (bioretention) and gray (dry detention basin) practices in the Scott County GI with Gray Infrastructure scenario are able to mitigate the increases in annual average sediment (see Figure B-56), TN (see Figure B-57), and TP (see Figure B-58) load under future high intensity climate conditions.

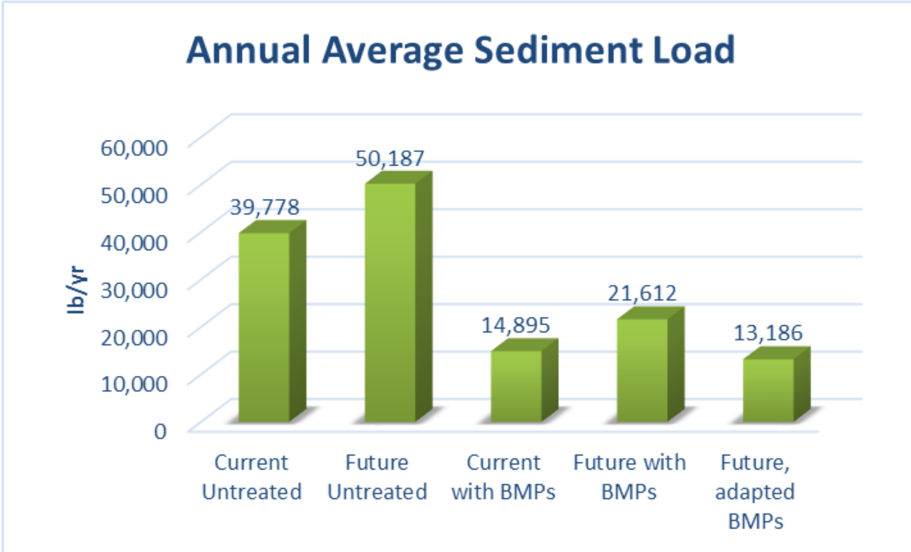


Figure B-56. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario.

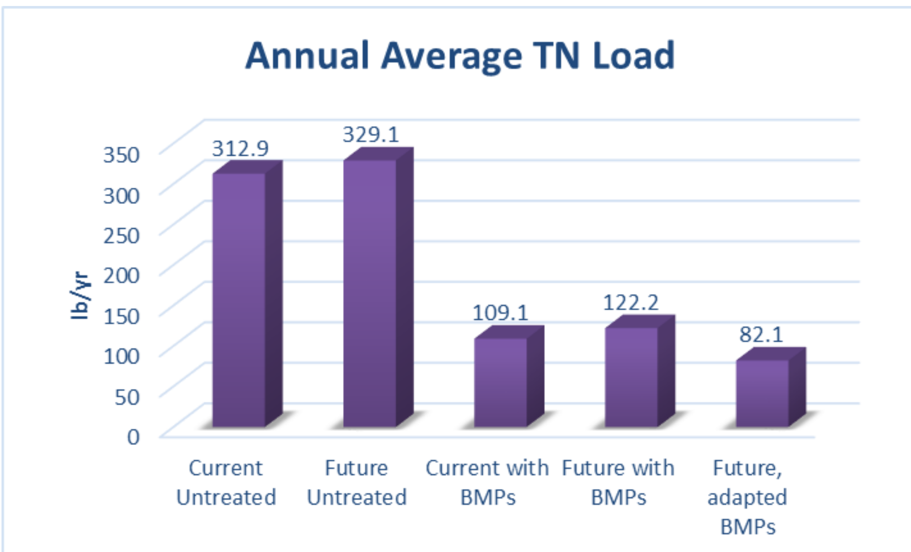


Figure B-57. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario.

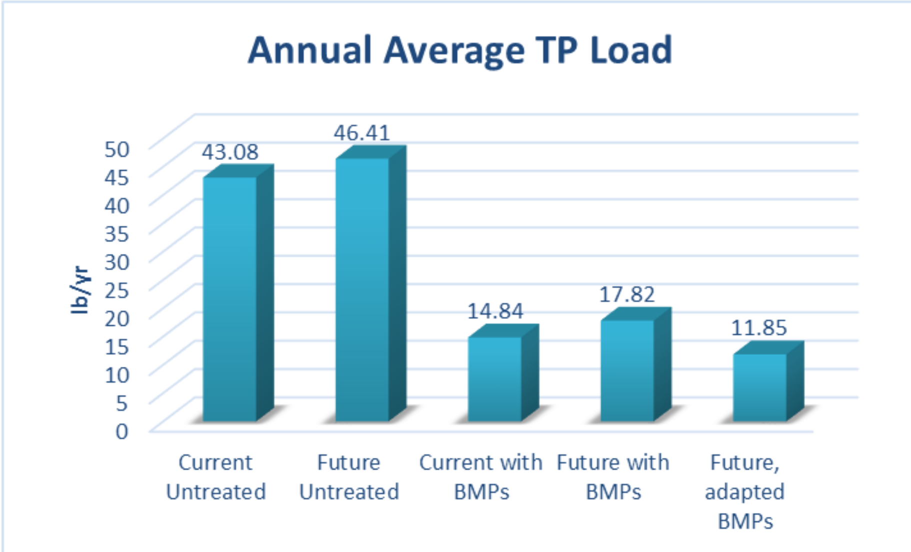


Figure B-58. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario.

Figure B-59 presents the flow duration curves for the current, future, and future adapted BMP scenarios, and demonstrates that the increased BMP footprints adapted for future high intensity climate achieve a very similar flow duration response to the current climate BMP configurations in the evaluated range of flows.

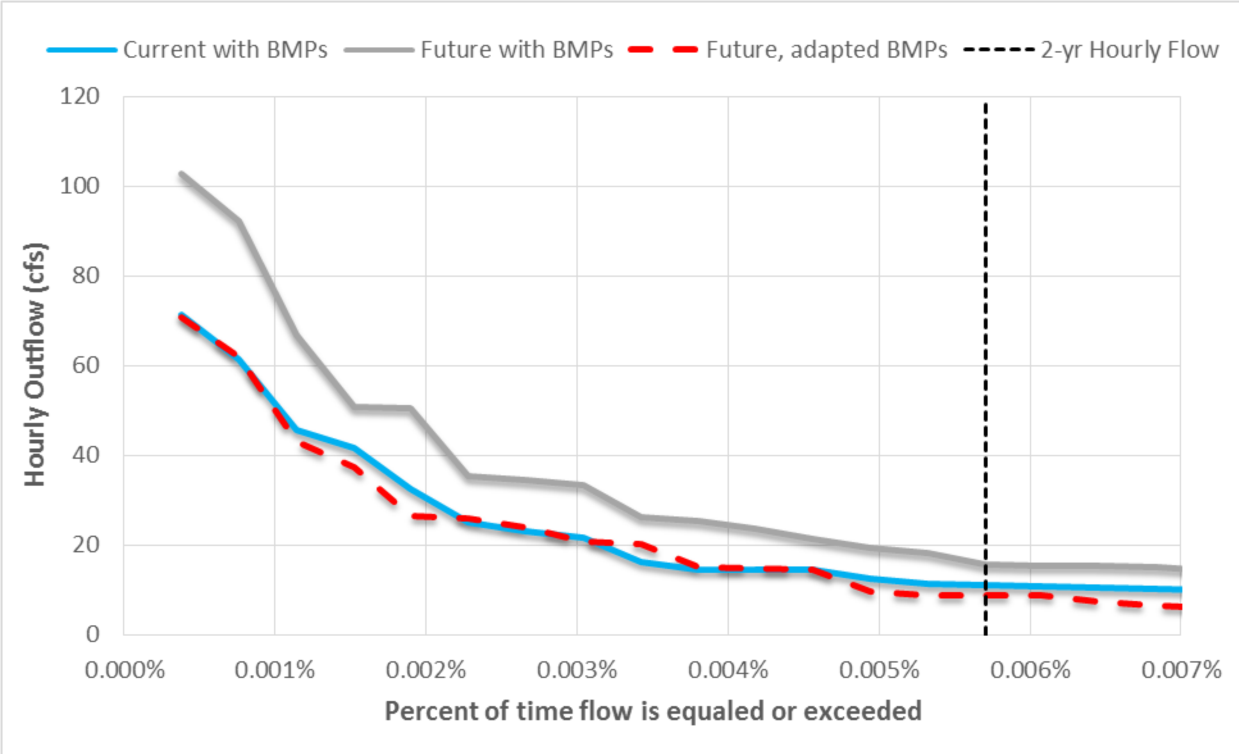


Figure B-59. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario.

As was observed in the FDC comparison (see Figure B-59), the increased bioretention and dry detention basin footprints are able to mitigate the increase in maximum hourly peak flow between the current and future high intensity climate conditions.

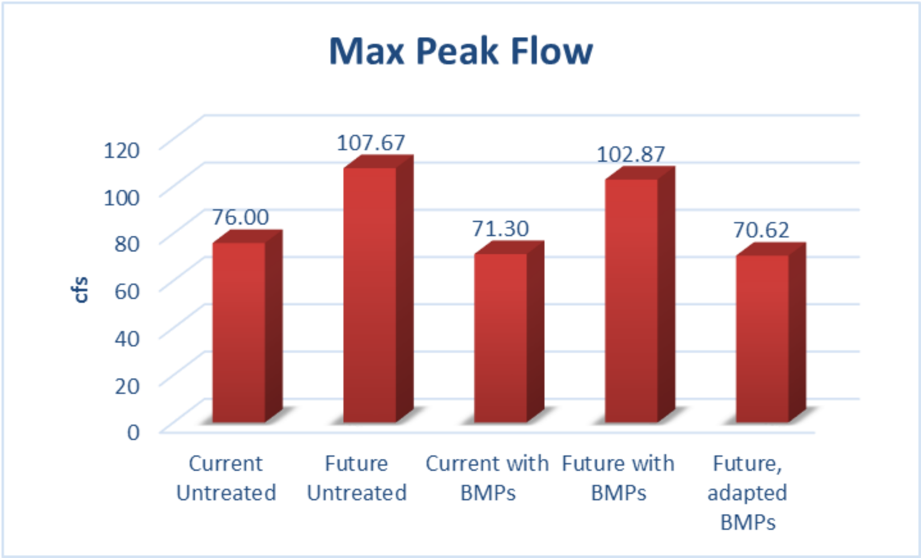


Figure B-60. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario.

Comparison of the monthly outflow volume for the current and future BMP scenarios indicates that the increased practice sizes are very effective at reducing monthly outflow volume compared to the future (not adapted) practices. Monthly outflow volumes with the future adapted practices are very similar to, or lower than, the current climate outflows for all months except July.

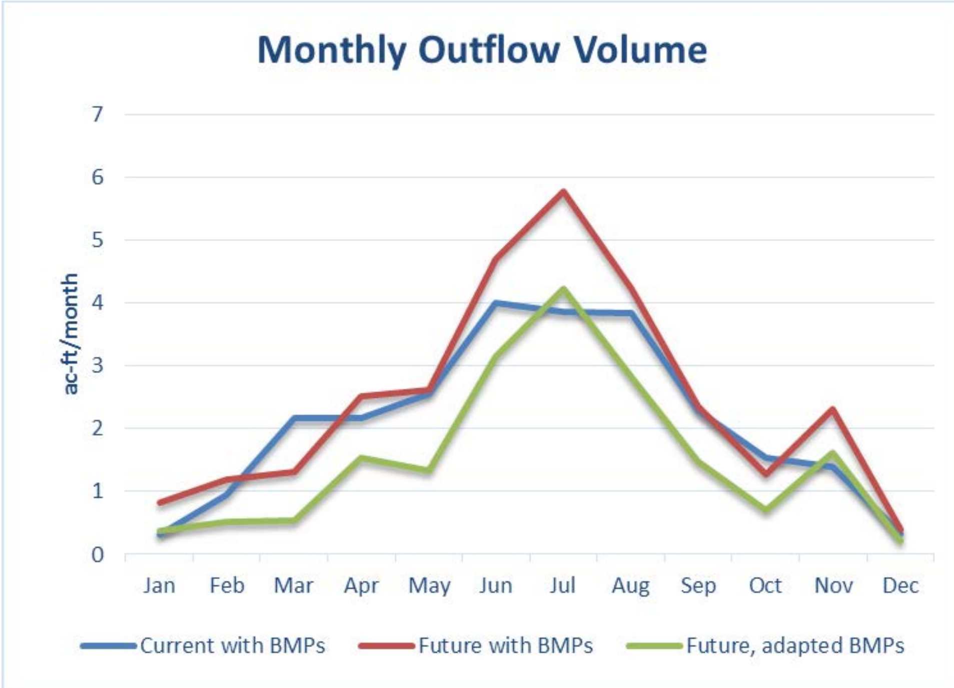


Figure B-61. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario.

Table B-8 summarizes the increases in BMP footprints for the Scott County GI with Gray Infrastructure (high intensity) scenario that would be required to maintain current performance under future climate conditions. The adapted bioretention footprint is approximately 2.7 times larger than the current footprint, and the adapted dry detention basin footprint is approximately 4.7 times larger than the current footprint.

Table B-8. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (high intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		Increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI with Gray Infrastructure	Future high intensity	Bioretention	34,848	2.7	93,286	7.1	168
		Dry detention basin	26,136	2.0	123,136	9.4	371

B.1.2.3. Green Infrastructure (GI) Only

Future Low Intensity

Due to the predicted decrease in precipitation depth and intensity in the future low intensity climate scenario, the overall runoff volume and outflow volume decrease compared to the current climate conditions (see Figure B-62). The decrease in site outflow in the future low intensity climate scenario results in decreased sediment load, TN load, and TP load compared to the current climate conditions (see Figure B-63, Figure B-64, and Figure B-65, respectively). Because there was no decrease in the performance of the GI only practices between current and future low intensity climate, this scenario was not investigated for adaptation.

	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs
Infiltration			13.54	12.92
ET			1.95	2.25
Outflow	34.78	32.31	19.28	17.14

Figure B-62. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) Only (low intensity) scenario.

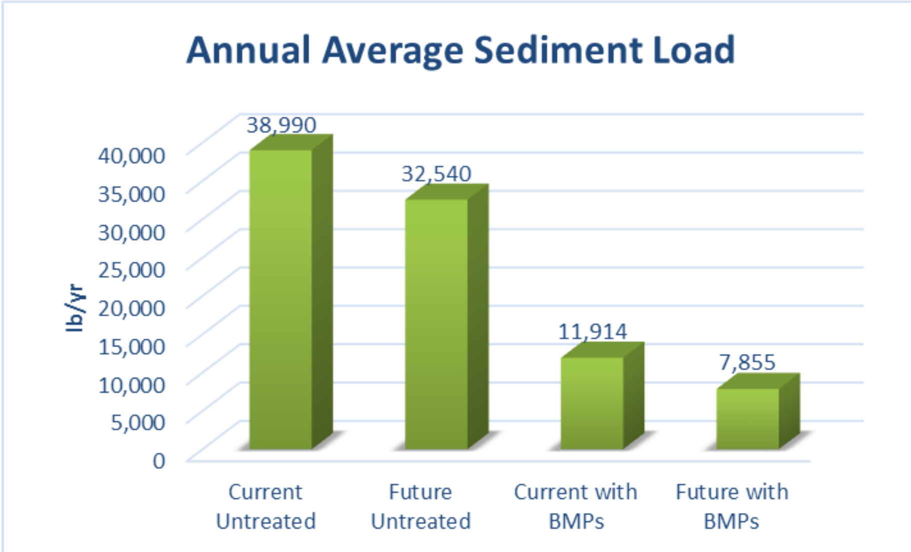


Figure B-63. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) Only (low intensity) scenario.

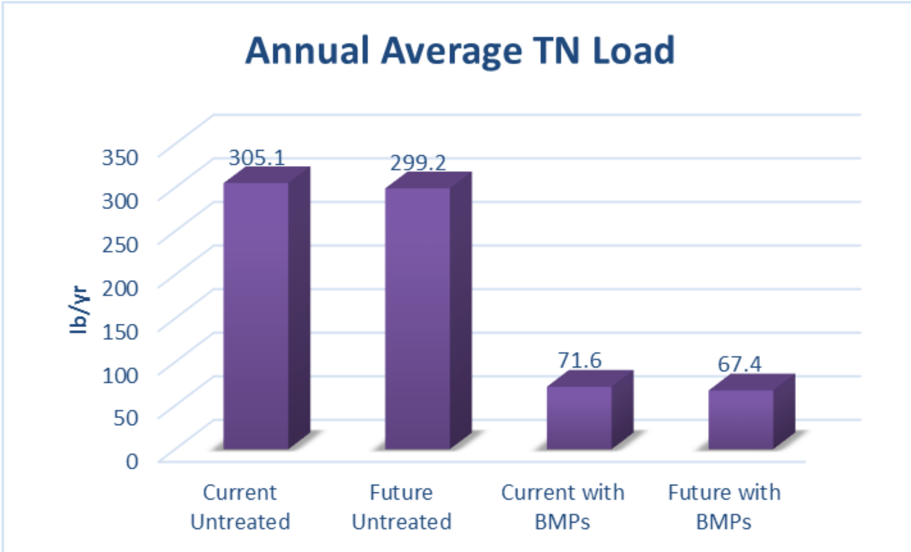


Figure B-64. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) Only (low intensity) scenario.

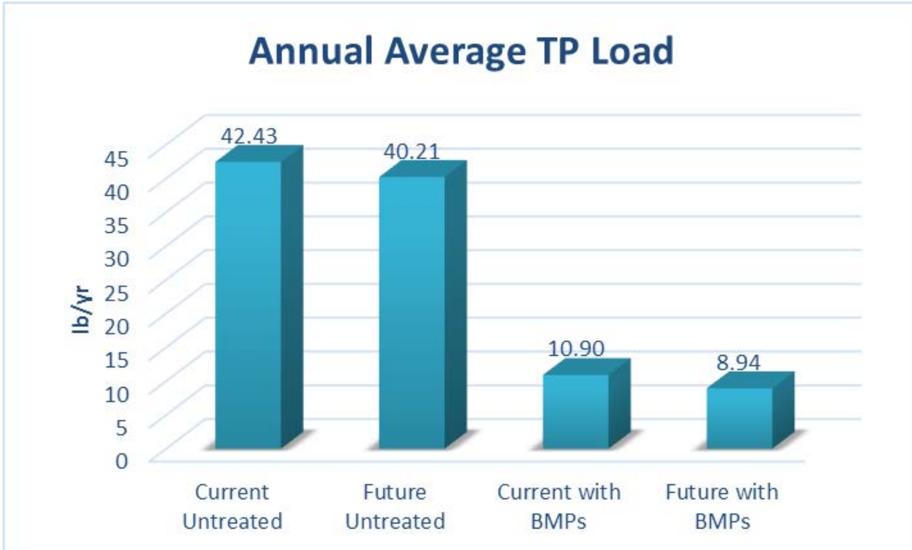


Figure B-65. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) Only (low intensity) scenario.

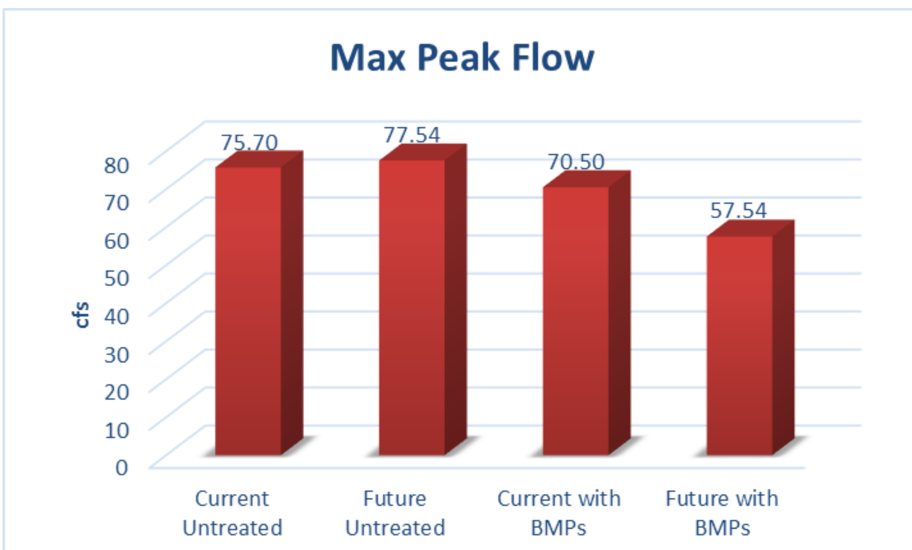


Figure B-66. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) Only (low intensity) scenario.

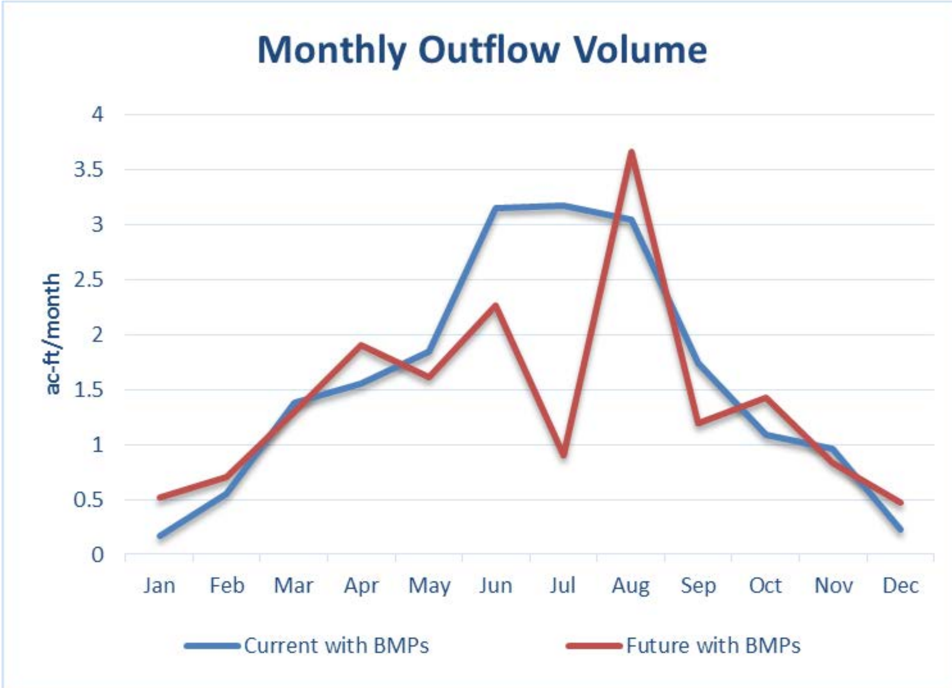


Figure B-67. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) Only (low intensity) scenario.

Future Medium Intensity

The predicted increase in annual precipitation depth and intensity in the Scott County future medium intensity climate scenario results in an increase in outflow between the current (19.28 cfs) and future (22.81 cfs) climate when the green practices (bioretention, rooftop downspout disconnection, and permeable pavement) are not resized for adaptation.

With future adaptation, the increased practice footprints reduce the volume of outflow below the "current with BMPs" scenario due to a larger proportioning of runoff to ET and infiltration. As discussed in Chapter 4 of the report, the soils in the Scott County study site have low infiltration capacity, so outflow remains the dominant runoff pathway, even for this GI Only scenario and even when practice sizes are increased.

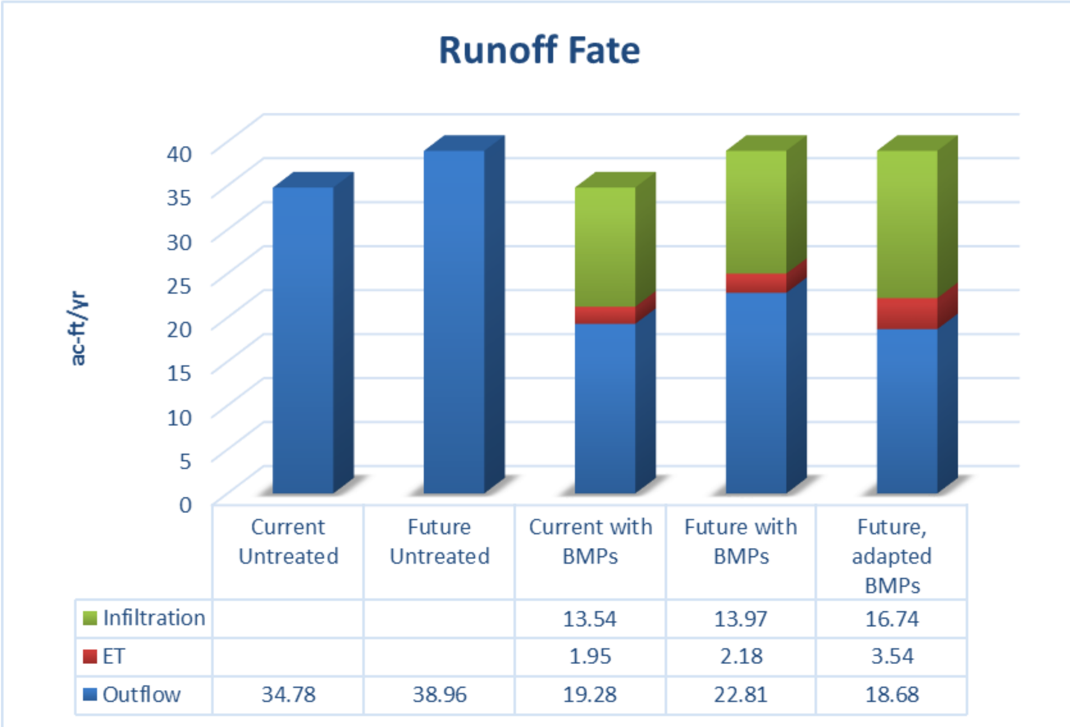


Figure B-68. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario.

The following figures demonstrate that the adapted green practices in the Scott County GI Only scenario are able to mitigate the increases in annual average sediment (see Figure B-69), TN (see Figure B-70), and TP (see Figure B-71) load under future high intensity climate conditions.

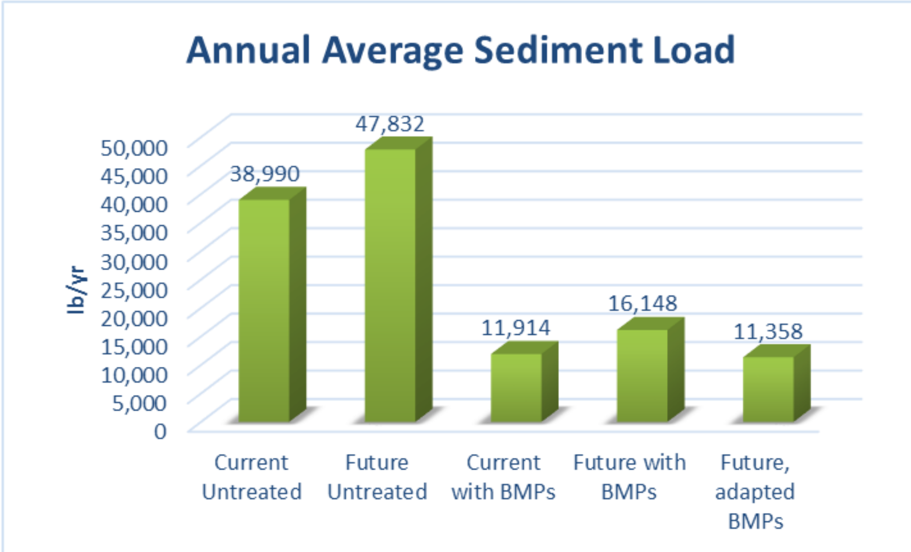


Figure B-69. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario.

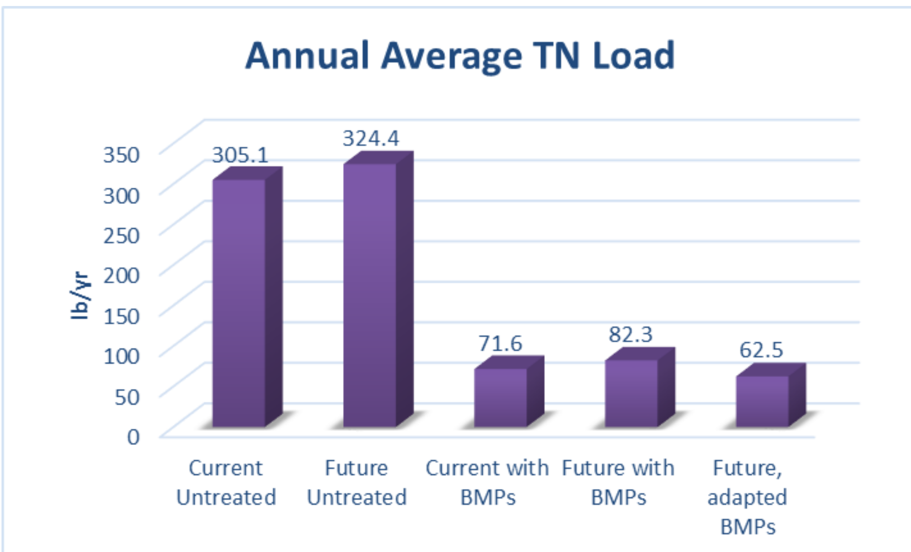


Figure B-70. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario.

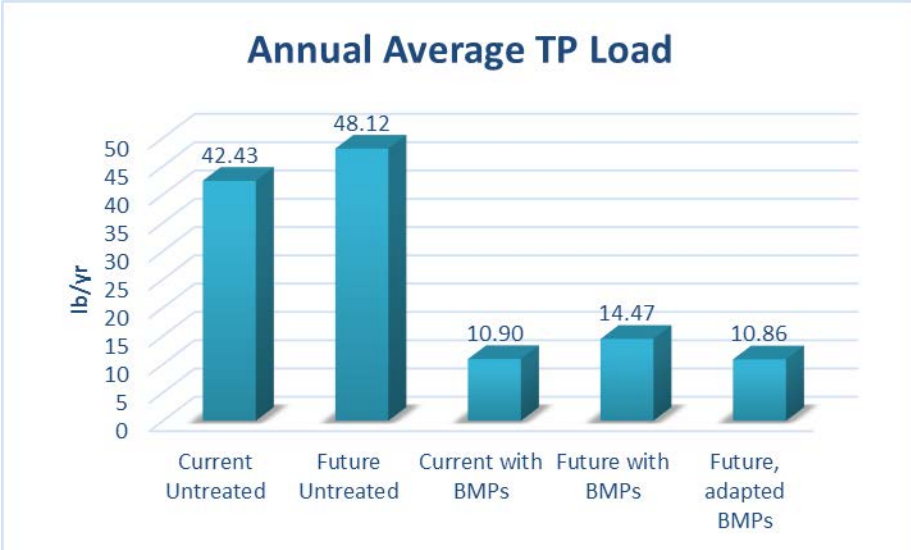


Figure B-71. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario.

The flow duration curve analysis (see Figure B-72) for the Scott County GI Only (medium intensity) scenario suggests that the adapted practices are able to reasonably match the outflow response of the current practices within the evaluated range of flows.

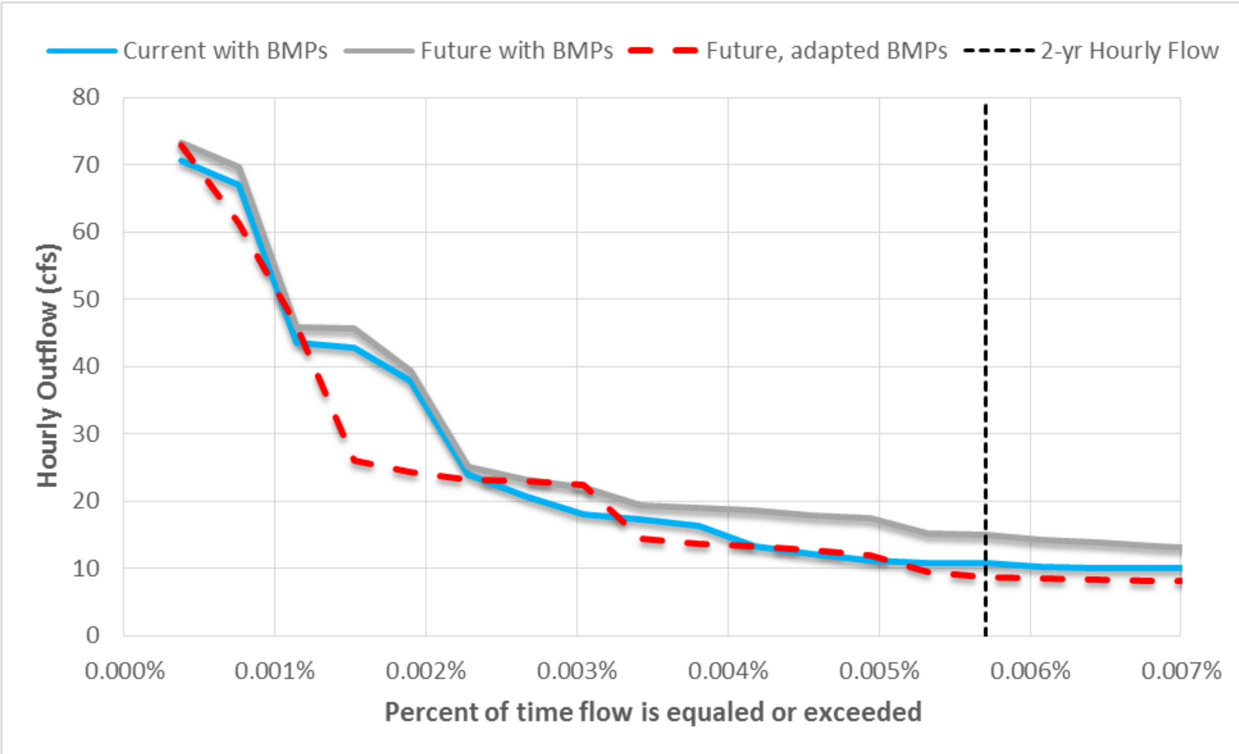


Figure B-72. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario.

Figure B-73 indicates that, although maximum hourly peak flow was not targeted as part of the adaptation simulation, the green practices, when adapted to meet the other performance measures, are only able to reduce the hourly peak flow by about 0.5 cfs. This result may suggest a lower ability of GI to mitigate hourly peak flows compared to Conventional (Gray) Infrastructure (which is typically designed specifically to address peak matching requirements).

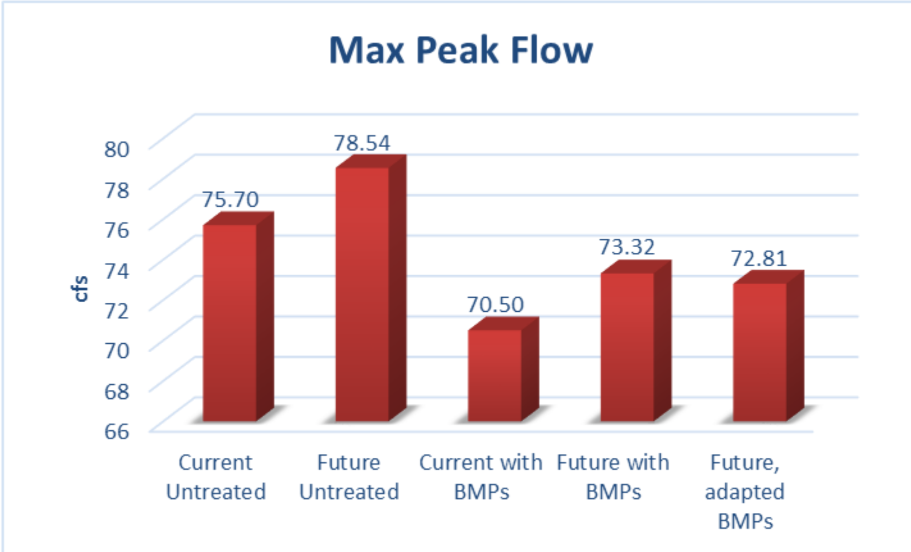


Figure B-73. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario.

Figure B-74 indicates the adapted green practices for the Scott County future medium intensity climate scenario are able to achieve a reasonable match to the current climate monthly outflow volumes. Monthly outflow volumes with the future adapted practices are very similar to, or lower than the current climate outflows for all months except May, November, and December.

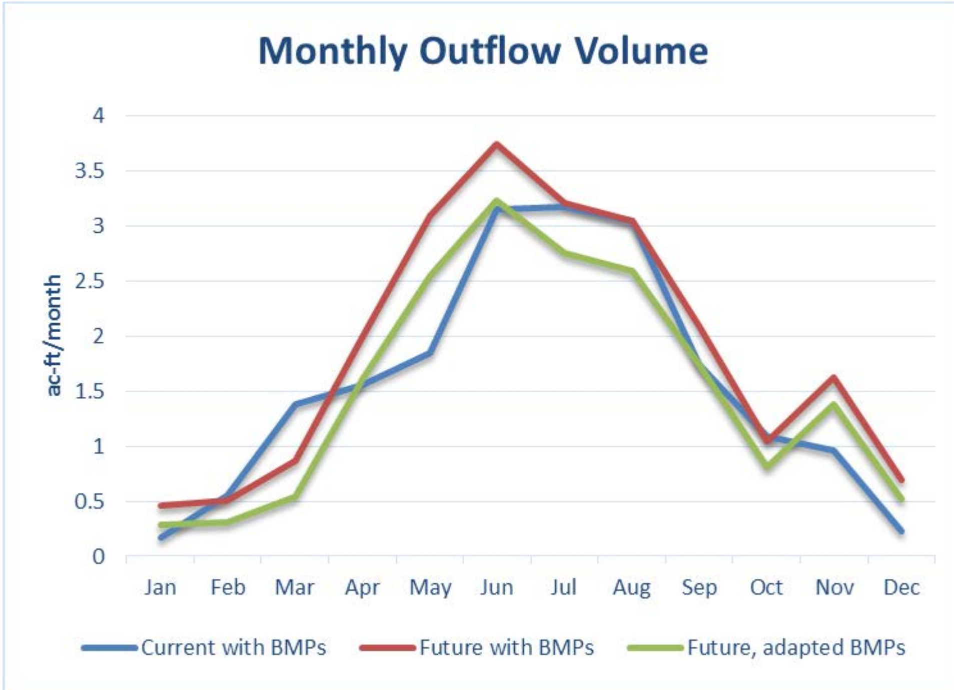


Figure B-74. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario.

Table B-9 summarizes the increases in BMP footprints for the Scott County GI Only (medium intensity) scenario that would be required to maintain current performance under future climate conditions. Only bioretention was modified for future climate adaptation. Permeable pavement and rooftop downspout disconnection were not modified for two reasons: (1) permeable pavement is already implemented in 100% of sidewalk areas, and its expansion to include residential driveways and streets was ruled impractical due primarily to maintenance concerns; and (2) impervious surface disconnection is already implemented to the maximum extent practicable in this scenario for residential rooftops, and disconnection of additional impervious surface is not considered feasible.

Table B-9. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Green Infrastructure (GI) Only (medium intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI Only	Future medium intensity	Bioretention (modified)	43,275	3.3	71,675	5.5	66
		Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
		Permeable pavement	39,390	3.0	39,390	3.0	0

Future High Intensity

The increase in precipitation depth and intensity in the Scott County future high intensity climate scenario results in the observed increase in runoff, and consequently outflow, compared to the current climate. The comparison of the “current with BMPs” and “future with BMPs” runoff fates indicates that the current practice sizing in the GI Only scenario is not sufficient to mitigate the increase in runoff volume, with a greater fraction of runoff partitioning to outflow.

Increasing the green practice footprints increases the proportioning of runoff to infiltration and ET, allowing the site to maintain the current climate outflow performance under future high intensity climate conditions. As discussed above, due to the poor infiltration capacity of the soils in the Scott County study site, outflow is an important runoff fate pathway. However, the increase green practice footprints in the future adapted scenario increase the proportioning of runoff to infiltration enough to make it the dominant runoff fate pathway in future high intensity climate.

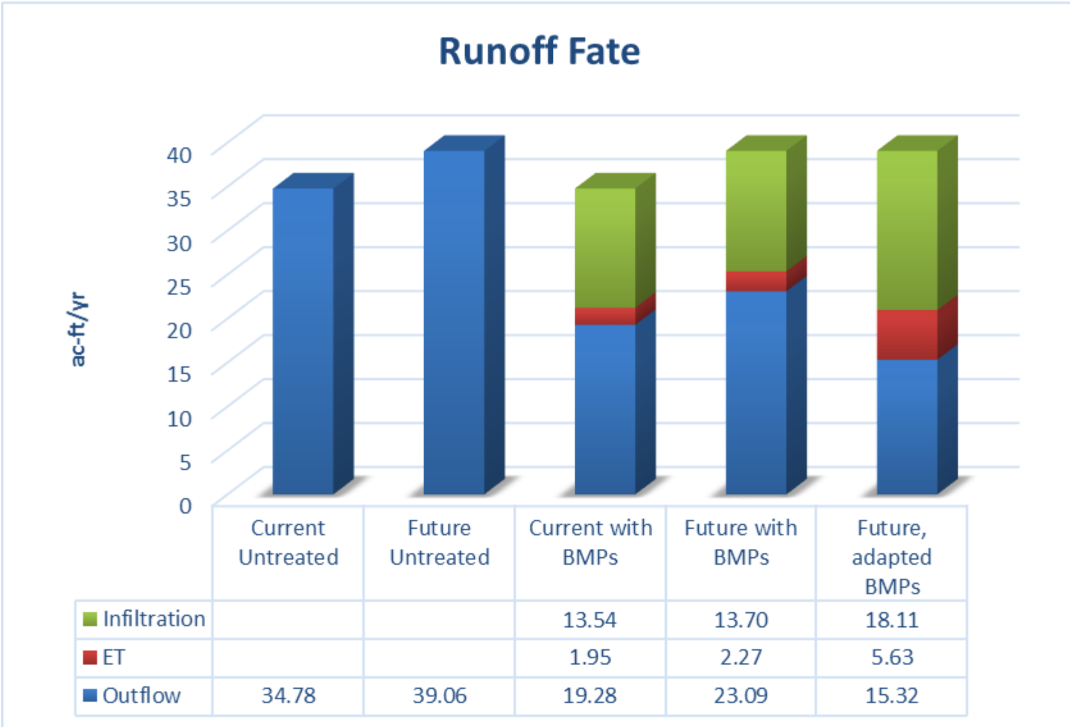


Figure B-75. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario.

Figure B-76, Figure B-77, and Figure B-78 demonstrate that with the increased practice sizes, the GI Only site is able to mitigate the increased sediment, TN, and TP loads due to future climate impacts.

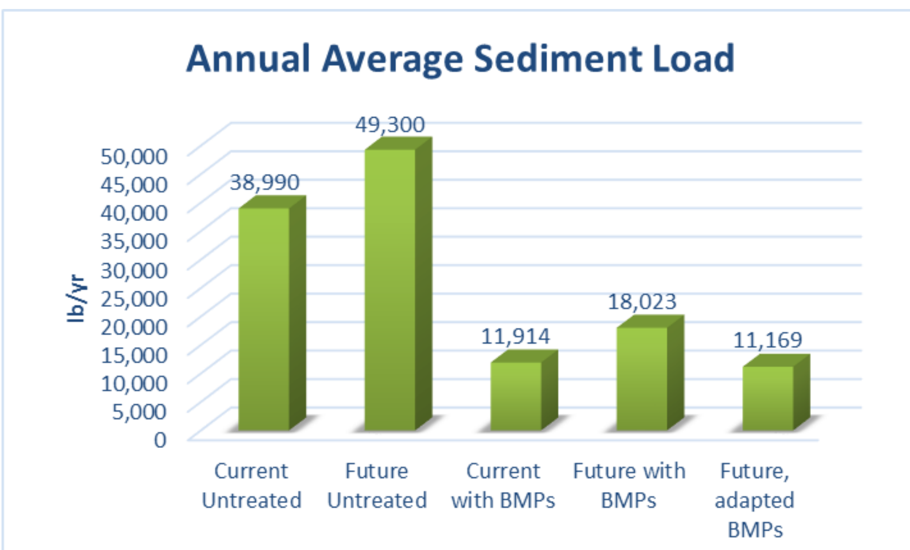


Figure B-76. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario.

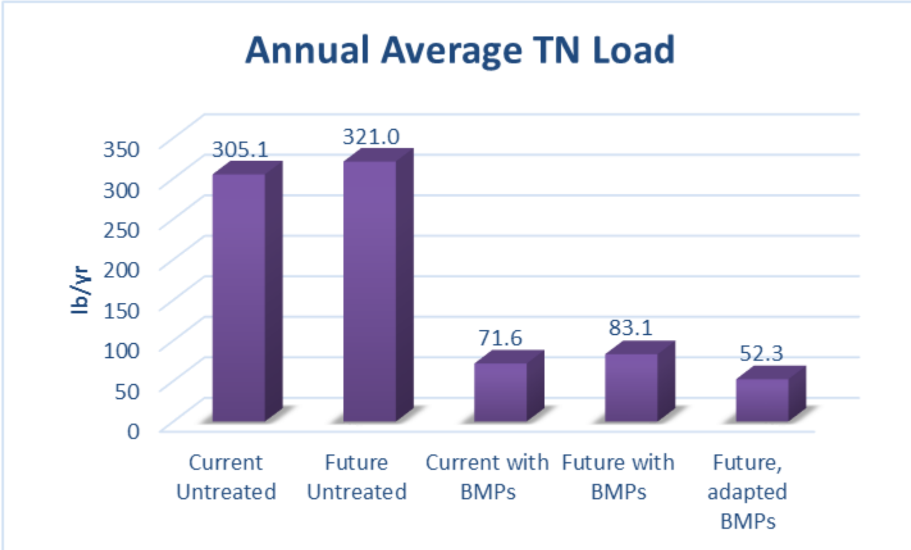


Figure B-77. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario.

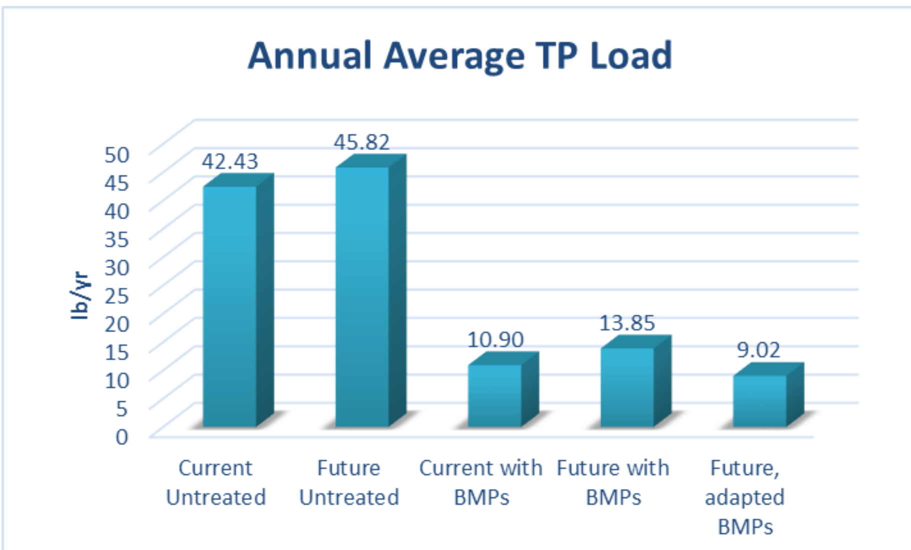


Figure B-78. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario.

The FDC evaluation for the Scott County GI Only (high intensity) scenario indicates that the green practices alone are able to achieve a reasonably close flow response to the current climate FDC within the evaluated range of flows. However, there is a discrepancy between the highest hourly peak flows, indicating the adapted practices are unable to mitigate the increase in the highest flows due to climate change (high intensity).

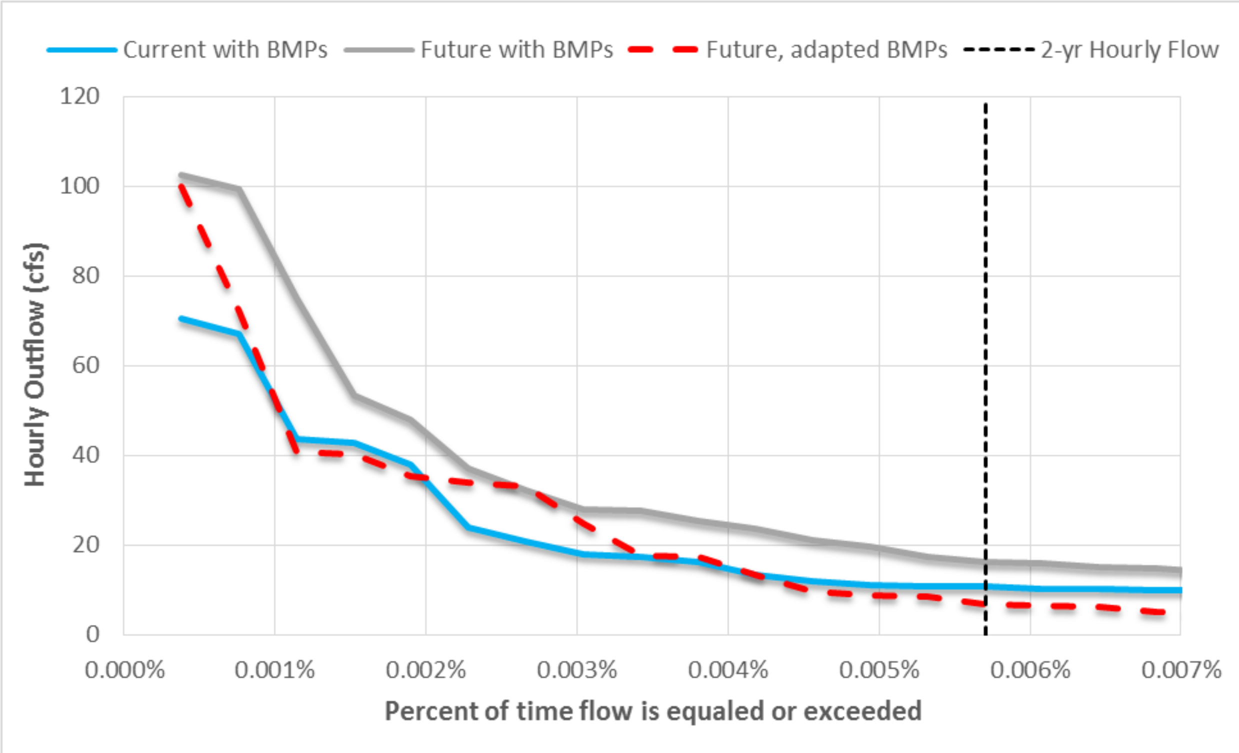


Figure B-79. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario.

Figure B-80 provides additional insight into the behavior seen in the uppermost range of flows in the flow duration curve analysis. The GI Only practices, even with adaptation, do not significantly reduce the maximum hourly peak flow under the future climate (high intensity) compared to the original practice sizes ("future with BMPs").

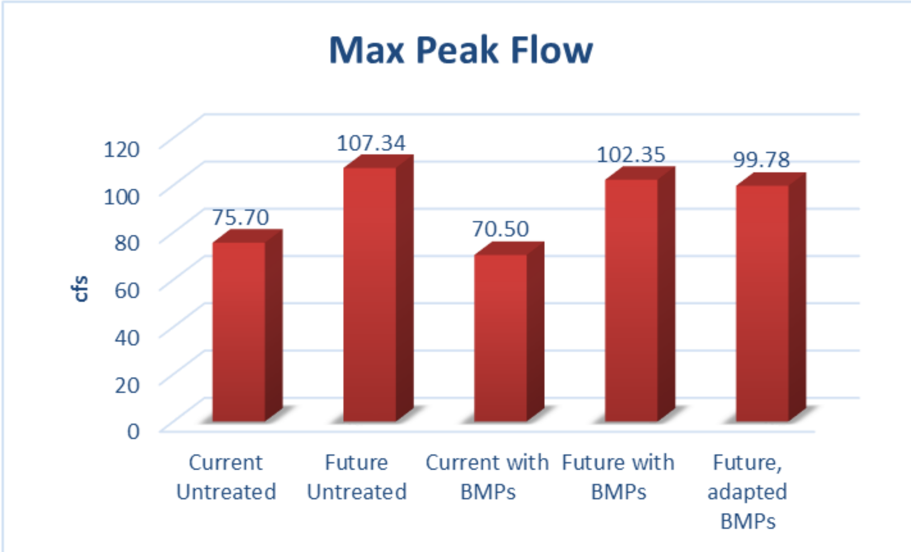


Figure B-80. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario.

Figure B-81 indicates that with resizing, the future adapted GI Only practices are successful at mitigating increased monthly outflow volumes under future climate. The future adapted monthly outflows are lower than, or very close to, the current monthly outflows for all months except July.

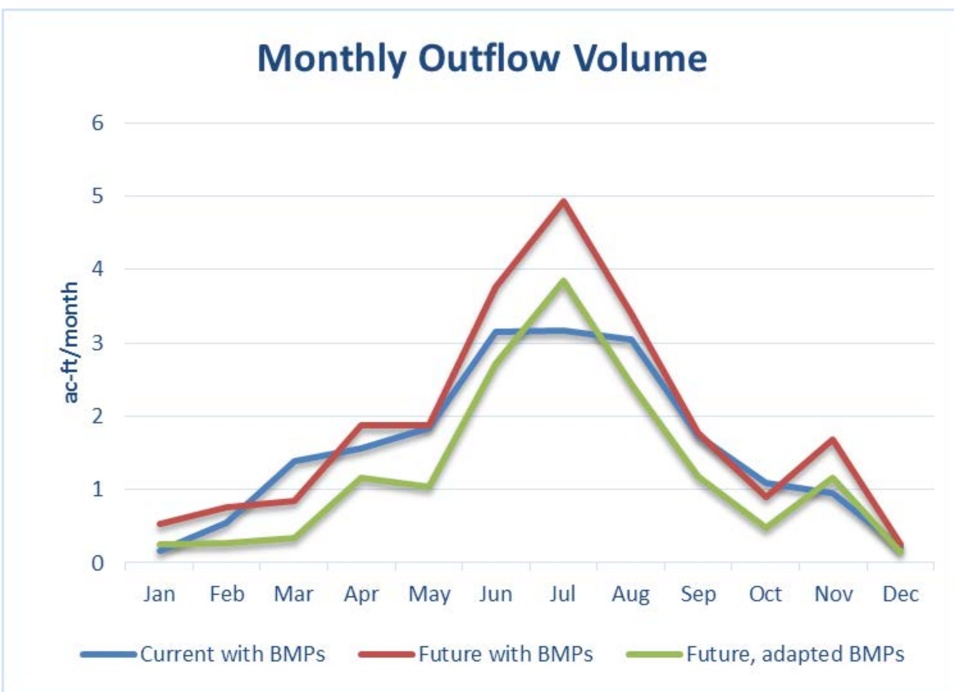


Figure B-81. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario.

Table B-10 summarizes the increases in BMP footprints for the Scott County GI Only (high intensity) scenario that would be required to maintain current performance under future climate conditions. As discussed above, rooftop downspout disconnection and permeable pavement were not selected for adaptation in the Scott County GI Only scenarios.

Table B-10. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Green Infrastructure (GI) Only (high intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI Only	Future high intensity	Bioretention (modified)	43,275	3.3	111,735	8.6	158
		Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
		Permeable pavement	39,390	3.0	39,390	3.0	0

B.1.2.4. Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI)

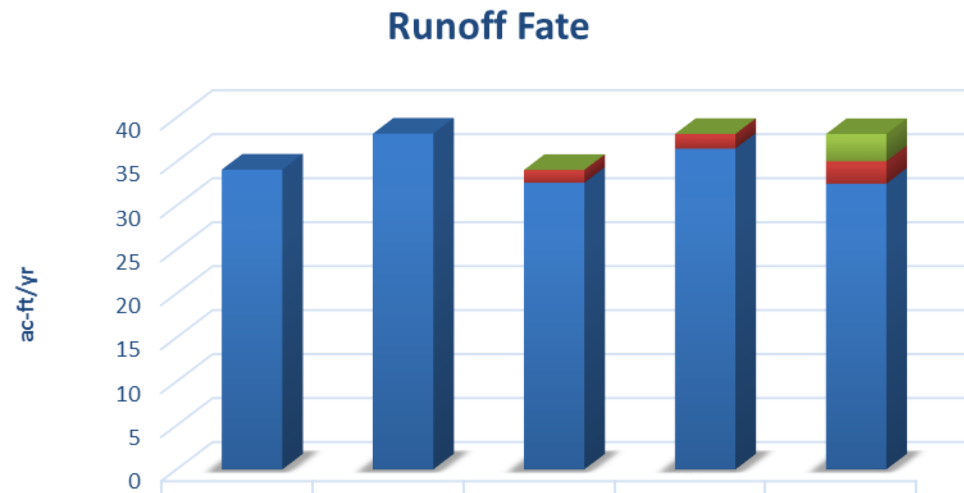
Future Low Intensity

The Conventional (Gray) Infrastructure scenario was not investigated for adaptation in the future low intensity climate scenario because there was no decrease in the performance of the conventional (Gray) practice (wet pond) between the current and future climate. Therefore, the future low intensity climate scenario was also not investigated for adaptation through the addition of distributed GI practices as there was no performance gap to address.

Future Medium Intensity

The change in flow and pollutant-related performance for the Scott County Conventional (Gray) scenario due to future climate impacts was discussed in *Section B.1.2.1.* The purpose of the Conventional (Gray) Infrastructure with Distributed GI scenario is to implement distributed GI practices without resizing the conventional (Gray) practice as a means of future climate adaptation.

Figure B-82 indicates that the addition of distributed bioretention to the conventional site is able to reduce outflow below the current climate outflow by increasing the partitioning of runoff to infiltration and ET. Due to the poorly infiltrating soils on the Scott County site, outflow remains the dominant runoff fate pathway, even with the addition of infiltrating bioretention.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			0.00	0.00	3.10
ET			1.46	1.66	2.55
Outflow	34.10	38.19	32.59	36.48	32.49

Figure B-82. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario.

Figure B-83 indicates that the distributed bioretention practices combined with the wet pond are able to achieve high load reductions for sediment, and allow the site to meet current loading for annual average sediment load without requiring resizing of the existing wet pond.

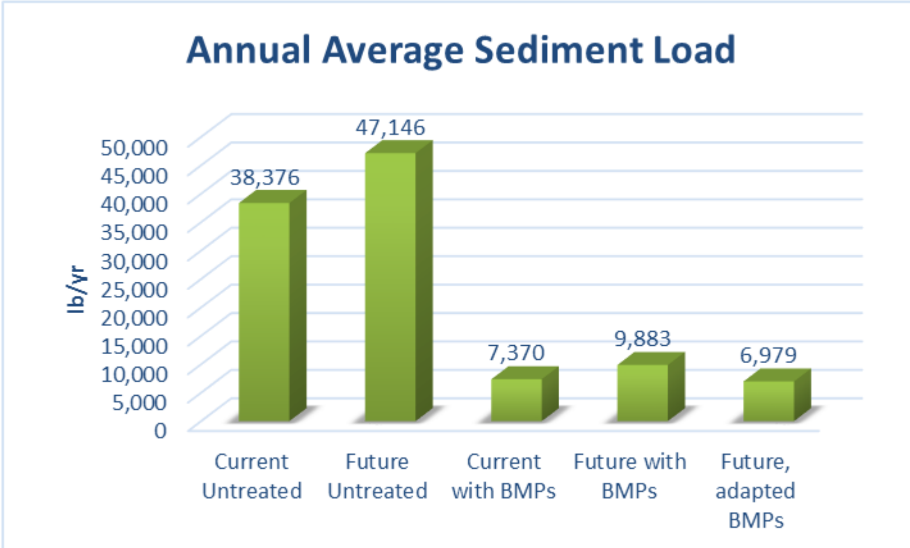


Figure B-83. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario.

The following figures suggest that the distributed bioretention practices combined with the wet pond are able to achieve modest load reductions for TN and TP, and allow the site to meet current loading for annual average sediment load without requiring resizing of the existing wet pond.

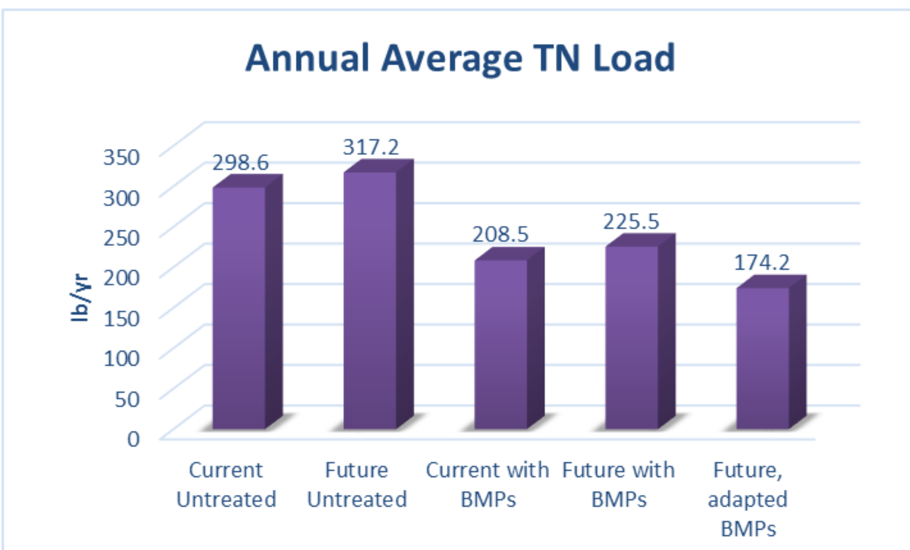


Figure B-84. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario.

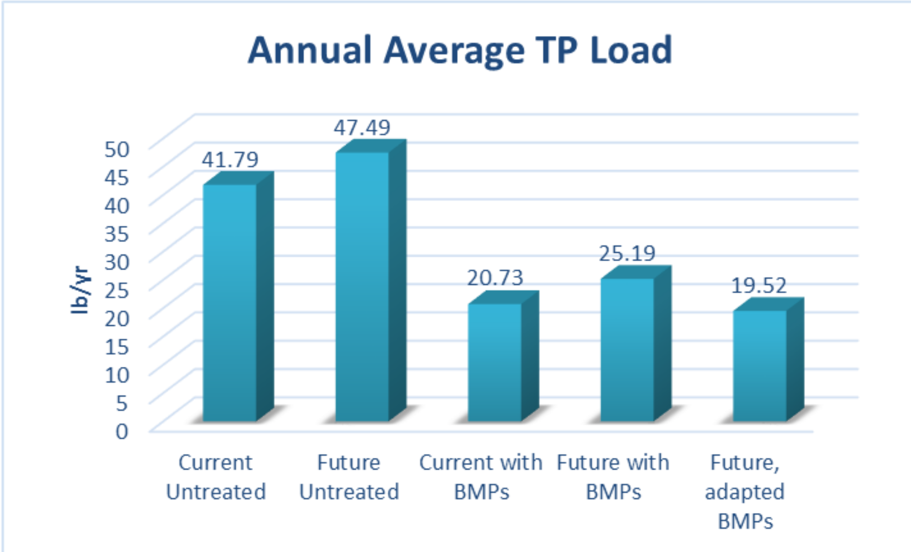


Figure B-85. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario.

The FDC evaluation for the Scott County Conventional (Gray) Infrastructure with Distributed GI (medium intensity) climate scenario indicates that with the addition of distributed bioretention practices, the site is able to achieve a reasonably similar response to the current FDC in the evaluated range of flows.

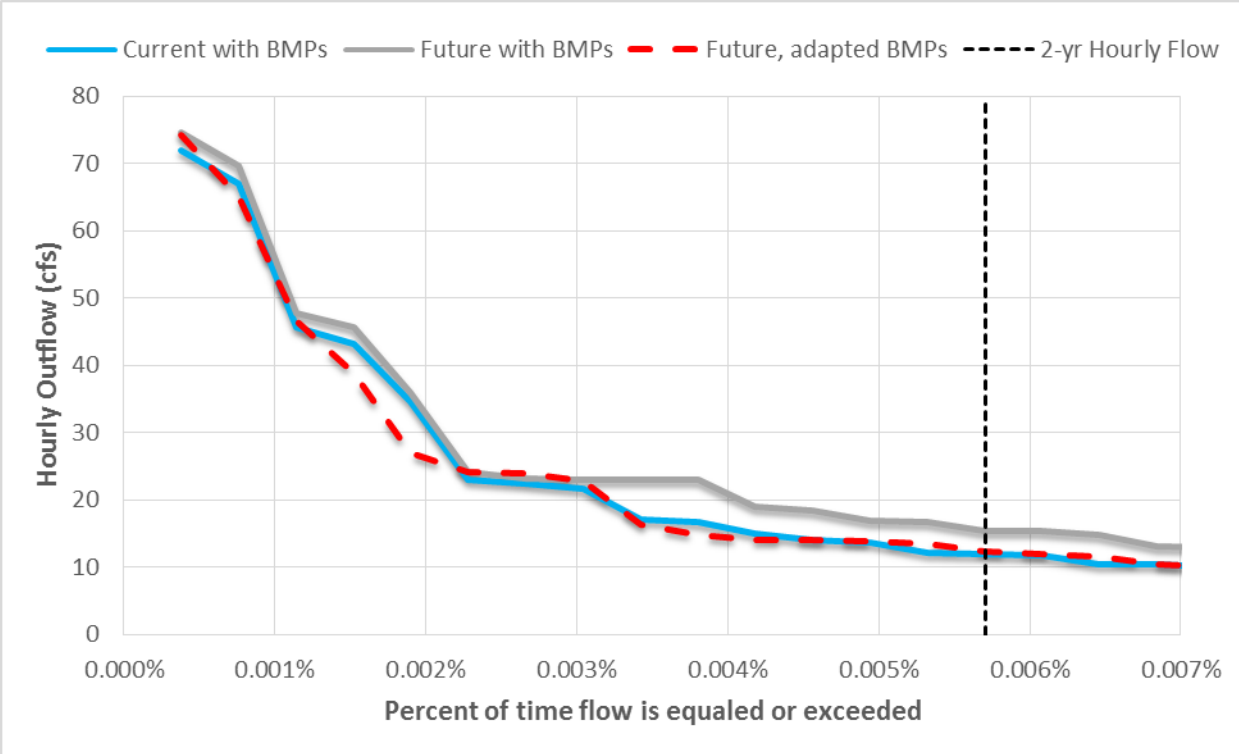


Figure B-86. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario.

As discussed above, maximum hourly peak flow was not targeted as a performance criterion for the adaptation simulation. However, it appears that the addition of distributed bioretention for medium intensity climate adaptation does not significantly reduce maximum hourly peak flow below the "future with BMPs" hourly peak flow.

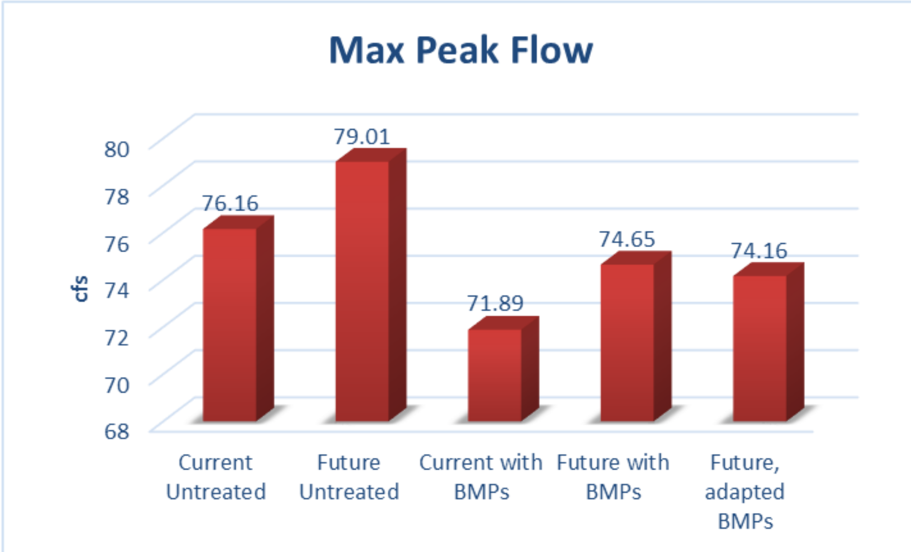


Figure B-87. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario.

Figure B-88 demonstrates that the addition of distributed bioretention practices combined with the existing wet pond results in monthly outflow volumes that are more similar to the current performance. Although outflow is higher in some months, on an annual basis, the future adapted scenario produces a lower outflow volume than the “current with BMPs” scenario.

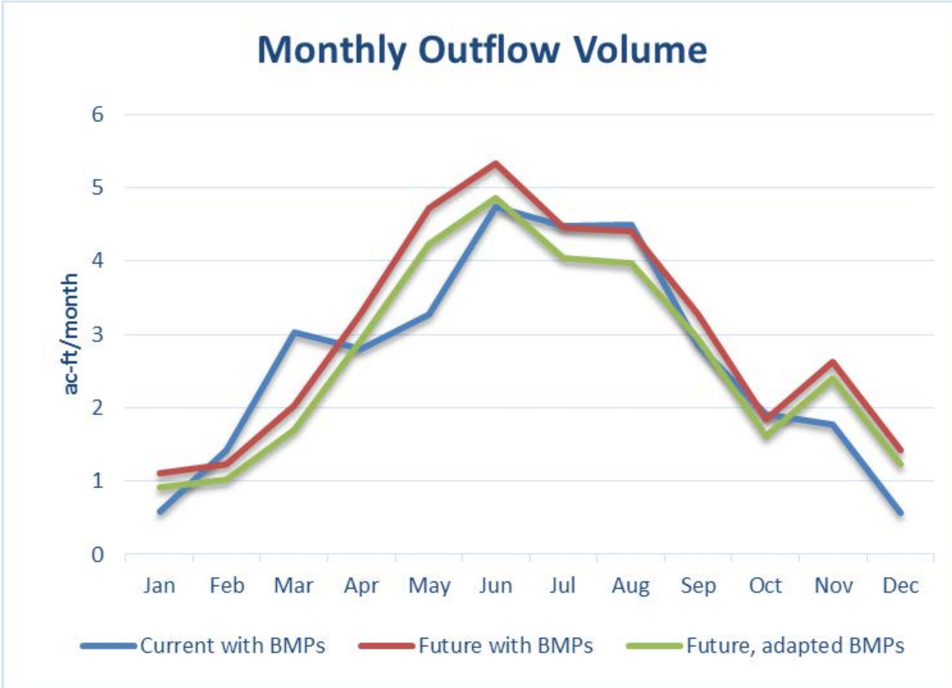


Figure B-88. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario.

Table B-11 summarizes the increases in BMP footprints for the Scott County Conventional (Gray) Infrastructure with Distributed GI (medium intensity) scenario that would be required to maintain current performance under future climate conditions. Adaptation would require the addition of 18,280 square feet of bioretention (roughly 1.4% of the total site area).

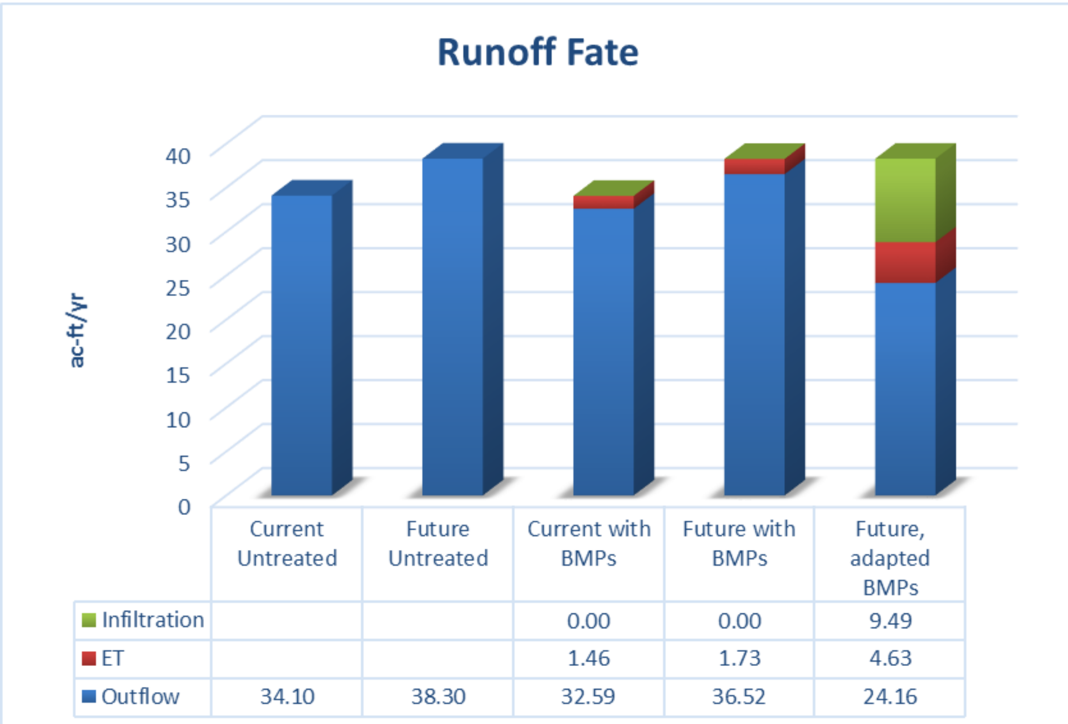
Table B-11. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (medium intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure with Distributed GI	Future medium intensity	Wet pond	32,670	2.5	32,670	2.5	0
		Distributed bioretention	0	0.0	18,280	1.4	--

Future High Intensity

The change in flow and pollutant-related performance for the Scott County Conventional (Gray) scenario due to future climate impacts was discussed in *Section B.1.2.1.* . The purpose of the Conventional (Gray) Infrastructure with Distributed GI scenario is to implement distributed GI practices without resizing the conventional (Gray) practice as a means of future climate adaptation.

Figure B-89 indicates that the addition of distributed bioretention to the conventional site is able to reduce outflow below the current climate outflow by increasing the partitioning of runoff to infiltration and ET. However, due to the poorly infiltrating soils on the Scott County site, outflow remains the dominant runoff fate pathway, even with the addition of infiltrating bioretention.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			0.00	0.00	9.49
ET			1.46	1.73	4.63
Outflow	34.10	38.30	32.59	36.52	24.16

Figure B-89. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario.

The wet pond alone achieves a reasonably high load reduction for annual average sediment load, even with future (high intensity) climate impacts. The current load reduction is 81% and the future (before adaptation) load reduction is 76%. Without resizing the wet pond, the addition of distributed bioretention practices improves the future load reduction to 90%, enabling the site to maintain current performance for sediment load reduction under projected future climate conditions.

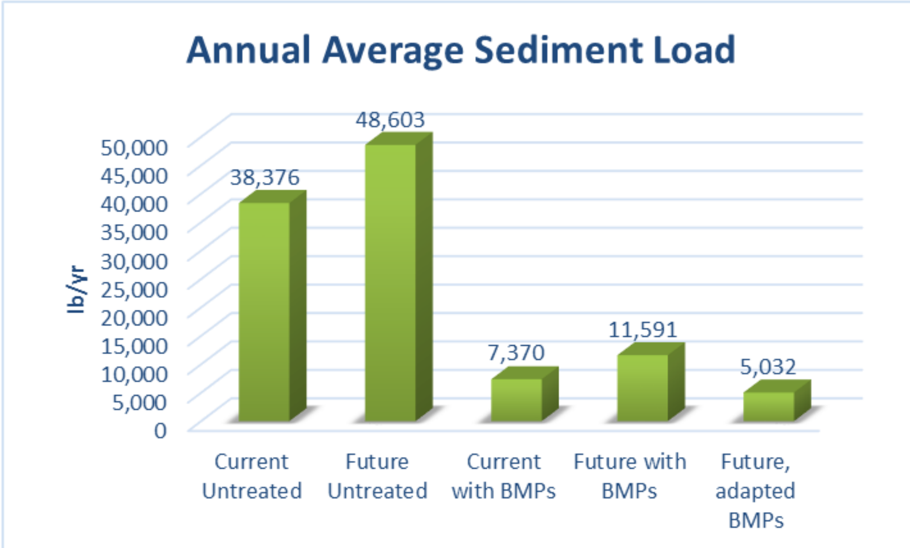


Figure B-90. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario.

The addition of distributed bioretention in the future high intensity climate scenario was primarily driven by the required decrease in outflow needed to maintain current outflow reduction performance. Because outflow reduction was the driving mechanism, the resulting bioretention footprint is larger than would be required to address pollutant loading alone. As a result, the future adapted TN and TP loads are much lower than loads under the current climate conditions.

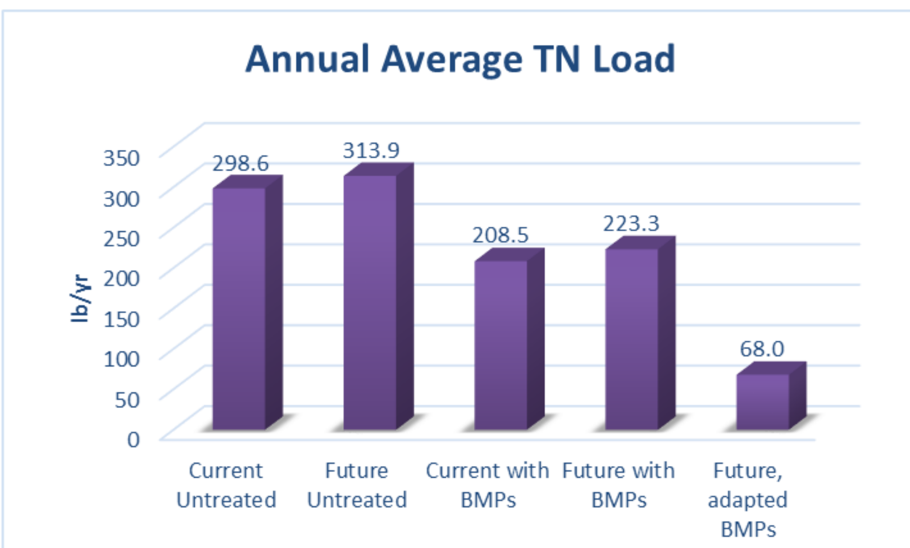


Figure B-91. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario.

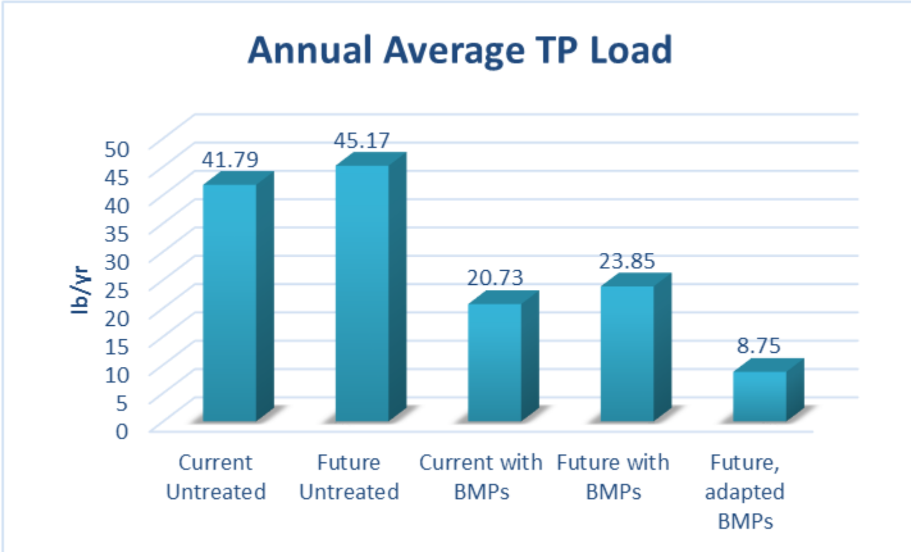


Figure B-92. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario.

The FDC analysis for the future high intensity scenario suggests that although the addition of distributed bioretention practices is able to maintain the current climate outflow volume, these practices as designed are not effective at reducing the highest hourly peak flow rates. As a result, there is divergence between the "current with BMPs" and "future, adapted BMPs" flow duration curves, particularly for the highest outflows.

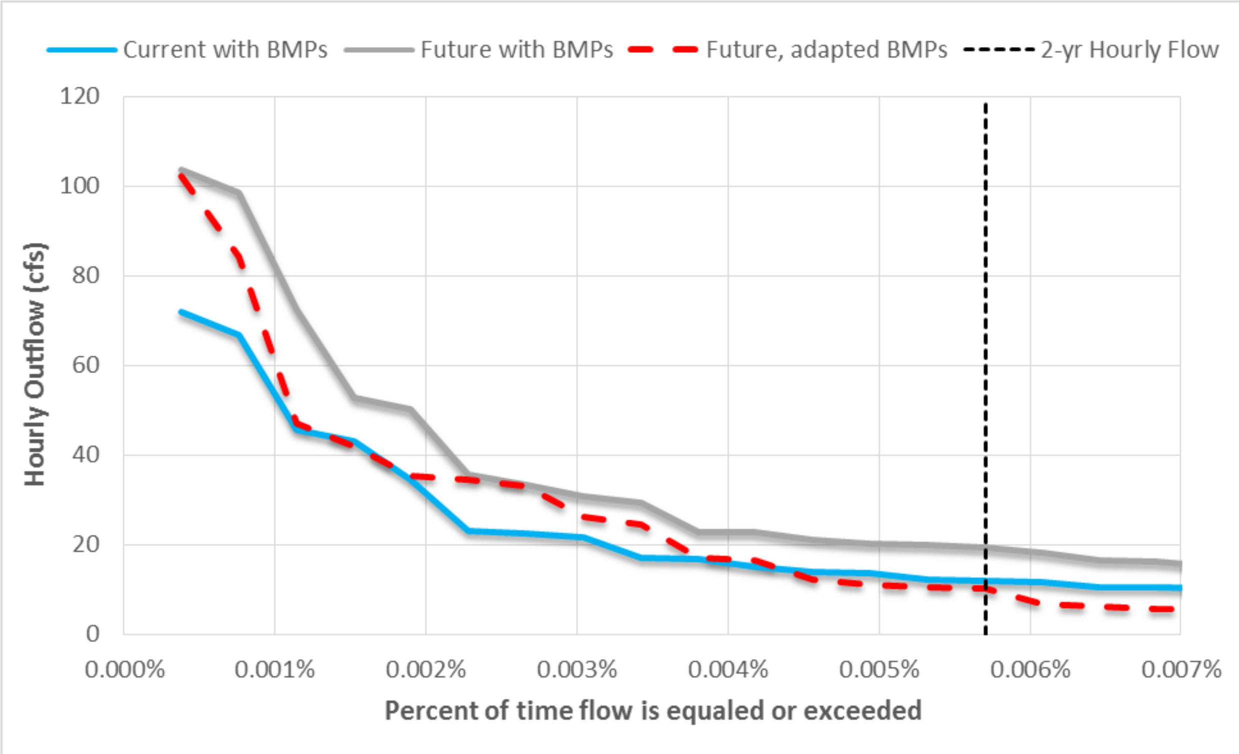


***Figure* B-93. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario.**

Figure B-94 indicates that the addition of distributed bioretention to the conventional site does not result in a significant decrease in the maximum hourly peak flow under future (high intensity) climate.

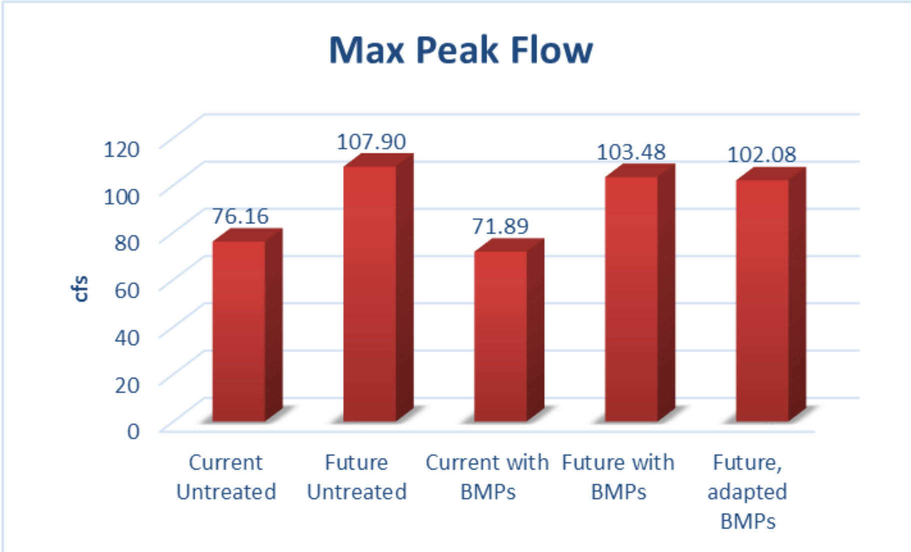


Figure B-94. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario.

As noted above, although the distributed bioretention practices, when combined with the existing wet pond, are not successful at mitigating the highest outflows under future high intensity climate, these practices are effective at managing monthly outflow volume. The "future, adapted BMPs" monthly outflow volumes are consistently lower or approximately the same as the "current with BMPs" monthly outflow volumes for all months.

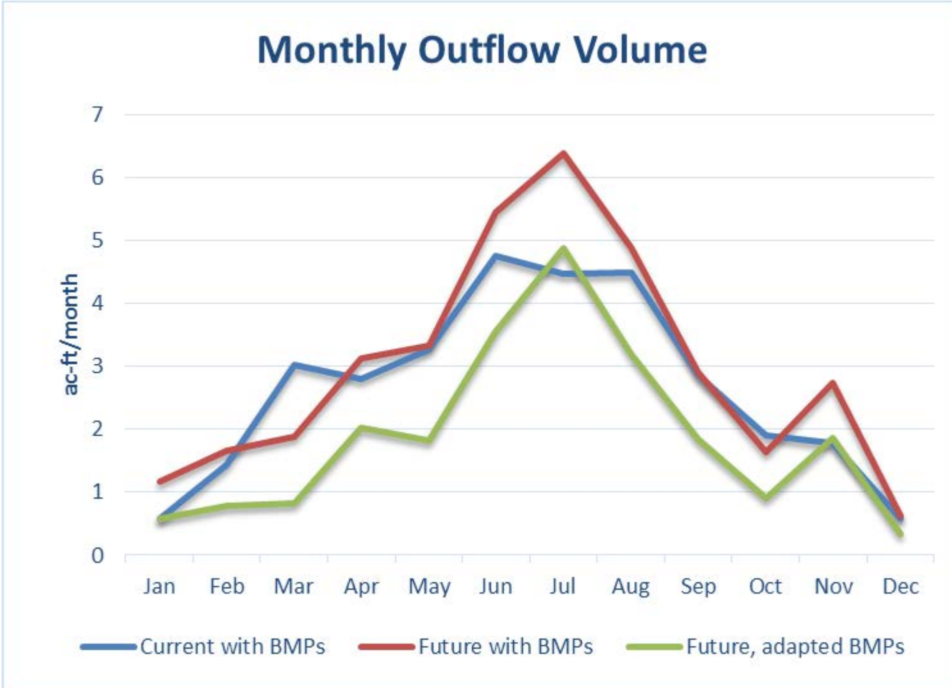


Figure B-95. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario.

Table B-12 summarizes the increases in BMP footprints for the Scott County Conventional (Gray) Infrastructure with Distributed GI (high intensity) scenario that would be required to maintain current performance under future climate conditions. Adaptation would require the addition of 56,770 square feet of bioretention (roughly 4.3% of the total site area).

Table B-12. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (high intensity) scenario

Stormwater management scenario	Climate scenario	Practice	Current		Future adapted		% increase in footprint
			Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure with Distributed GI	Future high intensity	Wet pond	32,670	2.5	32,670	2.5	0
		Distributed bioretention	0	0.0	56,770	4.3	--

B.1.2.5. Cost Estimation

Future Medium Intensity

Table B-13 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all four Scott County stormwater management scenarios under future medium intensity climate, as well as the percentage increase in cost (current to future adapted) and increase (millions of dollars) per acre of site.

Table B-13. Comparison of the current and future estimated 20-year present value costs for the Scott County, MN stormwater management scenarios, future medium intensity climate

Location	Climate scenario	Stormwater management scenario	Current cost 20-yr present value, $millions	Future adapted cost (20-yr present value, $millions)	Increase in cost (20-yr present value, $millions)	% increase in cost	Increase per acre of site $millions
Scott County, MN	Future medium intensity	Conventional (Gray) Infrastructure	3.05	8.99	5.94	195	0.30
		GI with Gray Infrastructure	4.92	7.37	2.46	50	0.12
		GI Only	8.51	11.80	3.29	39	0.16
		Conventional (Gray) Infrastructure with Distributed GI	3.05	4.69	1.65	54	0.08

Future High Intensity

Table B-14 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all four Scott County stormwater management scenarios under future high intensity climate, as well as the percentage increase in cost (current to future adapted) and increase (millions of dollars) per acre of site.

Table B-14. Comparison of the current and future estimated 20-year present value costs for the Scott County, MN stormwater management scenarios, future high intensity climate

Location	Climate scenario	Stormwater management scenario	Current cost (20-yr present value, $millions)	Future adapted cost 20-yr present value, $millions	Increase in cost (20-yr present value, $millions)	% increase in cost	Increase per acre of site $millions
Scott County, MN	Future high intensity	Conventional (Gray) Infrastructure	3.05	10.59	7.54	248	0.38
		GI with Gray Infrastructure	4.92	14.82	9.90	201	0.50
		GI Only	8.51	16.44	7.93	93	0.40
		Conventional (Gray) Infrastructure with Distributed GI	3.05	8.16	5.11	168	0.26

B.1.3. Maricopa County, AZ

B.1.3.1. Conventional (Gray) Infrastructure

As discussed in *Section 4.2.* of the report, the simulated future climate scenario for Maricopa County, AZ resulted in an overall increase in precipitation depth and intensity. However, when current and future precipitation depths are compared on a monthly basis across the simulation period, monthly average precipitation actually decreases in 7 months (February−June, September, and December) and only increases substantially in 3 months (January, October, and November). The increases are small in July and August. However, on an annual basis, the increases in precipitation depth and intensity outweigh the decreases, and the net result is a modest overall increase in both metrics. The increase in precipitation depth and intensity in the future climate scenario results in an increase in annual runoff volume (acre-feet per year) (see Figure B-96).

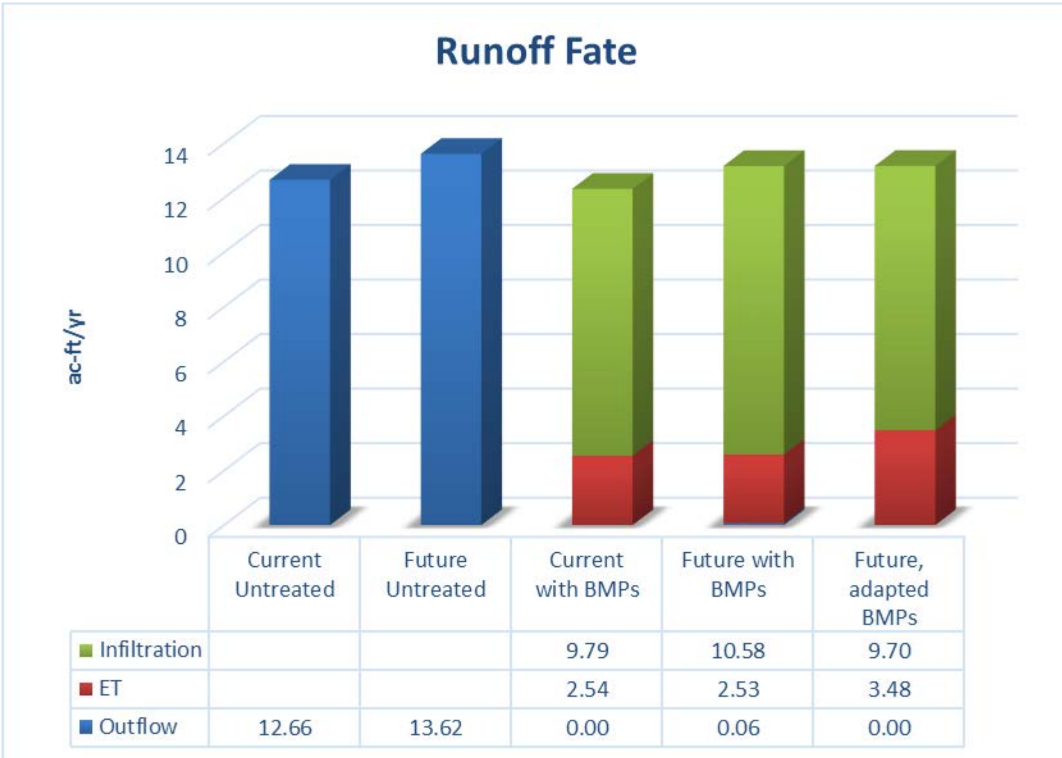


Figure B-96. Current and future partitioning of runoff fate for the Maricopa County, AZ Conventional (Gray) Infrastructure scenario.

The infiltration basin in the Maricopa County Conventional (Gray) Infrastructure scenario achieves zero outflow under the current climate conditions. Approximately 79% of runoff is lost to infiltration, and the remaining fraction (21%) to ET. Under future climate conditions, although the annual runoff volume increases, only a very small fraction (less than 0.5%) of runoff is converted to outflow. Increasing the surface area of the infiltration basin for climate adaptation results in zero site outflow, with annual runoff partitioning 73% to infiltration and 26% to ET. Increasing the footprint of the infiltration basin increases the surface area available for infiltration and ET. In this arid region, ET comprises a relatively large fraction of the overall water balance under both current and future climate conditions.

Because there is zero site outflow on an annual basis under the “current with BMPs” scenario, the corresponding annual average sediment load is zero. Under future climate conditions, the annual average sediment load increases to 363 pound/year, a result of a more than doubling of the annual sediment load under future climate conditions (“future untreated”) compared to the current climate (“current untreated”). Increasing the surface area of the infiltration basin reduces the sediment load from the site to zero.

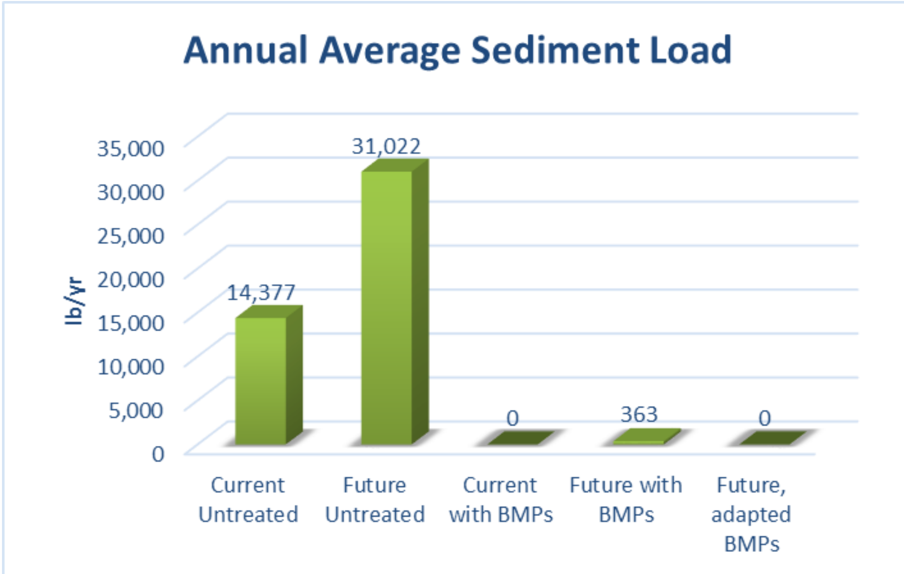


Figure B-97. Current and future performance for annual average sediment load, Maricopa County, AZ Conventional (Gray) Infrastructure scenario.

Under future climate conditions, annual TN load is predicted to increase by approximately 3.5 pound/year. The infiltration basin is very effective at reducing TN load from the site. Increasing the footprint enables the basin to achieve zero outflow under future climate conditions ("future, adapted BMPs").

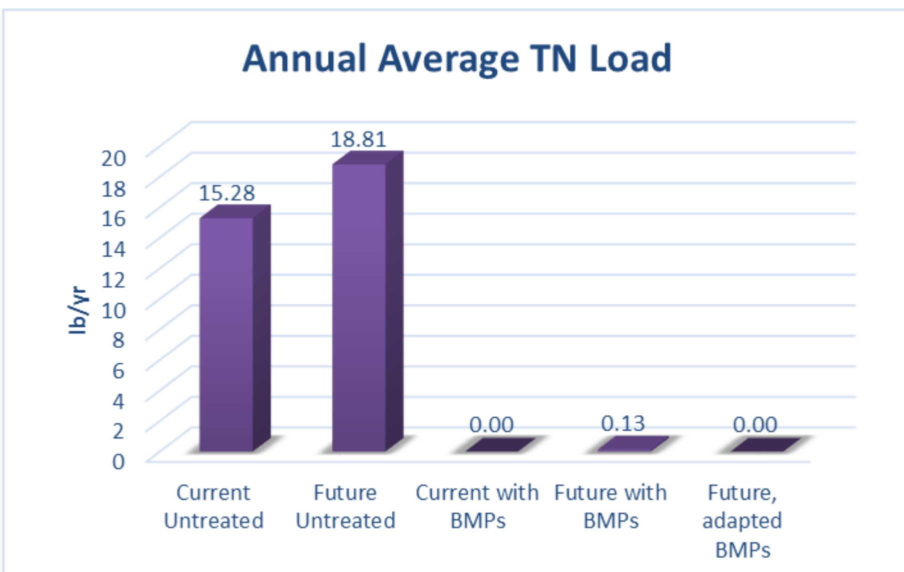


Figure B-98. Current and future performance for annual average total nitrogen (TN) load, Maricopa County, AZ Conventional (Gray) Infrastructure scenario.

Annual average TP load from the site also increases under the future climate by a large factor. Without resizing, the infiltration basin is still highly effective at reducing TP loading, with an annual average TP load of 0.005 pound/year. Increasing the footprint for future adaptation results in zero annual TP load.

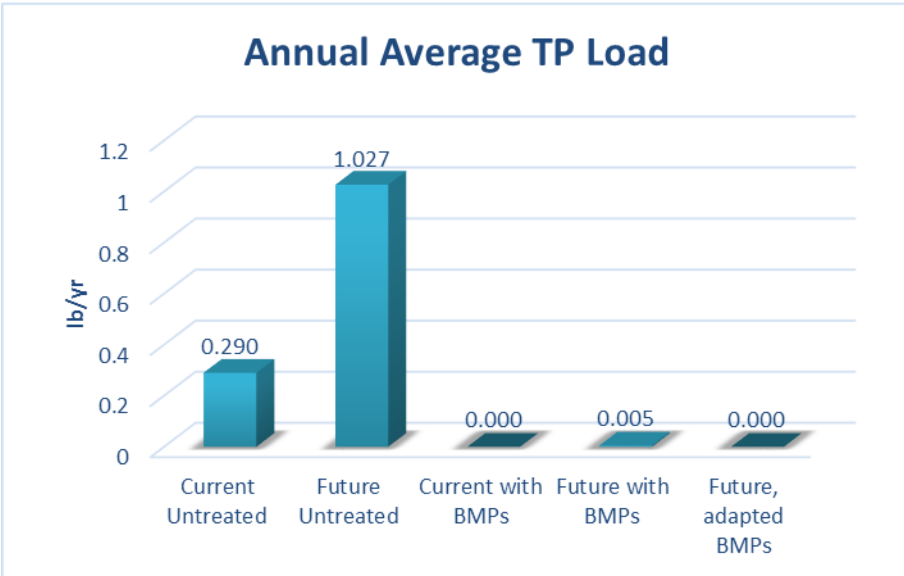


Figure B-99. Current and future performance for annual average total phosphorous (TP) load, Maricopa County, AZ Conventional (Gray) Infrastructure scenario.

A flow duration curve analysis was not performed for the Maricopa County Conventional (Gray) Infrastructure scenario. Because there is zero outflow under the "current with BMPs" scenario, a current climate flow duration curve could not be plotted. The objective of the adaptation simulation was, therefore, to increase the footprint of the infiltration basin until zero outflow was achieved.

Figure B-100 presents the maximum hourly peak flow results and demonstrates that hourly peak flow nearly doubles between the current and future untreated climate conditions. As discussed above, the infiltration basin completely eliminates outflow through infiltration and evapotranspiration under the current climate conditions. Without resizing, the basin is unable to main its current performance under future climate conditions, and hourly peak flow increases from zero to 6.7 cfs. Increasing the basin size reduces hourly peak flow to 0 cfs.

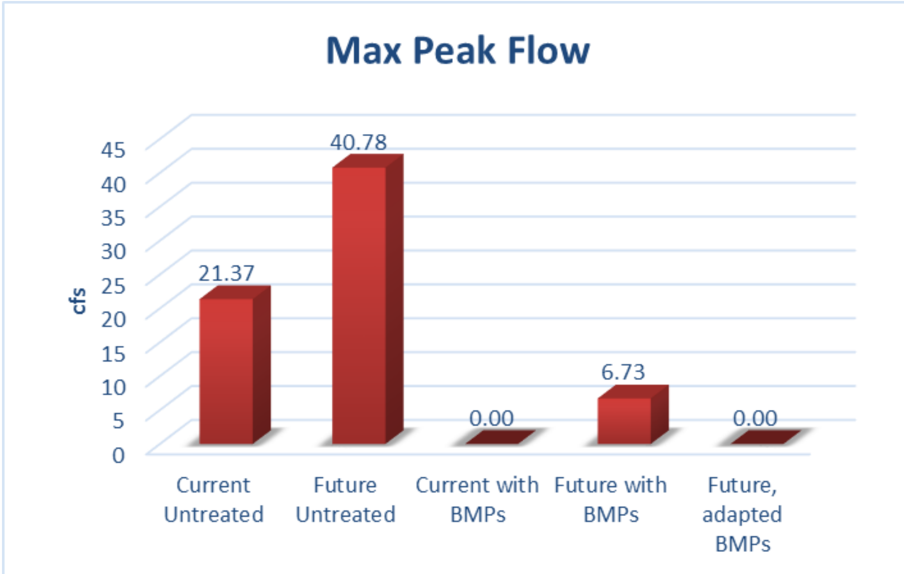


Figure B-100. Current and future performance for maximum hourly peak flow, Maricopa County, AZ Conventional (Gray) Infrastructure scenario.

Figure B-101 provides an alternate means of analyzing the infiltration basin's performance at managing runoff volume on a monthly basis. Under future climate, due to increased runoff volumes, the infiltration basin experiences outflow in the months of January, October, and November. The future adapted BMP size eliminates outflow in all months.

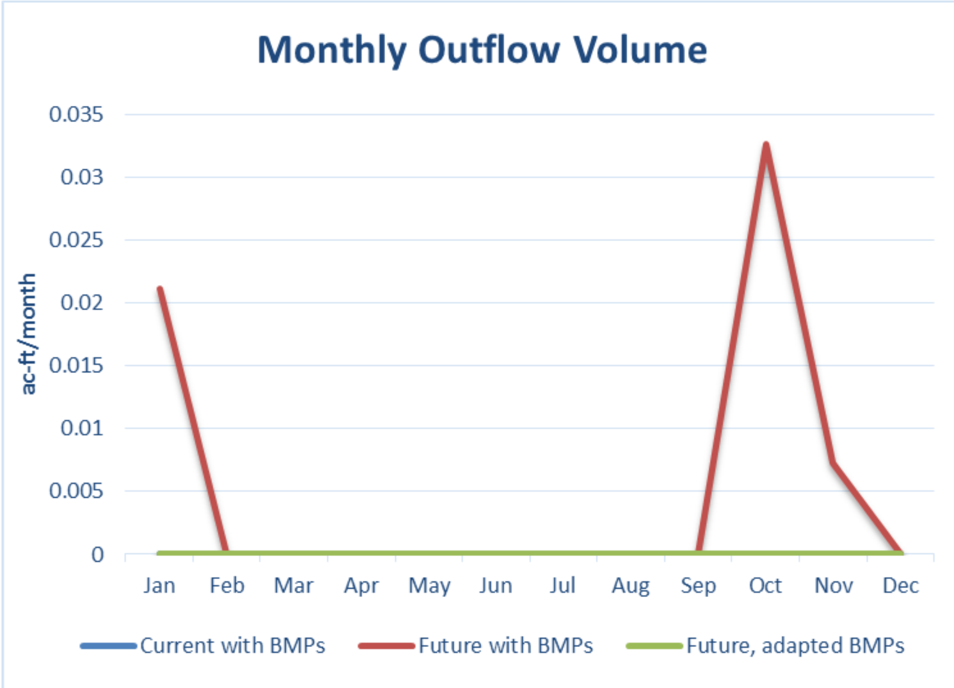


Figure B-101. Current and future performance for monthly outflow volume, Maricopa County, AZ Conventional (Gray) Infrastructure scenario.

Table B-15 summarizes the increase in infiltration basin footprint for the Maricopa County Conventional (Gray) Infrastructure scenario that would be required to maintain current performance under future climate conditions.

Table B-15. Comparison of current and future adapted best management practice (BMP) footprints, Maricopa County, AZ Conventional (Gray) Infrastructure scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure	Infiltration basin	49,997	11.5	71,776	16.5	44

B.1.3.2. Green Infrastructure (GI) Only

In current climate conditions, the combination of green practices (bioretention, cistern, permeable pavement, and stormwater infiltration basin) in the Maricopa County GI Only scenario achieves near-zero outflow. Outflow comprises a small fraction of the overall runoff volume fate. The fraction of outflow increases slightly under future climate without practice resizing. With the future adapted BMP footprints, the surface area available for infiltration and ET increases, enabling the site to achieve a slightly lower outflow volume than in the “current with BMPs” scenario. In the “future, adapted BMPs” scenario, the fraction of ET is greater than 28%, compared to 20% in the “current with BMPs” scenario.

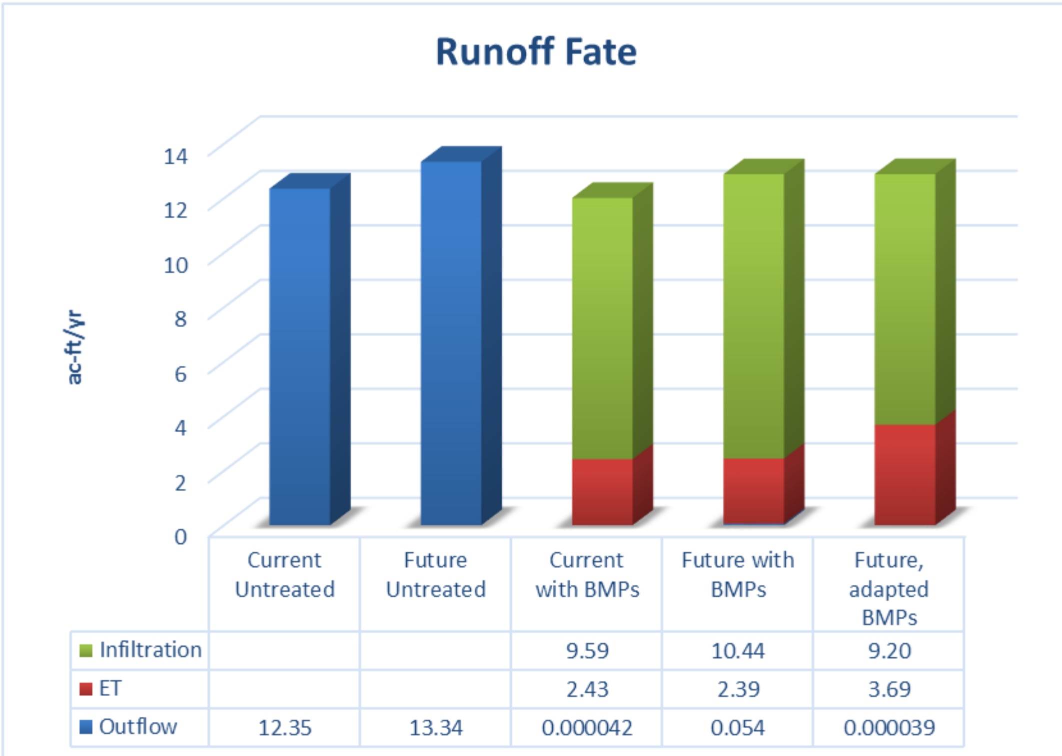


Figure B-102. Current and future partitioning of runoff fate for the Maricopa County, AZ Green Infrastructure (GI) Only scenario.

The practices in the GI Only scenario combine to achieve a very high reduction for annual average sediment load. Under future climate conditions, the green practices reduce sediment load by greater than 99%. Their effectiveness is reduced to approximately 97% under future climate without resizing. Increasing the practice footprints reduces the annual average sediment load to 0.3 pound/year, which is below the current load.

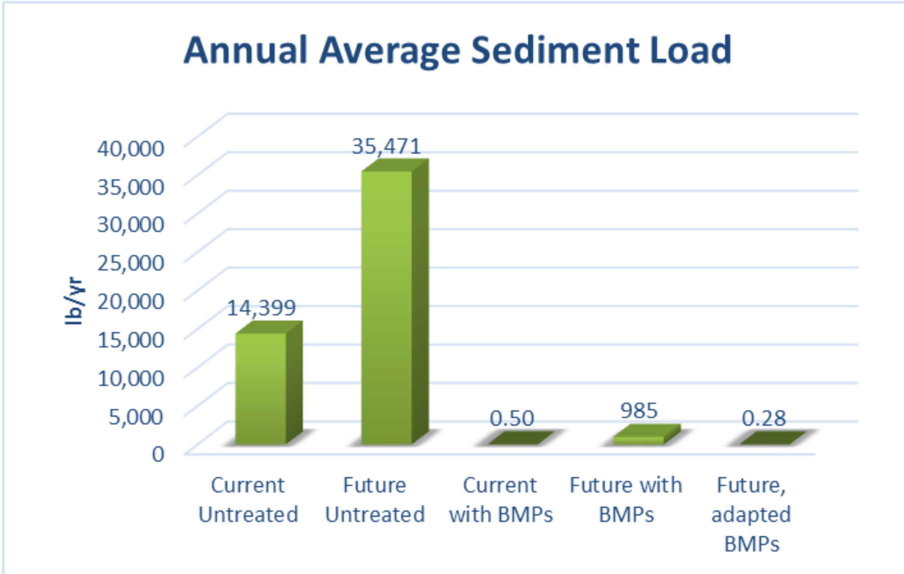


Figure B-103. Current and future performance for annual average sediment load, Maricopa County, AZ Green Infrastructure (GI) Only scenario.

A slight increase in annual average TN load is observed when the current BMPs are not resized under future climate. Increasing the practice footprints for future climate adaptation achieves a minimal annual TN load that is equivalent to the "current with BMPs" scenario.

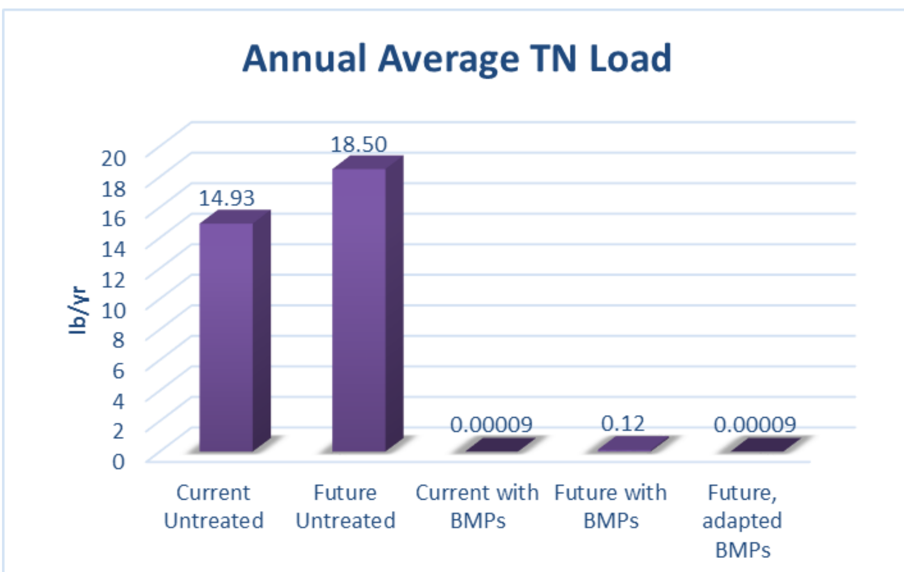


Figure B-104. Current and future performance for annual average total nitrogen (TN) load, Maricopa County, AZ Green Infrastructure (GI) Only scenario.

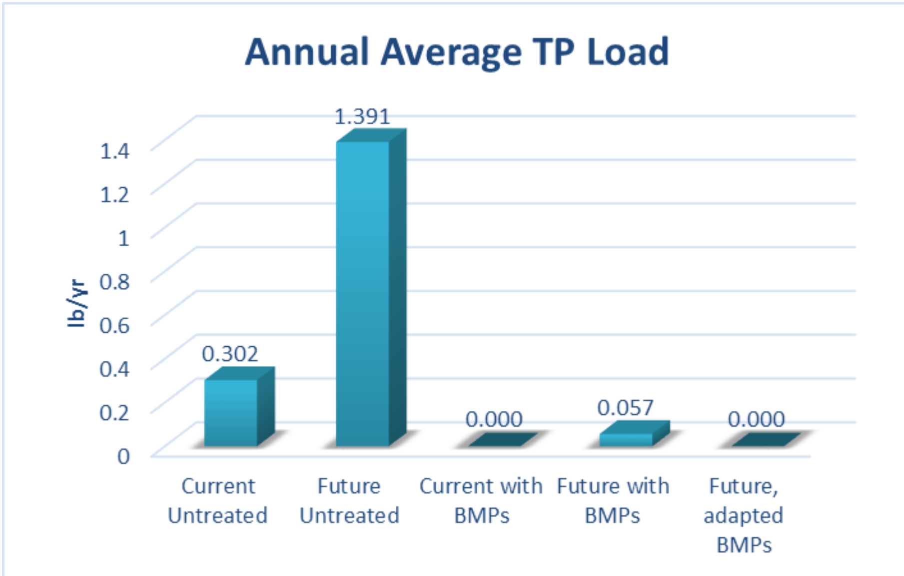


Figure B-105. Current and future performance for annual average total phosphorous (TP) load, Maricopa County, AZ Green Infrastructure (GI) Only scenario.

An FDC analysis was not performed for the Maricopa County GI Only scenario due to both the "current with BMPs" and "future with BMPs" scenarios producing minimal outflow. As an alternate means of comparing flow-based performance, the maximum hourly peak flow for all climate scenarios is shown below. The future adapted BMP sizes are effective at mitigating the increase in hourly peak flow under future climate and reducing it below the "current with BMPs" value.

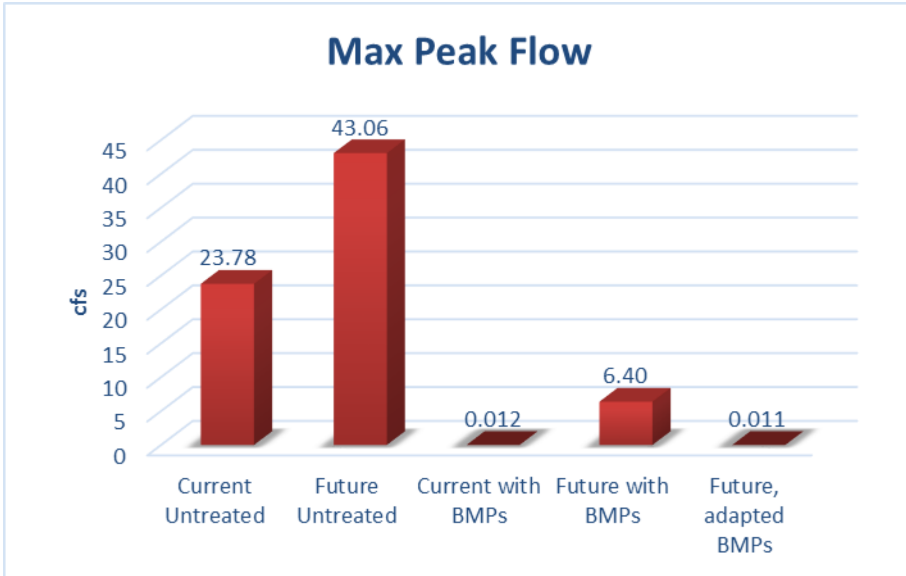


Figure B-106. Current and future performance for maximum hourly peak flow, Maricopa County, AZ Green Infrastructure (GI) Only scenario.

Under future climate, due to increased runoff volumes, the green practices in the GI Only scenario experience outflow in the months of January, October, and November. The future adapted BMP sizes achieve effectively zero monthly outflow volume in all months.

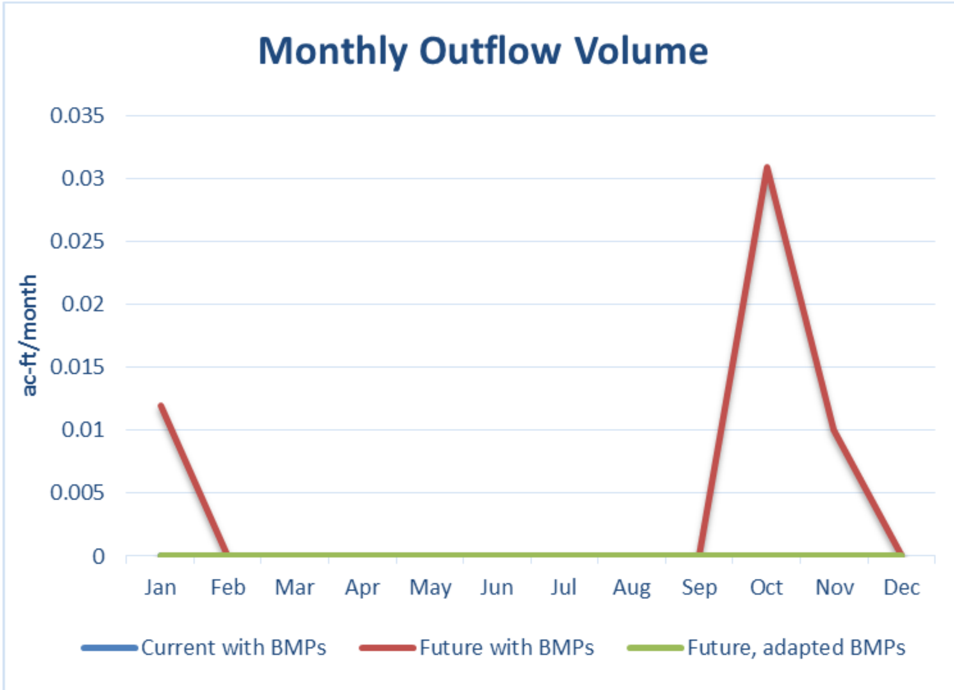


Figure B-107. Current and future performance for monthly outflow volume, Maricopa County, AZ Green Infrastructure (GI) Only scenario.

Table B-16 summarizes the increases in BMP footprints for the Maricopa County GI Only scenario that would be required to maintain current performance under future climate conditions.

Table B-16. Comparison of current and future adapted best management practice (BMP) footprints, Maricopa County, AZ Green Infrastructure (GI) Only scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI Only	Permeable pavement	86,382	19.8	124,482	28.6	44
	Bioretention	13,405	3.1	24,125	5.5	80
	Cistern	2,495	0.6	3,564	0.8	43
	Stormwater harvesting basin	32,034	7.4	53,034	12.2	66

B.1.3.3. Cost Estimation

Table B-17 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for both Maricopa County stormwater management scenarios. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site.

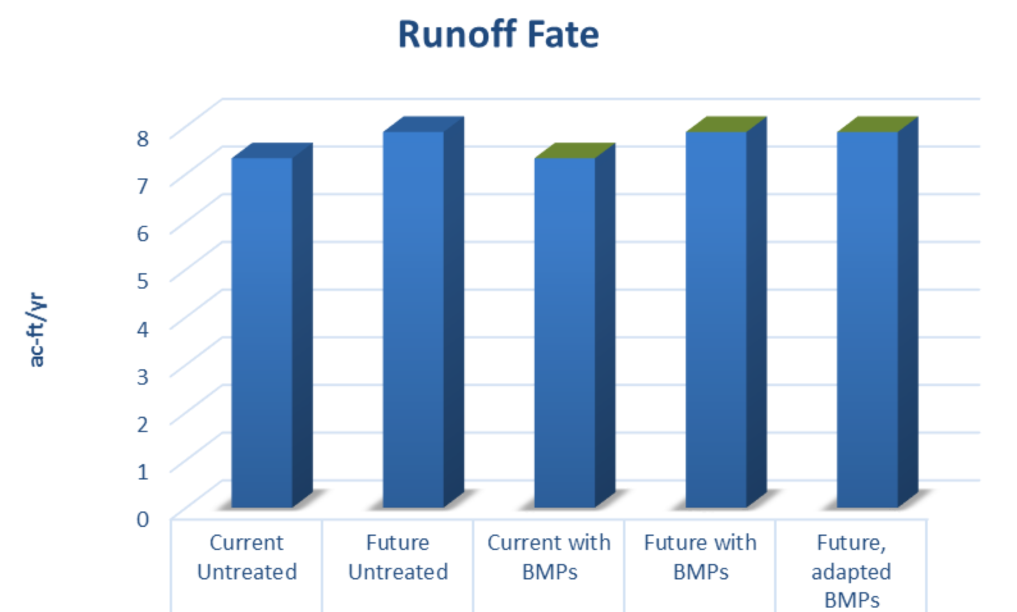
Table B-17. Comparison of the current and future estimated 20-year present value costs for the Maricopa County, AZ stormwater management scenarios

Location	Stormwater management scenario	Current cost 20-yr present value, $millions	Future adapted cost (20-yr present value, $millions)	Increase in cost 20-yr present value, $millions	% increase in cost	Increase per acre of site $millions
Maricopa County, AZ	Conventional (Gray) Infrastructure	4.79	6.83	2.04	43	0.20
	GI Only	3.98	6.33	2.35	59	0.23

B.1.4. Atlanta, GA

B.1.4.1. Conventional (Gray) Infrastructure

The precipitation analysis for Atlanta, GA (see *Section 4.2.* of the report) demonstrated an across the board increase in annual precipitation depth across all 30 years of the simulation period when compared with the current climate. Precipitation intensity is also predicted to increase, with the greatest increase occurring among the largest events. The result is an overall increase in runoff volume, which can be seen in Figure B-108.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			0.00	0.00	0.00
ET			0.00	0.00	0.00
Outflow	7.33	7.88	7.33	7.88	7.88

Figure B-108. Current and future partitioning of runoff fate for the Atlanta, GA Conventional (Gray) Infrastructure scenario.

The practices in the Atlanta Conventional (Gray) Infrastructure scenario are unique in that they are both underground. As a result, there is no opportunity for ET, and the practices are not designed to be infiltrating. The underground sand filter provides water quality treatment through filtration, and the underground detention basin addresses peak flow and flooding requirements. Runoff is discharged after temporary storage and treatment. By nature of these practices, the runoff fate pathways do not change significantly between the current and future climate scenarios (i.e., increasing their footprint will not increase the proportioning of runoff fate into pathways other than outflow).

Although the Atlanta study site is ultra-urban with 90% impervious, there is still an opportunity for greater sediment loading due to wash-off from increased precipitation depth and intensity. Under current climate conditions, the conventional practices achieve a combined sediment load reduction of 82%. This is reduced slightly to 79% under future climate. With resizing, the combination of the sand filter and detention basin achieve a sediment load reduction of 85%.

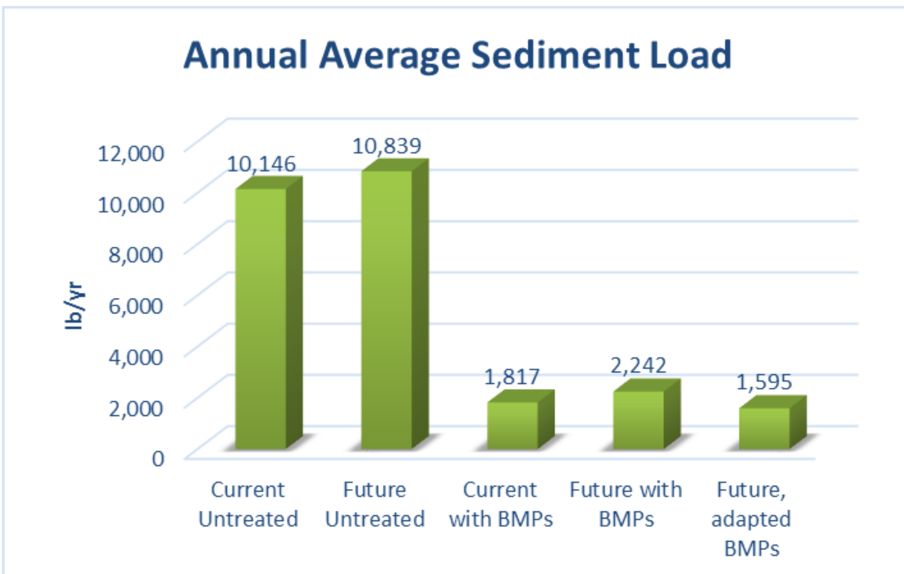


Figure B-109. Current and future performance for annual average sediment load, Atlanta, GA Conventional (Gray) Infrastructure scenario.

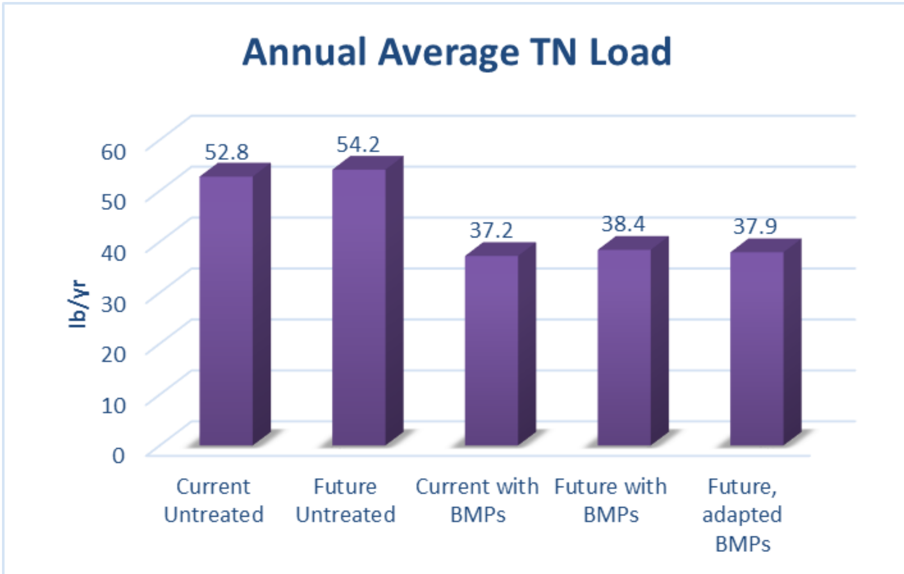


Figure B-110. Current and future performance for annual average total nitrogen (TN) load, Atlanta, GA Conventional (Gray) Infrastructure scenario.

With their current sizing, the conventional practices are unable to meet the current annual average TP load of 2.11 pound/year. With future adaptation, the increased BMP footprints are able to reduce the TP load to 2.10 pound/year, which is slightly below the current load of 2.11 pound/year.

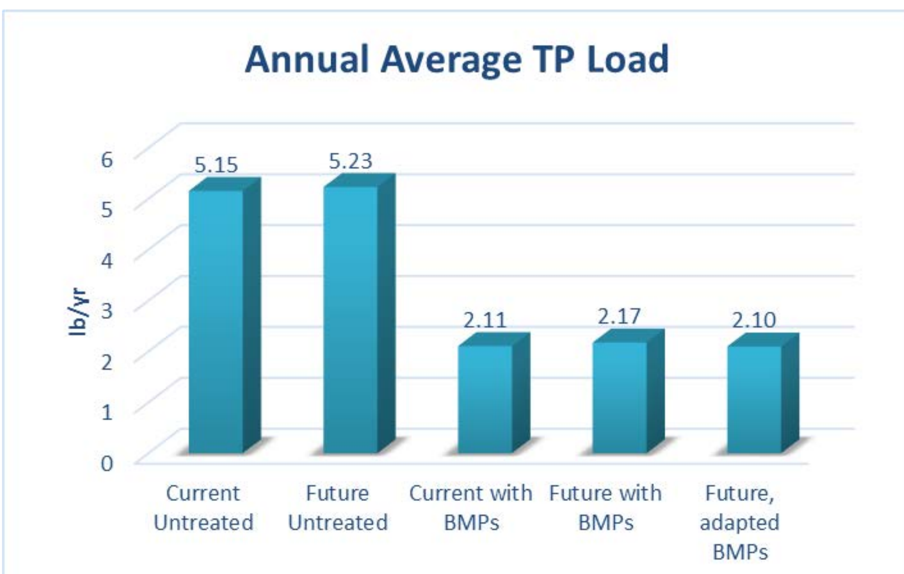


Figure B-111. Current and future performance for annual average total phosphorous (TP) load, Atlanta, GA Conventional (Gray) Infrastructure scenario.

Figure B-112 presents the flow duration curves for the current, future, and future adapted BMP scenarios and demonstrates that the increased BMP footprints adapted for future climate achieve a very similar flow duration response to the current climate BMP configurations in the evaluated range of flows.

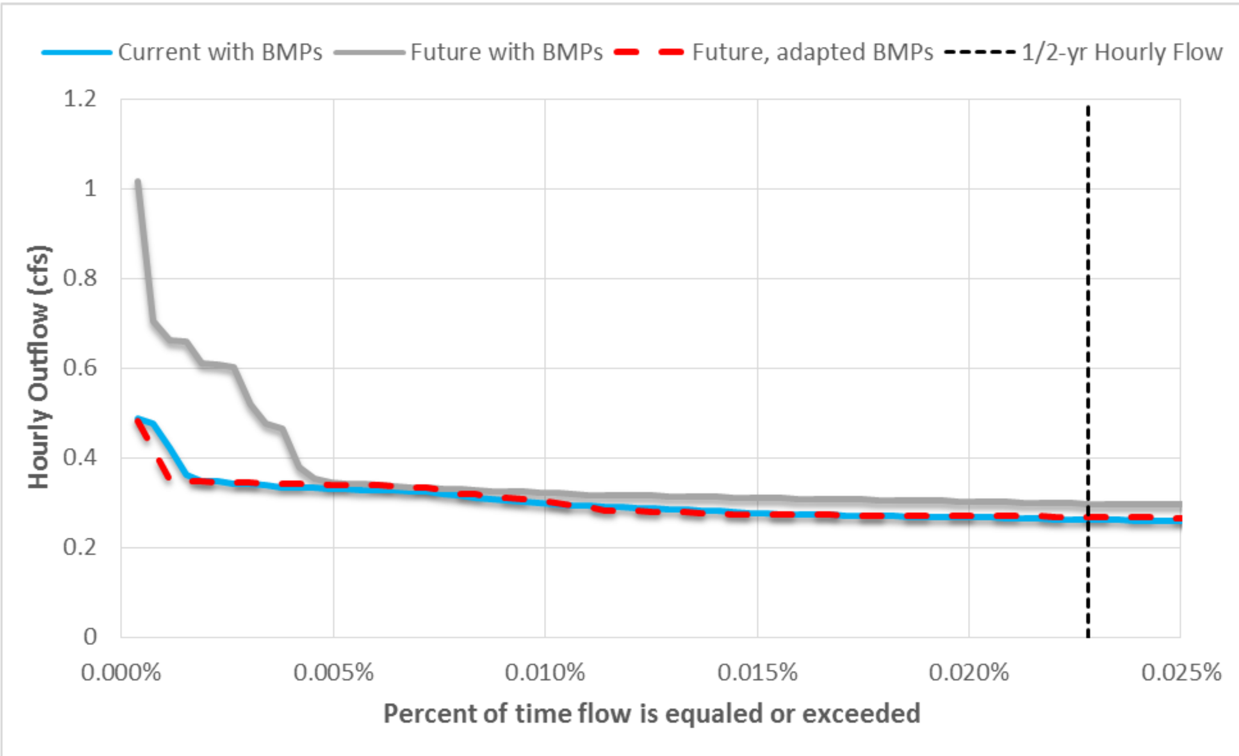


Figure B-112. Flow duration curve (FDC) evaluation for current and future climate, Atlanta, GA Conventional (Gray) Infrastructure scenario.

Peak flow management in the Conventional (Gray) Infrastructure scenario for Atlanta is primarily provided by the underground detention basin, which is designed to be effective at peak flow reduction. The increase in hourly peak flow between the “current with BMPs” and “future with BMPs” scenarios indicates that with the current practice sizing, the current hourly peak flow of 0.49 cfs cannot be maintained. Increasing the BMP footprints for future adaptation reduces the hourly peak flow to 0.48 cfs.

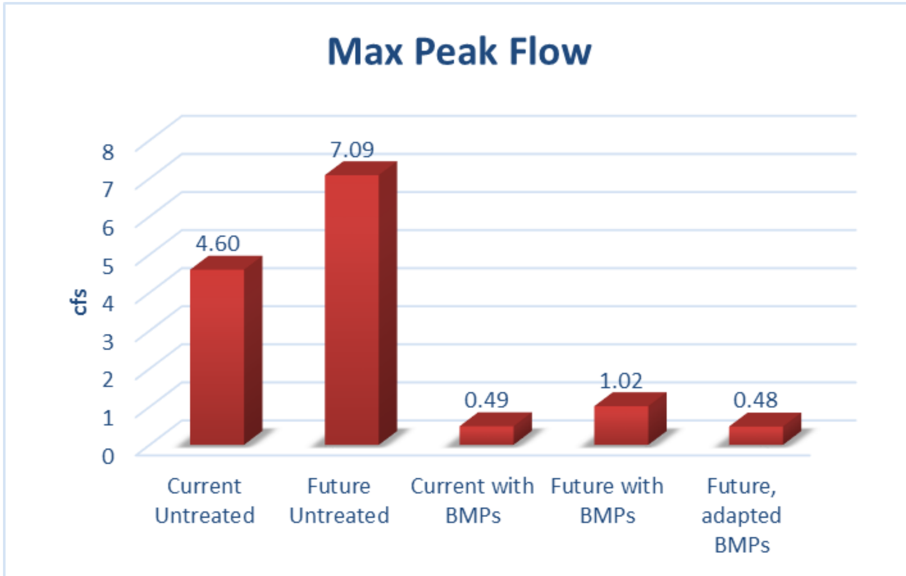


Figure B-113. Current and future performance for maximum hourly peak flow, Atlanta, GA Conventional (Gray) Infrastructure scenario.

As discussed above, the underground practices (sand filter, detention basin) comprising the Conventional (Gray) Infrastructure scenario are not infiltrating; they provide runoff treatment and temporary storage to address flooding control requirements prior to discharging. Therefore, the monthly outflow comparison plot illustrates that there is virtually no difference in monthly outflow volume between the “future, with BMPs” and “future, adapted BMPs” site conditions. Adaptation via resizing does not achieve additional volume control for these conventional practices.

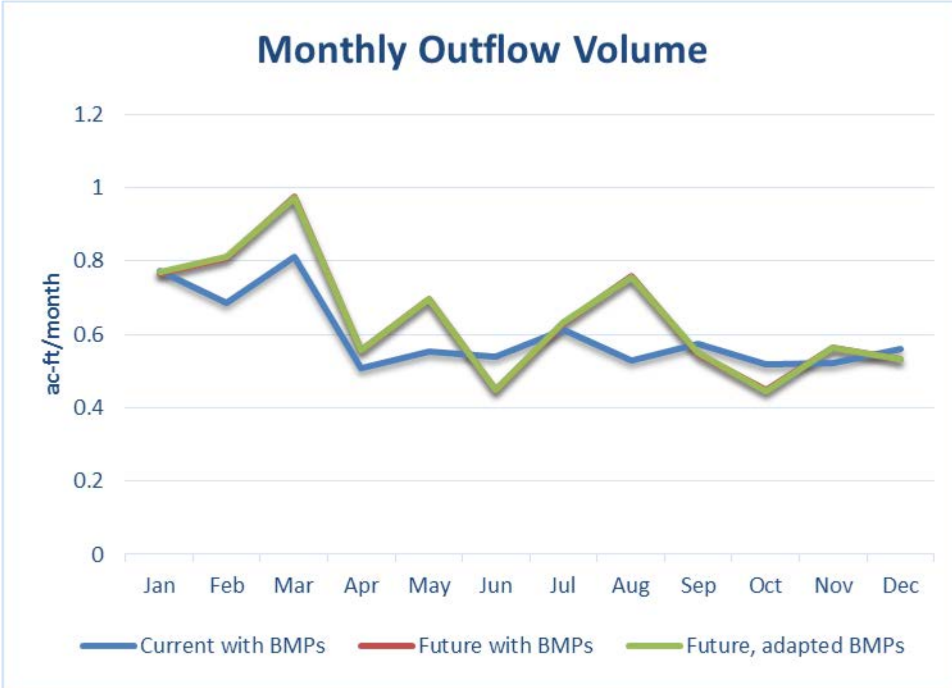


Figure B-114. Current and future performance for monthly outflow volume, Atlanta, GA Conventional (Gray) Infrastructure scenario.

Table B-18 summarizes the increases in BMP footprints for the Atlanta Conventional (Gray) Infrastructure with practices adapted for future conditions in order to maintain current performance (with the exception of TN and runoff volume) under future climate conditions.

Table B-18. Comparison of current and future adapted best management practice (BMP) footprints, Atlanta, GA Conventional (Gray) Infrastructure scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Conventional (Gray) Infrastructure	Underground sand filter	2,500	2.9	4,600	5.3	84
	Underground dry detention basin	5,000	5.7	6,200	7.1	24

B.1.4.2. Green Infrastructure (GI) with Gray Infrastructure

The partitioning of runoff volume fate in the Atlanta GI with Gray Infrastructure scenario is markedly different from the Conventional (Gray) Infrastructure scenario due to the addition of green practices (bioretention, green roof, permeable pavement) that facilitate ET and infiltration of runoff and combine with the gray practice (underground detention) to provide peak flow and flooding management. In the “current with BMPs” condition, 44% of runoff is infiltrated, 21% of is converted to ET, and the remaining fraction (34%) is discharged as outflow. In the “future with BMPs” site condition, the partitioning is similar: 43, 21, and 36%, respectively. The increased BMP footprints in the future adapted scenario slightly increase the partitioning into infiltration and ET due to increased surface area; 45% of runoff is infiltrated, 24% is evapotranspired, and 31% is discharged as outflow.

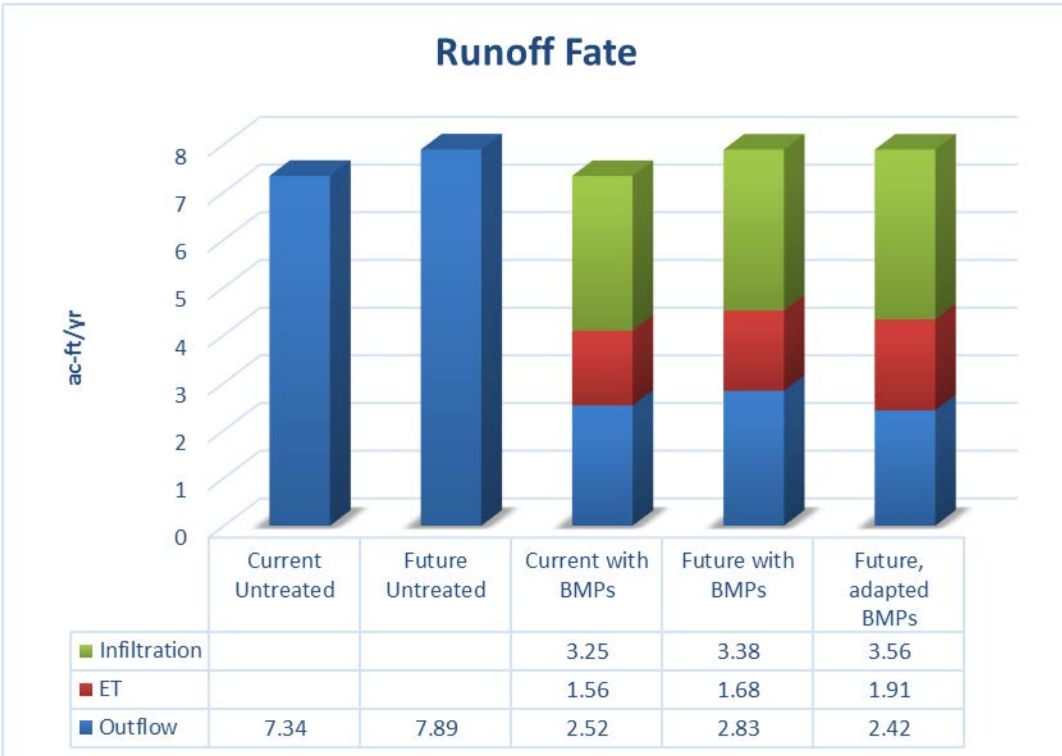


Figure B-115. Current and future partitioning of runoff fate for the Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario.

Figure B-116 presents a comparison of the annual average sediment load from the GI with Gray Infrastructure site scenario under the five simulated climate conditions and demonstrates that, with adaptation, the combination of BMPs is able to reduce the future sediment load below the current climate sediment load.

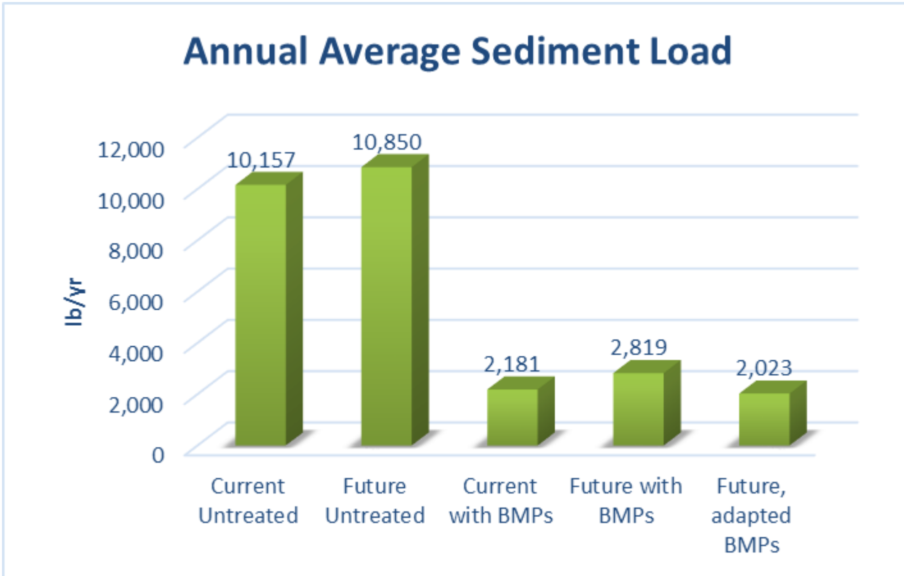


Figure B-116. Current and future performance for annual average sediment load, Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario.

Figure B-117 and Figure B-118 present the simulated performance for TN and TP load reduction. These results indicate that the combination of practices in the GI with Gray Infrastructure scenario can successfully maintain their current performance when their footprints are increased for future adaptation. The TN load reductions in the “current with BMPs,” “future with BMPs,” and “future, adapted BMPs” scenarios are 73, 70, and 76%, respectively. The TP load reductions are 76, 73, and 79%, respectively.

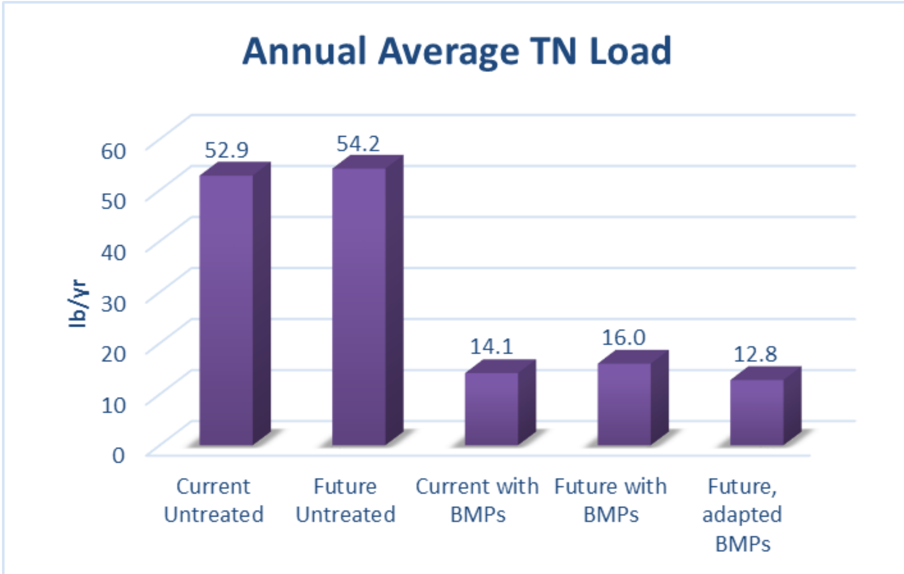


Figure B-117. Current and future performance for annual average total nitrogen (TN) load, Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario.

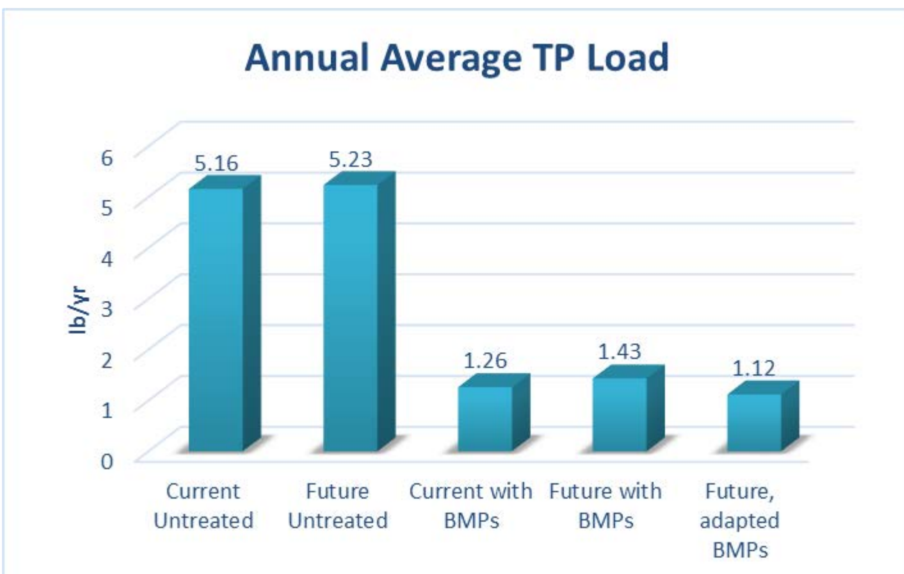


Figure B-118. Current and future performance for annual average total phosphorous (TP) load, Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario.

Figure B-119 indicates that when resized for future climate adaptation, the Green and Gray practices achieve a flow duration response that is very similar to the current climate response.

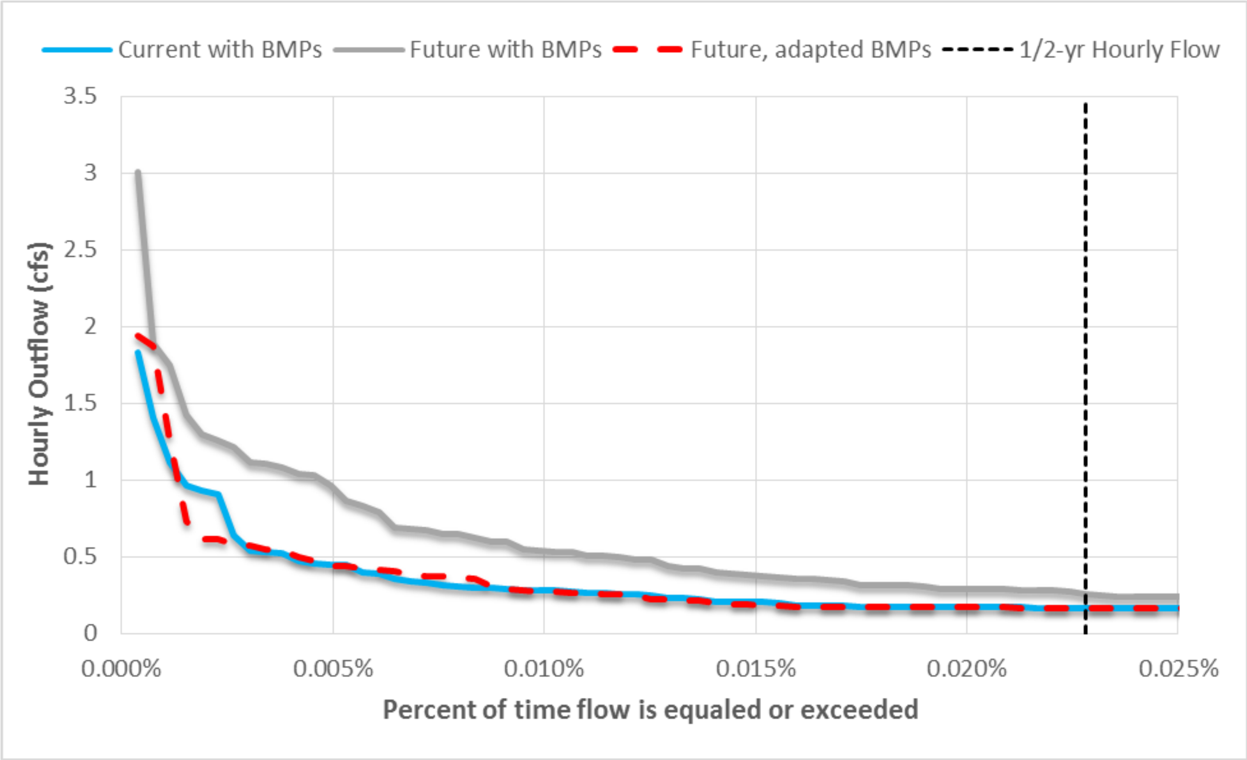


Figure B-119. Flow duration curve (FDC) evaluation for current and future climate, Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario.

Under current climate conditions, the combination of Green and Gray practices reduces the maximum hourly peak flow from 4.6 to 1.8 cfs. In the future, without resizing, the practices are still effective at decreasing peak flow. However, increasing their footprints in the "future, adapted BMPs" scenario results in a future hourly peak flow (1.9 cfs) that is only slightly higher than the "current with BMPs" hourly peak flow.

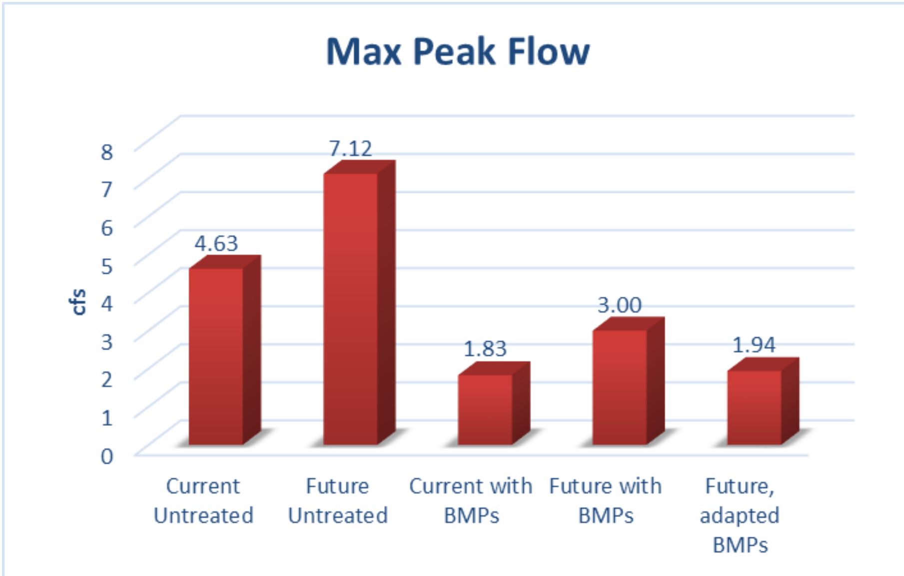


Figure B-120. Current and future performance for maximum hourly peak flow, Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario.

The monthly outflow volume comparison plot indicates variable performance of the adapted BMPs in maintaining the current climate outflow volumes on a monthly basis. Although the “future, adapted BMPs” outflows are lower than the “future with BMPs” outflows in every month, the adapted BMP outflows are higher than the “current with BMPs” outflows in some months and lower in others. However, as the runoff fate plot demonstrated, the adapted practices achieve a lower annual outflow volume overall compared to the current practices.

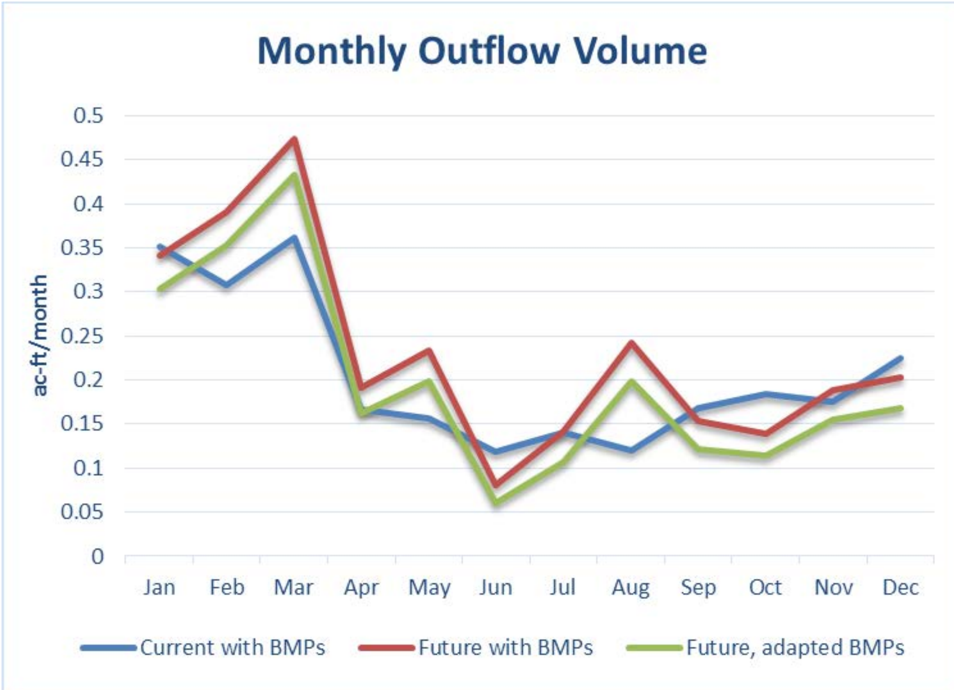


Figure B-121. Current and future performance for monthly outflow volume, Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario.

Table B-19 summarizes the increases in BMP footprints for the Atlanta Conventional (Gray) Infrastructure with scenario that would be required to maintain current performance under future climate conditions.

Table B-19. Comparison of current and future adapted best management practice (BMP) footprints, Atlanta, GA Green Infrastructure (GI) with Gray Infrastructure scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI with Gray Infrastructure	Bioretention with underdrain	2,810	3.2	3,934	4.5	40
	Underground dry detention basin	2,500	2.9	3,300	3.8	32
	Green roof	30,492	35.0	35,184	40.4	15
	Permeable pavement	26,136	30.0	26,136	30.0	0

B.1.4.3. Cost Estimation

Table B-20 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for both Atlanta stormwater management scenarios. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site.

Table B-20. Comparison of the current and future estimated 20-year present value costs for the Atlanta, GA stormwater management scenarios

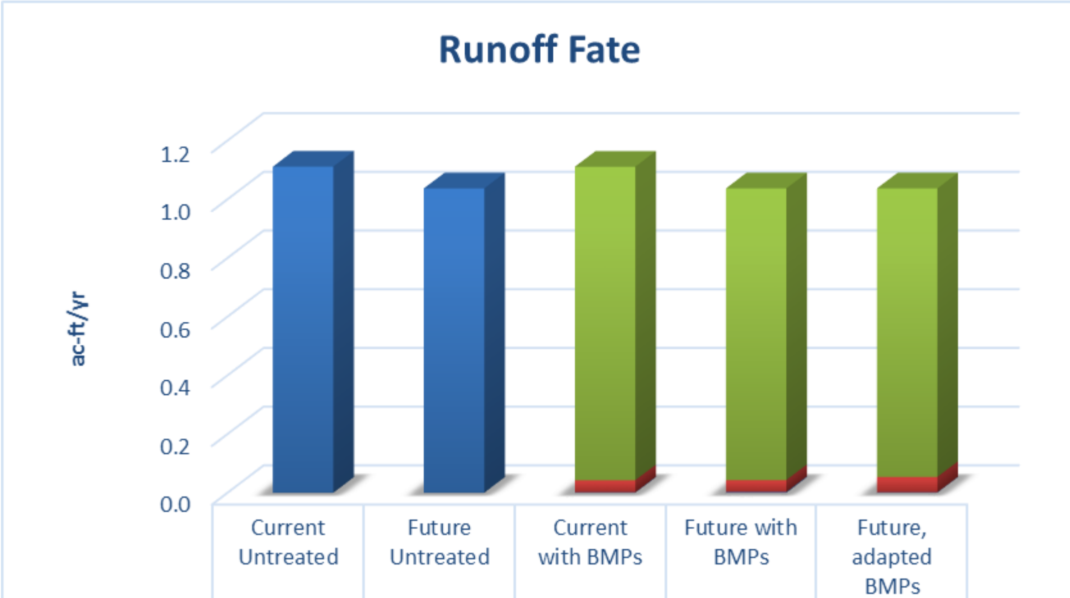
Location	Stormwater management scenario	Current cost 20-yr present value, $millions	Future adapted cost (20-yr present value, $millions)	Increase in cost 20-yr present value, $millions	% increase in cost	Increase per acre of site $millions
Atlanta, GA	Conventional (Gray) Infrastructure	1.38	2.27	0.89	64	0.09
	GI with Gray Infrastructure	2.31	2.60	0.29	13	0.03

B.1.5. Portland, OR

B.1.5.1. Green Infrastructure (GI) Only

As discussed in the precipitation analysis (see *Section 4.2.* of the report), Portland is unique in that the future climate simulation predicts an overall decrease in annual rainfall depth. On a monthly basis, average precipitation is predicted to decrease in all months except January, May, and December. In terms of intensity, the smallest, most frequent storms are predicted to increase in intensity. The intensity during the largest events remains approximately the same in the future climate as in the current climate. Between the smallest, most frequent and largest, least frequent events, the future rainfall intensity is sometimes higher than the current climate and sometimes lower.

Figure B-122 illustrates the overall decrease in total runoff volume between the current and future climate conditions as a result of the overall decrease in annual precipitation. The small size of the Portland GI Only site (0.35 acre) results in a very small runoff volume overall (1.1 acre-feet/year in “current untreated”) compared to the other investigation sites. The green practices (bioretention swales, permeable pavement) that comprise the Portland GI Only site are highly infiltrating. Almost all of the runoff is infiltrated, with a small fraction (less than 4% in “current with BMPs”) converted to ET and an even smaller fraction converted to outflow. Although it cannot be seen in the chart because outflow accounts for such a small fraction of the runoff balance, the outflow volume actually increases between the “current with BMPs” scenario to the “future with BMPs” from 0.0015 acre-feet/year to 0.0026 acre-feet/year. This increase in outflow volume is due to the increase in precipitation intensity for large storm events, resulting in a greater fraction of the runoff being discharged rather than infiltrated. With the adapted BMP footprints, the fraction of ET is increased due to the larger practice surface areas, resulting in a lower fraction of outflow.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			1.07	0.99	0.98
ET			0.041	0.040	0.052
Outflow	1.11	1.04	0.0015	0.0026	0.0015

Figure B-122. Current and future partitioning of runoff fate for the Portland, OR Green Infrastructure (GI) Only scenario.

Due to the slight increase in outflow in future climate, there is a small increase in annual average sediment load between the "current with BMPs" and "future with BMPs" scenarios. Increasing the practice footprints reduces the future adapted load (0.62 pound/year) below the current load (0.96 pound/year).

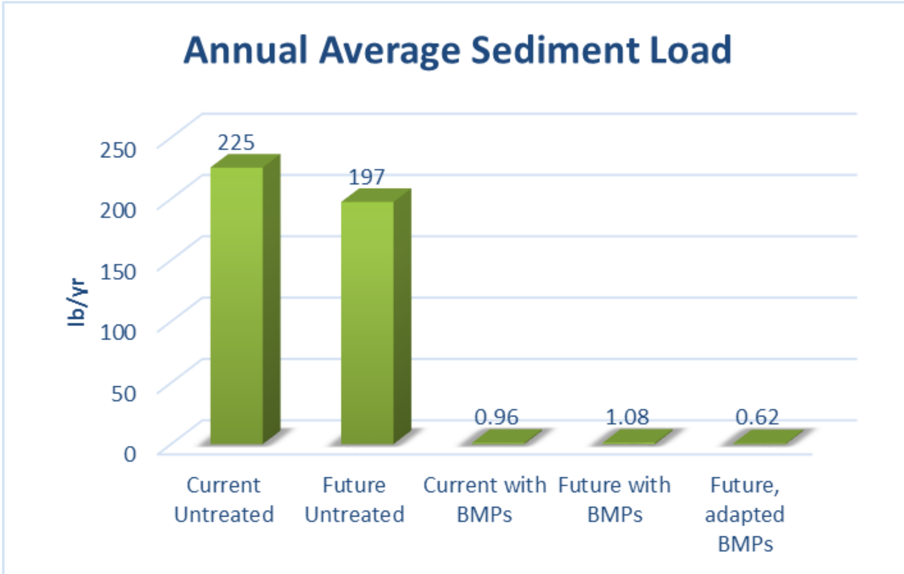


Figure B-123. Current and future performance for annual average sediment load, Portland, OR Green Infrastructure (GI) Only scenario.

The green practices in the Portland GI Only scenario combine to achieve very high load reductions for TN and TP on an annual basis. In all three scenarios with BMPs, the TN and TP loads are reduced by 99% or greater. The future adapted practice sizes result in lower TN and TP loads in the future compared to the current climate with BMPs.

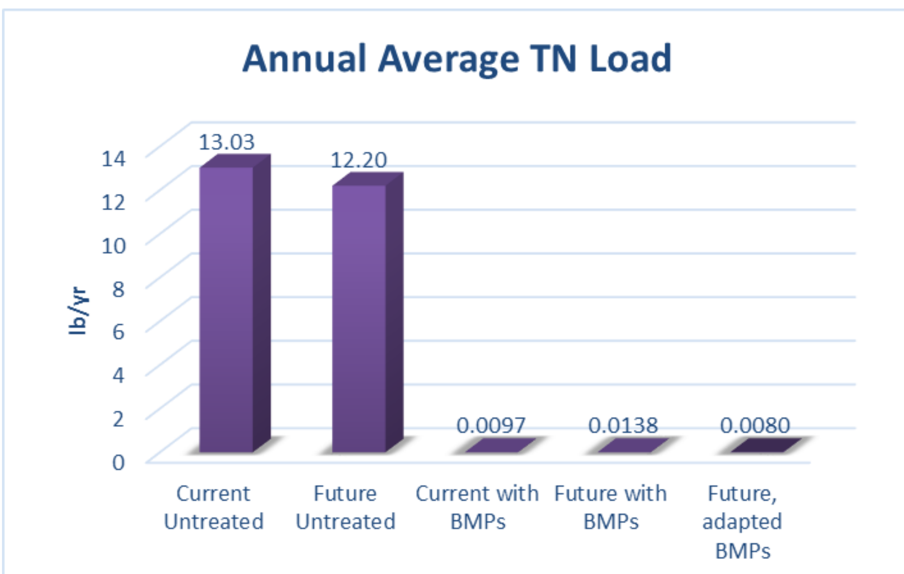


Figure B-124. Current and future performance for annual average total nitrogen (TN) load, Portland, OR Green Infrastructure (GI) Only scenario.

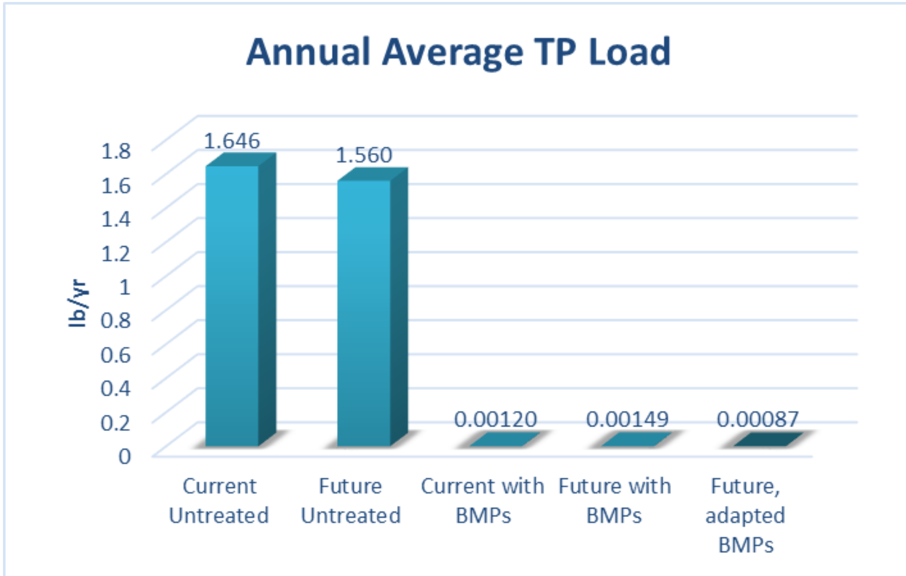


Figure B-125. Current and future performance for annual average total phosphorous (TP) load, Portland, OR Green Infrastructure (GI) Only scenario.

The flow duration curve analysis for the Portland GI Only site demonstrates that the future adapted practices achieve an hourly outflow response that is reasonably similar to performance under current climate conditions within the evaluated range of outflows.

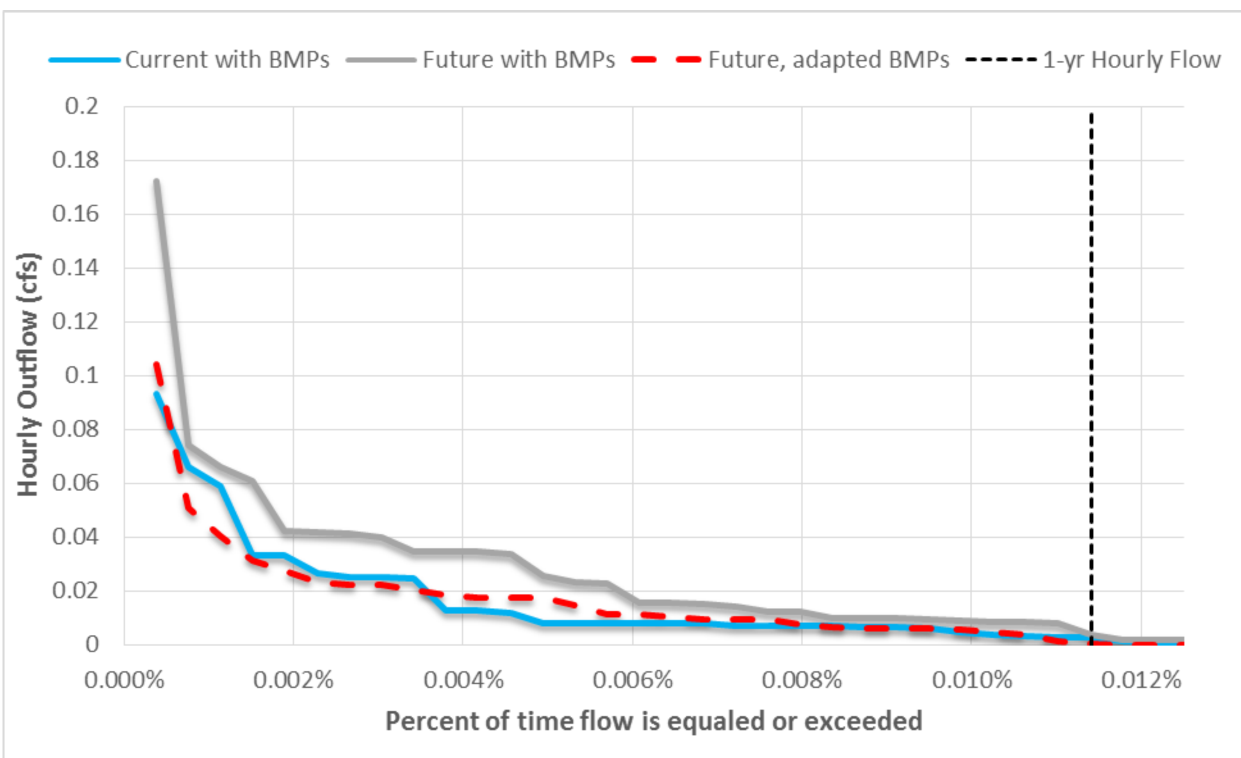


Figure B-126. Flow duration curve (FDC) evaluation for current and future climate, Portland, OR Green Infrastructure (GI) Only scenario.

Although the overall runoff volume is predicted to decrease under future climate conditions for Portland, the increase in the intensity of precipitation during select storms results in higher peak flows in the future compared to the current climate. With their current sizing, the practices in the GI Only scenario are unable to maintain the current peak flow; in the future, without resizing, the hourly peak flow nearly doubles. Recall that maximum hourly peak flow was not a target of the adaptation simulation; however, Figure B-127 demonstrates that the increased BMP footprints in the "future, adapted BMPs" scenario combine to reduce the hourly peak flow almost to the "current with BMPs" value.

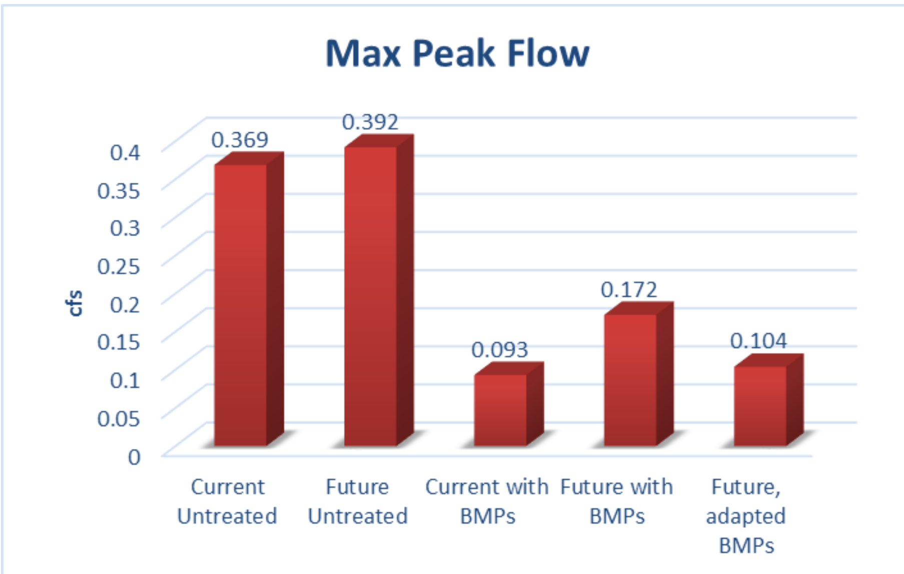


Figure B-127. Current and future performance for maximum hourly peak flow, Portland, OR Green Infrastructure (GI) Only scenario.

The monthly outflow volume comparison plot shown in Figure B-128 indicates a change in monthly outflow between the current and future climate conditions, with outflow shifting to later in the winter. The adapted future scenario tracks below the future scenario during all months with outflow.

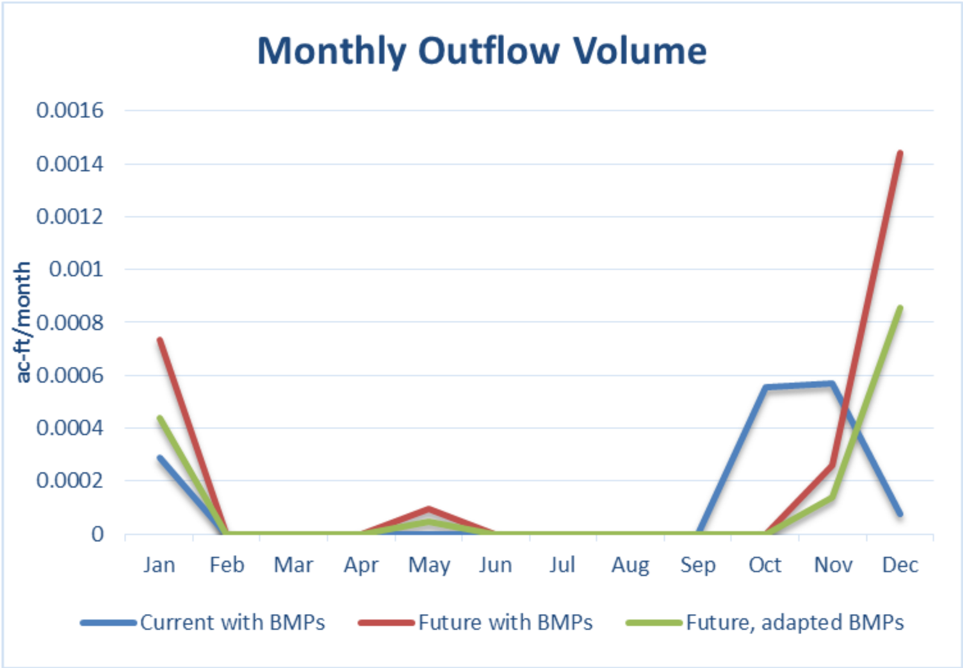


Figure B-128. Current and future performance for monthly outflow volume, Portland, OR Green Infrastructure (GI) Only scenario.

Table B-21 summarizes the increases in BMP footprints for the Portland GI Only scenario that would be required to maintain current performance under future climate conditions. Permeable pavement was not resized as part of the adaptation. The bioretention swales provide almost all of the water quantity and quality treatment for the site due to their large storage volumes and high infiltration capacity.

Table B-21. Comparison of current and future adapted best management practice (BMP) footprints, Portland, OR Green Infrastructure (GI) Only scenario

Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
		Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
GI Only	Bioretention swale	1,239	8.0	1,681	10.9	36
	Permeable pavement	345	2.2	345	2.2	0

B.1.5.2. Cost Estimation

Table B-22 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for the Portland GI Only scenario. Also provided are the increase in cost, both in dollars and percentage, and the increase in cost per acre of site.

Table B-22. Comparison of the current and future estimated 20-year present value costs for the Portland, OR Green Infrastructure (GI) Only stormwater management scenario

Location	Stormwater management scenario	Current cost 20-yr present value, $millions	Future adapted cost (20-yr present value, $millions)	Increase in cost 20-yr present value, $millions	% increase in cost	Increase per acre of site $millions
Portland, OR	GI Only	0.20	0.27	0.07	35	0.20

B.2. SENSITIVITY ANALYSIS

B.2.1. Harford County, MD

B.2.1.1. Conventional (Gray) Infrastructure

Intensity Change Minus 10%

As discussed in *Section 4.3.* of the report, the sensitivity analysis entailed modifying the current precipitation record to represent potential future climate conditions by applying a graduated set of percentage changes across the entire precipitation record. For this particular sensitivity scenario, the resulting change in annual runoff volume and pollutant load was a decrease under the future climate compared to the current climate, as illustrated in the figures below. For these reasons, this climate scenario was not investigated for adaptation simulation.

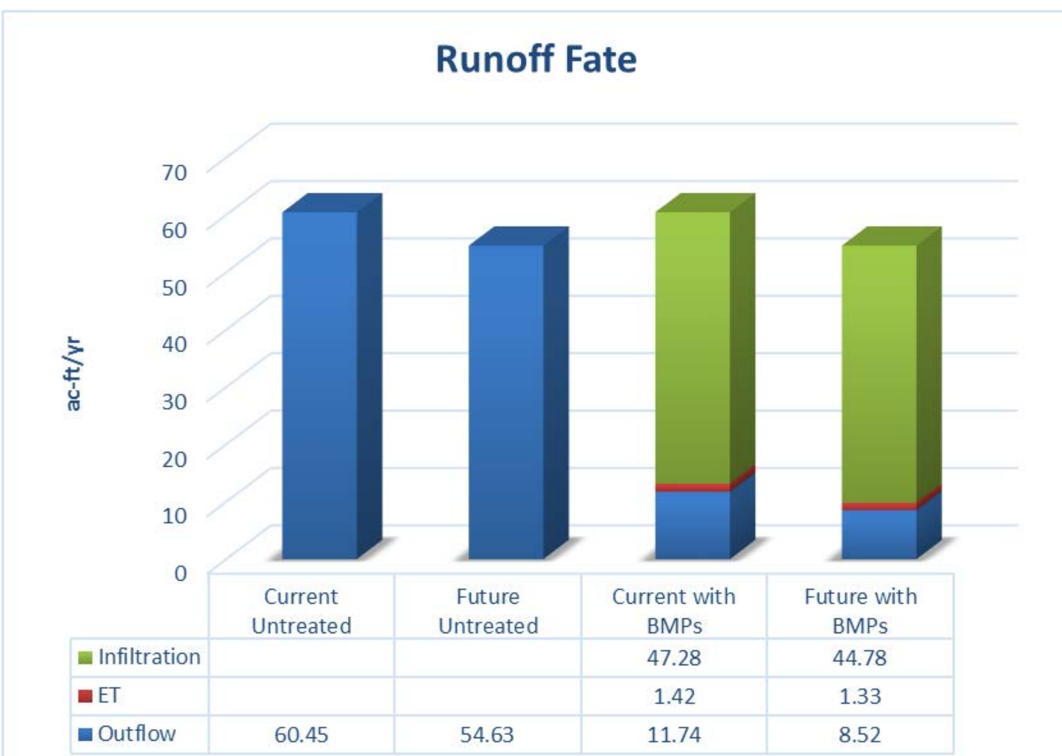


Figure B-129. Current and future partitioning of runoff fate for the Harford County, MD Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

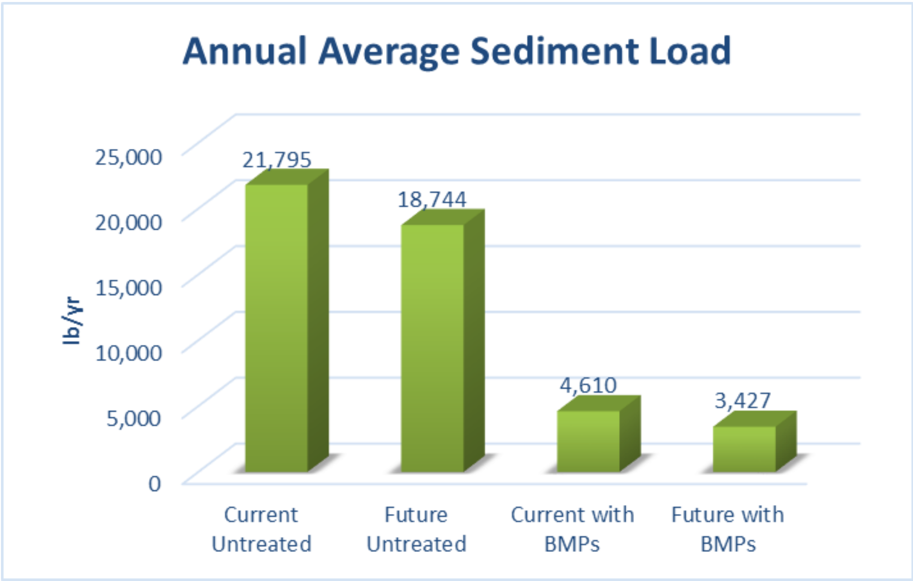


Figure B-130. Current and future performance for annual average sediment load, Harford County, MD Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

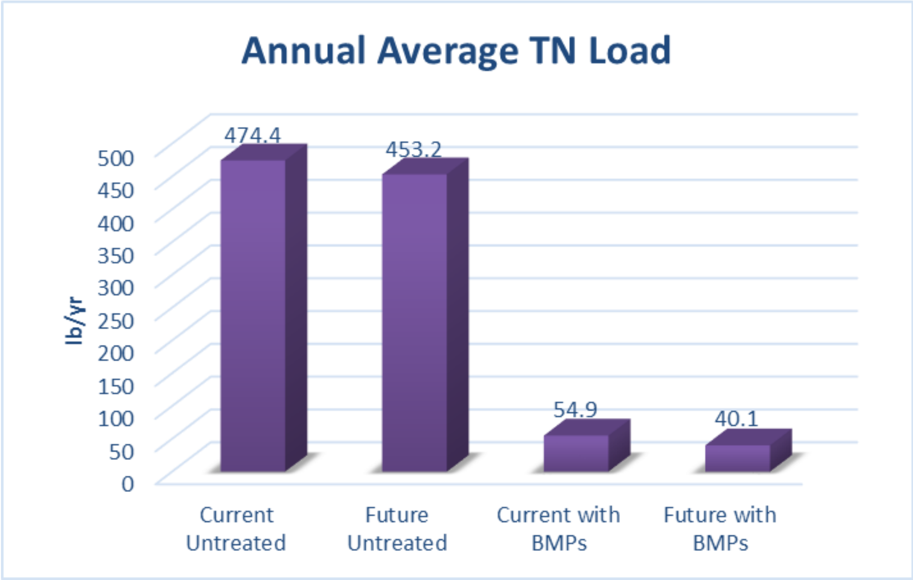


Figure B-131. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

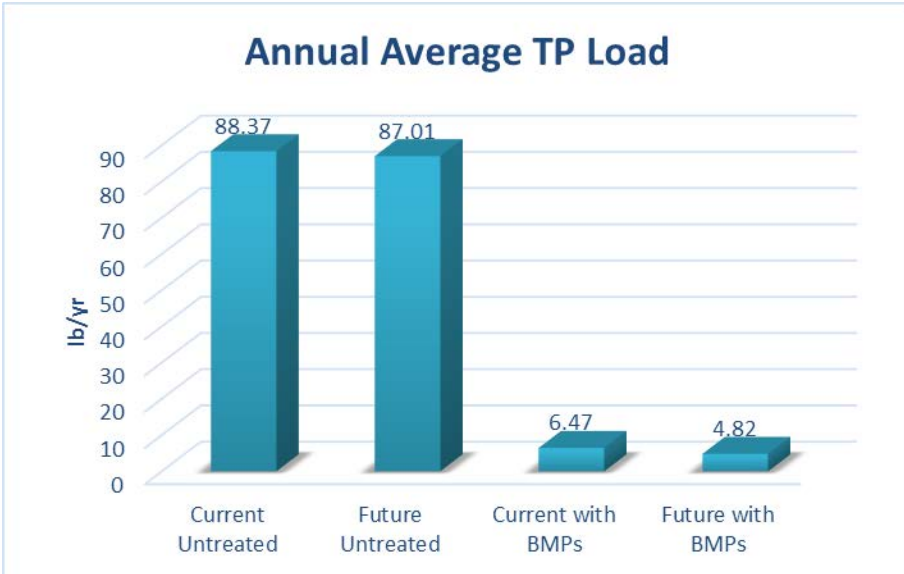


Figure B-132. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

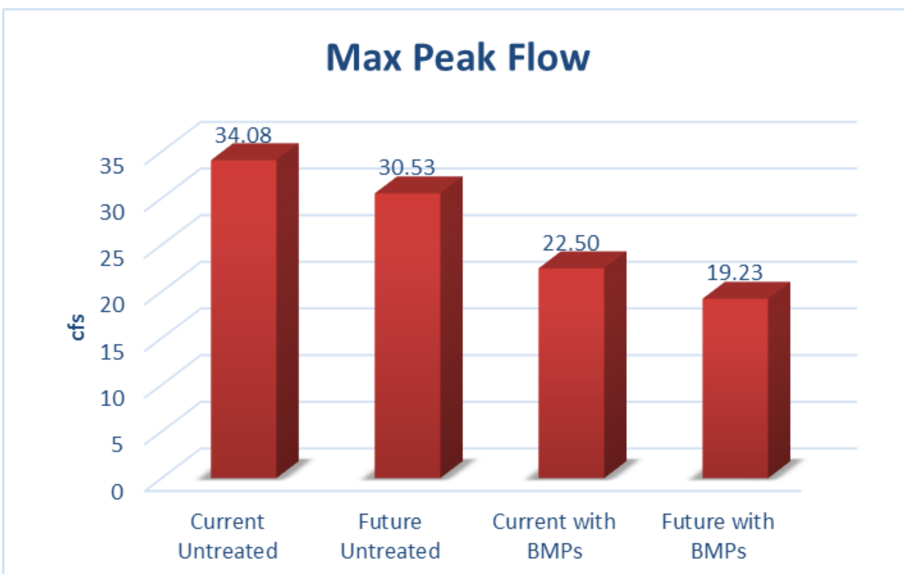


Figure B-133. Current and future performance for maximum hourly peak flow, Harford County, MD Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

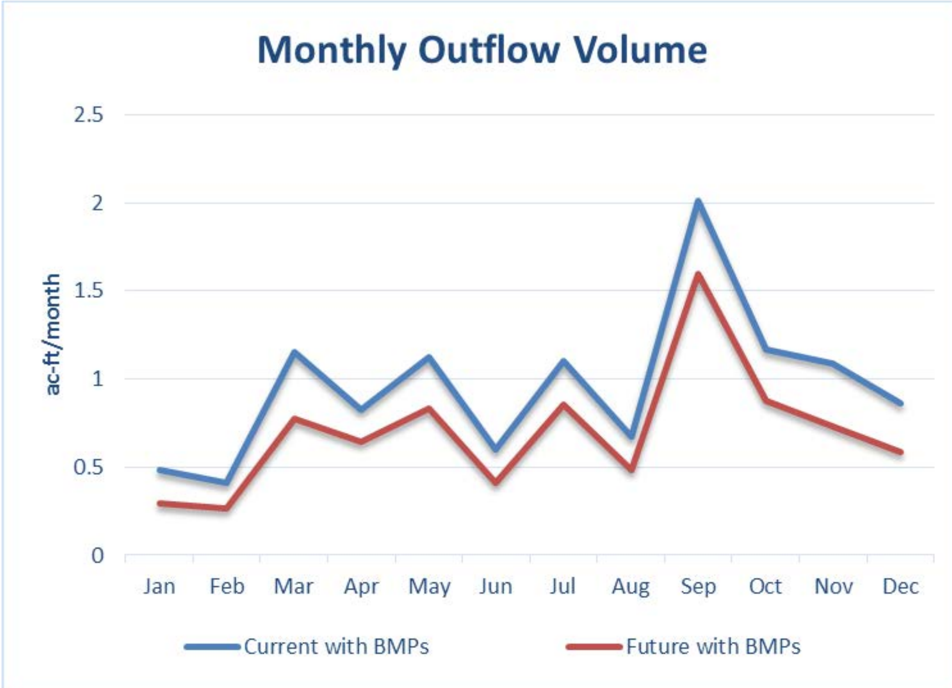


Figure B-134. Current and future performance for monthly outflow volume, Harford County, MD Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

Intensity Change Plus 10%

For this sensitivity analysis, we applied a 10% increase to the precipitation depths in the current conditions precipitation record. The 10% increase affects both intensity and precipitation volume, resulting in increases in both total runoff volume and outflow volume. Infiltration also increases between the "current with BMPs" and "future with BMPs" scenarios, suggesting that in the "intensity plus 10%" future climate, the conventional practices (surface sand filters and extended dry detention basin) are able to infiltrate some of the increased runoff volume prior to resizing. With increased practice footprints for future climate adaptation, the partitioning of runoff to infiltration and ET increases due to the larger surface areas, allowing outflow to be reduced below the current climate level.

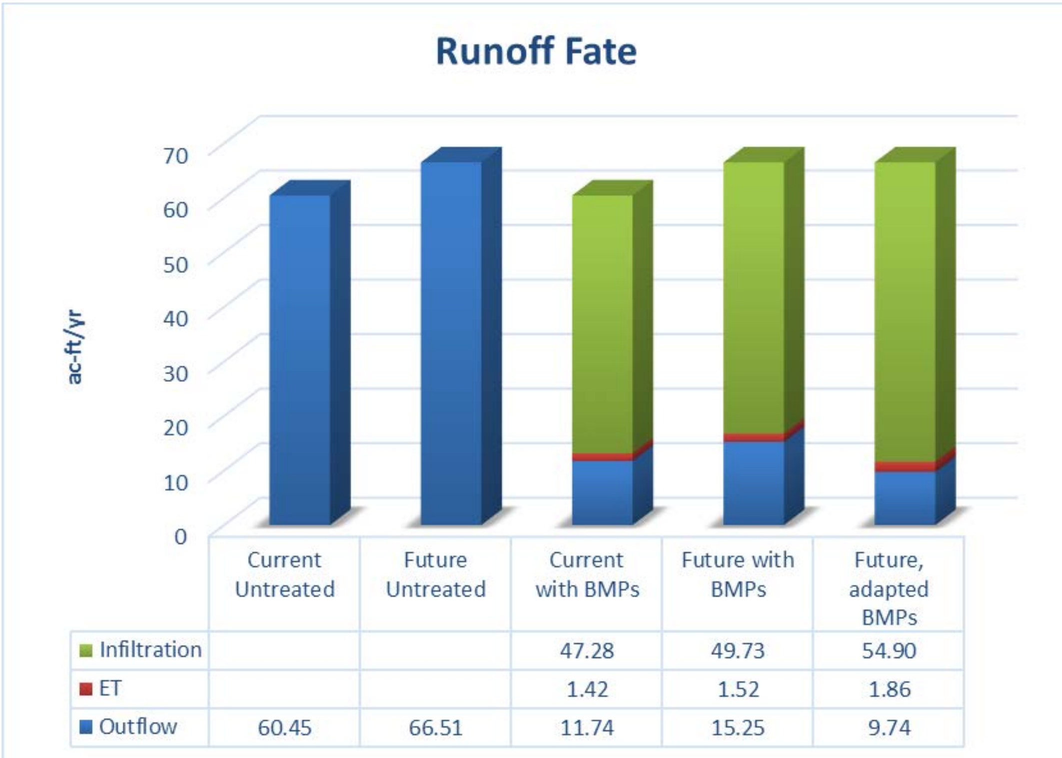


Figure B-135. Current and future partitioning of runoff fate for the Harford County, MD Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

The following figures present the pollutant load reduction performance for the current and future site scenarios under the "intensity plus 10%" climate simulation, and indicate that the future adapted practices combine to reduce the annual average loading for sediment, TN, and TP below the current climate load.

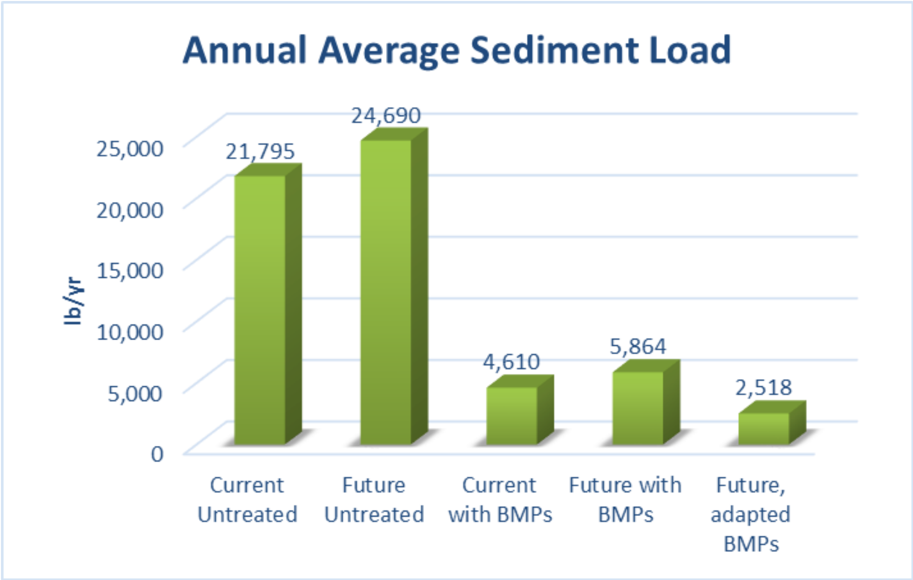


Figure B-136. Current and future performance for annual average sediment load, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

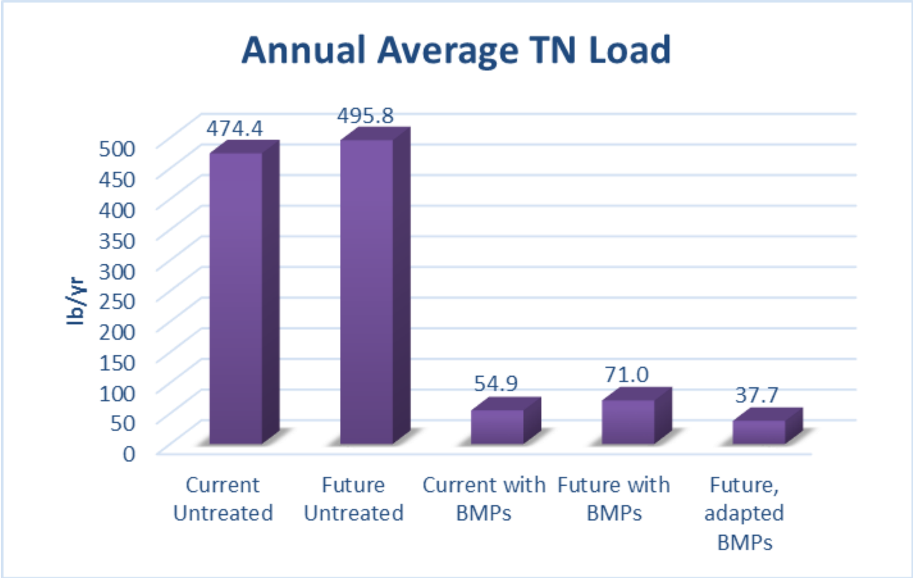


Figure B-137. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

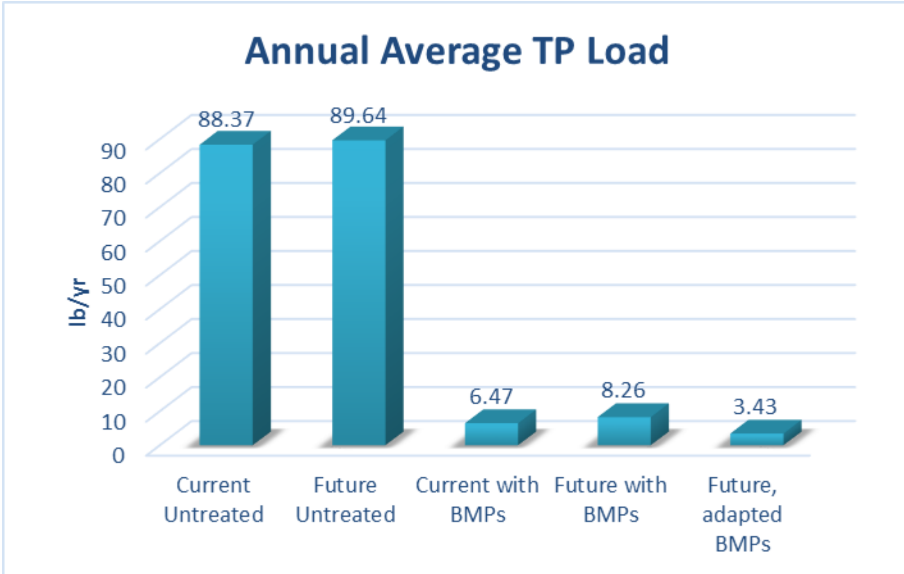


Figure B-138. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

When resized to adapt to the future "intensity plus 10%" climate conditions, the conventional practices achieve a combined flow duration curve response that is very similar to the current flow response within the range of evaluated flows.

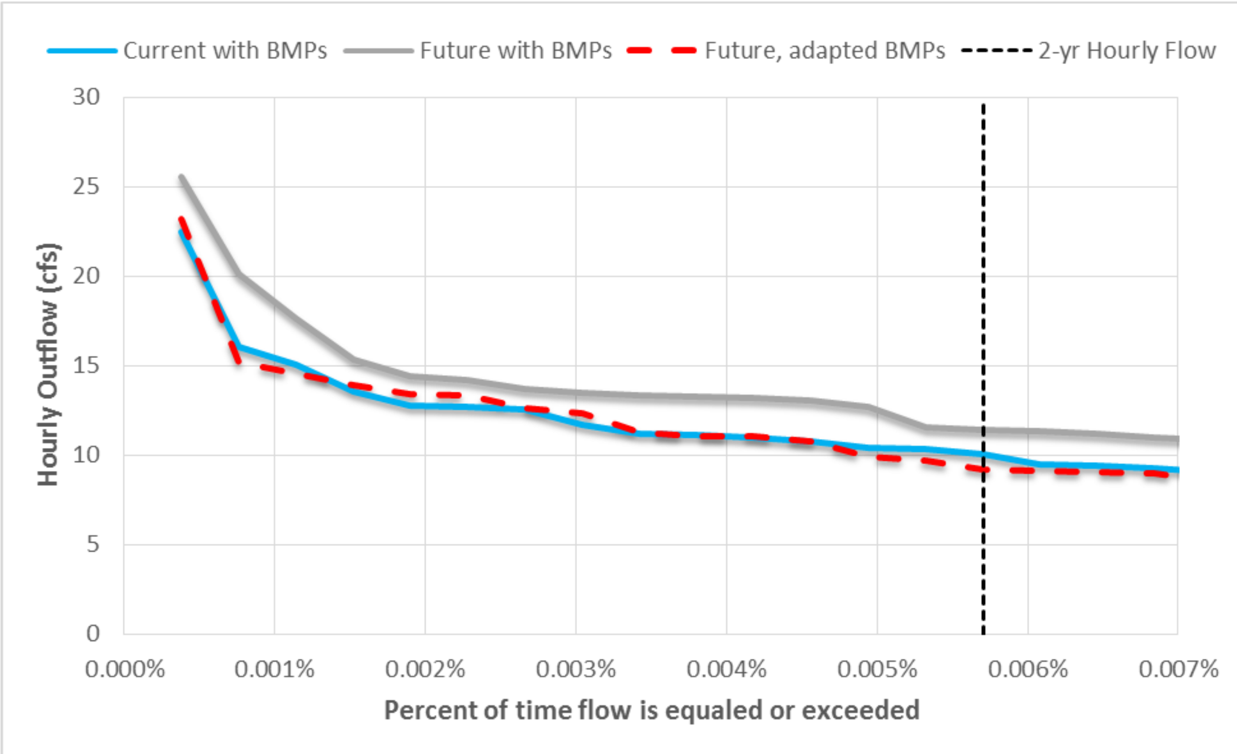


Figure B-139. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

Comparison of the maximum hourly peak flow for the current and future (intensity plus 10%) climate scenarios indicates that although the adapted practices are unable to maintain the current peak flow, they do reduce the future hourly peak flow to within 3% of the current hourly peak flow.

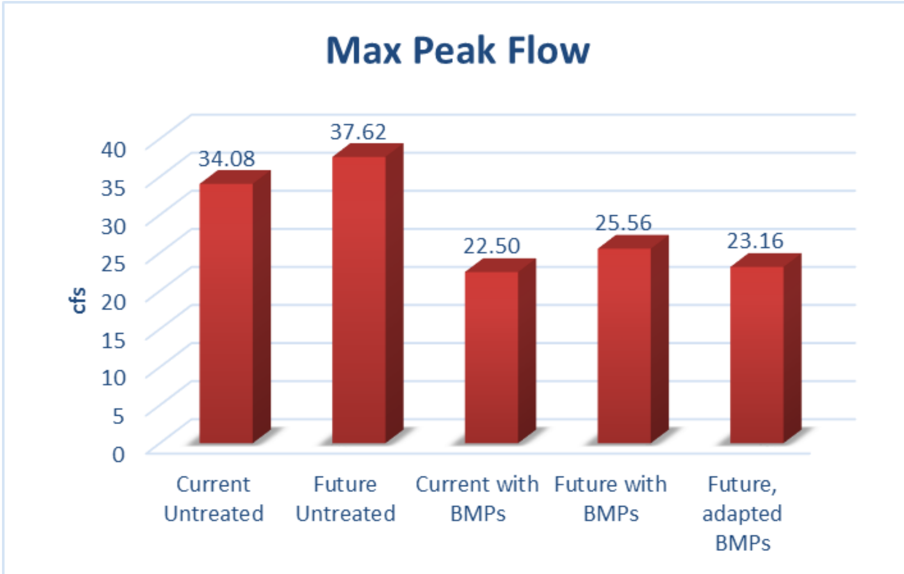


Figure B-140. Current and future performance for maximum hourly peak flow, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

The future adapted practices for the Harford County Conventional (Gray) Infrastructure scenario combine to decrease the future (intensity plus 10%) climate monthly outflow volumes below the current monthly outflow volumes for all months except January, where the outflows are approximately the same.

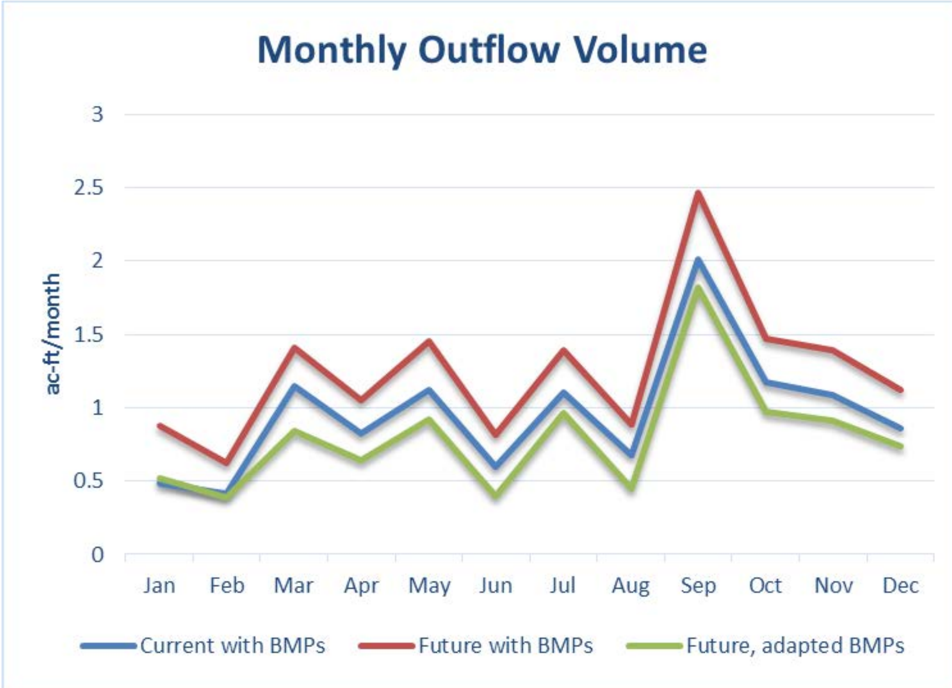


Figure B-141. Current and future performance for monthly outflow volume, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

Intensity Change Plus 20%

This sensitivity analysis entailed applying a 20% increase to the current climate precipitation record. This increase affects both intensity and precipitation volume, resulting in increases in both total runoff volume and outflow volume. Infiltration also increases between the "current with BMPs" and "future with BMPs" scenarios, suggesting that in the "intensity plus 20%" future climate, the conventional practices (surface sand filters and extended dry detention basin) are able to infiltrate some of the increased runoff volume prior to resizing. With increased practice footprints for future climate adaptation, the partitioning of runoff to infiltration and ET increases due to the larger surface areas, allowing outflow to be reduced below the current climate level.

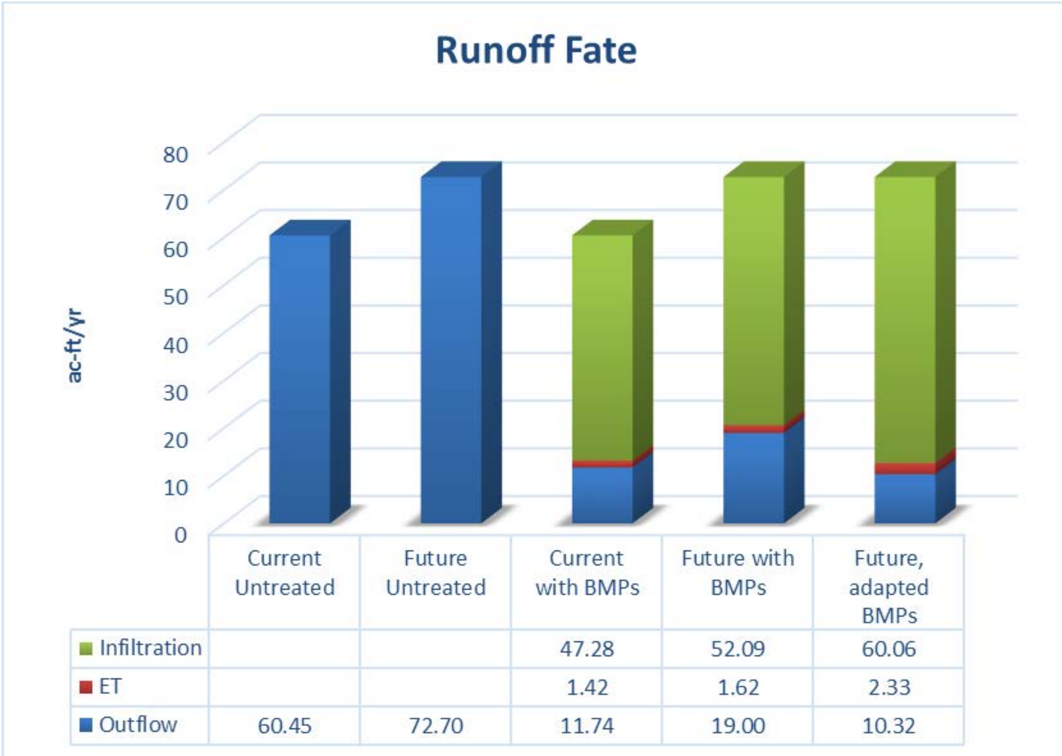


Figure B-142. Current and future partitioning of runoff fate for the Harford County, MD Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

The following figures present the pollutant load reduction performance for the current and future site scenarios under the "intensity plus 20%" climate simulation and indicate that the future adapted practices combine to reduce the annual average loading for sediment, TN, and TP below the current climate load.

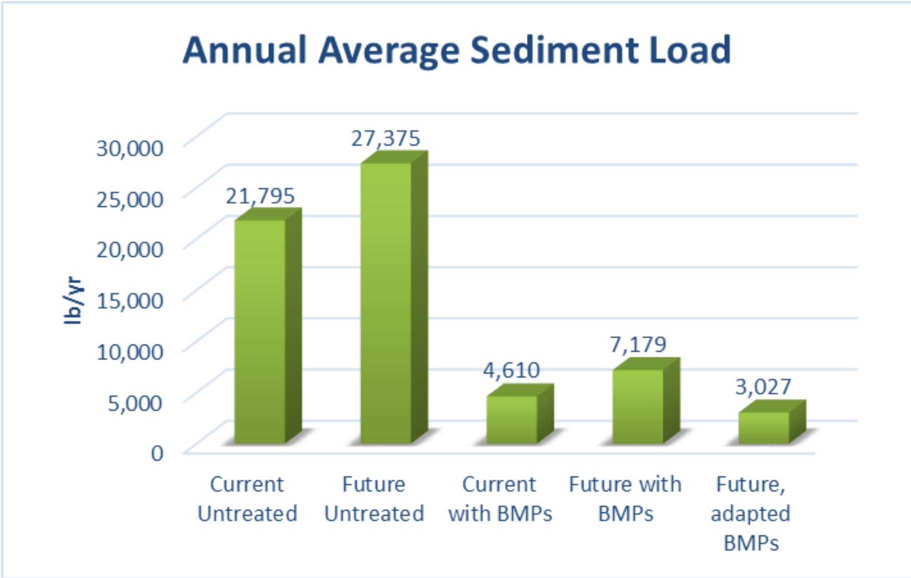


Figure B-143. Current and future performance for annual average sediment load, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

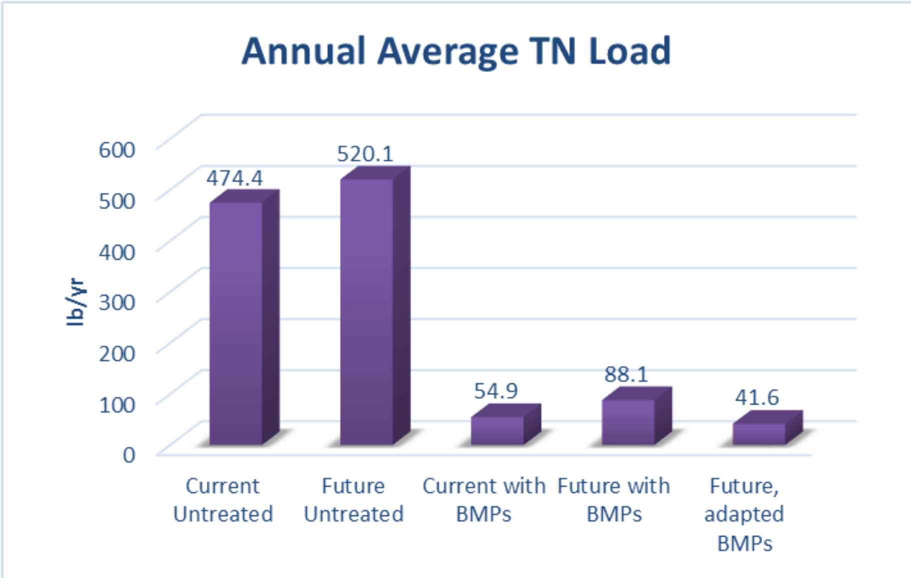


Figure B-144. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

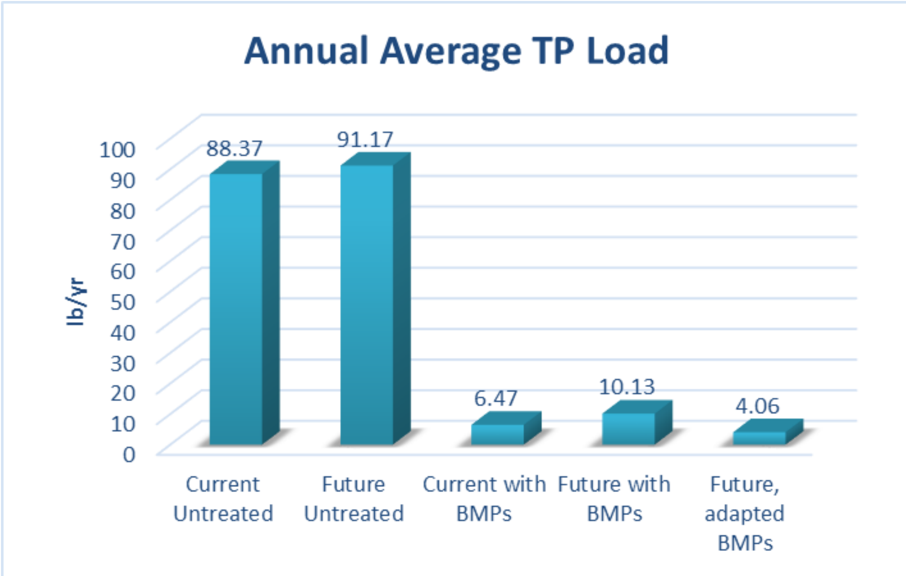


Figure B-145. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

When resized to adapt to the future "intensity plus 20%" climate conditions, the conventional practices achieve a combined flow duration curve response that is very similar to the current flow response within the range of evaluated flows.

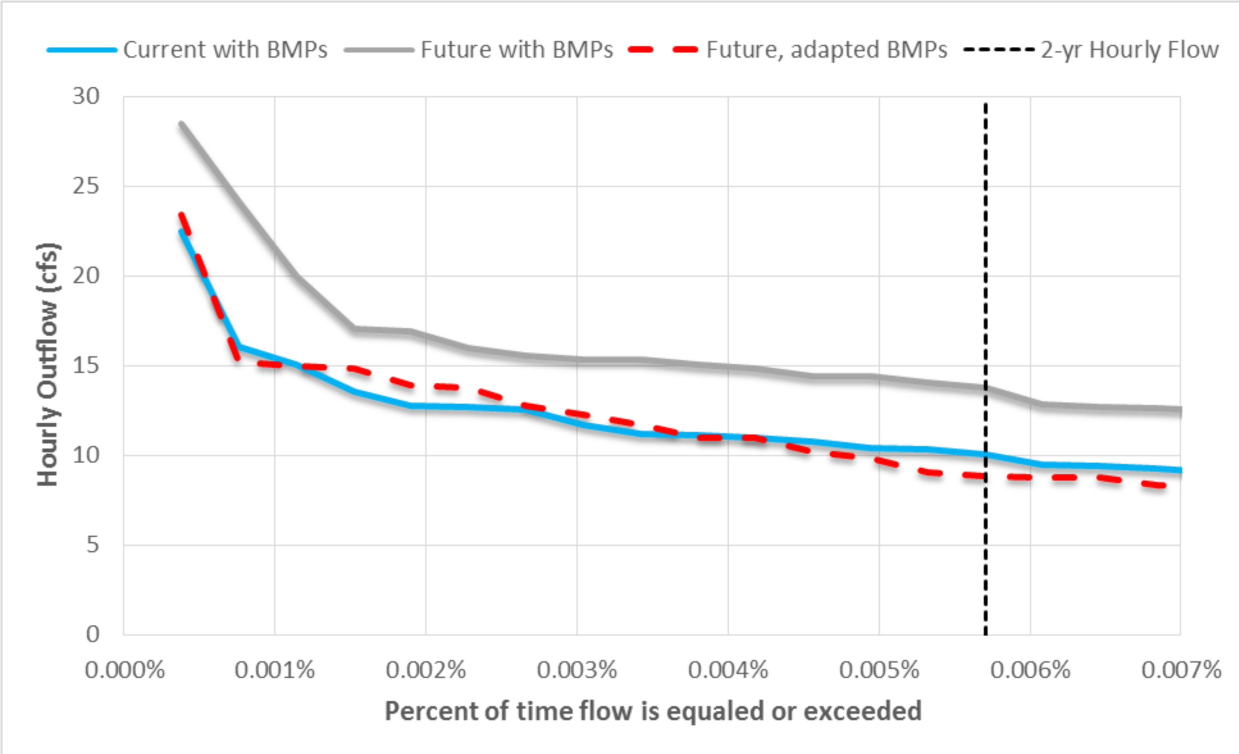


Figure B-146. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

Comparison of the maximum hourly peak flow for the current and future (intensity plus 20%) climate scenarios indicates that although the adapted practices are unable to maintain the current peak flow, they do reduce the future hourly peak flow to within 4% of the current hourly peak flow.

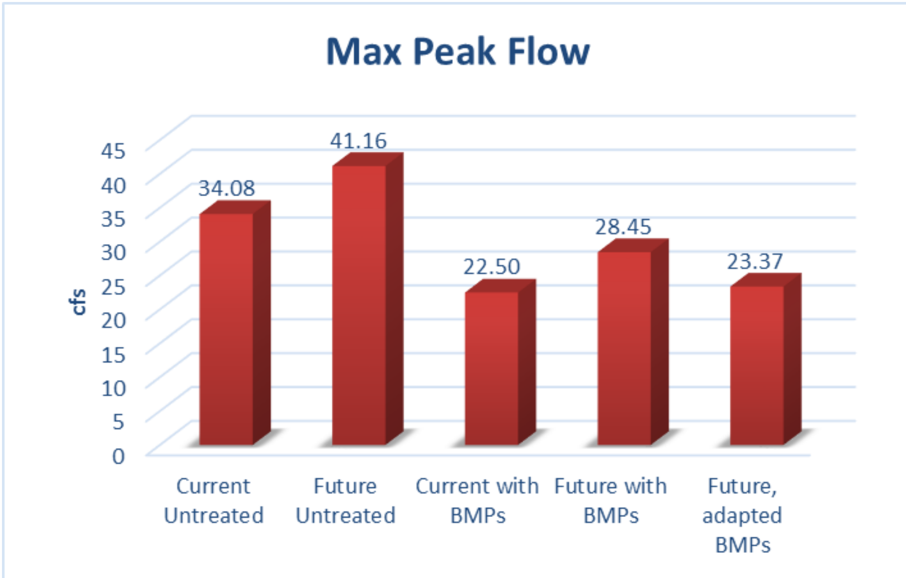


Figure B-147. Current and future performance for maximum hourly peak flow, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

The future adapted practices for the Harford County Conventional (Gray) Infrastructure scenario combine to maintain the future (intensity plus 20%) climate monthly outflow volumes at or below the current monthly outflow volumes for all months except January, where the future adapted outflow volume is slightly higher than the current outflow volume.

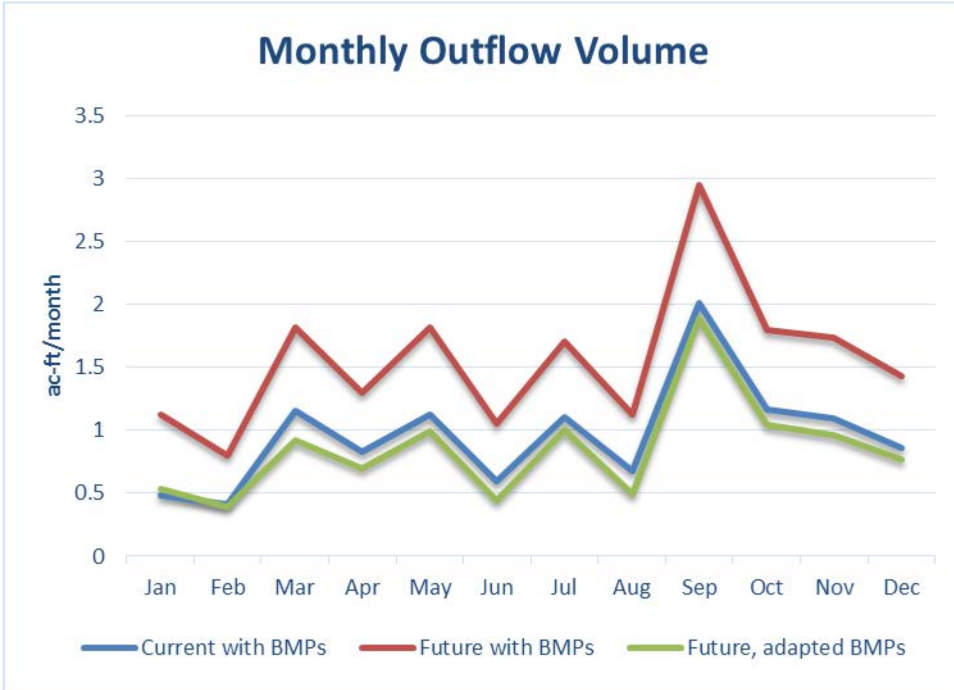


Figure B-148. Current and future performance for monthly outflow volume, Harford County, MD Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

B.2.1.2. Green Infrastructure (GI) with Gray Infrastructure

Intensity Change Minus 10%

This scenario was not selected for adaptation simulation; refer to discussion in *Section B.2.1.1.* and the following figures, which demonstrate decreased outflow volume and pollutant loading in the "intensity minus 10%" climate scenario compared to the current climate.

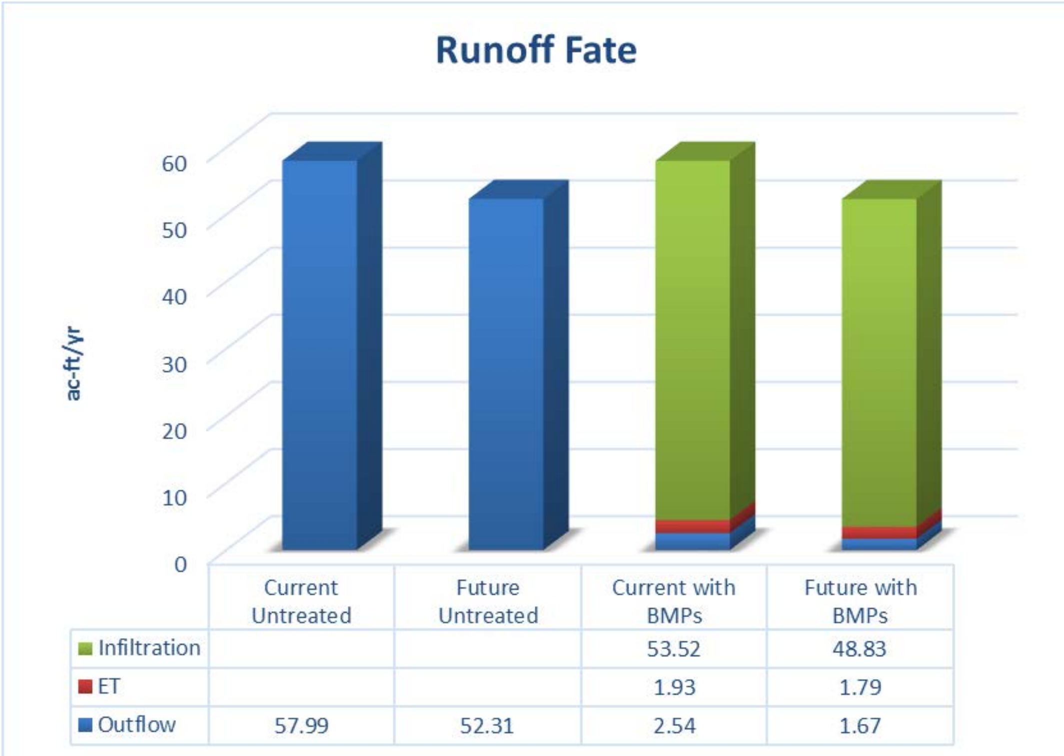


Figure B-149. Current and future partitioning of runoff fate for the Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

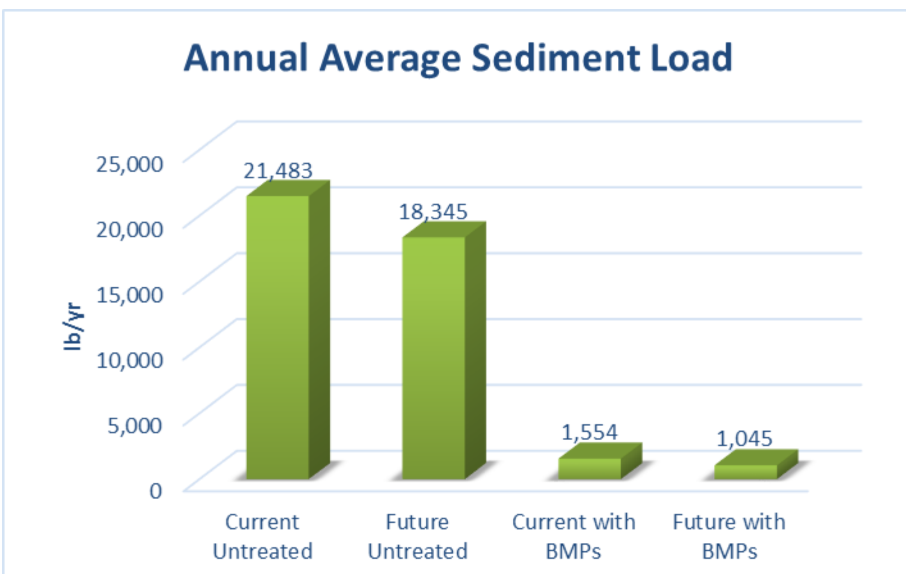


Figure B-150. Current and future performance for annual average sediment load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

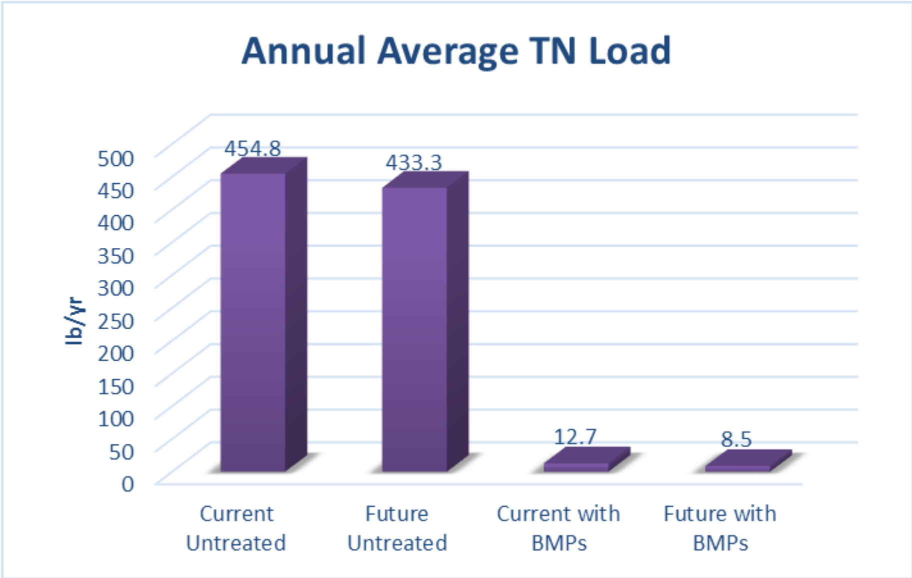


Figure B-151. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

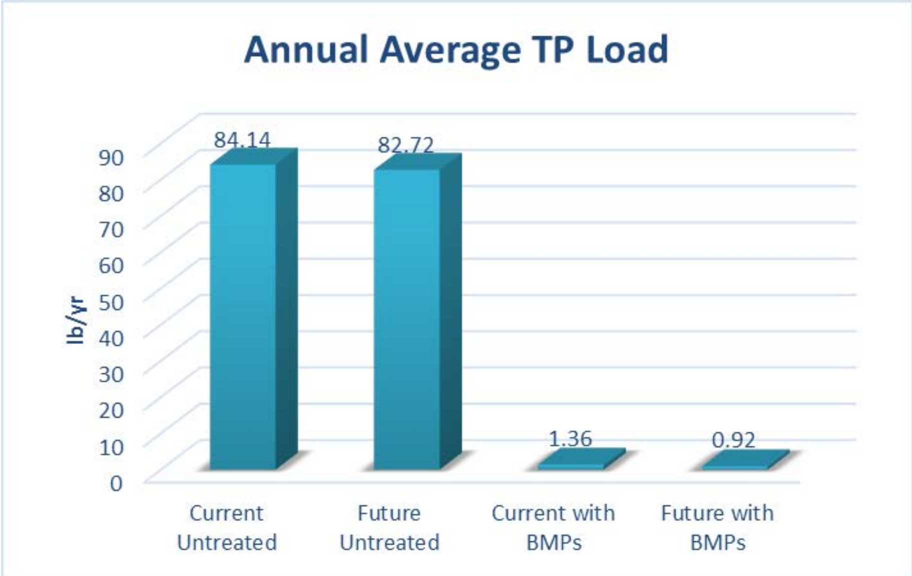


Figure B-152. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

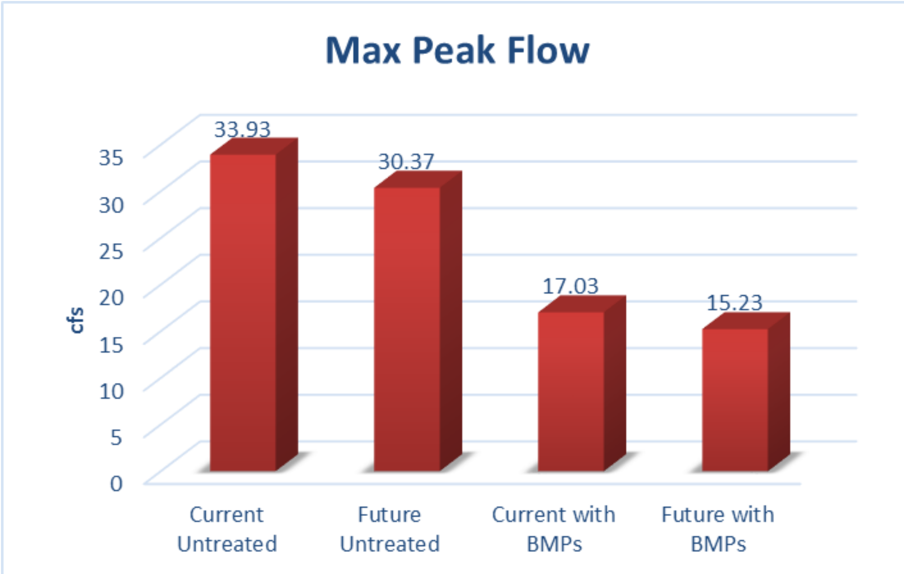


Figure B-153. Current and future performance for maximum hourly peak flow, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

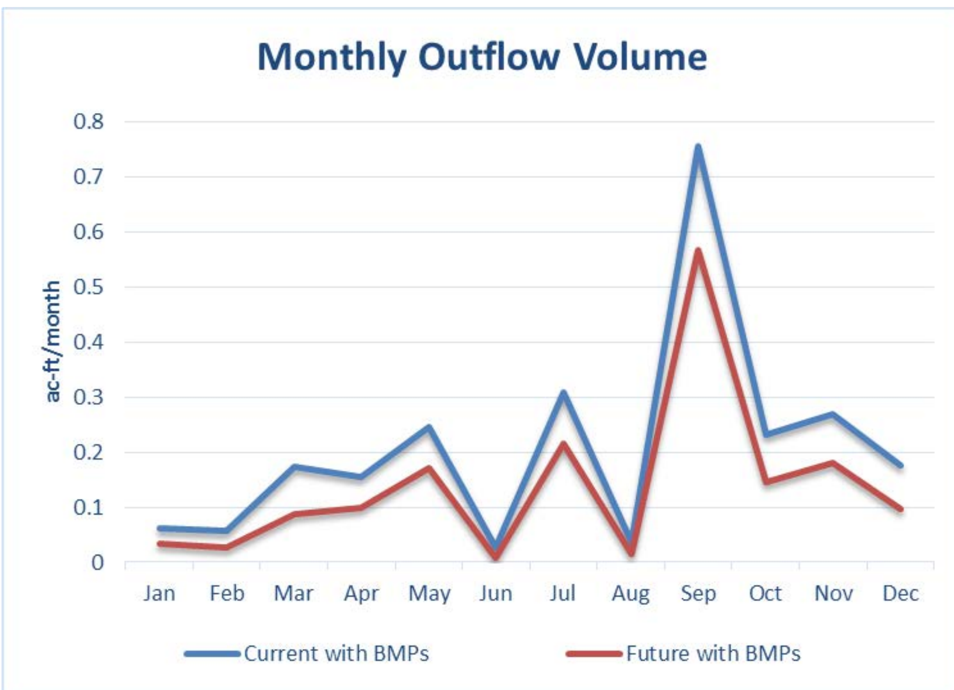
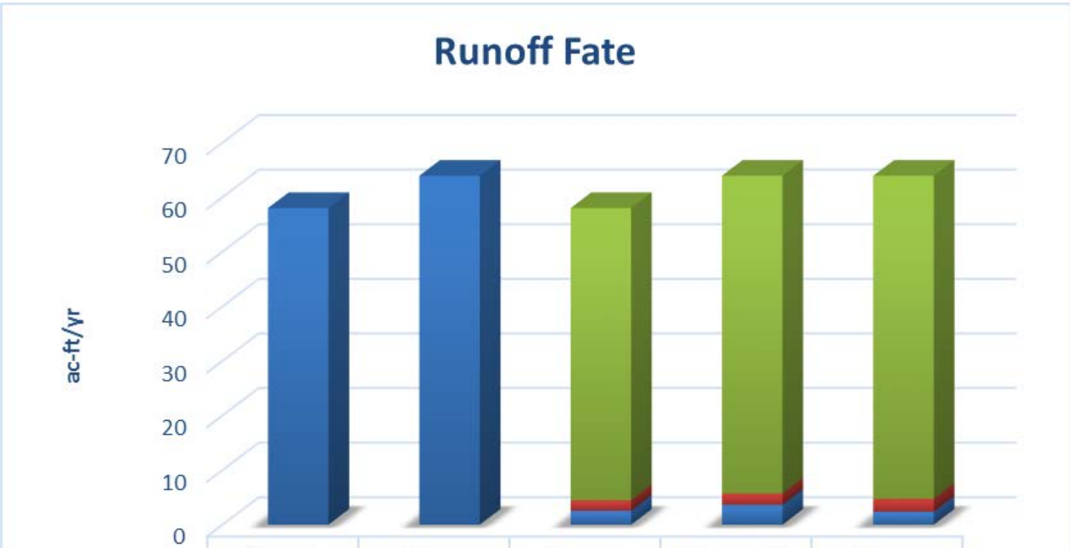


Figure B-154. Current and future performance for monthly outflow volume, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

Intensity Change Plus 10%

Increasing the intensity of the current climate precipitation record by 10% affects both intensity and precipitation volume for Harford County results in an increase both in total runoff volume and in outflow volume, as shown in Figure B-155. However, in the GI with Gray Infrastructure scenario, the practices are highly infiltrating such that the majority of the increase in runoff volume partitions into infiltration, with only a relatively small increase in outflow volume. With resizing for future adaptation, the fraction of runoff that is converted to infiltration and ET is increased further, enabling the site to maintain its current performance for outflow volume.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			53.52	58.19	59.16
ET			1.93	2.07	2.36
Outflow	57.99	63.91	2.54	3.64	2.38

Figure B-155. Current and future partitioning of runoff fate for the Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

The following figures indicate that the combination of practices in the GI with Gray Infrastructure scenario achieves a high load reduction for sediment, TN, and TP, and that resizing the practices for the future (intensity plus 10%) climate enables loads to be maintained at or below their current levels.

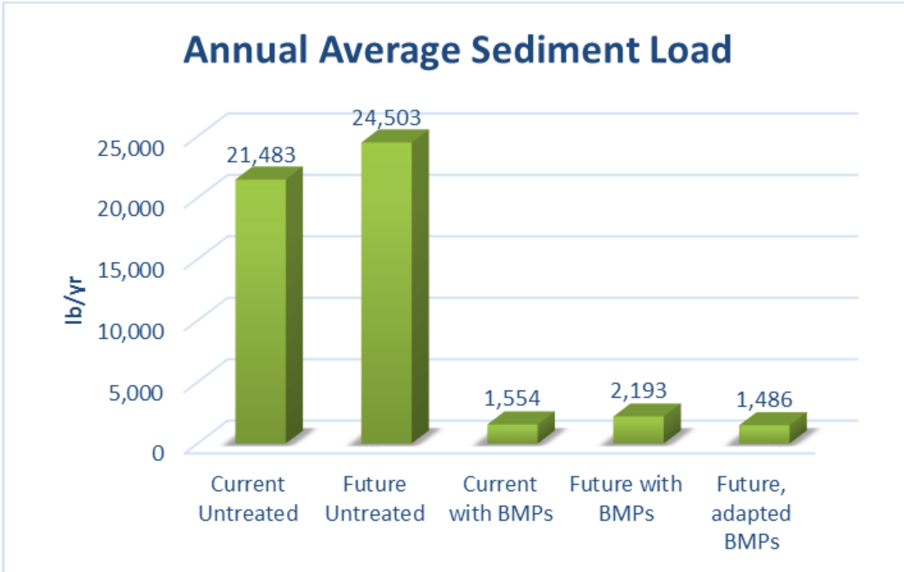


Figure B-156. Current and future performance for annual average sediment load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

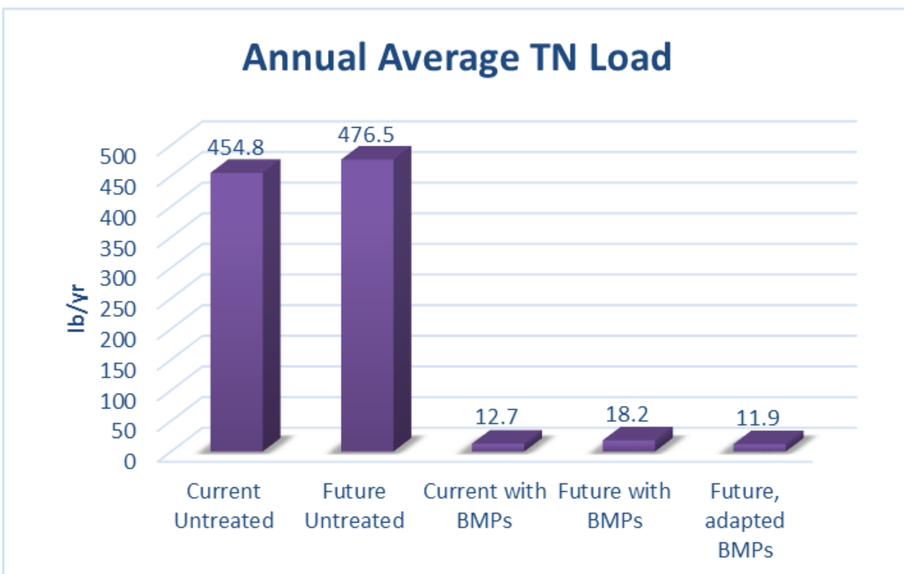


Figure B-157. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

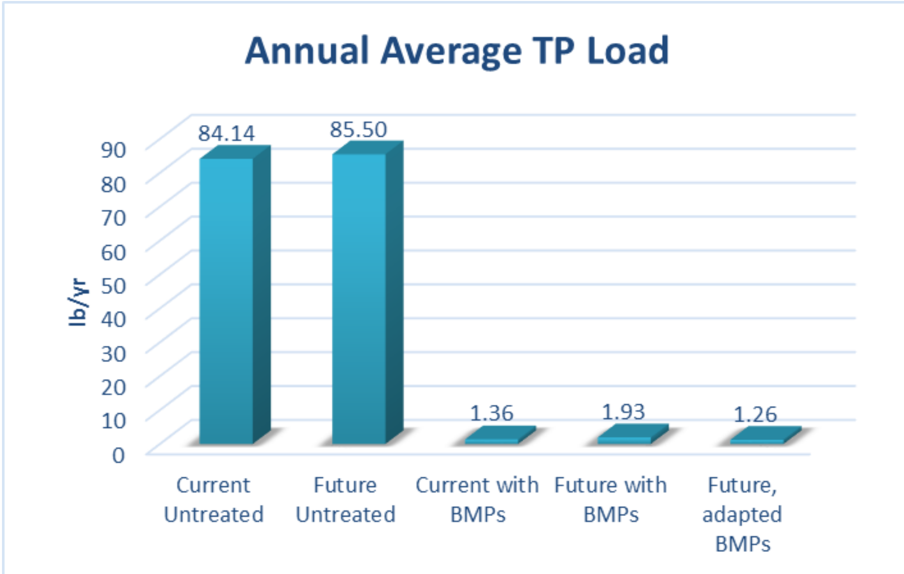


Figure B-158. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

The FDC evaluation for the GI with Gray Infrastructure scenario appears to indicate that the practices, when resized for future climate (intensity plus 10%) adaptation, are able to very closely reproduce the current climate flow duration curve response within the range of evaluated flows.

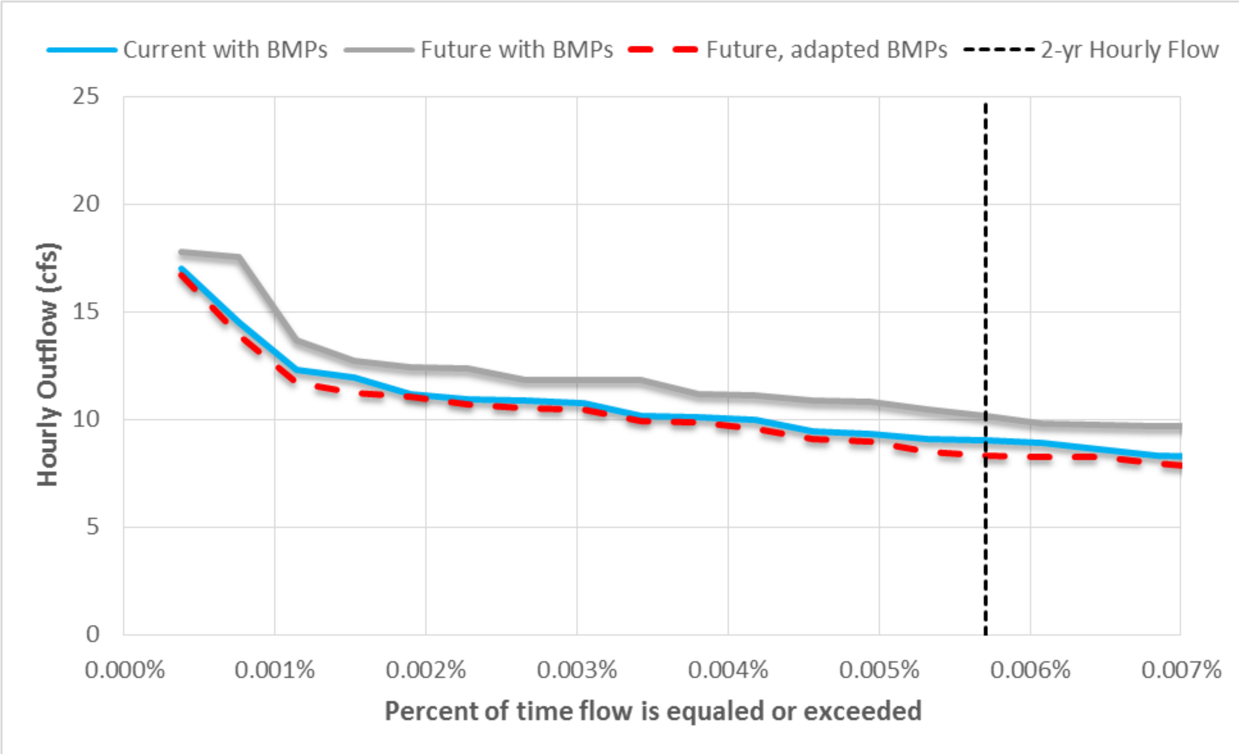


Figure B-159. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

With adaptation, the future (intensity plus 10%) practice footprints are also successful at reducing maximum hourly peak flow from the site to 16.7 cfs, which is lower than the current hourly peak flow of 17.0 cfs.

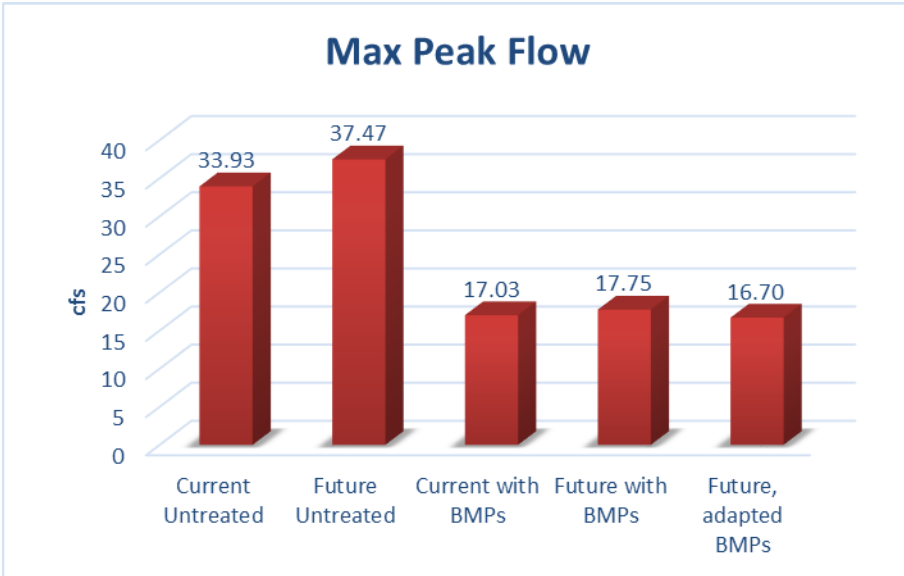


Figure B-160. Current and future performance for maximum hourly peak flow, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

Resizing the Green and Gray practices for the future "intensity plus 10%" climate produces a monthly outflow response that is nearly identical to the current BMP monthly outflow response.

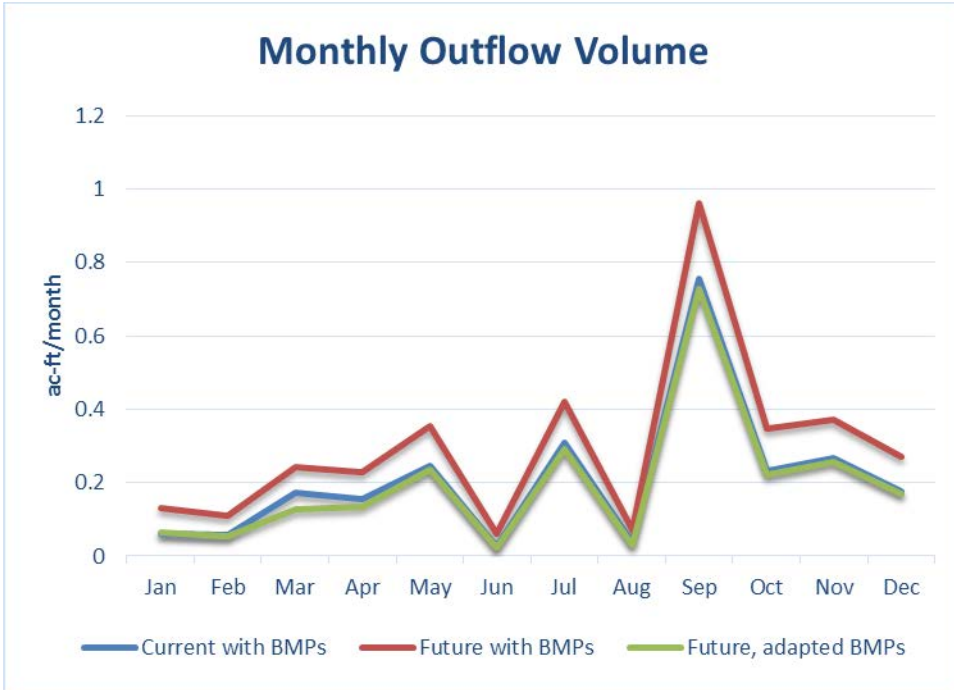


Figure B-161. Current and future performance for monthly outflow volume, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

Intensity Change Plus 20%

As discussed in *Section B.2.1.1.* , the "intensity plus 20%" climate scenario for Harford County results is an increase both in total runoff volume and in outflow volume, as shown in Figure B 162. However, in the GI with Gray Infrastructure scenario, the practices are highly infiltrating such that the majority of the increase in runoff volume partitions into infiltration, with only a relatively small fraction of the increased runoff partitioning to outflow. With resizing for future adaptation, the fraction of runoff that is converted to infiltration and ET is increased further, enabling the site to maintain its current performance for outflow volume.

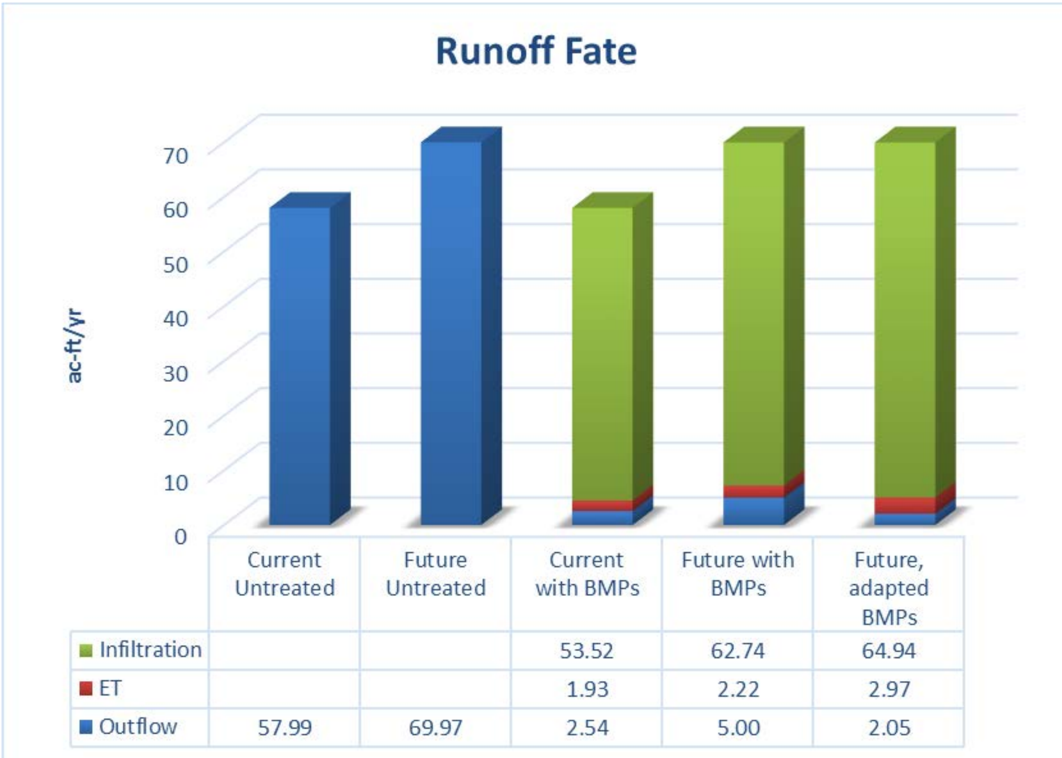


Figure B 162. Current and future partitioning of runoff fate for the Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

The following figures indicate that the combination of practices in the GI with Gray Infrastructure scenario achieves a high load reduction for sediment, TN, and TP, and that resizing the practices for the future (intensity plus 20%) climate enables loads to be maintained at or below their current levels.

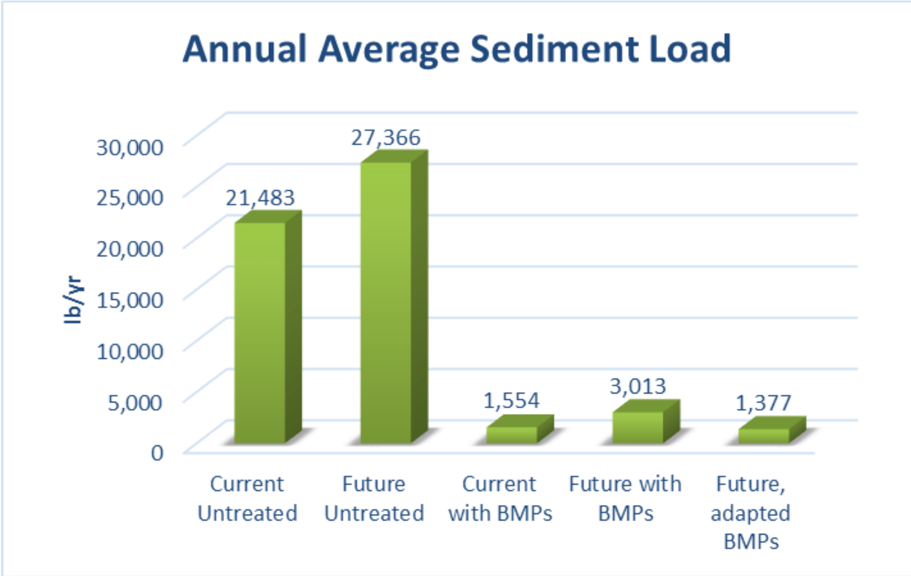


Figure B 163. Current and future performance for annual average sediment load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

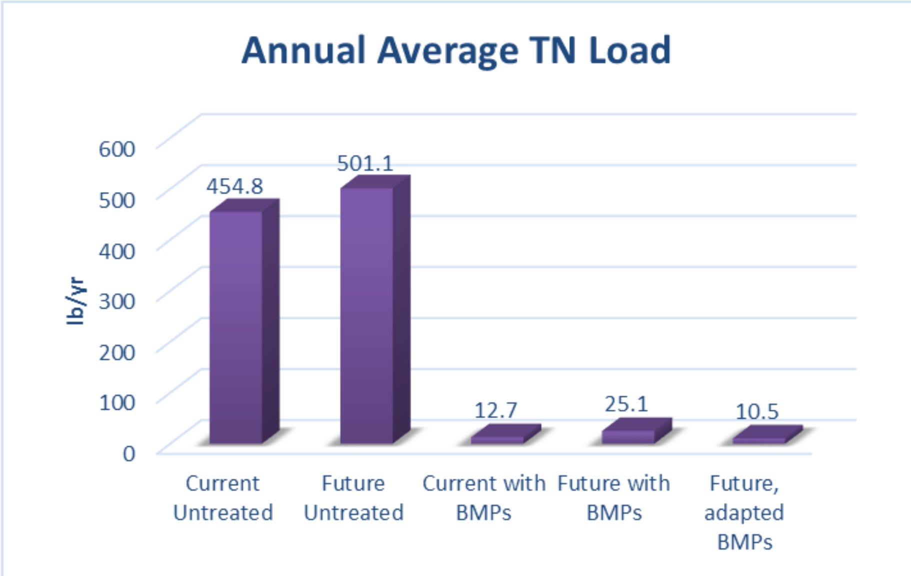


Figure B-164. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

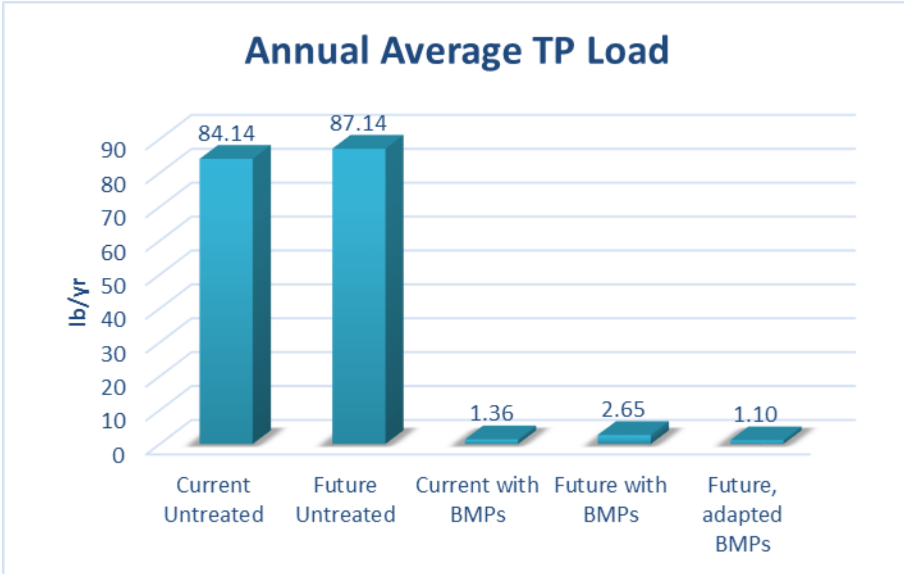


Figure B-165. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

The FDC evaluation for the GI with Gray Infrastructure scenario suggests that the practices, when resized for future climate (intensity plus 20%) adaptation, produce a flow duration response that is nearly identical to the current climate FDC within the evaluated range of outflows.

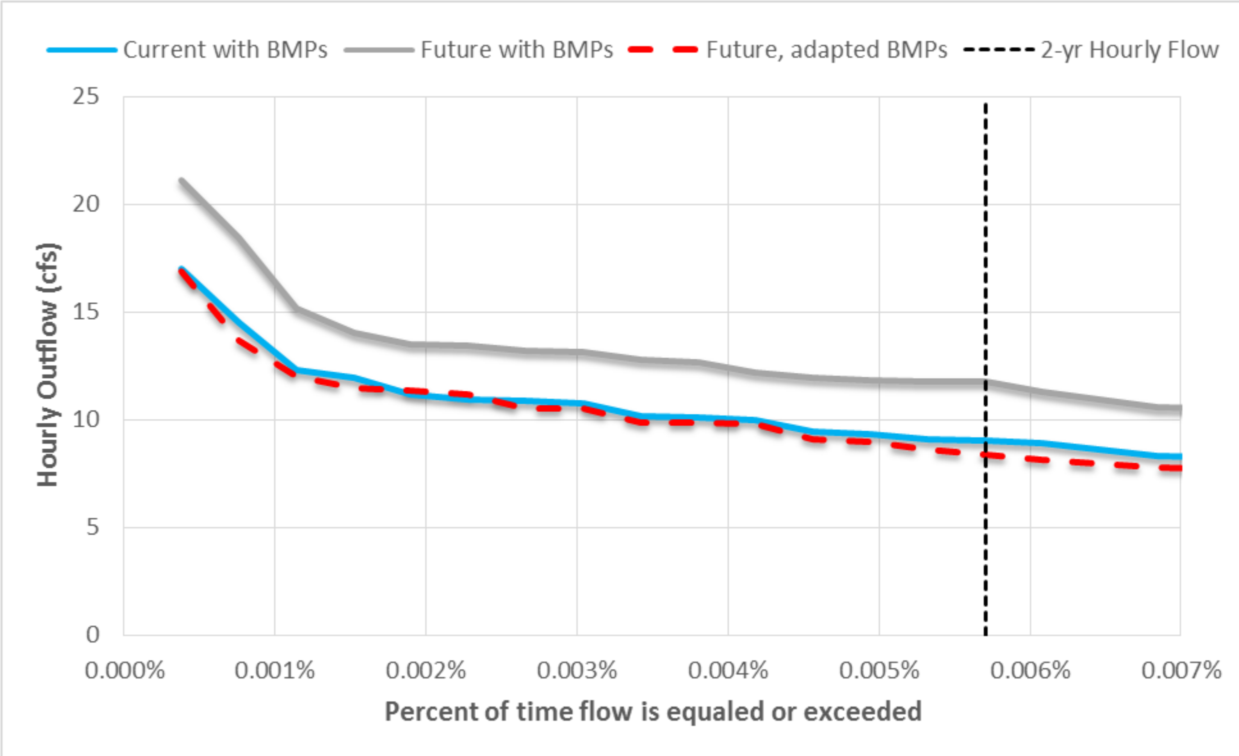


Figure B-166. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

With adaptation, the future (intensity plus 20%) practice footprints are also successful at reducing maximum hourly peak flow from the site to 16.9 cfs, which is slightly lower than the current hourly peak flow of 17.0 cfs.

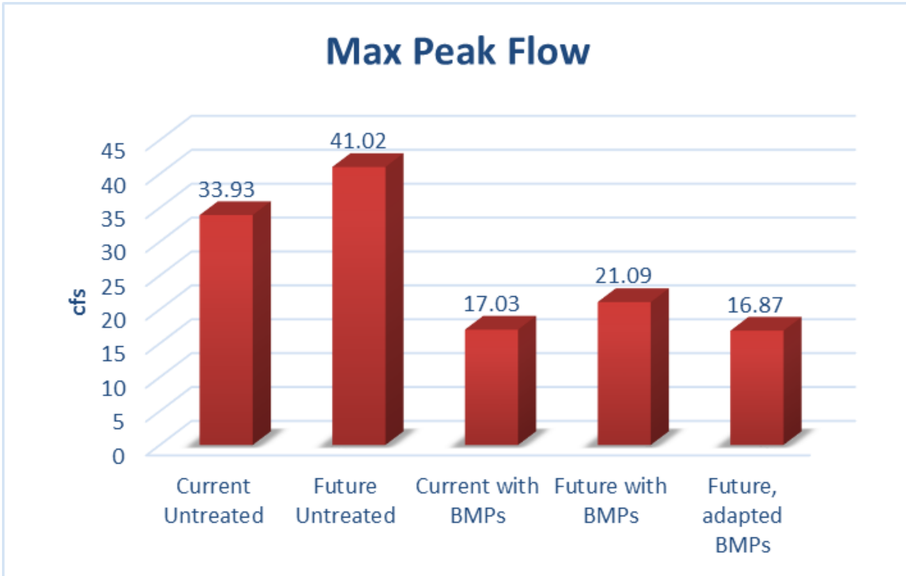


Figure B-167. Current and future performance for maximum hourly peak flow, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

Resizing the Green and Gray practices for the future "intensity plus 20%" climate produces a monthly outflow response that is nearly identical to the current BMP monthly outflow response.

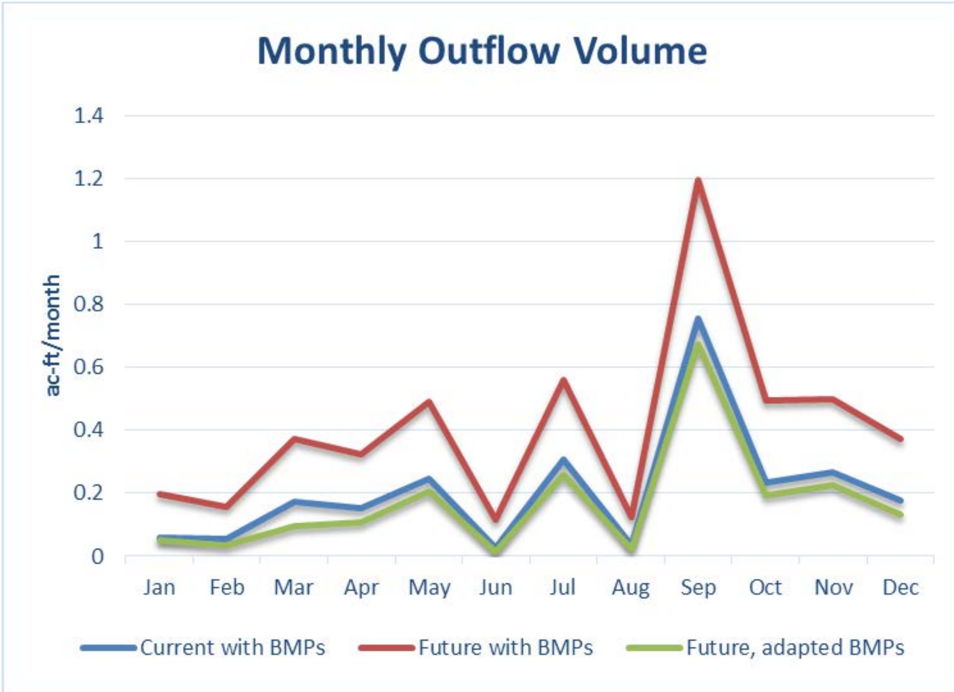


Figure B-168. Current and future performance for monthly outflow volume, Harford County, MD Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

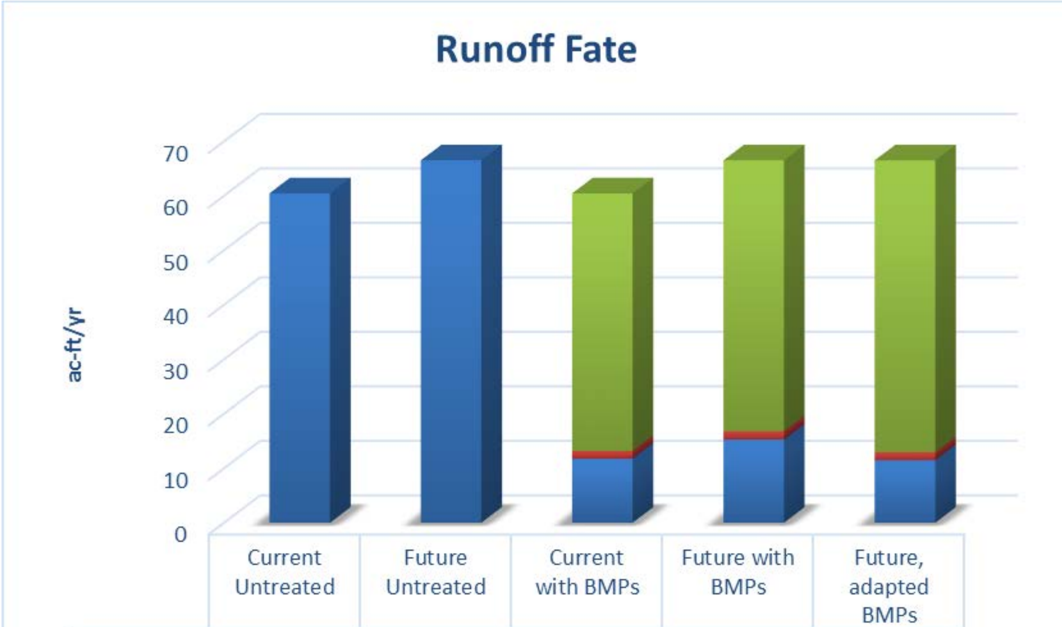
B.2.1.3. Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI)

Intensity Change Minus 10%

This scenario was not selected for adaptation simulation; refer to discussion in *Section B.2.1.1.* .

Intensity Change Plus 10%

As discussed in *Section B.2.1.1.* , the “intensity plus 10%” climate scenario for Harford County results is an increase both in total runoff volume and in outflow volume, as shown in Figure B-169. The objective of the Conventional (Gray) Infrastructure with Distributed GI scenario is to implement distributed GI practices without resizing the conventional (Gray) practice as a means of future climate adaptation. Figure B-169 indicates that the addition of distributed infiltration trenches to the conventional site is able to reduce future outflow below the current climate outflow by increasing the partitioning of runoff to infiltration.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			47.28	49.73	53.59
ET			1.42	1.52	1.45
Outflow	60.45	66.51	11.74	15.25	11.47

Figure B-169. Current and future partitioning of runoff fate for the Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

Figure B-170 indicates that the distributed infiltration trench practices combined with the conventional practices (surface sand filters and extended dry detention basin) are able to achieve high load reductions for sediment, and allow the site to meet current loading for annual average sediment load without requiring resizing of the current conventional practices.

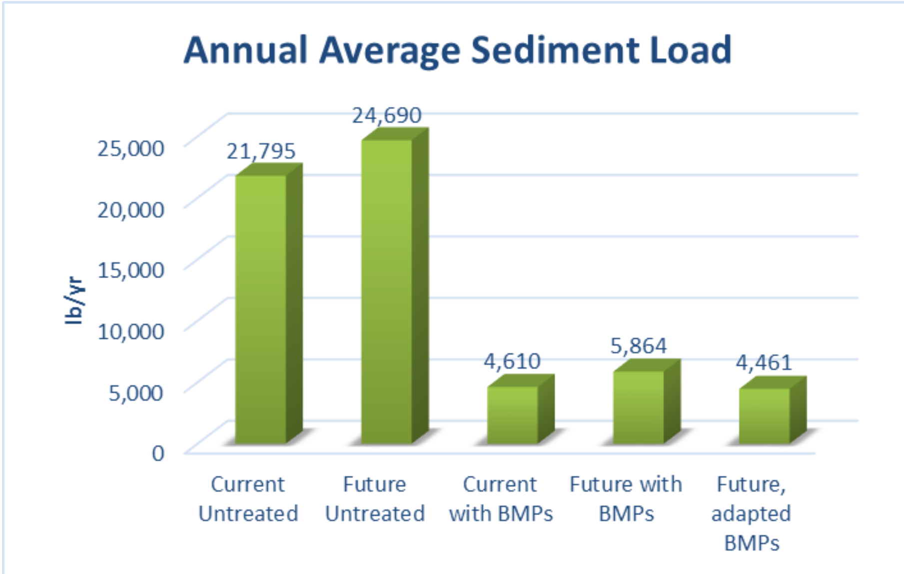


Figure B-170. Current and future performance for annual average sediment load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

The following figures suggest that the distributed green practices (infiltration trenches) combined with the conventional practices (surface sand filters and extended dry detention basin) are able to achieve large load reductions for TN and TP, and allow the site to meet current loading for annual average sediment load without requiring resizing of the current conventional practices.

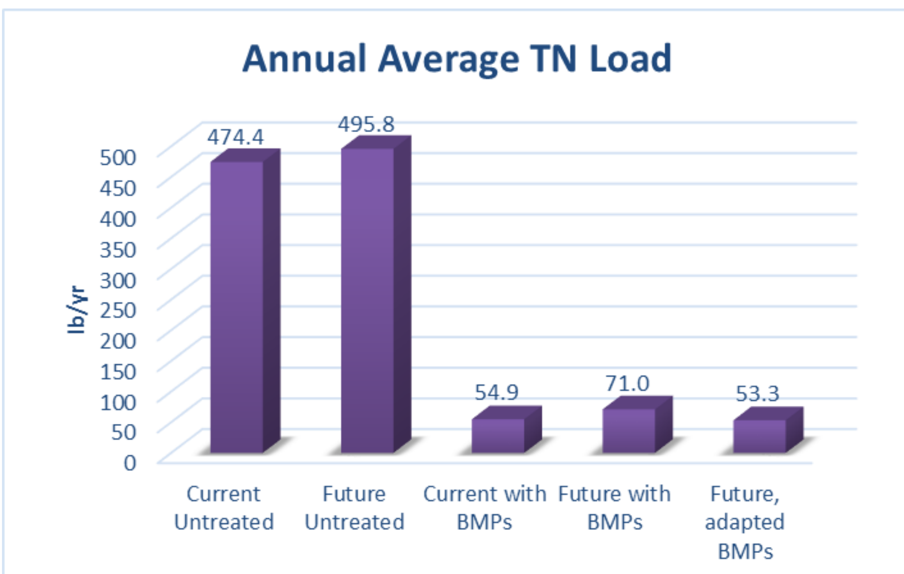


Figure B-171. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

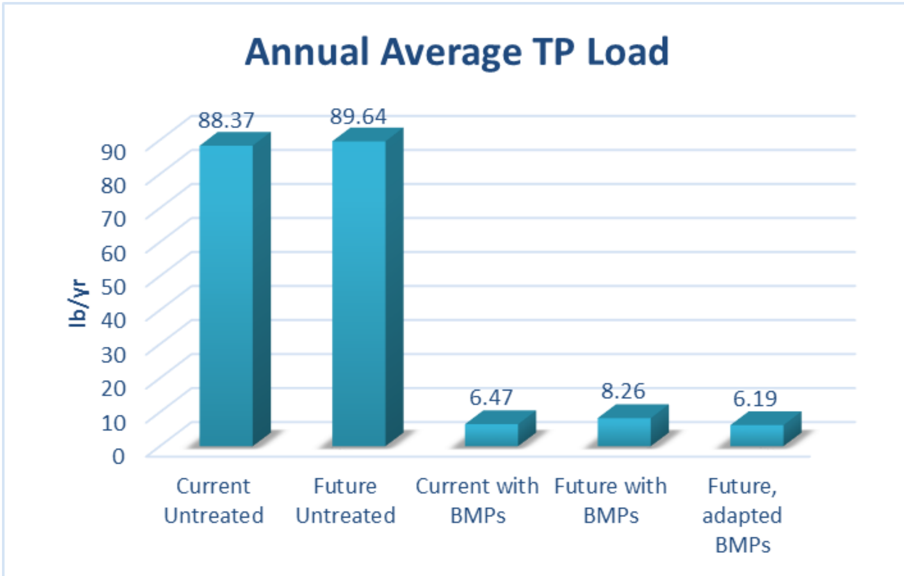


Figure B-172. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

The FDC evaluation for the Conventional (Gray) Infrastructure with Distributed GI scenario suggests that when distributed infiltration trenches are added to the current conventional practices for future climate (intensity plus 10%) adaptation, the combination produces a flow duration response that is nearly identical to the current climate FDC within the evaluated range of outflows.

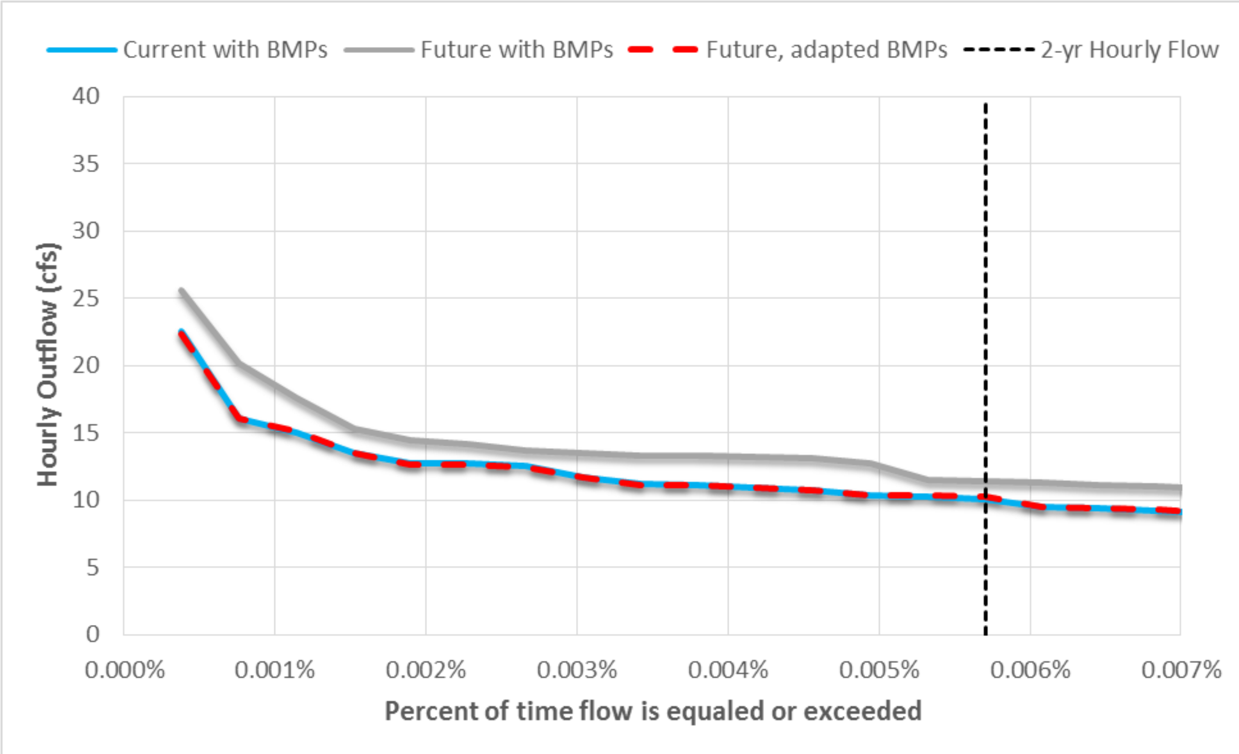


Figure B-173. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

As demonstrated in Figure B-174, the addition of distributed GI for future (intensity plus 10%) climate adaptation results in a future adapted maximum hourly peak flow that is slightly lower than the current maximum hourly peak flow.

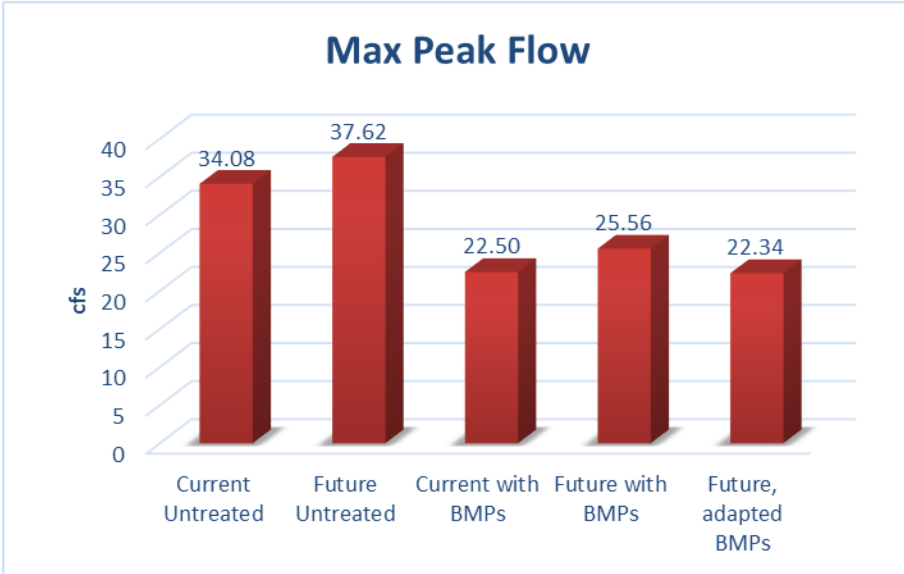


Figure B-174. Current and future performance for maximum hourly peak flow, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

The addition of distributed GI practices for the future "intensity plus 10%" climate also produces a monthly outflow response that is nearly identical to the current BMP monthly outflow response.

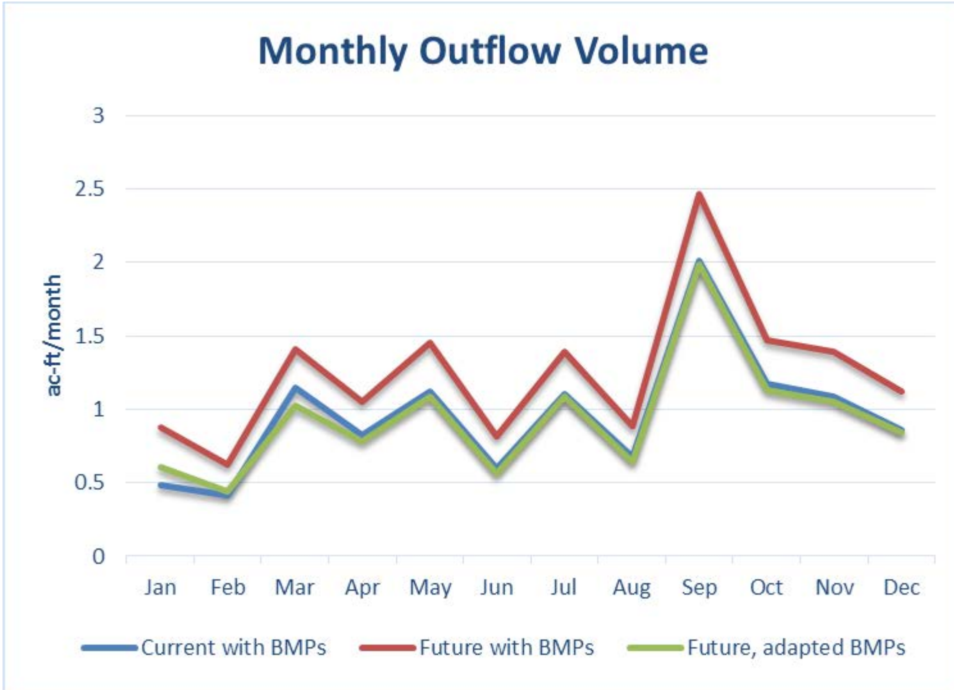


Figure B-175. Current and future performance for monthly outflow volume, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

Intensity Change Plus 20%

As discussed in *Section B.2.1.1.* , the "intensity plus 20%" climate scenario for Harford County results is an increase both in total runoff volume and in outflow volume, as shown in Figure B-176. The objective of the Conventional (Gray) Infrastructure with Distributed GI scenario is to implement distributed GI practices without resizing the conventional (Gray) practice as a means of future climate adaptation. Figure B-176 indicates that the addition of distributed infiltration trenches to the conventional site is able to reduce future outflow below the current climate outflow by increasing the partitioning of runoff to infiltration.

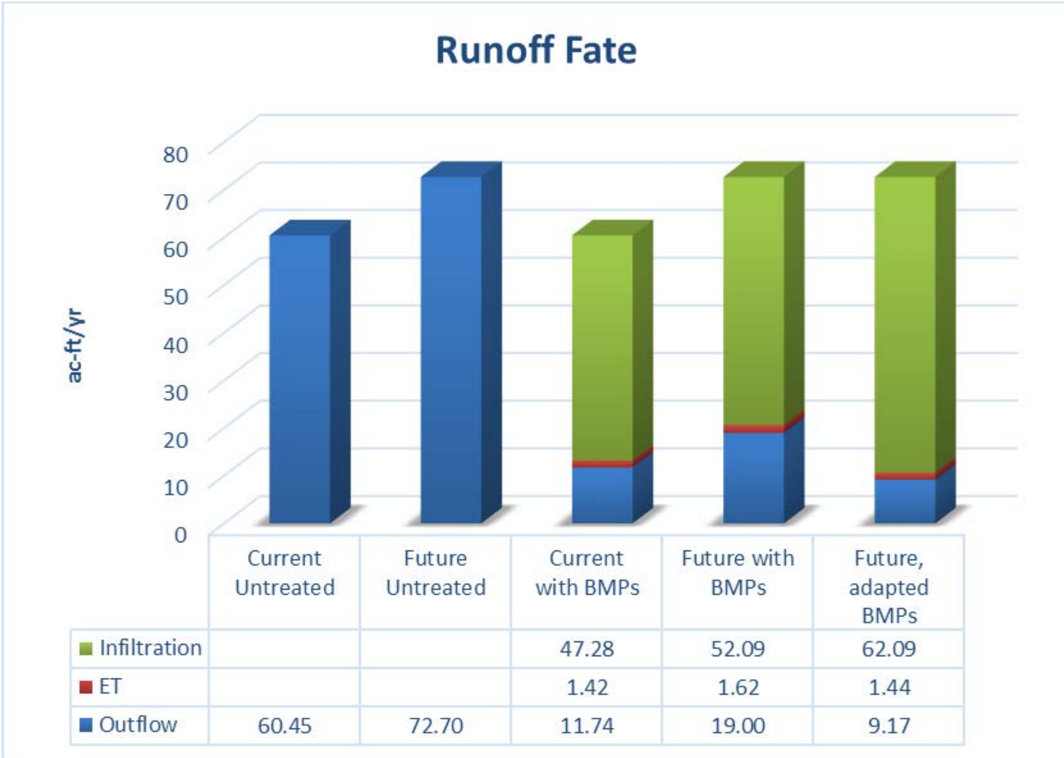


Figure B-176. Current and future partitioning of runoff fate for the Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

The following figures demonstrate that the distributed infiltration trench practices combined with the conventional practices (surface sand filters and extended dry detention basin) are able to achieve high load reductions for sediment, TN, and TP, and allow the site to meet current loading without requiring resizing of the current conventional practices.

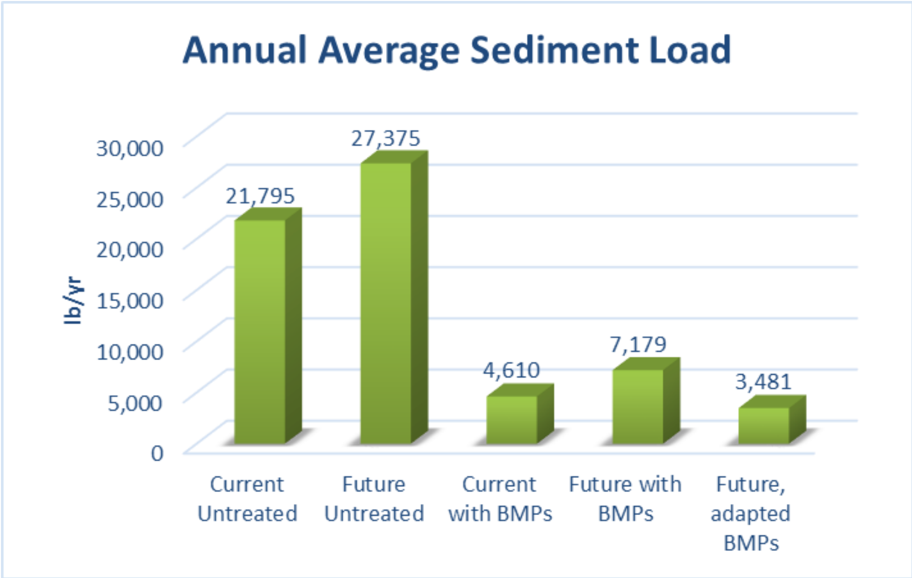


Figure B-177. Current and future performance for annual average sediment load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

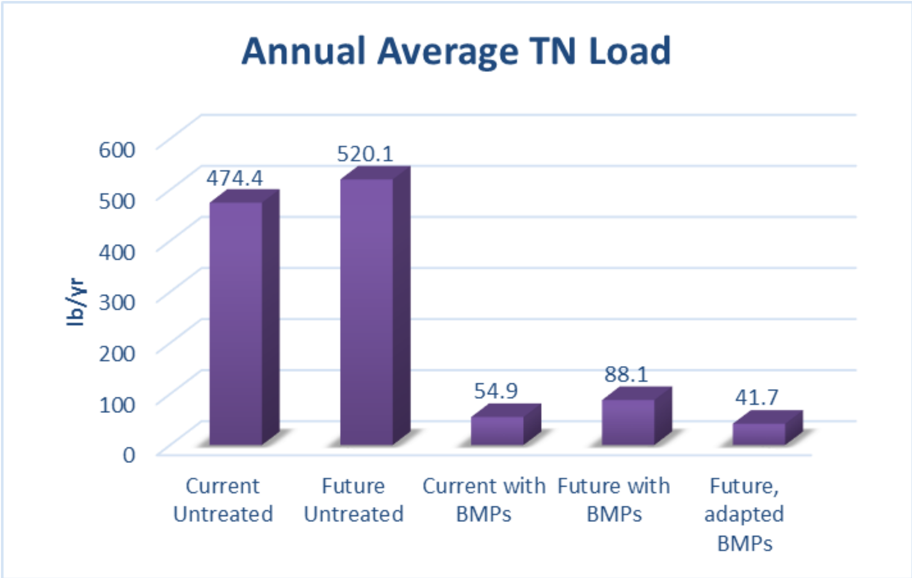


Figure B-178. Current and future performance for annual average total nitrogen (TN) load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

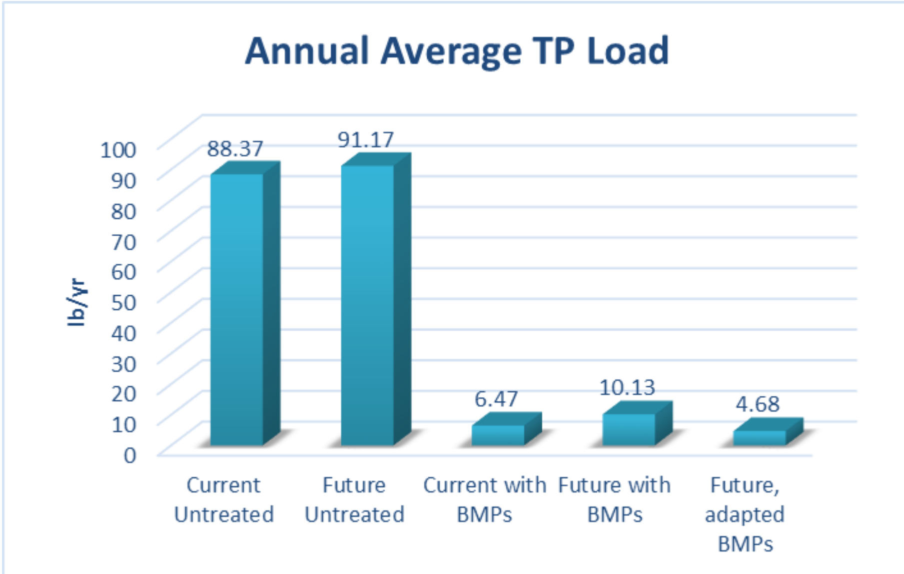


Figure B-179. Current and future performance for annual average total phosphorous (TP) load, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

The FDC evaluation for the Conventional (Gray) Infrastructure with Distributed GI scenario suggests that when distributed infiltration trenches are added to the current conventional practices for future climate (intensity plus 20%) adaptation, the combination produces a flow duration response that is nearly identical to the current climate FDC within the evaluated range of outflows.

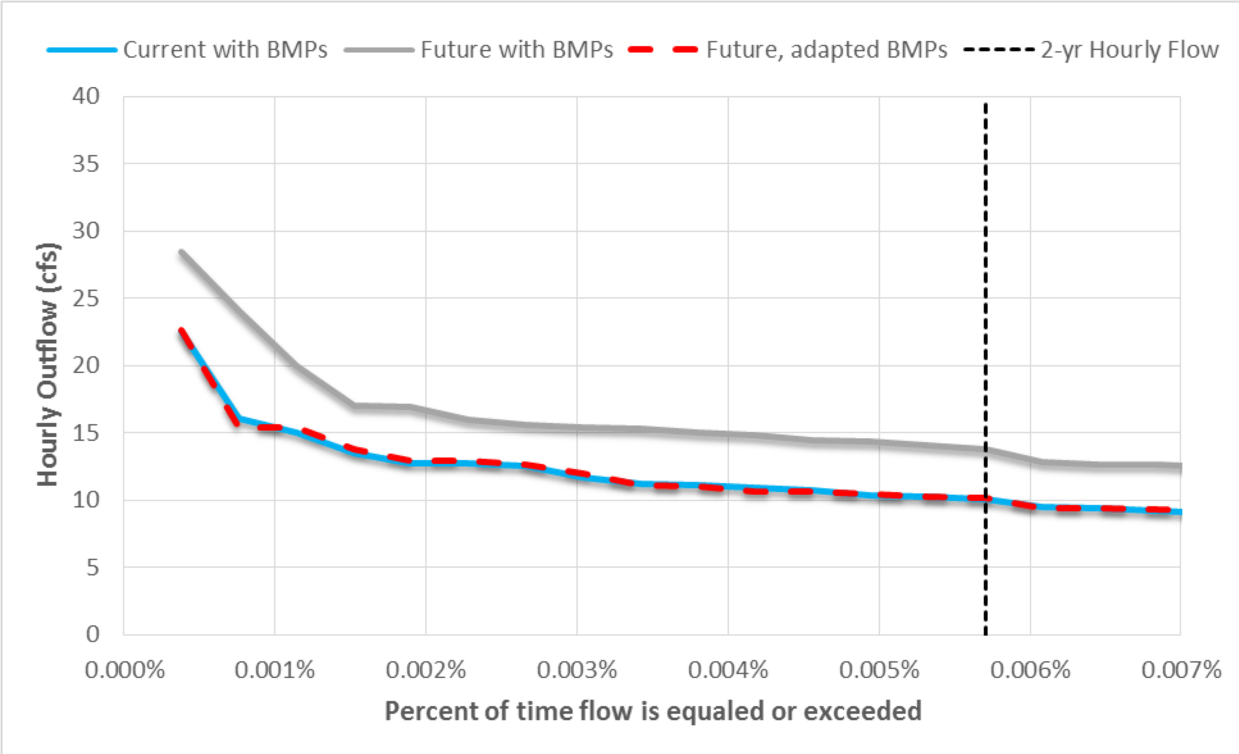


Figure B-180. Flow duration curve (FDC) evaluation for current and future climate, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

Although adding distributed GI to the conventional practices for future (intensity plus 20%) is unable to reduce maximum hourly peak flow to the “current with BMPs” hourly peak flow, the future adapted hourly peak flow is within less than 1% of the current hourly peak flow.

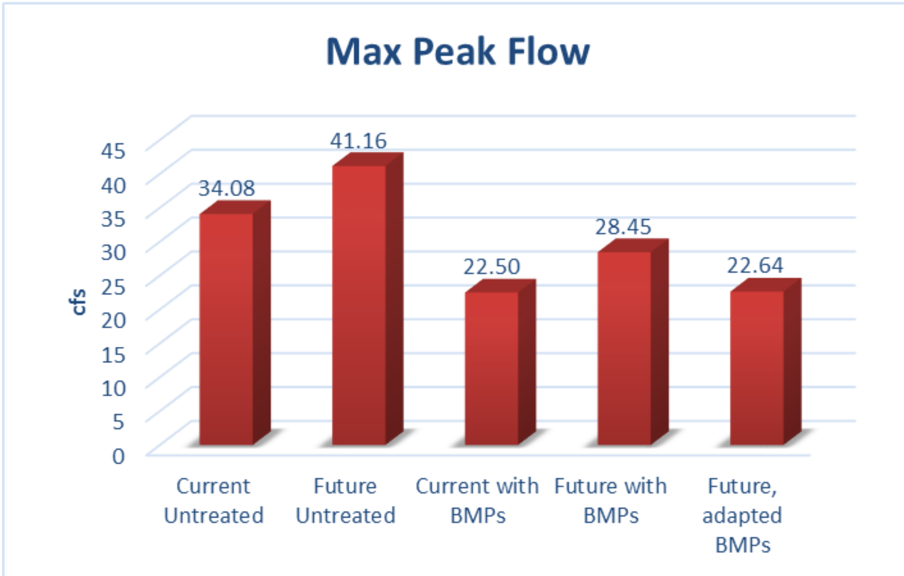


Figure B-181. Current and future performance for maximum hourly peak flow, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

Figure B-182 indicates that for the "intensity plus 20%" climate scenario, the addition of distributed GI to the current conventional site results in monthly outflow volumes that are lower for the future adapted climate scenario than the "current with BMPs" scenario for all months.

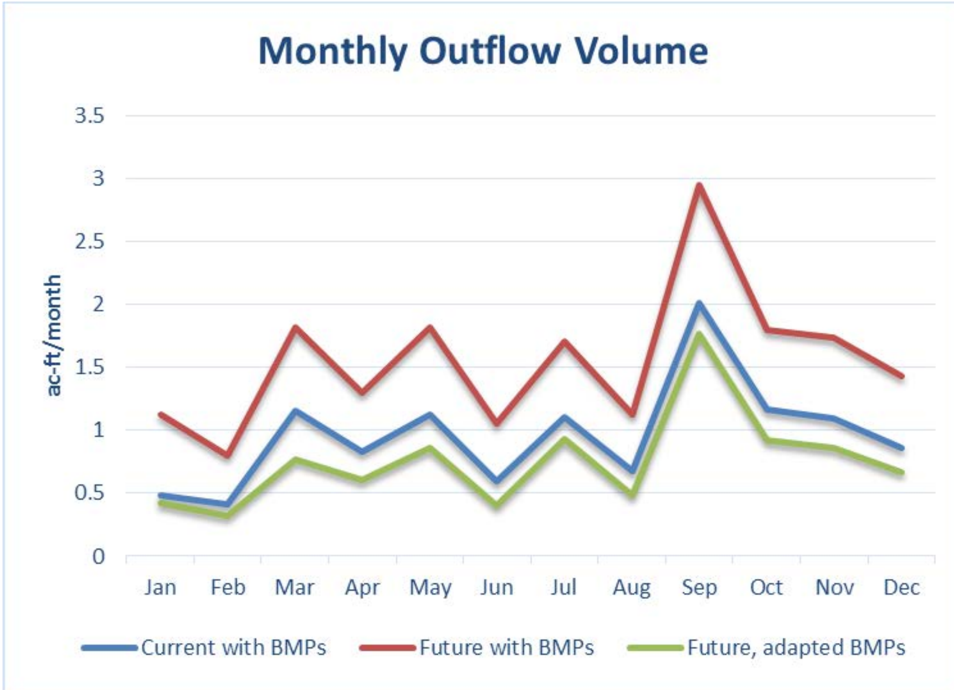


Figure B-182. Current and future performance for monthly outflow volume, Harford County, MD Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

B.2.1.4. Sensitivity Analysis Adaptation Summary

Table B-23 summarizes the increases in BMP footprints for all of the Harford County stormwater management scenarios that would be required to maintain current performance under future climate conditions for the “intensity plus 10%” climate simulation.

Table B-23. Comparison of current and future adapted best management practice (BMP) footprints, Harford County, MD stormwater management scenarios, intensity plus 10%

Location	Climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
				Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Harford County, MD	Intensity change plus 10%	Conventional (Gray) Infrastructure	Extended dry detention basin	25,000	2.9	25,000	2.9	0
			Surface sand filters	10,119	1.2	20,023	2.3	98
		GI with Gray Infrastructure	Dry detention basin	10,000	1.1	10,000	1.1	0
			Infiltration basin	12,858	1.5	18,943	2.2	47
			Infiltration trench	14,800	1.7	20,435	2.3	38
			Permeable pavement	201,242	23.1	201,242	23.1	0
		Conventional (Gray) Infrastructure with Distributed GI	Extended dry detention basin	25,000	2.9	25,000	2.9	0
			Surface sand filters	10,119	1.2	10,119	1.2	0
			Distributed infiltration trench	0	0.0	15,351	1.8	--

In the Conventional (Gray) Infrastructure scenario, the SUSTAIN optimization selected the extended dry detention basin only for adaptation. This outcome is somewhat surprising and follows a different pattern than the adaptations to the “20 Watersheds”-based future climate scenarios, where both sand filters and the detention basin were selected for resizing during the optimization as being the most cost-effective solution. The required basin footprint for future (intensity plus 10%) climate adaptation reflects a near doubling of size.

In the GI with Gray Infrastructure scenario, the SUSTAIN optimization targeted resizing only the infiltration basins and infiltration trenches, the opposite outcome as seen for the Conventional scenario. This is likely due in part to sediment and TP loads being the limiting factor, resulting in the selection of practices with the best infiltration capacity and load reduction. The required infiltration basin footprint reflects nearly a 50% increase, and nearly a 40% increase is required in the infiltration trench footprint. For the Conventional (Gray) Infrastructure with Distributed GI scenario, the addition of 15,351 square feet of distributed infiltration trenches would be needed to maintain current BMP performance. This footprint represents approximately 1.8% of the total site area.

Table B-24 summarizes the increases in BMP footprints that would be required to maintain current performance under future climate conditions for the "intensity plus 20%" climate simulation.

Table B-24. Comparison of current and future adapted best management practice (BMP) footprints, Harford County, MD stormwater management scenarios, intensity plus 20%

Location	Climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
				Footprint SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Harford County, MD	Intensity change plus 20%	Conventional (Gray) Infrastructure	Extended dry detention basin	25,000	2.9	25,000	2.9	0
			Surface sand filters	10,119	1.2	28,043	3.2	177
		GI with Gray Infrastructure	Dry detention basin	10,000	1.1	10,000	1.1	0
			Infiltration basin	12,858	1.5	27,846	3.2	117
			Infiltration trench	14,800	1.7	23,350	2.7	58
			Permeable pavement	201,242	23.1	201,242	23.1	0
		Conventional (Gray) Infrastructure with Distributed GI	Extended dry detention basin	25,000	2.9	25,000	2.9	0
			Surface sand filters	10,119	1.2	10,119	1.2	0
			Distributed infiltration trench	0	0.0	32,514	3.7	--

In the Conventional (Gray) Infrastructure scenario, the extended dry detention basin footprint must increase by a factor of 2.8 for future (intensity plus 20%) climate adaptation. In the GI with Gray Infrastructure scenario, the required infiltration basin footprint reflects a more than doubling in size, and nearly a 60% increase is required in the infiltration trench footprint. For the Conventional (Gray) Infrastructure with Distributed GI scenario, the addition of 32,514 square feet of distributed infiltration trenches would be required to maintain current performance. This footprint represents approximately 3.7% of the total site area.

B.2.1.5. Cost of Adaptation

Table B-25 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all three Harford County stormwater management scenarios under future "intensity plus 10%" climate, as well as the percentage increase in cost (current to future adapted) and increase (millions of dollars) per acre of site.

Table B-25. Comparison of the current and future estimated 20-year present value costs for the Harford County, MD stormwater management scenarios, Intensity Change Plus 10%

Location	Climate scenario	Stormwater management scenario	Current cost 20-yr present value, $millions	Future adapted cost 20-yr present value, $millions	Increase in cost (20-yr present value, $millions)	% increase in cost	Increase per acre of site $millions
Harford County, MD	plus 10%	Conventional (Gray) Infrastructure	5.31	8.00	2.69	51	0.13
		GI with Gray Infrastructure	5.15	6.24	1.09	21	0.05
		Conventional (Gray) Infrastructure with Distributed GI	5.31	6.93	1.62	30	0.08

Table B-26 provides an estimate of cost for the future "intensity plus 20%" climate scenario.

Table B-26. Comparison of the current and future estimated 20-year present value costs for the Harford County, MD stormwater management scenarios, Intensity Change Plus 20%

Location	Climate scenario	Stormwater management scenario	Current cost 20-yr present value, $millions	Future adapted cost 20-yr present value, $millions	Increase in cost (20-yr present value, $millions)	% increase in cost	Increase per acre of site $millions
Harford County, MD	Intensity change plus 20%	Conventional (Gray) Infrastructure	5.31	10.17	4.86	92	0.24
		GI with Gray Infrastructure	5.15	7.29	2.13	41	0.11
		Conventional (Gray) Infrastructure with Distributed GI	5.31	8.86	3.55	67	0.18

B.2.2. Scott County, MN

B.2.2.1. Conventional (Gray) Infrastructure

Intensity Change Minus 10%

As discussed in *Section 4.3.* of the report, the sensitivity analysis entailed modifying the current precipitation record to represent potential future climate conditions by applying a graduated set of percentage changes to the current precipitation record. For this particular sensitivity scenario, the resulting change in annual runoff volume and pollutant load was a decrease under future climate compared to the current climate, as illustrated in the figures below. For these reasons, this climate scenario was not investigated for adaptation simulation.

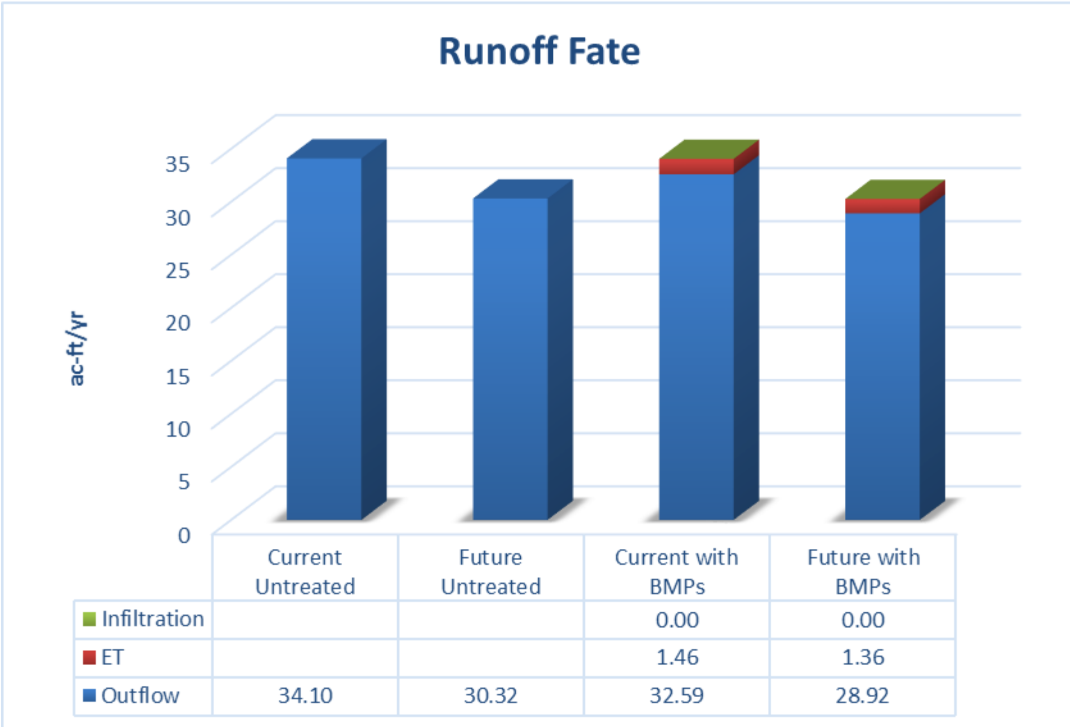


Figure B-183. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

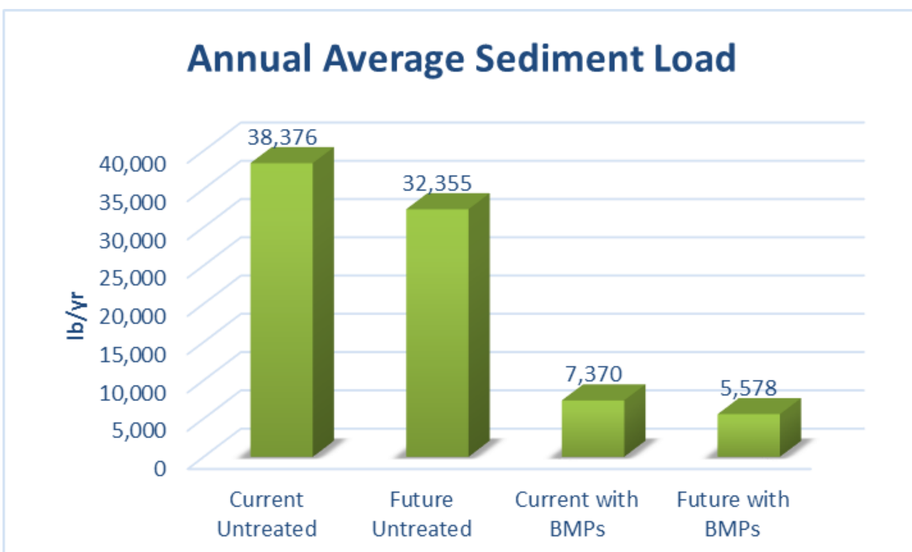


Figure B-184. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

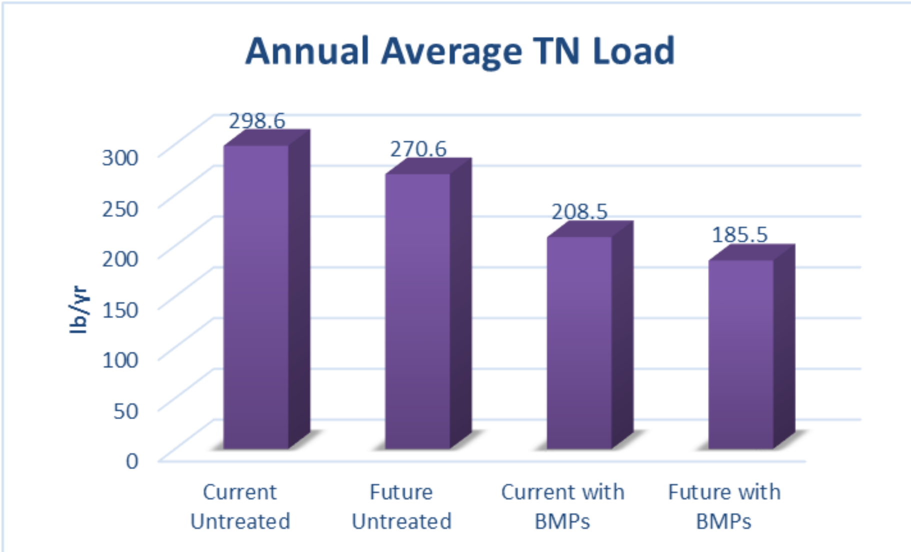


Figure B-185. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

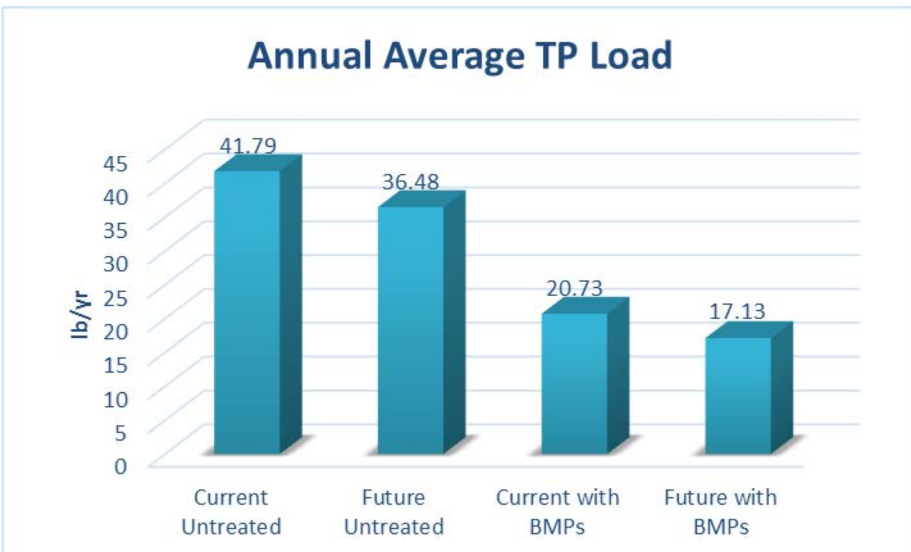


Figure B-186. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

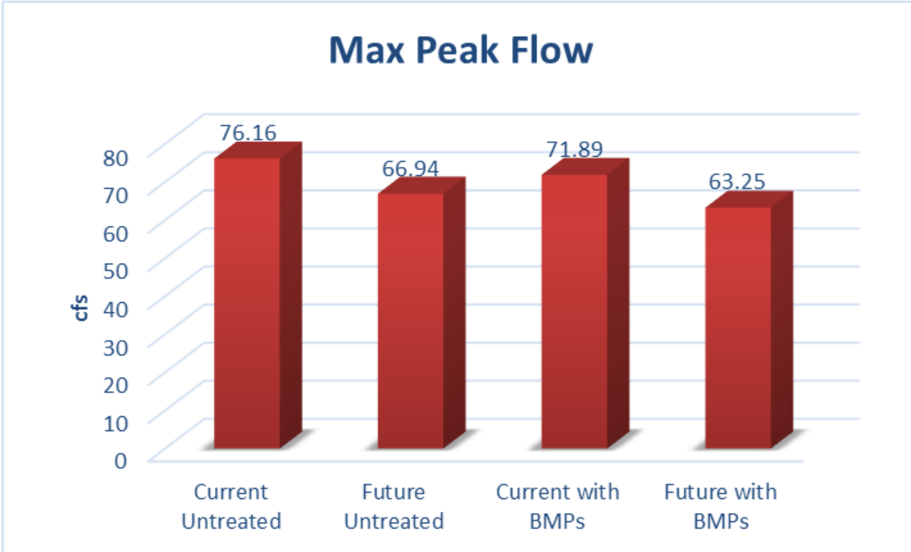


Figure B-187. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

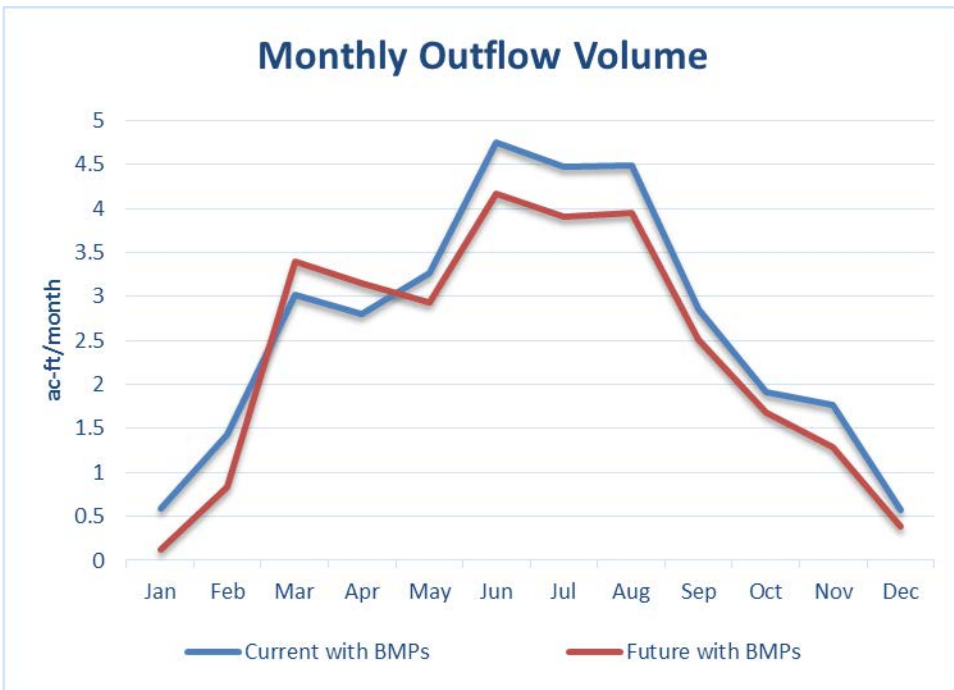


Figure B-188. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure (intensity minus 10%) scenario.

Intensity Change Plus 10%

This sensitivity analysis of a 10% increase in intensity resulted in an increase of both total runoff volume and outflow volume. As discussed previously, the soils of the Scott County, MN site are poorly infiltrating. The primary function of the conventional practice (wet pond) is to provide storage and peak flow control and to some degree ET. For these reasons, outflow is the dominant runoff fate pathway under both current and future climate conditions. For future adaptation, increasing the wet pond footprint increases the partitioning of runoff to ET due to the increased surface area. As a result, outflow is decreased below the current climate outflow.

Because the practice resizing for the future "intensity plus 10%" climate was driven by the required reduction in outflow volume, the future adapted BMP annual average loads for sediment (see Figure B-190), TP (see Figure B-191), and TN (see Figure B-192) are all well below the "current with BMPs" loads due to the relatively large footprint required to meet the flow performance measure.

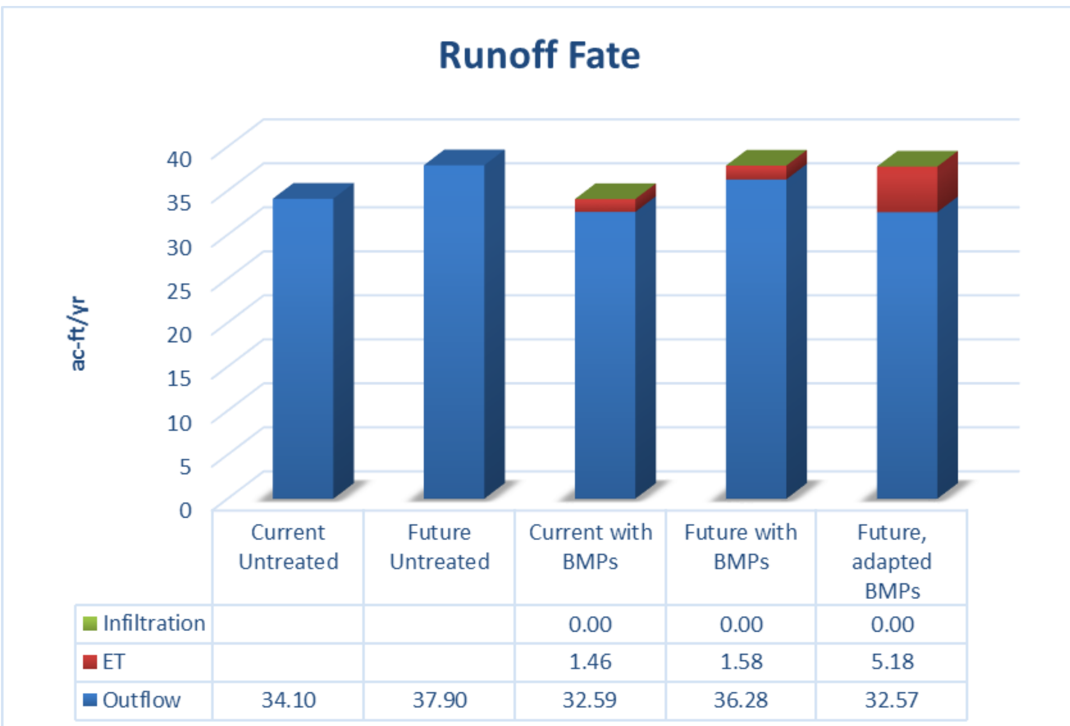


Figure B-189. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

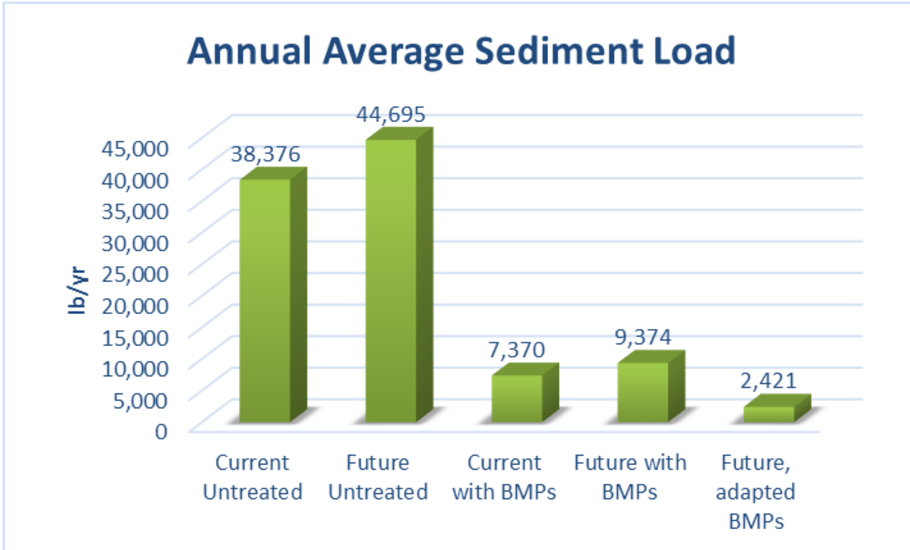


Figure B-190. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

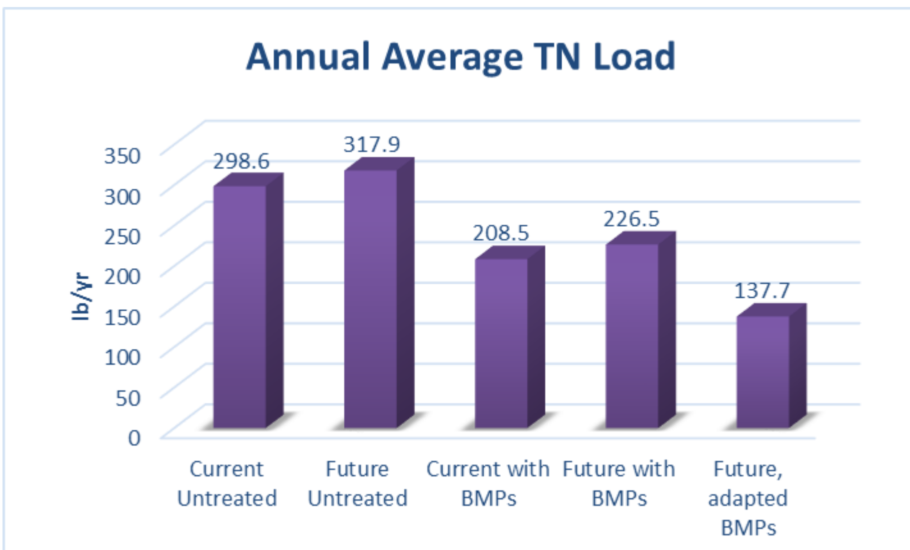


Figure B-191. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

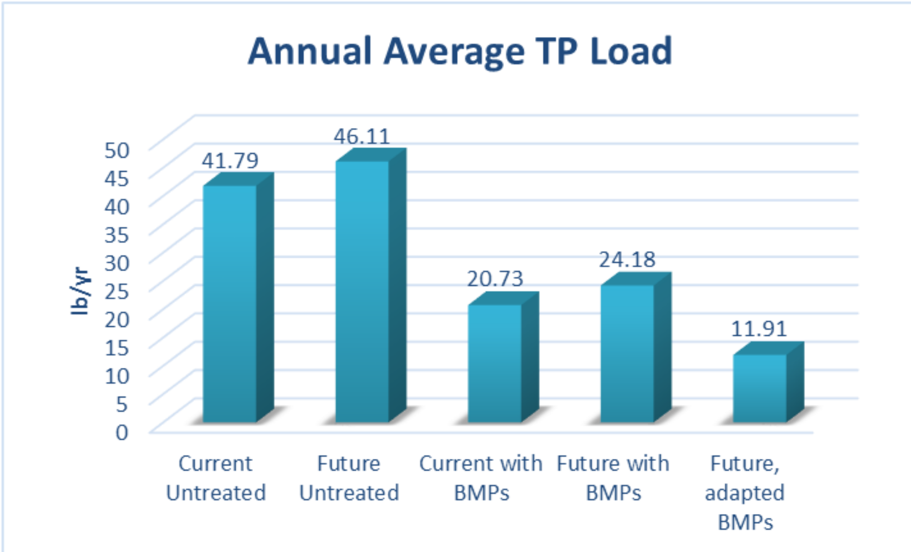


Figure B-192. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

As discussed above, the increase in footprint of the wet pond for adaptation in the future “intensity plus 10%” climate scenario was primarily driven by the required reduction in outflow volume that would be necessary to maintain the current climate outflow. As a result, the increased wet pond size produces a “future, adapted BMPs” flow duration curve that is reduced well below the “current with BMPs” curve for almost the entire range of flows evaluated.

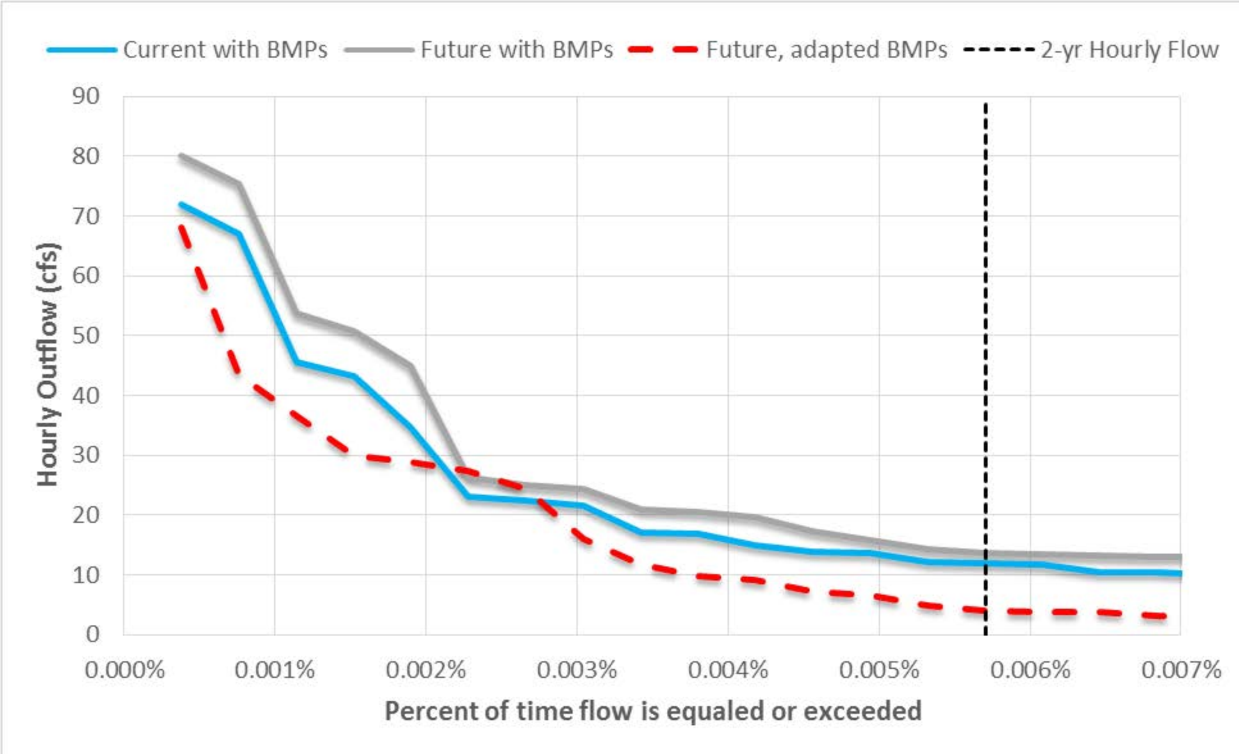


Figure B-193. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

Figure B-194 indicates that the future adapted ("intensity plus 10%") wet pond results in a reduction in maximum hourly peak flow due to the increased sizing of the practice to maintain current performance for outflow.

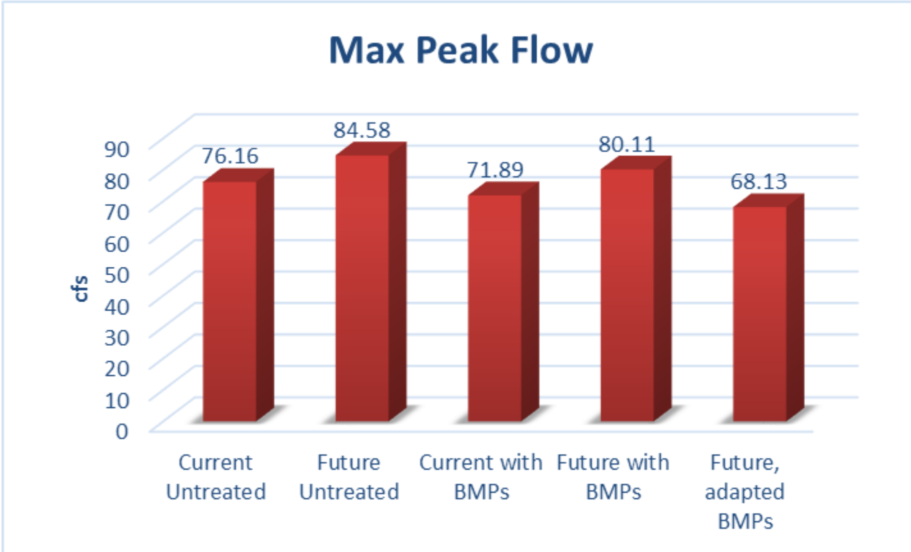


Figure B-194. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

Due to the resizing of the wet pond being driven by the required reduction in outflow for the future "intensity plus 10%" climate scenario, the resulting adaptation produces a monthly outflow volume response that is very similar to the current monthly outflow response.

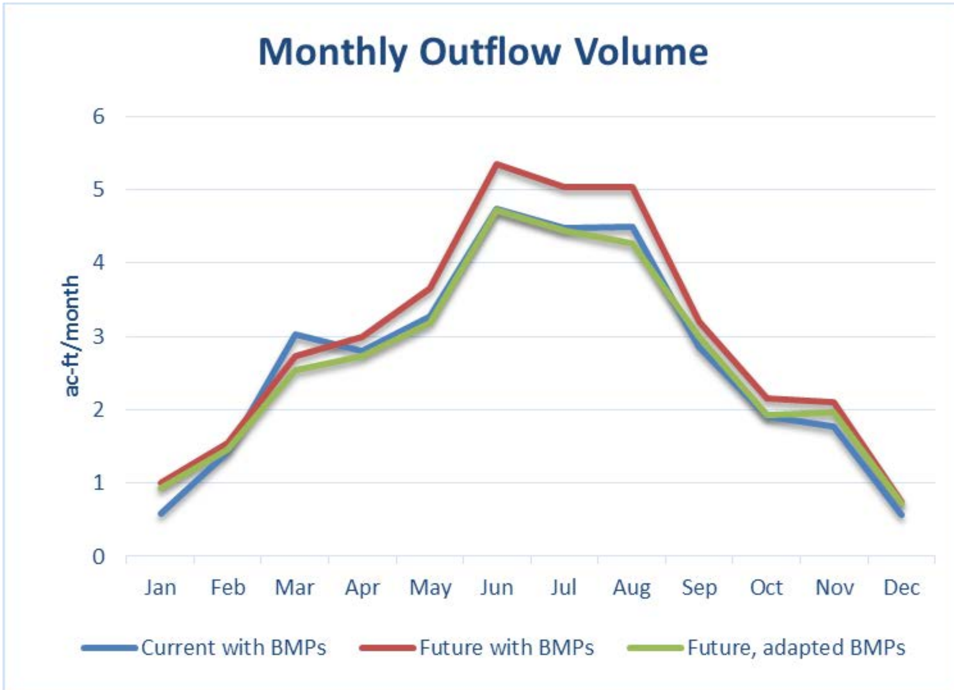


Figure B-195. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 10%) scenario.

Intensity Change Plus 20%

As discussed in *Section 4.3.* of the report, the sensitivity analysis entailed modifying the current precipitation record to represent potential future climate conditions by applying a graduated set of percentage changes across the entire record. For this particular sensitivity scenario, the result was an increase, both in total runoff volume and in outflow volume. For future adaptation, increasing the wet pond footprint increases the partitioning of runoff to ET due to the increased surface area. As a result, outflow is decreased below the current climate outflow.

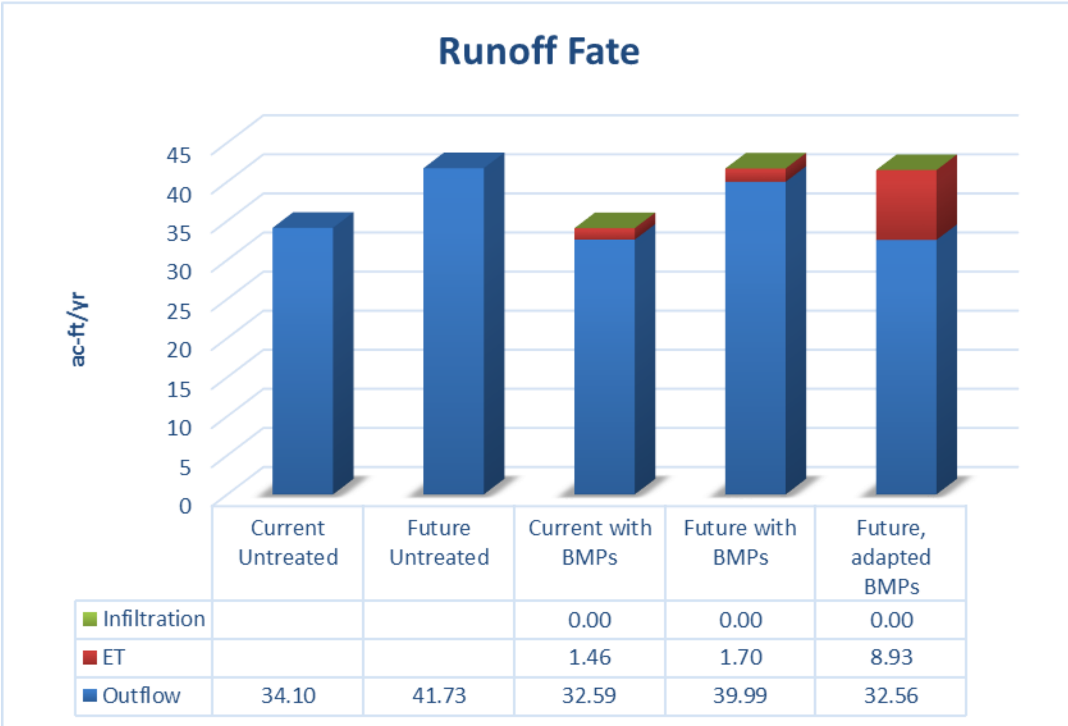


Figure B-196. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

Because the practice resizing for the future “intensity plus 20%” climate was driven by the required reduction in outflow volume, the future adapted BMP annual average loads for sediment, TN, and TP are all well below the “current with BMPs” loads due to the relatively large footprint required to meet the flow performance measure, as shown in the following figures.

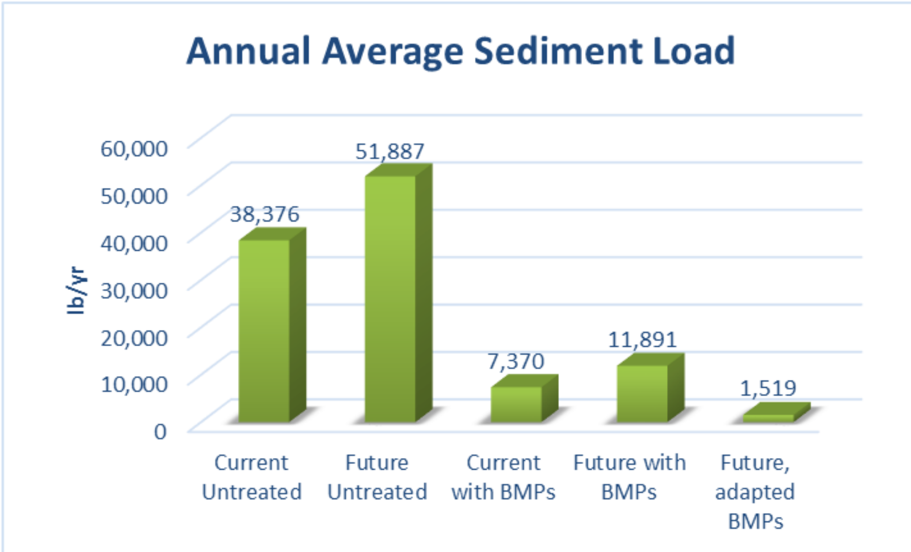


Figure B-197. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

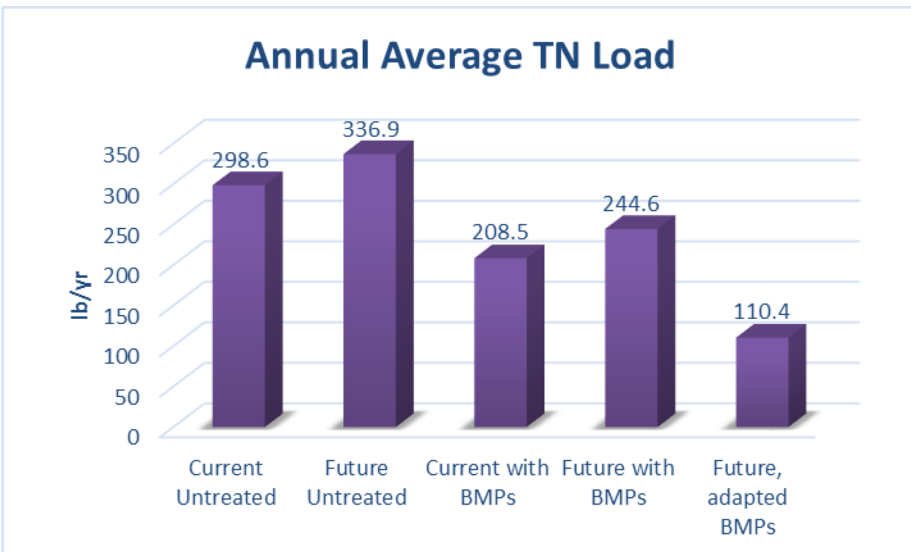


Figure B-198. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

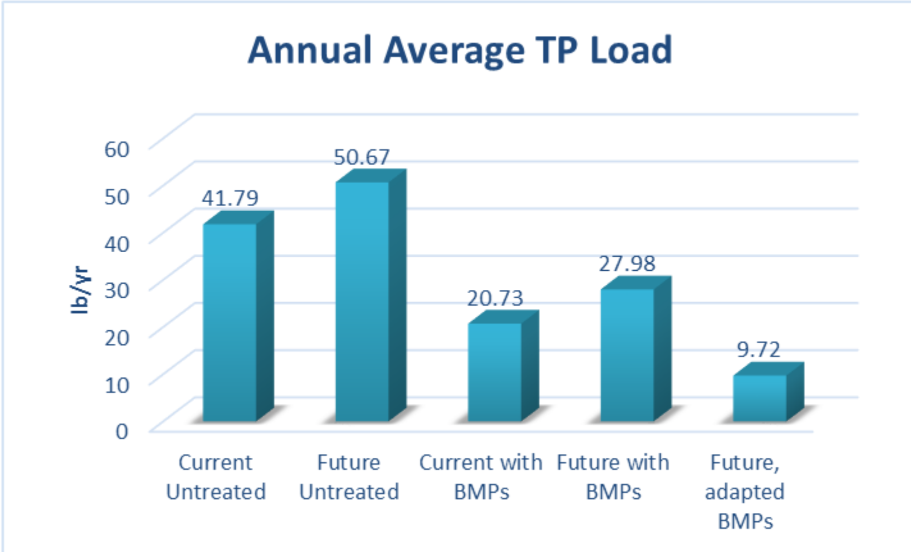


Figure B-199. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

The increased wet pond size for the future (“intensity plus 20%”) climate adaptation produces a flow duration curve that is reduced below the “current with BMPs” curve for the entire range of outflows evaluated.

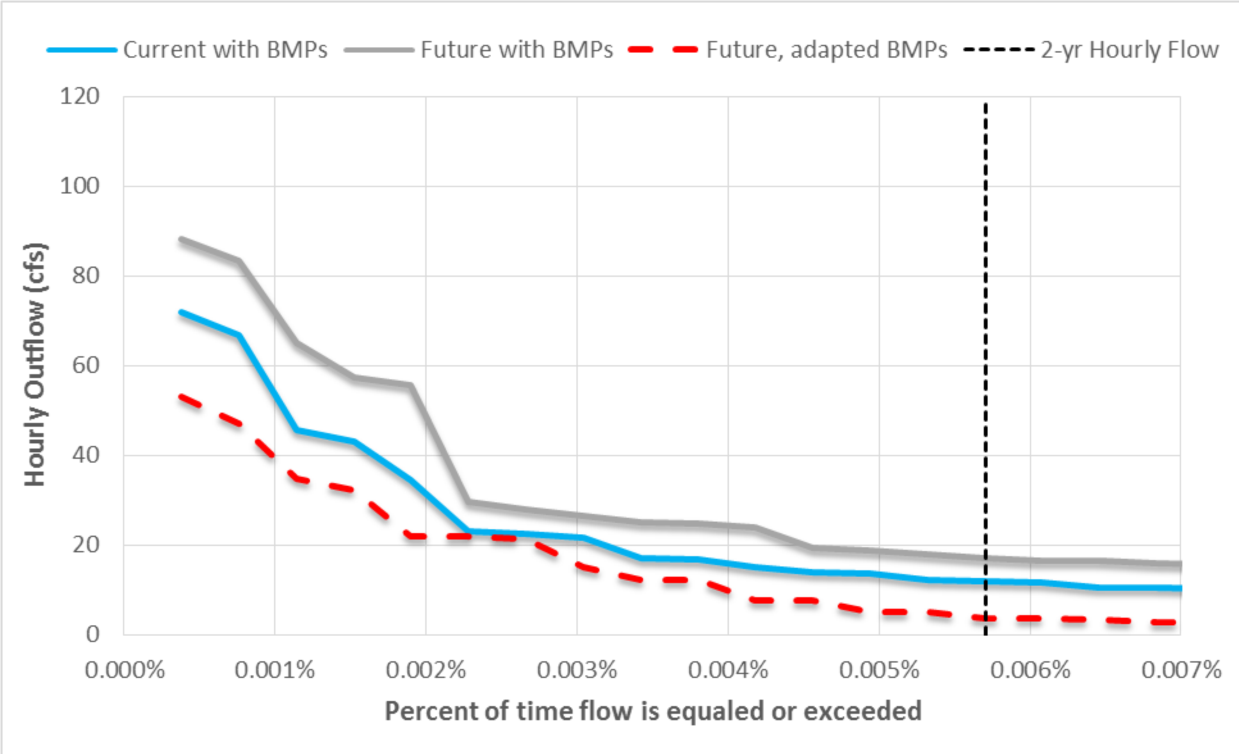


Figure B-200. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

Figure B-201 indicates that the future adapted ("intensity plus 20%") wet pond results in a reduction in maximum hourly peak flow due to the increased sizing of the practice to maintain current performance for outflow.

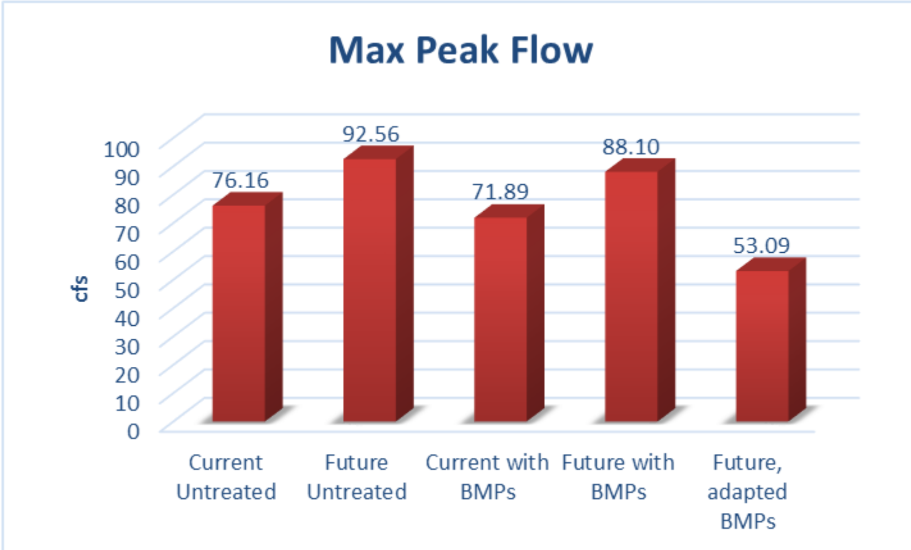


Figure B-201. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

The future adapted conventional practice (wet pond) footprint for the “intensity plus 20%” climate scenario results in monthly outflow volumes that are less than, very close to, or only slightly higher than current outflows for all months.

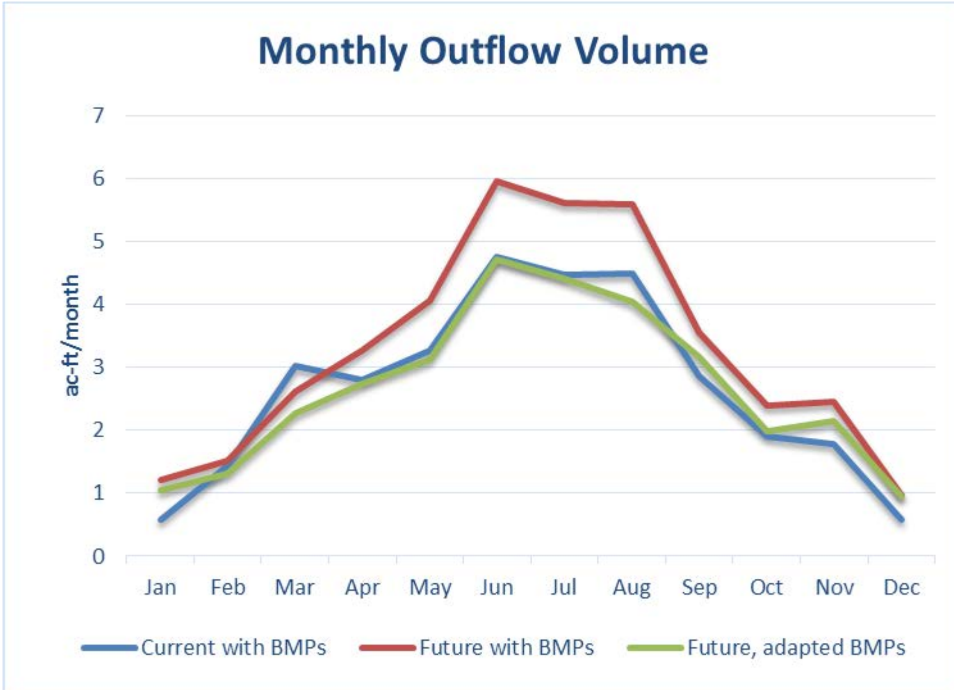


Figure B-202. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure (intensity plus 20%) scenario.

B.2.2.2. Green Infrastructure (GI) with Gray Infrastructure

Intensity Change Minus 10%

This scenario was not selected for adaptation simulation; refer to discussion in *Section B.2.2.1.* and the following figures, which demonstrate decreased outflow volume and pollutant loading in the "intensity minus 10%" climate scenario compared to the current climate.

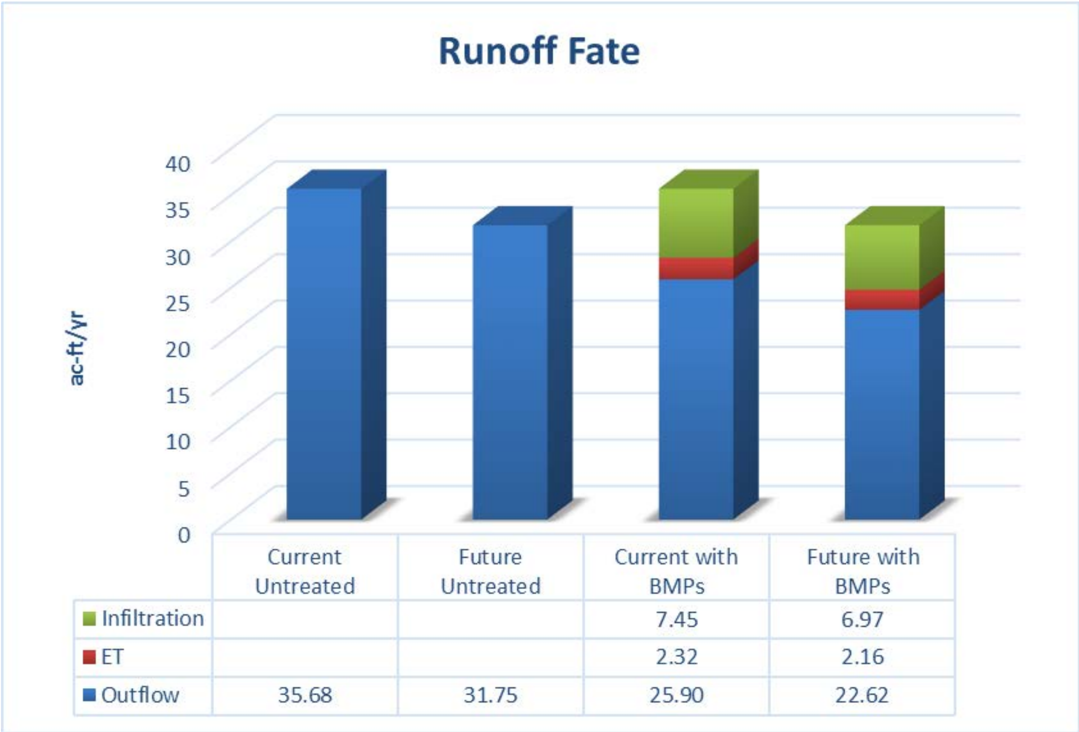


Figure B-203. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

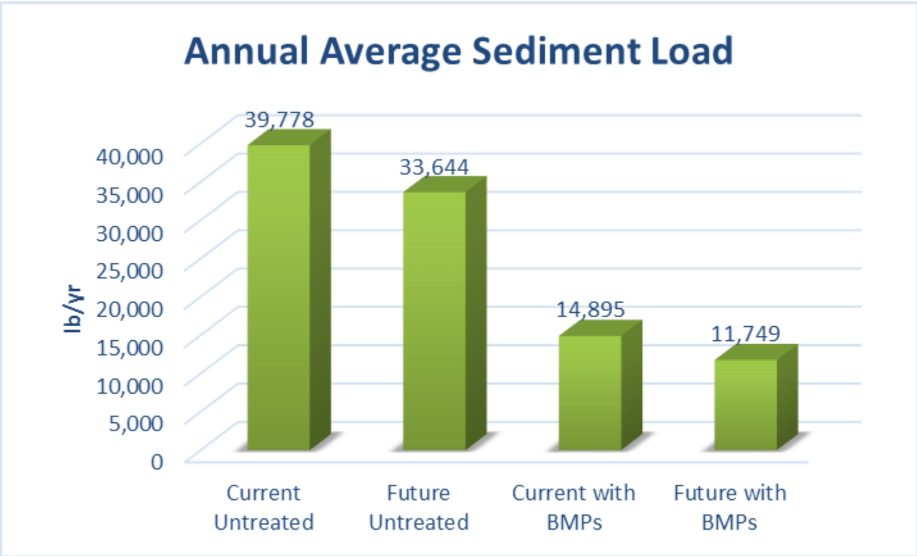


Figure B-204. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

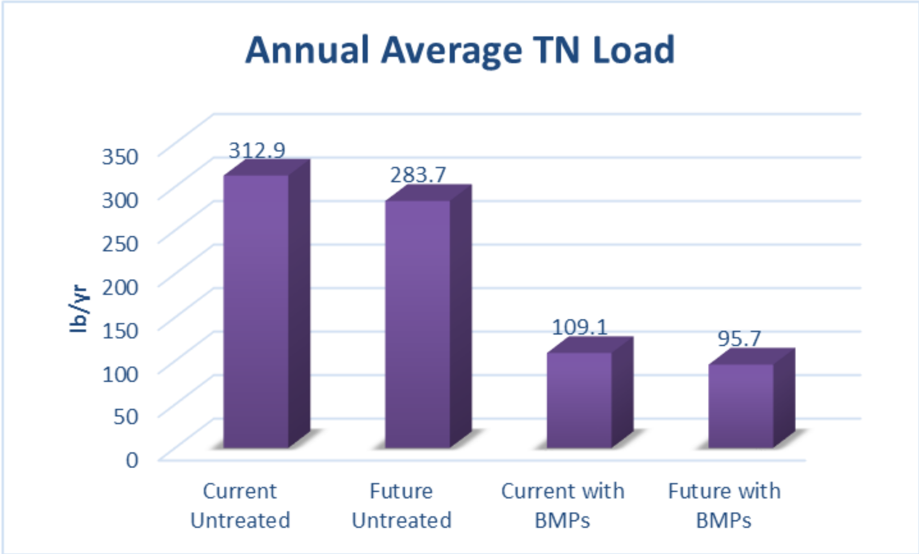


Figure B-205. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

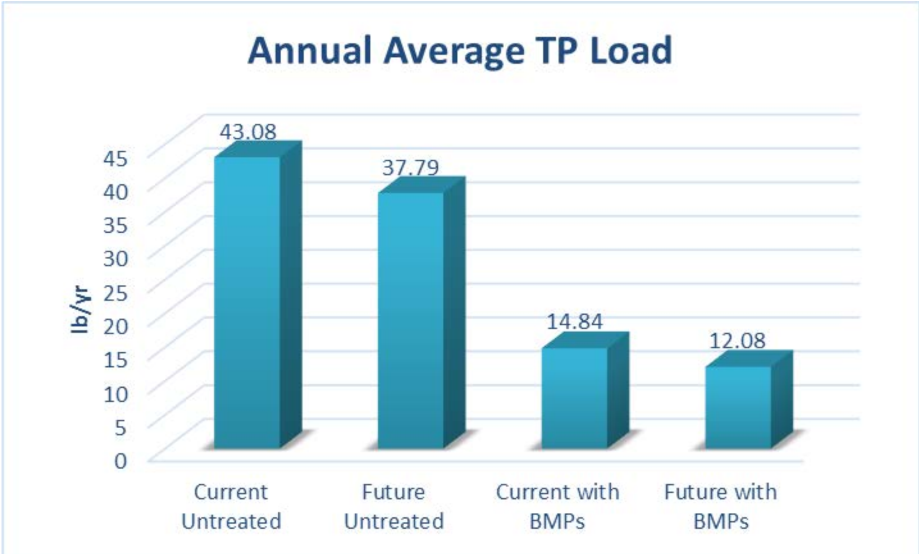


Figure B-206. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

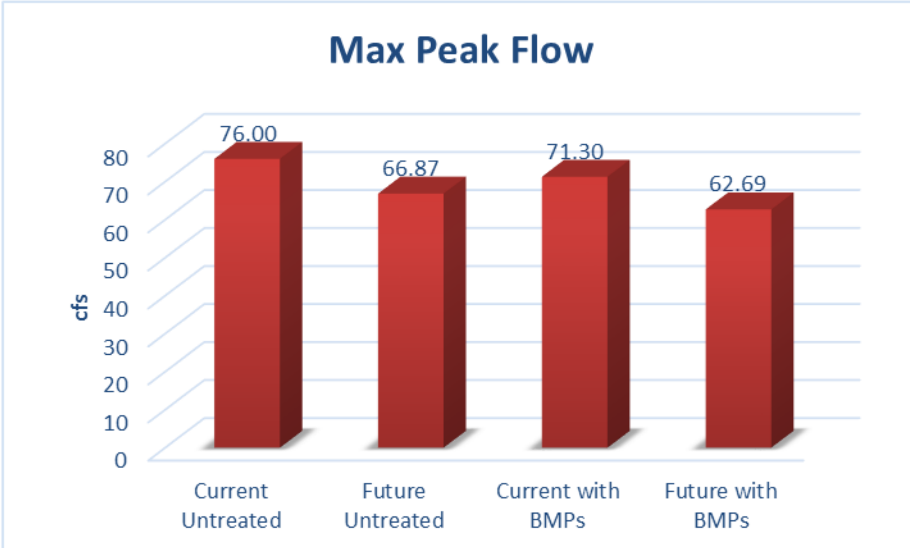


Figure B-207. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

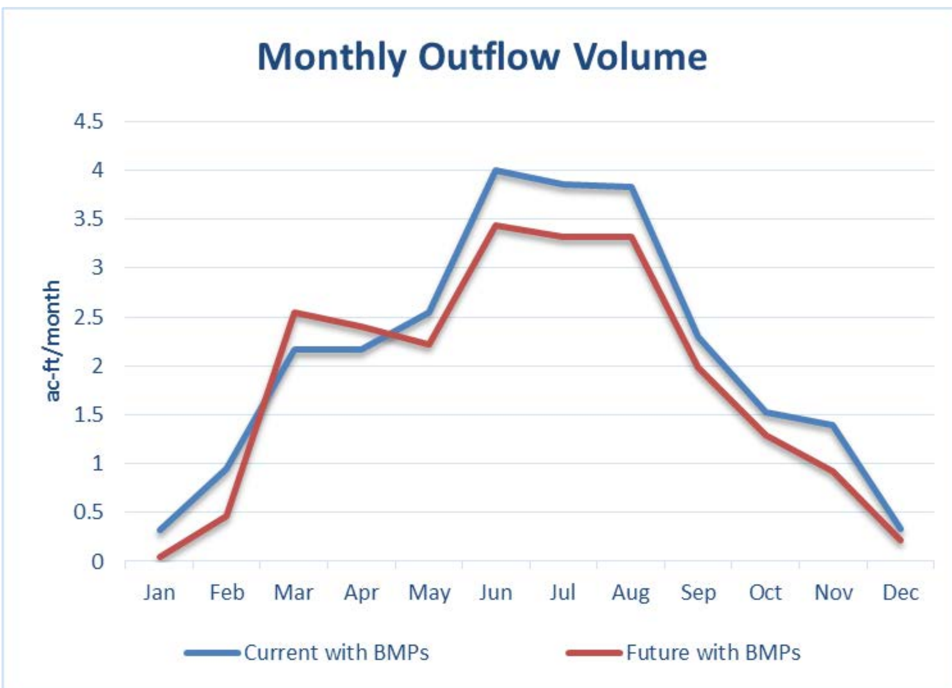


Figure B-208. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity minus 10%) scenario.

Intensity Change Plus 10%

As discussed in *Section B.2.2.1.* , the “intensity plus 10%” climate scenario for Scott County results is an increase both in total runoff volume and in outflow volume, as shown in Figure B-209. Because the soils in the Scott County site are poorly infiltrating, the majority of the increase in runoff volume partitions into outflow. When the green (bioretention) and gray (dry detention basin) practices are resized for future adaptation, the fraction of runoff that is converted to infiltration and ET is increased, enabling the site to maintain its current performance for outflow volume.

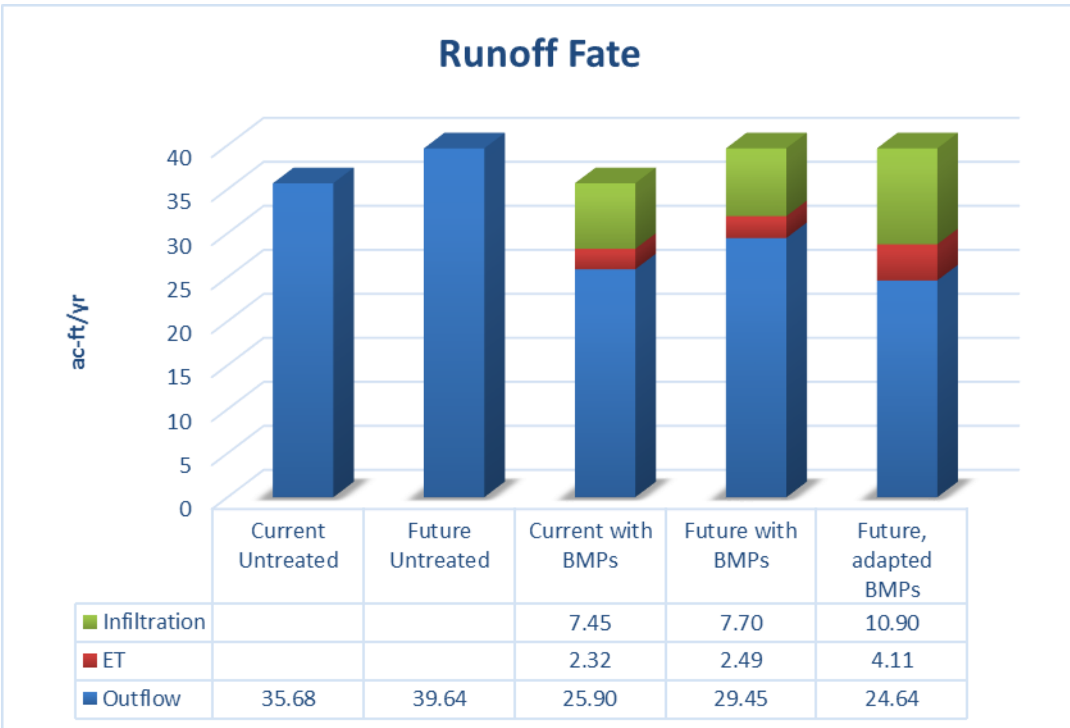


Figure B-209. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

The following figures demonstrate that the adapted Green (bioretention) and Gray (dry detention basin) practices in the Scott County GI with Gray Infrastructure scenario are able to mitigate the increases in annual average sediment (see Figure B-210), TN (see Figure B-211), and TP (see Figure B-212) load under future “intensity plus 10%” climate conditions.

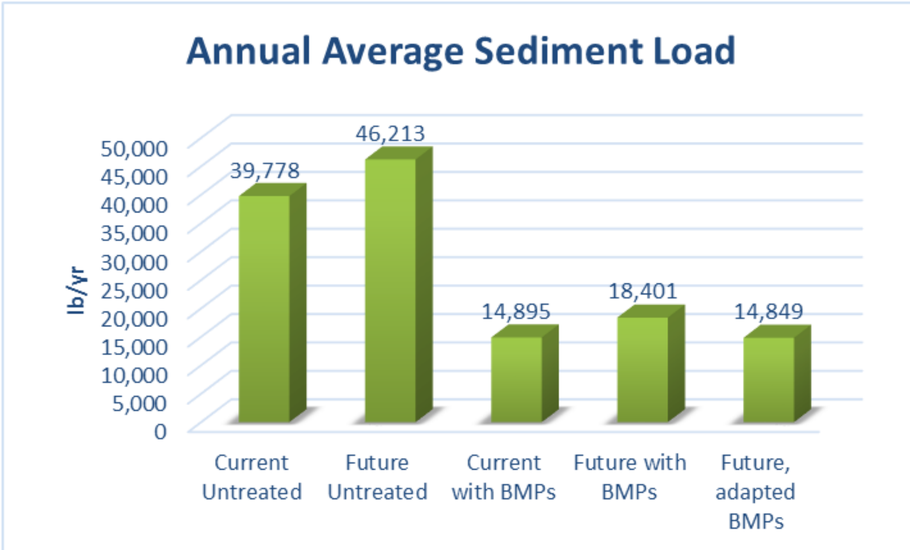


Figure B-210. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

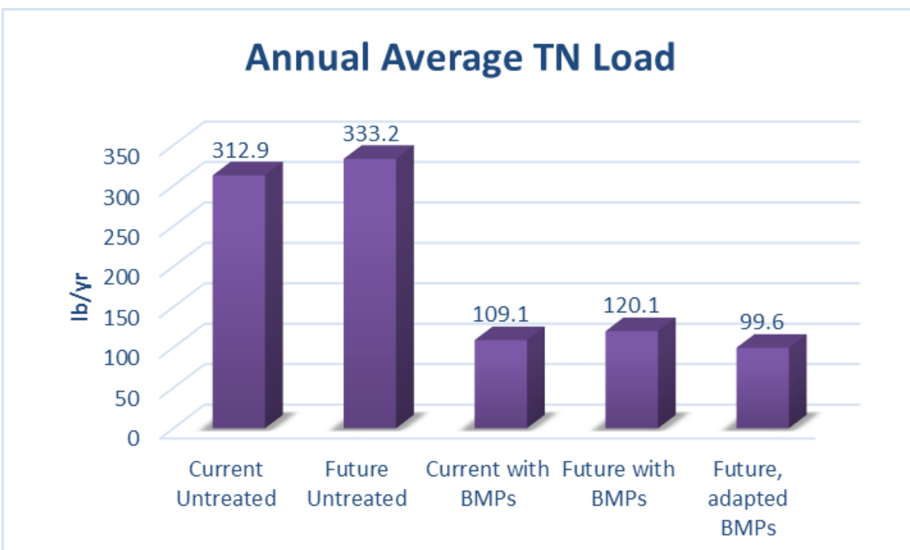


Figure B-211. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

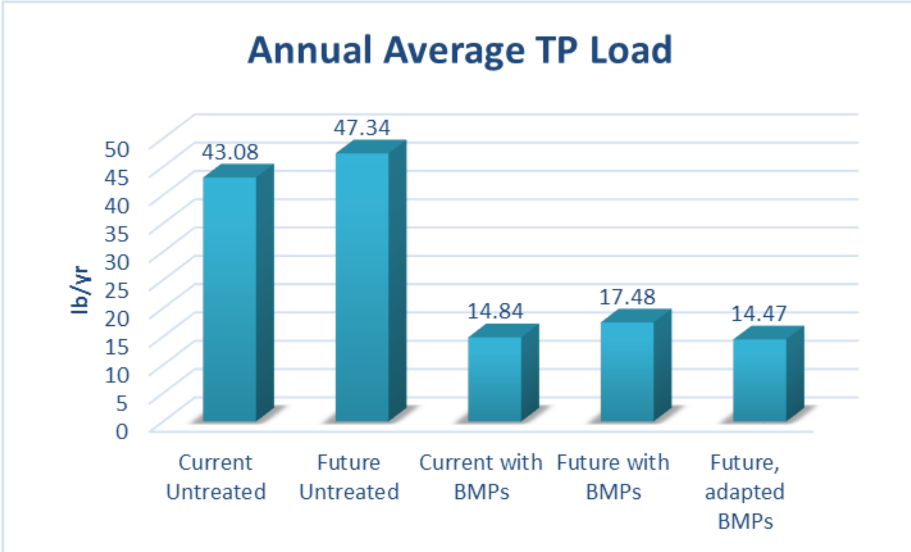


Figure B-212. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

The flow duration curve analysis (see Figure B-213) for the Scott County GI with Gray Infrastructure ("intensity plus 10%") scenario suggests that the adapted practices are able to reasonably match the outflow response of the current practices within the evaluated range of flows.

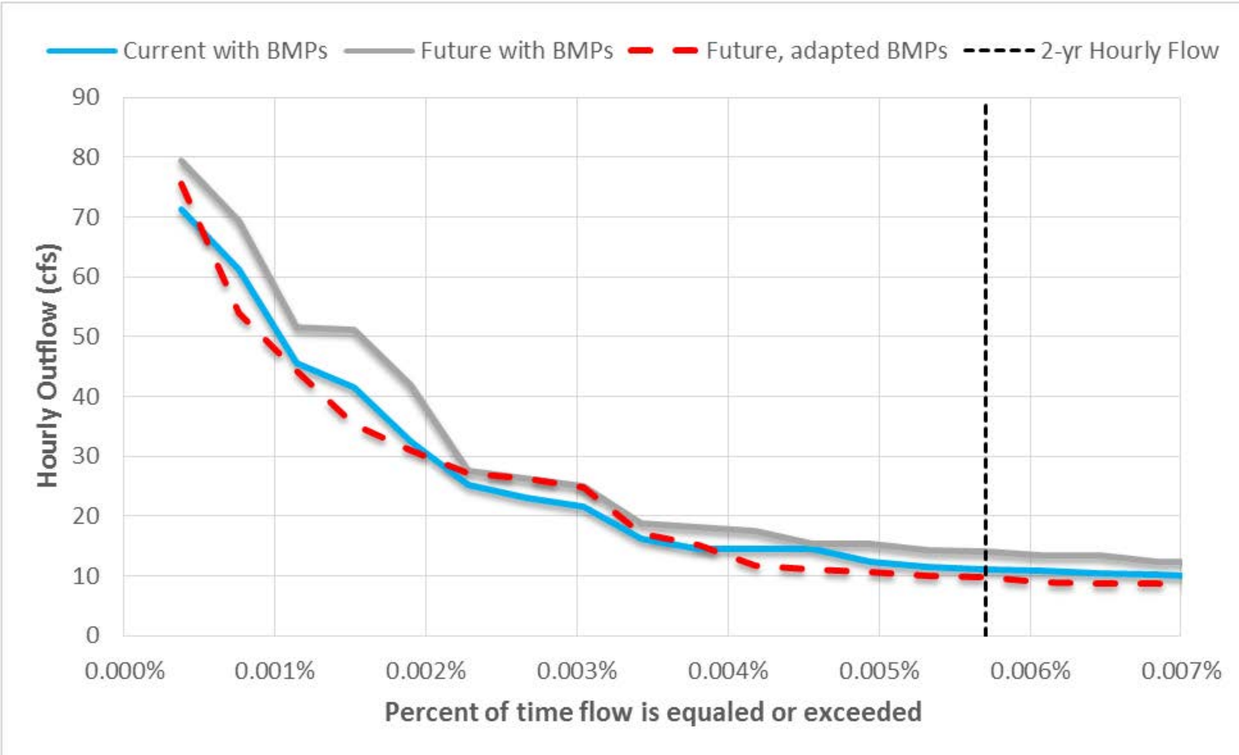


Figure B-213. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

Although maintaining maximum hourly peak flow at current performance is not an objective of the adaptation simulation, Figure B-214 indicates that the adapted Green and Gray practices are able to reduce hourly peak flow to some extent compared to the future (not adapted) practice sizing.

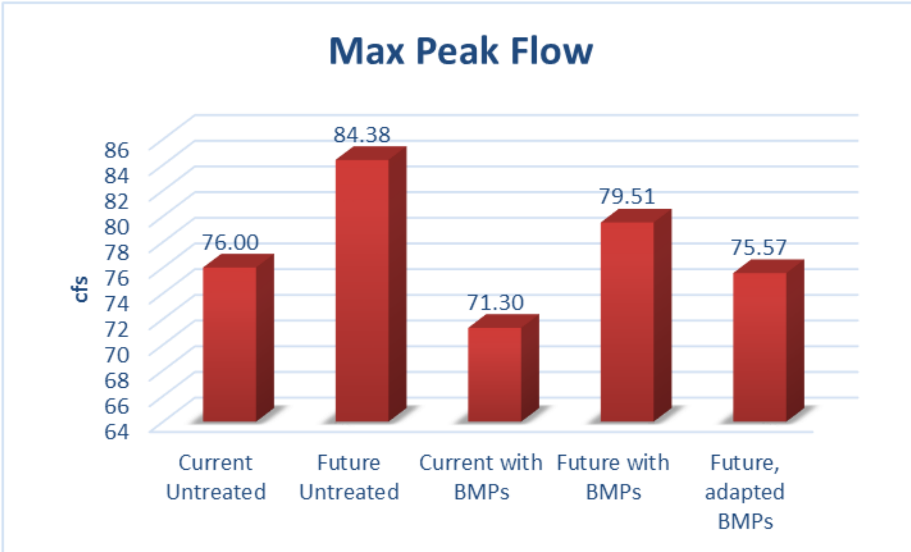


Figure B-214. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

The future ("intensity plus 10%") climate adaptation produces a monthly outflow volume response that is very similar to the current monthly outflow response. The greatest observed discrepancy is in March, when the future adapted monthly outflow volume is lower than the current monthly outflow volume by more than 1 acre-foot.

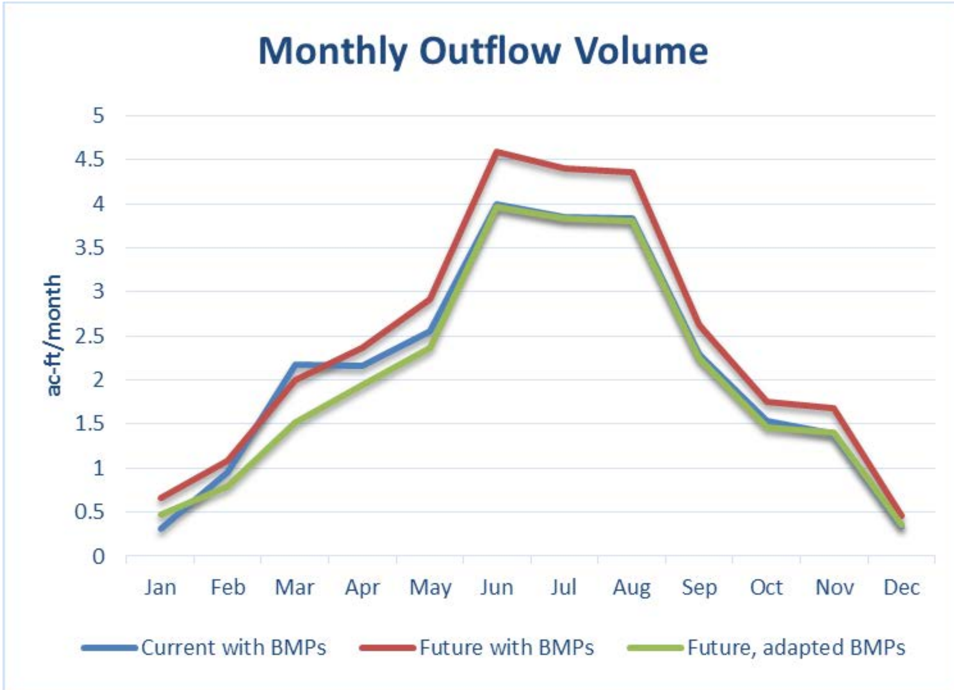


Figure B-215. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 10%) scenario.

Intensity Change Plus 20%

As discussed in *Section B.2.2.1.* , the "intensity plus 20%" climate scenario for Scott County results is an increase both in total runoff volume and in outflow volume, as shown in Figure B-216. Because the soils in the Scott County site are poorly infiltrating, the majority of the increase in runoff volume partitions into outflow. When the Green (bioretention) and Gray (dry detention basin) practices are resized for future adaptation, the fraction of runoff that is converted to infiltration and ET is increased, enabling the site to maintain its current performance for outflow volume, although outflow remains the dominant runoff fate pathway.

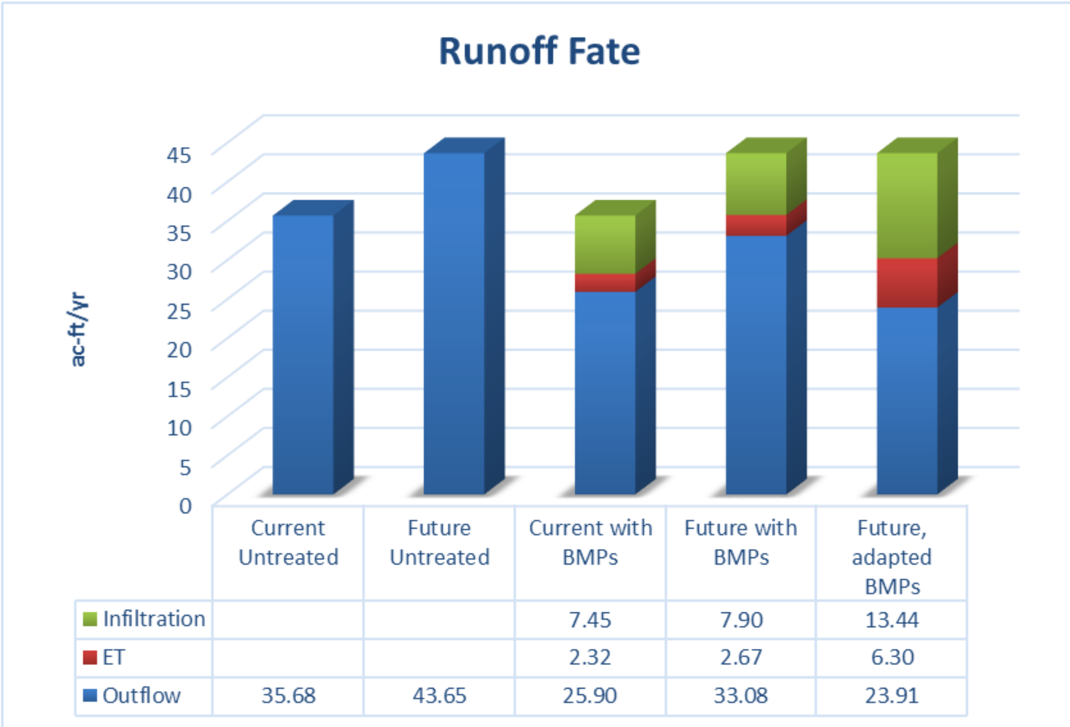


Figure B-216. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

The following figures demonstrate that the adapted Green (bioretention) and Gray (dry detention basin) practices in the Scott County GI with Gray Infrastructure scenario are able to mitigate the increases in annual average sediment (see Figure B-217), TN (see Figure B-218), and TP (see Figure B-219) load under future "intensity plus 20%" climate conditions.

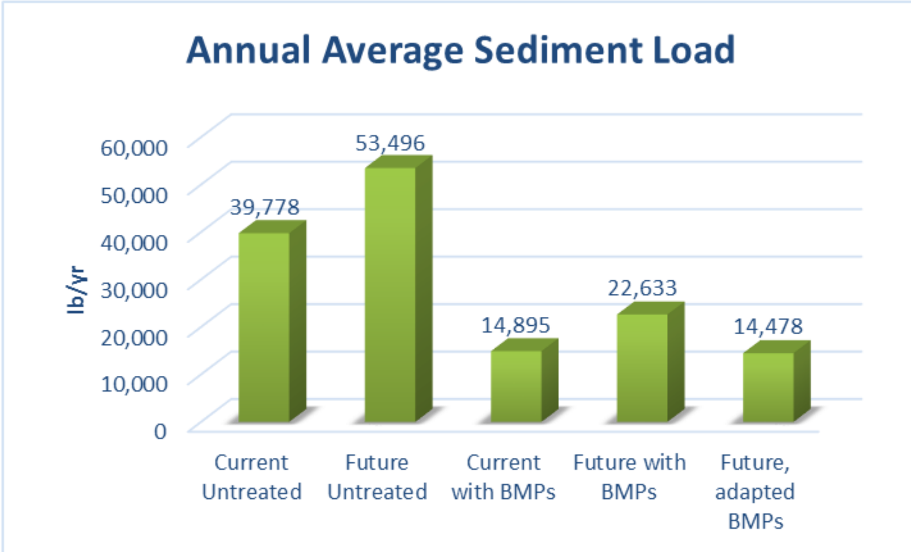


Figure B-217. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

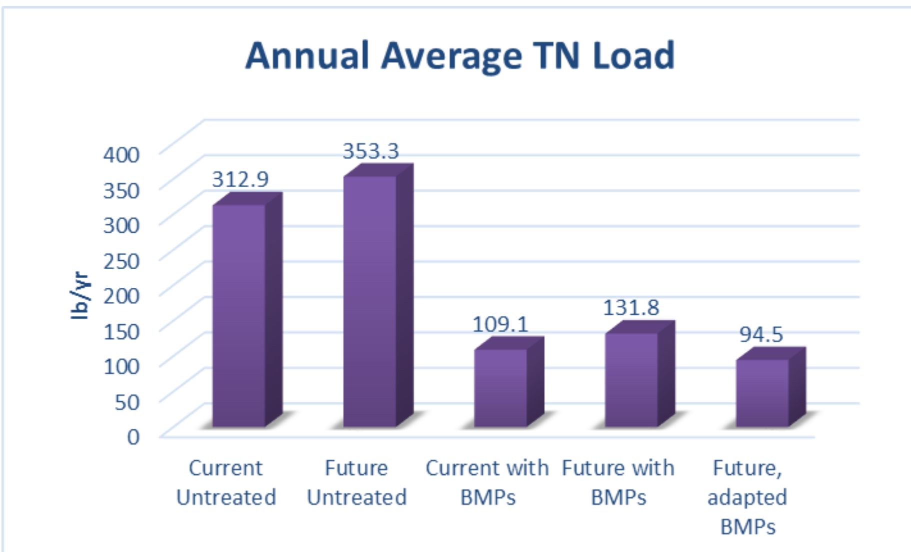


Figure B-218. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

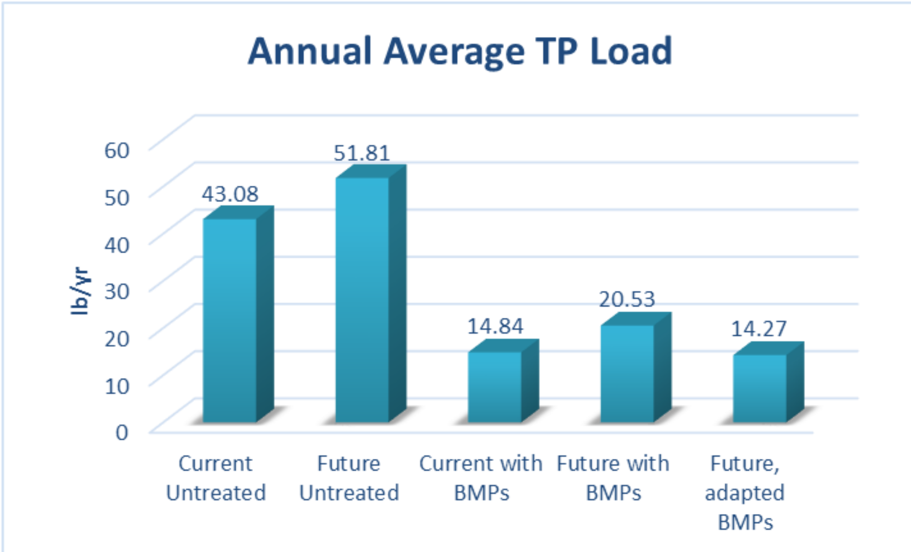


Figure B-219. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

The flow duration curve analysis (see Figure B-220) for the Scott County GI with Gray Infrastructure ("intensity plus 20%") scenario suggests that the adapted practices are able to reasonably match the outflow response of the current practices within the evaluated range of flows.

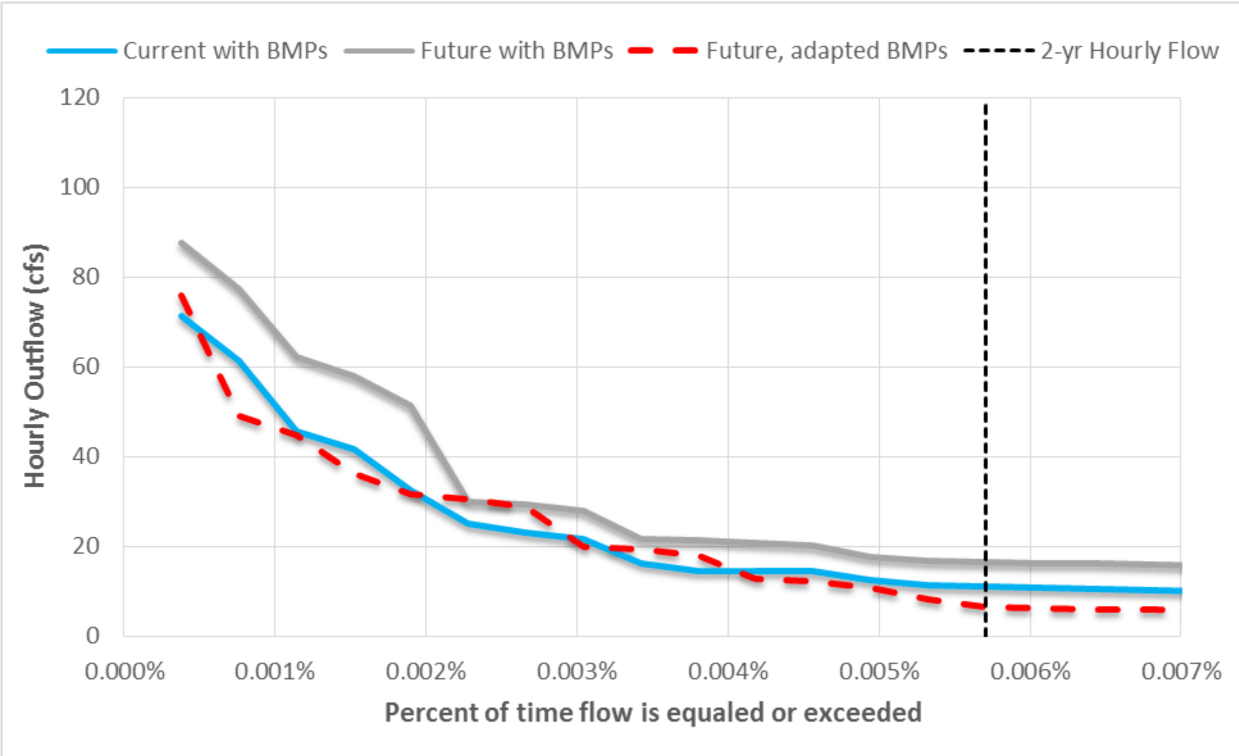


Figure B-220. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

Although maintaining maximum hourly peak flow at current performance as not an objective of the adaptation simulation, Figure B-221 indicates that the adapted Green and Gray practices are able to slightly reduce hourly peak flow compared to the future (not adapted) practice sizing.

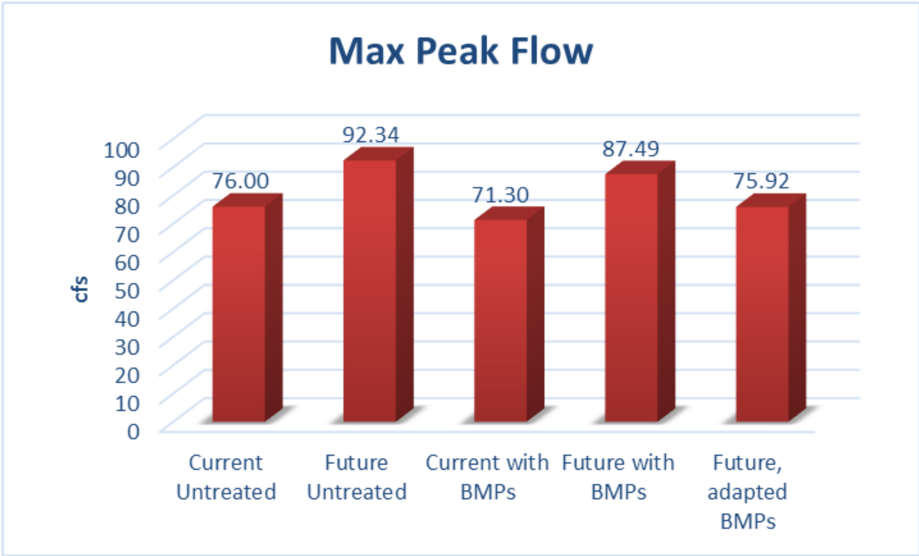


Figure B-221. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

The adapted practice footprints in the GI with Gray Infrastructure scenario are able to reduce the future ("intensity plus 20%") monthly outflow volumes so that they are approximately the same as, or lower than, the current monthly outflow volumes for all months.

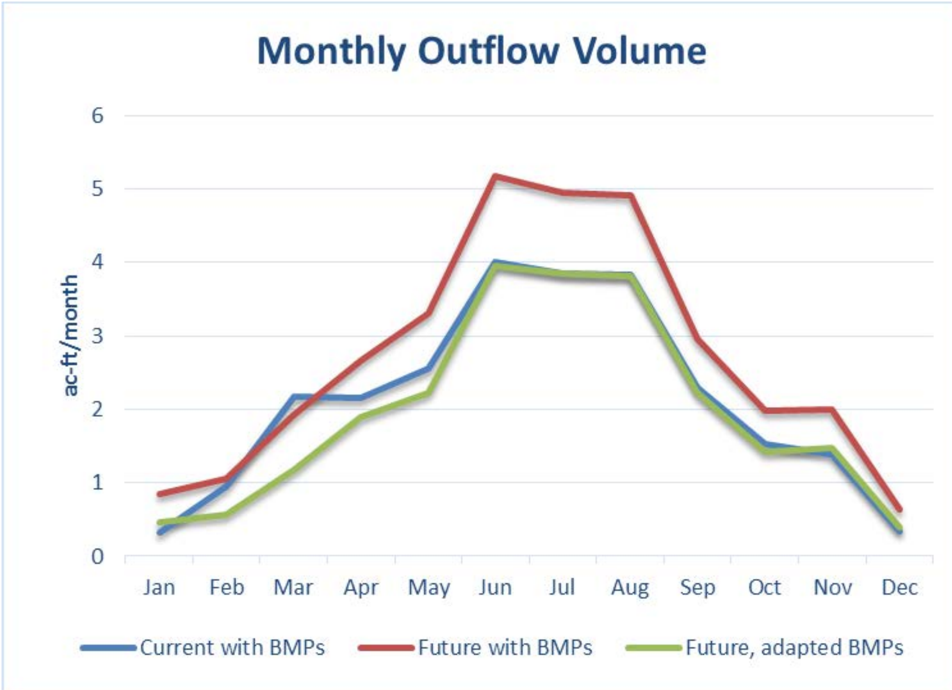


Figure B-222. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) with Gray Infrastructure (intensity plus 20%) scenario.

B.2.2.3. Green Infrastructure (GI) Only

Intensity Change Minus 10%

This scenario was not selected for adaptation simulation; refer to discussion in *Section B.2.2.1.* and the following figures, which demonstrate decreased outflow volume and pollutant loading in the "intensity minus 10%" climate scenario compared to the current climate.

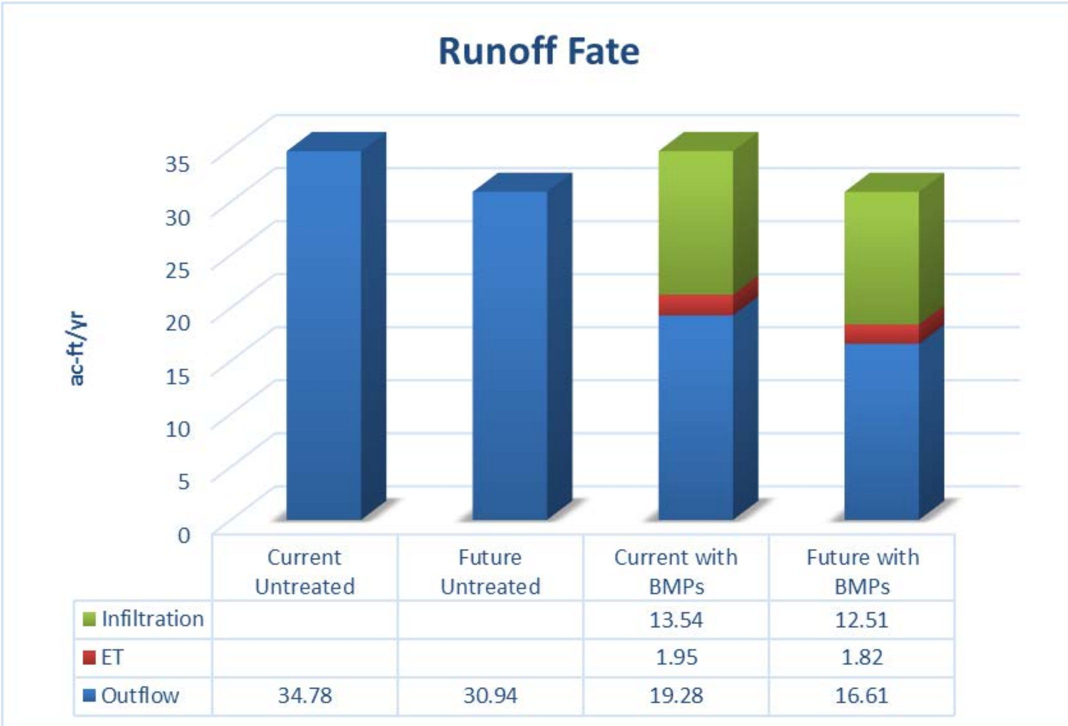


Figure B-223. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) Only (intensity minus 10%) scenario.

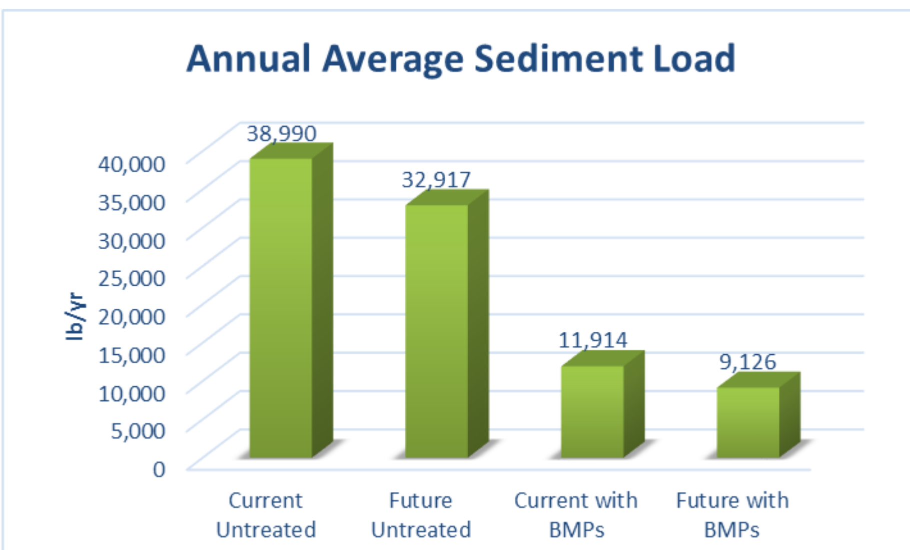


Figure B-224. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) Only (intensity minus 10%) scenario.

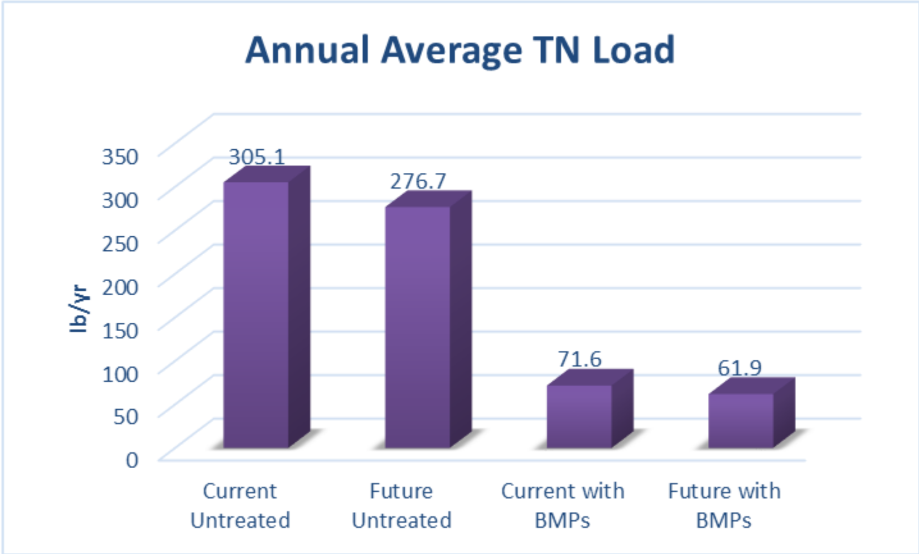


Figure B-225. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) Only (intensity minus 10%) scenario.

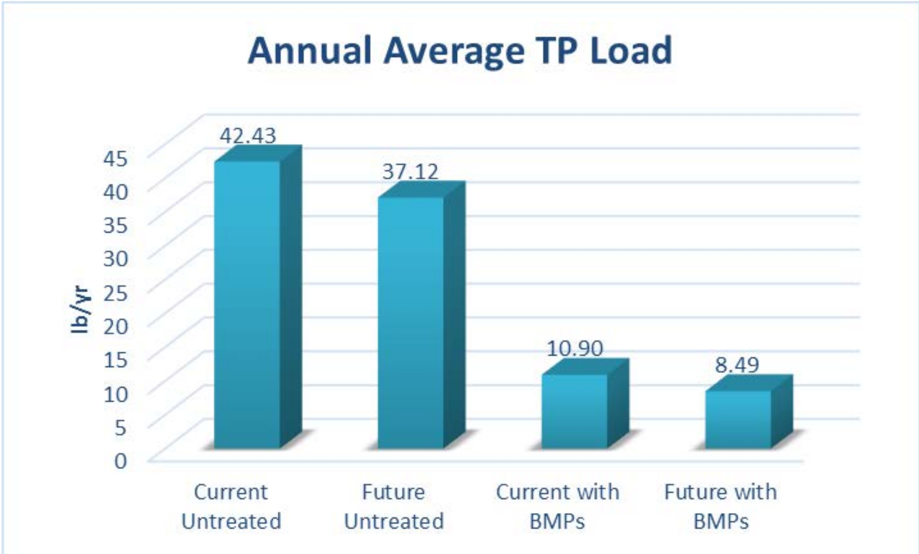


Figure B-226. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) Only (intensity minus 10%) scenario.

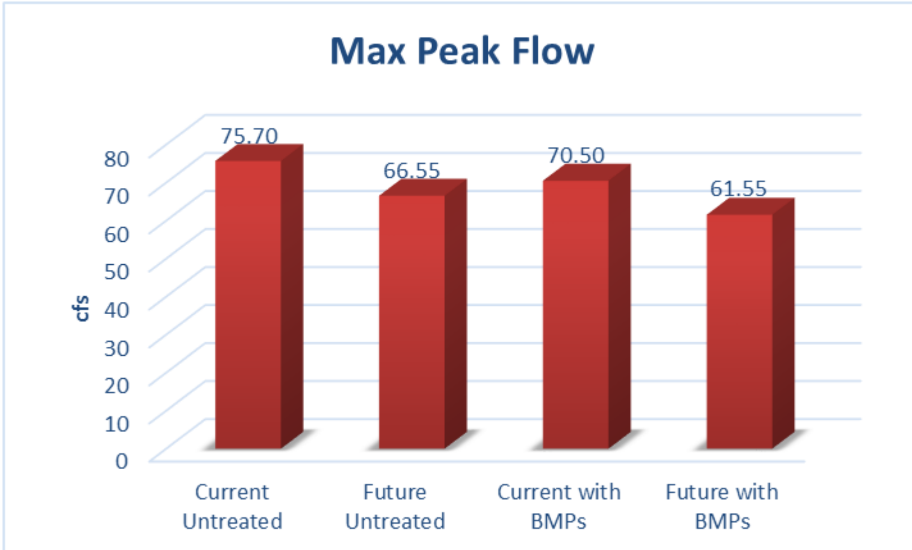


Figure B-227. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) Only (intensity minus 10%) scenario.

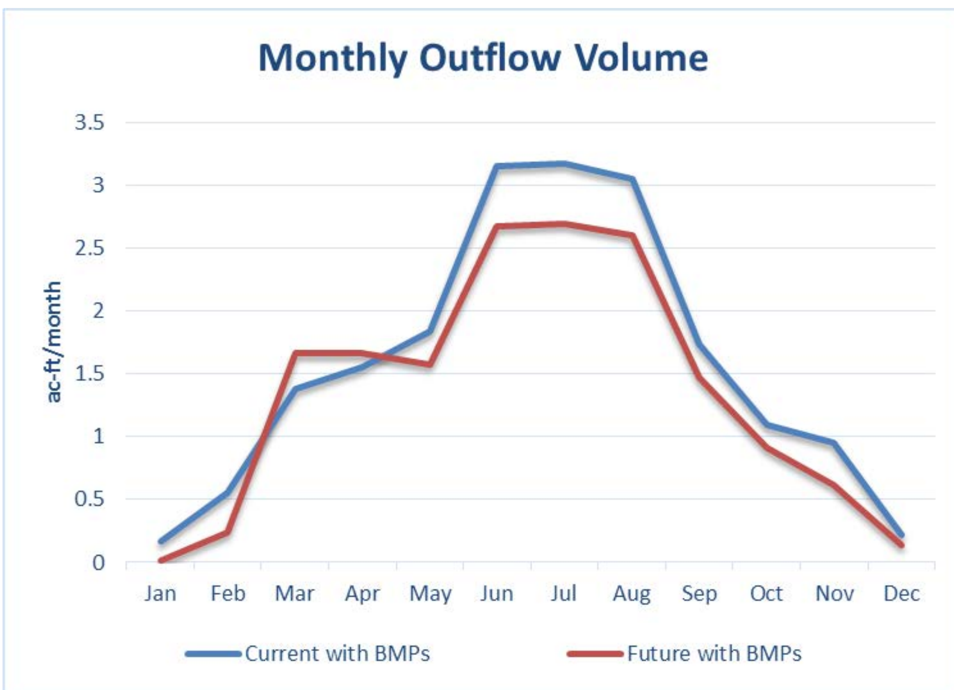


Figure B-228. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) Only (intensity minus 10%) scenario.

Intensity Change Plus 10%

As discussed in *Section B.2.2.1.* , the "intensity plus 10%" climate scenario for Scott County results is an increase both in total runoff volume and in outflow volume when the green practices (bioretention, rooftop downspout disconnection, and permeable pavement) are not resized for adaptation, as shown in Figure B-229. With future adaptation, the increased practice footprints reduce the volume of outflow below the "current with BMPs" scenario due to a larger proportioning of runoff to ET and infiltration. The soils in the Scott County study site have low infiltration capacity, so outflow remains the dominant runoff pathway, even for this GI Only scenario and even when practice sizes are increased.

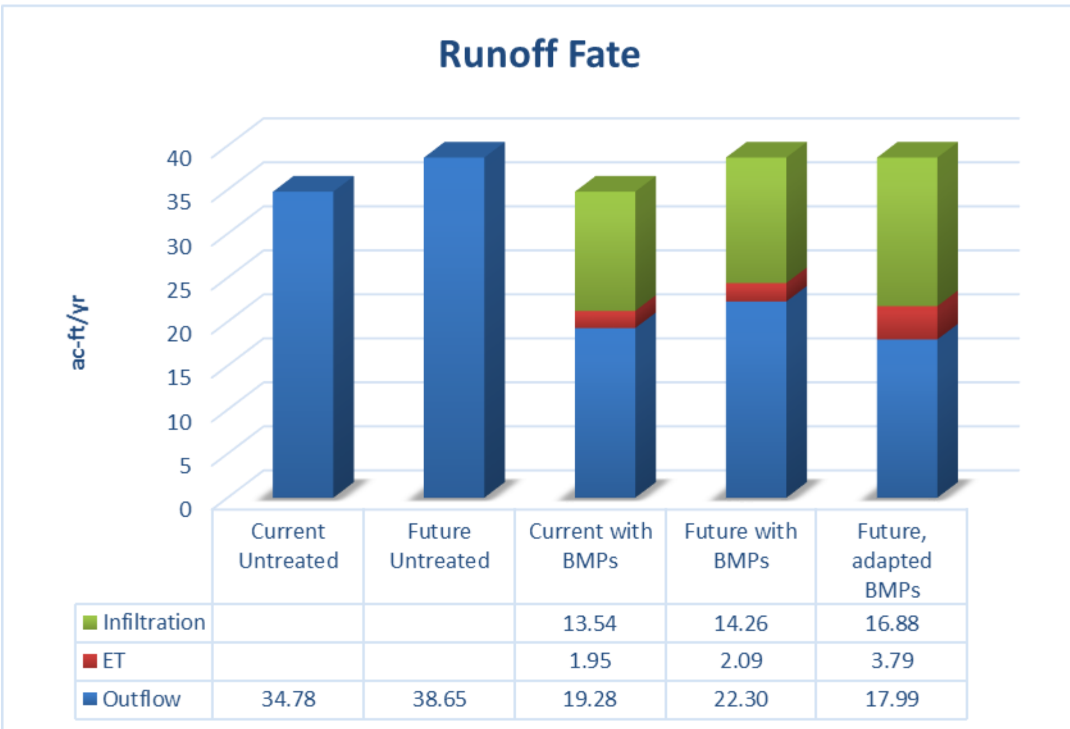


Figure B-229. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) Only (intensity plus 10%) scenario.

The following figures demonstrate that the adapted green practices in the Scott County GI Only scenario are able to mitigate the increases in annual average sediment (see Figure B-230), TN (see Figure B-231), and TP (see Figure B-232) load under future 'intensity plus 10%" climate conditions.

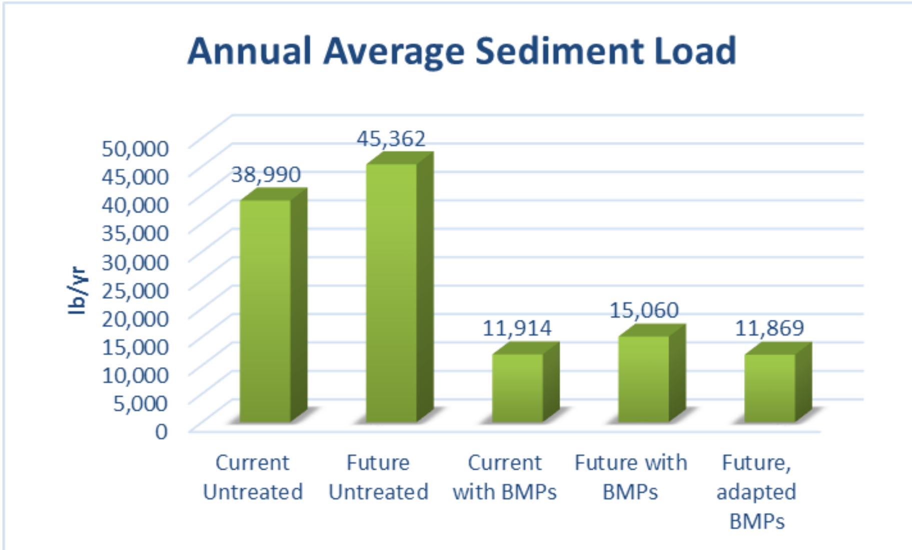


Figure B-230. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) Only (intensity plus 10%) scenario.

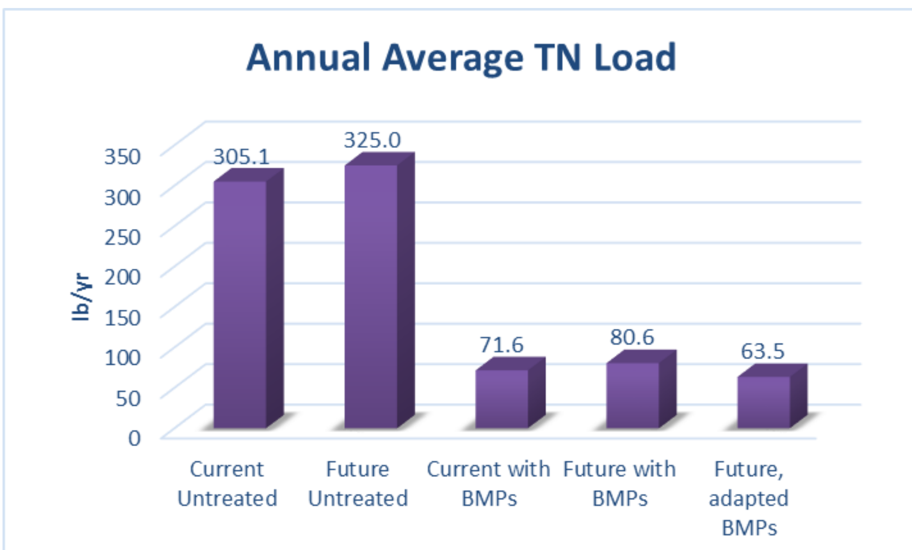


Figure B-231. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) Only (intensity plus 10%) scenario.

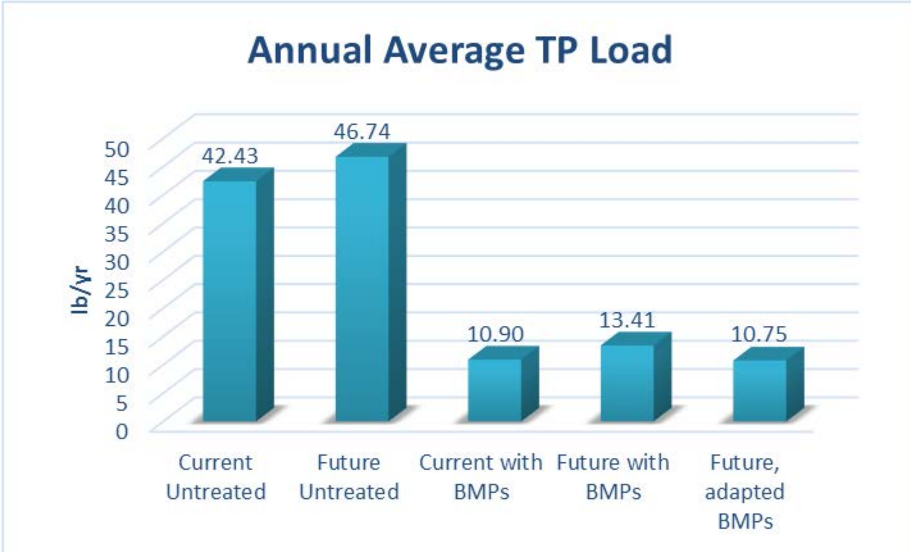


Figure B-232. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) Only (intensity plus 10%) scenario.

The flow duration curve analysis (see Figure B-233) for the Scott County GI Only ("intensity plus 10%") scenario suggests that the adapted practices are able to reasonably match the outflow response of the current practices within the evaluated range of flows.

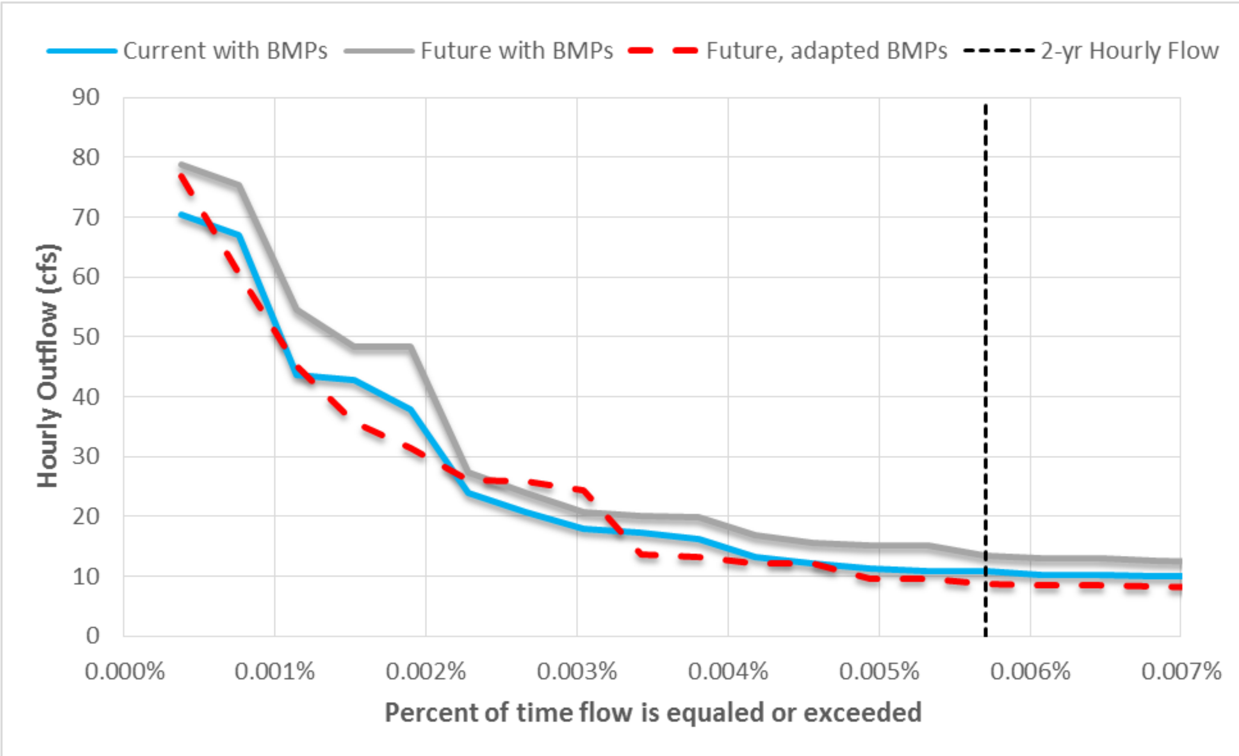


Figure B-233. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) Only (intensity plus 10%) scenario.

Figure B-234 indicates that, although maximum hourly peak flow was not targeted as part of the adaptation simulation, the green practices, when adapted to meet the other performance measures, are only able to reduce the hourly peak flow by about 2 cfs for the "intensity plus 10%" climate scenario. This result may suggest a lower ability of GI to mitigate peak flows compared to conventional (Gray) infrastructure.

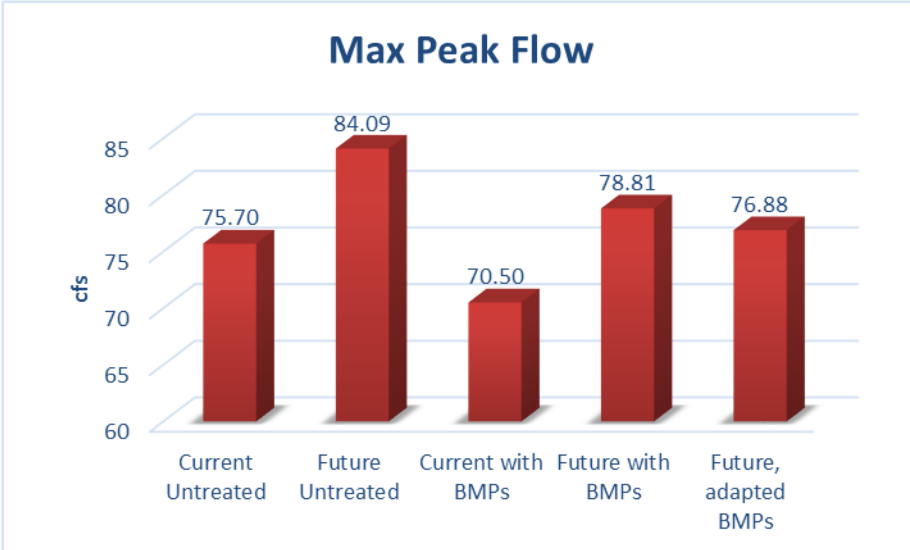


Figure B-234. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) Only (intensity plus 10%) scenario.

The future ("intensity plus 10%") climate adaptation for the GI Only scenario produces a monthly outflow volume response that is very similar to the current monthly outflow response.

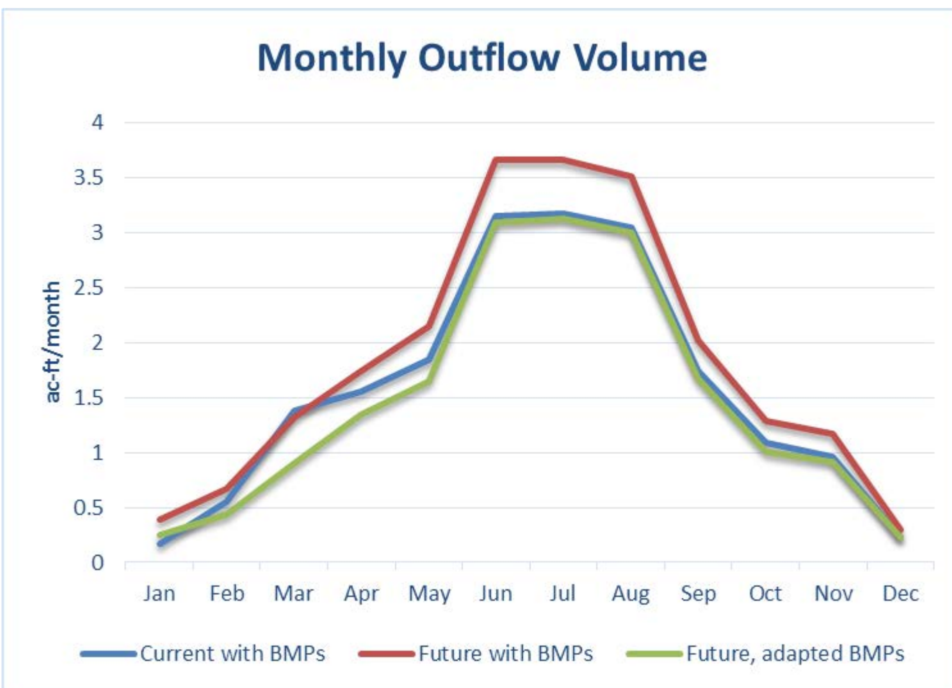


Figure B-235. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) Only (intensity plus 10%) scenario.

Intensity Change Plus 20%

As discussed in *Section B.2.2.1.* , the “intensity plus 20%” climate scenario for Scott County results is an increase both in total runoff volume and in outflow volume when the practices are not resized for adaptation, as shown in Figure B-23936. Increasing the green practice (bioretention, rooftop downspout disconnection, and permeable pavement) footprints increases the proportioning of runoff to infiltration and ET, allowing the site to maintain the current climate outflow performance under future “intensity plus 10%” climate conditions. As discussed above, due to the poor infiltration capacity of the soils in the Scott County study site, outflow is an important runoff fate pathway. However, the increased green practice footprints in the future adapted scenario increase the proportioning of runoff to infiltration enough to make infiltration the dominant fate pathway for the “intensity plus 10%” climate scenario.

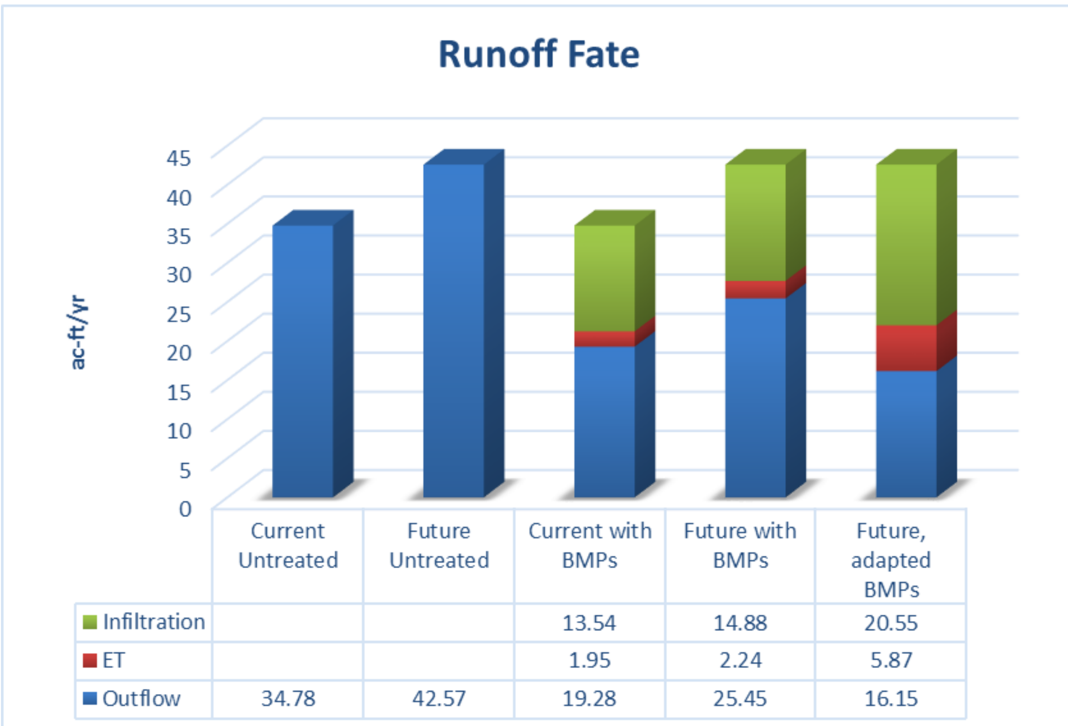


Figure B-236. Current and future partitioning of runoff fate for the Scott County, MN Green Infrastructure (GI) Only (intensity plus 20%) scenario.

Figure B-237, Figure B-238, and Figure B-239 demonstrate that with the increased practice sizes, the GI Only site is able to mitigate the increased sediment, TN, and TP loads due to future climate impacts in the “intensity plus 20%” climate scenario.

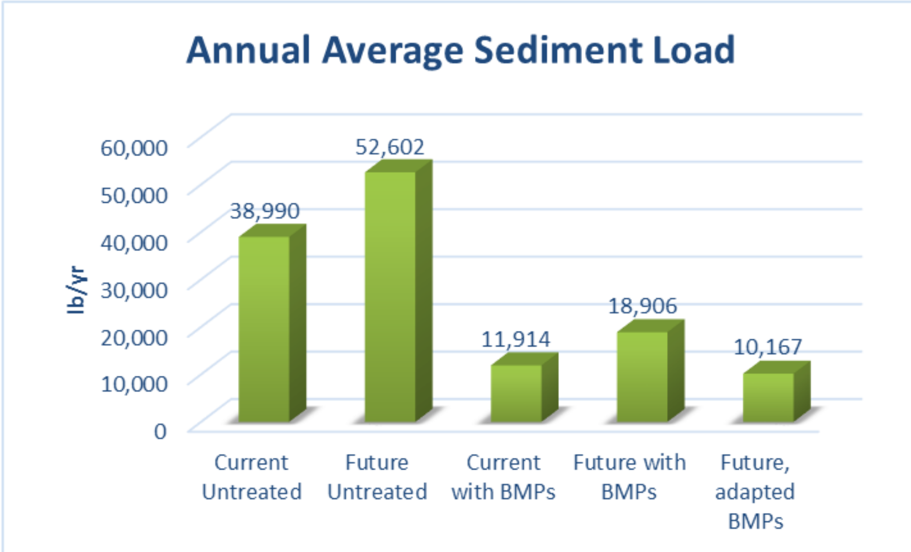


Figure B-237. Current and future performance for annual average sediment load, Scott County, MN Green Infrastructure (GI) Only (intensity plus 20%) scenario.

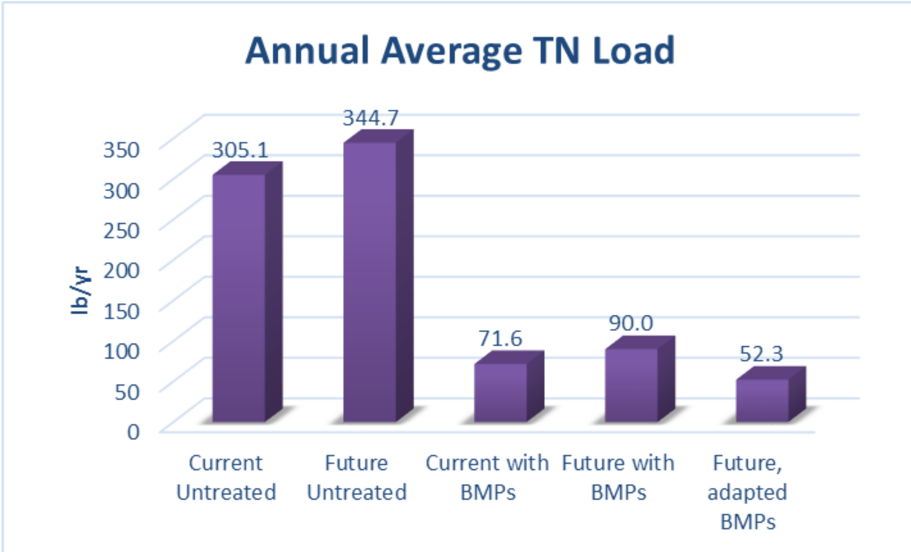


Figure B-238. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Green Infrastructure (GI) Only (intensity plus 20%) scenario.

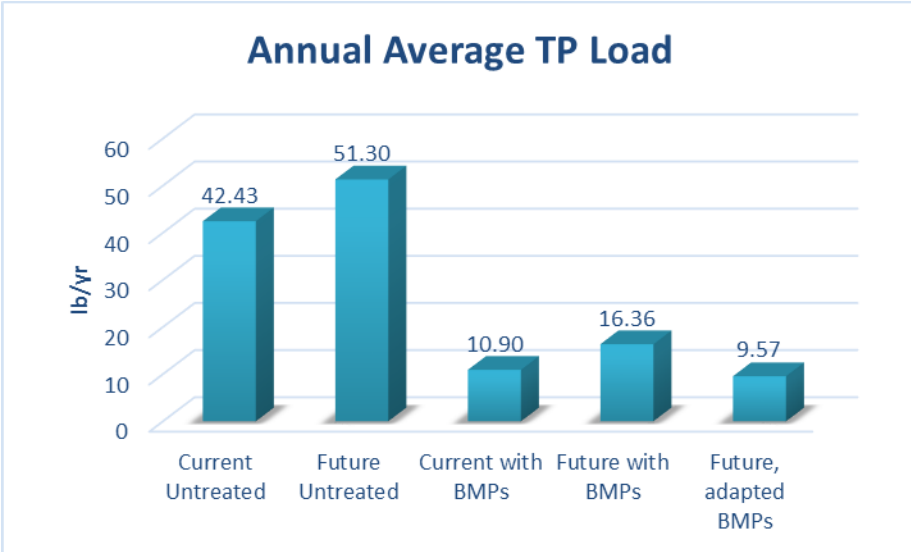


Figure B-239. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Green Infrastructure (GI) Only (intensity plus 20%) scenario.

The FDC evaluation for the Scott County GI Only ("intensity plus 20%") scenario indicates that the green practices alone are able to achieve a reasonably close flow response to the current climate FDC within the evaluated range of flows. However, there is a discrepancy between the highest hourly peak flows, indicating the adapted practices may be unable to mitigate the increase in the highest flows.

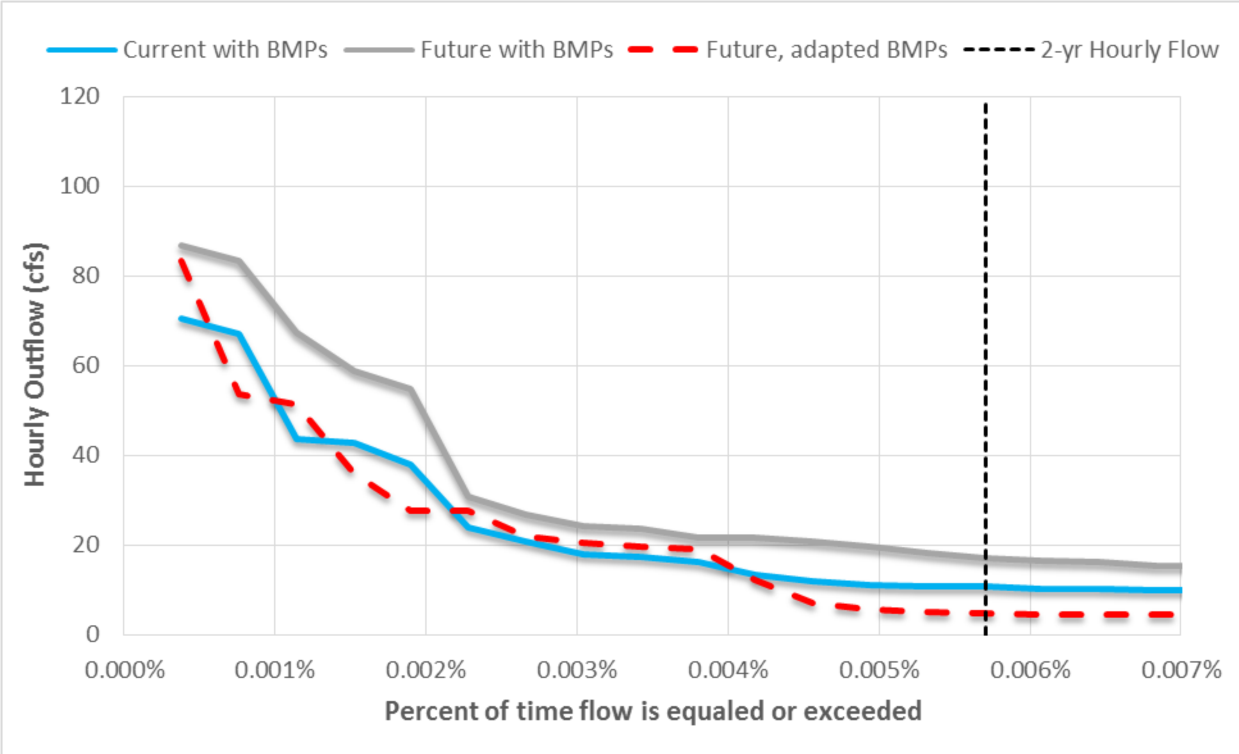


Figure B-240. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Green Infrastructure (GI) Only (intensity plus 20%) scenario.

Figure B-241 provides additional insight into the behavior seen in the uppermost range of flows in the flow duration curve analysis. The GI Only practices, even with adaptation, do not appear to significantly reduce the maximum peak flow under future climate ("intensity plus 20%") conditions compared to the original practice sizes ("future with BMPs").

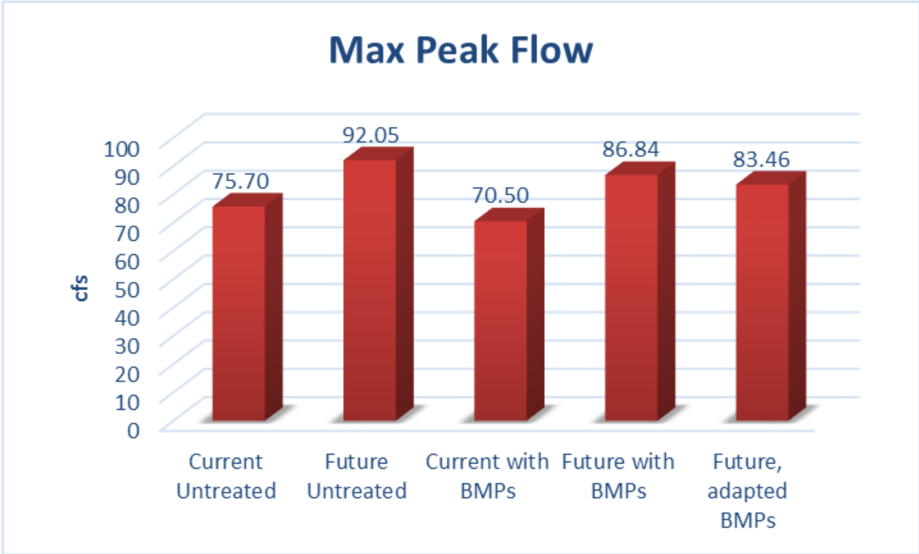


Figure B-241. Current and future performance for maximum hourly peak flow, Scott County, MN Green Infrastructure (GI) Only (intensity plus 20%) scenario.

Figure B-242 indicates that with resizing, the future adapted GI Only practices are successful at mitigating increased monthly outflow volumes under future ("intensity plus 20%") climate. The future adapted monthly outflows are lower than, or very close to, the current monthly outflows for all months.

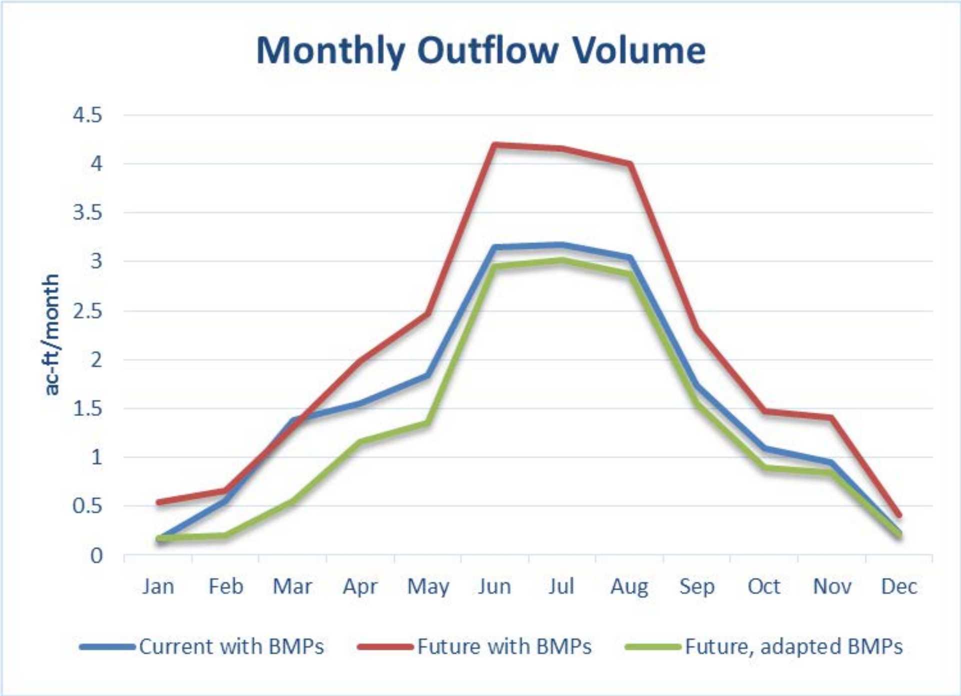


Figure B-242. Current and future performance for monthly outflow volume, Scott County, MN Green Infrastructure (GI) Only (intensity plus 20%) scenario.

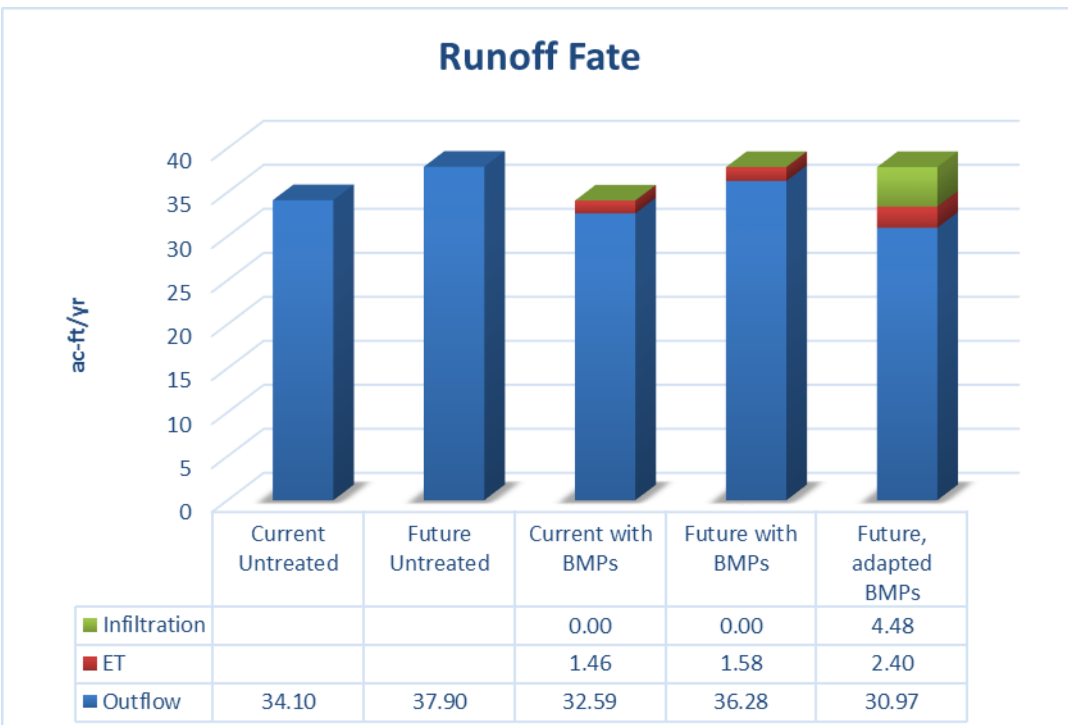
B.2.2.4. Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI)

Intensity Change Minus 10%

As discussed in *Section B.2.2.1.* , the Conventional (Gray) Infrastructure scenario was not investigated for adaptation in the future "intensity minus 10%" climate scenario because there was no decrease in the performance of the conventional (Gray) practice (wet pond) between the current and future climate. Therefore, the future low intensity climate scenario was also not investigated for adaptation through the addition of distributed GI practices because there was no performance gap to address.

Intensity Change Plus 10%

The change in flow and pollutant related performance for the Scott County Conventional (Gray) scenario due to future climate sensitivity ("intensity plus 10%") impacts was discussed in *Section B.2.2.1.* . The purpose of the Conventional (Gray) Infrastructure with Distributed GI scenario is to implement distributed GI practices without resizing the conventional (Gray) practice as a means of future climate adaptation. Figure B- 243 indicates that the addition of distributed bioretention to the conventional site is able to reduce outflow below the current climate outflow by increasing the partitioning of runoff to infiltration and ET. Due to the poorly infiltrating soils on the Scott County site, outflow remains the dominant runoff fate pathway for this scenario, even with the addition of infiltrating bioretention.



	Current Untreated	Future Untreated	Current with BMPs	Future with BMPs	Future, adapted BMPs
Infiltration			0.00	0.00	4.48
ET			1.46	1.58	2.40
Outflow	34.10	37.90	32.59	36.28	30.97

Figure B- 243. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

Figure B-244 indicates that the distributed bioretention practices combined with the wet pond are able to achieve high load reductions for sediment, and allow the site to meet current loading for annual average sediment load under "intensity plus 10%" climate without requiring resizing of the existing wet pond.

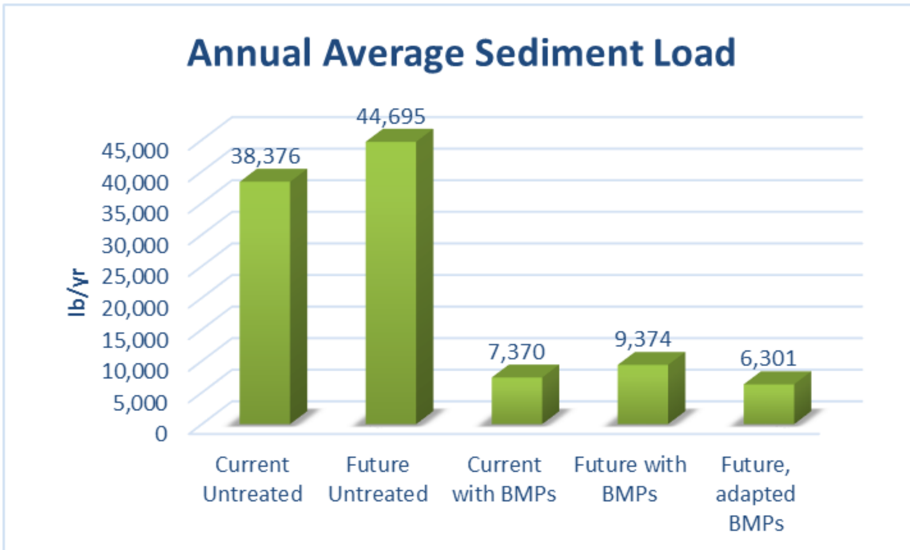


Figure B-244. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

The following figures suggest that the distributed bioretention practices combined with the wet pond are able to achieve modest load reductions for TN and TP, allowing the site to meet current loading for annual average sediment load under the "intensity plus 10%" climate conditions without requiring resizing of the existing wet pond.

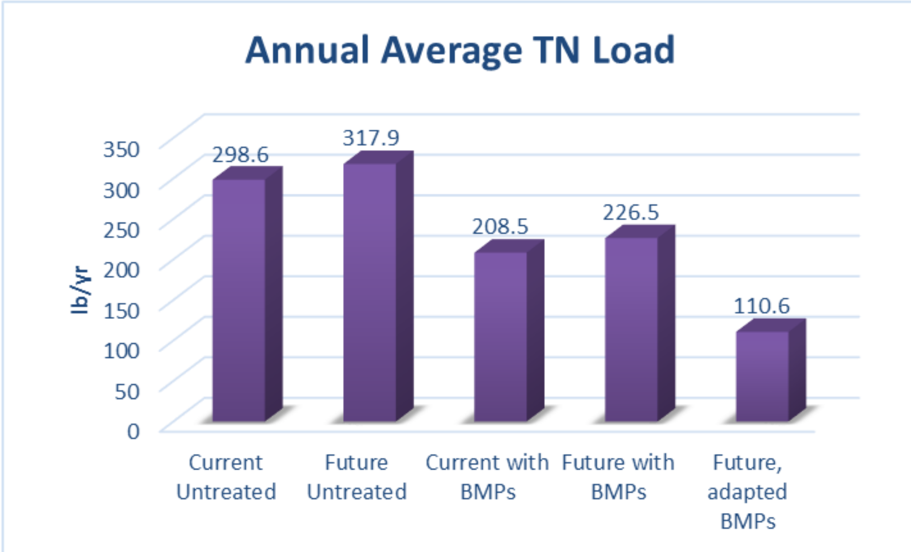


Figure B-245. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

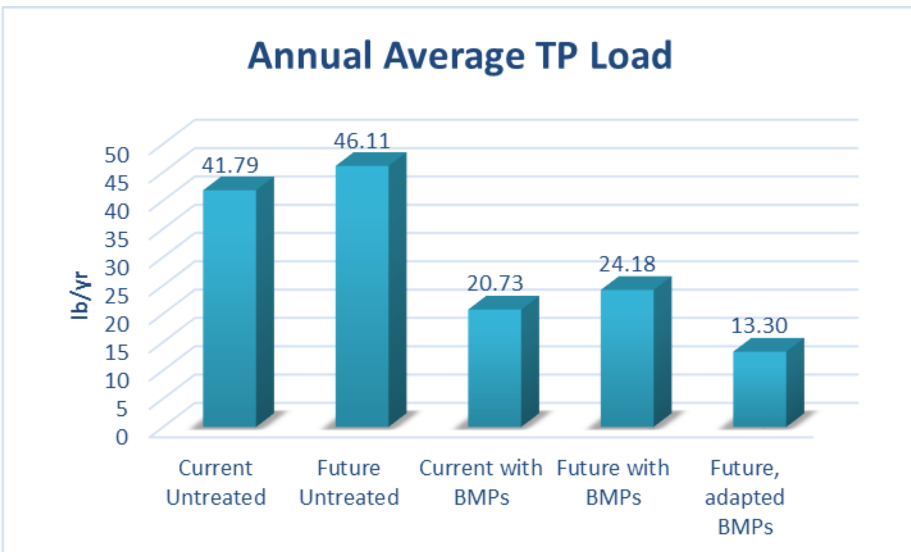


Figure B-246. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

The FDC analysis for the future “intensity plus 10%” scenario suggests that although the addition of distributed bioretention practices is able to maintain the current climate outflow volume, these practices as designed are not effective at reducing the highest peak flow rates. As a result, the flow duration curves between the “current with BMPs” and “future, adapted BMPs” diverge, particularly for the highest outflows.

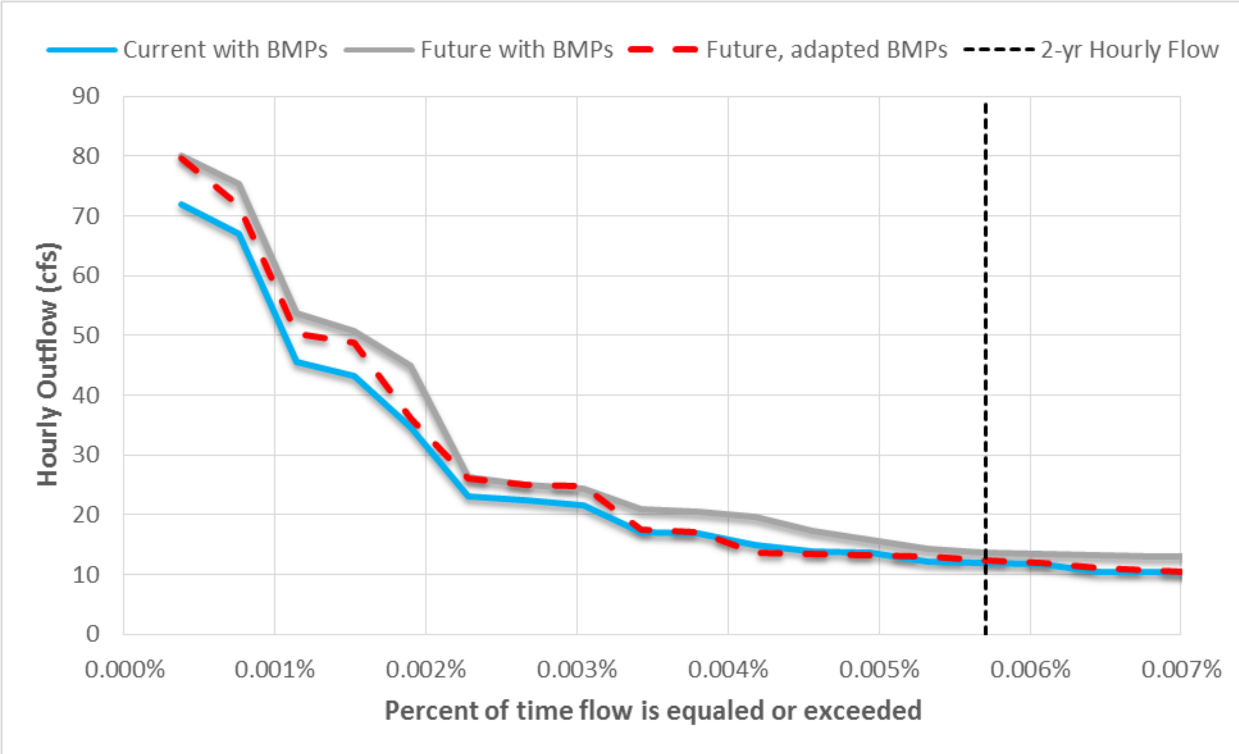


Figure B-247. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

Figure B-248 indicates that the addition of distributed bioretention to the conventional site does not result in a significant decrease in the maximum hourly peak flow under future (“intensity plus 10%”) climate conditions.

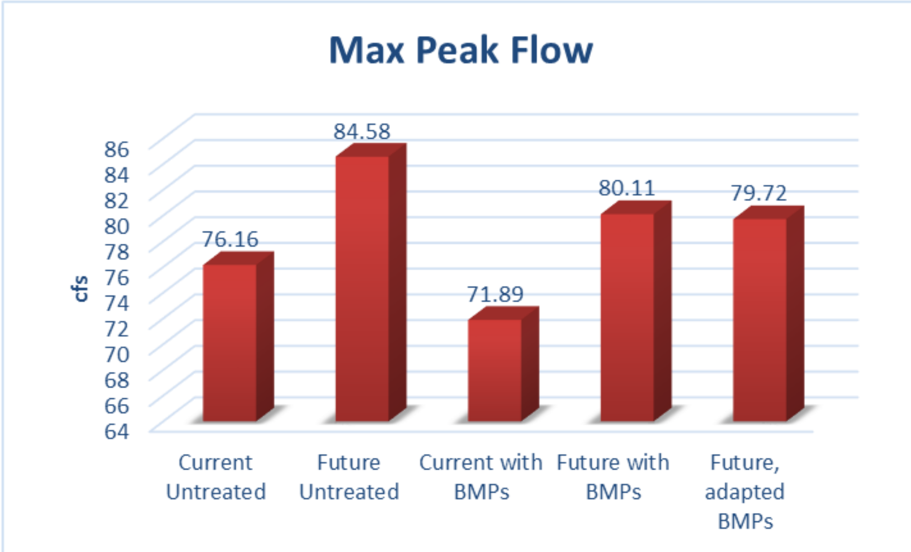


Figure B-248. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

The future ("intensity plus 10%") climate adaptation for the Conventional (Gray) Infrastructure with Distributed GI scenario produces a monthly outflow volume response that is very similar to the current monthly outflow response.

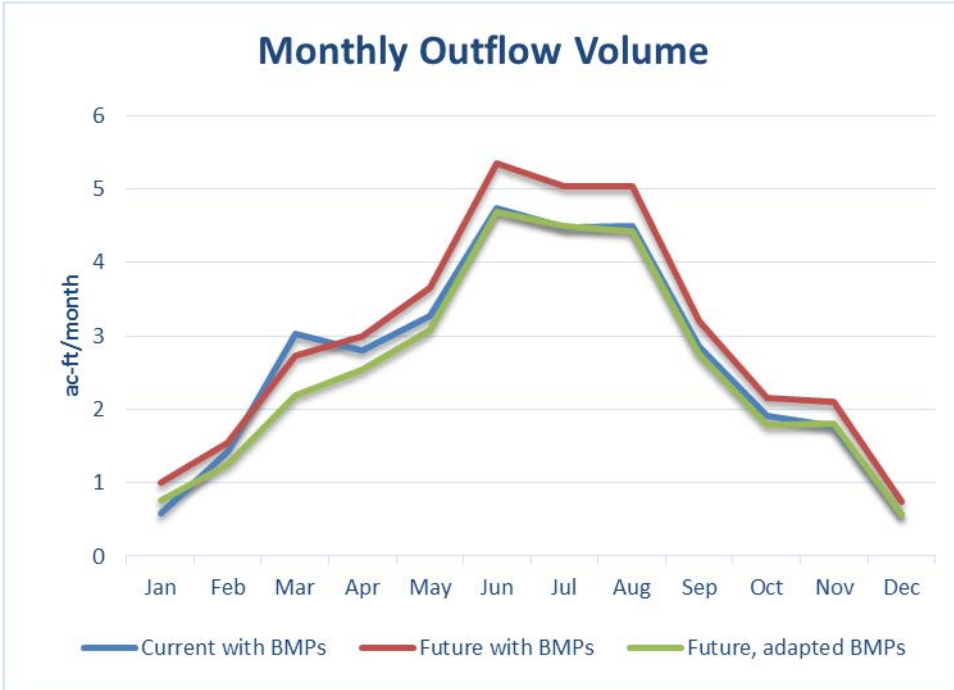


Figure B-249. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 10%) scenario.

Intensity Change Plus 20%

The change in flow and pollutant-related performance for the Scott County Conventional (Gray) scenario due to future climate sensitivity ("intensity plus 20%") impacts was discussed in *Section B.2.2.1.* . The purpose of the Conventional (Gray) Infrastructure with Distributed GI scenario is to implement distributed GI practices without resizing the conventional (Gray) practice as a means of future climate adaptation.

Figure B-250 indicates that the addition of distributed bioretention to the conventional site is able to reduce outflow below the current climate outflow by increasing the partitioning of runoff to infiltration and ET. Due to the poorly infiltrating soils on the Scott County site, outflow remains the dominant runoff fate pathway for this scenario, even with the addition of infiltrating bioretention.

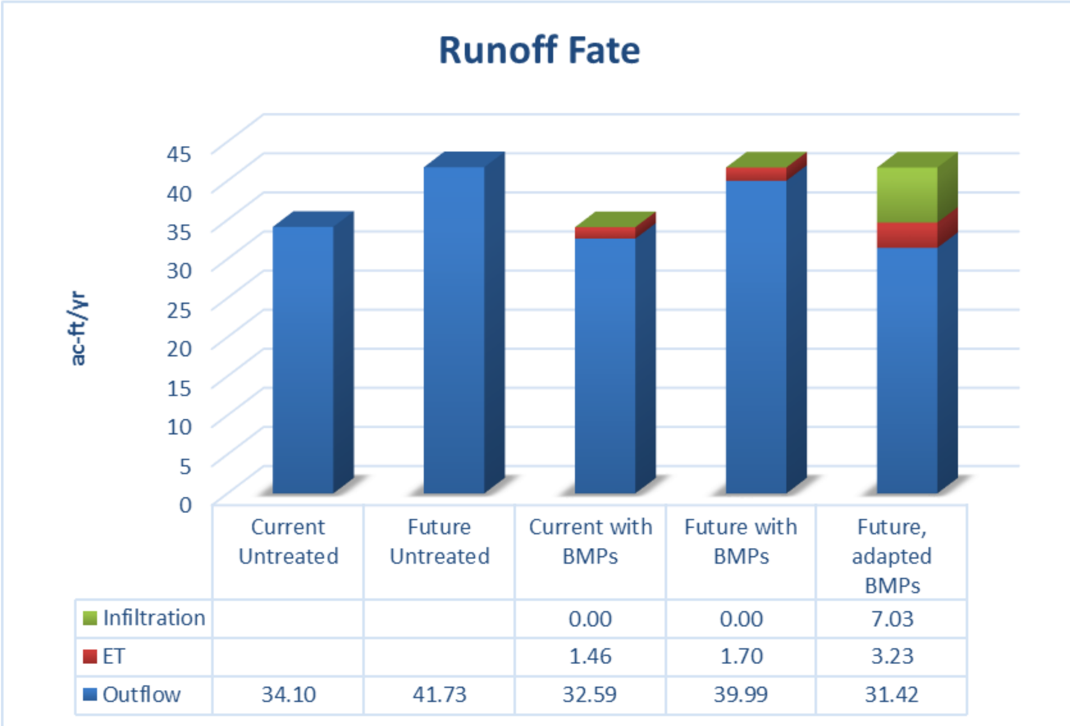


Figure B-250. Current and future partitioning of runoff fate for the Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

Figure B-251 indicates that the distributed bioretention practices combined with the wet pond are able to achieve high load reductions for sediment, and allow the site to meet current loading for annual average sediment load under "intensity plus 20%" climate without requiring resizing of the existing wet pond.

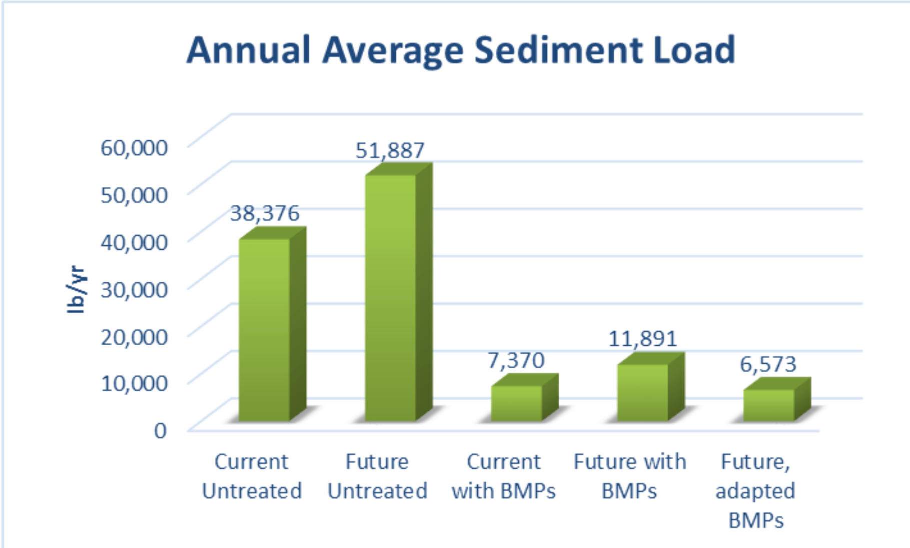


Figure B-251. Current and future performance for annual average sediment load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

The following figures suggest that the distributed bioretention practices combined with the wet pond are able to achieve modest load reductions for TN and TP, allowing the site to meet current loading for annual average sediment load under future "intensity plus 20%" climate conditions without requiring resizing of the existing wet pond.

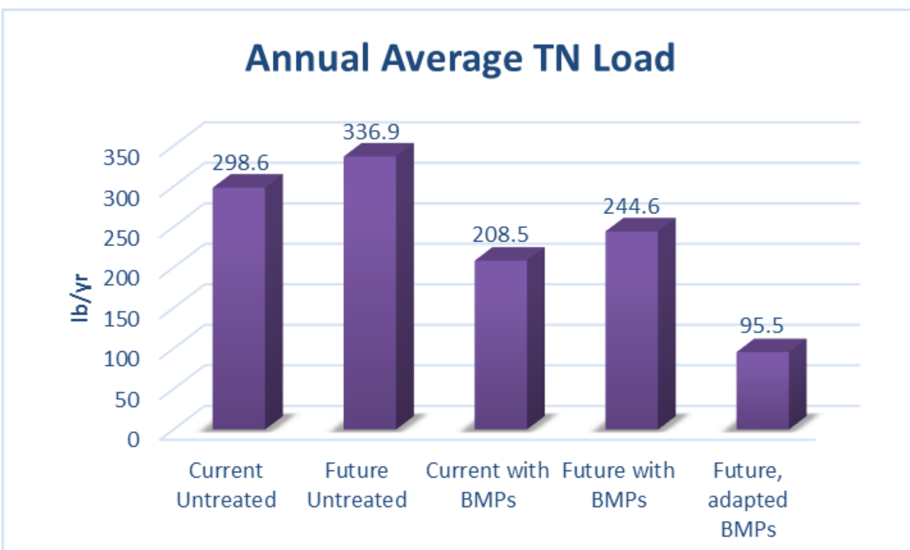


Figure B-252. Current and future performance for annual average total nitrogen (TN) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

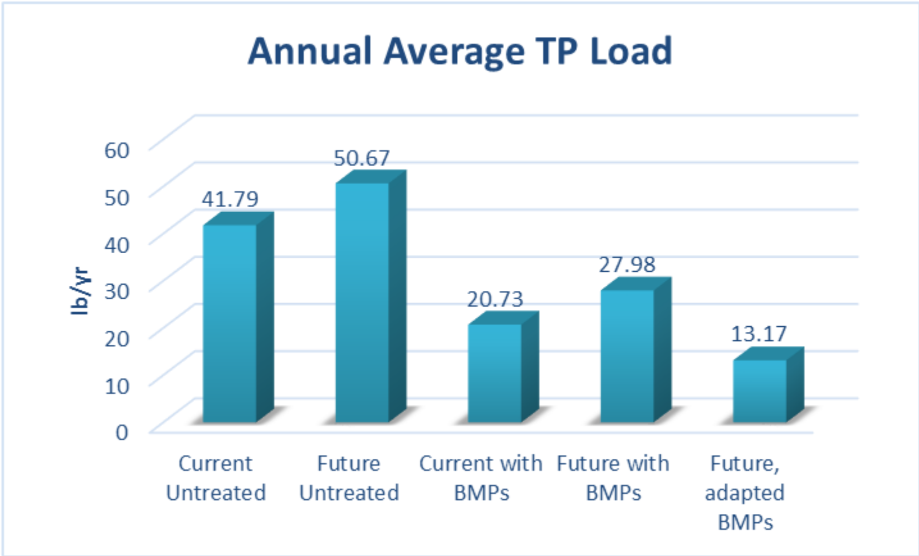


Figure B-253. Current and future performance for annual average total phosphorous (TP) load, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

The FDC analysis for the future "intensity plus 20%" scenario suggests that although the addition of distributed bioretention practices can maintain the current climate outflow volume, these practices as designed are not effective at reducing the highest peak flow rates. As a result, the flow duration curves between the "current with BMPs" and "future, adapted BMPs" diverge, particularly for the highest outflows.

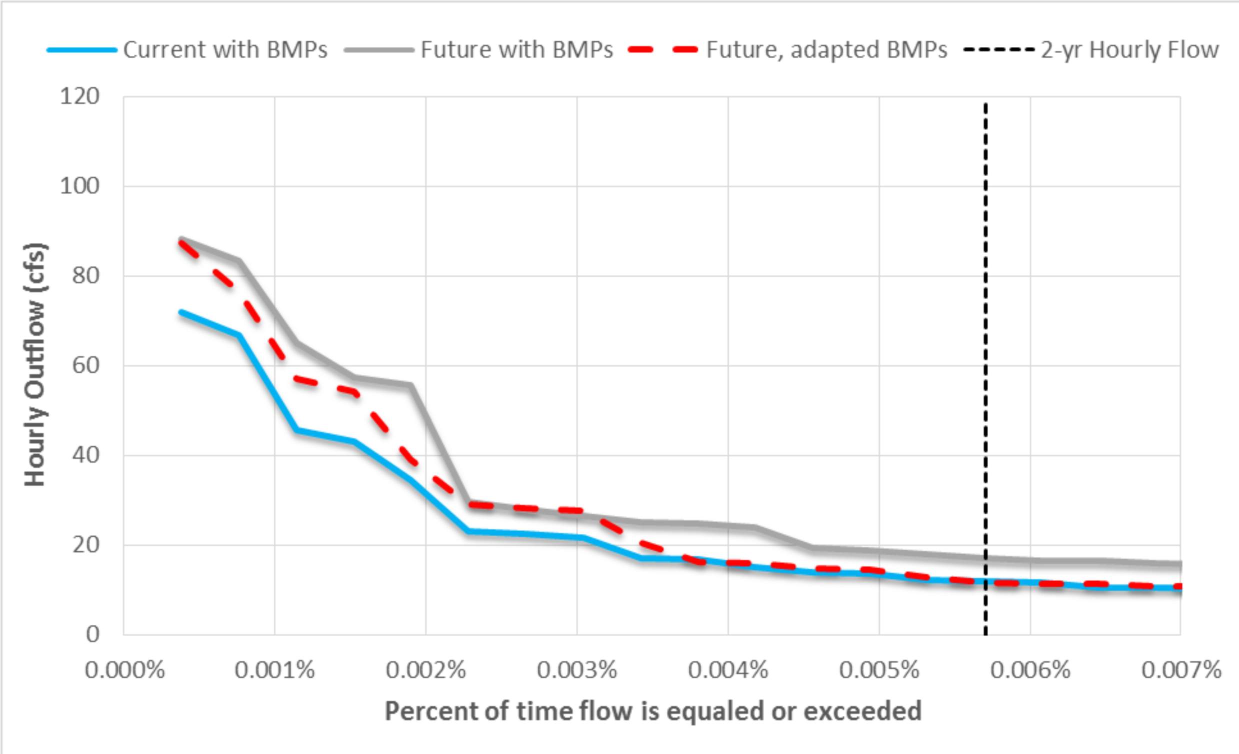


Figure B-254. Flow duration curve (FDC) evaluation for current and future climate, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

Figure B-255 indicates that the addition of distributed bioretention to the conventional site does not result in a significant decrease in the maximum hourly peak flow under future ("intensity plus 10%") climate conditions.

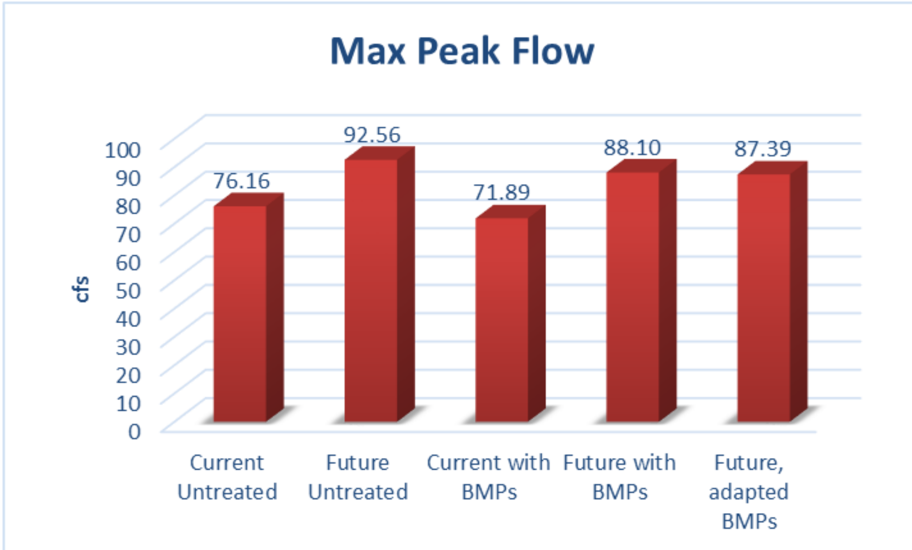


Figure B-255. Current and future performance for maximum hourly peak flow, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

The future ("intensity plus 20%") climate adaptation for the Conventional (Gray) Infrastructure with Distributed GI scenario produces a monthly outflow volume response that is very similar to the current monthly outflow response. Outflow volumes in the adapted scenario are approximately the same as, or lower than, the current climate scenario for all months.

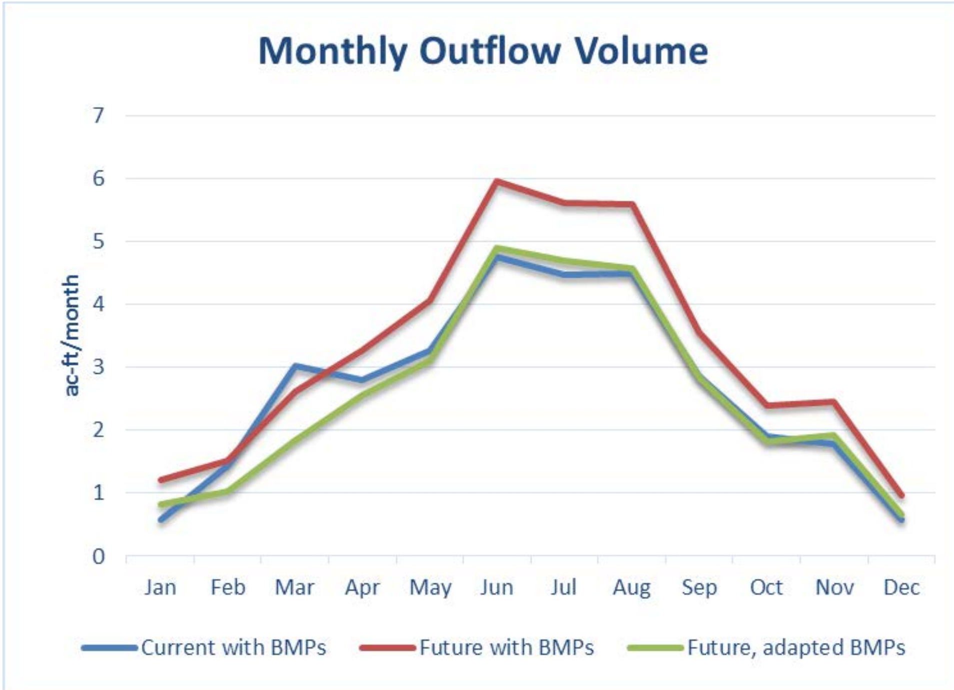


Figure B-256. Current and future performance for monthly outflow volume, Scott County, MN Conventional (Gray) Infrastructure with Distributed Green Infrastructure (GI) (intensity plus 20%) scenario.

B.2.2.5. Sensitivity Analysis Adaptation Summary

Table B-27 summarizes the increases in BMP footprints for all of the Scott County stormwater management scenarios that would be required to maintain current performance under future climate conditions for the "intensity plus 10%" climate simulation. Adaptation for the Conventional (Gray) Infrastructure scenario would require the wet pond footprint to increase by nearly 230%. For the GI with Gray Infrastructure scenario, no increase in the dry detention basin footprint is required, but the bioretention footprint would need to more than double in size. Adaptation for the GI Only scenario would require an 86% increase in bioretention footprint. When distributed GI is added to the Conventional (Gray) Infrastructure scenario for adaptation, the required bioretention footprint of 17,500 square feet would comprise approximately 1.3% of the total site area.

Table B-27. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN stormwater management scenarios, intensity plus 10%

Location	Climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
				Foot-print SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Scott County, MN	Intensity change plus 10%	Conventional (Gray) Infrastructure	Wet pond	32,670	2.5	107,484	8.2	229
		GI with Gray Infrastructure	Bioretention	34,848	2.7	70,348	5.4	102
			Dry detention basin	26,136	2.0	26,136	2.0	0
		GI Only	Bioretention (modified)	43,275	3.3	80,405	6.2	86
			Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
			Permeable pavement	39,390	3.0	39,390	3.0	0
		Conventional (Gray) Infrastructure with Distributed GI	Wet pond	32,670	2.5	32,670	2.5	0
			Distributed bioretention	0	0.0	17,500	1.3	--

Table B-28 summarizes the increases in BMP footprints for all of the Scott County stormwater management scenarios that would be required to maintain current performance under future climate conditions for the “intensity plus 20%” climate simulation. Adaptation for the Conventional (Gray) Infrastructure scenario would require the wet pond footprint to increase by nearly 430%. For the GI with Gray Infrastructure scenario, the dry detention basin footprint would need to increase by 163%, and the bioretention footprint would need to increase by 139%. Adaptation for the GI Only scenario would require a 172% increase in bioretention footprint. When distributed GI is added to the Conventional (Gray) Infrastructure scenario for adaptation, the required bioretention footprint of 30,500 square feet would comprise approximately 2.3% of the total site area.

Table B-28. Comparison of current and future adapted best management practice (BMP) footprints, Scott County, MN stormwater management scenarios, intensity plus 20%

Location	Climate scenario	Stormwater management scenario	Practice	Current		Future adapted		% increase in footprint
				Foot-print SF	Footprint as % of site area	Footprint SF	Footprint as % of site area	
Scott County, MN	Intensity change plus 20%	Conventional (Gray) Infrastructure	Wet pond	32,670	2.5	172,171	13.2	427
		GI with Gray Infrastructure	Bioretention	34,848	2.7	83,348	6.4	139
			Dry detention basin	26,136	2.0	68,636	5.3	163
		GI Only	Bioretention (modified)	43,275	3.3	117,601	9.0	172
			Rooftop downspout disconnection	94,901	7.3	94,901	7.3	0
			Permeable pavement	39,390	3.0	39,390	3.0	0
		Conventional (Gray) Infrastructure with Distributed GI	Wet pond	32,670	2.5	32,670	2.5	0
			Distributed bioretention	0	0.0	30,500	2.3	--

B.2.2.6. Cost of Adaptation

Table B-29 provides an estimate of the 20-year present value costs for the current and future adapted climate conditions for all four Scott County stormwater management scenarios under future "intensity plus 10%" climate, as well as the percentage increase in cost (current to future adapted) and increase (millions of dollars) per acre of site.

Table B-29. Comparison of the current and future estimated 20-year present value costs for the Scott County, MN stormwater management scenarios, intensity plus 10%

Location	Climate scenario	Stormwater management scenario	Current cost (20-yr present value, $millions)	Future adapted cost 20-yr present value, $millions	Increase in cost (20-yr present value, $millions)	% increase in cost	Increase per acre of site $millions
Scott County, MN	Intensity change plus 10%	Conventional (Gray) Infrastructure	3.05	8.96	5.92	194	0.30
		GI with Gray Infrastructure	4.92	8.11	3.20	65	0.16
		GI Only	8.51	12.76	4.25	50	0.21
		Conventional (Gray) Infrastructure with Distributed GI	3.05	4.62	1.58	52	0.08

Table B-30 provides an estimate of cost for the future "intensity plus 20%" climate scenario.

Table B-30. Comparison of the current and future estimated 20-year present value costs for the Scott County, MN stormwater management scenarios, intensity plus 20%

Location	Climate scenario	Stormwater management scenario	Current cost (20-yr present value, $millions)	Future adapted cost 20-yr present value, $millions	Increase in cost (20-yr present value, $millions)	% increase in cost	Increase per acre of site $millions
Scott County, MN	Intensity change plus 20%	Conventional (Gray) Infrastructure	3.05	14.08	11.03	362	0.55
		GI with Gray Infrastructure	4.92	11.31	6.40	130	0.32
		GI Only	8.51	17.12	8.61	101	0.43
		Conventional (Gray) Infrastructure with Distributed GI	3.05	5.79	2.75	90	0.14

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