Memorandum

TO: Lisa Rhodes and Tom Maguire (MassDEP)

FROM: David Roman (Comprehensive Environmental)

DATE: September 27, 2023

SUBJECT: Summary of Target Recharge Volume Evaluation

Background

- The purpose of this memorandum is to summarize the process and results related to the evaluation of target recharge values included in the proposed revisions to the Wetlands Protection regulations (310 CMR 10.05(6)(k)3.) under Stormwater Management Standard 3 for use in sizing Stormwater Control Measures (SCMs). This evaluation was performed to respond to questions raised by the Massachusetts Stormwater Management Advisory Committee.[1]
- As presented at the Advisory Committee meeting held on October 15, 2020, the current numerical recharge targets are failing to approximate the annual recharge volume lost from new development. MassDEP therefore is proposing that the required static Recharge Volume (Rv) be at least 1-inch times the total post-construction impervious area on site for Hydrologic Soil Group (HSG) A, B, C, and to the Maximum Extent Practicable (MEP) for HSG D soils. One intent of this proposal was to align with the 2016 Small Municipal Separate Stormwater Sewer System (MS4) permit requirement to retain 1-inch of stormwater runoff onsite. For reference, the Rv required by the 2008 Stormwater Handbook assigned a different Target Depth Factor to each HSG Soil Group – i.e., HSG A = 0.60 inches; HSG B = 0.35 inches; HSG C = 0.25 inches; and HSG D = 0.1 inches.
- After the Advisory Committee process, MassDEP (Thomas Maguire) and Region 1 of the United States Environmental Protection Agency (US EPA) (Mark Voorhees) performed separate analyses to verify whether the proposed 1-inch Rv was reasonable. Both analyses were reviewed by Viki Zoltay, State Hydrologist, from the Massachusetts Department of Conservation and Recreation (MassDCR). MassDEP incorporated comments received from Mass DCR and US EPA and revised its analysis.
- This Memorandum is organized into three parts: 1) a summary of the evaluation process, 2) results, and 3) discussion. Supporting appendices for the MassDEP analysis (**Appendix A**) and the US EPA analysis (**Appendix B**) are also included.

Analysis Summary

- **Baseflow Separation Analysis**. MassDEP analyzed United States Geological Survey (USGS) streamflow gaging stations and precipitation data from 69 watersheds in Massachusetts and neighboring states to estimate the proportion of precipitation that becomes baseflow across Massachusetts. Results of the analysis were used to estimate a statewide recharge depth range for use in sizing SCMs to meet predevelopment groundwater recharge and to support baseflow. Assuming a conservative approach, the static SCM recharge depth from this analysis is 0.70 to 0.80 inches, as revised to incorporate technical review comments from MassDCR. This range strikes a balance between locations with a higher proportion of stratified drift that require a larger proportion of recharge relative to precipitation (e.g., Cape Cod) and locations that receive more precipitation and will therefore require a higher SCM design depth to support recharge. See

[1] Advisory Committee Website: https://www.mass.gov/info-details/massachusetts-stormwater-management-updates-advisory-committee#meeting-schedule-and-materials-.

Appendix A for a summary writeup of this analysis, including a summary of revisions that were made based on comments from the Advisory Committee and technical reviewers.

- **Continuous Rainfall-Runoff Simulation Analysis**. US EPA (Mark Voorhees) performed modeling using the Stormwater Management Model (SWMM) model that was previously used on the Charles River Basin to develop the 2016 MS4 Permit Regulations and the results of cumulative SCM performance modelling using the EPA System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model. Both the calibrated SWMM and SUSTAIN models used in the recharge analysis described here are included in the EPA Region 1 Opti-Tool package.[2] The purpose of the modeling exercise was to evaluate the required Design Storage Volume (DSV) depth of infiltration SCMs (i.e., infiltration basin, infiltration trench, and permeable pavement) for HSG A, B, C, and D soils and their potential infiltration rates to meet average annual predevelopment recharge targets. Recharge targets were defined based on the 90th percentile and annual average Boston rainfall from 1992 to 2020. The following steps were performed for each HSG type:
    - Started with average annual precipitation and normalized to a per unit area basis (MG/acre/yr).
    - Estimated average annual runoff yield from Impervious Cover (IC) and from each HSG in MG/acre/yr based on continuous simulation results from SWMM Hydrologic Response Unit (HRU) modeling assuming a combination of forest and meadow coverage. Average annual runoff volumes for each HSG were estimated by taking the average of HRU model continuous simulation results of two approaches: 1) Horton infiltration equation; and 2) the Curve Number method. Results were then compared with continuous simulation HRU modelling being conducted in the Taunton River watershed using the Hydrologic Simulation Program Fortran (HSPF) model.
    - Approximated average annual groundwater recharge target volume per unit area (MG/acre/yr) by assuming that half of average annual precipitation results in evapotranspiration (ET) – i.e., dividing precipitation in half, then subtracting runoff. Use of a 50% estimate for ET is supported by the results reported in literature, reported estimates by the Cornell Northeast Regional Climate Center, and the results of the Taunton Watershed HSPF modelling in which ET was modelled explicitly.[3]
    - Added 10% to the approximated groundwater recharge target volume per unit area to account for evapotranspiration loss at the SCM – this value represents the required recharge on an average annual basis in MG/acre/yr.
    - Converted the required recharge to a percentage of annual IC runoff yield – this value represents the percent volume reduction needed by the SCM to meet the recharge target.
    - Used updated EPA Region 1 Performance Curves for the same climatic period (1992 – 2020) used in the HRU modelling for each SCM type and the required volume reduction percentage based on corresponding HSG infiltration rates (e.g., 1.02 for HSG A; 0.52 for HSG B; 0.17 for HSG C; 0.10 for HSG D) to determine a "*Static*" DSV (hereafter "EPA *Static")* depth based on cumulative runoff IC. Results are presented at **Appendix B**.
    - **Note**: The "EPA *Static*" DSV depth presented by the Continuous Rainfall-Runoff Simulation Analysis is not directly comparable to the "*Static Method*" (hereafter ("MassDEP *Static")* presented in the MassDEP Stormwater Handbook for which the target Rv is being developed. The "EPA *Static*" DSV depth means that dynamic factors such as exfiltration have already been accounted for in the sizing. By contrast, the MassDEP

[2] Opti Tool Package: https://www.epa.gov/tmdl/opti-tool-epa-region-1s-stormwater-management-optimization-tool.
[3] Northeast Regional Center ET estimates: https://www.nrcc.cornell.edu/wxstation/pet/pet.html.

Stormwater Handbook allows applicants to use the "MassDEP *Static*" method or multiple "*Dynamic*" methods. The "MassDEP *Static*" method is the most conservative and assumes that the SCM must capture the full target Rv from upstream impervious area while the "*Dynamic*" methods assume that the Rv exfiltrates over time, thus resulting in a smaller Rv depending on the saturated hydraulic conductivity of the underlying soils. The "EPA *Static*" DSV presented by the Continuous Rainfall-Runoff Simulation Analysis results must therefore be increased to enable a level of comparison with the "MassDEP *Static*" method. For simplicity, an increase of 8% was applied when performing comparisons with the Baseflow Separation Results (*see footnote for reasoning*).[4]

- Results from the Continuous Rainfall-Runoff Simulation Analysis indicate that the "EPA *Static*" DSV depth to meet recharge targets ranges widely depending on annual precipitation amount, SCM type, and HSG (see **Appendix B**). For example, higher annual precipitation, infiltration trenches, and HSG D soils require the largest DSV depths. Assuming a conservative approach using recharge targets from 90th percentile precipitation, infiltration trench results, and results from infiltration rates generated from HSG C soils, the "*EPA* Static" DSV depth would range from approximately 0.55 to 0.68 inches. Applying an 8% correction factor would result in a DSV depth range of 0.59 inches to 0.73 inches.

Comparison of Results

- Results from both methods have overlapping ranges in recharge volume estimates – i.e., the resulting SCM recharge depth from the Baseflow Separation Analysis is 0.70 to 0.80 inches as compared to 0.59 to 0.73 inches from the Continuous Rainfall-Runoff Simulation Analysis.
- As demonstrated in both **Appendix A** (results from Baseflow Separation Analysis) and **Appendix B** (results from the Baseflow and Continuous Rainfall-Runoff Simulation Analysis), there is a great deal of variability associated with findings from each method.
- It is further noted that the Continuous Rainfall-Runoff Simulation Analysis was performed based on precipitation data from Boston which is lower than the statewide average because of coastal influence.
- To be more representative of statewide conditions, it is likely that the conservative Continuous Rainfall-Runoff Simulation Analysis "*EPA Static*" DSV depth range results would increase when considering 90th percentile Statewide precipitation.

Discussion of Results

- Based on analysis of these results, MassDEP is considering revising the proposed Stormwater Management Standard 3 for new development to require a SCM Rv depth of at least **0.8 inches** for HSG A, B, and C soils as compared to the previous proposal of 1.0 inch. For redevelopment, the proposed standard would be 0.8 inches of recharge to the MEP if this change is adopted.

- As indicated by **Appendix A**, this value of 0.80 inches strikes a balance between locations with a higher proportion of stratified drift that require a larger proportion of recharge relative to

[4] An analysis of a simple site with 1-acre of impervious area indicates that an infiltration SCM sized in accordance with the MassDEP "*Simple Dynamic*" method could be sized to be smaller than an infiltration SCM sized using the MassDEP "*Static*" method based on the infiltration rate of the underlying soils. The finding are as follows: 8.27 in/hr (41% smaller); 2.41 in/hr (17% smaller); 1.02 in/hr (8% smaller); 0.52 in/hr (4% smaller); and 0.27 in/hr (2% smaller). Based on these findings, an 8% correction factor was applied to correspond to the 1.02 in/hr rate.

precipitation (e.g., Cape Cod), locations that receive more precipitation and will therefore require a higher SCM design depth to support recharge (e.g., inland locations), and potential future increases in annual Statewide average precipitation depths. [5, 6]

- This value also aligns with conservative results from the Continuous Rainfall-Runoff Simulation Analysis, particularly when viewed through a statewide lens with higher annual precipitation than the Boston area. Findings from recent unpublished work in the Taunton River Watershed performed by EPA Region 1 indicate that recharge may decrease in the future because of increasing temperatures and ET (i.e., recharge is equal to infiltration minus ET).[7] This suggests that selection of a conservative recharge value is reasonable for SCM sizing.
- Adopting a SCM recharge depth of 0.80 inches means that an SCM would be sized in accordance with the "*MassDEP Static*" method in the MassDEP Stormwater Handbook – i.e., an SCM would be designed to capture 0.80 inches of runoff multiplied by the contributing impervious area. Use of "*Dynamic*" methods or the "*Continuous Simulation*" method in the MassDEP Stormwater Handbook have the potential to decrease the required "*Static*" recharge depth to a depth below the recommended value of 0.80 inches.

[5] For example, the average annual precipitation in Worcester is approximately 12% higher than in Boston.

[6] As annual precipitation increases, natural annual recharge will concurrently increase, meaning the sizing of artificial recharge basins will need to be increased to meet the regulatory requirement at 310 CMR 10.05(6)(k)3. that "the annual recharge from the post-development site shall approximate the annual recharge from the pre-development conditions."

7 Unpublished EPA study is a draft technical memorandum completed on July 26, 2021, for a project entitled "Holistic watershed management for existing and future land use development activities: opportunities for action for local decision makers: Phase 1 – modeling and development of flow duration curves".

Appendix A

Baseflow Separation Analysis Writeup

ESTIMATION OF PERCENT OF ANNUAL PRECIPITATION THAT SUPPORTS BASEFLOW IN MASSACHUSETTS FOR USE IN SIZING STORMWATER CONTROL MEASURES

September 2023

Thomas Maguire, Massachusetts Department of Environmental Protection

Background

Creation of impervious surfaces as part of land development reduces baseflow to rivers (Simmons and Reynolds 1982). Reduced baseflows decrease streamflow, impairs water quality, diminishes the geographic extent of pulse-fed wetlands, lessens water available for withdrawal such as for public drinking waters, and affects aquatic and terrestrial habitats. To maintain baseflow to rivers and other types of wetlands, the Massachusetts Department of Environmental Protection (MassDEP) Wetlands Protection regulations require that when land surfaces are rendered impervious by land development that "the annual recharge from the post-development site shall approximate the annual recharge from the pre-development conditions", 310 CMR 10.05(6)(k)3.

Freshwater wetlands include, but are not limited to, rivers, marshes, and swamps. Hydrologic inputs to freshwater wetlands occur through several mechanisms including precipitation falling directly onto wetlands, direct runoff, interflow, and baseflow. Baseflow is the portion of flow to surface waters (including wetlands) that is provided by groundwater. Aquifers are recharged by precipitation that infiltrates into the soil and then percolates down to the aquifer (also known as the saturated zone or water table). Recharge should not be confused with infiltration which occurs during and immediately after precipitation, as water seeps into the soil (also known as the unsaturated zone). Some of this water is lost to evapotranspiration and interflow (subsurface flow from the unsaturated zone that discharges faster than groundwater). Recharge is the portion of infiltration that continues to seep downward and percolates into the saturated zone.

No statewide quantification of the annual pre-development recharge has been completed to standardize the value to which stormwater recharge practices are designed. The method specified in MassDEP (1997) based on Hydrologic Soil Groups (HSG) was adapted with changes from the procedure specified by the State of Maryland.[1] The current method specified in MassDEP (2008) to size stormwater recharge practices also is based on HSGs. However, HSGs are designated by the United States Natural Resources Conservation Service (U.S. NRCS) to quantify the runoff potential of a soil (U.S. NRCS 2009). As Fennessey and Hawkins 2001 indicate, "*The Hydrologic Soil Group has nothing to do with recharge, and should not be used as an indicator of recharge, or for any other purpose that it was not originally intended for*". This study was undertaken to quantify pre-development recharge to size Stormwater Control Measures (SCMs) without the use of HSGs.

Literature Review

A literature review was conducted to identify any studies that quantified recharge in Massachusetts. Four (4) relevant studies were identified:

1) One direct measurement study was conducted on Nantucket (Knott and Olimpio, 1986). Two sites were assessed. At Site 1, "*the average annual recharge rate between 1964 and 1983 was 26.1 inches per year, or 68 percent of the average annual precipitation*." At Site 2 "*the multilevel*

[1] See Maryland Department of the Environment, 2009, Table 1.2 Estimates of Annual Recharge Rates, Based on Soil Type. It was assumed the reported Maryland annual recharge volumes divided by 44-inches/year precipitation (assumed Statewide average for Massachusetts) would equal the recharge depth in inches.

water samplers were not constructed deep enough to" measure recharge directly and it was concluded that "*the average recharge rate was at least 16.7 inches per year, or at least 44 percent of the average annual precipitation based on the data's similarity to Site 1*."

2) Bent (1998) computed groundwater recharge rates from continuous records of daily mean discharge at 11 long-term streamflow-gaging stations in a study area encompassing western Massachusetts, eastern New York, and northwestern Connecticut. Mean annual groundwater recharge rates ranged from 17.9 to 28.9 inches per year, with a median value of 22.6 inches per year.

3) Bent (1995) computed mean groundwater recharge rates from continuous records of daily mean discharge during water years 1967-91 for six streamflow-gaging stations in southeastern Massachusetts and Rhode Island near Buzzards Bay. Estimates of mean groundwater recharge were 19.7 to 22.6 inches per year for stations with drainage areas primarily underlain by till and bedrock deposits, and 23.8 to 25.2 inches per year for stations with drainage areas primarily underlain by stratified drift deposits.

4) Masterson and others (1998) assumed a natural recharge rate of 21.6 and 25.9 inches per year in their groundwater modeling of western Cape Cod but did not cite the source of these values. These two values were selected to test model sensitivity.

A summary of these studies is presented by **Table 1**. For comparison, a simplified Baseflow Index (BFI) was calculated for each applicable recharge study – the calculated BFI for these reviewed recharge studies ranged from 0.44 to 0.68. See "methods and results" for discussion of BFI calculation assumptions.

Table 1. Summary of reviewed recharge studies

Study and Location	Mean Annual Groundwater Recharge (in/yr)	Estimated BFI Range[1]
Knott and Olimpio 1986; Nantucket	16.7 - 26.1	0.44 to 0.68
Bent 1998; MA/NY/CT	17.9 - 28.9	0.39 to 0.63
Bent 1995; Buzzards Bay	19.7 - 25.2	0.43 to 0.54
Masterson 1998; western Cape Cod	21.6 and 25.9	N/A

[1]Baseflow Index (BFI) computed based on annual precipitation data presented by each study. The computed BFI is equal to mean annual groundwater recharge divided by mean annual precipitation.

Methods and Results

This analysis was conducted to estimate the proportion of precipitation that becomes baseflow across Massachusetts, then use that result to estimate a Statewide effective recharge value. A summary of analysis steps is listed below.

- **Step 1 (Select and Tabulate Data from Streamflow Gages)**. 69 United State Geological Survey (USGS) stream gages were selected throughout the State with daily flow records ranging from 6 years to 109 years. The watersheds represented by these gages are either fully or partially located in the State and range in size from 0.4 to 689 square miles. See **Attachment 1** for a list of gages and their characteristics.
- **Step 2 (Perform Baseflow Separation and Compute BFI)**. The **W**eb-Based **H**ydrograph **A**nalysis **T**ool (WHAT) (Lim, 2005 and Lim, 2010) was used for the full period of record of each stream gage to separate direct runoff from baseflow. Results from WHAT were used to

calculate a baseflow index (BFI) for each gage as the ratio of separated baseflow to total flow. The BFI for individual gages ranged from 0.51 to 0.76 with an average of 0.65 (**Attachment 1**).

- **Step 3 (Evaluate Computed BFI Variability).** Gages were separated into bins (categories) to evaluate potential BFI variability (**Figure 1**). Seven (7) bins were constructed that represent a range of conditions (e.g., large drainage area vs. small drainage area; low impervious area vs. high impervious area, etc.). As indicated by **Figure 1**, BFI is variable across each bin, but generally follows a range of 0.63 to 0.70 – i.e., baseflow comprises approximately 63% to 70% of total flow for evaluated gages in the database. For reference, the area-weighted average BFI was 0.67 for all 69 gages.

- **Step 4 (Compare Computed BFI to Previous Studies)**. The computed BFI of previous studies ranged from 0.44 to 0.68 (**Table 1**) as compared to this study with computed BFI values ranging from 0.51 to 0.76. Previous studies therefore generally had lower computed BFIs than this study (i.e., 10%± lower). This difference may be due to multiple factors such as: smaller sample sizes of previous studies; different computation methodologies that were used – i.e., the Bent (1995) and Bent (1998) studies computed recharge using the RORA[2] and HYPSEP[3] methods; and different time periods (i.e., data for these studies were generally analyzed from the 1960's through the 1990's).

- **Step 5 (Convert BFI into Recharge Depth for SCM Design)**. This analysis assumes that the percentage of precipitation that recharges groundwater is equal to the BFI. The final step of the analysis was to therefore convert the computed BFI (assumed amount of precipitation that contributes to recharge) into a representative Statewide "Static" recharge depth for use in SCM design.[4] To convert BFI into a representative rechange depth, daily precipitation data from 1992 and 2018 at the Boston Airport and Worcester Airport weather stations was analyzed. The Boston Airport weather station is expected to be generally representative of coastal conditions (climate normal precipitation of 43.6 inches per year), while the Worcester Airport weather station is expected to be generally representative of inland conditions (climate normal precipitation of 48.3 inches per year).[5] Similarly, 1992 is representative of a normal precipitation year, while 2018 is representative of a wetter than normal year.[6]

  For each daily precipitation record from the Boston Airport and Worcester Airport weather stations, measured precipitation was assigned to bins ranging from 0.30 inches per day to 1.5 inches per day in 0.10 inch per day increments. Days with recorded snow or below freezing were assumed to result in no contributing recharge and were discounted from the analysis. The amount of resulting daily rainfall was then input into each applicable bin, then summed across each year. For example, assume that 53.3 inches of rain fell in a year. Of that 53.3 inches, say 33.0 inches (62%) was less than 0.50 inches per day and 47 inches (90%) was less than 1.5 inches per day. Assuming a required BFI of 0.70, a SCM would need to be designed to capture more than 0.50 inches to support groundwater recharge and baseflow.

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[2] USGS RORA: https://water.usgs.gov/ogw/gwrp/methods/recession_curve/rora_exec.html.

[3] USGS HYSEP: https://pubs.er.usgs.gov/publication/wri964040.

[4] Static recharge depth means that an SCM is sized in accordance with the "*Static*" method in the MassDEP Stormwater Handbook. Use of "*Dynamic*" methods or the "*Continuous Simulation*" method in the MassDEP Stormwater Handbook have the potential to decrease the required "*Static*" recharge depth.

[5] Statewide annual precipitation ranges from 40.9 inches per year to 54.1 inches per year (average of 49.0 inches per year) based on an analysis of 134 stations across the state for which the National Oceanic and Atmospheric Administration (NOAA) reports precipitation statistics for the Climate Normal Period of 1991-2020. The Boston and Worcester Airport weather stations generally represent the lower and upper end up this range, respectively.

[6] A wetter year was selected to provide a conservative annual recharge estimate since more annual recharge occurs during wetter years.

As summarized by **Table 3** for each weather station and evaluated year, the minimum required SCM design depth to support groundwater recharge ranges from approximately 0.40 inches to 0.80 inches. The required design depth increases relative to increases in annual precipitation (e.g., “wet” years, inland areas with higher precipitation, etc.).

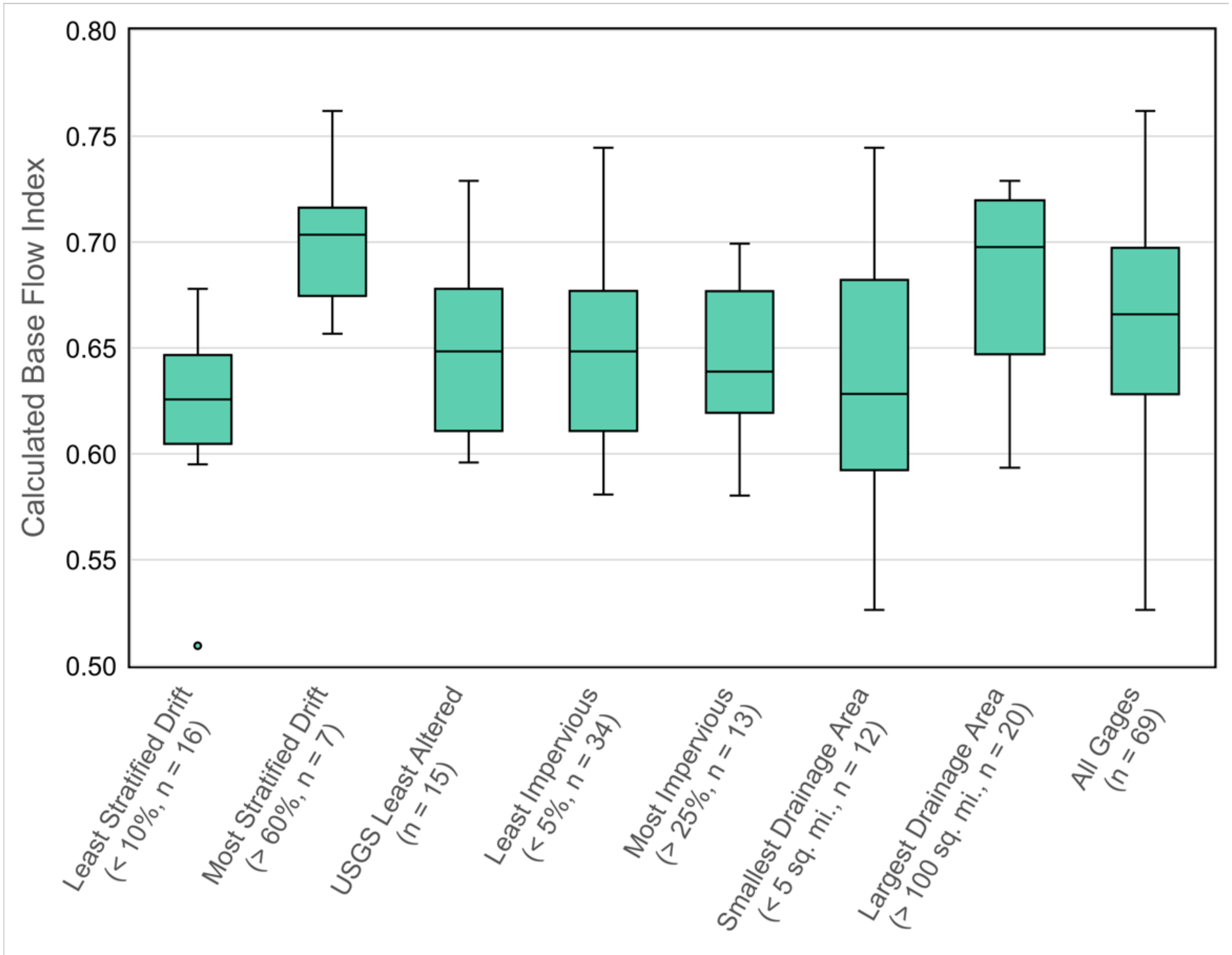

Figure 1. Comparison of calculated Base Flow Index based on category

Table 3. Required SCM design depth to support groundwater recharge and baseflow

BFI / Proportion of Annual Precipitation Requiring Recharge	Required SCM Design Depth (inches)			
	Boston		Worcester	
	1992	*2018*	*1992*	*2018*
60%	0.40	0.50	0.50	0.60
65%	0.50	0.55	0.60	0.70
70%	0.60	0.65	0.75	0.80

Discussion

Based on results from this analysis, the minimum required SCM design depth to support pre-development groundwater recharge ranges from approximately 0.40 inches to 0.80 inches (**Table 3**). This range varies based on BFI and rainfall amounts. For conservatism, and to ensure that groundwater recharge and baseflow is supported Statewide, it is recommended the required SCM recharge depth be at least 0.70 to 0.80 inches. This range strikes a balance between locations with a higher proportion of stratified drift that require a larger proportion of recharge relative to precipitation (e.g., Cape Cod[7], see **Figure 1**), inland locations that receive more precipitation and will therefore require a higher SCM design depth to support recharge (e.g., inland locations), and potential future increases in annual Statewide average precipitation depths.

The recommended SCM recharge depth range of 0.70 to 0.80 inches means that an SCM would be sized in accordance with the "*Static*" method in the MassDEP Stormwater Handbook – i.e., an SCM would be designed to capture 0.70 inches to 0.80 inches of runoff multiplied by the contributing impervious area. Use of "*Dynamic*" methods or the "*Continuous Simulation*" method in the MassDEP Stormwater Handbook have the potential to decrease the required "*Static*" recharge depth to a depth below the recommended range of 0.70 to 0.80 inches.

Analysis History

This analysis was first performed in 2020 and presented at a Massachusetts Stormwater Management Updates Advisory Committee (AC) meeting in October 15, 2020 for 121 evaluated stream gages. Results presented to the AC indicated that the average BFI for the evaluated gages was approximately 0.70 – 0.05 higher than finalized results presented by this analysis. After the AC meeting, results from the analysis were reviewed by Viki Zoltay, State Hydrologist from the Massachusetts Department of Conservation and Recreation, and internally by MassDEP. Primary changes to the analysis were to exclude results from stream gages where a large percentage of their drainage area was out of State (e.g., Merrimack River Below Concord River at Lowell); to evaluate and verify computations (i.e., units); to explore potential variability based on different basin characteristics (see **Figure 1**); and to convert results into a recharge depth for SCM design.

[7] The baseflow analysis determined river basins that contained a high percentage of stratified drift had a higher BFI than basins with lower percentages of stratified drift.

Limitations

The following assumptions and limitations are noted relative to this analysis.

- The period of record timeline for all evaluated stream gauges does not match (**Step 1**, **Attachment 1**). For this analysis, it was determined that using the full record length would be more beneficial than excluding large chunks of data; however, it is possible that selection of different (or matching) periods of record could yield different results (e.g., only use streamflow data during the climate normal period of 1991 through 2020).
- There are multiple methods that may be used to perform baseflow separation (**Step 2**). This analysis relies upon the WHAT Tool which separates baseflow by the "local minimum method" – i.e., connects local minimum points by comparing the slope of the hydrograph. This method may overestimate baseflow during rainy days. The WHAT tool algorithm also does not account for reservoir releases or snowmelt. It is possible that different baseflow separation methods may yield different results.
- There are multiple methods that may be used to estimate BFI and subsequent groundwater recharge rates (**Step 3**). This analysis assumes that the percentage of precipitation that recharges groundwater is equal to the BFI. This assumption has not been validated through comparison of watershed specific precipitation data with baseflow separation results. Different computation methods such as USGS RORA, or basin-specific USGS HSPF models may yield different results.
- Daily precipitation data was assigned into relatively coarse 0.10 inch bins when evaluating the amount of rainfall that falls into a specific bin (**Step 5**). In addition, binning of precipitation data was performed on a daily basis rather than on a "per storm" basis based on antecedent conditions. Separation of precipitation data into "storm specific" bins based on antecedent conditions may yield different results.
- Two representative (2) weather stations and two (2) representative years were used when converting BFI into a minimum recharge depth for SCM design (**Step 5**). Analysis of more locations and more years would increase confidence in results. For example, several parts of Western Massachusetts receive more precipitation than the representative inland weather station (Worcester Airport).

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Attachment 1. Analysis stream gage characteristics and baseflow index computations

Gage	Gage Name	Drainage Area (mi²)	Impervious (%)	Coarse Grain Stratified Drift (%)	Record Length (yrs)	Sum of Daily Flow Over Record Length (cfs)[1]	Sum of Daily Direct Runoff Over Record Length (cfs)[1]	Sum of Daily Base Flow Over Record Length (ft³)[1]	Base Flow Index
01162500	PRIEST BROOK NEAR WINCHENDON, MA	19.4	0.6%	9.5%	102.4	1,281,959.8	479,903.1	802,056.8	0.63
01169000	North River at Shattuckville	89.0	0.6%	6.2%	82.2	5,891,322.5	2,218,887.3	3,672,435.3	0.62
01169900	SOUTH RIVER NEAR CONWAY, MA	24.1	1.0%	12.6%	54.2	1,078,486.4	374,421.7	704,064.7	0.65
01170100	Green River near Colrain	41.4	0.3%	2.7%	54.5	1,851,965.6	651,224.4	1,200,741.2	0.65
01173000	Ware River at Intake Works Near Barre	96.3	1.1%	18.2%	94.2	5,847,445.5	1,876,949.5	3,970,495.9	0.68
01174000	Hop Brook near New Salem	3.4	0.9%	2.1%	34.9	76,038.0	26,739.7	49,298.3	0.65
01174900	Cadwell Creek near Belchertown	2.6	0.2%	0.7%	35.0	66,444.9	25,937.5	40,507.5	0.61
01175500	Swift River at West Ware	189.0	0.3%	11.0%	109.0	6,166,793.6	1,715,455.4	4,451,338.2	0.72
01176000	Quaboag River at West Brimfield	150.0	2.0%	21.2%	109.0	10,167,987.3	2,756,677.8	7,411,309.5	0.73
01180000	Sykes Brook at Knightville	1.7	0.2%	0.0%	28.0	25,755.3	9,511.3	16,244.0	0.63
01180500	Middle Branch Westfield River at Goss Heights (Huntington)	52.7	0.2%	2.8%	99.0	3,888,110.8	1,571,214.3	2,316,896.5	0.60
01181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON, MA	94.0	0.4%	4.0%	85.0	6,136,063.8	2,388,492.0	3,747,571.8	0.61
01198000	GREEN RIVER NEAR GREAT BARRINGTON, MA	51.0	0.4%	9.9%	35.5	1,157,779.1	372,960.3	784,818.8	0.68
01332000	North Branch Hoosic River at North Adams	40.9	0.9%	5.6%	58.0	2,046,336.9	819,192.1	1,227,144.7	0.60
01333000	GREEN RIVER AT WILLIAMSTOWN, MA	42.6	1.0%	11.3%	70.9	2,237,342.6	736,325.9	1,501,016.7	0.67
01185500	WEST BRANCH FARMINGTON RIVER NEAR NEW BOSTON, MA	91.7	0.5%	4.2%	107.3	7,328,650.7	2,694,318.7	4,634,332.0	0.63
01168500	DEERFIELD RIVER AT CHARLEMONT, MA	361.0	0.6%	2.5%	107.2	36,174,644.5	14,089,841.4	22,084,803.1	0.61
01179500	WESTFIELD RIVER AT KNIGHTVILLE, MA	161.0	0.7%	2.6%	106.0	13,183,670.2	5,340,067.3	7,843,603.0	0.59
01170000	DEERFIELD RIVER NEAR WEST DEERFIELD, MA	557.0	0.7%	5.2%	81.3	40,315,738.0	14,282,295.4	26,033,442.6	0.65
01123360	QUINEBAUG R BL E BRIMFIELD DAM AT FISKDALE, MA	62.6	1.1%	22.0%	35.9	1,743,973.0	564,073.5	1,179,899.5	0.68
01171500	MILL RIVER AT NORTHAMPTON, MA	52.6	1.5%	15.7%	81.8	3,026,120.8	1,045,154.4	1,980,966.4	0.65
01095220	STILLWATER RIVER NEAR STERLING, MA	29.1	1.6%	17.9%	26.3	546,122.1	194,657.5	351,464.6	0.64
01177000	CHICOPEE RIVER AT INDIAN ORCHARD, MA	689.0	1.7%	21.1%	92.1	31,522,418.9	9,291,270.8	22,231,148.1	0.71
01183500	WESTFIELD RIVER NEAR WESTFIELD, MA	497.0	1.8%	12.8%	106.2	36,844,228.7	12,879,475.2	23,964,753.5	0.65
01331500	HOOSIC RIVER AT ADAMS, MA	46.7	1.9%	12.6%	88.9	2,980,057.7	908,221.6	2,071,836.1	0.70
01197000	EAST BRANCH HOUSATONIC RIVER AT COLTSVILLE, MA	57.6	1.9%	13.9%	84.5	3,383,171.9	1,250,406.1	2,132,765.8	0.63
01096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	63.7	2.3%	26.6%	70.9	2,971,860.5	970,510.2	2,001,350.2	0.67
01103455	TROUT BROOK AT DOVER, MA	3.7	3.5%	40.1%	8.2	16,621.6	4,247.9	12,373.6	0.74
01197500	HOUSATONIC RIVER NEAR GREAT BARRINGTON, MA	282.0	3.5%	12.4%	107.3	21,013,237.2	6,952,843.3	14,060,393.9	0.67
01095503	NASHUA RIVER, WATER STREET BRIDGE, AT CLINTON, MA (RADAR)	110.0	4.2%	22.3%	9.1	251,330.1	102,211.8	149,118.4	0.59
01095375	QUINAPOXET RIVER AT CANADA MILLS NEAR HOLDEN, MA	46.3	4.6%	19.9%	23.8	594,072.6	198,515.9	395,556.7	0.67
01109070	SEGREGANSET RIVER NEAR DIGHTON, MA	10.6	4.9%	15.8%	53.6	438,270.6	183,758.3	254,512.3	0.58
01101000	PARKER RIVER AT BYFIELD, MA	21.3	5.0%	42.7%	74.8	1,042,018.9	308,774.2	733,244.7	0.70
01105870	JONES RIVER AT KINGSTON, MA	15.7	5.3%	95.8%	54.1	684,342.0	194,212.2	490,129.9	0.72
01094400	NORTH NASHUA RIVER AT FITCHBURG, MA	64.2	6.4%	21.2%	47.9	2,164,067.7	738,729.0	1,425,338.8	0.66
01096500	NASHUA RIVER AT EAST PEPPERELL, MA	435.0	6.9%	32.1%	84.9	18,737,588.6	7,144,164.4	11,593,424.2	0.62

Gage	Gage Name	Drainage Area (mi^2)	Impervious (%)	Coarse Grain Stratified Drift (%)	Record Length (yrs)	Sum of Daily Flow Over Record Length (cfs)[1]	Sum of Daily Direct Runoff Over Record Length (cfs)[1]	Sum of Daily Base Flow Over Record Length (ft^3)[1]	Base Flow Index
01105880	HERRING RIVER AT NORTH HARWICH, MA	9.4	7.8%	100.0%	35.2	130,380.9	31,053.9	99,327.0	0.76
01104475	STONY BROOK RES., UNNAMED TRIB 1, NEAR WESTON, MA	0.9	9.5%	34.4%	13.5	7,740.2	2,364.1	5,376.1	0.69
01163200	OTTER RIVER AT OTTER RIVER, MA	34.1	9.7%	25.4%	55.7	1,304,294.2	425,950.9	878,343.3	0.67
01104455	STONY BROOK, UNNAMED TRIBUTARY 1, NEAR WALTHAM, MA	0.5	55.9%	43.2%	21.4	7,422.0	2,874.8	4,547.3	0.61
01103025	ALEWIFE BROOK NEAR ARLINGTON, MA	8.4	53.1%	60.6%	14.0	52,155.2	16,974.0	35,181.2	0.67
01105585	TOWN BROOK AT QUINCY, MA	4.1	52.0%	33.0%	35.9	89,435.2	33,466.4	55,968.8	0.63
01100568	SHAWSHEEN RIVER AT HANSCOM FIELD NEAR BEDFORD, MA	2.1	49.7%	4.3%	24.9	41,238.7	15,015.2	26,223.5	0.64
01102500	ABERJONA RIVER AT WINCHESTER, MA	24.7	45.6%	43.6%	81.3	957,216.5	346,958.4	610,258.1	0.64
01104420	CAMBRIDGE RES., UNNAMED TRIB 3, NR LEXINGTON, MA	0.8	39.5%	13.1%	9.8	5,748.6	2,377.6	3,371.0	0.59
01102345	SAUGUS RIVER AT SAUGUS IRONWORKS AT SAUGUS, MA	20.8	30.9%	38.7%	26.5	310,438.2	103,540.1	206,898.2	0.67
01100600	SHAWSHEEN RIVER NEAR WILMINGTON, MA	36.5	29.7%	38.5%	56.8	1,240,776.8	435,991.2	804,785.6	0.65
01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	4.4	29.6%	28.4%	54.3	179,616.3	75,391.7	104,224.6	0.58
01105583	MONATIQUOT RIVER AT EAST BRAINTREE, MA	28.7	28.9%	32.6%	14.4	252,149.6	91,066.7	161,082.9	0.64
01110000	QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	25.6	27.7%	38.5%	80.9	1,238,412.3	372,495.4	865,917.0	0.70
01100627	SHAWSHEEN RIVER AT BALMORAL STREET AT ANDOVER, MA	72.8	27.6%	52.6%	13.2	625,755.7	200,953.7	424,802.0	0.68
01098500	COCHITUATE BK BL LAKE COCHITUATE AT FRAMINGHAM, MA	17.5	26.2%	65.4%	11.7	128,837.7	40,453.9	88,383.8	0.69
01168250	COLD RIVER AT FLORIDA, MA	6.5	0.9%	0.0%	5.7	43,304.0	21,249.3	22,054.7	0.51
01100561	SPICKET RIVER NEAR METHUEN, MA	62.1	12.5%	9.7%	14.9	578,173.6	203,858.9	374,314.7	0.65
01105730	INDIAN HEAD RIVER AT HANOVER, MA	30.3	17.8%	68.6%	54.1	1,267,950.4	435,303.5	832,646.9	0.66
01109060	THREEMILE RIVER AT NORTH DIGHTON, MA	84.3	13.2%	64.5%	54.1	3,302,253.4	973,416.6	2,328,836.9	0.71
01105500	EAST BRANCH NEPONSET RIVER AT CANTON, MA	27.2	20.1%	60.2%	67.9	1,308,036.2	387,954.2	920,082.0	0.70
01104415	CAMBRIDGE RES., UNNAMED TRIB 2, NR LEXINGTON, MA	0.4	14.7%	21.0%	18.2	4,956.2	2,348.2	2,608.0	0.53
01095434	GATES BROOK NEAR WEST BOYLSTON, MA [(2)]	3.1	23.6%	26.9%	8.9	14,067.1	4,314.7	9,752.4	0.69
01108000	TAUNTON RIVER NEAR BRIDGEWATER, MA	261.0	11.4%	51.7%	73.5	13,383,072.2	3,810,593.7	9,572,478.5	0.72
01104500	CHARLES RIVER AT WALTHAM, MA	227.0	15.9%	47.5%	89.1	10,347,783.2	2,884,971.0	7,462,812.1	0.72
01104200	CHARLES RIVER AT WELLESLEY, MA	211.0	15.2%	46.6%	61.0	6,506,637.2	1,786,786.5	4,719,850.6	0.73
01103500	CHARLES RIVER AT DOVER, MA	183.0	13.4%	46.3%	82.8	9,449,151.0	2,605,619.9	6,843,531.1	0.72
01110500	BLACKSTONE RIVER AT NORTHBRIDGE, MA	141.0	21.1%	25.0%	63.8	4,512,392.4	1,349,983.4	3,162,409.0	0.70
01102000	IPSWICH RIVER NEAR IPSWICH, MA	125.0	13.4%	42.4%	90.2	6,376,631.1	1,856,191.3	4,520,439.8	0.71
01097000	ASSABET RIVER AT MAYNARD, MA	116.0	13.2%	39.1%	79.1	912,165.5	266,651.5	645,513.9	0.71
01094500	NORTH NASHUA RIVER NEAR LEOMINSTER, MA	110.0	11.5%	23.6%	84.9	6,386,855.2	2,073,753.9	4,313,101.3	0.68
01098530	SUDBURY RIVER AT SAXONVILLE, MA	106.0	19.9%	42.0%	40.8	2,999,876.1	950,280.3	2,049,595.8	0.68
011055566	NEPONSET RIVER AT MILTON VILLAGE, MA	101.0	23.0%	49.7%	23.8	2,605,722.5	796,159.6	1,809,562.9	0.69

[1]Streamgauge data were available for each day as daily values in cubic feet per second. For simplicity, BFI was calculated as the sum of daily flow (in cfs) divided by the sum of daily baseflow (in cfs). No censoring or annual averages were taken since the full period of record was considered. To more accurately represent units, these daily values could have been converted to an actual daily flow (i.e., cfs to cf) before summing. The computed BFI would be the same for either of these calculation methods.

Appendix B

Continuous Simulation Results

UNIT-AREA GROUNDWATER RECHARGE ESTIMATES FOR ESTIMATING IMPERVIOUS COVER RUNOFF CAPTURE FOR INFILTRATION FOR NEW DEVELOPMENT ACTIVITES – DRAFT 04/20/2022

Average Annual Unit Area Estimates of Hydrologic Budget and Nutrient Export for the Climatic period of Boston Massachusetts (1992-2020)

Land Area Type and Condition	Hydrologic Soil Group	Average Annual Precipitation,* Gallons/acre/year*	Range in Average Annual Modelled Runoff Yields, Gallons/acre/year	Estimated Average Annual Modelled Runoff Yield, Gal./acre/yr	Range in Average Annual Groundwater Recharge, Gal./acre/year	Estimated Average Annual Groundwater Recharge, Gal./acre/year	Range in Estimated Phosphorus Load Export, lbs/acre/yr	Estimated Average Annual Phosphorus Load Export, lbs/acre/yr	Range in Estimated Nitrogen Load Export, lbs/acre/yr	Estimated Average Annual Nitrogen Load Export, lbs/acre/yr
Grass-Meadow/Forested with well-drained soils	A	1,162,000	11,000 to 34,000	17,000	547,000 to 570,000	564,000	0.01 to 0.06	0.03	0.1 to 0.3	0.1
Grass-Meadow/Forested with moderately well-drained soils	B	1,162,000	65,000 to 99,000	76,000	482,000 to 516,000	505,000	0.06 to 0.17	0.12	0.5 to 0.8	0.6
Grass-Meadow/Forested with less well drained soils	C	1,162,000	147,000 to 183,000	155,000	398,000 to 434,000	426,000	0.12 to 0.29	0.24	1.0 to 1.5	1.3
Grass-Meadow/Forested with poorly drained soils	D	1,162,000	201,000 to 283,000	249,000	298,000 to 380,000	332,000	0.17 to 0.47	0.39	1.3 to 2.4	2
Impervious cover	Not Applicable	1,162,000	748,000 to 1,410,000	1,091,000	0	0	Not Applicable	1.97	Not Applicable	13.2

Notes: Runoff Yields estimated using the StormWater Management Model (SWMM) v5.0 with climatic data (hourly precipitation and daily temperature) for Boston, MA (1992-2020). The results provided for each hydrologic soil group (HSG) are averages of results of 4 separate continuous simulations (1992-2020) that inlcude the dynamic Horton infiltration equation and 3 using the Curve Number method to capture a range of CNs for the various HSGs. Nutrient export rates are based on the rates that have been derived for that MA and NH MS4 permits (appendix F attachment 3) and adjusted proportionally according to modelled estimated runoff yields.

Achieve 90th% Annual Recharge Target with Infiltration Practices for Capture of Impervious Cover Runoff (Boston, MA 1992-2022 Climatic Conditions)

Average Annual Unit Area Estimates of Hydrologic Budget and Nutrient Export for the Climatic period of Boston Massachusetts (1992-2020)*				% IC Runoff Reduction & level of control By Infiltration Practices			Subsoil Type		Infiltration Basin		Infiltration Trench		Permeable Pavement (includes Roof Runoff and Run-on)	
Land surface	average Annual Precipitation, MG/acre/yr	Average Annual Runoff (SW) yield*, MG/acre/yr	90th% Annual GW Recharge Yield, MG/acre/yr	Required Recharge at Site w/ 10% add-on for ET loss at BMP, MG/ac/yr	Percent Average Annual IC Runoff Volume Reduction by Infiltration practice, %	Level of IC Runoff depth Control (from Cum IC Runoff Delivery Curve), inches	HSG	Infiltration rate of Infiltration system, in/hr	Static Design Storage Volume (DSV) of Infiltration Basin, in	estimated cost for surface infiltration basin new development, $/IC acre	Static Design Storage Volume (DSV) of Infiltration Trench, in	estimated cost for surface infiltration trench new development, $/IC acre	Static Design Storage Volume (DSV) of Permeable Pavement, in	estimated cost for permeable pavement new development, $/IC acre
Grass/Forested HSG A (well drained)	1.159	0.017	0.657	0.723	66%	0.64	A	8.27	0.15	$ 3,800	0.20	$ 10,700	0.20	$ 4,000
							A	2.41	0.36	$ 8,800	0.56	$ 27,100	0.56	$ 12,000
Grass/Forested HSG B (moderately well drained)	1.159	0.076	0.621	0.683	63%	0.59	B	1.02	0.37	$ 9,000	0.51	$ 24,800	0.51	$ 11,000
							B	0.52	0.46	$ 11,200	0.60	$ 28,900	0.60	$ 12,000
Grass/Forested HSG C (less well drained)	1.159	0.155	0.509	0.560	51%	0.41	C	0.27	0.40	$ 9,700	0.55	$ 26,700	0.55	$ 11,000
							C	0.17	0.50	$ 12,100	0.68	$ 32,600	0.68	$ 14,000
Grass/Forested HSG D (poorly drained)	1.159	0.249	0.400	0.440	40%	0.28	D	0.1	0.50	$ 12,100	0.72	$ 34,353	0.72	$ 15,000
							D	0.05	0.85	$ 20,400	1.25	$ 58,470	1.25	$ 25,000
Impervious cover	1.159	1.091												

*Notes: Runoff Yields estimated using the StormWater Management Model (SWMM) v5.0 with climatic data (hourly precipitation and daily temperature) for Boston, MA (1992-2020). The results provided for each hydrologic soil group (HSG) are averages of results of 4 separate continuous simulations (1992-2020) that include the dynamic Horton infiltration equation and 3 using the Curve Number method to capture a range of CNs for the various HSGs. Nutrient export rates are based on the rates that have been derived for that MA and NH MS4 permits (appendix F attachment 3) and adjusted proportionally according to modelled estimated runoff yields.

Achieve Annual Recharge Targets with Infiltration Practices for Capture of Impervious Cover Runoff (Boston, MA 1992-2022 Climatic Conditons - Average Annual Precipitation = 42.78 in)														
Average Annual Unit Area Estimates of Hydrologic Budget and Nutrient Export for the Climatic period of Boston Massachusetts (1992-2020)*				**% IC Runoff Reduction & level of control By Infiltration Practices**			**Subsoil Type**		**Infiltration Basin**		**Infiltration Trench**		**Permeable Pavement (includes Roof Runoff and Run-on)**	
Land surface	**average Annual Precipitation, MG/acre/yr**	**Average Annual Runoff (SW) yield*, MG/acre/yr**	**Average Annual GW Recharge Yield, MG/acre/yr**	**Required Recharge at Site w/ 10% add-on for ET loss at BMP, MG/ac/yr**	**Percent Average Annual IC Runoff Volume Reduction by Infiltration practice, %**	**Level of IC Runoff depth Control (from Cum IC Runoff Delivery Curve), inches**	**HSG**	**Infiltration rate of Infiltration system, in/hr**	**Static Design Storage Volume (DSV) of Infiltration Basin, in**	**estimated cost for surface infiltration basin new development, $/IC acre**	**Static Design Storage Volume (DSV) of Infiltration Trench, in**	**estimated cost for surface infiltration trench new development, $/IC acre**	**Static Design Storage Volume (DSV) of Permeable Pavement, in**	**estimated cost for permeable pavement new development, $/IC acre**
Grass/Forested HSG A (well drained)	1.159	0.017	0.563	**0.619**	**57%**	**0.50**	**A**	**8.27**	**0.10**	**$ 2,600**	**0.17**	**$ 9,000**	**0.17**	**$ 4,000**
							A	**2.41**	**0.22**	**$ 5,500**	**0.42**	**$ 21,000**	**0.42**	**$ 9,000**
Grass/Forested HSG B (moderately well drained)	1.159	0.076	0.504	**0.554**	**51%**	**0.40**	**B**	**1.02**	**0.27**	**$ 6,600**	**0.36**	**$ 18,000**	**0.36**	**$ 8,000**
							B	**0.52**	**0.34**	**$ 8,300**	**0.42**	**$ 21,000**	**0.42**	**$ 9,000**
Grass/Forested HSG C (less well drained)	1.159	0.155	0.425	**0.467**	**43%**	**0.31**	**C**	**0.27**	**0.33**	**$ 8,000**	**0.42**	**$ 21,000**	**0.42**	**$ 9,000**
							C	**0.17**	**0.40**	**$ 10,000**	**0.55**	**$ 26,000**	**0.55**	**$ 11,000**
Grass/Forested HSG D (poorly drained)	1.159	0.249	0.331	**0.364**	**33%**	**0.22**	**D**	**0.1**	**0.40**	**$ 10,000**	**0.58**	**$ 28,000**	**0.58**	**$ 12,000**
							D	**0.05**	**0.69**	**$ 17,000**	**1.02**	**$ 48,000**	**1.02**	**$ 21,000**
Impervious cover	1.159	1.091	*Notes: Runoff Yields estimated using the StormWater Management Model (SWMM) v5.0 with climatic data (hourly precipitation and daily temperature) for Boston, MA (1992-2020). The results provided for each hydrologic soil group (HSG) are averages of results of 4 separate continuous simulations (1992-2020) that include the dynamic Horton infiltration equation and 3 using the Curve Number method to capture a range of CNs for the various HSGs. Nutrient export rates are based on the rates that have been derived for that MA and NH MS4 permits (appendix F attachment 3) and adjusted proportionally according to modelled estimated runoff yields.											