# Mystic River Watershed Alternative TMDL Development for Phosphorus Management - Final Report

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*Cover Photo:* The Tufts University sailing program practicing on Upper Mystic Lake in Medford with informal swimming at the Bacow Sailing Pavilion. Upper Mystic Lake is a popular destination with additional access at Massachusetts Department of Conservation and Recreation's Shannon Beach, and the Medford and Winchester Boat Clubs. Photo credit unknown.

## EXECUTIVE SUMMARY

The Mystic River Watershed, located a few miles north of Boston, is a 76-square mile area that drains into Boston Harbor. Encompassing all or portions of 22 urban and suburban communities, the watershed is highly developed and faces multiple water quality impairments. The Massachusetts Department of Environmental Protection's (MassDEP's) water quality assessment indicates that nutrients and pathogens are the primary causes of "use impairment" in the freshwater portion of Mystic River watershed, the focus of this report. Cultural eutrophication–the degradation of aquatic environments by nutrient pollution caused by human activity and urban development–is a major cause of impairments in the watershed as evidenced by excessive algal and macrophyte growth and harmful cyanobacteria blooms. Regular occurrences of severe algal blooms during the summer months reduce water clarity and contribute to anoxic bottom waters that do not support aquatic life. Algal blooms and macrophyte growth degrade the aesthetic quality of the river, reduce water clarity, and impair designated uses such as fishing and boating.

Photo Above: The Mystic River Run and Paddle (May 2016). This annual race celebrates the return of the river herring and draws the public to the Mystic River. This image looks downstream from Route 16 to the Blessing of the Bay Boathouse in Somerville with the Boston skyline in the background. Photo credit: Ram Subramanian.

### *Clean Water Act Requirements*

Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's (EPA's) Water Quality Planning and Management Regulations (Title 40 of the Code of Federal Regulations [CFR] Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for impaired water bodies. A TMDL establishes the amount of a pollutant that a water body can assimilate without exceeding the applicable water quality standard. A TMDL consists of the sum of individual waste load allocations for point sources and load allocations for nonpoint sources and natural background conditions. The Massachusetts Water Quality Standards (WQS), codified at 314 CMR 4.00, identify the Mystic River as a Category 5 water body on the Massachusetts 303(d) "List of Impaired Waters" (2014) for phosphorus, arsenic, chlordane, chlorophyll, DDT (dichlorodiphenyltrichloroethane), dissolved oxygen, E. coli, PCBs (Polychlorinated biphenyls) [in fish tissue], Secchi depth, and sediment bio-chronic toxicity.

This report addresses those impairments associated with excessive nutrient loading including phosphorus, chlorophyll, dissolved oxygen, and secchi depth (water clarity).

## *Alternative TMDL Process*

In 2013, the EPA announced a new framework (Vision) for prioritizing and implementing TMDLs and pollution control strategies. The guidance for this Vision (found here: https://www.epa.gov/sites/production/files/2015-07/documents/vision_303d_program_dec_2013.pdf) allows states to adopt strategies tailored to their water quality program goals and priorities. The Vision acknowledges that alternative restoration approaches may be more immediately beneficial or practical in achieving water quality standards than a traditional TMDL. The Vision calls on states to strategically focus efforts and demonstrate progress over time.

EPA is supporting MassDEP in piloting an alternative TMDL designed to address nonattainment of nutrient related water quality standards over a period of time. The approach, based on rigorous data gathering, scientific analysis, and modeling, provides guidance to communities based on a scientific understanding of conditions. The agencies have already begun working with communities to develop stormwater management (SWM) strategies to begin progress on implementing effective stormwater control measures (SCMs) to restore the river and degraded lakes and ponds. This "adaptive management" approach for the Mystic will be an iterative process of implementing control actions over an extended period of time while progress is monitored, and new information is gathered to further inform management needs for attaining water quality standards.

## *Study and Analysis*

The objectives of this technical analysis, conducted between 2017 and 2019, were to: estimate annual loadings of phosphorus; relate phosphorus loads to response variables in critical surface water reaches of the watershed; estimate the load reductions needed to improve water quality and attain water quality standards; and introduce a pilot Opti-Tool analysis that demonstrates cost-effective and opportunistic stormwater load reduction strategies that communities can consider adopting.

Much of the scientific research needed to document existing conditions occurred prior to this project, during which time EPA Region 1 collaborated with the Mystic River Watershed Association (MyRWA), MassDEP, U.S. Geological Survey (USGS) and the Massachusetts Water Resources Authority (MWRA). Baseline water quality monitoring included the collection of composite samples linked to streamflow. This project builds on past analyses to develop target reductions in phosphorus inputs in order to improve water quality in the Mystic River.

To assist with developing phosphorus budgets and recommending load reductions, EPA convened a Technical Steering Committee (TSC) to provide data, expertise and advice. The Technical Steering Committee met three times annually. In addition to the Technical Steering Committee, the consultant team also benefited from expert review provided by Dr. Jeff Walker (Walker Environmental Research LLC). Further refinements to analyses were conducted based on Dr.

Walker's input following consultation with the Technical Steering Committee. This interactive approach resulting in the project team providing the most comprehensive and complete assessment possible at this time and one that the Technical Steering Committee determined is suitable to support an adaptive management process for the Mystic River watershed. Technical Steering Committee members and our expert reviewer are listed in the Acknowledgements.

The components of the analytical approach, discussed in detail in the report, are listed below:

- Develop conceptual model of hydrology and nutrient dynamics
- Evaluate existing water quality monitoring data
- Review modeling endpoint approaches
- Estimate watershed phosphorus loading
- Evaluate combined sewer overflow (CSO) and sanitary sewer overflow (SSO) data
- Conduct BATHTUB modeling and calibrate results
- Determine critical period of interest for phosphorus load reduction analysis
- Evaluate watershed phosphorus load reduction analysis
- Develop nutrient stormwater management strategies using Opti-Tool

The pollutant of concern for this study is phosphorus because it is directly causing or contributing to the excessive algal biomass. Since there are no numeric criteria available for phosphorus (i.e., no specific concentration of phosphorous that represents a violation of standards), a surrogate water quality target was needed to calculate pollutant load reductions to the river. Chlorophyll-*a* was chosen as the surrogate water quality target. Chlorophyll-*a* is the photosynthetic pigment found in algae and is, therefore, a direct indicator of algal biomass. EPA and the Technical Steering Committee determined that a seasonal average chlorophyll-a concentration of $<10$ μg/L would be protective of narrative eutrophication standards in the watershed, from which associated total phosphorus reductions could be derived.

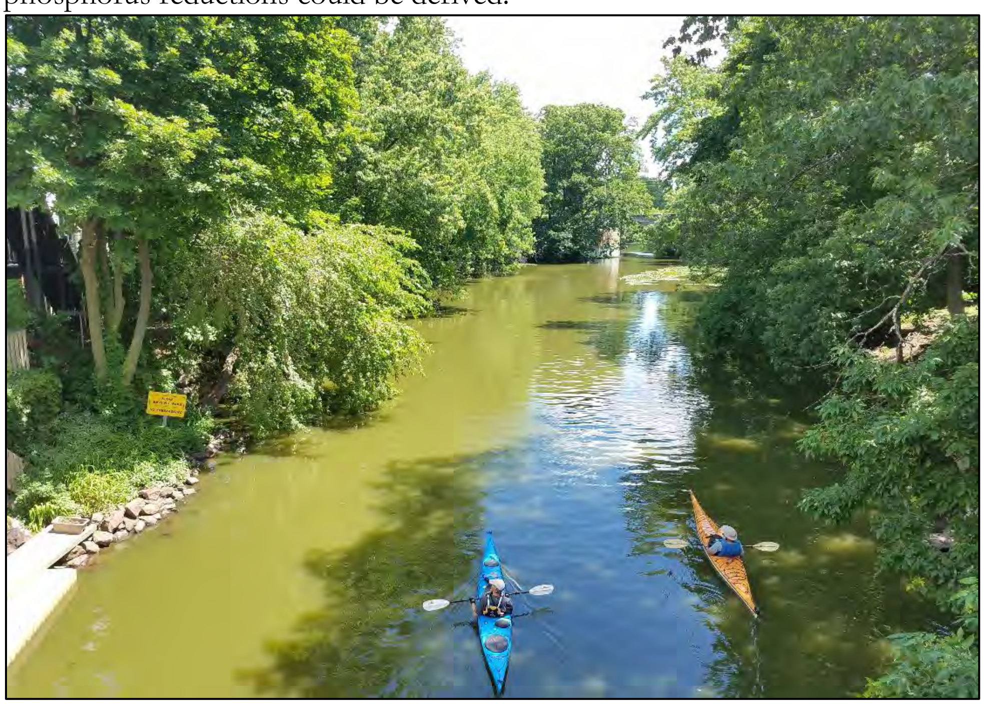

Photo Left: Cyanobacteria bloom in the freshwater segment of the Mystic River between Arlington and Medford in June of 2017. Photo credit: Jack Bitney.

## Results

Watershed analyses conducted during this study demonstrate that inadequately controlled stormwater (SW) runoff from developed landscapes are the predominant source of nutrient loads–specifically phosphorus loads–to the surface waters of the Mystic River watershed. Under existing conditions, this study estimated that to meet the selected chlorophyll-*a* water quality target for attaining water quality standards in the most impacted segment, the lower Mystic River, will require a 67 percent reduction of stormwater phosphorus loadings from the watershed  However, this estimate assumes all reduction would be achieved through stormwater control measures.

Load reduction estimates were also modeled for future conditions to account for key variables: wet vs. dry years; future control of combined sewer overflows and sanitary sewer overflows and sediment load reduction. Overall, the analysis showed that elimination of combined sewer overflows and sanitary sewer overflows had minimal impact compared to reducing stormwater loads and internal loads released from bottom sediments of the river system. The difference between wet vs. dry years is significant, with much greater difficulty meeting water quality targets during dry years. The stormwater load reductions required to meet water quality targets under future conditions (which account for baseline stormwater management, combined sewer overflows/sanitary sewer overflows controls and an estimate of associated reductions in internal loads) were between 59 and 62 percent.

## The Path Ahead

Knowing how and where to site cost-effective stormwater controls to reduce phosphorus loads from stormwater runoff will be critical for meeting state and federal water quality regulations. The Opti-tool analysis included in this report shows that by optimizing sizing and location of BMPs, significant cost savings can be realized. ERG and the project team is currently working with communities in the watershed to develop cost-effective stormwater best management practices with a focus on green infrastructure solutions and changes to local bylaws/ordinances to streamline the process. EPA envisions a sustained collaborative process of working with the communities to develop realistic and effective strategic stormwater management approaches to effectively advance watershed restoration efforts.

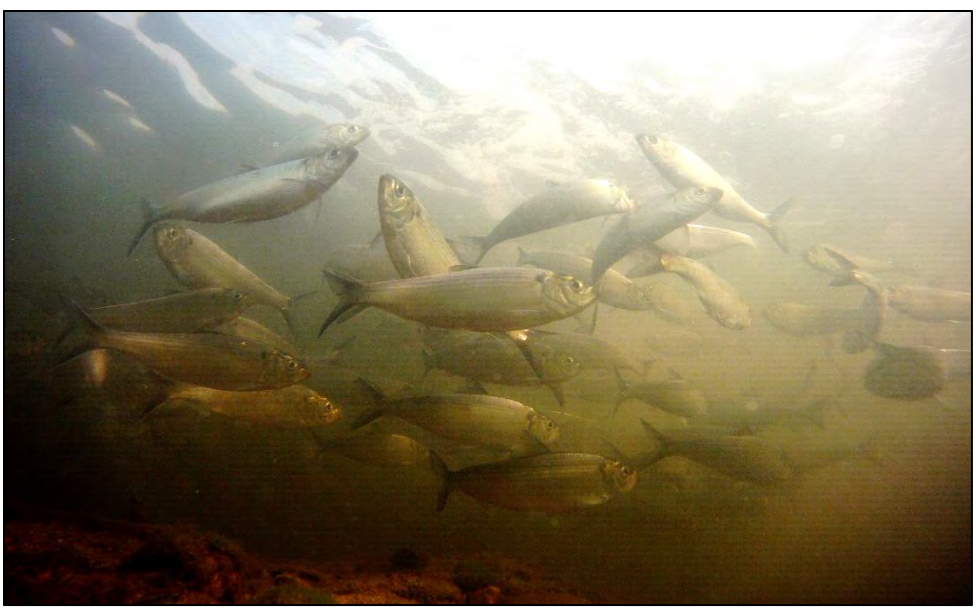

Photo Left: River herring above the fish ladder in Upper Mystic Lake in 2012. This was the first year since the late 1800s that had significant passage of anadromous fish into the Upper Mystic Lake. Photo credit: Patrick Herron, Mystic River Watershed Association.

## Acknowledgements

The following individuals participated on the technical steering committee and EPA thanks them for their valuable contribution to this project.

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Photo Above: Rowers practicing on the Malden River, a tributary to the Lower Mystic River in Medford. Photo credit: Greig Cranna.

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## Abbreviations

| | |
|---|---|
| CSO | Combined sewer overflow |
| Chl-a | Chlorophyll-a |
| CSS | Combined sewer separation |
| DCIA | Directly connected impervious area |
| DCR | Massachusetts Department of Conservation and Recreation |
| EPA | U.S. Environmental Protection Agency |
| ERG | Eastern Research Group |
| HRU | Hydrologic Response Units |
| HUC | Hydrologic Unit Code |
| LLRM | Lake Loading Response Model |
| MassDEP | Massachusetts Department of Environmental Protection |
| MS4 | Municipal Separate Storm Sewer System |
| MWRA | Massachusetts Water Resources Authority |
| MyRWA | Mystic River Watershed Association |
| SSO | Sanitary sewer overflow |
| TMDL | Total Maximum Daily Load |
| TN | Total nitrogen |
| TP | Total phosphorus |
| USGS | U.S. Geological Survey |
| WQS | Water quality standards |

# I. Introduction

## I.A. Background

The Mystic River Watershed is a 76-square mile watershed that drains into Boston Harbor. Located in the Greater Boston, Massachusetts metropolitan area, it encompasses all or portions of 22 urban and suburban communities. The watershed faces multiple water quality impacts related to cultural eutrophication including excessive algal growth, harmful cyanobacteria blooms, and invasive macrophyte growth. Sources of pollutants from the watershed include stormwater runoff, combined sewer overflows (CSO), sanitary sewer overflows (SSO), non-point runoff, contaminated sediment, and three Superfund sites. The watershed suffers from many legacy pollutants as well as present day pollutant loadings. Several environmental justice communities are located within the watershed, and although most developable land is built upon, there is high development and re-development pressure throughout the watershed.

The Mystic River is listed as a Class B water with a Category 5 water quality rating in the Massachusetts 303(d) "List of Impaired Waters" (2014) for phosphorus, arsenic, chlordane, chlorophyll, DDT, dissolved oxygen, *E. coli*, PCB in fish, Secchi depth, and sediment bio-chronic toxicity. Due to the multiple stressors present in this watershed, development of a traditional Total Maximum Daily Load (TMDL) to address all pollutants would be a lengthy and complicated task, especially considering resource limitations. Instead, the Massachusetts Department of Environmental Protection (MassDEP), U.S. Environmental Protection Agency (EPA) Region 1 (serving New England) and the Mystic River Watershed Association (MyRWA) have embarked on a plan to pilot an alternate but equally rigorous method ("Alternative TMDL") for determining how to address impairments, including the nutrient water quality studies documented herein. These studies as well as other efforts have determined that effective nutrient management will likely go a long way towards addressing sources of other impairments in the watershed such as bacteria and sediment-bound contaminants.

## I.B. Purpose

The purpose of this project is to support elements of EPA's TMDL Vision process by providing technical support for watershed restoration efforts to address phosphorus load reduction needed to meet water quality targets in the Mystic River Watershed. This project provides an opportunity to achieve multiple TMDL "vision" goals:

- Estimate the load reduction needed to meet water quality targets in critical water bodies within the watershed;
- Engage with communities, state and regional governmental agencies and the local watershed group;
- Inform and guide load reduction implementation by municipalities in the watershed;
- Integrate actions needed to address multiple Clean Water Act programs, such as point and non-point pollution.

Findings will inform the development of analytical tools for EPA Region 1 to estimate phosphorus load reductions that are needed to attain applicable Massachusetts surface water quality standards (WQS) related to cultural eutrophication. Another project goal is to strengthen regional collaborations for enhanced watershed nutrient management approaches.

### I.C. Organization and Overview

This report is a compilation of nine related technical memoranda that Eastern Research Group (ERG), its sister company PG Environmental, and subcontractors Horsley Witten Group (HW), Paradigm Environmental and Dr. Nigel Pickering, have developed over the past two years. Components of the study are listed and described below:

- **Phase 1**
    - Conceptual Model of Hydrology and Nutrient Dynamics in the Mystic River Basin (Section II)
    - Review of Existing Water Quality Monitoring Data (Section III)
    - Review of Modeling Endpoint Approaches (Section IV)
    - Watershed Phosphorus Loading Estimates (Section V)
- **Phase 2**
    - Evaluation of Combined Sewer Overflow and Sanitary Sewer Overflow Data for the Mystic River Watershed (Section VI)
    - BATHTUB Modeling Approach and Calibration Results (Section VII)
    - Critical Period of Interest for Phosphorus Load Reduction Analysis (Section VII.C.9)
    - Evaluation of Watershed Phosphorus Load Reduction Analysis (Section IX)
    - Broad-Based Nutrient Stormwater Management Strategies for the Mystic River Watershed using Opti-Tool (Section X)

Phase 1 of the project began with a review of the hydrographic and geographic features of the Mystic River in 2017-2018, and of the vegetation management practices used in the river in the preceding two decades. This review informed the development of a conceptual model of flows and nutrient dynamic processes within the Mystic River. Concurrently, the investigators performed an exploratory review of the available flow and water quality data within the watershed, identification of gaps in the data record, and identification of potentially useful GIS information. The result was the identification of information and data sources that might be usefully exploited in planning modeling of the watershed, presented in Sections II and III of this report. In addition, these sections document the region of interest (i.e., the freshwater portion of the Mystic River above Amelia Earhart Dam) used for later modeling activities.

Under the federal Clean Water Act, Massachusetts statutes, and applicable regulations, narrative nutrient standards are applicable to the watershed. Section IV of this report presents and discusses several options for translating the applicable narrative water quality standard to one or more numeric endpoints. A numeric endpoint provides a standard for water quality modelers to ascertain that water quality conditions comply with applicable standards. This section includes a review of all approaches considered by EPA, the consultant team and the Technical Steering Committee (TSC), including approaches that were not ultimately utilized in later modeling and analyses.

Using available water quality data and GIS information as inputs, the project team developed a modeling approach to estimate an annual time series of total phosphorus and streamflow within the watershed modeling domain. The methodology employed for estimating nutrient load and flow time series from combined sewer overflows (CSOs) and from sanitary sewer overflows (SSOs) is documented; time series based on all other sources (e.g., precipitation-driven overland flow, groundwater, etc.) are also documented in this report.

Early in Phase I, EPA and the project team identified a discrepancy between measurements of total phosphorus at two different labs used by local monitoring programs to measure in-stream water quality. The source of the discrepancy—which was consistent and predicable between the two datasets—was not resolvable during the Phase I or Phase II development period and, therefore, EPA determined to adjust the observed total phosphorus measurements to make the data from both laboratories mutually consistent. This rendered both datasets usable for model calibration purposes and will allow future adjustments to the dataset and model results should EPA make a final determination regarding the source of the discrepancy. The basis for the total phosphorus data adjustment is documented in Section V.D.

Sections VII through X cover work completed under Phase II including the setup and calibration of BATHTUB model, which was used to model water quality response for select reaches of the watershed. The information and rationale used in selecting a critical period of interest for the model is described as well as the modeling scenarios evaluated (e.g., baseline conditions, current conditions, future loading conditions) and the resulting load reduction targets needed to meet water quality standards.

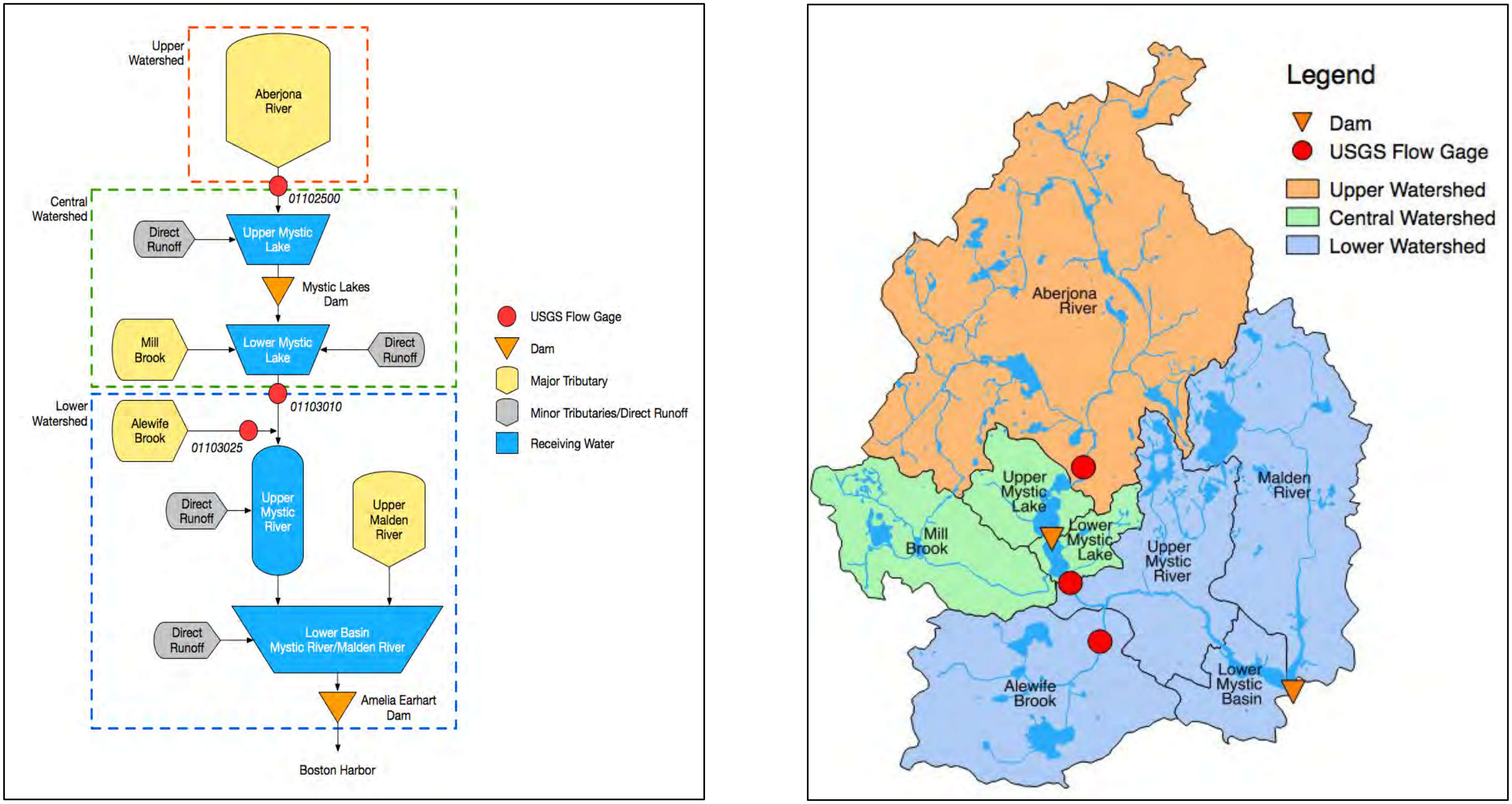
# II. Conceptual Model of the Hydrology and Nutrient Dynamics in the Mystic River Basin

This section presents a conceptual model of the hydrology and water quality dynamics in the Mystic River Watershed. The purpose of this conceptual model is to describe the primary sources and sinks of nutrients, and to highlight the important features (e.g., dams/impoundments) and dynamics (e.g., macrophytes) that affect water quality conditions in the Mystic River. The conceptual model is intended to serve as a foundation for evaluating alternative target endpoints (Section IV) and modeling strategies (Section V).

## II.A. Watershed Overview

The *freshwater* portion of the Mystic River Watershed—the focus of this study – has a total drainage area of 63 sq. miles. The watershed can be divided into three sub-watersheds referred to as the upper, central, and lower watersheds. The delineation of these sub-watersheds was based on the locations of U.S. Geological Survey (USGS) streamflow gages as well as the impacts of the Mystic Lakes on both the hydrology and water quality of the river.

Figure II-I shows a schematic diagram and corresponding map of the major sub-basins, water bodies, streamflow gages, and dams across the watershed.




Note this figure does not include all flow gages or dams across the watershed.

**Figure II-I Schematic Diagram and Map of Mystic River Watershed**

### II.B. Upper Watershed

The upper watershed contains the Aberjona River basin, which has a total drainage area of 25 sq. miles (40 percent of the total freshwater Mystic River Watershed). A USGS streamflow gage (Station 01102500) is located near the outlet of the Aberjona just before it flows into Upper Mystic Lake. There is currently one major impoundment on the Aberjona River at the Center Falls Dam in Winchester, which is located about 0.5 mile upstream of the USGS flow gage. Historically, several smaller dams were also constructed to support mill operations (Knight, 2016). The exact number and locations of existing small dams along the Aberjona River requires further research. There are also numerous impounded ponds (e.g., Horn Pond, Wedge Pond) along the tributaries to the Aberjona River. These impoundments likely reduce the phosphorus loads originating from the land surface through settling and vegetative uptake.

The primary source of nutrient loading in the upper watershed is stormwater runoff. There are no combined sewer areas or wastewater treatment facility discharges. However, much of the watershed is served by separate sanitary sewer systems and storm sewer drainages systems. Illicit discharges of sanitary sewage to separate storm drainage systems are not uncommon in suburban/urban watersheds and are known to exist within the upper watershed, although programs to eliminate them are underway. Additionally, SSOs are also known to occur infrequently, typically only during major storm events. Internal loading from sediment fluxes is likely not significant but may occur in some impounded areas such as above the Center Falls Dam in Winchester.

### II.C. Central Watershed

The central watershed encompasses the Upper and Lower Mystic Lakes, which have a total drainage area of 9 sq. miles (15 percent of total freshwater watershed) excluding the upper watershed. The two lakes are separated by the Upper Mystic Lake Dam, which was recently rebuilt in 2012. Both lakes have a maximum depth of about 80 ft. While the Upper Mystic Lake undergoes seasonal stratification from spring to fall, Lower Mystic Lake is perennially stratified due to entrapment of saltwater that prevents complete turn over in the fall (Ludlam and Duval, 2001). Water quality and streamflow data show that the two lakes have a significant effect on both the hydrology and water quality of water flowing from the mouth of the Aberjona River to the head of the Mystic River.

The primary source of nutrients to Upper Mystic Lake is the discharge from the Aberjona River in addition to direct runoff from the local drainage basin. Discharge from the Aberjona River first enters what is referred to as the upper lobe of Upper Mystic Lake. Due to the nutrient loading from the Aberjona River, the upper lobe, which is shallow and not likely to stratify, frequently experiences eutrophic conditions, including cyanobacteria blooms and excessive aquatic vegetation.

Outflow from Upper Mystic Lake passes through the dam into Lower Mystic Lake, which also receives inflow from direct runoff of its local drainage basin and from Mill Brook (drainage area of 5.5 sq. miles). Because of the stratification in the two lakes, internal loading from sediment fluxes may not be a significant source of nutrients during the growing season because the bottom water (hypolimnion) is thought to not fully mix with the surface water (epilimnion); however, this question is still under investigation.

The Massachusetts Department of Conservation and Recreation (DCR) operates the Mystic Lakes Dam. Information about dam operations such as release schedules or target water levels are not currently available. However, prior to storm events, additional water is often released to increase available storage in Upper Mystic Lake and prevent flooding along its shoreline. Because of these operations, the dam has a significant effect on the flow and water quality dynamics between the Aberjona and Mystic Rivers.

### II.D. Streamflow Impact of Mystic Lakes Dam

Figure II-II shows the instantaneous streamflow over a 7-day period in November 2016 at the Aberjona River gage above Upper Mystic Lake (01102500) and at the Mystic River gage just below Lower Mystic Lake (01103010). The Aberjona River gage shows a typical storm hydrograph during the night of November 15. The Mystic River gage also shows evidence of an increase in flows due to stormwater; however, the shape and magnitude of the hydrograph is significantly altered. The peak flow is lower below the lakes and occurs about 6 hours later. There is also a significant diurnal pattern in flows at the Lower Mystic Lake outlet due to the release of water during low tides at the Amelia Earhart Dam located about 5 miles downstream (discussed below) near the mouth of the Mystic River. Lastly, the total volume of flow during storm events is in fact higher at the Aberjona River gage than at the Mystic River gage likely due to some of the flow being stored in Upper Mystic Lake.

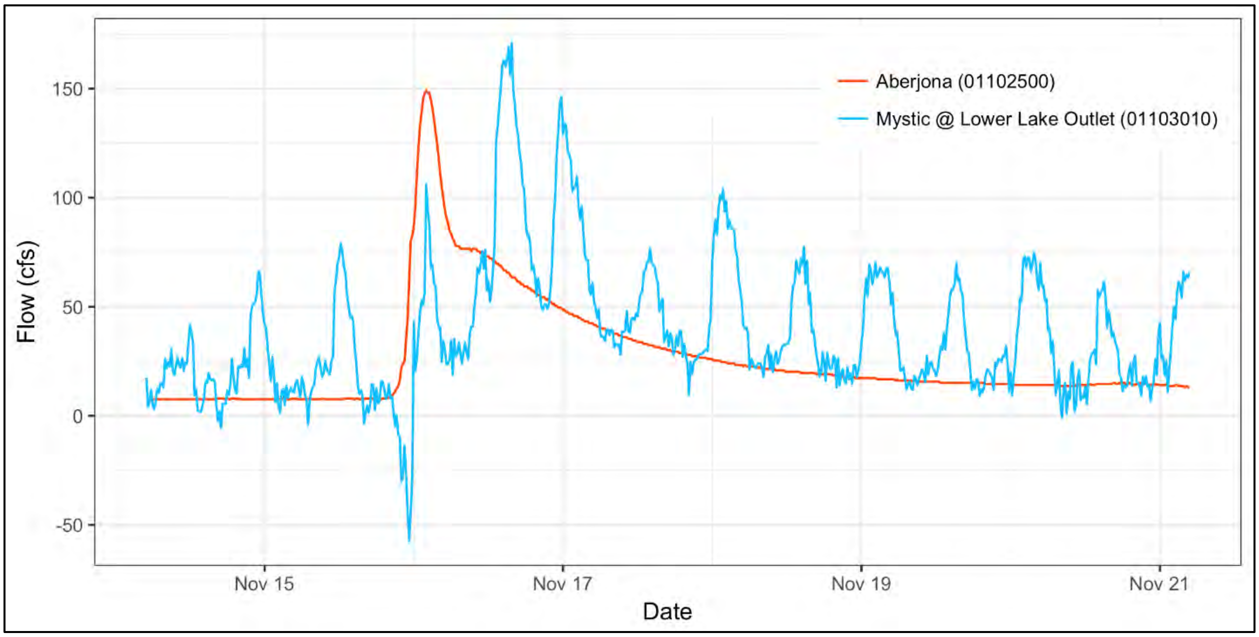



**Figure II-II Instantaneous Streamflow Above and Below Mystic Lakes**

### II.E. Water Quality Impact of Mystic Lakes Dam

In addition to the change in the streamflow hydrograph, the lakes also have a significant effect on water quality. Figure II-III shows the distribution of monthly total phosphorus (TP) concentrations measured by the MyRWA Baseline Monitoring Program at the Aberjona River streamflow gage (ABR006), the Mystic Lakes dam (UPL001) at the outlet to the Upper Mystic Lake, and below the outlet of the Lower Mystic Lake at the mouth of the Mystic River mainstem (MYR071). TP concentrations are highest coming out of the Aberjona River but drop significantly at the outlet of Upper Mystic Lake likely due to settling of particulate phosphorus and uptake by aquatic plants. In Lower Mystic Lake, concentrations increase from the levels coming through the dam due to loads from Mill Brook and other tributaries. This figure demonstrates the critical role the lakes have in “resetting” the water quality from the upper watershed (Aberjona River) to the Mystic River mainstem. Upper Mystic Lake is thus a major sink of nutrients due to the long residence time that promotes settling of particulate phosphorus and uptake by aquatic vegetation and algae.

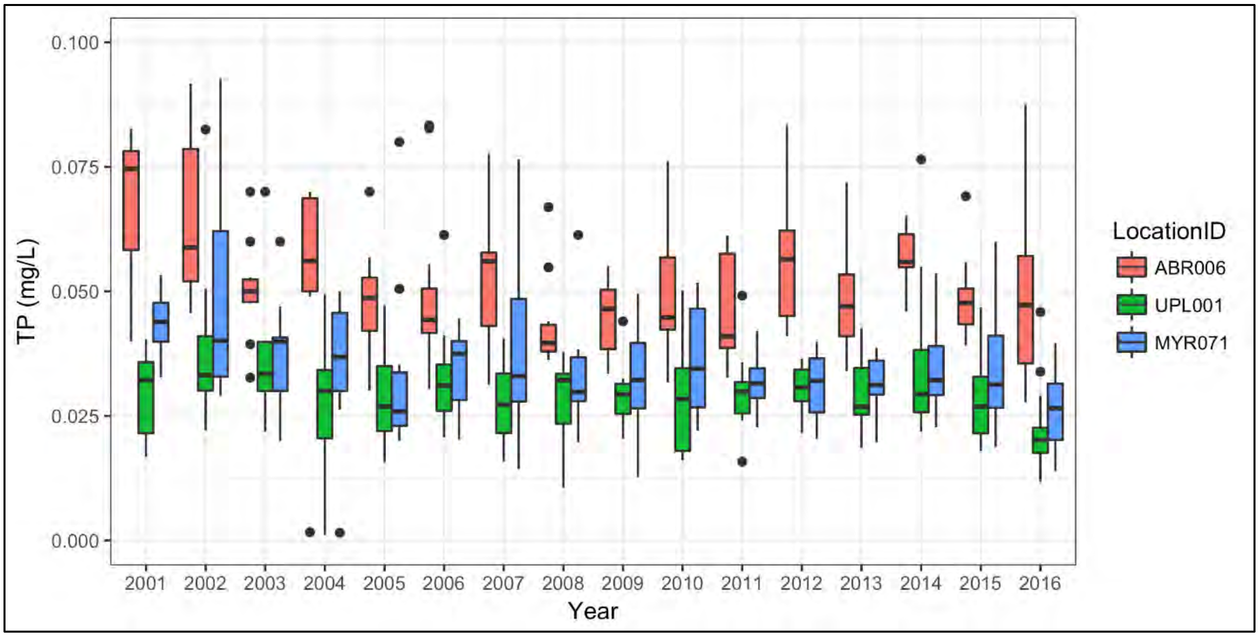



**Figure II-III Annual Distributions of Monthly TP Concentrations at the Aberjona River Outlet (ABR006), Mystic Lake Dam (UPL001), and Start of the Mystic River Mainstem (MYR071)[1]**

### *II.F. Lower Watershed*

The lower watershed includes the Mystic River, Alewife Brook, Malden River and numerous smaller tributaries, which have a total drainage area of 28 sq. miles (45 percent of the freshwater portion of the watershed) excluding the central and upper watersheds. Land use in this area is heavily urbanized, especially in areas around the lower section of the Mystic River. A portion of this area contributes to the MWRA combined sewer system, which has numerous CSO outfalls along Alewife Brook and the Mystic River. Over the past decade, many of these outfalls have been closed. Among the remaining open outfalls, the frequency and magnitude of CSO discharges has been drastically reduced. For the period of 2000 to 2016, CSO mitigation projects by the MWRA and the cities of Cambridge and Somerville have reduced annual CSO discharge volumes to the freshwater portion of the Mystic River by approximately 88 percent (59 to 7 million gallons) for the typical rainfall year.

The primary sources of nutrient loads are from the outflow of Lower Mystic Lake, stormwater runoff, CSOs, illicit discharges, and internal loading. Due to the long history of CSO discharges to the low gradient Alewife Brook and impounded Mystic River, the sediments in Alewife Brook and the Mystic River are likely highly organic with elevated phosphorus levels, which could cause significant internal loading. The legacy sediments are likely to also drive a high sediment oxygen demand, especially in Alewife Brook where the entire water column has been observed to become hypoxic (and occasionally anoxic) during hot, dry periods in the summer.

[1] Boxplot hinges are 25th, 50th, and 75th percentiles of the concentration distribution. Upper and lower whiskers represent largest and smallest values inside 1.5 x Interquartile Range.

### *II.G. Hydrologic and Hydraulic Impacts of Amelia Earhart Dam*

Discharge from Mystic River is controlled by the Amelia Earhart Dam, which is operated by DCR. The dam includes 3 locks, which unintentionally allow saltwater intrusion from Boston Harbor. The dam is typically operated by pumping water out of the lower basin prior to storm events to increase available storage and prevent flooding along the shoreline. Water is also typically released each day at low tide. The exact operational schedule and targets for this dam are unknown.

Along the entire Mystic River, as well as most of Alewife Brook and the lower section of the Malden River, there is a very small gradient in elevation of both the sediment and water surfaces (about 1 ft.). As a result, flow velocities are very low in these water bodies and the entire system acts as one large impoundment.

Figure II-IV shows the relative water surface elevation at three USGS stations along the Mystic River and Alewife Brook during an 11-day period from Sept 1, 2016 to Sept 10, 2016. The relative water surface elevation was computed by subtracting the mean elevation at each station from the instantaneous value. This was necessary because stage data at the Alewife station is not reported relative to the same vertical datum as the other stations. The rapid drop in elevation on Sept 6 was likely due to pumping at the Amelia Earhart Dam in preparation for an upcoming storm. All three stations reflect the same change in elevation indicating that the entire Mystic River and Alewife Brook behave as a single impoundment.

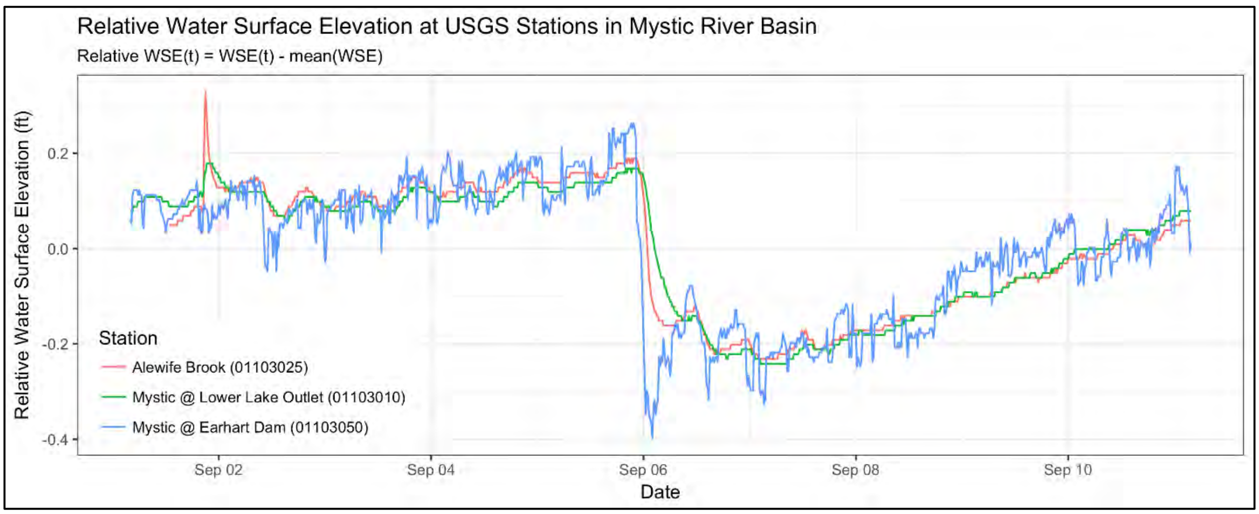



**Figure II-IV Relative Water Surface Elevation at USGS Gages on Alewife Brook and Mystic River (Sept. 1 – 10, 2016)**

### *II.H. Water Quality Gradient Along the Mystic River*

Water quality in the upper reach of the Mystic River in the lower watershed is relatively good quality due to the reduced phosphorus levels in the outflow from Lower Mystic Lake. Phosphorus and chlorophyll-a levels then gradually increase going downstream along the Mystic River towards the Amelia Earhart Dam. In the lower reaches of the lower Mystic River Watershed, excessive macrophyte growth due to nutrient enrichment constitutes major water quality impairment, as further described below.

Figure II-V shows chlorophyll-a and TP concentrations at five stations along the Mystic River and one station in the lower basin of the Malden River during 2015 and 2016. MyRWA collected the data for its phosphorus loading study. The high concentrations, in late summer of 2016, are most likely caused by an herbicide application on the Mystic River to remove aquatic vegetation. The result of this application was an instant release of phosphorus to the water column, which, combined with an increase in light availability, likely spurred significant phytoplankton growth. A cyanobacteria bloom was also observed during this period.

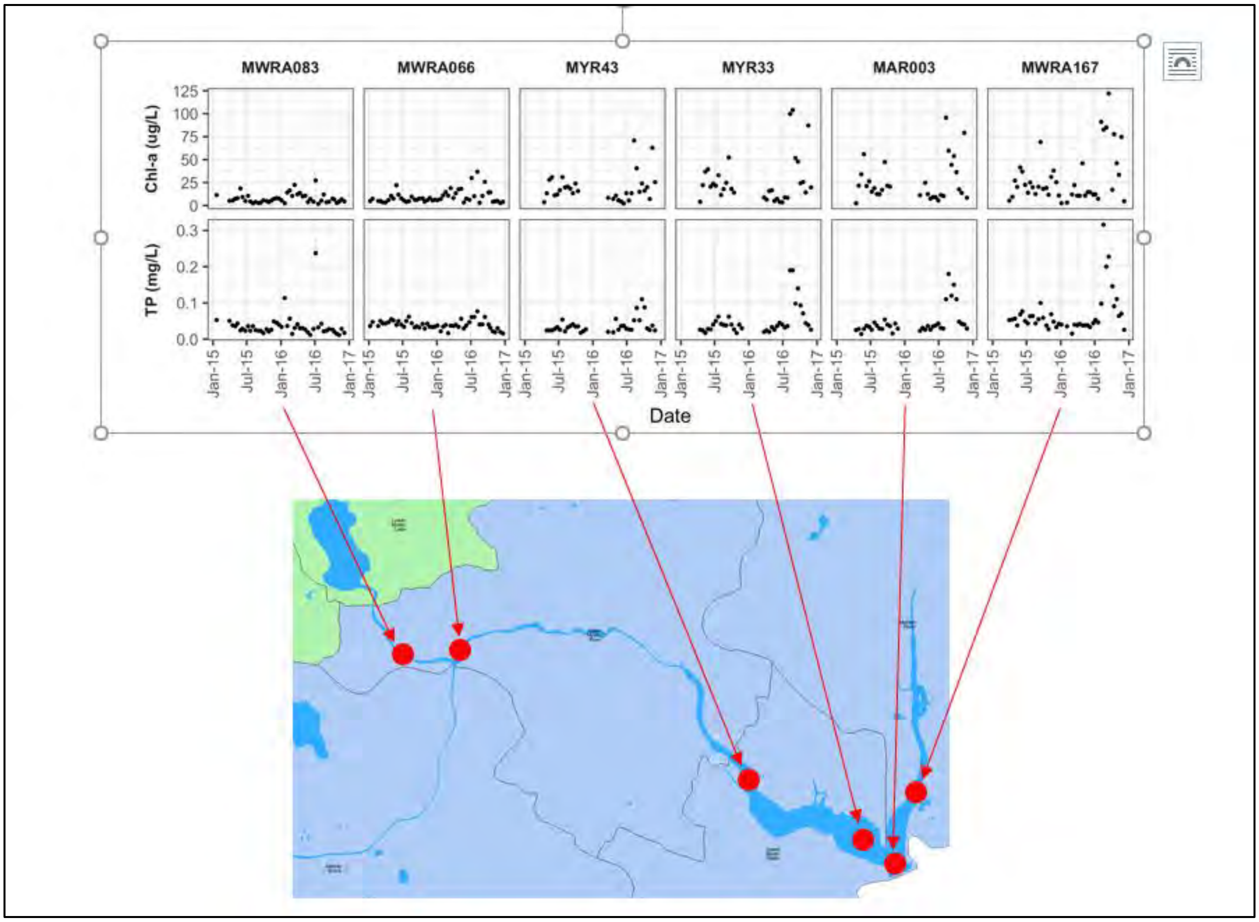



**Figure II-V Chlorophyll-a and TP Concentrations Along the Mystic and Malden Rivers, 2015 – 2016**

## *II.I. Long Term Changes in Water Quality*

Over the long term, there has been a gradual decline in chlorophyll-a and TP concentrations along the Mystic River based on the MWRA data, except for 2016, due to the herbicide treatment mentioned above. More information on the 2016 data is presented in Section II.J below. Figure II-VI shows the annual mean, median, and 90$^{th}$ percentile of chlorophyll-a and TP at the three MWRA stations based on data from June – October of each year. The decline in chlorophyll-a is most pronounced at the lower-most station, MWRA167. In 2012-2014, 90$^{th}$ percentile of chlorophyll-a was below 25 ppb, which is slightly greater than the target 20 ppb in the Lower Charles River TMDL. As discussed below, the declines in TP and chlorophyll-a in the lower Mystic coincide with a steady increase in growth and coverage of aquatic macrophytes during this period.

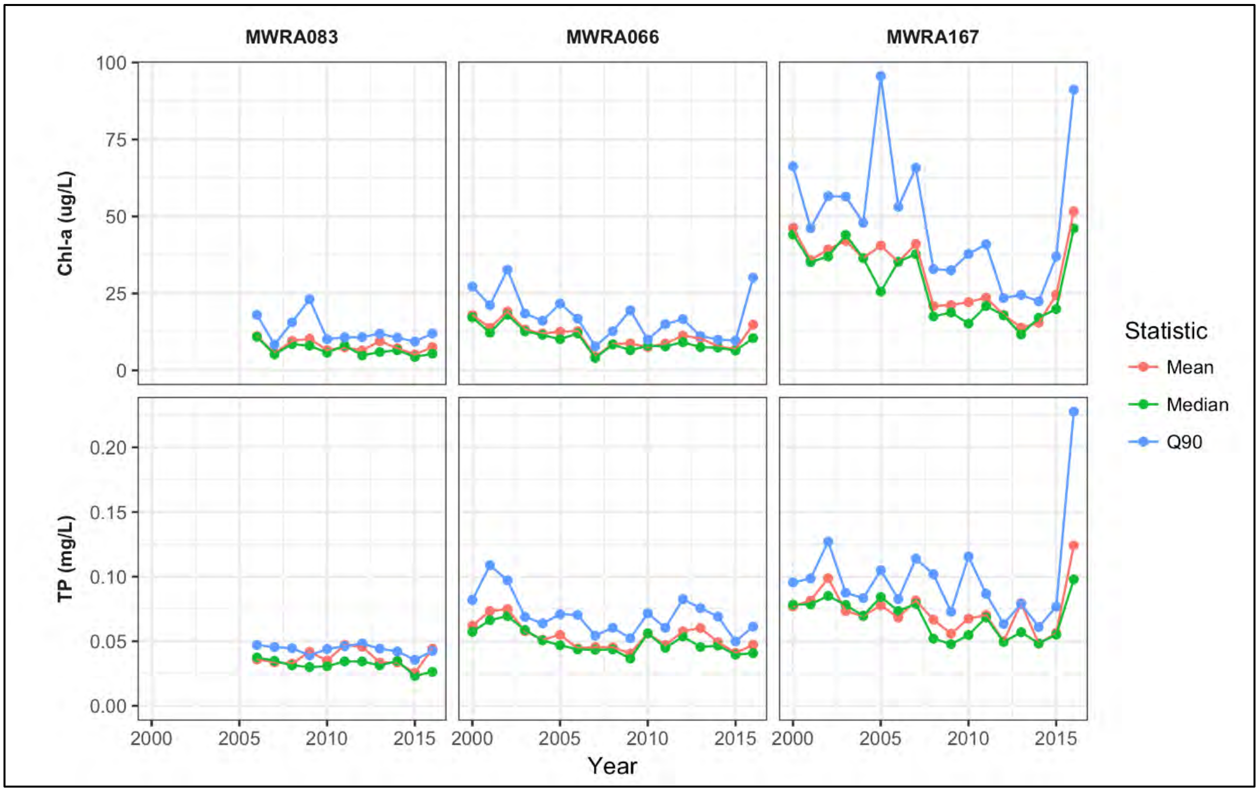



**Figure II-VI Annual Mean, Median, 90th Percentile of Chlorophyll-a and TP at Three Stations on the Mystic River, 2000 – 2016 (June – Oct. only)**

### *II.J. Impact of Aquatic Vegetation on Water Quality*

Aquatic vegetation is a major nuisance on the Mystic River. Over the past 10 years, the coverage of water chestnut and water hyacinth has grown dramatically. MyRWA currently spends significant resources to manually remove this vegetation to allow boat passage. Treatment of the vegetation includes mechanical and manual harvesting, as well as herbicidal treatments, which began more recently. The vegetation is likely having a significant impact both on the hydraulics of the river by increasing drag and forcing flow through a narrow channel, as well as on water quality through nutrient uptake, increased water column shading, and increased particulate settling. Consequently, the increase in aquatic vegetation in the lower Mystic is likely the primary cause for the declining trend in chlorophyll-a and TP concentration described above.

In 2016, a major dose of herbicide was applied to the Mystic River to remove vegetation. Shortly after this treatment, both phosphorus and chlorophyll-a levels spiked (see Figure II-II-6). This response indicates that aquatic vegetation is likely a major control on phytoplankton growth along the Mystic River mainstem and in the lower basin. Presently, most of the aquatic vegetation found in the lower Mystic can be rooted or free floating and is capable of taking up nutrients from both bottom sediments and the water column. The combination of increased flow resistance due to the rooted plants, which increases particulate settling rates, and the uptake of nutrients from the water column is likely the primary cause for the declining trend in TP. At the typical TP levels observed in the lower Mystic (<100 µg/L), decreases in TP in open water areas (i.e., free of excessive aquatic plants) will likely result in less phytoplankton growth and lower chlorophyll-a. Also, the abundance of vegetation is likely to be a contributing cause to suppressing phytoplankton growth by reducing light availability through shading and causing light limitation. Thus, it is reasonable to infer that the long-term decline in chlorophyll-a and TP levels shown above in Figure II-VI (excluding 2016 due to the herbicide treatment) are likely caused by the increasing abundance of aquatic vegetation removing phosphorus from the water column and limiting light penetration.

# III. REVIEW OF EXISTING WATER QUALITY MONITORING DATA

The purposes of this section are as follows:

- Describe and summarize the known, available water quality monitoring data.
- Review the data for precision, accuracy, representativeness, comparability, and completeness.

According to available data, water quality surveillance of the watershed has been ongoing since at least 1989. Consistent with the scope of this analysis, the examination will be restricted to data collected from 2000 through 2016. Data for 2017 were not available until late in the project and were only included for BATHTUB model validation.

## *III.A. Data Gaps and Recommendations for Future Sampling Efforts*

Based on the review of the available data and discussions with MyRWA and EPA Region 1, the following data gaps have been identified which could be addressed through future monitoring efforts.

### III.A.1. Ecological/Biological Indicators of Over-Enrichment

Currently, little data is available on excess vegetative growth. Measurements are limited to chlorophyll-a and do not include macrophyte abundance, percent cover, or broader measures of species richness. MyRWA and EPA should consider including, at a minimum, percent of macrophyte cover in the water body during monitoring events for baseline and phosphorus loading.

### III.A.2. Streamflow

As discussed below, in the section of this memo on the available USGS flow data, there are few locations in the watershed where it is currently feasible to make direct flow measurements. To develop reliable estimates of nutrient loads through the watershed, measurements or reliable estimates of flows in the watershed will be needed. This task is further complicated by multiple impoundments. Should methods for reliable direct measurement prove infeasible, other approaches for estimating flow based on well-established modeling techniques (e.g., using climatological, land use, and soil type data available in GIS databases) may be explored to estimate precipitation driven flows.

### III.A.3. Sediment

Sediment attributes (e.g., total phosphorus concentrations, sediment oxygen demand) would be useful for future modeling but was not available for the modeling portion of the project, and it is recommended to include these attributes in future watershed surveillance efforts, if feasible.

## *III.B. MyRWA and MWRA Monitoring Data*

### III.B.1. Data Characterization

The MyRWA provided water quality monitoring data to ERG on January 31, 2017 and provided supplementary data on February 11, 2017. The dataset was composed of samples collected under:

- MyRWA's baseline water quality monitoring.
- MyRWA's phosphorus loading monitoring survey.
- MWRA Boston Harbor water quality monitoring.
- MWRA's combined sewer overflow event monitoring.

The **baseline monitoring program** has been in operation since 2000 and is used to monitor a variety of trends in watershed water quality. Collected constituents include pathogen indicators, nutrients, and physical-chemical water quality parameters (e.g., total suspended solids, pH, etc.).

The **phosphorus loading monitoring program** has been conducted since 2015 and is used to collect information on parameters that contribute to eutrophication impairments (e.g., phosphorus) and response parameters, which could potentially be used as indicators of nutrient over enrichment.

The MWRA water quality monitoring in general started in 1989, with the beginning of the CSO monitoring program. The **Boston Harbor monitoring** in the Harbor proper began in 1993, and in the rivers in 1995. This program was created to establish long-term water quality trends in the Harbor and tributary watersheds for pathogen indicators, nutrients, and physical-chemical water quality parameters.

**CSO monitoring** is conducted to evaluate water quality risks associated with the discharge of untreated sewages and stormwater runoff into the watershed during CSO events. Monitoring is conducted on an ongoing basis in Alewife Brook, Chelsea River, Little River, and the Mystic River. Note that monitoring is not restricted to CSO discharge events. The CSO monitoring program collects data on pathogen indicators and on physical-chemical water quality parameters.

Table III-1 summarizes the water quality parameters collected under each program included in the dataset.

## Table III-1. Water Quality Parameters Included in Each Monitoring Program[2]

| Parameter | Monitoring Program | | | |
|---|---|---|---|---|
| | Baseline | Boston Harbor | CSO | Phos. Loading |
| **Nitrogen** | | | | |
| Total Nitrogen | ✓ | ✓ | | |
| Particulate Nitrogen | | ✓ | | |
| Nitrogen, total dissolved | | ✓ | | |
| Ammonia-nitrogen | ✓ | ✓ | | |
| Nitrite | ✓ | | | |
| Inorganic nitrogen (nitrate and nitrite) | ✓ | ✓ | | |
| Nitrate | ✓ | | | |
| **Phosphorus** | | | | |
| Total Phosphorus | ✓ | ✓ | | ✓ |
| Phosphorus, Particulate Organic | | ✓ | | |
| Dissolved Phosphorus | | ✓ | | |
| Orthophosphate | | ✓ | | ✓ |
| **Biological** | | | | |
| Chlorophyll-a | | ✓ | | ✓ |
| Pheophytin a[3] | | ✓ | | |
| **Oxygen** | | | | |
| Dissolved Oxygen | ✓ | ✓ | ✓ | ✓ |
| Dissolved Oxygen (Perc. Saturation) | ✓ | ✓ | ✓ | ✓ |
| **Water Clarity** | | | | |
| Attenuation Coefficient | | ✓ | | |
| Secchi Disk Depth | | ✓ | ✓ | |
| Turbidity | | ✓ | ✓ | ✓ |
| **Other Physical/Chemical** | | | | |
| Carbon, Total Particulate | | ✓ | | |
| pH | ✓ | ✓ | ✓ | |
| Salinity | ✓ | ✓ | ✓ | |
| Specific conductance | ✓ | ✓ | ✓ | ✓ |
| Total suspended solids | ✓ | ✓ | | |
| Water Temperature | ✓ | ✓ | ✓ | ✓ |
| **Pathogen Indicators** | | | | |
| Escherichia coli | ✓ | ✓ | ✓ | |
| Enterococcus | ✓ | ✓ | ✓ | |
| Fecal Coliform[4] | ✓ | ✓ | ✓ | |

The watershed is subdivided into nine sub-basins[5]. As illustrated in Figure III-I, water quality monitoring stations are present in each of the sub-basins and are typically located at or near confluences between the drainage areas.

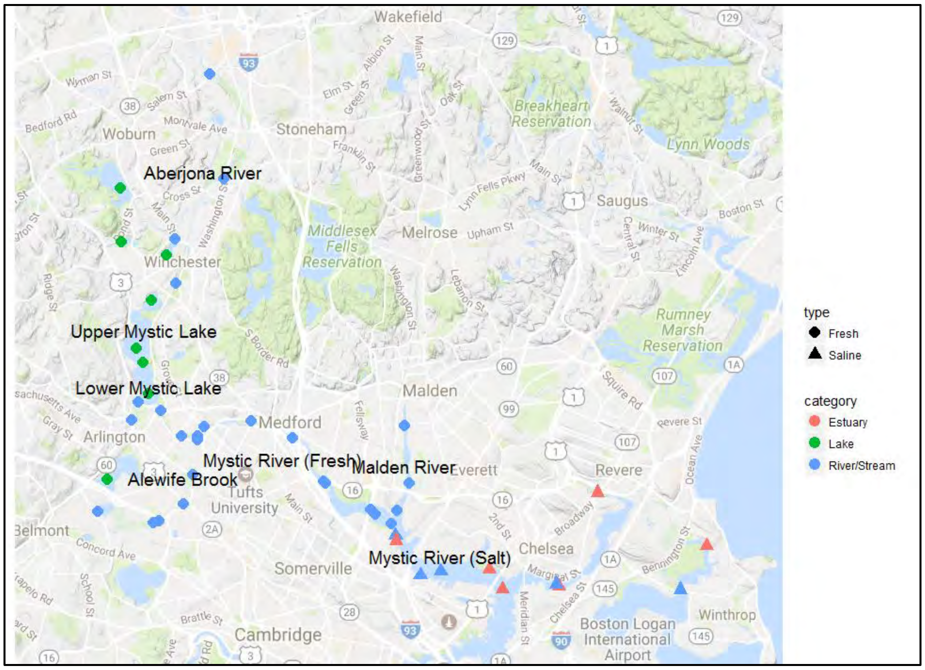



**Figure III-I. Mystic River Watershed Drainage Basins and Monitoring Locations**

Most water bodies in the watershed have been sampled all years from 2000 – 2016 (Table III-2). Six water bodies, mostly located in the upper portions of the watershed, have been sampled in 2015 and 2016 as part of the phosphorus loading survey but have not been monitored otherwise. Two water bodies in the lower portion of the watershed, Mill Creek and the Belle Island Inlet, have been monitored for approximately the past decade.

[2] Particulate nitrogen, particulate phosphorus, particulate carbon, total dissolved phosphorus, and total dissolved nitrogen are only tested at brackish/saltwater locations downstream of the Amelia Earhart dam.
[3] Phaeophytin is not currently tested using our WQ sondes; though there are older data in the dataset.
[4] Fecal coliform is not currently tested in any of the freshwater locations for either MWRA monitoring program, but like phaeophytin, there will be older data in the dataset. It is currently tested at locations downstream of the dam.
[5] Note that this delineation is provided for general information purposes and to provide the reader with an approximate sense of patterns of drainage within the watershed and is not intended to provide a definitive delineation of drainage within the basin.

**Table III-2. Temporal Range and Duration of Monitoring within Water Bodies**

| Water Body | Sample Range | | No. Years Monitored | | | | |
|---|---|---|---|---|---|---|---|
| | Min Year | Max Year | All Programs | Program Subtotals | | | |
| | | | | Baseline | Phos. Loading | Boston Harbor | CSO |
| Aberjona River | 2000 | 2016 | 17 | 17 | 2 | – | – |
| Horn Pond | 2015 | 2015 | 1 | – | 1 | – | – |
| Horn Pond Brook | 2015 | 2015 | 1 | – | 1 | – | – |
| Winter Pond | 2015 | 2015 | 1 | – | 1 | – | – |
| Wedge Pond | 2015 | 2016 | 2 | – | 2 | – | – |
| Upper Mystic Lake | 2000 | 2016 | 17 | 17 | 2 | – | – |
| Lower Mystic Lake | 2015 | 2015 | 1 | – | 1 | – | – |
| Mill Brook | 2000 | 2016 | 17 | 17 | 1 | – | – |
| Spy Pond | 2015 | 2015 | 1 | – | 1 | – | – |
| Winns Brook | 2000 | 2016 | 17 | 17 | – | – | – |
| Little River | 2000 | 2016 | 17 | – | – | – | 17 |
| Alewife Brook | 2000 | 2016 | 17 | 17 | – | – | 17 |
| Mystic River (Fresh) | 2000 | 2016 | 17 | 17 | 2 | – | 17 |
| Meetinghouse Brook | 2000 | 2016 | 17 | 17 | 1 | – | – |
| Malden River | 2000 | 2016 | 17 | 17 | 2 | 15 | – |
| Mystic River (Salt) | 2000 | 2016 | 17 | 9 | – | 17 | 17 |
| Mill Creek | 2008 | 2016 | 9 | 9 | – | – | – |
| Chelsea River | 2000 | 2016 | 17 | 9 | – | – | 15 |
| Belle Isle Inlet | 2009 | 2016 | 8 | 8 | – | – | – |

Restricting the examination to parameters that are likely to be of the greatest significance when assessing conditions related to eutrophication, it is apparent that total phosphorus and dissolved oxygen data are temporally and spatially well represented, and Secchi depth data are available for most of the water bodies (see Figure III-III). In particular, multiple monitoring locations on the main stem of the Mystic River downstream of Lower Mystic Lake possess large historical datasets for most parameters of potential interest for developing in-stream water quality targets (Figure III-IV).

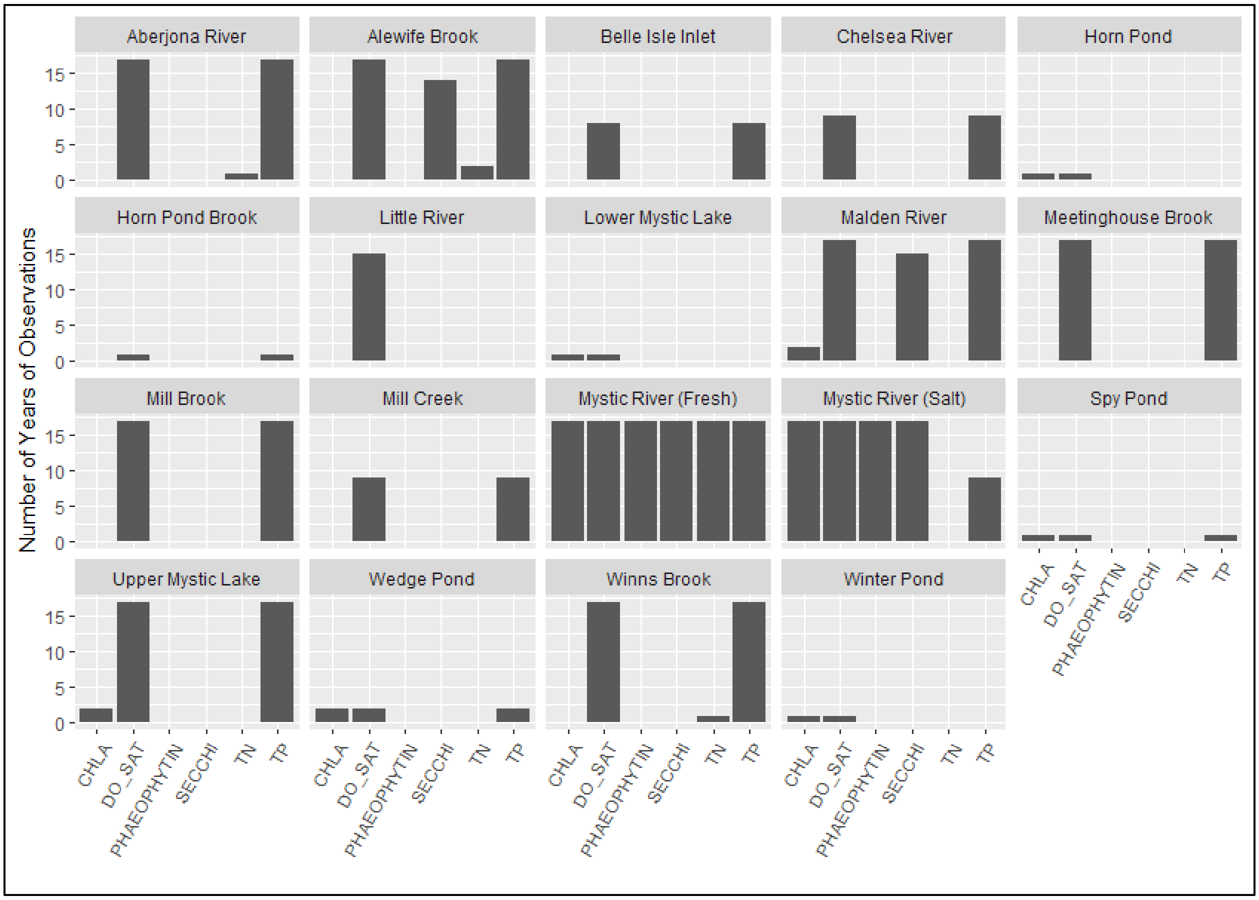
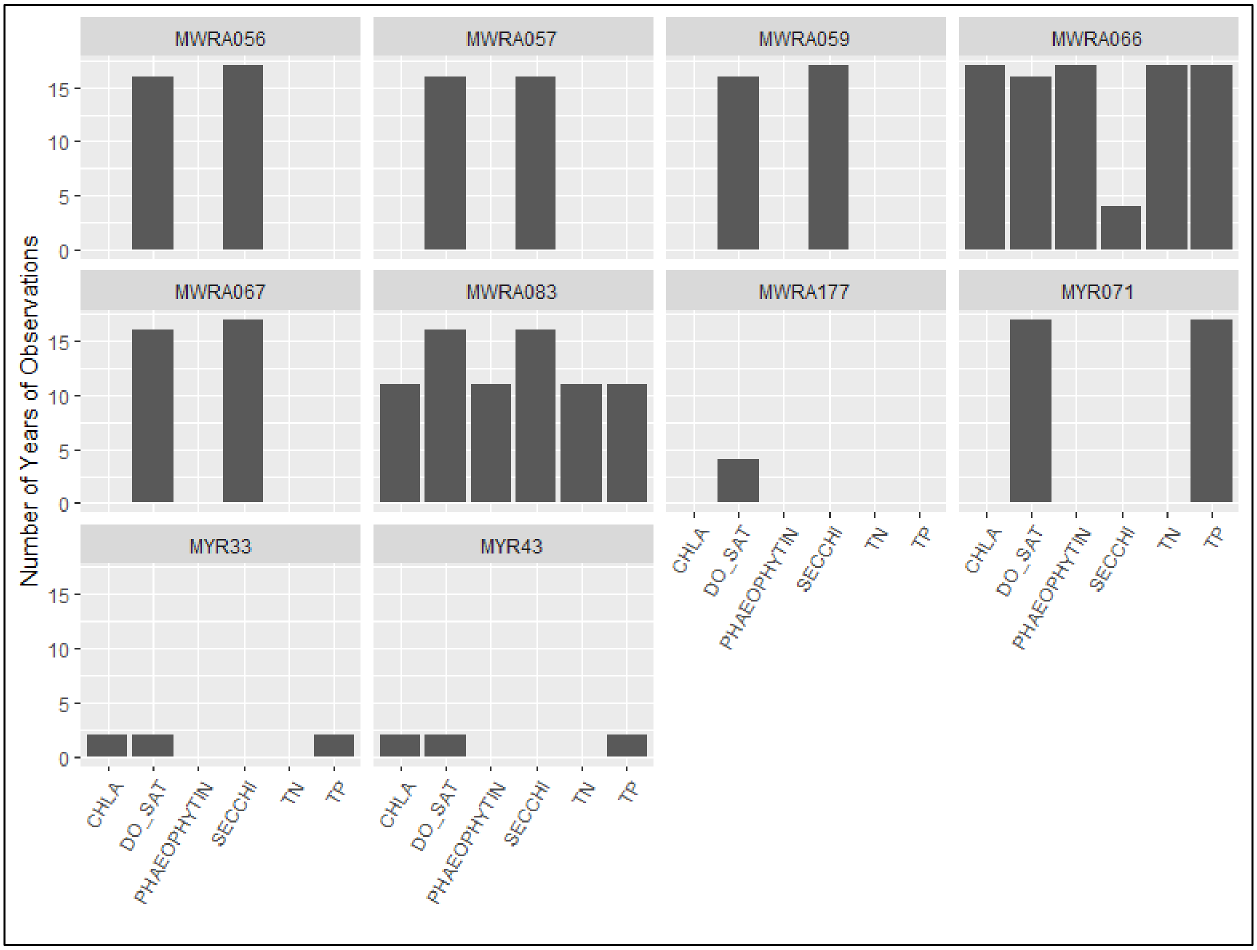


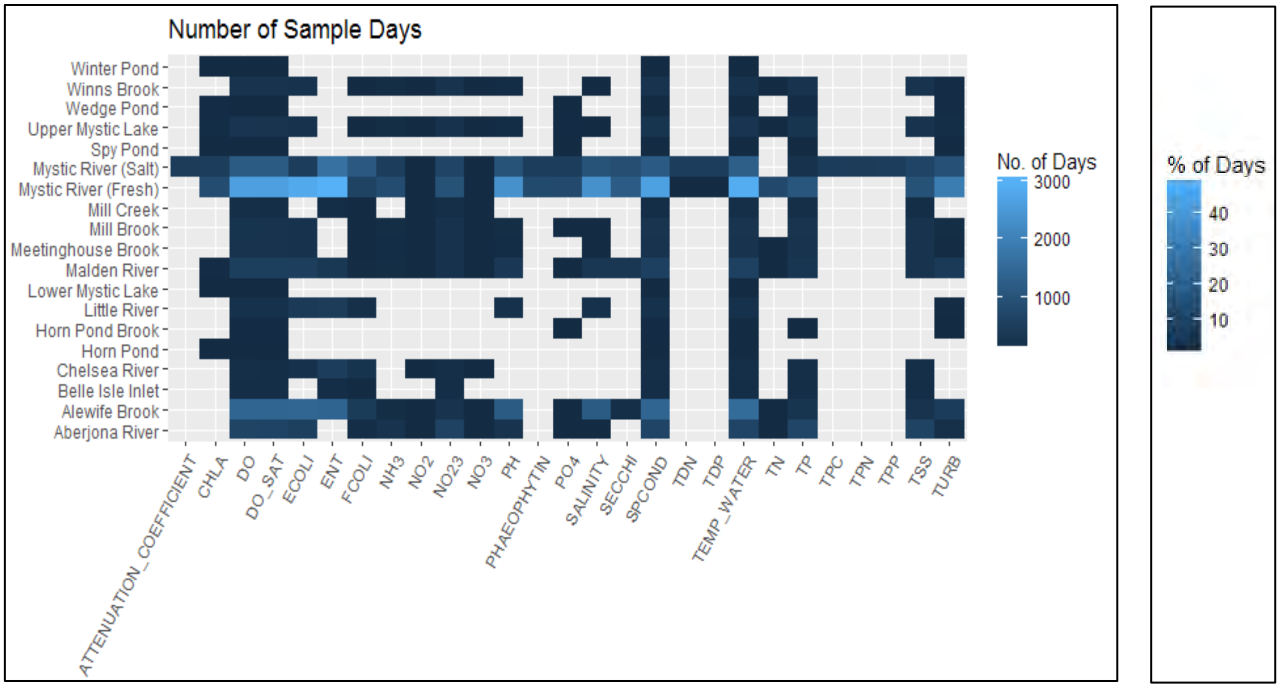

**Figure III-II. Number of Years in Which Observations Were Made for Eutrophication Related Parameters in the Watershed**




Refer to Appendix B for additional detail on water quality parameter codes.

**Figure III-III Number of Years in Which Observations Were Made for Eutrophication Related Parameters in The Mystic River**

As shown in Figure III-III, data for water quality parameters relevant to nutrient impairment have been collected throughout the watershed—particularly in the main waterways—and at a relatively high frequency. Sampling frequencies associated with the Boston Harbor monitoring and phosphorus loading programs occurred bi-weekly on a seasonal basis, with much of the monitoring for the baseline monitoring program occurring monthly. Refer to Appendix A for additional detail on sampling frequency broken down by water body, monitoring location, and monitoring program.




Refer to Appendix B for additional detail on water quality parameter codes.

**Figure III-IV. Temporal Coverage (both number of days and Percentage of Total Available Days from 2000 – 2016) of Water Quality Parameters by Water Body**

In terms of seasonal coverage, the number of observations was relatively evenly split between summer (June – October) and winter (November – May). The fraction of summer observations ranged from approximately 35 percent to 70 percent within the watershed and showed typical values of 53 +/- 19 percent (average +/- standard deviation) for all water bodies with at least 10 observations for a given parameter.

While temporal and geographic coverage is robust within the dataset, specific season/parameter/water body combinations do exist where relatively limited data coverage is available. Table III-3 identifies specific instances where data limitations exist for nutrient response variables at a seasonal level.

## Table III-3 Number of Seasons Where Few (N ≤ 3) Samples were Collected for a Waterbody-Parameter Combination

| Parameter | No. of Seasons with n≤3[1] | |
|---|---|---|
| | Jun-Oct | Nov-May |
| *Alewife Brook* | | |
| Secchi Depth | 3 | 9 |
| Turbidity | – | 5 |
| *Little River* | | |
| Dissolved Oxygen | 7 | 7 |
| Dissolved Oxygen (% Saturation) | 7 | 7 |
| pH | 7 | 5 |
| Specific Conductivity | 8 | 7 |
| Water Temperature | 7 | 7 |
| Turbidity | 2 | 3 |
| *Malden River* | | |
| Dissolved Oxygen | 1 | 19 |
| Dissolved Oxygen (% Saturation) | – | 10 |
| pH | – | 9 |
| Secchi Depth | – | 12 |
| Specific Conductivity | – | 13 |
| Water Temperature | – | 12 |
| Turbidity | 2 | 20 |
| *Mystic River (Fresh)* | | |
| Secchi Depth | – | 2 |
| Total Dissolved Nitrogen | 1 | 4 |
| Total Dissolved Phosphorus | 1 | 4 |
| Turbidity | – | 1 |
| *Mystic River (Salt)* | | |
| Attenuation Coefficient | 6 | 1 |
| Chlorophyll-a | 2 | – |
| Ammonia-Nitrogen | 2 | – |
| Inorganic Nitrogen | 2 | – |
| Phaeophytin | 2 | – |
| Orthophosphate | 2 | – |
| Total Dissolved Nitrogen | 2 | – |
| Total Dissolved Phosphorus | 1 | – |
| Total Particulate Carbon | 1 | – |
| Total Particulate Nitrogen | 2 | – |
| Total Particulate Phosphorus | 3 | – |
| Total Suspended Solids | 3 | – |
| Turbidity | 2 | 3 |

Where a water body-parameter combination is absent, or a "–" is listed, then n > 3 observations.

Appendix C includes a series of boxplots that summarize the observed characteristics of the dataset (i.e., minimum, 25th percentile, median, 75th percentile, and maximum). Additionally, a small number of unusual outlier values have been noted on the figures. Appendix D includes a table of the outlier observations with any documented data quality issues noted.

Dataset attributes that were assessed included the frequency of observations flagged for quality concerns and the frequency of censored observations (i.e., measurement results below the analytical method detection limit). Data quality documentation is currently available for only two of the monitoring programs—Baseline and Phosphorus Loading. As shown in Table III-4, approximately 98 percent of the observations from these two programs were free of documented data quality issues.

**Table III-4. Summary of Documented Data Quality Issues**

| Flag | Flag Description | Program Subtotals | | Grand Total | |
|---|---|---|---|---|---|
| | | Baseline | Phos. Loading | No. | Percent of Total |
| B | Analyte detected in the blank | – | 6 | 6 | 0.023 |
| E | Instrument error | – | 7 | 7 | 0.027 |
| F | Field replicate quality control failure | 308 | – | 308 | 1.186 |
| H | Holding time issues | – | 15 | 15 | 0.058 |
| J | Detected above method detection limit but below quantitation limit—result is an estimate | – | 11 | 11 | 0.042 |
| K | pH calibration error | – | 101 | 101 | 0.389 |
| L | Lab duplicate relative percent difference exceeded | 168 | 2 | 170 | 0.655 |
| O | Other unspecified issues | 2 | – | 2 | 0.008 |
| No Flag | No documented data quality issue | 22,652 | 2,697 | 25,349 | 97.613 |

The majority of the non-detect numbers were total suspended solids data and nitrogen data. In some cases (e.g., total suspended solids and nitrites), non-detect values make up a substantial portion of the observations. In these instances, accurate estimates of water quality parameters may be difficult to develop with a high degree of confidence. See Table III-5 for a summary of non-detect data.

**Table III-5 Summary of Non-Detect Data.[1]**

| Water body | No of Samples | | Method Detection Limit | Units |
|---|---|---|---|---|
| | Detected | Non-Detect | | |
| **Total Suspended Solids** | | | | |
| Aberjona River | 275 | 283 | 2 - 11.4 | mg/L |
| Alewife Brook | 148 | 41 | 1 - 7.7 | mg/L |
| Chelsea River | 77 | 4 | 5 - 5 | mg/L |
| Malden River | 119 | 63 | 1 - 20 | mg/L |
| Meetinghouse Brook | 70 | 120 | 1 - 10 | mg/L |
| Mill Brook | 106 | 81 | 2 - 20 | mg/L |
| Mystic River (Fresh) | 829 | 116 | 0.24 - 10.9 | mg/L |
| Mystic River (Salt) | 1048 | 6 | 0.24 - 10 | mg/L |
| Upper Mystic Lake | 50 | 133 | 1 - 8.3 | mg/L |

| | | | | |
|---|---|---|---|---|
| Winns Brook | 92 | 96 | 1 - 12 | mg/L |
| **Total Particulate Nitrogen** | | | | |
| Mystic River (Salt) | 439 | 1 | 0.0027 | mg/L |
| **Total Particulate Carbon** | | | | |
| Mystic River (Salt) | 441 | 1 | 0.016 | mg/L |
| **Total Phosphorus** | | | | |
| Aberjona River | 582 | 13 | 0.05 - 0.05 | mg/L |
| Chelsea River | 92 | 3 | 0.01 - 0.025 | mg/L |
| Malden River | 253 | 2 | 0.05 - 0.05 | mg/L |
| Meetinghouse Brook | 199 | 3 | 0.05 - 0.05 | mg/L |
| Mill Brook | 221 | 3 | 0.05 - 0.05 | mg/L |
| Mill Creek | 92 | 1 | 0.01 | mg/L |
| Mystic River (Fresh) | 1041 | 6 | 0.05 - 0.11 | mg/L |
| Mystic River (Salt) | 175 | 2 | 0.01 - 0.012 | mg/L |
| Spy Pond | 16 | 1 | 0.005 | mg/L |
| Upper Mystic Lake | 233 | 6 | 0.005 - 0.05 | mg/L |
| **Total Dissolved Phosphorus** | | | | |
| Mystic River (Salt) | 455 | 1 | 0.0034 | mg/L |
| **Orthophosphate** | | | | |
| Aberjona River | 0 | 7 | 0.005 - 0.005 | mg/L |
| Alewife Brook | 13 | 3 | 0.005 - 0.005 | mg/L |
| Horn Pond Brook | 1 | 5 | 0.005 - 0.005 | mg/L |
| Malden River | 0 | 14 | 0.005 - 0.005 | mg/L |
| Mill Brook | 3 | 4 | 0.005 - 0.005 | mg/L |
| Mystic River (Fresh) | 744 | 35 | 0.00031 - 0.005 | mg/L |
| Mystic River (Salt) | 903 | 4 | 0.00031 - 0.030 | mg/L |
| Spy Pond | 0 | 7 | 0.005 - 0.005 | mg/L |
| Upper Mystic Lake | 0 | 10 | 0.005 - 0.005 | mg/L |
| Wedge Pond | 0 | 7 | 0.005 - 0.005 | mg/L |
| **Nitrate** | | | | |
| Malden River | 4 | 1 | 0.1 | mg/L |
| Mill Brook | 5 | 1 | 0.1 | mg/L |
| Mystic River (Salt) | 7 | 1 | 0.1 | mg/L |
| Winns Brook | 5 | 1 | 0.1 | mg/L |
| **Inorganic Nitrogen (Nitrite plus Nitrate)** | | | | |
| Belle Isle Inlet | 43 | 38 | 0.1 – 0.5 | mg/L |
| Chelsea River | 60 | 27 | 0.1 – 0.5 | mg/L |
| Mystic River (Salt) | 1023 | 52 | 0.00028 – 0.5 | mg/L |
| **Nitrite** | | | | |
| Aberjona River | 6 | 12 | 0.1 - 0.1 | mg/L |
| Alewife Brook | 0 | 6 | 0.1 - 0.1 | mg/L |
| Chelsea River | 0 | 6 | 0.05 - 0.1 | mg/L |
| Malden River | 0 | 5 | 0.1 - 0.1 | mg/L |

| | | | | |
|---|---|---|---|---|
| Meetinghouse Brook | 0 | 6 | 0.1 - 0.1 | mg/L |
| Mill Brook | 0 | 6 | 0.1 - 0.1 | mg/L |
| Mill Creek | 1 | 4 | 0.1 - 0.1 | mg/L |
| Mystic River (Fresh) | 0 | 6 | 0.1 - 0.1 | mg/L |
| Mystic River (Salt) | 0 | 6 | 0.05 - 0.1 | mg/L |
| Upper Mystic Lake | 0 | 6 | 0.1 - 0.1 | mg/L |
| Winns Brook | 0 | 6 | 0.1 - 0.1 | mg/L |
| **Ammonia** | | | | |
| Mystic River (Salt) | 865 | 42 | 0.00039 – 0.010 | mg/L |
| Upper Mystic Lake | 56 | 1 | 0.00039 | mg/L |
| Winns Brook | 56 | 1 | 0.00039 | mg/L |

1. Locations with zero non-detect observations have been excluded.

### III.B.2. *Data Review*

The investigators reviewed the available data for accuracy/precision, representativeness, comparability, and completeness and concluded that the data are largely acceptable for use in assessing appropriate nutrient endpoint targets in the watershed.

Precision measures the reproducibility of repeated measurements and accuracy measures the "correctness" of an estimate. Overall, the dataset exhibited satisfactory levels of accuracy and precision where quality was documented. A relatively small fraction of the dataset included documented data quality issues (see Table III-4), though this conclusion may be revised upon receipt of quality control data for the CSO and Boston Harbor monitoring programs. Where data quality concerns have been documented in the Baseline and Phosphorus Loading data, excluding flagged data is recommended, with the possible exception of the J-flagged data (i.e., observations where the parameter was positively detected in the water, but at a level where quantitation is less precise than is usual).

The data are largely representative, both spatially and temporally, of the watershed. Most water bodies in the watershed have been monitored for the entire duration of interest (2000 – 2016). Two water bodies have been monitored for a majority of the period of interest, and the remainder has been intensively sampled in 2015 – 2016. In addition, the dataset also captures seasonal variation in parameters. Table III-3 documents specific water bodies where the available data are limited. In addition, Table III-5 documents limited instances—particularly with TSS and nitrites—where a large fraction of the data are censored and which may influence the ability to draw accurate inferences regarding water quality parameters (e.g., averages, standard deviations) for these constituents. However, these limitations are unlikely to present difficulties when developing nutrient modeling endpoints, as other constituents are present in the dataset and are likely to be more informative for purposes of developing protective in-stream water quality targets.

Comparability is an expression of the confidence with which one data set can be compared to another. Based on the available information, the data from the different programs, which compose the dataset, appear comparable.

The available data appears sufficiently complete for use in developing water quality targets. The vast majority of the data are valid and composed of point estimates (i.e., detect values) that can be used to develop reference conditions or stressor-response relationships for use in establishing modeling endpoints and protective instream water quality targets.

## III.C. USGS Flow Data

Valid daily flow data are available from two USGS monitoring stations for the Aberjona River and Alewife Brook (Table III-6). These stations collectively drain 8.96 square miles of the watershed, which accounts for approximately 12 percent of the watershed's land area. The two stations possess historical records, which extend prior to 2000 and to 2007, respectively.

**Table III-6. Summary of USGS Monitoring Stations**

| Gauge ID No. | Description | Location (Lat; Lon) | Discharge Data Availability | HUC | Net Drainage Area (sq. mi.) |
|---|---|---|---|---|---|
| 01102500 | Aberjona River at Winchester, MA | 42°26'50.5"; 71°08'18.9" | <2000 – 2/2017 | 01090001 | 24.7 |
| 01103010 | Mystic River at Arlington, MA | 42°25'14"; 71°08'33" | 6/2016 – 2/2017[1] | 01090001 | Undetermined |
| 01103025 | Alewife Brook Near Arlington, MA | 42°24'25"; 71°08'04" | 10/2007 – 2/2017 | 01090001 | 8.36 |
| 01103038 | Malden River at Malden, MA | 42°25'04"; 71°04'23" | 7/2016 – 2/2017[1, 2] | 01090001 | Undetermined |
| 01103040 | Mystic River at RT16 at Medford, MA | 42°24'20.6"; 71°05'45.6" | 10/2015 – 2/2017[1] | 01090001 | Undetermined |
| 01103050 | Mystic River at Amelia Earhart Dam | 42°23'44"; 71°04'32" | None[3] | 01090001 | 62.7 |

1. USGS has indicated that all or some of the discharge data collected at these stations are unreliable.
2. Stream temperature data are also available.
3. Gauge height data are available.

Three additional monitoring stations are equipped to estimate discharge volumes, however, USGS has indicated their measurements may be unreliable or inaccurate due to a combination of the shallowness of the river and low stream velocities. Currently, it is unclear if all discharge data from these stations are unusable or if some portion of the streamflow data might be utilized.

## III.D. GIS Datasets

Geospatial data are available from the sources listed in Table III-7, below. The data layers that were considered for calculating phosphorus loads in the watershed include: impervious cover, land use, and hydrologic soil types. In addition, phosphorous loads may be estimated for the Mystic River using similar export rates developed for the Massachusetts Municipal Separate Storm Sewer System (MS4) Permit and which are available from EPA Region 1.

### Table III-7. GIS Data Sources Available for the Mystic River Watershed

| Data layer | Source | Description |
|---|---|---|
| Land use/land cover | Massachusetts Office of Geographic Information (MassGIS) or Multi-Resolution Land Characteristics Consortium (MLCD) | Land use/land cover (LULC) layers contain information on the physical land type, e.g., forest, wetlands, of an area as well as information on how people are using the land, e.g., row crops, low-intensity development. Land cover can be determined in the field or by interpreting remotely sensed imagery (i.e., satellite imagery, aerial photos). Two sources for LULC datasets are MassGIS's Land Use (2005) or NLCD 2011. |
| Impervious surface | MassGIS | Impervious surfaces are surfaces that do not allow water to penetrate, forcing water to runoff. As water runs off, it can carry pollution from waterways and other surfaces into water bodies. Common impervious surfaces include roads, parking lots, rooftops, driveways and sidewalks, and compacted soils. |
| NRCS HUC Basins (8,10,12) (Sub-watersheds) | MassGIS | A hydrologic unit code (HUC) is the number assigned to a hydrologic unit, which is a drainage area that nests in a multi-level drainage system. Its boundaries are defined by hydrographic and topographic criteria that delineate an area of land upstream from a specific point on a river, stream or similar surface water. HUCs are identifiers as assigned to basin polygons by the USGS. |
| Soils | MassGIS (NRCS SSURGO) or NRCS Web Soil Survey | Information on underlying soils can help determine how much water can be absorbed or how much will runoff. There are specific hydrologic soil groups identified for areas that are based on estimates of runoff potential. Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms. The soils in the United States are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D). |
| Sewer-shed | Cambridge and Somerville | Drainage system for the local storm sewer (separate and/or combined) discharging into the Mystic River Watershed. Data available for Cambridge and Somerville only. |

# IV. Review of Modeling Endpoint Approaches

Water quality segments within the Mystic River Watershed are currently impaired for eutrophication-related parameters—high phosphorus, nitrogen, and chlorophyll-a levels have been documented throughout the watershed. Over enrichment has resulted in algae blooms and periods of excessive, nuisance vegetation growth. The purpose of selecting water quality targets is to establish a set of modeling and water quality endpoints (i.e., target water quality conditions) that meet Massachusetts' water quality standards and are protective of the designated uses established in the WQS (314 CMR 4.00). Attainment of appropriate targets could eventually result in acceptable levels of algal growth and the cessation of use impairments caused by excessive macrophyte growth.

This section reviews the following approaches for establishing targets in the watershed:

- Use of existing regional/local targets.
- Use of reference water body conditions.

- Development of targets based on stressor-response relationships.
- Development of targets based on mechanistic models.

### IV.A. Water Quality Standards Applicable to the Mystic River Watershed

Once a tidal river, the Lower Watershed currently functions as a large impoundment due to a dam located at the basin outlet. Another significant impoundment on the main stem of the river exists at the outlet of the Upper Mystic Lake (Figure IV-I and Figure IV-II).

In 314 CMR 4.00, Massachusetts establishes two eutrophication related standards applicable to the watershed: a narrative nutrient standard and a numeric dissolved oxygen standard.

- **Nutrients.** The narrative standard prohibits discharges containing nutrients in concentrations that would "*cause or contribute to cultural eutrophication, including excessive growth of aquatic plants or algae, and otherwise render water unsuitable for designated uses*." [314 CMR 4.05(5)]
- **Dissolved Oxygen.** For Class B waters, the concentration of dissolved oxygen shall be greater than or equal to 5 mg/L at all times. [314 CMR 4.05(3)(a)(1)]

### IV.B. Existing Regional/Local Targets

Several examples exist that establish protective water quality targets for either (1) local or regional water bodies, or (2) specific water body types. These include the *Total Maximum Daily Load for Nutrients in the Lower Charles River Basin, Massachusetts* (Charles River TMDL), Massachusetts' numeric standards and impairment assessment criteria (Massachusetts Department of Environmental Protection [DEP], 2016), and the criteria included in EPA's *Quality Criteria for Water* (1986); informally known as the "Gold Book." These targets are summarized in Table IV-1.

**Table IV-1. Existing Water Quality Targets**

| Parameter | Numeric Target | Target Duration/ Frequency | Source |
|---|---|---|---|
| Total Phosphorus | <100 µg/L (Free flowing rivers) | Instantaneous | Gold Book (1986) |
| | <50 µg/L (Entering lakes/impoundments) | Instantaneous | |
| | <25 µg/L (Exiting lakes/impoundments) | Instantaneous | |
| Dissolved Oxygen | >5 mg/L | Instantaneous | MA Surface Water Quality Standards [314 CMR 4.05(3)(a)(1)] |
| Dissolved Oxygen, Saturation | <125% | Instantaneous | Upper/Middle Charles TMDL (MA DEP, 2016) |
| Chlorophyll-a | <10 µg/L | Seasonal Average | Lower Charles TMDL (MA DEP & EPA, 2007) and Upper/Middle Charles TMDL (MA DEP, 2016) |
| | <18.9 µg/L | 90$^{th}$ Percentile | |

### IV.C. Reference Water Body Conditions

The reference water body condition method utilizes observations of water quality conditions (e.g., total phosphorus and chlorophyll-a concentrations) in water bodies with limited anthropogenic impacts—or, at least, limited eutrophication—to establish "natural" or background nutrient conditions in regional waters. In principle, reference condition targets should approximate the best possible attainable water quality in the absence of human activity or if human impacts are entirely controlled (Dodds and Oakes, 2004).

EPA suggests several methods for establishing reference nutrient conditions for a water body (Buck, et al., 2000). Of those applicable to the Mystic River Watershed, the first requires the identification of reference water bodies comparable to the Mystic River water bodies but which display limited or no human influences on water quality. The 75$^{th}$ percentile water quality condition of the reference water bodies is estimated, and this percentile is applied as a target in the water body of interest. The second approach calculates the 25$^{th}$ percentile concentration of the general population of water bodies—including water bodies with clear human impacts—to develop a target. Figure IV-I conceptually illustrates these two approaches.

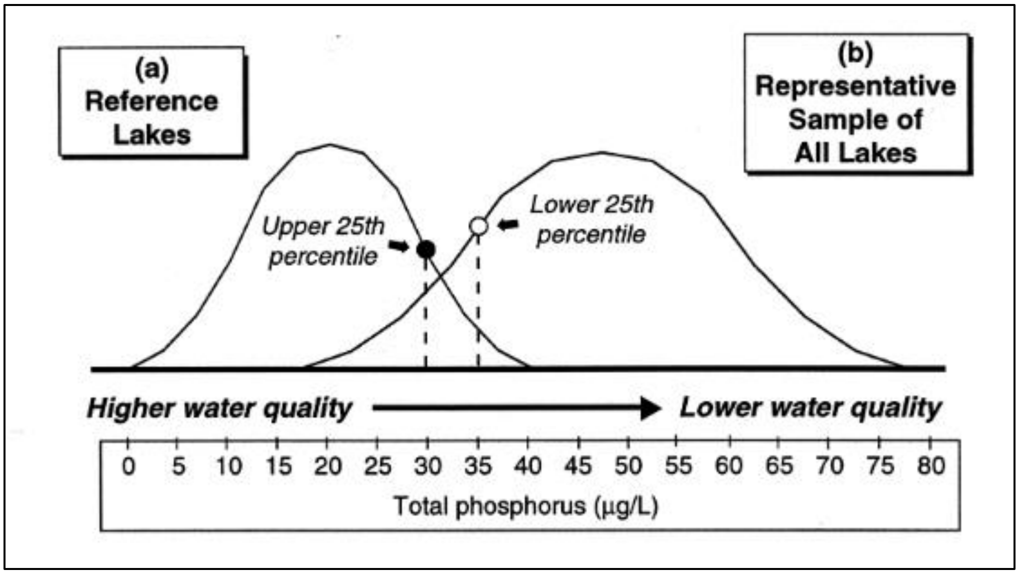



**Figure IV-I. Reference Condition Approach for Establishing Numeric Water Quality Targets (EPA, 1998)**

EPA has utilized this reference approach to develop eco-region-based nutrient criteria for application through the United States. In eco-region XIV sub-region 59 (EPA, 1998), where the Mystic River is located, EPA was unable to identify suitable reference water bodies and, consequently, based their eco-regional criteria on the 25$^{th}$ percentile of the general population of water bodies. To confirm that no new, appropriate reference water bodies have been identified following the publication of the eco-regional criteria, the project team reviewed recent survey efforts undertaken as part of EPA's National Aquatic Resources Survey. The project team was unable to identify any water bodies that could serve as appropriate reference water bodies for the Mystic River.

Table IV-2 summarizes EPA's eco-region XIV sub-region 59 criteria and, for comparative purposes, the 25$^{th}$ percentile parameter values for Upper Mystic Lake, the Upper Mystic River, and for the entire watershed. Monitoring data for the water bodies of interest display 25$^{th}$ percentile observational values ranging from 20 µg/L - 34 µg/L for total phosphors and 1.9 µg/L - 6.6 µg/L for chlorophyll-a.

**Table IV-2. Eco-regional Criteria and Observed 25th Percentile (2000 – 2016) Mystic River Watershed Values**

| Type/Location | Total Phosphorus (µg/L) | Total Nitrogen (mg/L) | Chlorophyll-a[1] (µg/L) | Secchi Depth (meters) | Turbidity (NTU) |
|---|---|---|---|---|---|
| *Eco-region XIV, Sub-region 59* | | | | | |
| Rivers & Streams | 23.75 | 0.59 | 0.44[2] | – | 1.68[3] |
| *Mystic River Watershed 25th Percentile Observations (2000 – 2016)* | | | | | |
| Upper Mystic Lake[4] | 20 | – | 6.6 | – | 1.7 |
| Upper Lobe of Upper Mystic Lake[5] | 25 | – | 6.0 | – | 5.1 |
| Mystic River (Lower Basin)[4] | 30 | 1.0 | 1.9 | 0.84 | 3.8 |
| Total Mystic River Watershed[4] | 34 | 1.0 | 2.0 | 0.70 | 3.9 |

1. Fluorometric method
2. Aggregated by subregion
3. Average of reported and calculated values
4. Aggregate of all monitoring station located in the water body
5. Measured at monitoring station UPLUPL

### IV.D. Stressor-Response Relationships

Water quality targets developed based on stressor-response relationships utilize empirical relationships between nutrients and response variables (e.g., chlorophyll-a, excessive macrophyte growth) to estimate protective numeric, water body-specific targets. This technique includes four steps: (1) develop a conceptual model, (2) assemble and explore water quality data, (3) develop statistical relationships between variables, and (4) derive protective targets based on those relationships.

A benefit of the stressor-response approach is that nutrient targets are based on functional relationships between nutrients and attainment of designated uses. This reduces risk associated with developing excessively stringent targets, as can happen with reference condition approaches. However, there is substantial risk that, after analysis, no reliable relationship will be discernable. This can occur when the water body of interest is extremely impaired—resulting in a saturated response signal—or when multiple confounding effects, which cannot be sufficiently controlled for, contribute to the impairment.

For purposes of demonstration, the project team performed a preliminary stressor-response analysis using Mystic River Watershed data described in Section III of the report. As a preliminary analysis, the direct relationship was assessed between variables, while not controlling for covariate effects and other confounding phenomenon (e.g., flow, phosphorus uptake by macrophytes, etc.). In addition, the project team restricted the analysis to Upper Mystic Lake and the main stem of the Mystic River in the Lower Watershed, and to total phosphorus concentration values as a stressor variable.

Table IV-3 presents the results of the relationship between total phosphorus and chlorophyll-a concentrations in the upper lobe of Upper Mystic Lake, all sites within Upper Mystic Lake, and in the Mystic River. Simple linear regressions were performed on paired concentration values (i.e., total phosphorus and chlorophyll-a on a given day and monitoring location). Based on the resulting relationship, a total predicted phosphorus concentration was calculated to produce a 10 µg/L chlorophyll-a concentration (i.e., the seasonal average target for the Lower and Upper/Middle Charles River TMDLs). Data was restricted to the period April – October when evidence of algae growth was greatest. Predicted total phosphorus concentrations varied from 15 µg/L to 29 µg/L. Regressions for the Mystic River and the total Upper Mystic Lake were not significant; however, regression parameters for the upper lobe of the Upper Mystic Lake were significant ($p < 0.05$; Figure IV-IV).

**Table IV-3. Simple Linear Regression on Paired TP & Chlorophyll-a Monitoring Results Collected April – October**

| Water body | Linear Regression Parameters | | | Total Phosphorus[1] (µg/L) |
|---|---|---|---|---|
| | Slope | Intercept | r-squared | |
| Upper Lobe of Upper Mystic Lake[2] | 1.433 | -27.89 | 0.43 | 26 |
| Upper Mystic Lake | 0.5872 | 1.092 | 0.37 | 15 |
| Mystic River | 0.1332 | 6.164 | 0.12 | 29 |

1. Total phosphorus concentration implied by linear regression. Corresponds to a chlorophyll-a concentration of 10 µg/L.
2. Monitoring station UPLUPL.

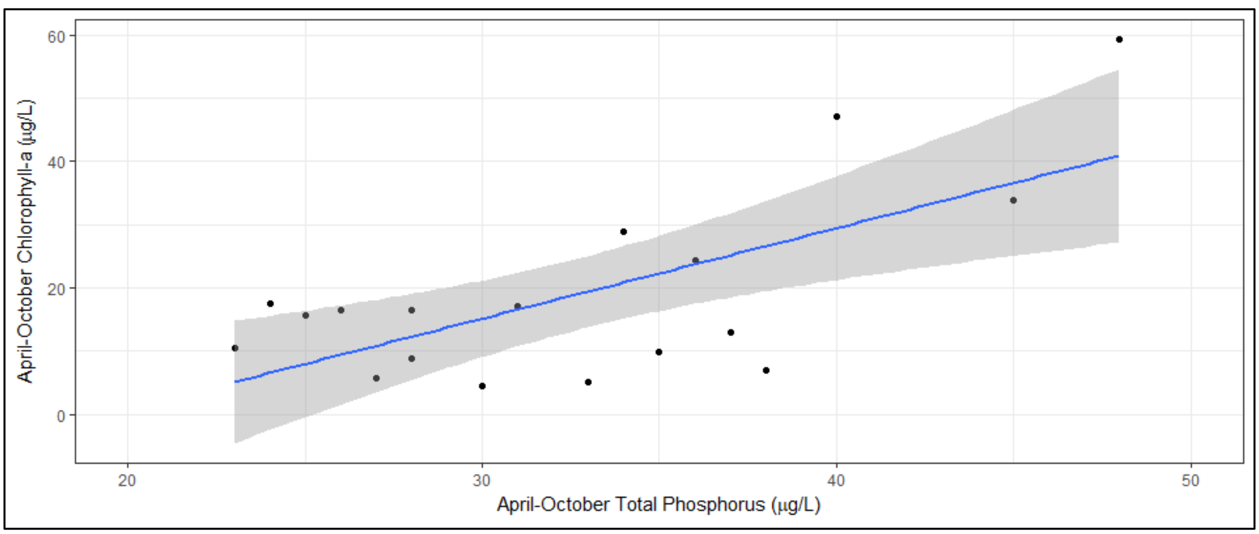



**Figure IV-II. April – October Total Phosphorus vs. Chlorophyll-a Concentrations in the Upper Lobe of the Upper Mystic Lake (Monitoring Station UPLUPL)**

Regressions based on seasonal averages in the Mystic River resulted in implied seasonal average total phosphorus concentrations of approximately 33 and 41 µg/L to meet Charles River TMDL targets. However, like the regressions in Table IV-3 for the Mystic River, these relationships were not statistically significant. Table IV-4, Figure IV-III and Figure IV-IV show regressions of seasonal average total phosphorus concentrations and chlorophyll-a as seasonal average and a seasonal 90th percentile value, respectively (shaded area indicates 95% confidence interval). Data was aggregated based on April – October measurements in each year. Upper Mystic Lake was not included in this analysis since only 2 years of data were available.

### Table IV-4. Simple Linear Regression on Average TP and Average or 90th Percentile Chlorophyll-a[1]

| Water body | Linear Regression Parameters | | | Chlorophyll-a Target (µg/L) | Total Phosphorus[2] (µg/L |
|---|---|---|---|---|---|
| | Slope | Intercept | r-squared | | |
| Mystic River: Seasonal Average Chlorophyll-a | 0.16929 | 4.43453 | 0.14 | 10 | 33 |
| Mystic River: Seasonal 90th Percentile Chlorophyll-a | 0.3679 | 3.7722 | 0.19 | 18.9 | 41 |

1. Averages and 90th percentile values aggregated by year for the period April – October.
2. Concentration predicted by regression equation for Charles River TMDL target.

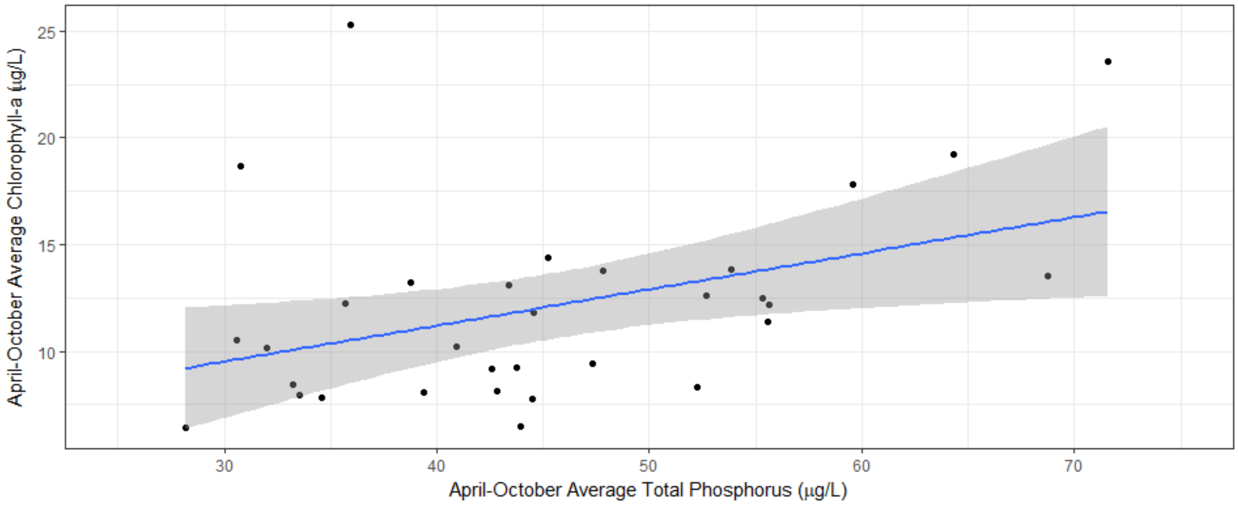



**Figure IV-III. April – October Average Total Phosphorus vs. Average Chlorophyll-a Concentrations in the Mystic River**

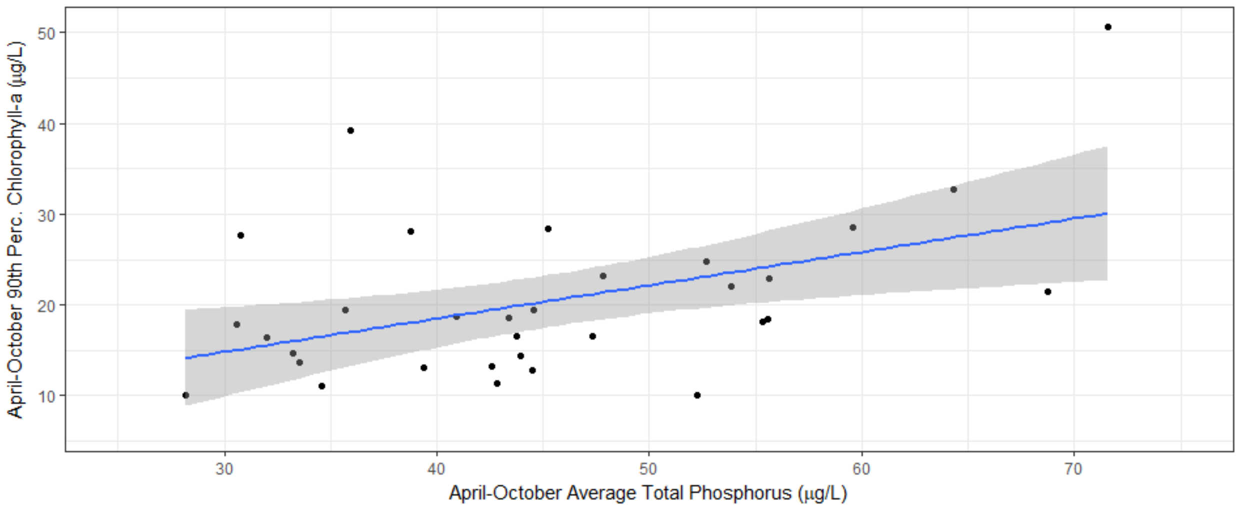



**Figure IV-IV. April – October Average Total Phosphorus vs. 90th Percentile Chlorophyll-a Concentrations in the Mystic River**

### *IV.E. Mechanistic Models*

Mechanistic models use systems of equations to represent ecological and hydrodynamic processes within a water body. These can be used to predict changes in eutrophication-related processes in response to changes in the level of water body enrichment. Like stressor-response models, mechanistic water quality models can be used to develop nutrient targets based on functional relationships and using site-specific empirical data. While stressor-response relationships are treated like statistical "black box" processes, mechanistic models are largely deterministic models of system behavior (U.S. EPA, 2001).

Mechanistic models have substantial input data requirements and would require a higher level of effort relative to the options discussed above. Models of this type are not in widespread use for developing modeling endpoints or protective nutrient targets, though they have been successfully implemented in the past (Paul et al., 2011).

### IV.F. Recommendations

The project team recommends the use of existing water quality targets designed for nearby water bodies. While the Mystic River Watershed possesses some unique hydrologic features, the Charles River shares many similar features (climate, hydrologic features) and the targets developed in its TMDL are protective of the applicable Massachusetts water quality standards. Thus, the project team decided to use the 10ug/L target for chl-a from the Charles River TMDL and apply it to the load reduction analysis for the Mystic River. During modeling and calibration, it was determined that the 10ug/L target was not easily applied to stormwater management BMPs. Instead, the team decided to use a TP target of 30ug/L based on the Charles River TMDL, which references a TP target of 30ug/L to achieve water quality conditions that correlate to 10ug/L for chl-a.

A mechanistic model is not recommended due to high resource and data requirements. Stressor-response relationships require the selection of a response variable target (e.g., macrophyte cover and chlorophyll-a) and, consistent with the results of the preliminary analysis documented in this memorandum, may not produce results of sufficiently robust statistical significance on which to base the alternative TMDL analysis. A reference condition approach—particularly in the absence of reliable reference water bodies—may prove to be unreliable, as the resultant target does not reflect a functional relationship between nutrients and over-enrichment conditions.

# V. Watershed Phosphorus Loading Estimates

Average annual phosphorus loading was estimated for the watershed area sub-basins tributary to the freshwater portion of the Mystic River. These estimates will be used to estimate loading to critical receiving water bodies that will be modeled using the Lake Loading Response Model (LLRM, Wagner, 2009) and BATHTUB water quality models (please note, LLRM analysis is ongoing and results are not presented in this report). Output from the receiving water model will then be used in subsequent analyses to identify the reductions in phosphorus loads necessary to bring the watershed into compliance with selected water quality targets (see Table IV-1 for TP and chl-a targets). In addition, observed loading data corresponding to several USGS gage stations in the watershed have been compiled for use in calibration of the land load estimates.

## V.A. Stormwater Loads

Stormwater loads to the receiving water system are carried across the land surface by runoff during most precipitation events. Regional pollutant loading export rates (PLERs) are commonly used as a way to estimate annual phosphorus loads from various Hydrologic Response Units (HRUs), where each HRU is comprised of a unique combination of land use, cover type (impervious or pervious), and soil type. PLERs define the TP mass per unit area per time (i.e., lbs./acre/year) that is exported from each type of HRU. HRUs are a common modeling method to categorize areas of land that function similarly in terms of their hydrologic fluxes and pollutant loads.

To develop stormwater loads, EPA Region 1's Opti-Tool modeling package was utilized. Opti-Tool incorporates model generated time-series of hourly stormwater runoff volumes and nutrient runoff quality that reflects pollutant build-up/wash-off processes and that has been calibrated to stormwater quality and climatic data representative of the New England region. The Opti-Tool package includes companion HRU Storm Water Management Models (SWMM) that were used to dynamically simulate rainfall-runoff events for land-use based impervious and pervious HRU categories that reflect land cover characteristics in the Mystic River Watershed. Using the SWMM HRU models, Opti-Tool can be used to simulate runoff volumes and pollutant loads (e.g., annual loads) for defined sub-basins within the watershed for any period of interest.

Opti-Tool includes SWMM HRU models for each HRU category that collectively are used to represent key watershed characteristics in the Mystic watershed related to surface runoff. Individual HRU models applied to the Mystic include land use specific for impervious cover (e.g., commercial impervious) and land use specific for pervious cover and hydrological soil group (HSG) A, B, C, and D (e.g., high density residential pervious HSG B). Hourly precipitation data representative of the Mystic watershed and daily maximum and minimum temperatures are used as inputs to conduct continuous HRU model simulations to generate annualized stormwater runoff volumes and loads. The HRU model outputs produce land-use category specific PLERs for impervious cover and pervious cover (according to HSG) and rainfall-runoff total (in/year). The unit PLER and flow can be generated for any period of interest, including on an annual basis for each individual year, or as overall average annual values for the period of record analyzed.

Using the resultant unit export rates, the annual stormwater load and/or flow for a given HRU category within the watershed area of interest is generated by multiplying the total area represented by the HRU type (e.g., commercial impervious) by the corresponding HRU specific PLER. OptiTool loads and flows for each land use were used as input to the land loading models. That loading model accumulated loads and flows and then attenuated the loads to provide values at the outlet of each sub-basin. The basin values were used as the input to the BATHTUB model.

Table V-1 presents the climatological datasets used as inputs to the Opti-Tool model to generate annual total stormwater phosphorus loads and flows.

**Table V-1. Opti-Tool-SWMM HRU Model Climatological Input Datasets**

| Type | Description | Source |
|---|---|---|
| Precipitation | Hourly time series of precipitation values at Boston Gen E Logan International Airport (WSAF-WBAN ID 725090 14739) from 1992 - 2016 | https://gis.ncdc.noaa.gov/maps/ncei/cdo/hourly |
| Temperature | Daily time series of maximum and minimum temperature values at Boston Gen E Logan International Airport (WSAF-WBAN ID 725090 14739) from 1992 - 2016 | https://gis.ncdc.noaa.gov/maps/ncei/cdo/hourly |

The delineation of sub-basins for quantifying flows and loads through HRU accounting within the freshwater portion of the Mystic River Watershed was initially based on an existing sub-basin delineation available from the Massachusetts Office of Geographic Information (MassGIS). Modifications and refinements were made to further sub-divide several basins to better reflect watershed routing processes and more closely align with critical water body assessment locations. Some of these modifications were made using a digital elevation model and delineation for quality control. Further modifications to several impaired lake basins were made based on consultation with MassDEP staff and a review of previously developed procedurally generated delineations for the lake basins. Ultimately, all sub-basin delineations were visually compared to FEMA derived flood plain delineations as an added quality control measure.

Land-use categories within each sub-basin were delineated based on the intersection of three GIS layers: land use, impervious cover, and soil type. Table V-2 lists the land-use categories used in Opti-Tool and provides a crosswalk with the GIS layer categories.

### Table V-2. Land-Use Categories

| Opti-Tool Land-Use | MassGIS ID Code | MassGIS Description |
|---|---|---|
| Agriculture | 1 | Cropland |
| Agriculture | 2 | Pasture |
| Agriculture | 23 | Cranberry Bog |
| Agriculture | 26 | Golf Course |
| Agriculture | 36 | Nursery |
| Commercial | 15 | Commercial |
| Commercial | 29 | Marina |
| Commercial | 31 | Urban Public/Institutional |
| Forest | 3 | Forest |
| Forest | 4 | Non-Forested Wetland |
| Forest | 35 | Orchard |
| Forest | 37 | Forested Wetland |
| Forest | 40 | Brushland/Successional |
| High Density Residential | 10 | Multi-Family Residential |
| High Density Residential | 11 | High Density Residential |
| Highway | 18 | Transportation |
| Industrial | 5 | Mining |
| Industrial | 16 | Industrial |
| Industrial | 19 | Waste Disposal |
| Industrial | 39 | Junkyard |
| Low Density Residential | 13 | Low Density Residential |
| Low Density Residential | 38 | Very Low Density Residential |
| Medium Density Residential | 12 | Medium Density Residential |
| Open Land | 6 | Open Land |
| Open Land | 7 | Participation Recreation |
| Open Land | 8 | Spectator Recreation |
| Open Land | 9 | Water-Based Recreation |
| Open Land | 17 | Transitional |
| Open Land | 24 | Powerline/Utility |
| Open Land | 25 | Saltwater Sandy Beach |
| Open Land | 34 | Cemetery |
| Water | 14 | Saltwater Wetland |
| Water | 20 | Water |

The total impervious area (TIA) associated with each Opti-Tool land-use category was adjusted to directly connected impervious area (DCIA) or effective impervious area using the following formula (refer to Table V-3 for adjustment factors):

$$DCIA = C \times TIA$$

Unconnected impervious area (i.e., TIA minus DCIA) was then distributed proportionally among the pervious soil types within the land-use (e.g., if 70 percent of the soil was assigned as type A soils, then 70 percent of the unconnected impervious area was re-assigned to type A soils). Table V-3 shows DCIA adjustment factors from MA MS4 Permit.

### Table V-3. DCIA Adjustment Factors from MA MS4 Permit

| Opti-Tool Land-Use | Adjustment Factor (C) |
|---|---|
| Agriculture | 0.004 |
| Commercial | 0.570 |
| Forest | 0.001 |
| High Density Residential | 0.360 |
| Highway | 0.440 |
| Industrial | 0.670 |
| Low Density Residential | 0.110 |
| Medium Density Residential | 0.160 |
| Open Land | 0.080 |

Table V-4 integrates the land-use categories with soil and impervious cover categories. Table V-5 lists the data sources for the layers discussed above, all of which were obtained from the MassGIS.

### Table V-4. Opti-Tool Export Rates by HRU

| Opti-Tool HRU | Average Annual PLER (lbs./acre/year)[1] | Average Annual Rainfall-Runoff Rate (in/year) | Average Annual Flow-weighted TP SW concentration (mg/L) |
|---|---|---|---|
| Agriculture Impervious | 1.49 | 39.51 | 0.17 |
| Forest Impervious | 1.49 | 39.51 | 0.17 |
| Highway Impervious | 1.38 | 39.51 | 0.15 |
| Industrial Impervious | 1.79 | 39.51 | 0.20 |
| Commercial Impervious | 1.79 | 39.51 | 0.20 |
| High Density Residential Impervious | 2.36 | 39.51 | 0.26 |
| Medium Density Residential Impervious | 1.95 | 39.51 | 0.22 |
| Low Density Residential Impervious | 1.49 | 39.51 | 0.17 |
| Open Land Impervious | 1.49 | 39.51 | 0.17 |
| Agriculture Pervious | 0.44 | 2.50 | 0.78 |
| Forest Pervious | 0.11 | 2.50 | 0.19 |
| Developed[2] Pervious A | 0.03 | 0.46 | 0.29 |
| Developed[2] Pervious B | 0.11 | 2.50 | 0.19 |
| Developed[2] Pervious C[3] | 0.21 | 5.64 | 0.16 |
| Developed[2] Pervious C/D | 0.30 | 7.54 | 0.18 |
| Developed[2] Pervious D | 0.37 | 10.30 | 0.16 |

1. Based on simulations spanning 1992 – 2017.

2. Developed Pervious land categories include commercial, industrial, residential, highway, and open land (see Table 1-2 of Attachment F to 2016 MA MS4 General Permit).
3. Areas with undefined or unknown soil types were assumed to be soil type C.

## Table V-5. GIS Layers Used to Develop HRUs

| Type | Description | Source |
|---|---|---|
| Land Use (2005) | The Land Use (2005) data layer is a Massachusetts statewide seamless digital dataset of land cover/land use, created using semi-automated methods, and based on 0.5-meter resolution digital ortho imagery captured in April 2005. | http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html |
| Impervious Cover (2005) | The Impervious Surface raster layer represents impervious surfaces covering the Commonwealth of Massachusetts. The surfaces were acquired in April 2005 as part of the Color Ortho Imagery project. | http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/impervioussurface.html |
| NRCS SSURGO-Certified Soils (2014) | The SSURGO-certified soils dataset is generally the most detailed level of soil geographic data developed by the National Cooperative Soil Survey. The data include a detailed, field-verified inventory of soils and miscellaneous areas that normally occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale mapped. | http://landscapeteam.maps.arcgis.com/apps/SimpleViewer/index.html?appid=4dbfecc52f1442eeb368c435251591ec |
| Drainage Sub-Basins (2007) | MassGIS has produced a statewide digital data layer of the approximately 2,300 sub-basins as defined and used by the USGS Water Resources Division and the Massachusetts Water Resources Commission and as modified by Executive Office of Environmental Affairs (EOEA) agencies. | http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/subbas.html |
| Elevation (Topographic) Data (2005) | These data represent the "bare earth" elevation of the terrain surface without vegetation and artificial features. As a requirement for the orthorectification process of the 1:5,000 Color Ortho Imagery (2005), elevation points were compiled photogrammetrically by human operators from imagery acquired by Sanborn, Inc. in April 2005. | http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/elev2005.html |

Sub-basins delineated within the Mystic River Watershed were based on the connectivity to four critical reaches and seven ponds. The four critical reaches chosen were modeled using the receiving water model while ponds selected were those identified for future TMDL modeling using the LLRM model.

The three critical reaches are:

- Upper Lobe of Upper Mystic Lake.
- The Main-body of Upper Mystic Lake.
- Upper Mystic Basin
- Lower Mystic Basin.

The major lakes/ponds are:

- Blacks Nook Pond (MA71005), Cambridge.
- Horn Pond (MA71019), Woburn.
- Judkins Pond (MA71021), Winchester.
- Mill Pond (MA71031), Winchester.
- Spy Pond (MA71040), Arlington.
- Wedge Pond (MA71045), Winchester.
- Winter Pond (MA71047), Winchester.

The sub-basin delineation within the freshwater portion of the Mystic is presented in Figure V-1 (note: the stippled area denotes the area served by a combined sewer). Figure V-2 shows the expected routing scheme through the sub-basins in the Mystic River Watershed from the headwaters to the outlet. The delineation allows modelers to characterize flow and pollutant loading to each of the three critical reaches, seven major lakes/ponds, and at mainstream segments (the Aberjona River, the Malden River, and Alewife Brook).

Sub-basins were named for the pond or water body to which they drained (e.g., the upper reaches of the Aberjona River drainage area were labeled the Judkins Pond sub-basin since this is the water body located at the bottom of the drainage area) or to main stream segment in which they encompass. The exceptions to this naming convention are the Aberjona River 1 and Aberjona River 2 sub-basins which are split around the USGS streamflow gauge for the river.

Estimated annual stormwater (SW) phosphorus loads and runoff volumes (1992 – 2017) for the entire Mystic River watershed are presented in Figure V-I. Details for the three critical water quality segments and seven impaired ponds within the watershed are presented in Appendix E.

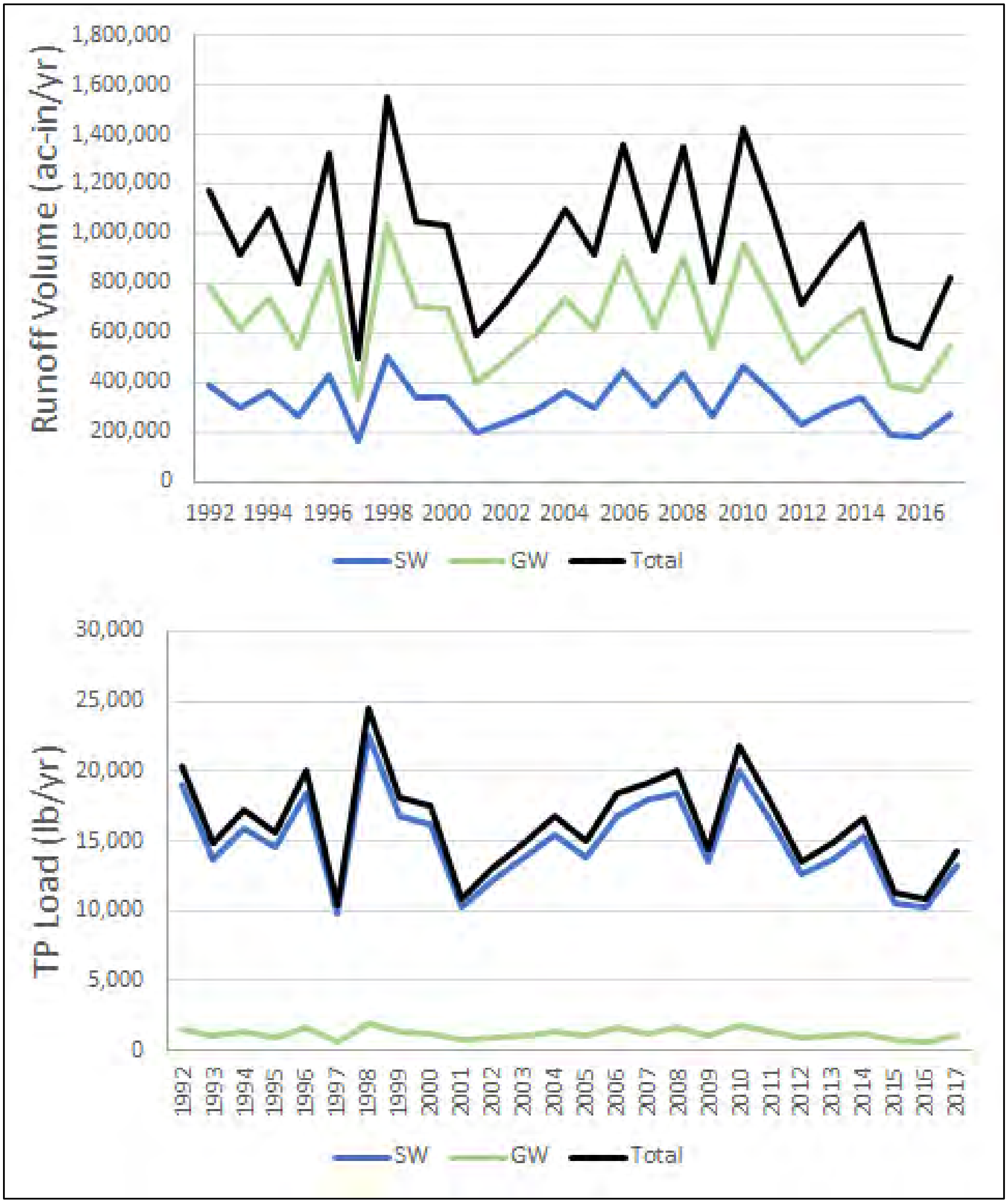



**Figure V-I. Estimated Annual Runoff Volume and TP Load for the Mystic River**

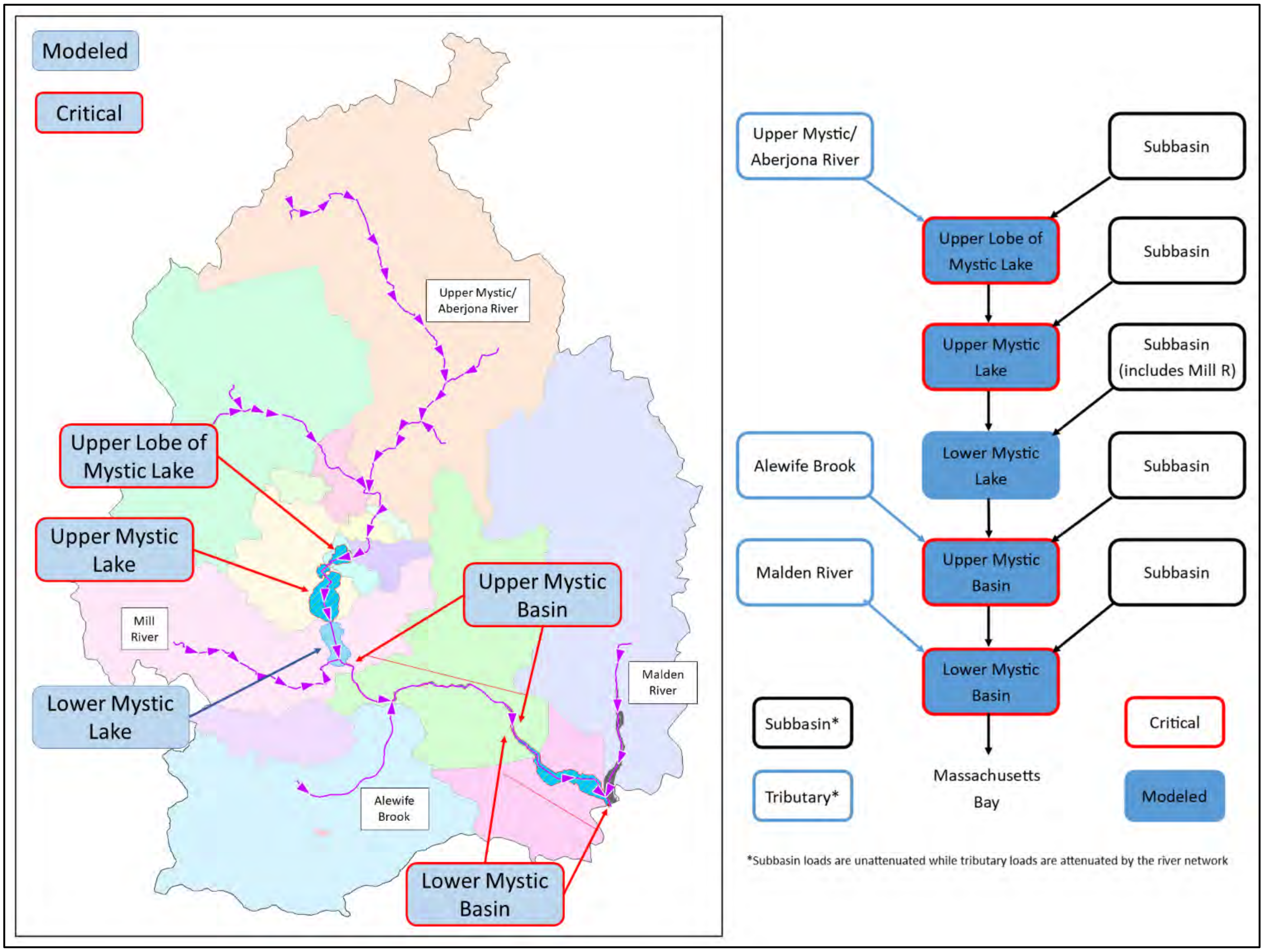



**Figure V-II. Mystic River Watershed Sub-Basin Delineation and Schematic Diagram for Final Model**

### *V.B. Groundwater Loads*

Groundwater loads to the river system are those that result from water that infiltrates through the soil and moves via groundwater flow through the underlying aquifer. In general, phosphorus movement is retarded through soils and aquifers by years or decades because it is highly adsorbed by clay particles in either media.

Groundwater flow was estimated by analysis of available streamflow records and separating these components into stormflow and baseflow (e.g., USGS, 1996; Arnold and Allen, 1999, Arnold, et al., 2005). Baseflow approximates groundwater flow assuming that the riparian evapotranspiration is minimal.

Streamflow data suitable for estimating stormflow and baseflow components is available at the Aberjona River and Alewife Brook USGS gages (Figure V-III). Using the Soil & Water Assessment Tool (SWAT) Baseflow (Bflow) program, baseflow was estimated at both locations and annual baseflow / total streamflow fractions were computed (Appendix F). Figure V-III and Figure V-IV display baseflow and total streamflow for the Aberjona River and Alewife Brook for 2016.

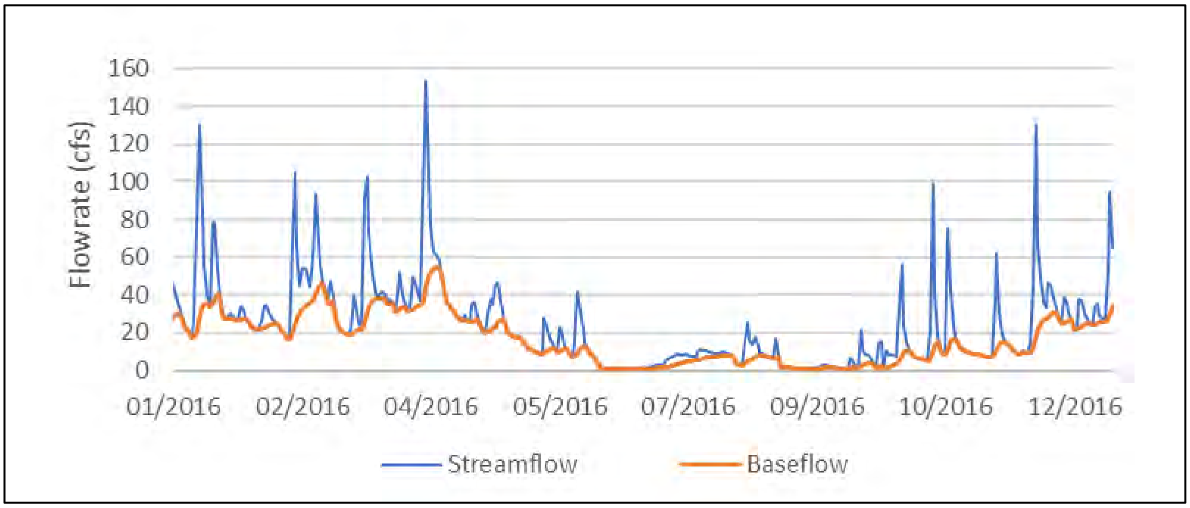



**Figure V-III. Baseflow Estimates and Streamflow Measurements at Aberjona River for 2016 (USGS Gage 01102500)**

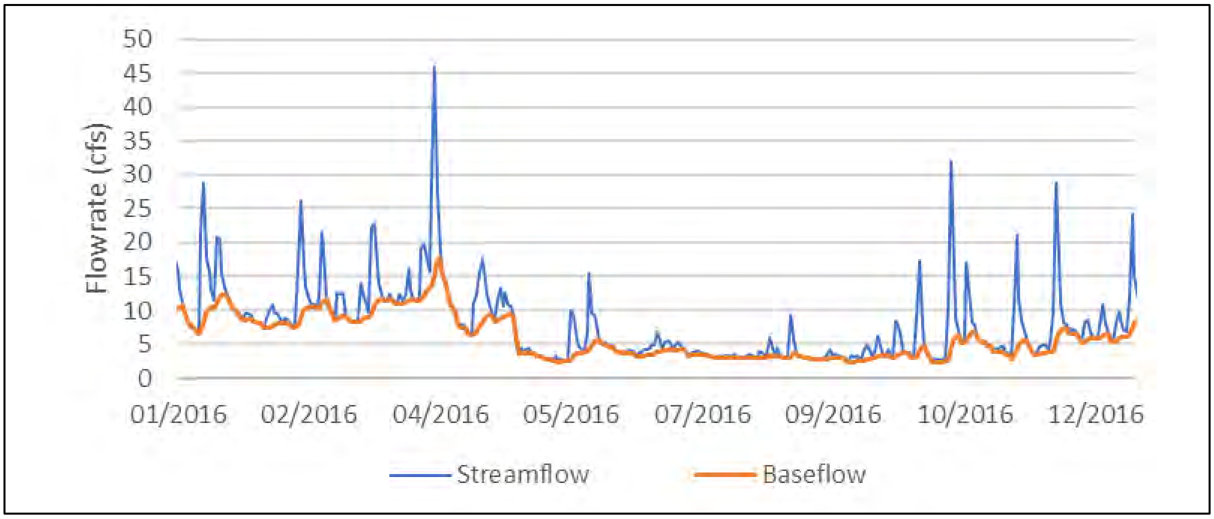



**Figure V-IV. Baseflow Estimates and Streamflow Measurements at Alewife Brook for 2016 (USGS Gage 01103025)**

From 1992 – 2017 in the Aberjona River, the average annual baseflow contribution to total streamflow was approximately 65 percent. From 2006 – 2016, the average in Alewife Brook was approximately 70 percent. For each HRU in these basins, baseflow is assumed to be an equivalent fraction. For HRU's not in either basin, an average (68 percent) of the two estimated values were applied. Annual groundwater flow contributions were computed for each HRU using the following equation:

Groundwater Flow = (f x Stormwater Flow) / (1 – f)

Where "Stormwater Flow" was the HRU rainfall-runoff total estimated using the Opti-Tool model and f is the groundwater fraction of total streamflow.

Groundwater phosphorus concentration can be estimated from well sampling data; however, such data is unavailable. It is difficult to estimate different groundwater concentrations for each HRU without a well sampling effort devoted to that end. A well sampling effort undertaken in the Boston metropolitan area found an average region TP concentration of 0.008 mg/L (Flanagan, et al., 2001). Based on this study, a groundwater TP concentration of 0.008 mg/L was assumed for all basins.

Using groundwater concentration (i.e., 0.008 mg/L) and baseflow for each sub-basin, the groundwater phosphorus load from the sub-basin was calculated as the product of the two inputs.

Estimated annual groundwater (GW) phosphorus loads and runoff volumes (1992 – 2017) for the entire Mystic River watershed were previously presented in Figure V-I. Details for the three critical water quality segments and seven impaired ponds within the watershed are presented in Appendix E.

### *V.C. Sediment Loads*

Ponds and impoundments typically act as sinks for nutrients, but they can become net sources to downstream waters when internal nutrient stores are mobilized and exported (Powers et al., 2015). In the Mystic River Watershed, there have been no direct measurements of nutrient release rates from the sediments, which represent a major data gap in this watershed.

In the Upper/Middle Charles Nutrient TMDL (EPA/DEP, 2007), which used measured nutrient release rates from sediments, EPA/DEP estimated that about 22 percent of upstream land loads were retained on net in sediments. As there have been no direct measurements of nutrient release rates from the sediments in the Mystic River Watershed, a net attenuation factor will be assumed through the watershed based on a reach detention time. The initial attenuation factor will be used as a calibration parameter (see Section VII for discussion of attenuation).

### *V.D. Observed Loads*

The estimation of observed loads was made at sites that have concurrent flows and water quality data to allow the most accurate estimation of the annual phosphorus load. These sites are the USGS gages at the Aberjona River (1939-2017), Alewife Brook (2005-2017), and Mystic River (2015-2017), which all have reliable daily flow records.

#### V.D.1. *Adjustments of Streamflow*

Data gaps on the order of several days exist in the streamflow records for the Aberjona River and for Alewife Brook. In order to develop flow estimates for missing days, a series of regression relationships were developed between the USGS sites (Figure V-V and Figure V-VI). These regressions were used to fill missing days in records at the two sites and to develop modeled estimates of daily average flow rates at the Alewife Brook and Mystic River for dates outside their respective periods of record.

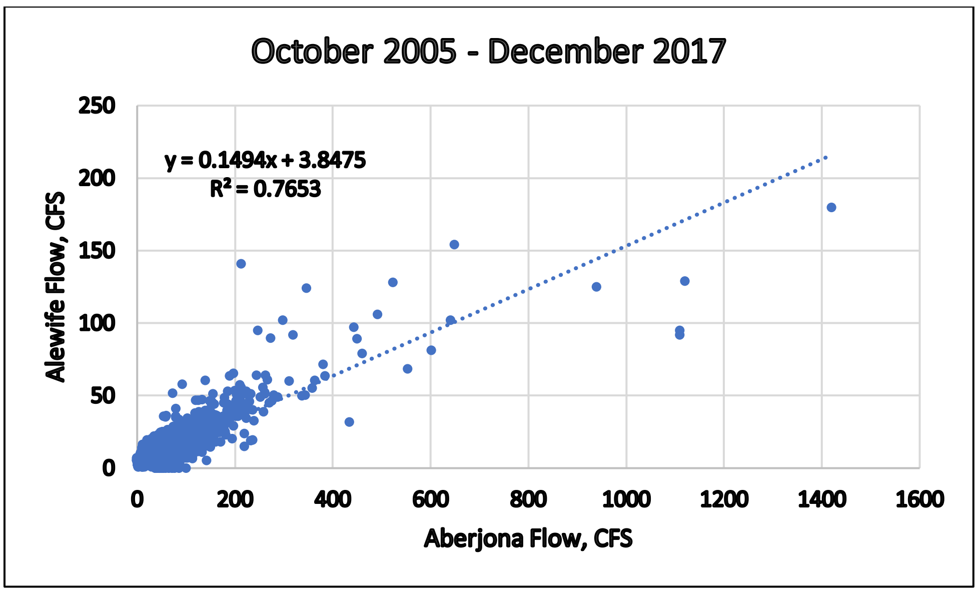



**Figure V-V. Regression of Flow Measurements at Aberjona River (01102500) and Alewife Brook (01103025) USGS Stations**

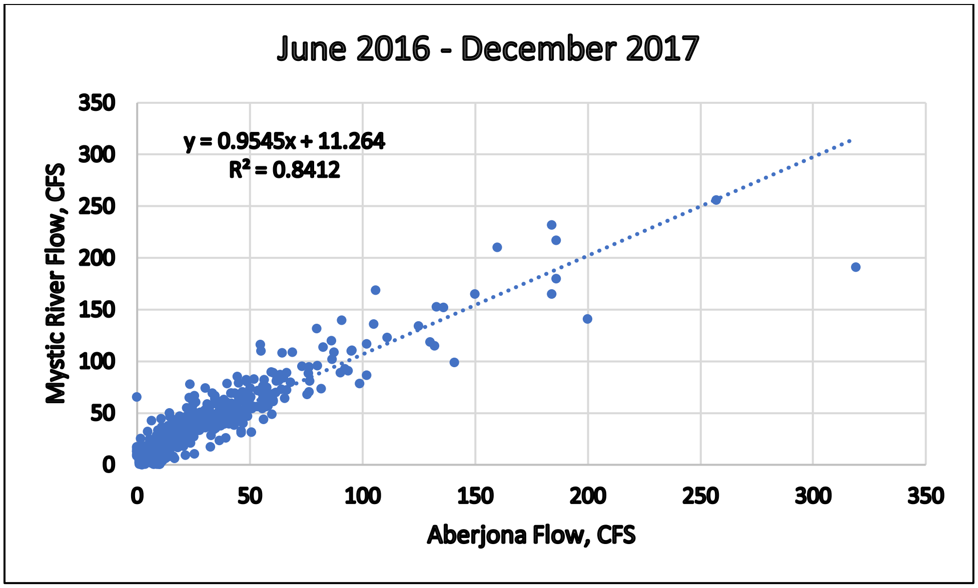



**Figure V-VI. Regression of Flow Measurements at Aberjona River (01102500) and Alewife Brook (01103025) USGS Stations**

### V.D.2. *Adjustments of Total Phosphorus Concentrations*

Differences in the TP concentrations from different laboratories for the same water body were known by MyRWA prior to commencing this study in early 2017. These differences were previously discussed in the memo "*Dataset Assessment for Development and Calibration of the Mystic River Watershed Loading and Receiving Water Quality Models*" (Walker, September 15, 2017).

The TP differences had to be reconciled prior to proceeding with the Alternative TMDL analysis. The options for reconciliation were: (1) choosing one of the two data sources as the preferred data, or (2) finding a way to convert from one source to another. Option 2 was preferred since it would allow more instances where TP and chl-a were both measured at the same site, which is a requirement for choosing a suitable model calibration period.

To reconcile the data, we went back to the original data in the memo by EPA and MyRWA entitled "*Mystic River TP Laboratory Split-Study Results and Discussion* (Hrycyna, September 7, 2017). They reported TP values measured using EPA-approved methods from the two laboratories: MWRA Deer Island (MWRA) and EPA Region 1 in Chelmsford (EPA). TP results for side-by-side field samples in the Mystic River Watershed were systematically higher at MWRA (Method 365.4) than EPA (Method 365.1). Consultation with other laboratory experts in water quality analysis led to the conclusion that the differences between labs for field samples is a result of better conversion/digestion of TP to orthophosphate for Method 365.4 versus 365.1. Because Method 365.1 was considered to be have an incomplete conversion to orthophosphate, it is likely an underestimate of TP.

For this study, Method 365.4 was considered to be "true" value of TP. Although there were some seasonal differences between April and December in the relationship between the two methods, we opted to use a single equation for all the data (see Figure V-VII). This approach results in a lower slope than Walker's (2017) equation because only the April data were available for that analysis. The final equation to convert TP data using Method 365.1 to Method 365.4 was:

$$Y = 1.15\ X + 21.7$$

where:

Y = MWRA TP concentrations using method 365.4
X = EPA TP concentrations using method 365.1

Biweekly and monthly sampling of phosphorus data at the Aberjona River Mystic River Watershed Association (MyRWA) monitoring site (ABR006), Mystic River site (MYR071), and Alewife Brook (ALB003, ALB006) were linearly interpolated on a daily basis in order to produce an estimated daily time series of TP concentrations (Figure V-VII through Figure V-X).

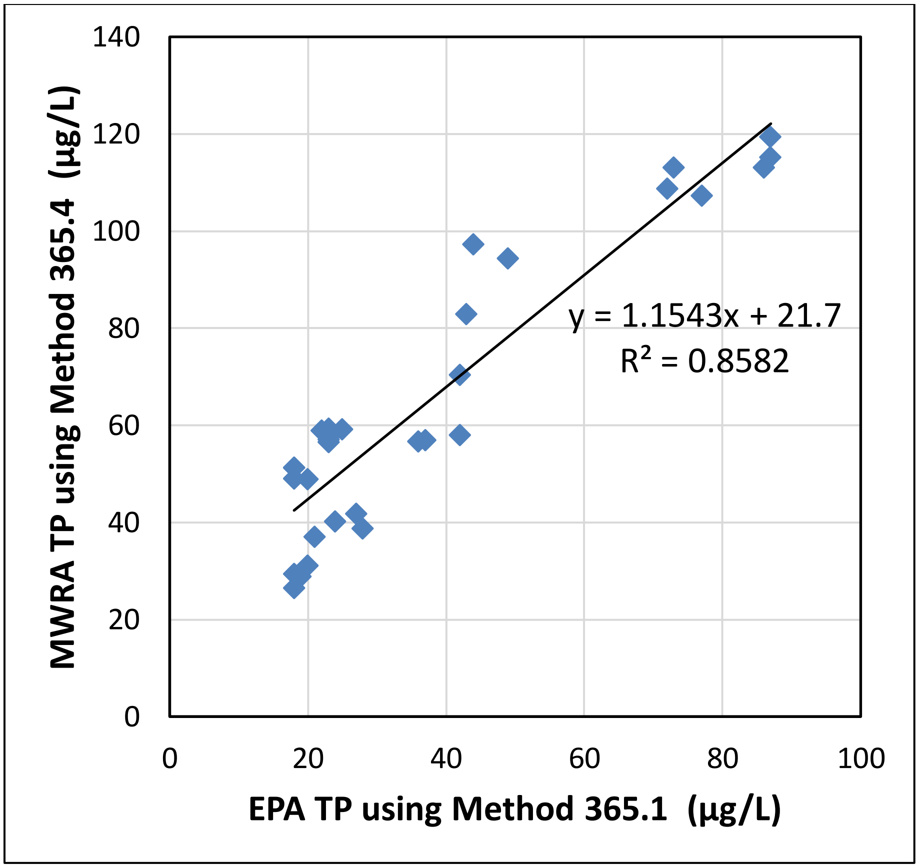



**Figure V-VII. Correction of TP Values from Method 365.1 to 365.4**

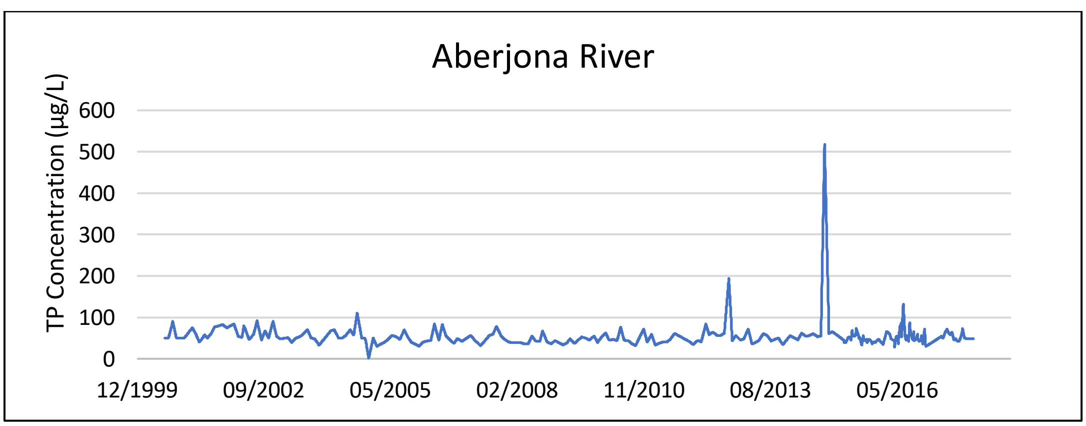



**Figure V-VIII. Adjusted Total Phosphorus Concentrations in the Aberjona River**

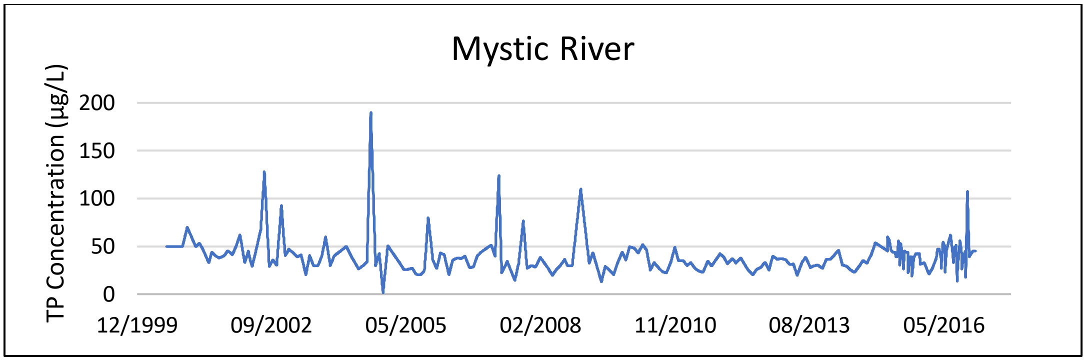



**Figure V-IX. Adjusted Total Phosphorus Concentrations in the Mystic River**

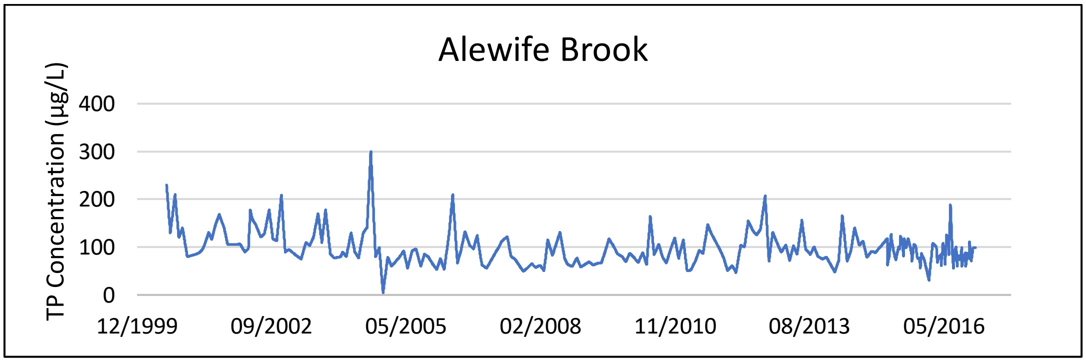



**Figure V-X. Adjusted Total Phosphorus Concentrations in Alewife Brook.**

### V.D.3. *Observed Total Phosphorus Loads*

Observed loads for TP were calculated for the river reaches where USGS flow gages and measurements of nutrient concentrations coincide. The measured TP sites and flow measurements were both available at USGS flow gages, namely, the Aberjona River (USGS 1102500, ABR006), Lower Mystic Lake (USGS 1103010, MYR071), and Alewife Brook (USGS 1103025, ALB003/ALB006) gages. At each of the three gages, estimates of concurrent streamflow and total phosphorus concentration were used to calculate the daily total phosphorus load (daily flow x daily concentration) and was summed to give a time series of annual loads.

### V.D.4. *Calibrated Streamflow*

A comparison of land-based and observed flows was performed for the two-gauge sites that have long-term flow data (Aberjona River, Alewife Brook). The analysis of 1992-2017 daily flow data revealed a close match to the observed average flow at Aberjona River but an underestimate of observed average flow at Alewife Brook. The average observed flow at Aberjona River was reasonable (21.3 in/yr.) since it compares well with typical flows for eastern Massachusetts rivers (20-25 in/yr.). In contrast, the average observed flow at Alewife Brook was very low (15.3 in/yr.). We have no explanation for this apparent low average flow at Alewife Brook but decided not to use it. Comparison of average annual streamflows from land-based estimates and observed values at the Aberjona River gauge were reasonable ($R^2$=0.72) with no visible bias. Given the uncertainty of the Alewife Brook flow data and the decent fit of modeled land-based loads with observed flows for the Aberjona gauge, we decided not to calibrate streamflow for this study.

### V.D.5. *Calibrated Total Phosphorus Loads*

Observed loads within a reach are often less than the land loads because there has been some attenuation (or retention) of nutrients within the river system. Attenuation of nutrients in river reaches occurs because of biological and chemical changes, plant uptake, particulate settling, and organic settling from algae or aquatic plant senescence. Higher residence time, or detention time, usually means more nutrient attenuation occurs.

Estimation of attenuated land loads was performed for the period 2007-2016 since this is the modeling period (see Section VII.C.3). Attenuated cumulative TP loads for each reach were initially determined from the modeled land values by using an estimate of instream attenuation factors based on reach detention time (volume/flow, days). These estimates were calibrated to match observed reach loads (see below).

A review of the literature on phosphorus attenuation in impoundments revealed two similar curves; Figure 7 of Powers et al. (2015) and Figure 4 of Kõiv et al. (2011). Both of these curves are shown in Figure V-XI. The equation derived from the Powers et al. (2015) data, which indicates slightly higher attenuation rates than Kõiv et al. (2011) was chosen for the Mystic watershed because the calibration process indicated that high attenuation factors were needed. The Powers equation for the attenuation factor is:

$$\text{Attenuation Factor} = 0.5598 + 0.1278 * \log_e (Rd/365),\ Rd = \text{detention time (days)}$$

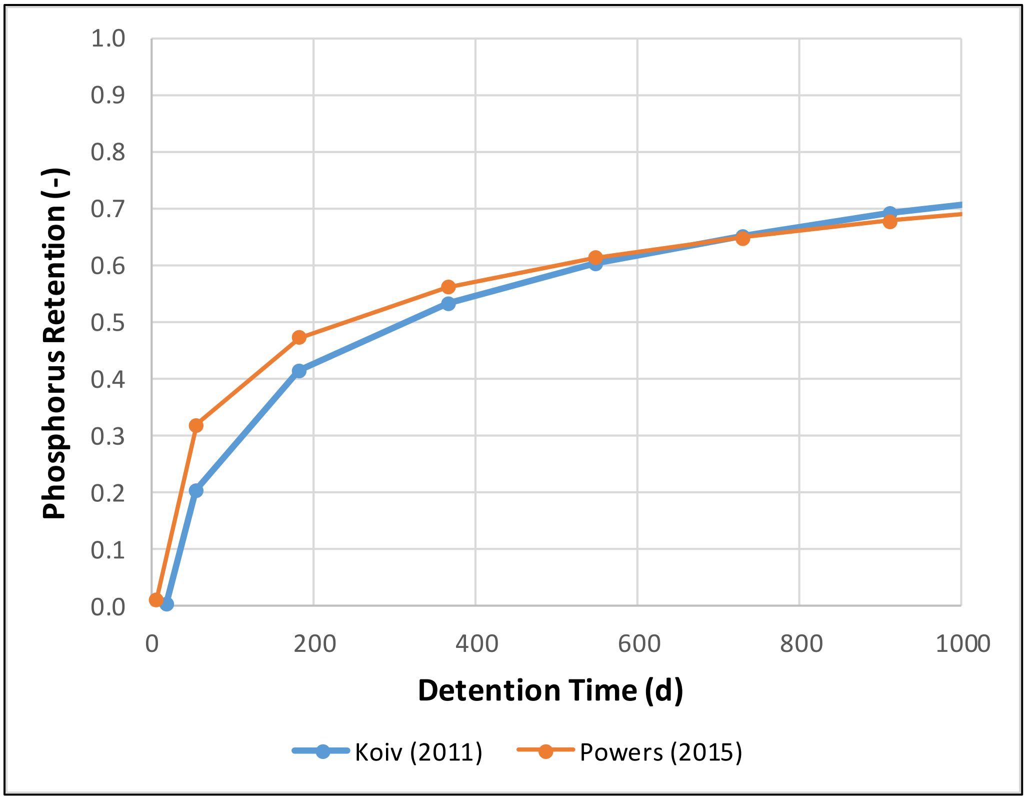



**Figure V-XI. Phosphorus Attenuation Curves**

Detention time (days) was computed from the estimated reach volume ($m^3$) and the modeled annual flow rate ($m^3/d$). Impoundment volumes were estimated from various pond studies (WH, 1987, 1988; DFW, no date; ENSR, 2000; DEP, 2010; and EPA, 2018). For river reaches (i.e. not pond reaches) that did not have information to compute an attenuation factor, the value was set to a nominal value of 0.05 (see Table VII-4).

Predicted TP land loads were calibrated to measured loads at three calibration sites (Aberjona, Lower Mystic, and Alewife USGS gauges) by changing the reach attenuation factors. The calibration objective was to minimize the error between observed and attenuated TP loads as closely as possible at the three sites while still maintaining reasonable attenuation coefficients (0.05 to 0.9) that were also reasonably close to the initial estimates. The process was conducted sequentially down the watershed, starting at the most upstream calibration point first. All initial attenuation factors above this point were adjusted by the same factor to best match the observed data.  This process was repeated downstream. Attenuation in all the reaches contributing to Alewife Brook was increased further to meet the observed load for that calibration site.

With this process, the investigators were able to reduce the error in the annual average loads to zero at the three sites and still have reasonable attenuation factors, although the ones in the Alewife Brook watershed seem a little high, possibly because the flow at this gauge is unreasonably low (see Section V.D.1X). The error at all sites except the three gauges is unknown because there were no TP load estimates at these other sites. The estimated and final attenuation factors for TP are given in Table V-6 and a comparison of modeled land versus attenuated sub-basin loads is given in Figure V-XII. There might also be some monthly error at the two-gauge sites, but this is not relevant to the receiving water model which is based on annual load inputs.

## Table V-6. Estimated Reach Detention Times and Attenuation Factors

| Reach Name | Reach Volume ($m^3$) | Cumulative Reach Flow ($m^3$/yr.)[1] | Detention Time (d) | Estimated Attenuation Factor (-) | Final TP Attenuation Factor (-) |
|---|---|---|---|---|---|
| Winter Pond | 58,768 | 254,236 | 84 | 0.37 | 0.70 |
| Horn Pond | 2,951,250 | 10,898,619 | 99 | 0.39 | 0.85 |
| Wedge Pond | 277,555 | 11,968,307 | 8 | 0.08 | 0.20 |
| Judkins Pond | 9,065 | 37,176,274 | 0 | 0.05 | 0.05 |
| Mill Pond | 6,475 | 37,395,435 | 0 | 0.05 | 0.05 |
| Aberjona River 1 | - | 37,704,020 | - | 0.05 | 0.05 |
| **Calibration Site is USGS Streamflow Gauge at Aberjona River (1102500)** | | | | | |
| Aberjona River 2 | - | 38,177,963 | - | 0.05 | 0.05 |
| Upper Lobe | 219,434 | 38,368,707 | 2 | 0.05 | 0.05 |
| Upper Mystic Lake | 7,385,437 | 40,449,476 | 67 | 0.34 | 0.26 |
| Lower Mystic Lake | 3,529,612 | 49,102,911 | 26 | 0.22 | 0.19 |
| **Calibration Site is USGS Streamflow Gauge at Lower Mystic Lake (1103010)** | | | | | |
| Blacks Nook Pond | 15,110 | 5,969 | 924 | 0.68 | 0.90 |
| Spy Pond | 1,690,000 | 2,110,121 | 292 | 0.53 | 0.80 |
| Alewife Brook | - | 17,560,488 | - | 0.05 | 0.48 |
| **Calibration Site is USGS Streamflow Gauge at Alewife Brook (1103025)** | | | | | |

[1] From land loading model

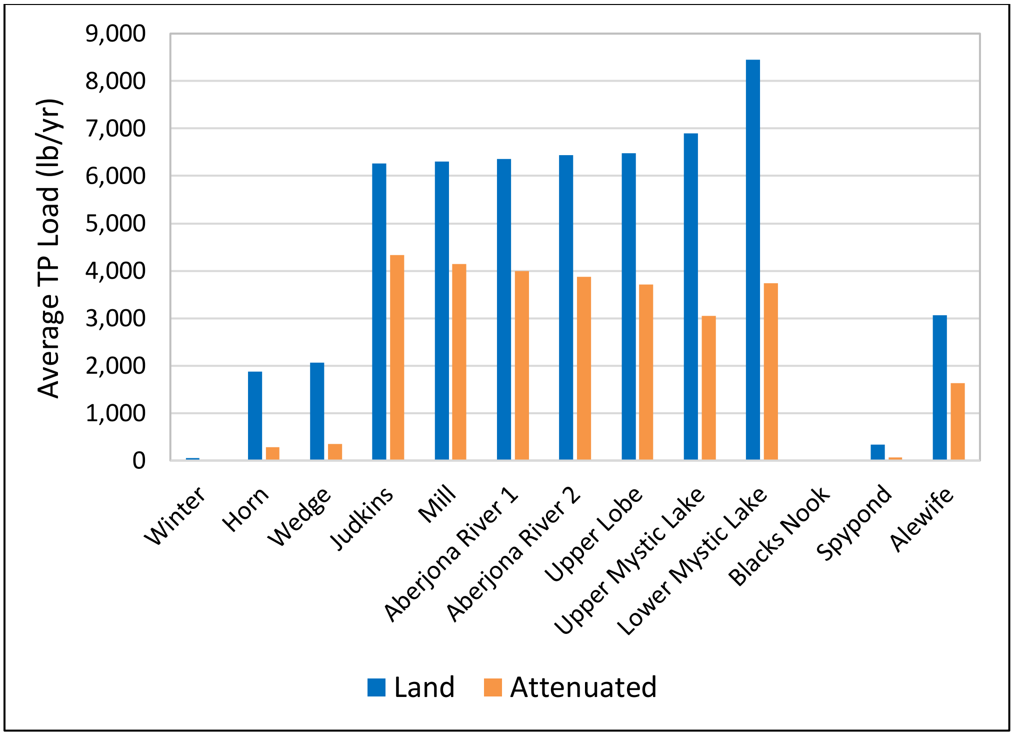



**Figure V-XII. Modeled Land vs. Attenuated Reach Phosphorus Loads (2007-2016)**

# VI. Evaluation of Combined Sewer Overflow and Sanitary Sewer Overflow Data for the Mystic River Watershed

The following describes the data types, sources and approaches used to develop estimates of CSO and SSO volumes and phosphorous loads in the Mystic River Watershed. CSO and SSO data were quantified in an effort to provide a more accurate estimate of all loads entering the waterbodies within the watershed. The land loads provided in Section V will be added to the CSO and SSO loads and modeled in Section VII. As discussed in Section V, annual loads are the expected input for the receiving water models; therefore, load estimates have been developed on an annual basis.

## *VI.A. Data Types and Sources*

Four primary data types were required to evaluate CSO and SSO contributions:

- Spatial data (CSO and SSO drainage areas).
- Volumetric data (annual CSO and SSO discharge volumes).
- Annual precipitation data.
- CSO and SSO discharge concentrations for total phosphorus and total nitrogen.

The CSO and SSO data used for this analysis included GIS data, Excel spreadsheets, reports and literature. The sources of these data are noted in the sections below.

### VI.A.1. *Spatial Data*

There are two sub watersheds in the Mystic River Watershed that contain CSO drainage areas: Alewife Brook and Mystic River. The outfalls included in these analyses are (location in parenthesis):

- Alewife Brook: CAM001 (Cambridge), CAM002 (Cambridge), MWR003 (Cambridge), CAM004 (Cambridge), CAM400 (Cambridge), CAM401A (Cambridge), CAM401B (Cambridge), SOM001A (Somerville).
- Mystic River: SOM007A/MWR205A (Somerville). MWR205 (Somerville), which is located downstream of the Amelia Earhart dam, was evaluated to compare total discharges from the Somerville Marginal CSO Facility.

The MWRA CSO map is presented in Appendix G (Figure G-XI-1). The data collected for the CSO drainage basins included a GIS polygon file provided by the City of Cambridge showing areas contributing to Alewife Brook with a corresponding attribute table noting the year those areas were separated. Maps showing the City of Cambridge's CSO drainage basins from 2000 and 2017 are presented in Appendix G (Figure G-XI-2 and Figure G-XI-3). Additional GIS data on CSO drainage areas were provided by the City of Somerville in Appendix G (Figure G-XI-4). Portions of Somerville's CSO drainage areas discharge to Alewife Brook while others discharge to the lower Mystic River directly, depending on the size of the storm event (see attached map).

There were no GIS data available for SSO drainage areas. A spreadsheet from the Massachusetts Water Resources Authority (MWRA) provided estimated volumetric discharge data and latitude and longitude for each SSO. Those locations were converted into a GIS point shapefile that was overlaid onto the Mystic River sub watersheds to assign SSOs volumes to their recipient sub watersheds.

### VI.A.2. *Volumetric Data*

The data sources for volumetric data gathered are shown in Table VI-1.

**Table VI-1. Volumetric Data Sources for CSOs and SSOs**

| Data Type | Source | Years | Data Comments |
|---|---|---|---|
| CSO data | MWRA | 2000 to 2017 | Modeled data; from Annual Reporting |
| | City of Cambridge | 2006 to 2017 | Annual NPDES Reports |
| | City of Somerville | 2016 | Annual NPDES Report |
| SSO data | MWRA | 2000 to 2017 | Data from MWRA directly; no SSOs for 2016 or 2017. Includes latitudinal/longitudinal information. |
| | Massachusetts Department of Environmental Protection (MassDEP) | 2000 to 2017 | Data between 2000-2016 received from Mystic River Watershed Association; spreadsheet format. No spatial data provided. Data includes all known discharges within the Mystic River Watershed (including MWRA data). 2017 data were digitized from forms provided by MassDEP for this project. |

The data were reviewed to determine completeness (e.g., data gaps, including missing values or no data) and for consistency (e.g., extreme data). For CSOs, data provided by the cities were also cross checked with the MWRA data. In the annual CSO reports, modeled CSO activation durations and volumes were compared to the reported CSO activations. In some instances, the reported data were not consistent with the modeled data (model was either over or under predicting), which appeared to be due to either the modeling of the CSO system/outfall or the resolution of the metered data versus modeled data. Based on the annual reports, improvements to the model appeared to have been made over time to address some of these issues.

For SSOs, MWRA and MassDEP noted that the reporting of SSO volumes was updated in 2012. Prior to 2012 the form only included SSO volume ranges, which generally were: <10,000 gallons, 10,000 to 100,000 gallons, 100,000 gallons to 1,000,000 gallons and > 1,000,000 gallons, limiting the upper limit of reported SSO volumes. Starting in 2012, the form was updated to allow an estimate of SSO volume and method for estimating.

### VI.A.3. *Precipitation Data*

Hourly precipitation data for Boston Logan International Airport was extracted from the Opti-Tool model for 1992 to 2016. Additional hourly data for 2017 was downloaded from NOAA's website (NOAA, 2018).

### VI.A.4. *Nutrient Concentrations*

Nutrient concentrations for CSO and SSO discharges were estimated to facilitate the calculation of annual phosphorus and nitrogen loads. TP and total nitrogen (TN) concentrations for CSOs were based on data from Breault et. al. (2012). The document reported average CSO TP and TN concentrations of 3.1 mg/L and 9.3 mg/L, respectively, for samples collected by MWRA. SSO TP and TN concentrations were based on the average annual influent wastewater concentrations for 2016 sampled at the Deer Island Sewage Treatment Plant of 5.23 mg/L and 41.8 mg/L, respectively.[6] The analysis used in this memorandum assumes that that SSOs discharges have similar concentrations to untreated wastewater.

## VI.B. CSO Data Analyses

After discussions with MWRA and EPA Region 1, the MWRA CSO data were further analyzed to evaluate how precipitation and time influenced the CSO data and how average CSO volumes compared to the annual data. Two data analyses were performed on the datasets: regression analyses and evaluation of statistical outliers. The purpose was to determine if the average annual CSO volume for the evaluation of phosphorus load reduction estimates (Section IX) was appropriate and/or if modifications to the annual CSO volumes would allow a more representative average. In particular the analysis focused on years where no CSOs were reported (modeled discharge estimates noted as '0') and CSO data extremes.

### VI.B.1. *CSO Analyses*

CSO volumetric data were plotted against time and annual precipitation depth to evaluate potential relationships. The volumetric data were also normalized by acreage of CSO drainage basins contributing to the CSO outfalls. Figure VI-I through Figure VI-IV represent these comparisons. There were significant linear relationships with time (years) and annual rainfall for the Alewife CSO drainage basin (p-value < 0.05). There were no similar significant relationships for the Mystic River CSO drainage basin, which might be due to the complex connection of Somerville's CSO system to Alewife Brook, the Mystic River, and other sewer systems.

### VI.B.2. *CSO Statistical Outliers*

A statistical analysis was conducted on each of the CSO datasets to determine if there were any outliers that could be having excessive influence on the volumetric averages. This process first involved defining the upper bounds of the annual volumetric data to identify the outliers using the following two equations:

$$\text{Upper Bound: } Q3 + (1.5 * IQR)$$

where Q3 is the third quartile value and IQR is the interquartile range or the difference between the first and third quartiles (Q1 and Q3). Outliers were defined as values higher than the upper bound. The results are presented in Table VI-2. The mean of the datasets was also calculated.

[6] SSO TP and TN concentrations were based on MWRA's North System influent only, which includes communities in the Mystic Watershed.

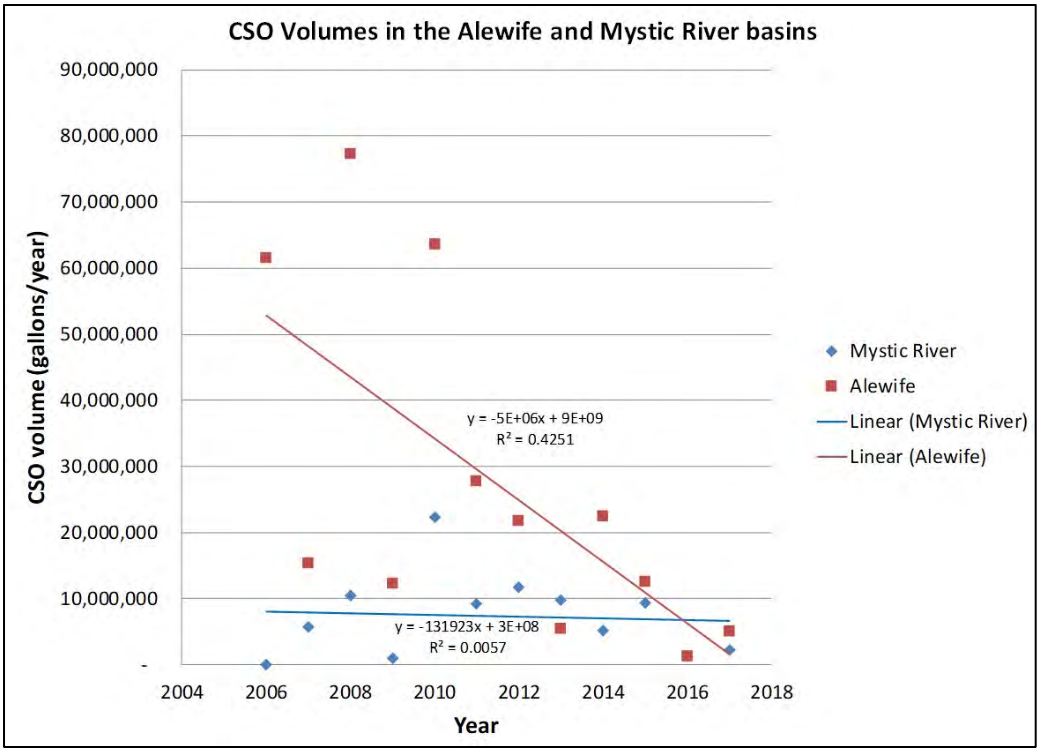



**Figure VI-I. Annual CSO Volumes over Time**

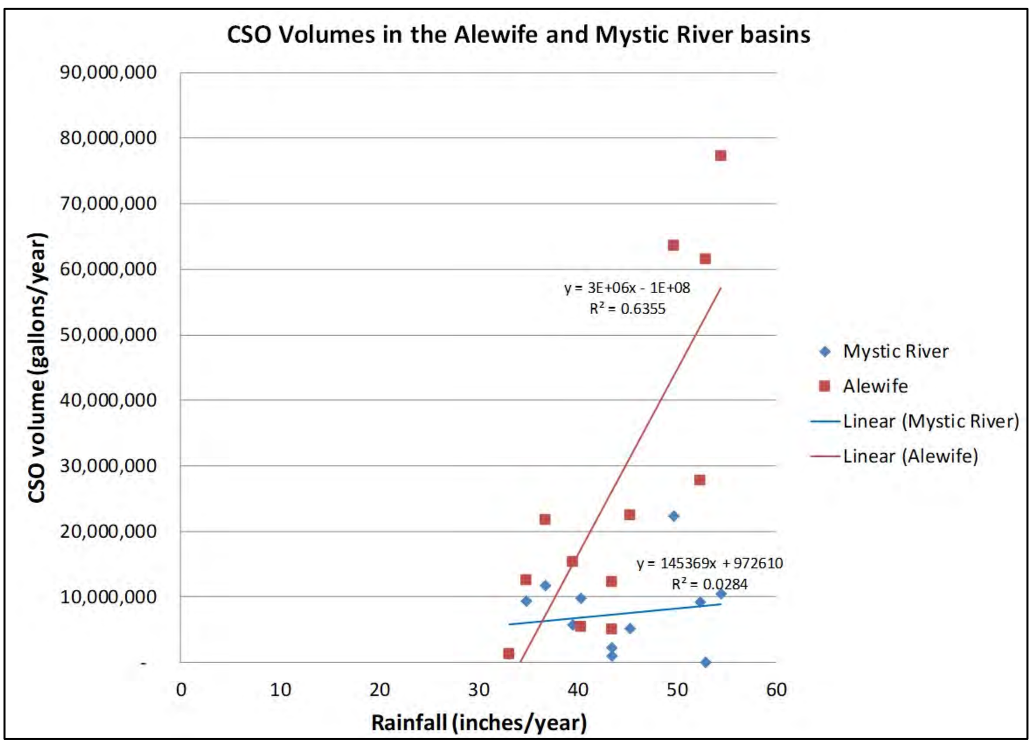



**Figure VI-II. Annual CSO Volumes versus Annual Rainfall**

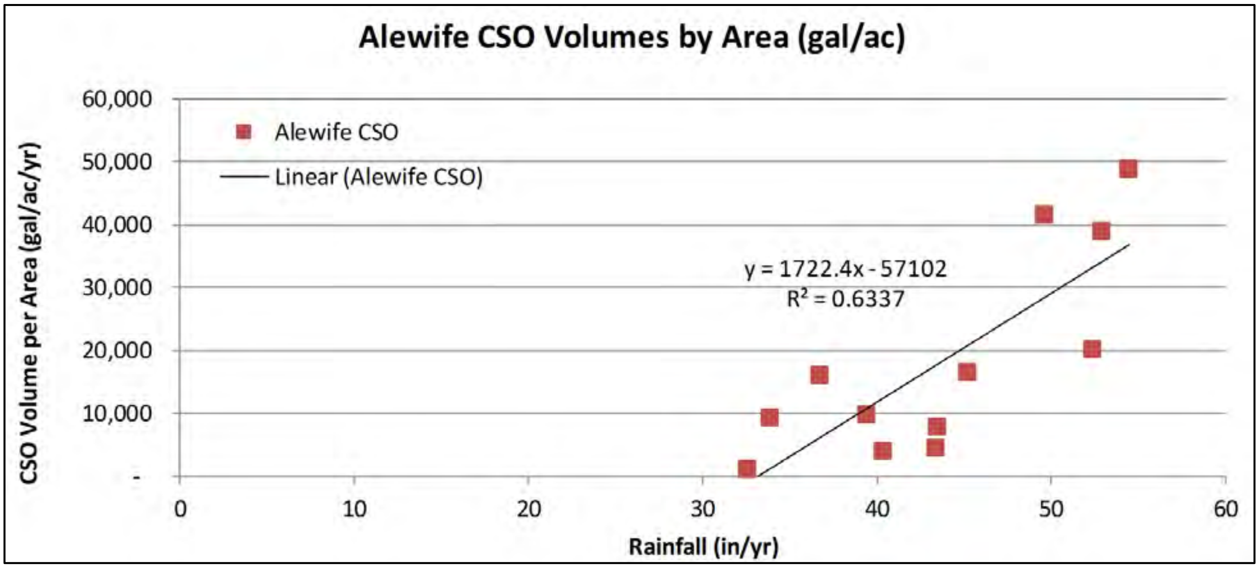



**Figure VI-III. Normalized Alewife Annual CSO Volumes versus Annual Precipitation**

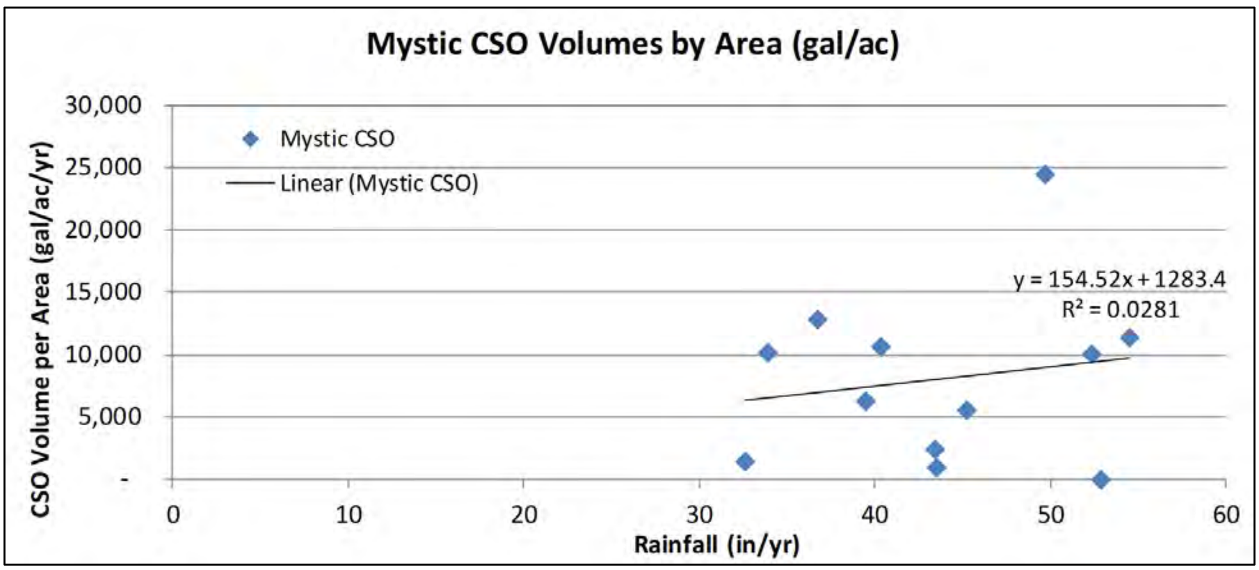



**Figure VI-IV. Normalized Mystic Annual CSO Volumes versus Annual Precipitation**

### Table VI-2. Statistical Outlier Analysis for CSO Datasets

| Statistical Data Type | Alewife CSO Volumes (gal) | Mystic River CSO Volumes (gal) |
|---|---|---|
| ***First Quartile (Q1)*** | 10,590,000 | 3,660,000 |
| ***Third Quartile (Q3)*** | 36,220,000 | 10,085,000 |
| ***Interquartile Range (IQR)*** | 25,630,000 | 6,425,000 |
| ***Upper Bound*** | 74,665,000 | 19,722,500 |
| ***Mean (all data)*** | 27,208,333 | 8,013,636 |
| ***Mean (without outliers)*** | 22,656,364 | 6,580,000 |

Two data points were identified as outliers: CSO volumes from 2010 in the Mystic River Drainage Basin and 2008 in the Alewife Drainage Basin. However, the volumetric mean was not modified because data points were within 10 percent of the upper bound, so was not considered to have undue influence on the volumetric mean. The CSO volumes from 2006 were not available for the Mystic River and was replaced with the mean using all data to complete the dataset from 2006 to 2017. The final datasets are provided in Table VI-3.

### Table VI-3. CSO Volumetric Datasets for Alewife and Mystic River Drainage Basins

| Year | Alewife CSO Volumes (gal) | Mystic River CSO Volumes (gal) |
|---|---|---|
| **2006** | 61,540,000 | 8,013,636[a] |
| **2007** | 15,320,000 | 5,750,000 |
| **2008** | 77,280,000 | 10,420,000 |
| **2009** | 12,310,000 | 920,000 |
| **2010** | 63,590,000 | 22,350,000 |
| **2011** | 27,780,000 | 9,240,000 |
| **2012** | 21,830,000 | 11,760,000 |
| **2013** | 5,430,000 | 9,750,000 |
| **2014** | 22,450,000 | 5,120,000 |
| **2015** | 12,620,000 | 9,360,000 |
| **2016** | 1,300,000 | 1,280,000 |
| **2017** | 5,050,000 | 2,200,000 |

a) CSO volume was not available. CSO volume replaced with mean value of all data (2006-2017).

## *VI.C. SSO Data Analyses*

The SSO data were first reviewed and summarized to characterize the raw data, including discharge frequency and duration, discharge locations and volumes. Then the data were processed to be able to assign SSO volumes by sub watershed for further evaluation. Finally, similar to CSO data, SSO data analyses were completed to understand how precipitation and time influenced the annual volumes and how average SSO volumes compared to annual data. The purpose of the analyses was to determine if the average annual SSO volume for the evaluation of phosphorus load reduction estimates (Section IX) was appropriate and/or if modifications to the annual SSO volumes would allow a more representative average.

### VI.C.1. *SSO Data Review*

A more in-depth review of the data entries was completed to understand the frequency and duration of SSOs, their discharge points and the magnitude of the reported volumes. The data are summarized below in Table VI-4 and

Table VI-5.

Overall, of the 774 total SSOs reported during the period of available data, only a small percentage of them were identified as discharging to a catch basin or directly to a waterbody (60 in all, 8% of total) despite the large number of them being a result of a rain event (528 in all, 68% of total). The locations, durations and volumes ranged significantly, which suggests that SSO discharges are dependent on the type and location of event (i.e., there is not a singular threshold event which will result in SSO discharges in all sub watersheds). For example, note that both 2010 and 2014 appear as years with much more frequent SSOs, accounting for approximately 68% and 8%, respectively, of the total discharges over the period from 2006 to 2017.

Further discussions with MWRA and MassDEP on the SSO data indicate that there can be variability in the data reporting. Data varies in the way that durations are reported (e.g., what is identified as the 'start' of the SSO event may be assumed or may be at the time it is 'found'), volumes are calculated (e.g., some locations are monitored, others are estimated), and number of SSOs identified (e.g., only 'found' SSOs are reported, may be others not being reported). Therefore, while the data is representative, it may not be consistent or accurate in all cases.

**Table VI-4. Review of SSO Data – Frequency, Duration and Discharge Points**

| Year | Total Number of SSOs reported | Average duration of SSOs (hrs.) | Min/Max Duration of SSOs (hrs.) | Community with Highest SSOs Reported/# of SSOs | Number of SSOs Directly Discharging to a Catch Basin | Number Directly Discharging to a Waterbody |
|---|---|---|---|---|---|---|
| 2006 | 24 | N/A | N/A | Arlington (6)/Winchester (6) | – | – |
| 2007 | 21 | N/A | N/A | MWRA (15) | – | – |
| 2008 | 24 | N/A | N/A | MWRA (15) | – | – |
| 2009 | 11 | N/A | N/A | MWRA (2)/Lexington (2) | – | – |
| 2010 | 524 | N/A | N/A | MWRA (107) | – | – |
| 2011 | 22 | N/A | N/A | N/A | – | – |
| 2012 | 26 | N/A | N/A | MWRA (4) | – | – |
| 2013 | 25 | 4.3 | 0.3/22 | Wakefield (10) | 3 | 1 |
| 2014 | 65 | 9.6 | 0.3/52 | Medford (29) | 7 | 43 |
| 2015 | 10 | 8.9 | 0.2/72.8 | Lexington (2) | – | 2 |
| 2016 | 8 | 14.5 | 0.5/66.5 | Burlington (3) | 1 | 3 |
| 2017 | 14 | 7.1 | 0/71.8 | Cambridge (5) | – | – |
| *Totals* | *774* | – | – | – | *11* | *49* |

**Table VI-5. Review of SSO Data – Volumes**

| Year | Total Number of SSOs reported | Number of SSOs as a result of a rain event | Number of entries where SSO volume was estimated | Average reported SSO volume (MG) | Minimum Reported SSO volume (gal) | Maximum Reported SSO Volume (MG) |
|---|---|---|---|---|---|---|
| 2006 | 24 | 17 | 18 | 2.10 | 10,000 | 26.9 |
| 2007 | 21 | 17 | 19 | 0.20 | 50 | 1 |
| 2008 | 24 | 20 | 20 | 0.30 | 1,000 | 1 |
| 2009 | 11 | 2 | 9 | 0.07 | 4,000 | 0.6 |
| 2010 | 524 | 404 | 303 | 0.30 | 3.5 | 9 |
| 2011 | 22 | 11 | 20 | 0.30 | 2 | 2.6 |
| 2012 | 26 | 1 | 22 | 0.20 | 10 | 1.9 |
| 2013 | 25 | 0 | 23 | 950 | 5 | < 0.1 |
| 2014 | 65 | 47 | 32 | 2.40 | 10 | 24.6 |
| 2015 | 10 | 3 | 10 | 0.01 | 10 | <0.1 |
| 2016 | 8 | 0 | 8 | <0.01 | 2 | 0.1 |
| 2017 | 14 | 6 | 11 | 0.09 | 10 | <0.1 |
| *Totals* | *774* | *528* | *495* | – | – | – |

### VI.C.2. *SSO Data Processing*

The two available SSO volumetric datasets (see Table VI-1) were merged before proceeding with the statistical analyses. The following analysis steps were used to process the MassDEP SSO data:

- Remove all MWRA data from the MassDEP datasets.
- Identify data points from the MassDEP data located in Mystic River Watershed.
- Convert volumetric ranges (see Section VI.A.2) to a single volume. For example, data identified as "<10,000 gallons" was converted to 10,000 gallons. Similarly, ">1,000,000 gallons were converted to 1,000,000 gallons. The intermittent range, "100,000 gallons to 1,000,000 gallons" was converted to a midpoint value (500,000 gallons).
- Assign SSO volumes to the sub watersheds.

In contrast to the MWRA data, the MassDEP datasets were not geospatially located, so the data were filtered and summarized by the communities in the Mystic River. A unit discharge (gallons/acre) was calculated for each community and then allocated to each sub watershed by area to estimate the total SSO volumes by sub watershed. Finally, MWRA and MassDEP SSO volumes were combined by sub watershed.

### VI.C.3. *SSO Trend Analyses*

SSO volumetric data were plotted over time and normalized by the annual rainfall data to transform the data for evaluating trends. The data are graphed in Figure VI-V and Figure VI-VI. These plots highlight the lack of observable or statistical relationships between the rainfall and SSO data in any of the sub watersheds.

### VI.C.4. *SSO Statistical Outliers*

Similar to the CSO outlier analysis presented in Section VI.B.2, an evaluation of SSO outliers was completed by comparing the dataset to upper volumetric bounds. The results are presented in Table VI-4. This evaluation identified several outliers; all sub watersheds had a statistical outlier in 2010, while other watersheds had outliers in 2006 and 2014. After reviewing the data, these outliers were removed and replaced by the upper bound value. The final datasets are provided in Table VI-5.

### VI.C.5. *SSO Missing Datasets*

Similar to the CSO datasets, missing (or no data) was evaluated to determine if the values should be replaced or not. Based on the evaluation of the trend analyses and the statistical outliers, it seemed likely that some sub watersheds with missing data may have zero annual SSO discharge. Therefore, no missing data was replaced.

### VI.C.6. *Total Phosphorus and Total Nitrogen Loads for Model Calibration*

The annual watershed phosphorus and nitrogen loading estimates were developed using the final CSO and SSO discharge volumes and the TP and TN concentrations noted in Section VI.A.4. The final TN and TP load estimates are presented in Table VI-6, Table VI-7, Table VI-8,

Table VI-9, and Table VI-10.

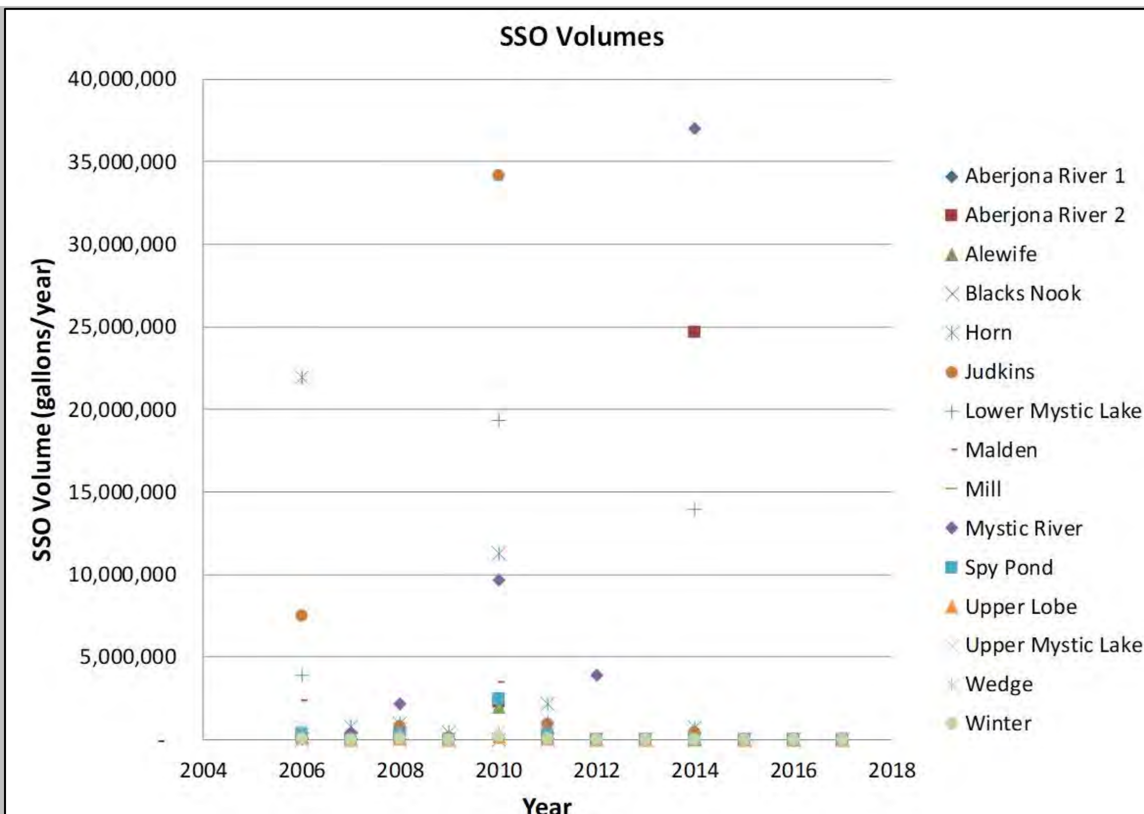



**Figure VI-V. Annual SSO Discharge Volumes by Sub-watershed versus Time**

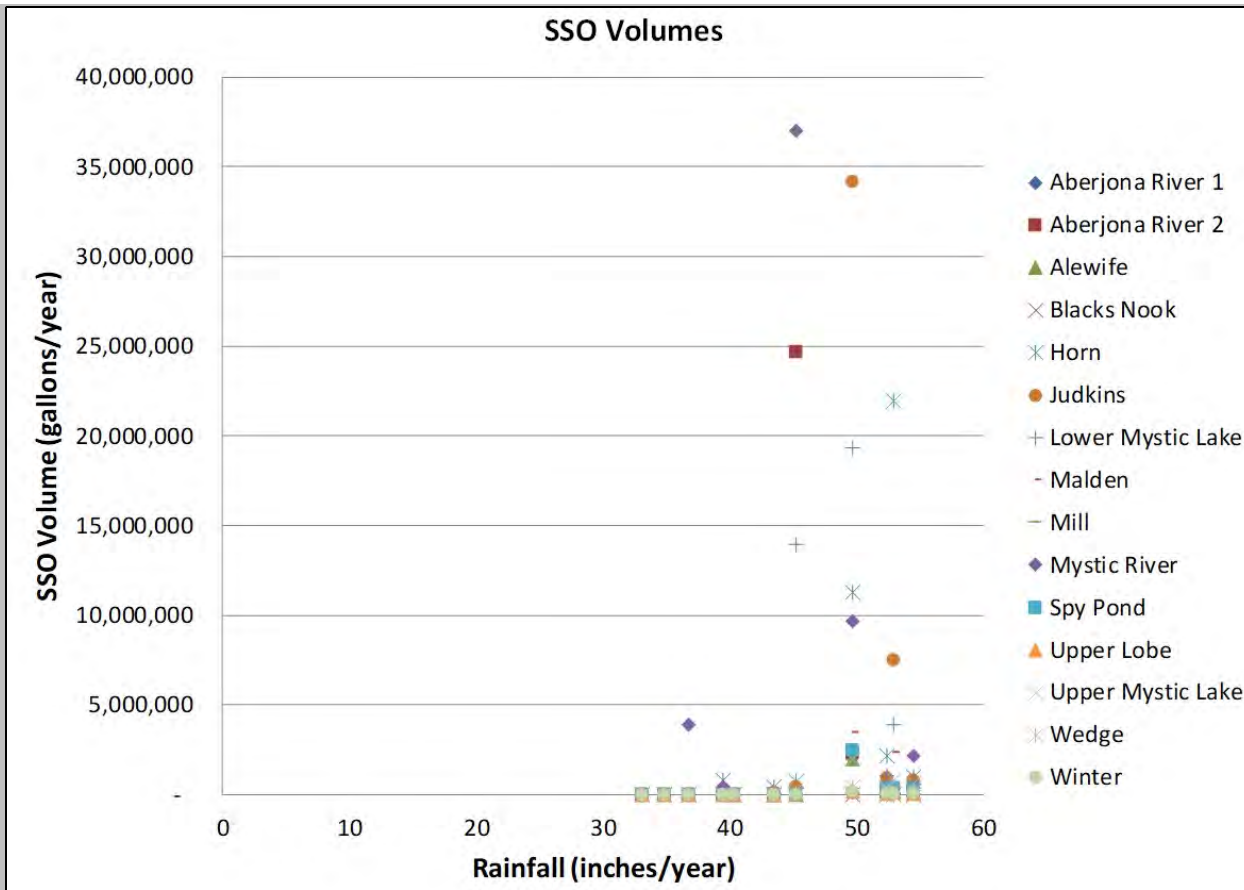



**Figure VI-VI. Annual SSO Discharge Volumes by Sub watershed versus Rainfall**

## Table VI-6. Statistical Outlier Analysis for Annual SSO Discharge Volumes (Gallons/yr.)

| Statistical Data Type | Mystic | Alewife | Aberjona River 1 | Aberjona River 2 | Blacks Nook | Horn | Judkins | Lower Mystic Lake | Malden | Mill | Spy Pond | Upper Lobe | Upper Mystic Lake | Wedge | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1st quartile (25%)* | 273 | 8,622 | 0 | 0 | 0 | 912 | 460 | 3,296 | 213 | 0 | 0 | 0 | 0 | 0 | 0 |
| *3rd quartile (75%)* | 2,591,755 | 181,440 | 46,771 | 168,117 | 75 | 1,311,220 | 847,633 | 1,764,945 | 128,257 | 25,145 | 262,014 | 56,666 | 459,882 | 114,294 | 47,818 |
| *Interquartile range* | 2,591,482 | 172,818 | 46,771 | 168,117 | 75 | 1,310,308 | 847,174 | 1,761,649 | 128,044 | 25,145 | 262,014 | 56,666 | 459,882 | 114,293 | 47,818 |
| *Upper bound (Q3+1.5*IQR)* | 6,478,979 | 440,668 | 116,927 | 420,293 | 187 | 3,276,683 | 2,118,394 | 4,407,418 | 320,324 | 62,863 | 655,035 | 141,665 | 1,149,705 | 285,733 | 119,544 |
| *Mean (all data)* | 4,454,583 | 241,727 | 31,859 | 2,290,032 | 249 | 3,205,967 | 3,687,084 | 3,252,328 | 621,826 | 17,128 | 286,506 | 38,599 | 339,345 | 83,825 | 36,425 |
| *Mean (w/o outliers)* | 1,494,411 | 67,331 | 47,810 | 84,824 | 52 | 519,601 | 261,804 | 640,451 | 50,047 | 25,704 | 189,330 | 57,925 | 301,668 | 73,825 | 31,069 |

## Table VI-7. Annual SSO Discharge Volumes for All Sub watersheds (Gallons/yr.)

| Year | Mystic | Alewife | Aberjona River 1 | Aberjona River 2 | Blacks Nook | Horn | Judkins | Lower Mystic Lake | Malden | Mill | Spy Pond | Upper Lobe | Upper Mystic Lake | Wedge | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2006** | 111,630 | 212,747 | 90,077 | 164,790 | 0 | 3,987,702 | 2,172,545 | 3,887,253 | 588,314 | 48,428 | 356,831 | 109,134 | 795,749 | 226,172 | 95,998 |
| **2007** | 462,267 | 17,056 | 0 | 45,000 | 0 | 798,129 | 256,280 | 59,757 | 450,000 | 0 | 11,752 | 0 | 4,200 | 360 | 232 |
| **2008** | 2,144,904 | 150,133 | 72,754 | 178,100 | 0 | 1,026,864 | 826,009 | 732,833 | 21,010 | 39,115 | 235,038 | 88,147 | 623,718 | 177,714 | 74,334 |
| **2009** | 363 | 9,945 | 0 | 0 | 55 | 426,822 | 131,302 | 17,436 | 18,069 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2010** | 9,701,117 | 475,150 | 138,580 | 428,612 | 219 | 3,987,702 | 2,172,545 | 6,177,132 | 588,314 | 74,504 | 722,475 | 167,899 | 1,286,235 | 338,584 | 141,642 |
| **2011** | 84,268 | 215,806 | 38,109 | 114,719 | 62 | 2,164,288 | 912,507 | 1,057,509 | 382 | 20,489 | 342,942 | 46,172 | 405,270 | 93,154 | 38,979 |
| **2012** | 3,932,309 | 33,861 | 0 | 0 | 181 | 36 | 60 | 0 | 611 | 0 | 0 | 0 | 0 | 0 | 0 |

| Year | Mystic | Alewife | Aberjona River 1 | Aberjona River 2 | Blacks Nook | Horn | Judkins | Lower Mystic Lake | Malden | Mill | Spy Pond | Upper Lobe | Upper Mystic Lake | Wedge | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2013** | 4 | 20,537 | 0 | 0 | 113 | 508 | 519 | 1 | 215 | 0 | 0 | 0 | 0 | 7 | 4 |
| **2014** | 7,596,241 | 5,573 | 34,645 | 428,612 | 3 | 764,894 | 462,123 | 6,177,132 | 9,939 | 18,626 | 85 | 41,975 | 257,041 | 84,733 | 35,467 |
| **2015** | 2 | 7,299 | 0 | 0 | 1 | 653 | 212 | 4,437 | 28 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2016** | 1 | 0 | 0 | 0 | 0 | 998 | 280 | 656 | 11 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2017** | 1,653 | 348 | 3,464 | 6,388 | 2 | 12,814 | 28,746 | 4,176 | 205 | 1,863 | 0 | 4,197 | 25,701 | 8,463 | 3,540 |

## Table VI-8. Estimated Annual Total Phosphorus and Total Nitrogen CSO Loads (lbs./yr.) for Alewife and Mystic Sub watersheds

| Year | Alewife CSO TP | Mystic River CSO TP | Alewife CSO TN | Mystic River TN |
|---|---|---|---|---|
| **2006** | 1,591.1 | 207.3 | 4,776.3 | 622.0 |
| **2007** | 396.3 | 148.8 | 1,189.0 | 446.3 |
| **2008** | 1,999.3 | 269.6 | 5,997.9 | 808.7 |
| **2009** | 318.5 | 23.8 | 955.4 | 71.4 |
| **2010** | 1,645.1 | 578.2 | 4,935.4 | 1,734.6 |
| **2011** | 718.7 | 239.0 | 2,156.1 | 717.1 |
| **2012** | 564.8 | 304.2 | 1,694.3 | 912.7 |
| **2013** | 140.5 | 252.2 | 421.4 | 756.7 |
| **2014** | 580.8 | 132.5 | 1,742.4 | 397.4 |
| **2015** | 326.5 | 242.2 | 979.5 | 726.5 |
| **2016** | 33.6 | 33.1 | 100.9 | 99.3 |
| **2017** | 130.6 | 56.9 | 391.9 | 170.7 |

## Table VI-9. Estimated Annual Total Phosphorus SSO Loads (lbs./yr.) for all Sub watersheds

| Year | Mystic | Alewife | Aberjona River 1 | Aberjona River 2 | Black s Nook | Horn | Judkins | Lower Mystic Lake | Malden | Mill | Spy Pond | Upper Lobe | Upper Mystic Lake | Wedge | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2006** | 4.9 | 9.3 | 3.9 | 7.2 | 0.0 | 174.0 | 94.8 | 169.7 | 25.7 | 2.1 | 15.6 | 4.8 | 34.7 | 9.9 | 4.2 |
| **2007** | 20.2 | 0.7 | 0.0 | 2.0 | 0.0 | 34.8 | 11.2 | 2.6 | 19.6 | 0.0 | 0.5 | 0.0 | 0.2 | 0.0 | 0.0 |
| **2008** | 93.6 | 6.6 | 3.2 | 7.8 | 0.0 | 44.8 | 36.1 | 32.0 | 0.9 | 1.7 | 10.3 | 3.8 | 27.2 | 7.8 | 3.2 |
| **2009** | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | 18.6 | 5.7 | 0.8 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2010** | 423.4 | 20.7 | 6.0 | 18.7 | 0.0 | 174.0 | 94.8 | 269.6 | 25.7 | 3.3 | 31.5 | 7.3 | 56.1 | 14.8 | 6.2 |
| **2011** | 3.7 | 9.4 | 1.7 | 5.0 | 0.0 | 94.4 | 39.8 | 46.2 | 0.0 | 0.9 | 15.0 | 2.0 | 17.7 | 4.1 | 1.7 |
| **2012** | 171.6 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2013** | 0.0 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2014** | 331.5 | 0.2 | 1.5 | 18.7 | 0.0 | 33.4 | 20.2 | 269.6 | 0.4 | 0.8 | 0.0 | 1.8 | 11.2 | 3.7 | 1.5 |
| **2015** | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2016** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2017** | 0.1 | 0.0 | 0.2 | 0.3 | 0.0 | 9.3 | 1.3 | 0.2 | 0.0 | 0.1 | 0.0 | 0.2 | 1.1 | 0.4 | 0.2 |

## Table VI-10. Estimated Annual Total Nitrogen SSO Loads (lbs./yr.) for all Sub watersheds

| Year | Mystic | Alewife | Aberjona River 1 | Aberjona River 2 | Blacks Nook | Horn | Judkins | Lower Mystic Lake | Malden | Mill | Spy Pond | Upper Lobe | Upper Mysti c Lake | Wedge | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2006** | 38.9 | 74.2 | 31.4 | 57.5 | 0.0 | 1,390.1 | 757.9 | 1,356.0 | 205.2 | 16.9 | 124.5 | 38.1 | 277.6 | 78.9 | 33.5 |
| **2007** | 161.3 | 5.9 | 0.0 | 15.7 | 0.0 | 278.2 | 89.4 | 20.8 | 157.0 | 0.0 | 4.1 | 0.0 | 1.5 | 0.1 | 0.1 |
| **2008** | 748.2 | 52.3 | 25.4 | 62.1 | 0.0 | 358.2 | 288.1 | 255.6 | 7.3 | 13.6 | 82.0 | 30.7 | 217.6 | 62.0 | 25.9 |
| **2009** | 0.1 | 3.5 | 0.0 | 0.0 | 0.0 | 148.9 | 45.8 | 6.1 | 6.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2010** | 3,384.1 | 165.8 | 48.3 | 149.5 | 0.1 | 1,391.1 | 757.9 | 2,154.8 | 205.2 | 26.0 | 252.0 | 58.6 | 448.7 | 118.1 | 49.4 |
| **2011** | 29.4 | 75.3 | 13.3 | 40.0 | 0.0 | 755.0 | 318.3 | 368.9 | 0.1 | 7.1 | 119.6 | 16.1 | 141.4 | 32.5 | 13.6 |
| **2012** | 1,371.7 | 11.8 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2013** | 0.0 | 7.2 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2014** | 2,649.9 | 1.9 | 12.1 | 149.5 | 0.0 | 266.8 | 161.2 | 2,154.8 | 3.5 | 6.5 | 0.0 | 14.6 | 89.7 | 29.6 | 12.4 |

| Year | Mystic | Alewife | Aberjona River 1 | Aberjona River 2 | Blacks Nook | Horn | Judkins | Lower Mystic Lake | Malden | Mill | Spy Pond | Upper Lobe | Upper Mystic Lake | Wedge | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2015** | 0.0 | 2.5 | 0.0 | 0.0 | 0.0 | 0.2 | 0.1 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2016** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **2017** | 0.6 | 0.1 | 1.2 | 2.2 | 0.0 | 4.5 | 10.0 | 1.5 | 0.1 | 0.6 | 0.0 | 1.5 | 9.0 | 3.0 | 1,2 |

# VII. BATHTUB MODELING APPROACH

This section summarizes the modeling approach and calibration and validation results for the BATHTUB receiving water model of the Mystic River. The BATHTUB model uses instream measurements of TP, TN, orthophosphate (OP), inorganic nitrogen (IN), chlorophyll-a (chl-a), and oxygen depletion in the hypolimnetic and metalimnetic layers (if the data are available) for calibrating the model.

The calibrated BATHTUB model was used to run nutrient reduction scenarios to identify the reductions necessary to bring the critical receiving water reaches (see Section V.A.1) into compliance with water quality targets selected for this project.

## *VII.A. Model Selection*

Prior to modeling of water quality of the Mystic River, three receiving water models were reviewed, namely, the LLRM (Wagner, 2009), BATHTUB (Walker, 2004), and AQUATOX (Clough, 2014) models (see memo "*Options for Modeling the Mystic River Watershed*" (ERG/Pickering/PGE, May 26, 2017). These models were selected based on the conditions, data, and modeling needs in the Mystic River Watershed. They all predict receiving water quality (nitrogen, phosphorus, chlorophyll-a, etc.) to water inputs and nutrient loads (nitrogen, phosphorus) from all contributing sources (land, point, and atmospheric loads) in the watershed. They are all scientifically sound and well suited for this task.

The LLRM and BATHTUB models are both regression-based models that are similar in complexity and effort, whereas the AQUATOX model is a much more mechanistic model. All three models predict the nutrient water quality responses in multiple reaches, lakes, and impoundments. The AQUATOX model was eliminated from consideration because it requires significantly more time and effort. The other two models are similar in complexity and level of effort however, the BATHTUB model offers a number of extra features like additional water quality inputs and outputs, the ability to link a number of reaches or sub-reaches together, and an easy-to-use interface.

The BATHTUB model is an appropriate choice for this study because it is a semi-empirical model that computes both the mass balance of each segment <u>and</u> utilizes empirical relationships between the water quality variables (see Figure VII-I). Those empirical relationships have been calibrated to a large dataset from Army Corps of Engineers (US-ACOE) reservoirs across the country (Walker, 1982; Walker, 1985). The tool is also appropriate to the level of available water quality data in the Mystic River since it has a limited number of calibration factors that can be adjusted thus avoiding over-calibration.

Based on input from the technical team and the TSC, the BATHTUB model was selected. BATHTUB Version 6.2 was used for this modeling task. BATHTUB has been used in in many other similar studies (Walker, 1996; Walker 2004). In particular, the BATHTUB model was used in the development of the Lake Champlain Phosphorus Total Maximum Daily Load study (TetraTech, 2015; EPA, 2016).

Since nitrogen was ultimately not used in the final calibration, discussion of nitrogen has been minimized in the rest of the BATHTUB modeling section.

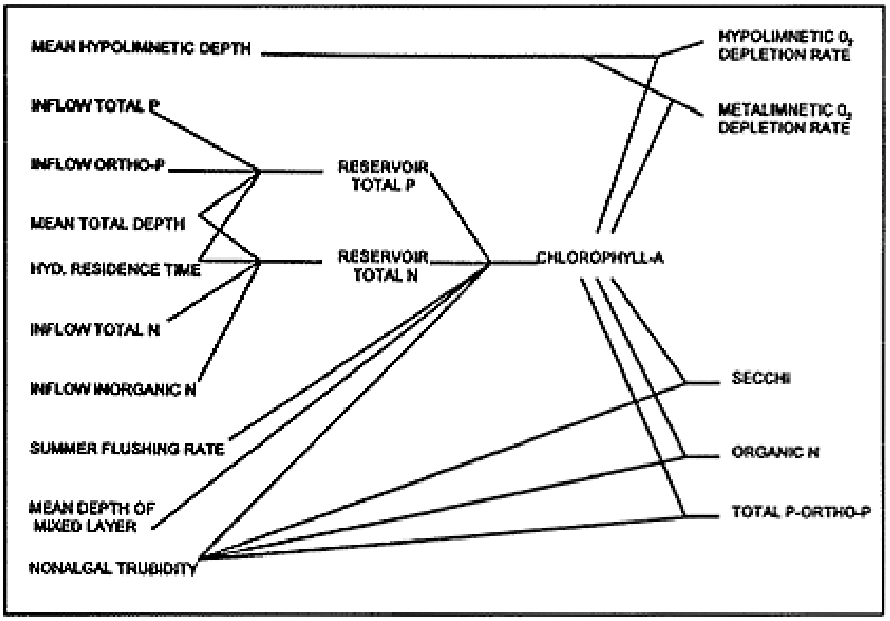



**Figure VII-I. BATHTUB Model Schematic**

## *VII.B. Model Setup*

### VII.B.1. *Segmentation*

The BATHTUB model allows for a number of segmentation options in the set up. A basic setup would use a single upstream tributary to a single water body. The model also allows for river reaches to be linked together, each with single or multiple tributary inputs, and multiple sub-reaches within a reach. The chosen configuration for this project is discussed below.

The final BATHTUB model was divided into 5 segments (see Figure VII-II) as described in the list below. Each segment is numbered from upstream to downstream, with abbreviated names in parentheses, and the critical reaches for water quality attainment identified:

1. Upper lobe of Upper Mystic Lake (Upper Lobe, critical).
2. Main body of Upper Mystic Lake (Upper Lake, critical).
3. Lower Mystic Lake (Lower Lake, not critical).
4. Upper part of the Lower Mystic Basin (Upper Basin, critical).
5. Lower part of the Lower Mystic Basin (Lower Basin, critical).

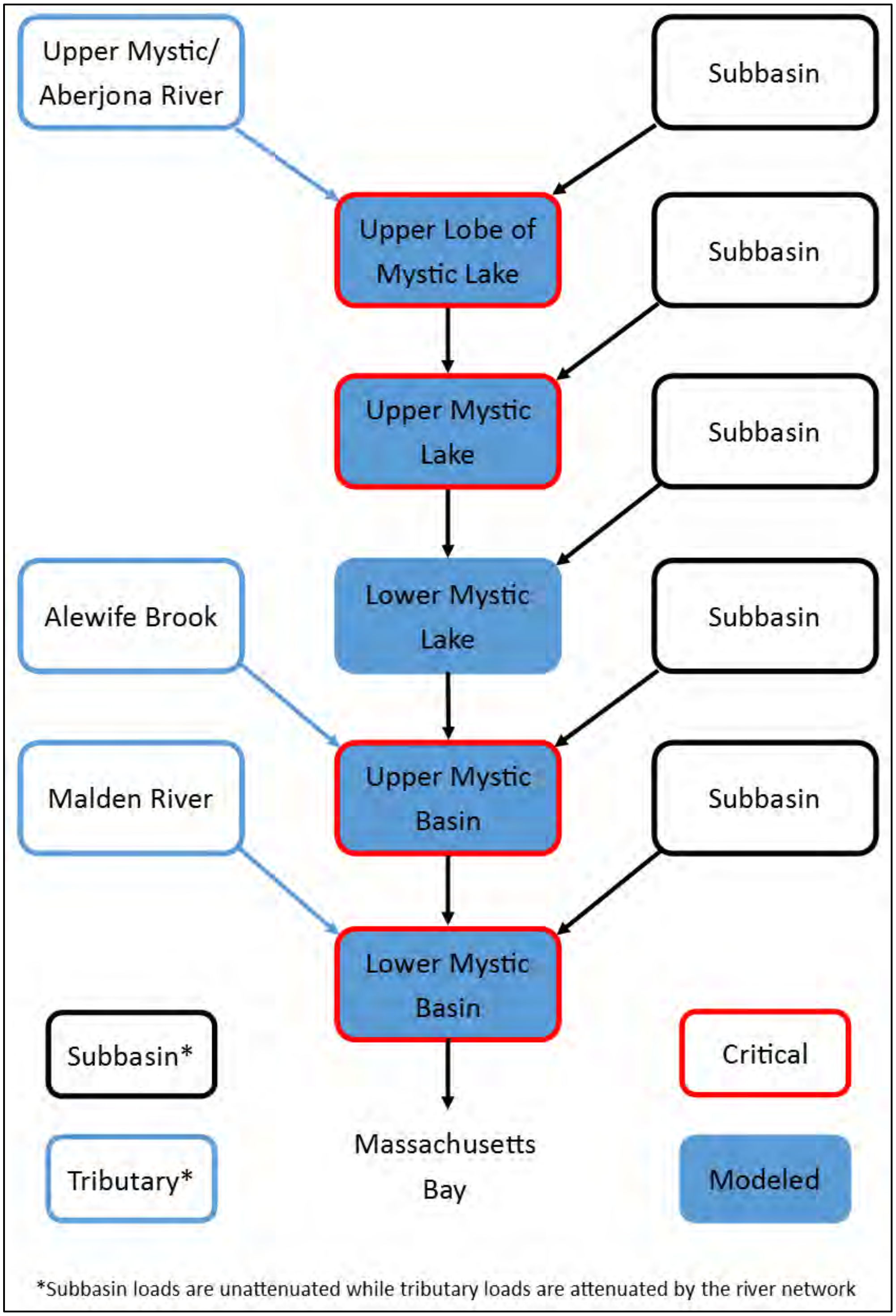



**Figure VII-II. BATHTUB Segmentation for the Mystic River.**

### VII.B.2. *Model Options*

The BATHTUB model allows the user to select a number of model options to represent the receiving water body response to the estimated input loads. The nutrient related options in BATHTUB include the following:

- Phosphorus Sedimentation Models
- Nitrogen Sedimentation Models
- Chlorophyll-a Models
- Secchi Depth Models
- Longitudinal Dispersion Models
- Application of Nutrient Availability Factors
- Application of Various Calibration Factors

More information on these options and the different equations used is given in the BATHTUB user manual (Walker, 2004).

The final choice of model options is primarily a function of the availability of water quality data. For example, Secchi depth and transparency data were limited in the segments and years modeled, so those options were dropped. In addition, nitrogen data were sparse and very different from predicted incoming land-based concentrations, so although nitrogen was included in initial testing of the model, it was not used in the final BATHTUB setup. The final model options used in this study are given in Table VII-1.

**Table VII-1. Model Options**

| Model Option | Default Choice | Final Choice | Calibrated |
|---|---|---|---|
| Nitrogen Model | Not computed | Not computed* | - |
| Phosphorus Model | 2nd order, available P | Same as default | No |
| TN Calibration | Sedimentation rates | Not computed* | No |
| TP Calibration | Sedimentation rates | Same as default | No |
| Nutrient Availability Factors | Not included | Not included | No |
| Chl-a Model | P, light, flushing | Same as default | Yes |
| Secchi Depth Model | Chl a and turbidity | Not computed | - |
| Transparency Model | Chl-a, turbidity | Not computed | - |
| Longitudinal Dispersion | Fischer-Numeric | Same as default | Yes |
| Internal Loading | Not included | Included | Yes |

* See reasons in Section VII.C.3.

### VII.B.3. *Atmospheric Fluxes*

Atmospheric TP loading was considered to have a minor effect on the total watershed load (see VII.C.10), so we used the BATHTUB default TP value (0.27 lb./ac/yr.) split evenly between organic and inorganic fractions.

Annual precipitation (PREC, in/yr.) for Logan Airport was derived from the NCEI (2018) daily data downloaded previously (see Section V.A.1).

Annual lake evaporation (ETw, in/yr.) was more difficult to estimate for the reasons below:

- The world-wide adopted FAO Penman-Monteith method is the best method for estimating potential and lake evaporation but it uses solar radiation that is no longer collected by US Class I national weather stations

- Available MassGIS data on potential and lake evaporation derived using similar radiation-based methods does not apply to the modeling period, and only has monthly averages not a time series of yearly values.
- Methods that do not include solar radiation (like Blaney-Criddle) are usually biased high or low and would have to be calibrated to a more reliable method.

Since annual lake evaporation is a minor variable in this model that only affects the total flow for each reach slightly, we used an alternative simpler approach for estimating yearly lake evaporation. The 1961-2005 annual time series of precipitation and lake evaporation data from the HSPF model in the Upper/Middle Charles TMDL (2011) was used to create a regression equation (PETW = 41.06 -0.0952*PREC, $R^2$=0.2) to predict annual lake evaporation from precipitation. Although the $R^2$ value for this relationship is low, it is based on the best available data and evaporation methods and it does reflect higher lake evaporation for drier years and vice versa (see Figure VII-III comparison for 2007 to 2017).

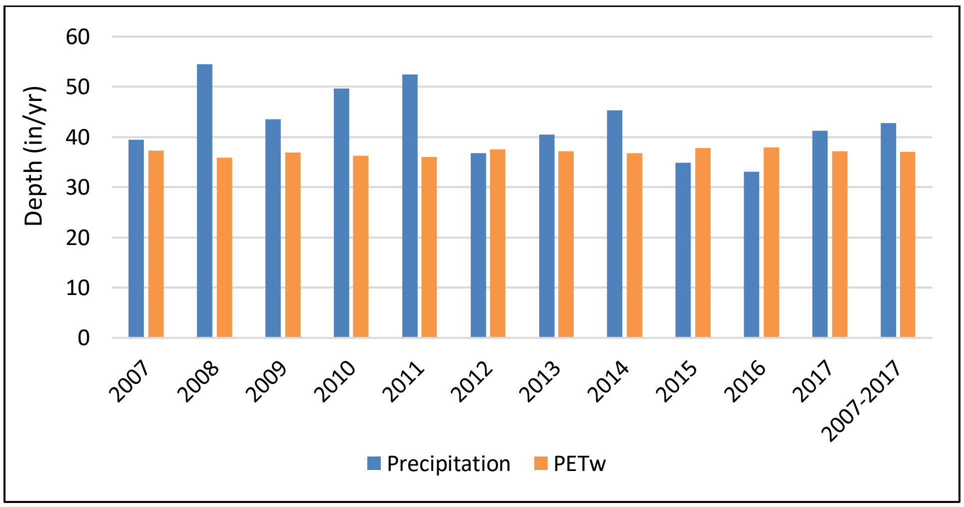



**Figure VII-III. Annual Precipitation and Lake Evaporation**

For the calibration period (2015), the values for annual precipitation and average lake evaporation were 34.8 and 37.7 in/yr., respectively. In comparison, for the scenario period (2007-2016), the average values for annual precipitation and lake evaporation were 43.0 and 37.0 in/yr., respectively. These two time periods represent the calibration and critical period for scenarios (see Sections VII.C.2 and VIII.D).

### VII.B.4. *Modeled Land Loads*

As described in Section V, cumulative annual flow (in/yr.) and TP loads (lb./yr.) were developed for each sub-basin and corresponding reach for the period 1992-2017. The annual land-based flows and loads include contributions from stormwater, baseflow, and CSOs/SSOs. The initial sub-basin delineation for the Lower Mystic Basin (8.63 $mi^2$) was split into the Upper (6.08 $mi^2$) and Lower Basins (2.55 $mi^2$) using available elevation, and a spatial understanding of connectivity between combined sewer areas (CSAs) and the associated receiving waters based on information from community and DEP knowledge (see Section VI.B).

### VII.B.5. *External Loads*

In this section, we estimate the total external loads for the BATHTUB model. The model allows the input of loads using flow and concentration. We used the BATHTUB "Tributary" feature to input the combined total load from the upstream reach and the local sub-basin using the scheme laid out in Figure VII-I. Because land loading is part of the "Tributary" input, explicit export coefficients were not used for the BATHTUB model.

External load was specified as a flow-weighted average concentration (load/flow) and an annual streamflow using the Tributary Input option in BATHTUB. The total external load is the sum of the attenuated upstream reach load plus the unattenuated land load from the local sub-basin (see Table VII-2). The total segment loads were then converted to an average concentration (i.e. load/flow) associated with the average annual streamflow for input into the BATHTUB model.

**Table VII-2. Upstream Reach and Local Sub-basin Contributions**

| Segment Name | Reach Name (attenuated load) | Sub-basin Name (unattenuated load) |
|---|---|---|
| Upper Lobe | Aberjona 2 | Upper Lobe |
| Upper Lake | - | Upper Lake |
| Lower Lake | - | Lower Lake |
| Upper Basin | Alewife | Upper Basin |
| Lower Basin | Malden | Lower Basin |

The BATHTUB model requires the total external contributions to be divided into organic and inorganic nutrient parts. Because the Mystic River had few nutrient measurements from tributaries, we used the average measured concentration ratio (60 percent inorganic TP) from the Upper/Middle Charles Nutrient TMDL (DEP-EPA, 2011). These ratios were used to split the total concentration into organic and inorganic concentrations. This assumption is justified because the Charles and Mystic tributary watersheds have very similar land use patterns and potential nutrient sources.

### VII.B.6. *Internal Loads*

The BATHTUB model can also use available sediment TP release rates for estimating the internal load instead of adjusting the sedimentation rates. Internal load in river reaches results from nutrient release from the accumulated organic sediments. Since there have been no direct measurements of nutrient release rates from the sediments in the Mystic River Watershed, measured release rates from the Upper/Middle Charles Nutrient TMDL (DEP-EPA, 2011) were used to constrain the initial model inputs. Average TP release rates from impoundments in the Upper/Middle Charles TMDL were less than 6 $mg/m^2/d$. TP values were set to a maximum of 6 $mg/m^2/d$ during the calibration process according to the presence of soft sediments (i.e., not actual sediment release rates) as detected by field monitoring by EPA (2018). Reaches with large areas of sediments were assigned a high value (6 $mg/m^2/d$) while those with no sediments or no data (e.g. Upper Lake and Upper Lobe) were assigned a low value (1 $mg/m^2/d$). As part of the calibration process, these internal loads were adjusted with the expected range (0-6 $mg/m^2/d$) to better match observed water body TP concentrations.

## *VII.C. Model Calibration and Validation*

### VII.C.1. *Water Quality Data Availability*

The average water quality data available for the modeled five segments in all calibration years and validation years are summarized in the following table. The unaveraged values for water quality data for the modeled segments are given in Appendix H. All values for TP concentration were previously adjusted to correct for differences in laboratory methods (see Section V.D.2).

**Table VII-3. Average Water Quality Data Available by Segment, Site and Year**

| Year | Segment | WQ Site IDs | Avg TP | Avg Chl-a |
|---|---|---|---|---|
| 2010 | Upper Lobe | UPLUPL | | |
| 2010 | Upper Lake | UPLCTR / UPL001 | 0.029 | |
| 2010 | Lower Lake | MYR071 | 0.036 | |
| 2010 | Upper Basin | MWRA083 / MWRA066 | 0.043 | 7.086 |
| 2010 | Lower Basin | MYR33 / MAR003 / MWRA167 | 0.054 | 14.582 |
| 2014 | Upper Lobe | UPLUPL | | |
| 2014 | Upper Lake | UPLCTR / UPL001 | 0.038 | |
| 2014 | Lower Lake | MYR071 | 0.034 | |
| 2014 | Upper Basin | MWRA083 / MWRA066 | 0.045 | 8.701 |
| 2015 | Upper Lobe | MYR33 / MAR003 / MWRA167 | 0.052 | 16.790 |
| 2015 | Upper Lake | UPLCTR / UPL001 | 0.032 | 8.929 |
| 2015 | Lower Lake | MYR071 | 0.036 | 4.749* |
| 2015 | Upper Basin | MYR43 | 0.056 | 17.944 |
| 2015 | Lower Basin | MYR33 / MAR003 / MWRA167 | 0.059 | 23.534 |
| 2016 | Upper Lobe | UPLUPL | 0.060 | 17.103 |
| 2016 | Upper Lake | UPLCTR / UPL001 | 0.029 | 8.709 |
| 2016 | Lower Lake | MYR071 | 0.036 | |
| 2016 | Upper Basin | MYR43 | 0.072 | 21.273 |
| 2016 | Lower Basin | MYR33 / MAR003 / MWRA167 | 0.089 | 30.636 |
| 2017 | Upper Lobe | UPLUPL | 0.053 | 13.351 |
| 2017 | Upper Lake | UPLCTR / UPL001 | 0.036 | 13.257 |
| 2017 | Lower Lake | MYR071 | 0.038 | |
| 2017 | Upper Basin | MYR43 | 0.062 | 22.476 |
| 2017 | Lower Basin | MYR33 / MAR003 / MWRA167 | 0.066 | 27.264 |

* Estimated from adjacent segments and other variables

### VII.C.2. *Calibration and Validation Periods*

The calibration period was determined by the availability of good quality and representative instream data in the critical receiving water bodies. Originally, the period 2015-2017 was recommended for calibration. However, 2015 was found to be a better choice because it is the only common period with good quality data for all five segments that have typical water quality without the interference from the macrophytes herbicide treatments in 2016 and 2017. Although this year is drier than average (see Figure VII-III), it serves as a critical-conditions period because the dry, sunny conditions provide more ideal conditions for phytoplankton growth due to increased direct sunlight, higher temperatures, and lower flows (increased residence times). Since one of the chl-a attainment targets was the 90th percentile, it is important to capture optimal growth conditions for model calibration. For these reasons, 2015 was used as the calibration period for the joint calibration of all segments.

### VII.C.3. *Receiving Water Parameters*

The BATHTUB model requires the input of the following physical parameters for each receiving water body: surface area, mean depth, length, epilimnion depth, hypolimnion depth, and non-algal turbidity. Since most ponds in Massachusetts do not stratify if less than 10 ft deep, epilimnion depth was estimated as 10 ft or the actual depth if less. Any remaining depth was assigned to the hypolimnion or set to zero if fully assigned to the epilimnion. Non-algal turbidity is an inverse measure of Secchi depth that represents the portion of light extinction that is due to factors other than algae (inorganic suspended solids, color). A value of 1 per 6 ft was used since Secchi depth measurements for the non-algal season in the segments and years modeled were not available. The value of 6 feet was an average determined for the non-algal season (outside of May-Sep) in non-modeled river segments for the years modeled.

### VII.C.4. *Dispersion*

The longitudinal dispersion rate was calculated in the model using the BATHTUB model default dispersion method (Fischer et.al., 1979; adapted by Walker, 1985). Longitudinal dispersion is a result of the mixing effect among adjacent segments, both between reaches and within reaches if there are sub-reaches. High dispersion rates create high mixing conditions and a low range of the values among segments whereas low dispersion rates create low mixing conditions with the segments all having distinctly different values.

Observed TP data showed more of a range of data values among the segments than the default model predicted. Therefore, the longitudinal dispersion rate was calibrated by using a multiplier of 0.2. This approach gave more differentiation of the TP values among the segments than using the default multiplier of 1.0, allowing the modeled TP (see Figure VII-VFigure VI-V) to better reflect the U-shaped pattern of observed TP values (see Figure VII-VI).

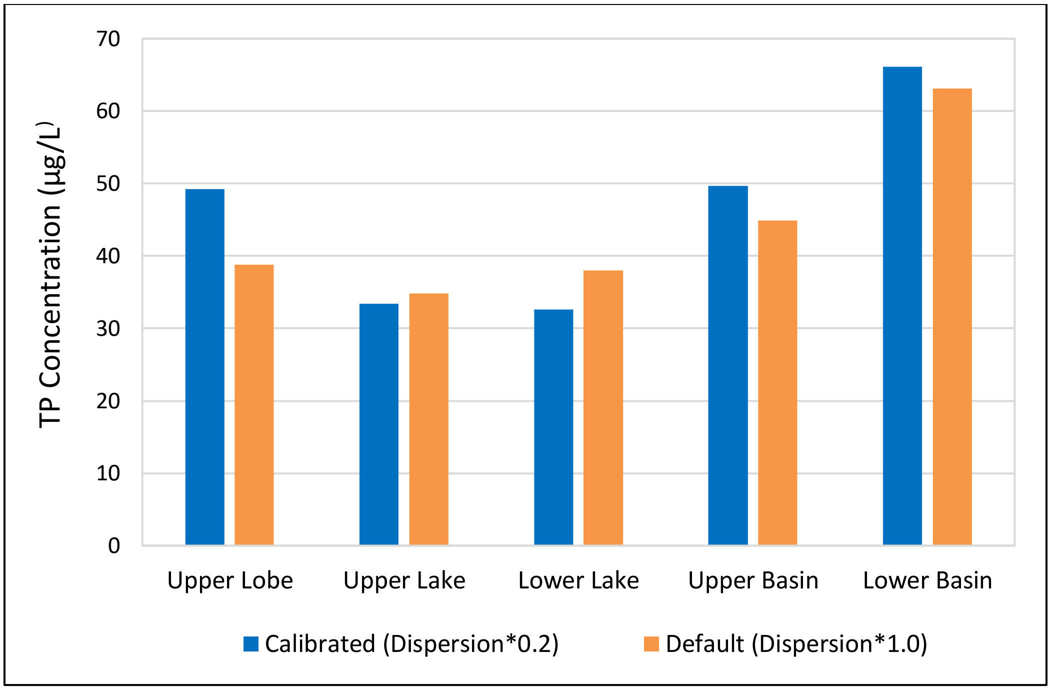



**Figure VII-IV. Dispersion Effect on Modeled Phosphorus Concentrations**

### VII.C.5. *Nutrient Availability Factors*

The BATHTUB model allows the use of organic and inorganic fractions to drive the nutrient sedimentation model through the use of a Nutrient Availability Factor (see Table VII-1). Organic phosphorus (OP) controls sedimentation and can influence the predicted TP values allowing more options for calibration. The OP fraction of TP was set to 40-50% percent for inflow to all segments based on observed data from the Upper Charles TMDL (DEP-EPA, 2011). Sensitivity trials that varied this ratio resulted in no model prediction improvement. Ultimately, this model option was not used in the final calibration run.

### VII.C.6. *Internal Loads*

The TP predictions in the five modeled segments were generally lower than measured values indicating that there is some internal loading of TP from the sediments. Average TP release rates from impoundments in the Upper/Middle Charles TMDL averaged less than 19.5 lb./ac/yr. for aerobic and anaerobic conditions, respectively. (DEP-EPA, 2011). The final calibrated values for the BATHTUB model were set to 19.5, 3.3, 3.3, 13.0 and 13.0 lb./ac/yr. for segments 1 to 5, respectively (see Section VII.B.1 for names).

### VII.C.7. *Chl-a Model*

Predicted chl-a values using the default chl-a method (P, light, flushing) in BATHTUB model were always too high (16-58% high with the percent errors larger downstream) even though TP was being accurately predicted.

The linear chl-a method in BATHTUB (P only) worked slightly better. That approach is consistent with the chl-a versus TP regressions developed in Table IV-3 ($R^2$ = 0.12 to 0.43).

In the final model, we used a chl-a calibration factor. The best calibration for chl-a used the default chl-a model with a global calibration factor of 0.6 applied to all segments. An atypical relationship between TP and chl-a in ponds can be the result of light limitation (Filstrup and Downing, 2017).

Calibration factors provide a means for adjusting model predictions to account for site-specific conditions. These modify the coefficients of the empirical models within the BATHTUB model. They are usually set to 1.0 and should be modified only with extreme caution and site-specific data. We justify the use of a calibration coefficient based on some evidence of light limitation the Mystic River. One possible explanation is that the natural tan color of the Mystic River limits light penetration into the water column. Another explanation is that the submerged and floating aquatic plants (see Section II.J) create a similar light penetration issue.

### VII.C.8. *Model Calibration*

In summary, the default BATHTUB model was calibrated to the Mystic River conditions using the following sequential approach:

- Changing the default multiplier for longitudinal dispersion from 1.0 to 0.2
- Adding internal TP loading to each modeled segment, and
- Changing the default multiplier for the chl-a model from 1.0 to 0.6.

The 2015 data were used to calibrate the model since it had the most available water quality data and that year was unaffected by transient nutrient and chlorophyll-a changes from herbicide applications in 2016 and 2017 used for macrophyte control in the Lower Basin. Despite this good set of data, the chl-a value for the Lower Lake had to be estimated from adjacent segments and other variables. Since this segment is not a critical reach, it is not a critical value.

A total of 22 calibration runs were performed and tracked both visually and for computed goodness-of-fit parameters for TP and chl-a. A high correlation coefficient ($R^2$) represents a strong linear relationship between predicted and observed values while a low root-mean square error (RMSE, μg/L) indicates good overall fit to the observed data. The best calibration run was a compromise between TP and chl-a runs with the goal of having similar $R^2$ values for both parameters. The final calibration run had an $R^2$ and RMSE for TP of 0.86 and 3.8 μg/L, and an $R^2$ and RMSE for chl-a of 0.84 and 1.5 μg/L, respectively. Excluding the estimated chl-a value for Lower Lake (not a critical segment) slightly improved the model fit for chl-a.

Predicted versus observed values of TP are given in Figure VII-V and Figure VII-VI. Similar plots are for chl-a are given in Figure VII-VII and Figure VII-VIII. The error bars in these plots are +/- one standard deviation.

Table VII-4 gives a breakdown of the mass balance for TP in each modeled segment excluding transfers from one model segment to the next. Since the focus of this mass balance is the five modeled segments of the BATHTUB model, we report **attenuated** land loads in this table. A pie chart of total loads to the Mystic River Watershed for the calibration period is given in Figure VII-IX.

A complete set of the BATHTUB inputs is provided in Appendix I.

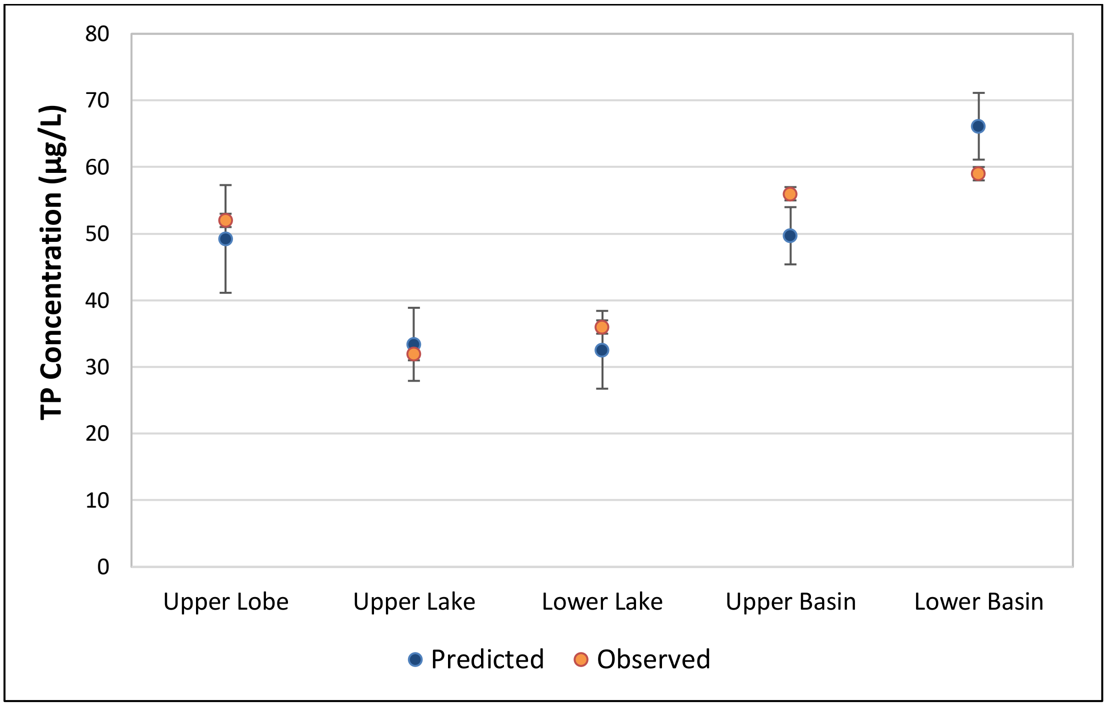



**Figure VII-V. Predicted vs. Observed TP by Segment for Calibration Period**

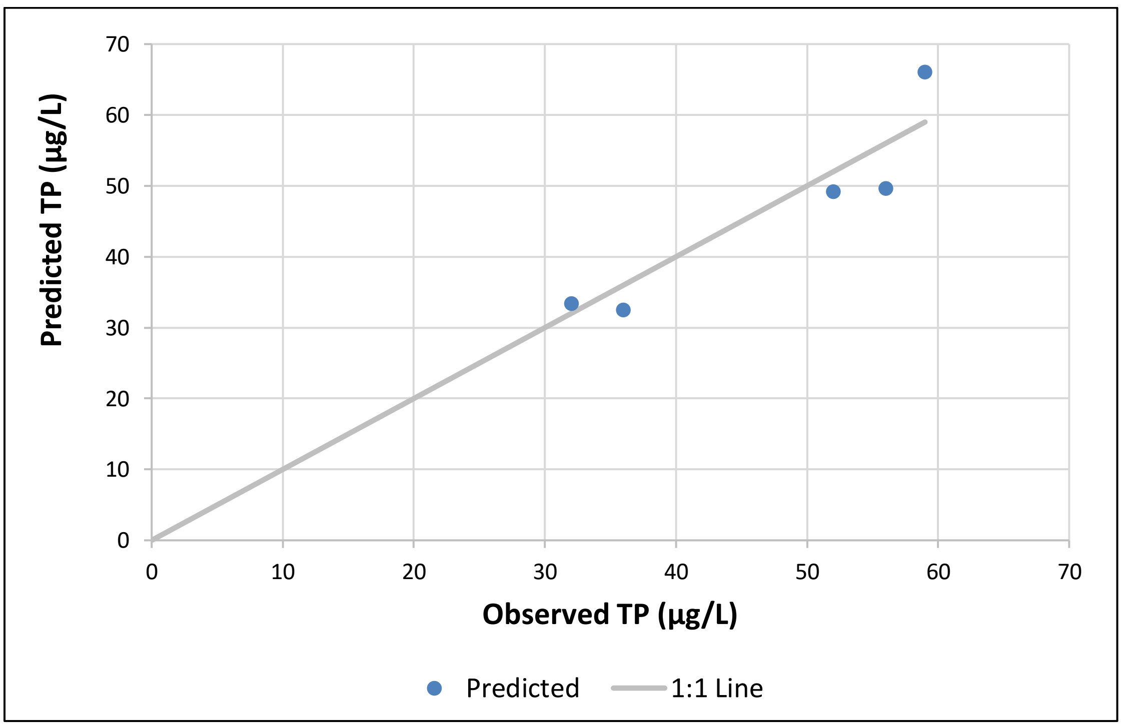



**Figure VII-VI. Predicted vs. Observed TP Relationship for Calibration Period**

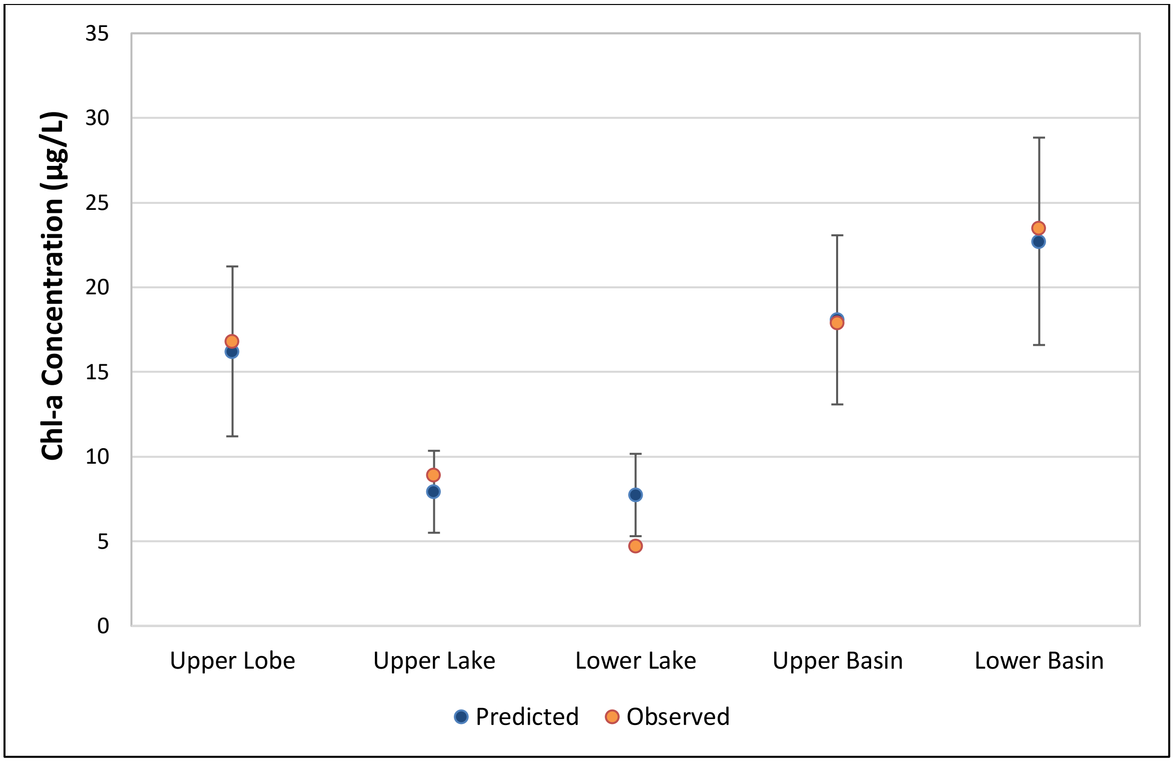



**Figure VII-VII. Predicted vs. Observed Chl-a by Segment for Calibration Period**

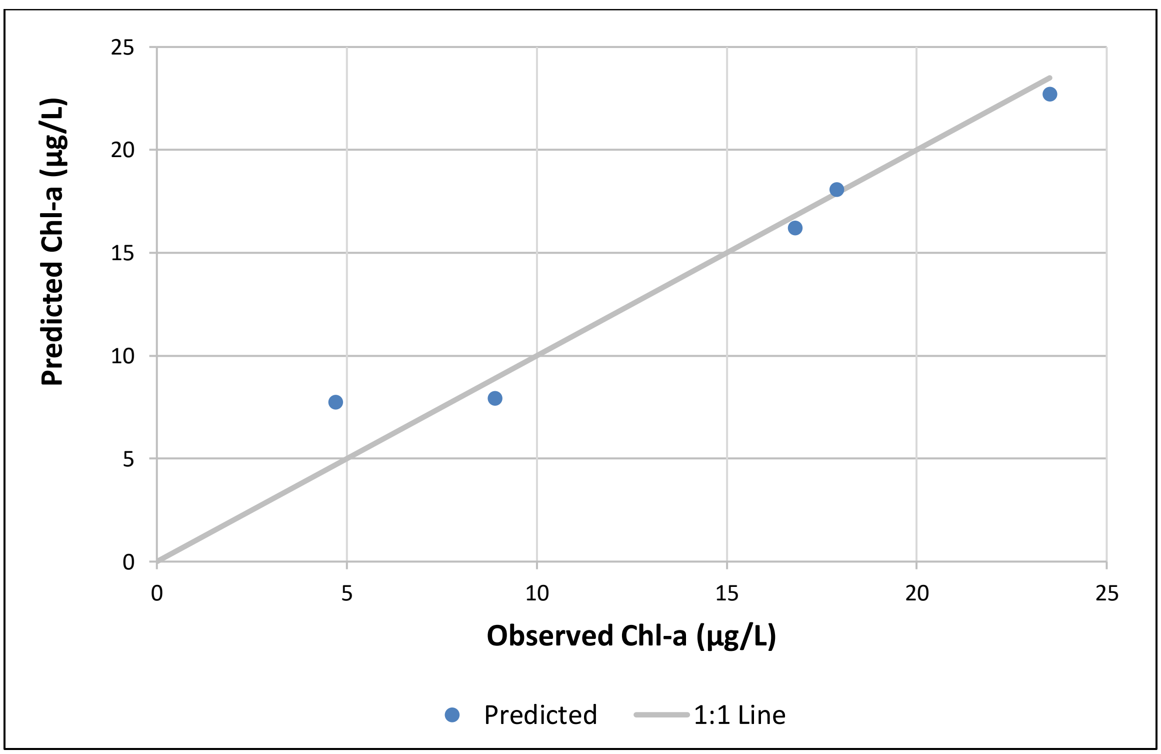


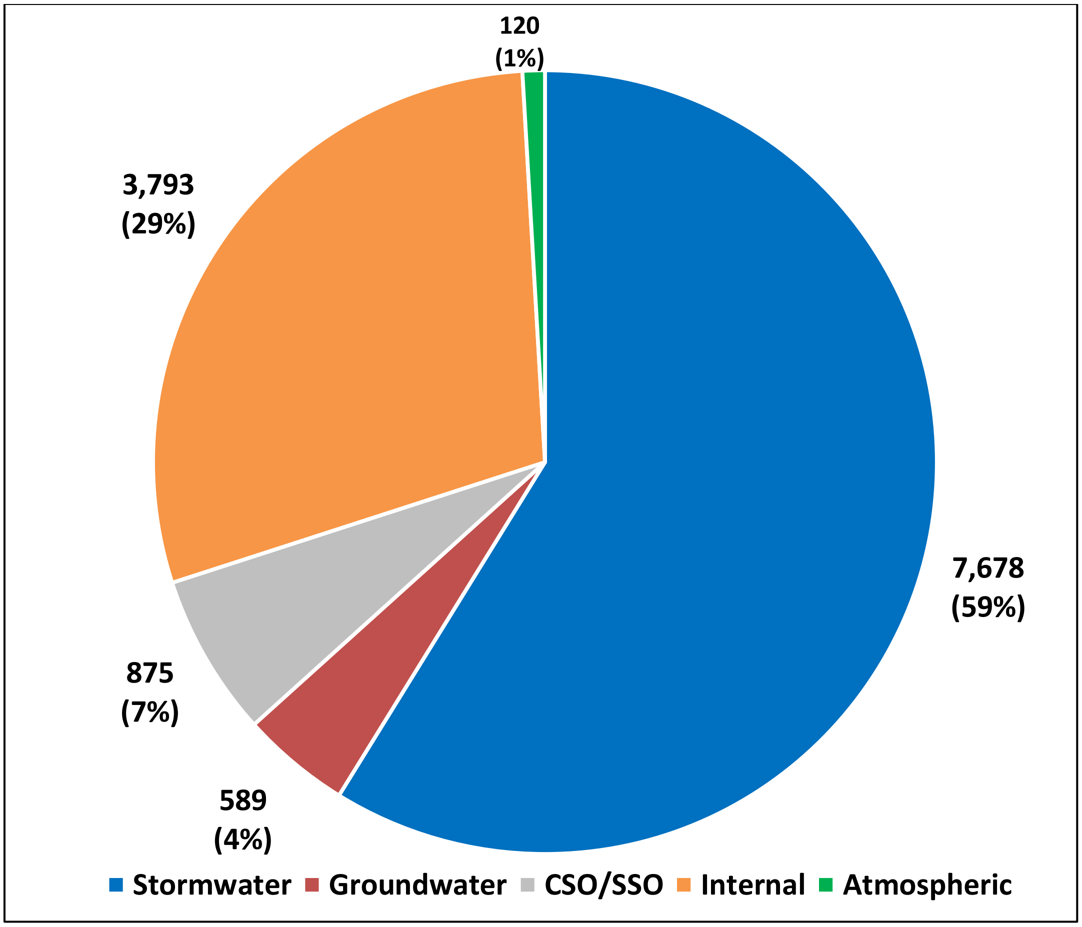

**Figure VII-VIII. Predicted vs. Observed Chl-a Relationship for Calibration Period**

## Table VII-4. Total Phosphorus Loads by Segment for Calibration Period

| Name | External Load* (lb./yr.) | Internal Load (lb./yr.) | Atmospheric Load (lb./yr.) | Total Load (lb./yr.) |
|---|---|---|---|---|
| Upper Lobe* | 2734.6 | 676.5 | 9.3 | 3420.4 |
| Upper Lake | 218.3 | 459.1 | 37.7 | 715.1 |
| Lower Lake | 1000.8 | 306.0 | 25.1 | 1332.0 |
| Upper Basin | 2250.2 | 740.9 | 15.2 | 3006.4 |
| Lower Basin | 2937.1 | 1610.8 | 33.1 | 4580.9 |
| **Mystic River** | **9141.0** | **3793.3** | **120.4** | **13054.8** |

| Name | External Load (%) | Internal Load (%) | Atmospheric Load (%) | Total Load (%) |
|---|---|---|---|---|
| Upper Lobe* | 80.0 | 19.8 | 0.3 | 100.0 |
| Upper Lake | 30.5 | 64.2 | 5.3 | 100.0 |
| Lower Lake | 75.1 | 23.0 | 1.9 | 100.0 |
| Upper Basin | 74.8 | 24.6 | 0.5 | 100.0 |
| Lower Basin | 64.1 | 35.2 | 0.7 | 100.0 |
| **Mystic River** | **70.0** | **29.1** | **0.9** | **100.0** |

* External load includes input from Upper Mystic/Aberjona River, other segments exclude load transfers




Loads are in lb./yr. External load = stormwater + groundwater +_CSO/SSO load

**Figure VII-IX. Calibration 2015 - Total Phosphorus Loads for Mystic River**

### VII.C.9. *Model Validation*

The 2016 and 2017 years were used to validate the BATHTUB that was model calibrated to the 2015 data. These years were excluded from the calibration because of herbicide treatment of macrophytes in the Upper/Lower Basin segments of the model. These treatments generally kill the vegetation, release nutrients into the water column, open up the water surface to allow greater light penetration, and result in high algal growth (see Section II.J). According to MyRWA (pers. comm., 2019), the treatment in 2016 was a contact herbicide that has rapid results, while the treatment in 2017 was a systemic herbicide that is slower acting but more prolonged. In the light of this information, we expected the predicted TP and chl-a values to be lower than the observed results for the Upper and Lower Basin, with more of a difference in 2016 than 2017.

In 2016, the predicted values were similar to observed values in the upper segments but lower in the Upper and Lower Basin segments. Differences were in the range of 13-23 μg and 7-13 μg/L for TP and chl-a, respectively. (Figure VII-VIII and Figure VII-IX). In 2017, the predicted values were higher that observed values in the most segments but much larger in the Upper and Lower Basin than in 2016, in the range of 9-13 μg/L for TP and 8-11 μg/L for chl-a, respectively (Figure VII-X and Figure VII-XI). This was expected because the systemic herbicide used in 2017 acts more slowly than the contact herbicide used in 2016. The reason for under prediction of TP and chl-a for the upper model segments in 2017 is unclear.

The 2010 and 2014 years were used to validate the outlier replacement technique used to develop the annual flow and loads for SSOs (see Section VI.C). These two years had significant occurrences and volumes of SSOs occur throughout the Mystic River Watershed. The BATHTUB was run in two modes, with and without SSO outlier replacement, to test which outlier approach gave predicted results closer to the observed TP values. In 2010, the predicted TP values using outlier replacement closely matched the observed values (-1.1 to 3.9 μg/L), while when outliers were included gave higher than observed TP values (3.1 to 8.1 μg/L) (Figure VII-12). In 2014, the results were similar but had more spread. Predicted TP values using outlier replacement matched the observed values on average (-5.8 to 8.3 μg/L), while with outliers included gave higher than observed TP values (-1.9 to 14.7 μg/L) (Figure VII-XIII).

These 2016 and 2017 validation runs confirm that the calibrated model was able to perform as expected for those years. The 2010 and 2014 validation runs confirm that the outlier replacement approach used for SSOs was not an inappropriate approach.

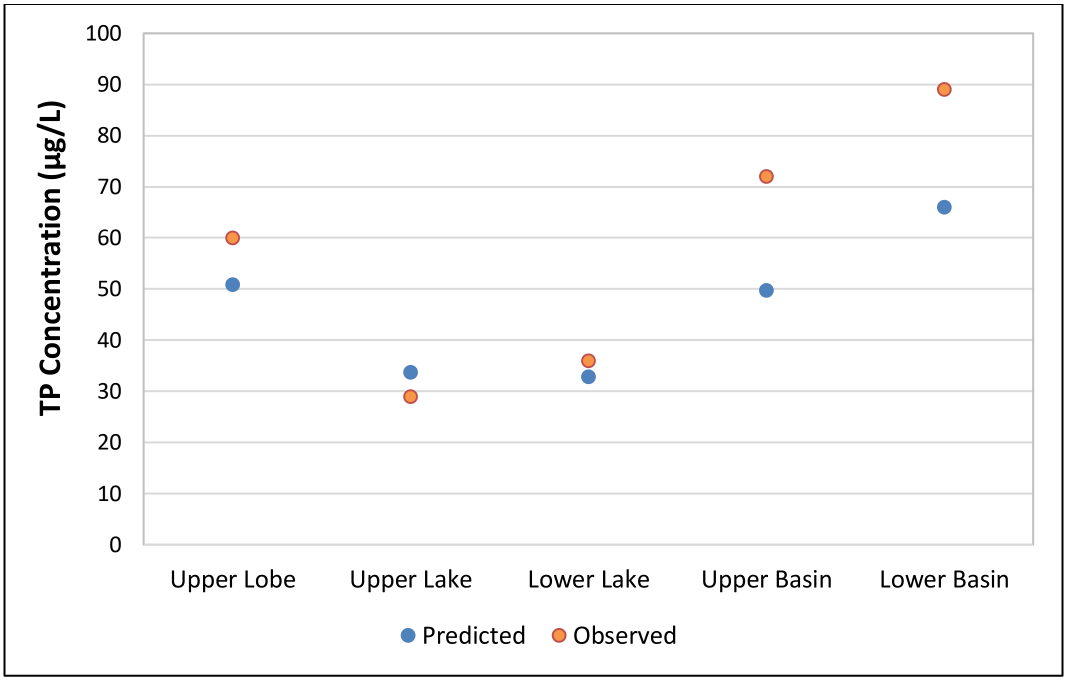



**Figure VII-X. Validation 2016 - Predicted vs. Observed TP by Segment**

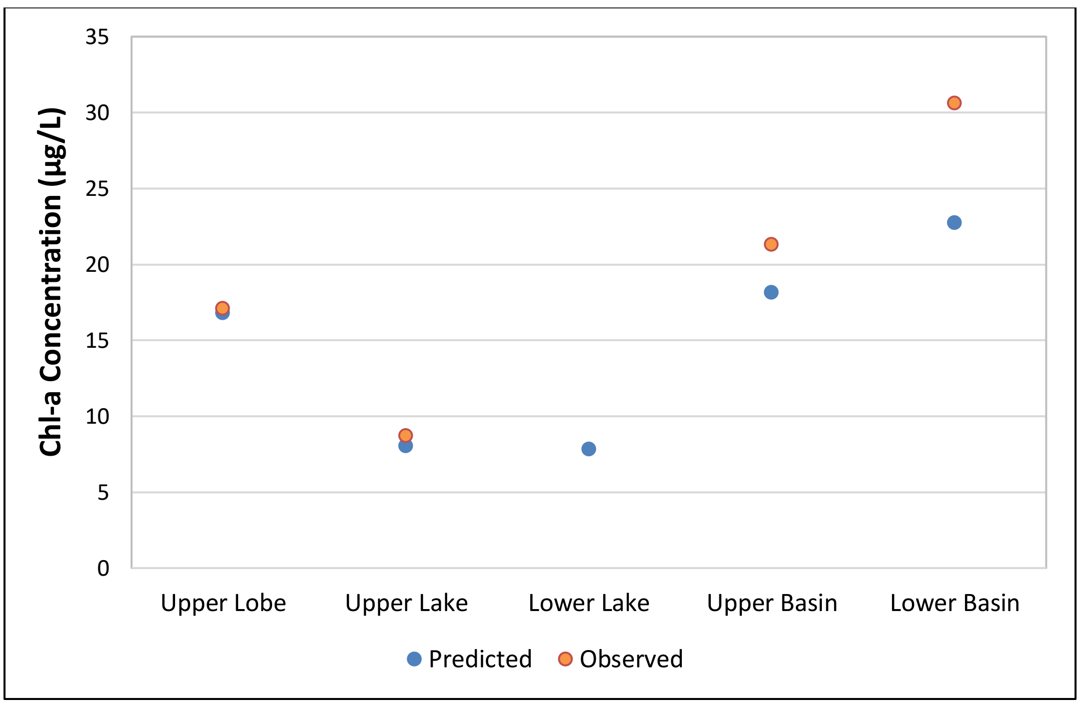



**Figure VII-XI. Validation 2016 - Predicted versus Observed Chl-a by Segment**

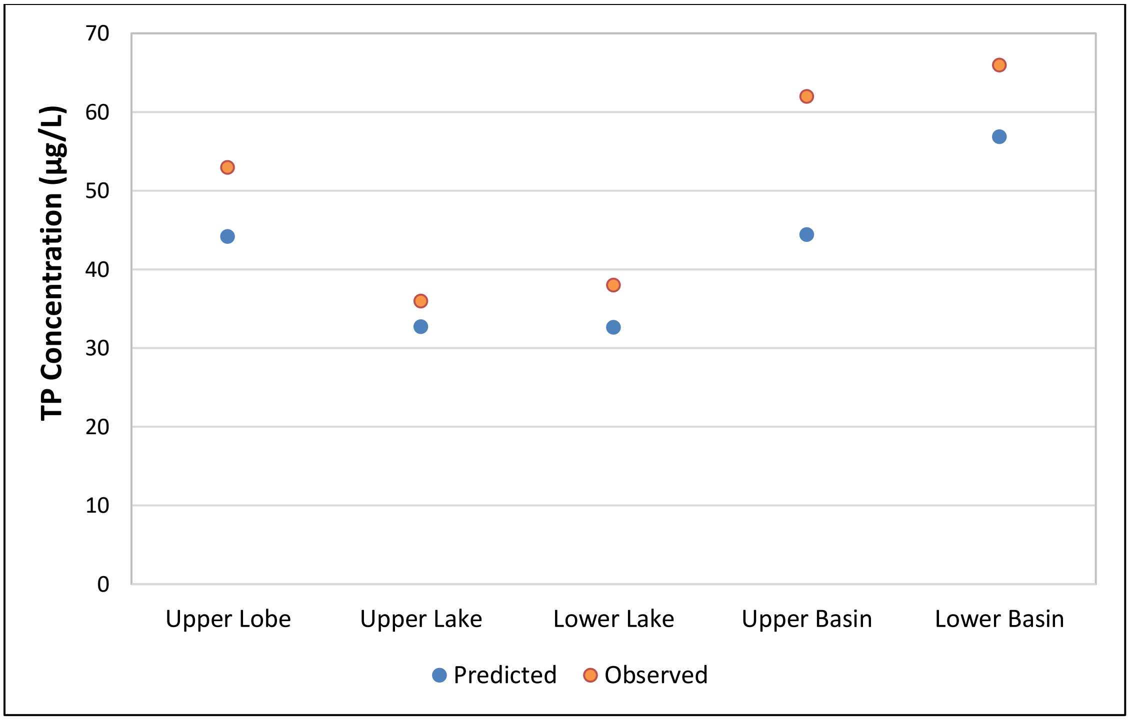



**Figure VII-XII. Validation 2017 - Predicted vs. Observed TP by Segment**

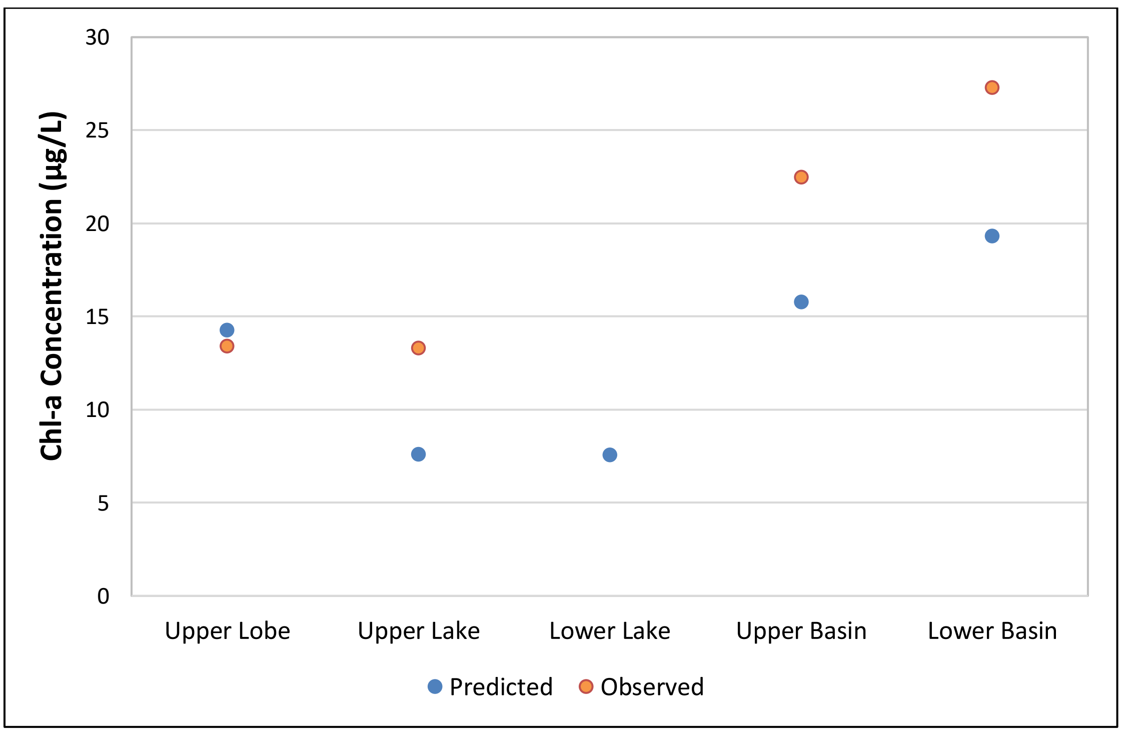



**Figure VII-XIII. Validation 2017 - Predicted vs. Observed Chl-a by Segment**

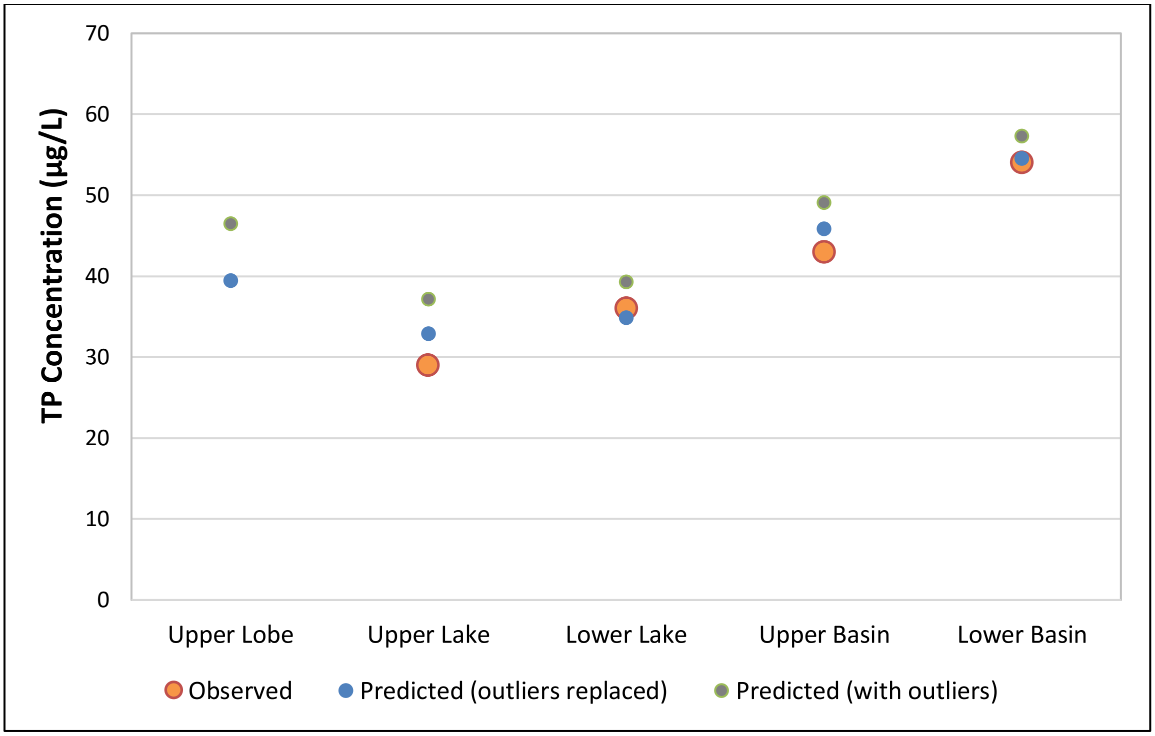



**Figure VII-XIV. SSO Outlier Replacement 2010 - Predicted versus Observed TP**

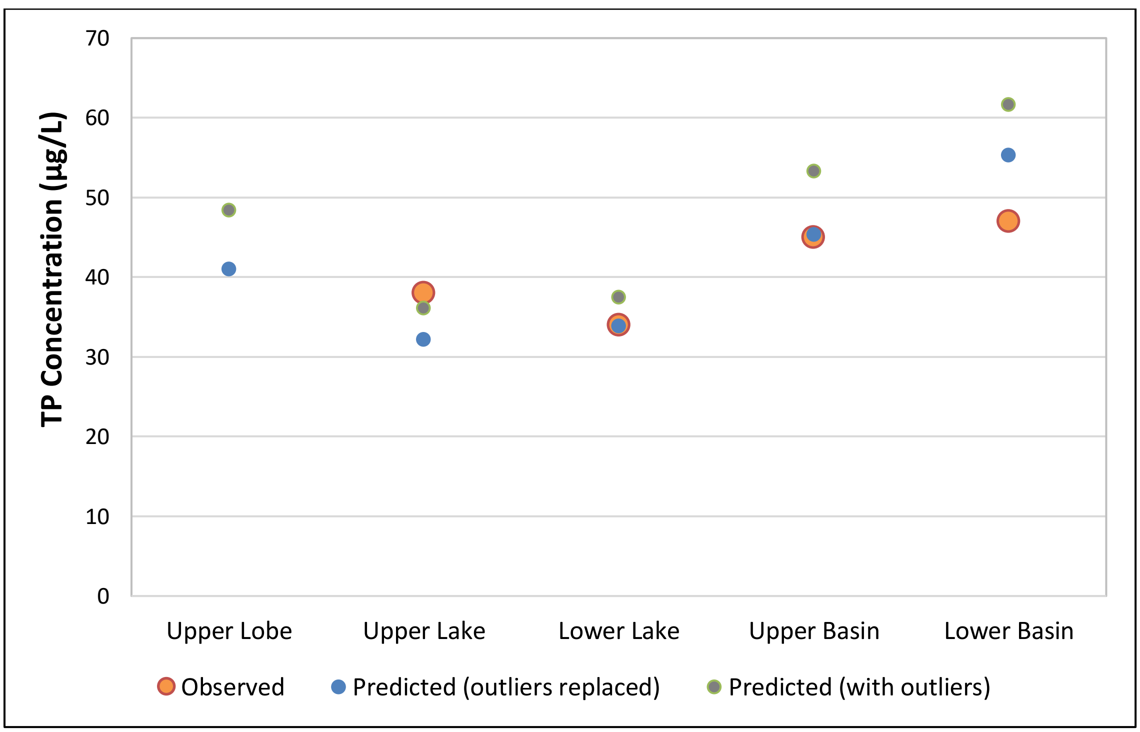



**Figure VII-XV. SSO Outlier Replacement 2014 - Predicted versus Observed TP**

### VII.C.10. *Model Sensitivity Analysis*

A model sensitivity analysis was performed on the calibrated BATHTUB model by varying six important variables (model parameters and TP input loads). Although BATHTUB has a built-in sensitivity analysis tool, we chose not to use it because it only allows analysis of two parameters, it does not allow the variation of input loads, and it does not have a consistent sensitivity range for all variables to allow cross-comparison of sensitivity among all items.

The sensitivity analysis that we performed multiplied the values by 50% or 200% of the original calibrated values of the following parameters/loads. Note that only the first two parameters (*) are included in the built-in tool in BATHTUB.

- Longitudinal dispersion*
- Sedimentation rate of TP*
- Atmospheric deposition TP load
- Internal/sediment load of TP
- Segment TP load (by varying concentration)
- Segment TP load (by varying flow)

To conduct this sensitivity analysis, two additional runs were necessary for each calibrated variable, performed by multiplying the test value by 50% or 200%. For each parameter/load, the output TP and chl-a values were recorded for the calibrated run and the two sensitivity runs. A normalized sensitivity range was calculated using the following formula:

$$\text{Sensitivity Factor} = (\text{Value}_{200\%} - \text{Value}_{50\%}) \,/\, \text{Value}_{\text{calibrated}}$$

Table VII-5 gives the results of the sensitivity analysis. The table lists the predicted TP and chl-a results for the three runs for each parameter/load and also shows the sensitivity factor both numerically and graphically.

From these results, we can conclude the sensitivity for tested parameters/loads was the following:

- Longitudinal dispersion – low
- Sedimentation rate of TP – high
- Atmospheric deposition TP load – very low
- Internal/sediment load of TP - moderate
- Segment TP load (by varying concentration) - high
- Segment TP load (by varying flow) - moderate

This analysis provides confirmation that several professional judgements made in calibrating the BATHTUB model consistently chose the correct approach:

- Use of default values for atmospheric deposition loads
- Calibration of longitudinal dispersion before internal load
- Use of internal load instead of sedimentation rate to adjust segment TP
- Not calibrating segment input flow to observed gauge values because of data ambiguity

The result for varying segment input TP load by concentration versus flow is worth additional discussion. Lowering the flow, and consequently the load, has a muted response on lowering TP and chl-a. This outcome is likely because flow has a negative feedback effect via residence time. Even though the load is lower, the lower flow results in a higher residence time in each segment, such that the TP/chl-a concentrations do not decrease as much compared to same change in load by lowering the input concentrations.

## Table VII-5. Results of BATHTUB Sensitivity Analysis

| Longitudinal Dispersion | 50% | 100% | 200% | 50% | 100% | 200% | Sensitivity | Sensitivity | Sensitivity | Sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| **Segment** | **TP** | **TP** | **TP** | **Chl-a** | **Chl-a** | **Chl-a** | **TP** | **Chl-a** | **TP** | **Chl-a** |
| Upper Lobe | 57.6 | 49.2 | 42.9 | 19.0 | 16.2 | 14.0 | -29.9% | -30.3% | | |
| Upper Lake | 33.1 | 33.4 | 33.7 | 7.9 | 7.9 | 8.0 | 1.7% | 1.6% | | |
| Lower Lake | 32.5 | 32.6 | 35.4 | 7.7 | 7.7 | 8.4 | 9.1% | 8.9% | | |
| Upper Basin | 49.6 | 49.7 | 47.9 | 18.0 | 18.1 | 17.4 | -3.4% | -3.7% | | |
| Lower Basin | 66.1 | 66.1 | 65.0 | 22.7 | 22.7 | 22.3 | -1.7% | -1.6% | | |
| | | | | | | | | | | |
| **Sedimentation Rate** | **50%** | **100%** | **200%** | **50%** | **100%** | **200%** | **Sensitivity** | **Sensitivity** | **Sensitivity** | **Sensitivity** |
| **Segment** | **TP** | **TP** | **TP** | **Chl-a** | **Chl-a** | **Chl-a** | **TP** | **Chl-a** | **TP** | **Chl-a** |
| Upper Lobe | 54.1 | 49.2 | 44.5 | 17.8 | 16.2 | 14.6 | -19.4% | -19.8% | | |
| Upper Lake | 42.4 | 33.4 | 25.4 | 9.9 | 7.9 | 6.0 | -50.8% | -49.3% | | |
| Lower Lake | 42.4 | 32.6 | 24.3 | 9.9 | 7.7 | 5.7 | -55.7% | -54.3% | | |
| Upper Basin | 56.7 | 49.7 | 43.3 | 20.8 | 18.1 | 15.5 | -26.9% | -29.1% | | |
| Lower Basin | 73.7 | 66.1 | 58.1 | 25.1 | 22.7 | 20.0 | -23.6% | -22.2% | | |
| | | | | | | | | | | |
| **Atmos Deposition** | **50%** | **100%** | **200%** | **50%** | **100%** | **200%** | **Sensitivity** | **Sensitivity** | **Sensitivity** | **Sensitivity** |
| **Segment** | **TP** | **TP** | **TP** | **Chl-a** | **Chl-a** | **Chl-a** | **TP** | **Chl-a** | **TP** | **Chl-a** |
| Upper Lobe | 49.1 | 49.2 | 49.4 | 16.2 | 16.2 | 16.3 | 0.6% | 0.6% | | |
| Upper Lake | 33.3 | 33.4 | 33.6 | 7.9 | 7.9 | 8.0 | 1.1% | 1.1% | | |
| Lower Lake | 32.4 | 32.6 | 32.9 | 7.7 | 7.7 | 7.8 | 1.4% | 1.4% | | |
| Upper Basin | 49.5 | 49.7 | 50.0 | 18.0 | 18.1 | 18.2 | 1.0% | 1.1% | | |
| Lower Basin | 65.9 | 66.1 | 66.5 | 22.6 | 22.7 | 22.9 | 1.0% | 0.9% | | |
| | | | | | | | | | | |
| **Internal Load** | **50%** | **100%** | **200%** | **50%** | **100%** | **200%** | **Sensitivity** | **Sensitivity** | **Sensitivity** | **Sensitivity** |
| **Segment** | **TP** | **TP** | **TP** | **Chl-a** | **Chl-a** | **Chl-a** | **TP** | **Chl-a** | **TP** | **Chl-a** |
| Upper Lobe | 44.6 | 49.2 | 58.1 | 14.6 | 16.2 | 19.1 | 27.5% | 27.7% | | |
| Upper Lake | 30.4 | 33.4 | 38.9 | 7.2 | 7.9 | 9.2 | 25.5% | 24.5% | | |
| Lower Lake | 30.0 | 32.6 | 37.2 | 7.1 | 7.7 | 8.8 | 21.8% | 21.2% | | |
| Upper Basin | 44.7 | 49.7 | 59.4 | 16.1 | 18.1 | 21.8 | 29.6% | 31.7% | | |
| Lower Basin | 57.7 | 66.1 | 82.3 | 19.9 | 22.7 | 27.6 | 37.3% | 34.0% | | |
| | | | | | | | | | | |
| **Segment Load (conc)** | **50%** | **100%** | **200%** | **50%** | **100%** | **200%** | **Sensitivity** | **Sensitivity** | **Sensitivity** | **Sensitivity** |
| **Segment** | **TP** | **TP** | **TP** | **Chl-a** | **Chl-a** | **Chl-a** | **TP** | **Chl-a** | **TP** | **Chl-a** |
| Upper Lobe | 32.2 | 49.2 | 80.7 | 10.2 | 16.2 | 25.6 | 98.6% | 95.0% | | |
| Upper Lake | 25.1 | 33.4 | 46.3 | 5.9 | 7.9 | 10.7 | 63.3% | 59.9% | | |
| Lower Lake | 24.7 | 32.6 | 44.8 | 5.8 | 7.7 | 10.4 | 61.7% | 59.1% | | |
| Upper Basin | 34.2 | 49.7 | 77.7 | 11.8 | 18.1 | 28.3 | 87.6% | 91.5% | | |
| Lower Basin | 46.4 | 66.1 | 101.4 | 15.9 | 22.7 | 32.6 | 83.2% | 73.7% | | |
| | | | | | | | | | | |
| **Segment Load (flow)** | **50%** | **100%** | **200%** | **50%** | **100%** | **200%** | **Sensitivity** | **Sensitivity** | **Sensitivity** | **Sensitivity** |
| **Segment** | **TP** | **TP** | **TP** | **Chl-a** | **Chl-a** | **Chl-a** | **TP** | **Chl-a** | **TP** | **Chl-a** |
| Upper Lobe | 54.6 | 49.2 | 47.7 | 18.4 | 16.2 | 15.1 | -14.1% | -20.3% | | |
| Upper Lake | 32.8 | 33.4 | 36.3 | 8.0 | 7.9 | 8.1 | 10.3% | 1.3% | | |
| Lower Lake | 31.0 | 32.6 | 36.5 | 7.5 | 7.7 | 8.2 | 17.0% | 7.9% | | |
| Upper Basin | 54.8 | 49.7 | 49.2 | 20.4 | 18.1 | 17.3 | -11.2% | -17.1% | | |
| Lower Basin | 76.1 | 66.1 | 62.4 | 26.5 | 22.7 | 20.6 | -20.8% | -25.9% | | |

# VIII. Critical Period of Interest for Phosphorus Load Reduction Analysis

This section documents the approach for evaluating and selecting the critical period of interest for the phosphorus load reduction analyses in the BATHTUB model discussed in Section IX. The approach involved evaluating available water quality data availability; identifying events or actions that may influence the water quality data; and identifying a range of representative climatic conditions.

## VIII.A. Water Quality Data

As discussed in Section III and noted in Table III-2 water quality monitoring data was available between 2000 and 2017. Six water bodies (located primarily in the upper watershed) were sampled more intensively in 2015 through 2017. The review of eutrophic related parameters, Chlorophyll-a (chl-a) and TP, including statistical analyses completed in Section IV indicated that there has been a gradual decline in chl-a and TP concentrations in the Mystic River. This appears to be primarily due to the growth of macrophytes, particularly in the last 10 years, which appear to be removing phosphorus from the water column and/or suppressing phytoplankton growth due to reduced light availability. The only exceptions to this trend are the instant releases caused by the use of herbicide applications in 2016 and 2017.

Based on these considerations, data between 2000 and 2015 was considered to be most representative of the available water quality datasets.

## VIII.B. Combined Sewer and Sanitary Sewer Overflow Data

As noted in Table VII-1 in Section VII, CSO and SSO data was available for the years 2000 to 2017, with the exceptions noted for missing 2006 CSO data in the Mystic River basin and missing SSO event data.

## VIII.C. Rainfall Data

Annual rainfall data was available from NCEI (2018). As noted in Section VII, the annual lake evaporation was not able to be directly estimated, so the 1961-2005 annual time series of precipitation and water surface evaporation data (PETW) from the HSPF model in the Upper/Middle Charles TMDL (2011) was used. Evaluations of the rainfall data and potential evapotranspiration were reported in inches per year and meters per year.

A review of the annual precipitation conditions was conducted using the standardized precipitation index, which is a statistical method for assessing rainfall (SPI; McKee, 2993). The SPI normalizes the data to provide a better understanding of whether a year was wet (positive SPI values, greater than average precipitation) or dry (negative SPI values, less than average precipitation). A summary table of the SPI values and the representative condition is provided below in Figure VIII-I.

Table VIII-1. The complete summary of the rainfall data between 1990 and 2017 is provided in Table VIII-2 SPI between 2000 and 2017 is shown in Figure VIII-I.

## Table VIII-1. Standard Precipitation Index (SPI) Reference Values

| SPI Value | Drought/Wetness Condition |
|---|---|
| *2 and above* | **Extremely wet** |
| *1.5 to 1.99* | **Severely wet** |
| *1.0 to 1.49* | **Moderately wet** |
| *-0.99 to 0.99* | **Near normal** |
| *-1.0 to -1.49* | **Moderately dry** |
| *-1.5 to -1.99* | **Severely dry** |
| *-2.0 and less* | **Extremely dry** |

## Table VIII-2. Summary of Rainfall Data Analyses

| Year | Precip (in/yr.) | PETW (in/yr.) | SPI value | Condition |
|---|---|---|---|---|
| **1990** | 46.5 | 36.6 | 0.5 | Near normal |
| **1991** | 42.3 | 37.0 | -0.1 | Near normal |
| **1992** | 43.7 | 36.9 | 0.1 | Near normal |
| **1993** | 43.2 | 36.9 | 0.0 | Near normal |
| **1994** | 47.6 | 36.5 | 0.7 | Near normal |
| **1995** | 35.1 | 37.7 | -1.2 | Moderately dry |
| **1996** | 48.7 | 36.4 | 0.9 | Moderately wet |
| **1997** | 28.3 | 38.4 | -2.2 | Severely dry |
| **1998** | 51.3 | 36.2 | 1.3 | Very wet |
| **1999** | 37.8 | 37.5 | -0.8 | Near normal |
| **2000** | 45.6 | 36.7 | 0.4 | Near normal |
| **2001** | 30.8 | 38.1 | -1.8 | Severely dry |
| **2002** | 41.1 | 37.1 | -0.3 | Near normal |
| **2003** | 44.4 | 36.8 | 0.2 | Near normal |
| **2004** | 44.6 | 36.8 | 0.2 | Near normal |
| **2005** | 43.7 | 36.9 | 0.1 | Near normal |
| **2006** | 52.9 | 36.0 | 1.4 | Moderately wet |
| **2007** | 39.5 | 37.3 | -0.5 | Near normal |
| **2008** | 54.5 | 35.9 | 1.7 | Very wet |
| **2009** | 43.5 | 36.9 | 0.0 | Near normal |
| **2010** | 49.7 | 36.3 | 1.0 | Moderately wet |
| **2011** | 52.4 | 36.1 | 1.4 | Moderately wet |
| **2012** | 36.8 | 37.6 | -1.0 | Moderately dry |
| **2013** | 40.4 | 37.2 | -0.4 | Near normal |
| **2014** | 45.3 | 36.7 | 0.3 | Near normal |
| **2015** | 34.8 | 37.7 | -1.2 | Moderately dry |
| **2016** | 33.1 | 37.9 | -1.5 | Severely dry |
| **2017** | 43.5 | 36.9 | 0.0 | Near normal |

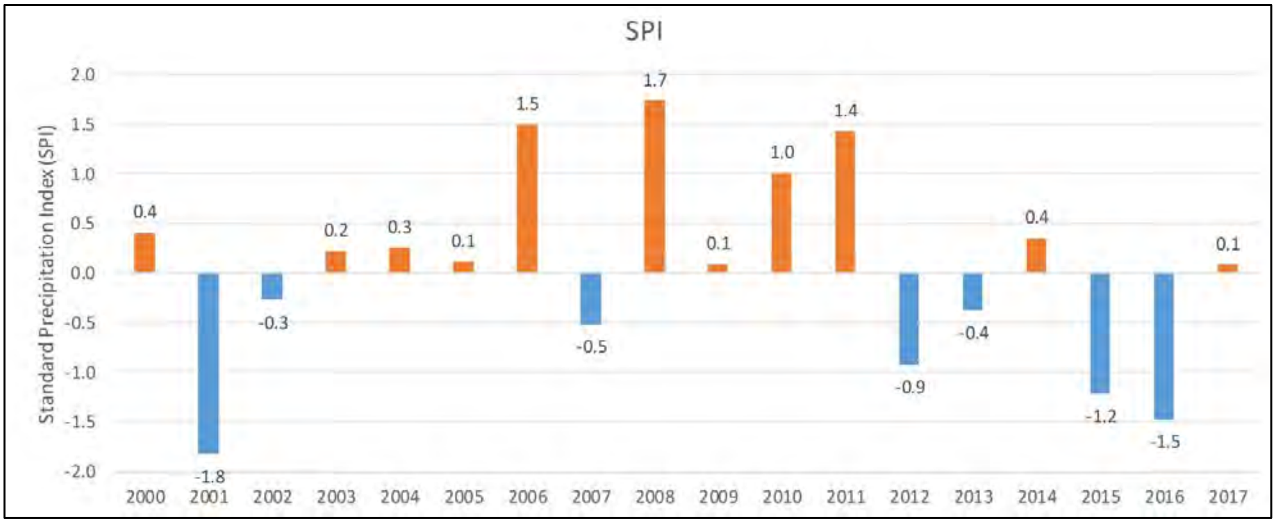



**Figure VIII-I. Standard Precipitation Index (SPI) between 2000-2017**

### *VIII.D. Critical Period Selection*

The critical period of interest for the phosphorus load reduction analyses is intended to be representative of critical climatic conditions related to the water quality endpoints (chl-a and TP), which may lead to excessive algal growth and cyanobacteria blooms in the Mystic River. Based on discussions with the technical team, a minimum of a 10-year period was recommended in order to capture the critical conditions that could lead to eutrophication. Initially, the period of 2008 to 2017 was identified to utilize the last 10-years of meteorological data and most recent water quality conditions in the water bodies. However, 2017 SSO data from MassDEP was not available at the time, so the critical period of 2007 to 2016 was selected for further review.

During the critical period, there was one very wet year (2008), two moderately wet years (2010, 2011), two moderately dry years (2012, 2015) and one severely dry year (2016). An average analysis of the rainfall and potential evapotranspiration are 43.0 and 37.0 inches/year, respectively. In comparison to the period of record (2000 to 2017), the average annual rainfall and potential evapotranspiration are 43.1 and 37.0, respectively. Overall, 2007 to 2016 was selected as the representative climatic period for further phosphorus load reduction analyses with the calibrated BATHTUB model.

### *VIII.E. Extreme Rainfall Years*

An additional evaluation of the data was also done to identify extreme rainfall years that may be used to compare against average annual data during the selected critical period. This included looking at both SPI values and 10$^{th}$ and 90$^{th}$ rainfall depth percentiles, which were used in the Upper/Middle and Lower Charles River TMDLs to evaluate the potential for exceedances for water quality and the margin of safety. During the critical period, the 10$^{th}$ percentile rainfall depth is 34.1 inches, while the 90$^{th}$ percentile rainfall depth is 52.6 inches. Comparatively, over a longer term, from 1990-2016, the 10$^{th}$ percentile rainfall depth is 34.4 inches and the 90$^{th}$ percentile rainfall depth is 51.6 inches. Comparing these values to Figure VIII-I above, 2008 would be identified as an extreme wet year, while 2016 would be considered an extreme dry year.

# IX. Evaluation of Watershed Phosphorus Load Reduction Analysis

This section documents the BATHTUB modeling methodology, loading estimates and the scenarios developed to evaluate the watershed phosphorus loading reductions necessary to address eutrophication within the Mystic River Watershed and attain water quality target (chl-a) and secondary indicatory (TP) identified in Section IV. The calibrated BATHTUB model discussed in Section VII was used for this project; the critical period of interest was identified in Section VIII for the phosphorus load reduction analysis, which is the 10-year period from 2007 to 2016. Our analysis, as described below, suggests that CSO and SSO management Ent, while important, have far less impact on annual phosphorus loads compared to stormwater.

## *IX.A. Phosphorus Loading Estimates for Critical Period of Interest*

Five different types of load estimates were developed for each reach and corresponding tributary as shown in Figure VII-II:

- Stormwater loads.
- Groundwater loads.
- Sediment nutrient efflux loads.
- Combined sewer overflow loads.
- Sanitary sewer overflow loads.

### IX.A.1. *Existing Conditions*

The watershed phosphorus loading estimates from Section V were averaged for the 10-year period from 2007 to 2016 and summarized by the five main segments (reaches) in the BATHTUB model: Upper Lobe, Upper Lake, Lower Lake, Upper Mystic Basin and Lower Mystic Basin. This includes both attenuated loads in the reaches and unattenuated loads in the tributaries. No adjustments were made to attenuation factors or to the average loads for the "existing conditions" scenario.

The existing conditions loads for the critical period of interest were summarized to determine the relative influence of each on the system. The analysis also included atmospheric loads, which are included in the BATHTUB model (see Section VII).

### IX.A.2. *Future Conditions*

In discussions with the TSC, further evaluation of phosphorus loadings under future conditions was requested in order to account for the ongoing work being done in the watershed to address both CSO and SSO overflows to downstream water bodies. The ERG team consulted with EPA, MassDEP, and MWRA to determine what expected changes should be reasonably applied to the loads under future conditions. The following are the assumptions used for the future condition scenarios discussed in Section IX.B. Refer to Section VI for further detailed discussion on the development of the CSO and SSO volumes and loads.

<u>CSO Loads</u>

In BATHTUB, the CSO loads and flows from the Cambridge combined sewer areas and parts of Somerville combined sewer areas contribute to Alewife Brook tributary, the CSO loads and flows from the rest of the Somerville's combined sewer area contributes to the Lower Basin segment. No

CSO flows go to the Upper Basin segment directly except via Alewife Brook. The annual CSO Loads used for the calibrated BATHTUB model were developed using modeled CSO volumes from MWRA's annual reports and a representative TP concentration of 3.1 mg/L, as discussed in Section VI.A.4. Under future conditions, the CSO volumes are assumed to meet the long-term control plan (LTCP) estimates for the typical rainfall year. As noted under MWRA's 2017 annual reporting of CSO discharge estimates (MWRA, 2018), the annual LTCP CSO volumes for the Alewife Brook and Upper Mystic River are 7.29 MG and 3.48 MG, respectively. To calculate the phosphorus loads, volumes were multiplied by the representative TP concentration.

<u>SSO Loads</u>

Similar to CSO Loads, SSO loads were developed by using estimated volumes obtained from MWRA and MassDEP and representative TP concentration of 5.23 mg/L, as discussed in Section VI.A.4. Under future conditions, a 50 percent reduction in SSO volumes is assumed for ongoing SSO mitigation work being done within the Mystic River Watershed. Volumes were multiplied by the representative TP concentration to determine the phosphorus loads.

<u>Stormwater Loads from Combined Sewer Separation</u>

In addition to CSO reductions, EPA also reached out to the cities of Cambridge and Somerville to determine potential for combined sewer separation (CSS) within areas still connected to CSOs at Alewife Brook and the Upper Mystic River (above the Amelia Earhart Dam). As of November 2018, the City of Cambridge has no immediate plans to evaluate or complete CSS and the City of Somerville is in the process of completing an alternative analysis to determine if CSS is a viable option. Upon discussion with the Technical Steering Committee, the ERG team developed three future conditions loading estimates: 0 percent CSS, 25 percent CSS, and 100 percent CSS. The 100 percent CSS condition is intended to provide a bookend for the maximum phosphorus load reductions that may be required and is not an expected outcome of ongoing or future efforts by the cities of Cambridge and Somerville.

Modeling of CSS for BATHTUB translates to adding the combined sewer land area added to the total acreage for each sub-basin HRU (discussed in Section V), which generate extra stormwater and groundwater loads and annual flow volumes. The combined sewer drainage areas GIS data were provided by the cities of Cambridge and Somerville (refer to Figure G-XI-1 through Figure G-XI-3 in Appendix G). The modeled land uses within the CSO drainage areas were extracted by overlaying the drainage areas and the MassGIS land use and soils data.

It is the ERG team's understanding based on conversations with MassDEP the majority of the CSO drainage areas draining to outfall SOM007A/MWR205A are treated at the Somerville Marginal facility and discharging through outfall MWR205, which is located downstream of the Amelia Earhart Dam. A volumetric comparison of the two outfalls during the critical period indicates that approximately 90 percent of the volume discharges through outfall MWR205 to the Massachusetts Bay, while 10 percent is discharging into the Upper Mystic River at SOM 007A/MWR205A. Consequently, for the purposes of evaluating future conditions, the ERG team has assumed that 10 percent of the land uses that were assumed to be contributing to outfall SOM007A/MWR205A are discharging to the Mystic River above the dam. Further, because the Somerville Marginal CSO Facility provides screening and disinfection only, there are no reductions in TP concentrations assumed for future conditions.

To evaluate the impact of the three CSS future conditions, the percent CSS (0, 25, or 100 percent) was multiplied by the land uses contributing to either the Alewife Brook tributary or the Lower

Basin reach. The land areas for each were added to the HRUs, which were then summarized for the BATHTUB model. In addition, the CSO loads were reduced according to the CSS future condition (25 or 100 percent), so that for the scenario with 100 percent CSS, the CSO loads were zeroed.

Other Stormwater Loads

No additional changes to the land uses or stormwater loads were assumed (e.g., new development or redevelopment of land).

Groundwater Loads

Since groundwater loads are computed from stormwater loads, changes due to the CSS future conditions results in changes to groundwater loads. The scale of the impact is dependent on the percent CSS noted above and proportional to the change in stormwater loads.

When stormwater reductions were made in the various scenarios, the groundwater loads were not changed.

Sediment Nutrient Efflux Loads

Under future conditions the ERG team assumed that there would be a decrease in sediment nutrients as a result of management and land loads  For modeling purposes, the ERG team estimated that the sediment load is reduced by 50 percent of the estimated stormwater phosphorus load reduction (e.g., Stormwater TP Load Reductions = 60 percent, Sediment Load Reductions = 30 percent). This methodology is slightly more conservative than the method used for the Upper/Middle Charles Nutrient TMDL (EPA/DEP, 2011).  Under that method, there was a 25 percent sediment nutrient efflux load reduction that could be assumed with the reduction of phosphorus loads and sediment loads were approximately 50 percent of the total phosphorus load reduction (including CSO/SSO loads, groundwater, etc.) required to meet the water quality target (e.g., Total TP Load Reductions = 50 percent, Sediment Load Reductions = 25 percent).

### IX.B. Scenarios for Evaluation of Phosphorous Reduction

The ERG team developed four scenarios to evaluate the watershed conditions necessary for the water quality target to be met: existing conditions (1 scenario) and future conditions (3 scenarios) (Table IX-1). As identified in Section IX.A, future conditions include reductions in CSOs and SSOs, in addition to evaluating conditions with CSS. Each of these four scenarios were run with a baseline model (#1 ,2, 3, 4) and a water quality (WQ) target model (# 1A, 2A, 3A, 4A) to provide comparisons between the results.

**Table IX-1. Modeled Scenarios for Phosphorus Load Reduction Evaluations**

| Scenario # | Scenario Name | CSO Load Reductions[a] | SSO Load Reductions[b] | CSS[c] | Stormwater Load Reductions | Sediment Load Reductions |
|---|---|---|---|---|---|---|
| 1 | Existing Conditions - Baseline | | | | | |
| 1A | Existing Conditions – WQ Target | | | | X | X |
| 2 | Future Conditions 1 - Baseline | X | X | | | |
| 2A | Future Conditions 1 – WQ Target | X | X | | X | X |
| 3 | Future Conditions 2 - Baseline | X | X | 25% | | |
| 3A | Future Conditions 2 – WQ Target | X | X | 25% | X | X |
| 4 | Future Conditions 3 - Baseline | X | X | 100% | | |
| 4A | Future Conditions 3 – WQ Target | X | X | 100% | X | X |

a) CSO volumes to the Alewife Brook and Mystic River (Lower Basin) reduced to meet the LTCP target.
b) SSO volume reductions at 50 percent across all tributaries and sub basins.
c) CSS percentage indicates percent of combined sewer area that is assumed to be separated. The separated land uses are added to the sub-basin area and generate additional stormwater flow and loads.

For each of the WQ target scenarios (#1A, 2A, 3A, 4A), multiple model runs were completed to evaluate the reductions in stormwater loads and sediment efflux necessary to meet the water quality target in all model segments. In Section IV, chlorophyll-a (chl-a) was identified as the WQ target, specifically the seasonal average chl-a (<10 µg/L). TP of 30 µg/L was used as a secondary indicator. This analysis focused on the seasonal average chl-a because the regressions of the TP and seasonal average chl-a concentrations performed in Section IV indicate a linear relationship, such that attainment of the seasonal average chl-a (10 µg/L) would provide attainment of the TP concentration needed to meet water quality goals. Iterations were conducted for each WQ target scenario until the seasonal average chl-a was met. Predicted TP concentrations are reported in the results and was compared to the water quality secondary indicator (30 µg/L) for reference.

## IX.C. Modeling Methodology

### IX.C.1. Model Setup

The BATHTUB model used for the load reduction analysis was calibrated by Dr. Nigel Pickering in November 2018.

### IX.C.2. Model Inputs

The BATHTUB model allows the user to change a number of model inputs. The BATHTUB input parameters that are adjusted for each segment in the model to achieve the various scenarios include drainage area, flow, total nitrogen, inorganic nitrogen, total phosphorous, orthophosphate, and the total phosphorus internal loading rate. The parameters are changed for the total segment, including both unattenuated loads to the reach (from adjacent sub basin area) and the attenuated loads from inflowing stream (tributaries). The flow and loads were average annual values calculated over the critical period from 2007 to 2016. The input data for BATHTUB was converted to metric units (see Section VII) from the units derived from the loading spreadsheet model (e.g., lb./year, ac-in/yr., mg/L). None of the calibrated model coefficients, model options, calibration factors, segment morphometry, atmospheric loads, and global variables were changed for this analysis.

Once the input parameters were changed in the BATHTUB model to reflect the average annual scenario conditions, the BATHTUB model was run. Model output was exported into an Excel spreadsheet. The model outputs that were recorded for each scenario run include the average chl-a and Total P concentrations for each model segment: Upper Lobe (1), Upper Lake (2), Lower Lake (3), Upper Basin (4), and Lower Basin (5).

### IX.C.3. *Analysis with Wet and Dry Year Data*

The model scenarios described above use the average annual flows and loads calculated over the critical period (2007-2016). In order to evaluate whether the water quality target would be met during extreme precipitation, additional model scenarios were developed to evaluate responses to the water quality target during a wet year and for a dry year. The selection of the years was based on precipitation and relative drought/wetness condition (as defined by the standard precipitation index and the $10^{th}$ and $90^{th}$ percentile) noted in Section VIII as well as the annual total nutrient loads based on data from Section V. While 2008 was considered to be the wettest year in the critical period, 2010 had the highest annual loads for total phosphorus and was considered to be moderately wet. 2016 was a severely dry year and had the lowest annual loads for total phosphorus. For extreme precipitation analyses, 2010 and 2016 were selected for wet year and dry year analyses, respectively.

## *IX.D. Model Results with Average Annual Data*

A total of 29 runs were performed for the water quality target scenarios (Table IX-2). A summary of the key results is shown in Table IX-3; further detailed inputs and outputs are outlined in Appendix J. The BATHTUB output spreadsheet files, which are not submitted as part of this memorandum, can be made available upon request.

The starting point for the stormwater phosphorus load reduction runs was determined based on the magnitude of reductions that is needed to meet the water quality target without sediment load reductions, which is approximately in the 70 to 80 percent range. The modeling of the stormwater phosphorus load reductions process started with reducing the percent reductions for stormwater each run until the predicted water quality conditions transition from exceeding the target to meeting it. Once the water quality target was met with only stormwater reductions, the sediment efflux reductions were incorporated. The sediment efflux was reduced by half of the estimated stormwater phosphorus load reduction. The iterative process then continued, lessening both the percent reductions for stormwater loads and sediment efflux (half of the stormwater reductions) until the water quality target was met. The ending point for the stormwater and sediment efflux reduction runs was when the water quality target was exceeded for all segments. Text in red font in Table IX-2 indicates the run that met the chl-a water quality target.

**Table IX-2. BATHTUB Model Runs[a] with Average Annual Data**

| Scenario | Run # | Stormwater Reduction (%) | Sediment Efflux Reduction (%) |
|---|---|---|---|
| **1** | 1 | 0 | 0 |
| **1a** | 2 | 80 | 0 |
| | 3 | 78 | 0 |

| | | | |
|---|---|---|---|
| | 4 | 78 | 39 |
| | 5 | 70 | 35 |
| | 6 | 68 | 34 |
| | 7 | 67 | 33 |
| | 8 | 66 | 33 |
| **2** | 9 | 0 | 0 |
| **2a** | 10 | 80 | 0 |
| | 11 | 73 | 0 |
| | 12 | 73 | 37 |
| | 13 | 64 | 32 |
| | 14 | 62 | 31 |
| | 15 | 61 | 31 |
| **3** | 16 | 0 | 0 |
| **3a** | 17 | 75 | 0 |
| | 18 | 73 | 0 |
| | 19 | 73 | 37 |
| | 20 | 63 | 32 |
| | 21 | 61 | 31 |
| | 22 | 60 | 30 |
| **4** | 23 | 0 | 0 |
| **4a** | 24 | 75 | 0 |
| | 25 | 71 | 0 |
| | 26 | 71 | 36 |
| | 27 | 62 | 31 |
| | 28 | 59 | 29 |
| | 29 | 58 | 28 |

a) Red font indicates the run that met the water quality target for chl-a.

Table IX-3 is a summary of the key results for each scenario: the base run and the run that met the water quality target with stormwater and sediment efflux reductions. This table shows the predicted phosphorus concentration and chl-a concentration. In addition, the model input, TP Load, is shown for comparison across scenarios. Cells highlighted in grey indicate segments that do not meet the water quality target. Figure IX-I and Figure IX-II further show the key results by segment for phosphorus and chl-a concentrations, respectively. More detailed scenario information is available in Appendix H.

## Table IX-3. Scenario Results[a] with Average Annual Data

| Scenario – Run # | Parameter | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|
| **1 - 1** | Total P Load (lb./yr.) | 3,907 | 416 | 1,558 | 3,298 | 3,849 |
| | Predicted P Conc. (µg/L) | 43.4 | 33.1 | 33.6 | 46.2 | 57.7 |
| | Predicted chl-a Conc. (µg/L) | 13.9 | 7.6 | 7.7 | 16.4 | 19.4 |
| **1a - 7** | SW P Load Reduction (%) | 67 | | | | |
| | P Sediment Efflux Reduction (%) | 33 | | | | |
| | Total P Load (lb./yr.) | 1,490 | 161 | 625 | 1,553 | 1,608 |
| | Predicted P Conc. (µg/L) | 20.8 | 18.6 | 19.4 | 25.3 | 31.1 |
| | Predicted chl-a Conc. (µg/L) | 5.9 | 4.1 | 4.3 | 8.1 | 10.0 |
| **2 - 9** | Total P Load (lb./yr.) | 3,892 | 410 | 1,526 | 2,968 | 3,707 |
| | Predicted P Conc. (µg/L) | 43.3 | 33.0 | 33.3 | 44.2 | 55.8 |
| | Predicted chl-a Conc. (µg/L) | 13.9 | 7.6 | 7.7 | 15.6 | 18.8 |
| **2a - 14** | SW P Load Reduction (%) | 62 | | | | |
| | P Sediment Efflux Reduction (%) | 31 | | | | |
| | Total P Load (lb./yr.) | 1,655 | 175 | 663 | 1,354 | 1,632 |
| | Predicted P Conc. (µg/L) | 22.4 | 19.8 | 20.4 | 24.9 | 31.1 |
| | Predicted chl-a Conc. (µg/L) | 6.5 | 4.4 | 4.6 | 7.9 | 9.9 |
| **3 - 16** | Total P Load (lb./yr.) | 3,892 | 410 | 1,526 | 3,033 | 3,704 |
| | Predicted P Conc. (µg/L) | 43.3 | 33.0 | 33.3 | 44.2 | 55.6 |
| | Predicted chl-a Conc. (µg/L) | 13.8 | 7.6 | 7.6 | 15.6 | 18.7 |
| **3a - 21** | SW P Load Reduction (%) | 61 | | | | |
| | P Sediment Efflux Reduction (%) | 31 | | | | |
| | Total P Load (lb./yr.) | 1,691 | 178 | 677 | 1,393 | 1,652 |
| | Predicted P Conc. (µg/L) | 22.7 | 20.0 | 20.6 | 24.9 | 31.1 |
| | Predicted chl-a Conc. (µg/L) | 6.6 | 4.5 | 4.6 | 7.9 | 9.9 |
| **4 - 23** | Total P Load (lb./yr.) | 3,892 | 410 | 1,526 | 3,227 | 3,697 |
| | Predicted P Conc. (µg/L) | 43.2 | 32.9 | 33.2 | 43.4 | 54.5 |
| | Predicted chl-a Conc. (µg/L) | 13.8 | 7.5 | 7.6 | 15.3 | 18.3 |
| **4a - 28** | SW P Load Reduction (%) | 59 | | | | |
| | P Sediment Efflux Reduction (%) | 29 | | | | |
| | Total P Load (lb./yr.) | 1,763 | 186 | 705 | 1,490 | 1,680 |
| | Predicted P Conc. (µg/L) | 23.4 | 20.4 | 21.1 | 25.0 | 31.1 |
| | Predicted chl-a Conc. (µg/L) | 6.9 | 4.6 | 4.7 | 7.9 | 9.9 |

a) Grey highlighted cell indicates the predicted value does not meet the chl-a target.

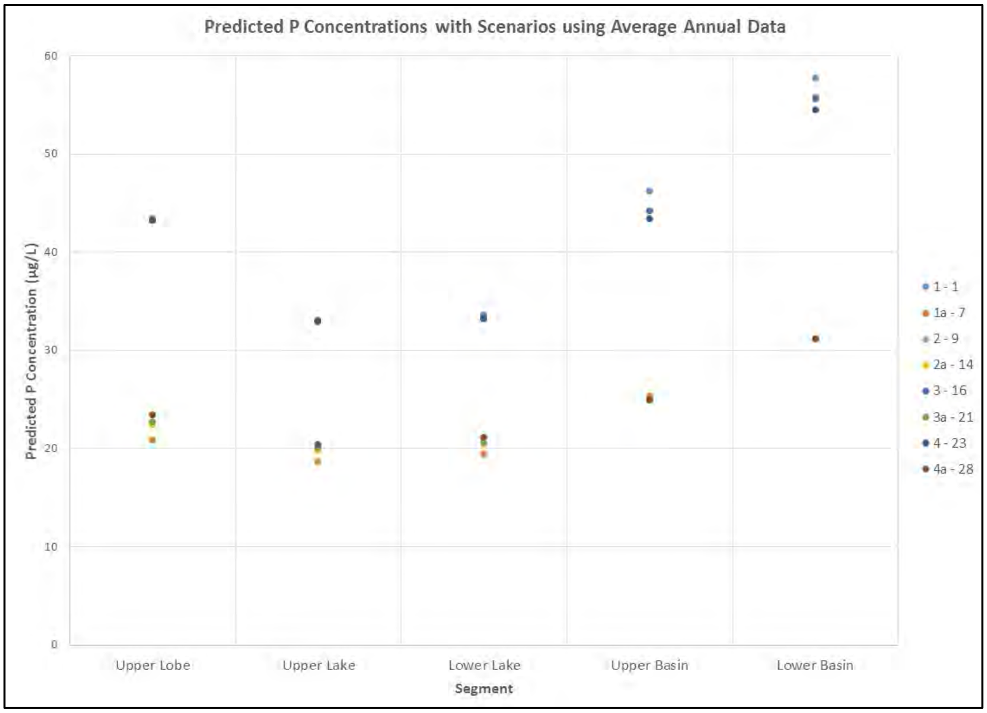



**Figure IX-I. Predicted Phosphorus Concentrations with Average Annual Data**

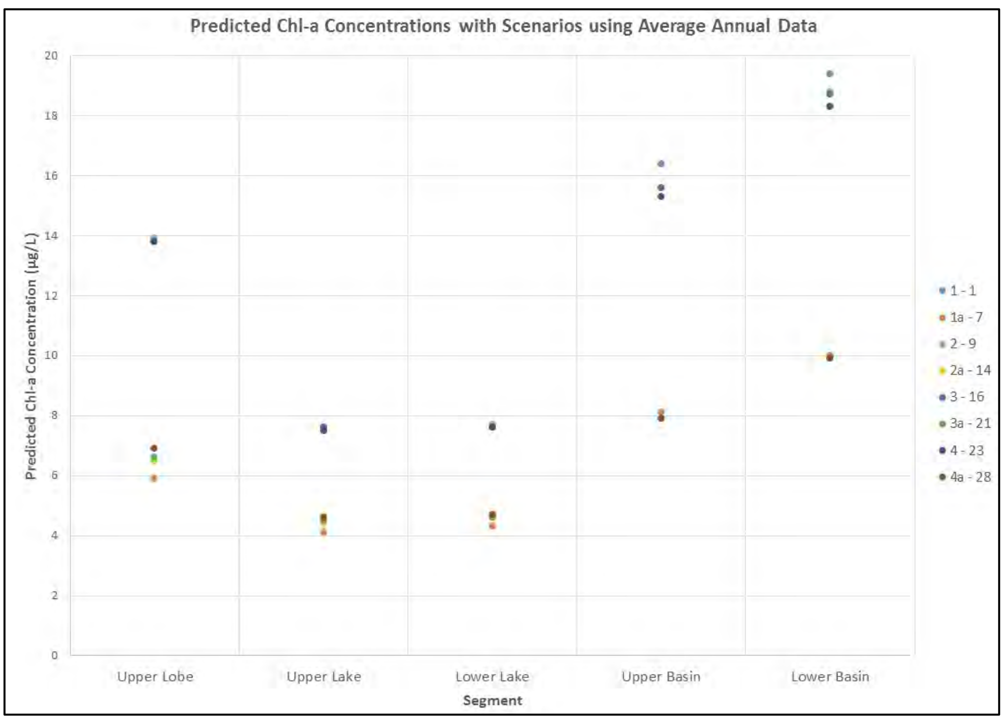



**Figure IX-II. Predicted Chlorophyll-a Concentrations with Average Annual Data**

## IX.E. Analysis with Wet and Dry Year Data

An additional eight runs were conducted to evaluate whether the chl-a water quality target would be met during extreme wet and dry years. The starting point for these runs under each scenario was the run that met the target (refer to Figure IX-II and Figure IX-III). The average annual flow and loads were replaced by either the wet or dry year annual flow and load values, as appropriate. The same stormwater reduction and sediment efflux reductions were applied as was used to meet the chl-a water quality target in the scenario when using the average annual flow and load values. Table IX-4 shows the additional runs that were conducted for this analysis. Text in red font in indicate Table IX-4 the run that met the chl-a water quality target.

### Table IX-4. Model Runs[a] with Wet and Dry Year Data

| Scenario | Run # | Wet/Dry Year Data | Stormwater Reduction (%) | Sediment Efflux Reduction (%) |
|---|---|---|---|---|
| **1a** | 7 | Wet (2010) | 67 | 33 |
| **1a** | 7 | Dry (2016) | 67 | 33 |
| **2a** | 14 | Wet (2010) | 62 | 31 |
| **2a** | 14 | Dry (2016) | 62 | 31 |
| **3a** | 21 | Wet (2010) | 61 | 31 |
| **3a** | 21 | Dry (2016) | 61 | 31 |
| **4a** | 28 | Wet (2010) | 59 | 29 |
| **4a** | 28 | Dry (2016) | 59 | 29 |

a) Red font indicates the run that met the water quality target for chl-a.

Table IX-5 is a summary of the key results for each run. Cells highlighted in grey indicate segments that do not meet the water quality target. Figure IX-III and Figure IX-IV further show the key results by segment for phosphorus and chl-a concentrations, respectively. More detailed scenario information is available in Appendix H.

### Table IX-5. Scenario Results[a] with Wet and Dry Year Data

| Scenario – Run # | Parameter | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|
| **1a – 7 (Wet)** | SW P Load Reduction (%) | 67 | | | | |
| | P Sediment Efflux Reduction (%) | 33 | | | | |
| | Total P Load (lb./yr.) | 2,153 | 301 | 1,089 | 2,758 | 2,445 |
| | Predicted P Conc. (µg/L) | 18.9 | 17.9 | 19.8 | 26.2 | 30.5 |
| | Predicted chl-a Conc. (µg/L) | 5.2 | 3.8 | 4.3 | 8.3 | 9.5 |
| **1a – 7 (Dry)** | SW P Load Reduction (%) | 67 | | | | |
| | P Sediment Efflux Reduction (%) | 33 | | | | |
| | Total P Load (lb./yr.) | 968 | 79 | 353 | 760 | 998 |
| | Predicted P Conc. (µg/L) | 24.9 | 20.3 | 20.1 | 26.3 | 35 |
| | Predicted chl-a Conc. (µg/L) | 7.5 | 4.7 | 4.6 | 8.6 | 11.6 |
| **2a -14 (Wet)** | SW P Load Reduction (%) | 62 | | | | |
| | P Sediment Efflux Reduction (%) | 31 | | | | |
| | Total P Load (lb./yr.) | 2,328 | 304 | 1,053 | 1,884 | 2,124 |
| | Predicted P Conc. (µg/L) | 20.0 | 18.7 | 20.2 | 23.2 | 27.4 |
| | Predicted chl-a Conc. (µg/L) | 5.6 | 4.0 | 4.4 | 7.1 | 8.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **2a – 14 (Dry)** | SW P Load Reduction (%) | 62 | | | | |
| | P Sediment Efflux Reduction (%) | 31 | | | | |
| | Total P Load (lb./yr.) | 1,090 | 90 | 398 | 944 | 1,177 |
| | Predicted P Conc. (µg/L) | 26.9 | 21.4 | 21.2 | 29.0 | 38.4 |
| | Predicted chl-a Conc. (µg/L) | 8.3 | 5.0 | 4.9 | 9.7 | 12.9 |
| **3a – 21 (Wet)** | SW P Load Reduction (%) | 61 | | | | |
| | P Sediment Efflux Reduction (%) | 31 | | | | |
| | Total P Load (lb./yr.) | 2,377 | 310 | 1,073 | 1,939 | 2,155 |
| | Predicted P Conc. (µg/L) | 20.4 | 19 | 20.4 | 23.3 | 27.5 |
| | Predicted chl-a Conc. (µg/L) | 5.7 | 4.1 | 4.4 | 7.2 | 8.4 |
| **3a – 21 (Dry)** | SW P Load Reduction (%) | 61 | | | | |
| | P Sediment Efflux Reduction (%) | 31 | | | | |
| | Total P Load (lb./yr.) | 1,115 | 92 | 407 | 965 | 1,186 |
| | Predicted P Conc. (µg/L) | 27.2 | 21.6 | 21.4 | 28.9 | 38.3 |
| | Predicted chl-a Conc. (µg/L) | 8.4 | 5 | 5 | 9.7 | 12.9 |
| **4a – 28 (Wet)** | SW P Load Reduction (%) | 59 | | | | |
| | P Sediment Efflux Reduction (%) | 29 | | | | |
| | Total P Load (lb./yr.) | 2,474 | 322 | 1,112 | 2,079 | 2,206 |
| | Predicted P Conc. (µg/L) | 21 | 19.5 | 21 | 23.4 | 27.7 |
| | Predicted chl-a Conc. (µg/L) | 5.9 | 4.2 | 4.5 | 7.2 | 8.5 |
| **4a – 28 (Dry)** | SW P Load Reduction (%) | 59 | | | | |
| | P Sediment Efflux Reduction (%) | 29 | | | | |
| | Total P Load (lb./yr.) | 1,164 | 96 | 425 | 1,015 | 1,188 |
| | Predicted P Conc. (µg/L) | 28.1 | 22 | 21.8 | 28.7 | 37.9 |
| | Predicted chl-a Conc. (µg/L) | 8.7 | 5.1 | 5.1 | 9.6 | 12.7 |

a) Grey highlighted cell indicates the predicted value does not meet the chl-a target.

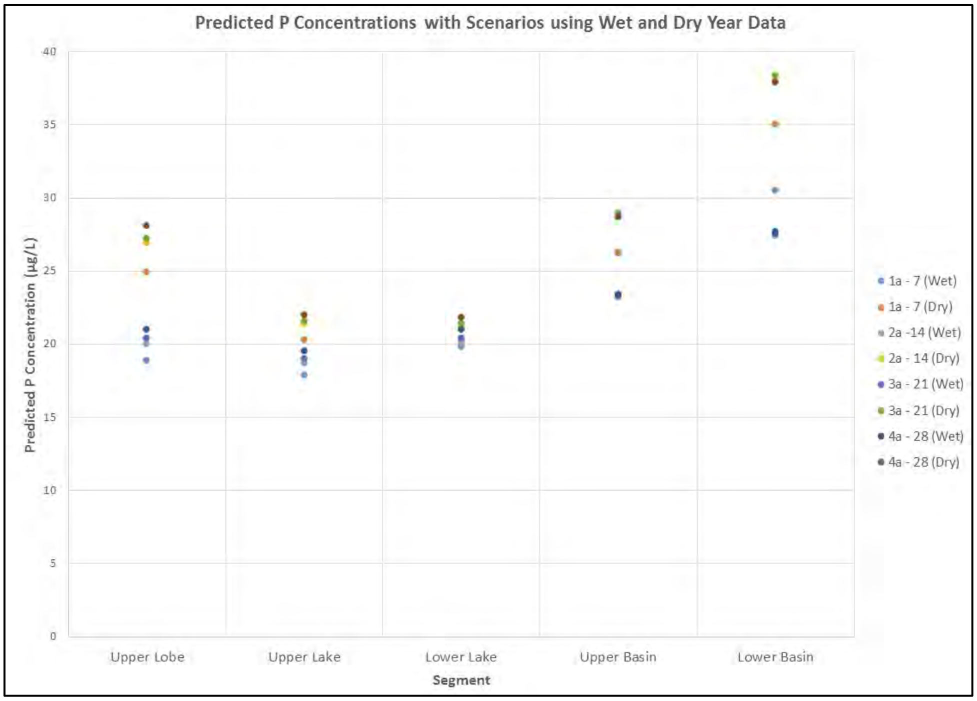



**Figure IX-III. Predicted Phosphorus Concentrations with Wet and Dry Year Data**

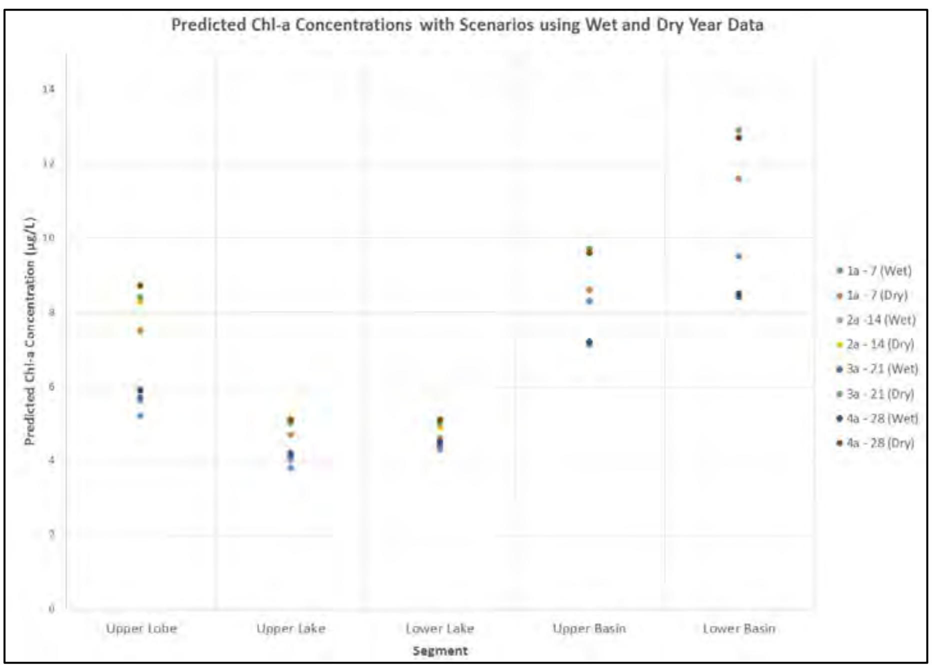



**Figure IX-IV. Predicted Chlorophyll-a Concentrations with Wet and Dry Year Data**

## IX.F. Discussion

In each base run for the four scenarios, the Upper Lake and Lower Lake segments meet the chl-a water quality target without any stormwater and sediment load reductions. The Lower Basin segment requires the most significant reductions to meet the water quality target (i.e., it is the critical segment in this analysis). Overall, under existing conditions, a 67 percent reduction is required for stormwater phosphorus loads with a 33 percent reduction in sediment efflux. The stormwater load reductions required under future conditions (scenarios 2A, 3A and 4A) were between approximately 59 and 62 percent with a 30 to 31 percent required sediment efflux reduction. Table X provides a total phosphorus load comparison between existing conditions and scenario 2A. Since the focus of this table is the entire watershed, we report **unattenuated** land loads here. Under future conditions scenarios 3A and 4A with CSS, the overall phosphorus loads, and flows increase, though not proportionally, which appears to be resulting in lower overall phosphorus concentrations and lower required reductions compared to scenario 2A.

**Table IX-6. Total Phosphorus Load Reductions for Scenario 2A**

| Item | Stormwater | Groundwater | CSO/SSO | Internal | Atmospheric | Total |
|---|---|---|---|---|---|---|
| Existing Conditions Total P Load (lb./yr.) | 14,887 | 1,141 | 1,696 | 3,793 | 120 | 21,638 |
| Scenario 2A P Load (lb./yr. | 9,974 | 1,141 | 412 | 1,271 | 120 | 12,919 |
| Reduction (%) | 67% | 0% | 24% | 34% | 0% | 60% |

For this analysis, stormwater and sediment efflux reductions were made consistently across all tributaries and sub-basins. However, further analysis can determine what the minimum required reductions are for the first three segments versus the last two segments (Upper Basin and Lower Basin) in order to meet the water quality target. For example, in scenario 1A, run #7, the water quality target for chl-a is just met in the Lower Basin segment with a concentration of 9.9 µg/L. However, in the Upper Lake and Lower Lake model segments, the concentrations are over half the water quality target at 4.1 and 4.3 µg/L, respectively. It is evident that the Upper Lobe, Upper Lake, and Lower Lake model segments do not require as significant reductions compared to the Upper Basin and Lower Basin model segments. An evaluation of high intensity land uses (e.g., commercial/industrial uses, high density/multi-family residential, transportation, etc.) such was done in the Upper/Middle and Lower Charles River TMDL evaluations, including analysis of relative loads and required reductions by segment, could provide additional clarification in the future as the TMDL implementation plan is established to meet the water quality targets.

Further analysis with wet and dry year data explores whether the chl-a water quality target can be met during extreme conditions. During a wet year (such as 2010) the chl-a target appears to be met without having to further adjust the stormwater reductions or sediment efflux reductions as compared to the average annual loads. It appears that the wet year provided dilution of the loads, and perhaps overall improved water quality, so much that less stormwater reductions would be needed to achieve the target. In contrast, a dry year (such as 2016) would not meet the chl-a target unless further stormwater reductions were applied. However, because 2016 was an extreme dry year (below the 10$^{th}$ percentile threshold), the exceedance of water quality targets under these conditions would be statistically infrequent. More detailed modeling with additional water quality data could help to provide greater confidence in the recommended phosphorus load reductions and the potential exceedances of chl-a.

# X. Broad-Based Nutrient Stormwater Management Strategies for the Mystic River Watershed using Opti-Tool

Highly urbanized areas often have limited opportunities for implementing large-scale Stormwater Control Measures (SCMs) for treating stormwater runoff. Distributed green infrastructure (GI) practices can provide cost-effective solutions that achieve load reduction numeric targets while effectively integrating within urbanized landscapes. In New England, almost 50 percent of daily rainfall events are less than 0.3 inches. The relatively small size of distributed GI facilities substantially increases the feasibility to provide treatment to runoff from impervious surfaces in constrained developed spaces and achieve meaningful water quality benefits in receiving waters.

Strategically optimizing the selection and placement of distributed SCMs within highly urbanized settings can also help to develop management strategies that are more cost-effective than the traditional approach of sizing BMPs at fixed locations to treat a design storm. The Opti-Tool, which was developed for the United States Environmental Protection Agency (USEPA) Region 1, is a continuous simulation model that can be used to optimize the selection and placement of distributed GI practices at a watershed scale. This case study demonstrates how the Opti-tool can be used to help with stormwater management planning in urban New England settings and highlights the value of conducting strategic planning to address stormwater impacts for achieving water resource goals. It presents an analytical framework that can be readily customized and applied in other settings to inform the stormwater management planning effort. This section also provides examples of GI implementation efforts in other locations where distributed GI practices were also found to be cost-effective stormwater management strategies.

## *X.A. Study Objectives*

Two stormwater management scenarios were formulated to evaluate two different stormwater management approaches that meet the required annual TP load reduction target for the Mystic River Watershed. These scenarios were configured and optimized using the Opti-Tool:

1. Design-Storm Objective: Optimize distributed BMP locations by land use type with fixed sizes to capture 1 inch of runoff for a design storm and develop cost-effectiveness curve (CE-Curve).
2. Mix-Storm Objective: Optimize distributed BMP locations and sizes by land use type to reflect flexible sizing approach and develop CE-Curve.

This section presents a step-by-step, high-level technical approach to identify structural controls associated with cost-effective stormwater management strategies. The Mystic River Watershed in Massachusetts was selected as a watershed to test the sensitivities of the two stormwater management scenarios and to identify the most cost-effective management approach that achieves the phosphorus reduction objectives.

## *X.B. Pilot Sub-Watershed Selection*

The Mystic River Watershed consists of 15 sub-watersheds, which drain into three primary river segments, and seven large impoundments (ponds/lakes). This stormwater management portion of the project uses one Mystic River sub-watershed to implement a high-level, generalized approach and step-by-step guidance that is transferable to other sub-watersheds.

The pilot sub-watershed that was selected is representative of the overall land use distribution in the Mystic River Watershed. This comparison was made by computing the root mean square error (RMSE) of the percent area distribution of each land use category between individual sub-watersheds and the entire Mystic River Watershed. The four watersheds with the minimum RMSE (indicating a close match to the overall watershed distribution) were: Malden, Judkins, Lower Mystic, and Mystic River. Each of the four were intersected with municipal boundaries. The Mystic River sub-watershed was selected for the pilot study because of its central location within the watershed. It also represents a large portion of one community, the City of Medford. The pilot sub-watershed is highlighted in yellow in Figure X-I.

The pilot sub-watershed comprises 5,151 acres of land and 179 acres of water bodies. Combined Sewer Overflow (CSO) basins within the pilot sub-watershed drain 1,010 acres of land. Half of the sub-watershed area is on low-slope topography (i.e., less than 5%) and 12% of the sub-watershed area has slope larger than 15% (Table X-1, Figure X-II). The dominant soil type in the pilot watershed is hydrologic soil group (HSG) C, which makes up 70% of the total watershed area (Table X-2, Figure X-III). Soil map units with no HSG attribute data were assumed to be C soils (Group C soils have relatively low infiltration rates). The dominant land use type in the pilot watershed is high-density residential (46%) followed by forest (24%) and commercial (15%) land uses (Figure X-IV). The pilot watershed is 49% impervious and the impervious portion of the watershed is mostly high-density residential (28%), followed by commercial (11%) and transportation (highways) (4%). The pervious portion of the watershed is mostly forest (23%) followed by high density residential pervious (18%) and commercial pervious (4%), as shown in Figure X-V and Table X-3.

One-fifth of the pilot sub-watershed area falls within a CSO basin. That area was excluded from the analysis because the CSO drainage area does not include separate stormwater drainage systems that discharge to the receiving water. Thus, no stormwater controls were explored in CSO areas.

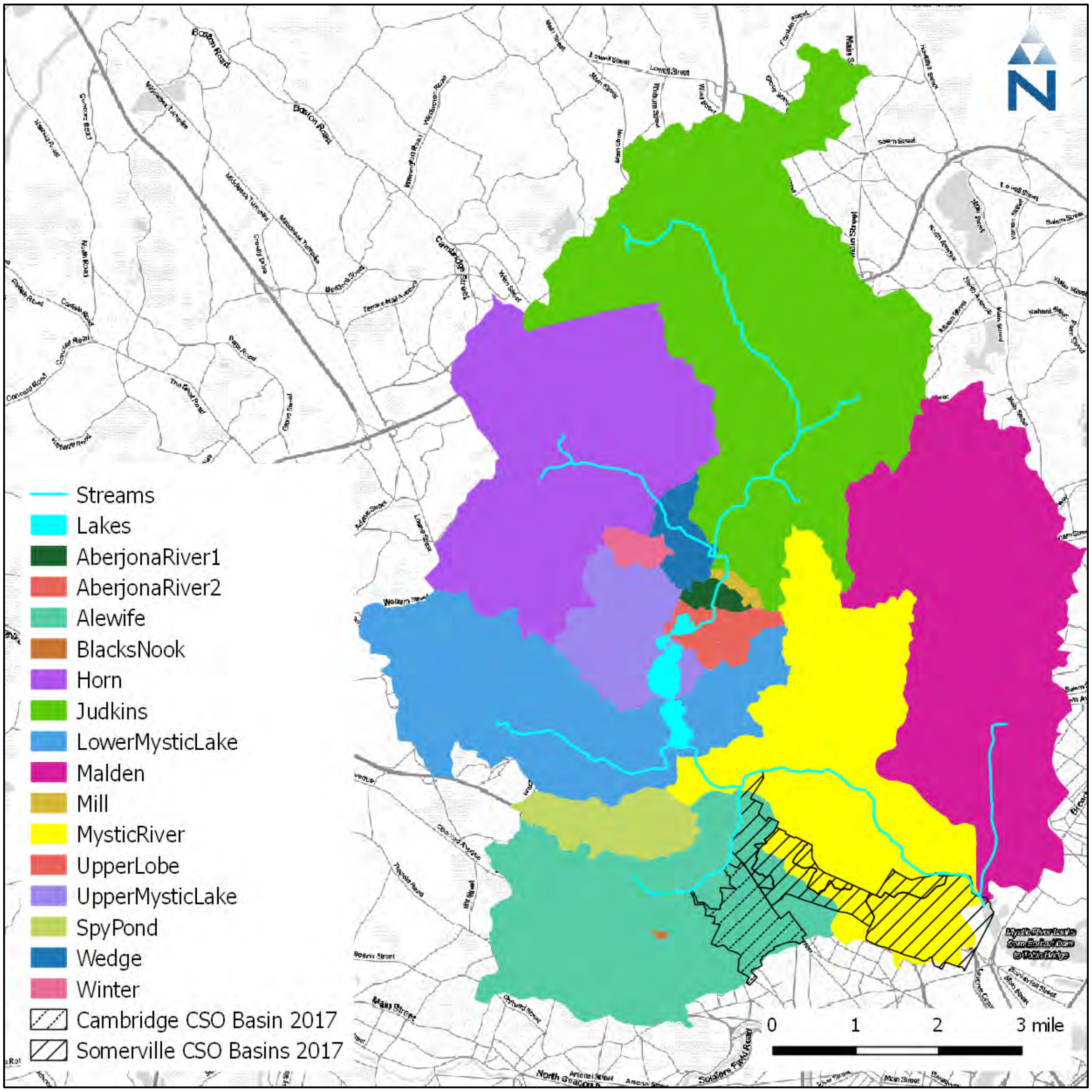



**Figure X-I. Location Map of Pilot Sub-Watershed, Mystic River (Highlighted in Yellow)**

**Table X-1. Ground Slope Classification in Pilot Sub-Watershed, Mystic River**

| Ground Slope Classification | Percent Slope | Area (acres) |
|---|---|---|
| Low | 0% - 5% | 2,852.92 |
| Moderate | 5% - 15% | 1,861.32 |
| High | >15% | 615.65 |
| | **Total area** | **5,329.89** |

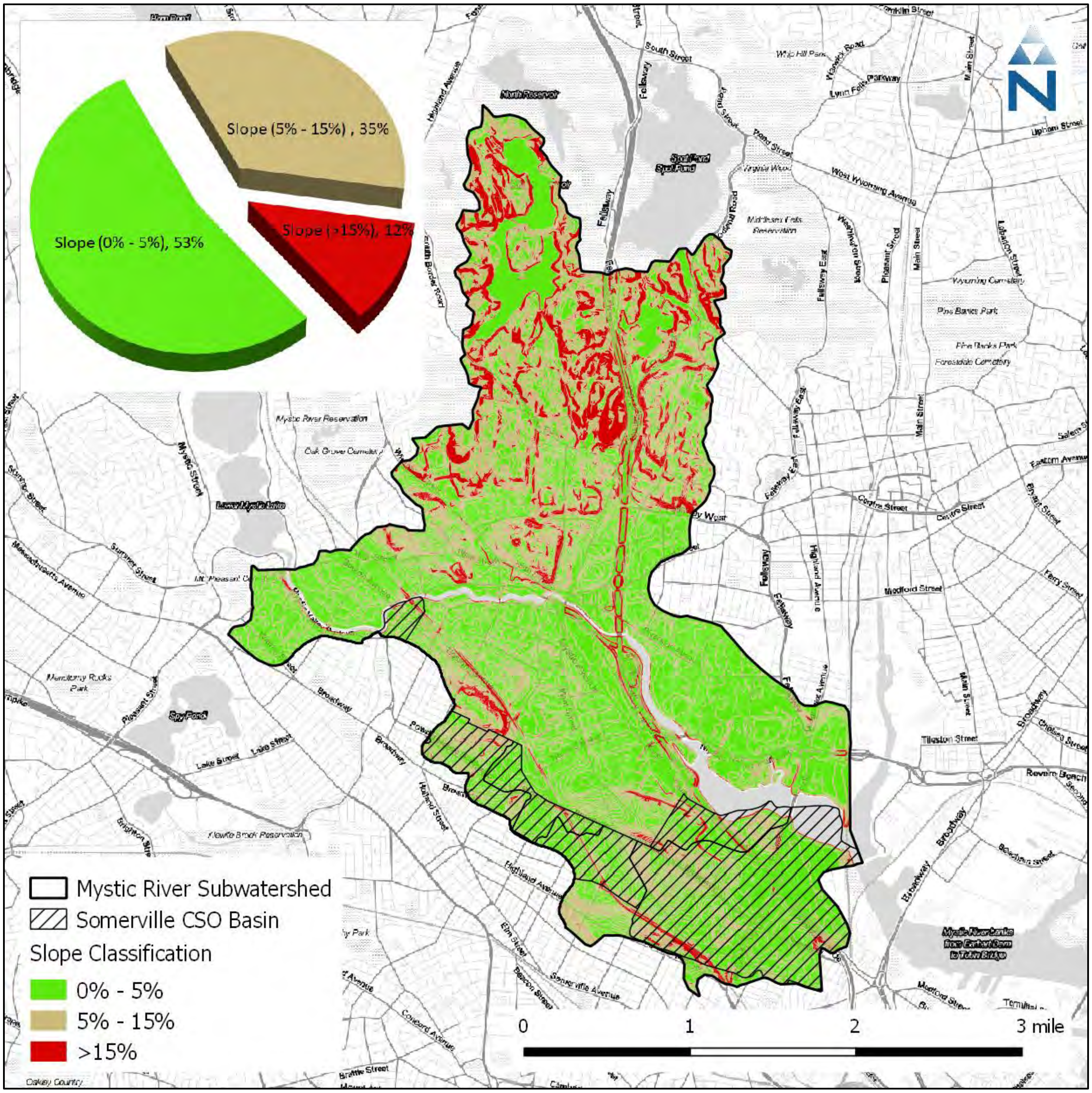



**Figure X-II. Ground Slope Map of Pilot Sub-Watershed, Mystic River**

**Table X-2. Hydrologic Soil Group Classification in Pilot Sub-Watershed, Mystic River**

| Soil Classification | HSG | Area (acres) |
|---|---|---|
| No Data | C | 3,601.45 |
| HSG-B | B | 560.90 |
| HSG-C | C | 85.04 |
| HSG-C/D | C/D | 283.45 |
| HSG-D | D | 799.05 |
| | **Total area** | **5,329.89** |

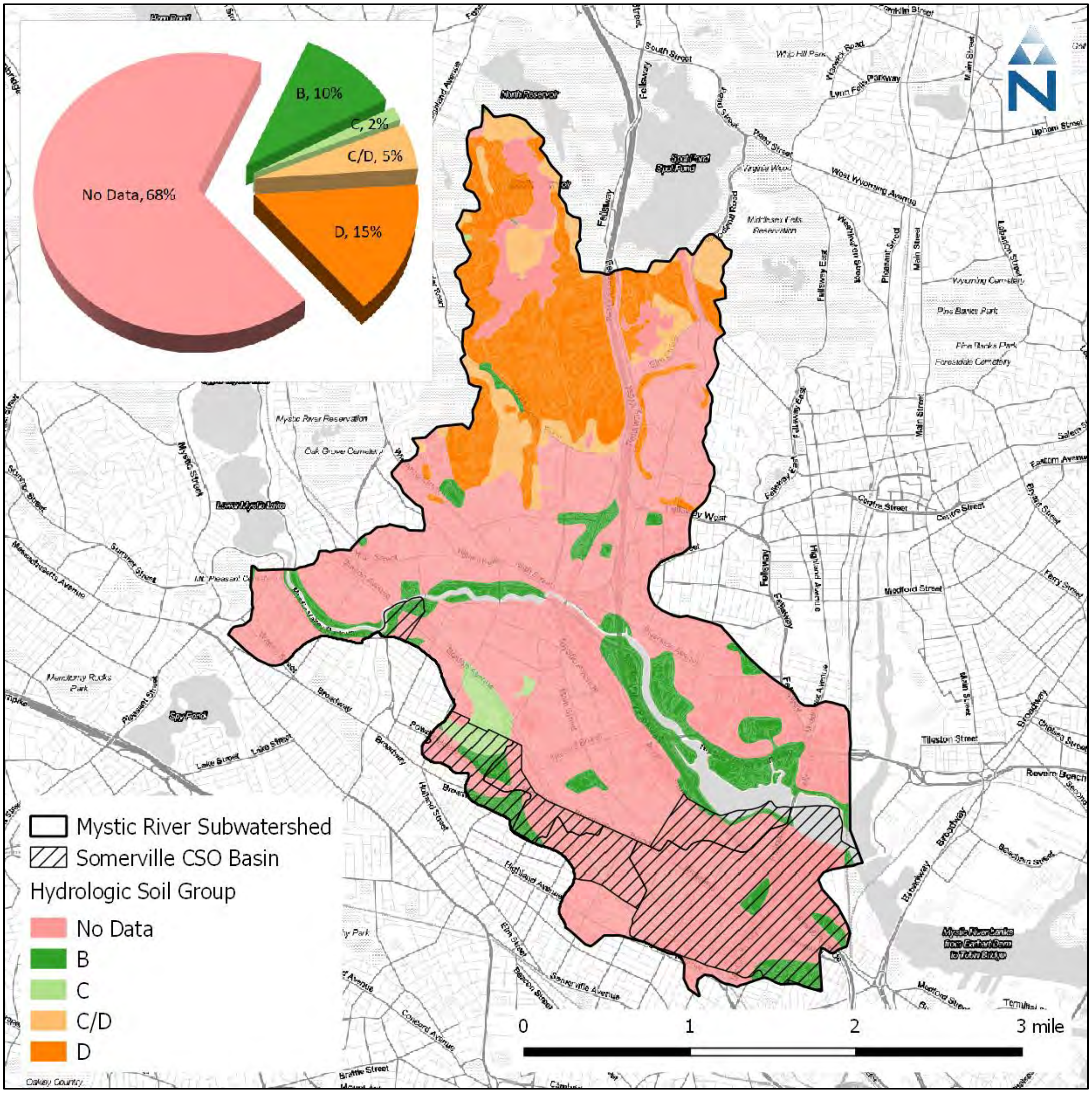



**Figure X-III. Soil Map (Hydrologic Soil Group) of Pilot Sub-Watershed, Mystic River**

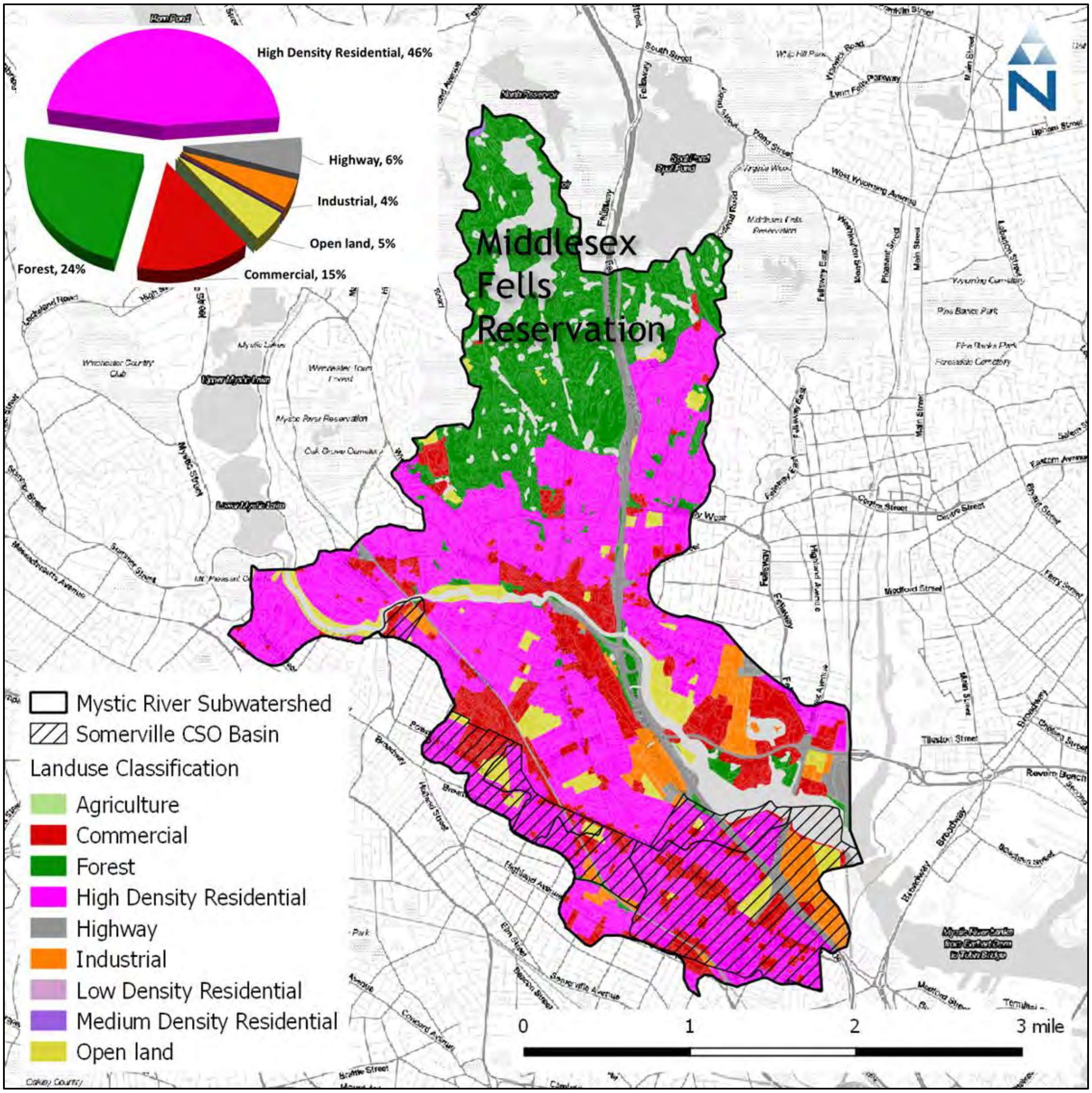



**Figure X-IV. Land Use Map of Pilot Sub-Watershed, Mystic River**

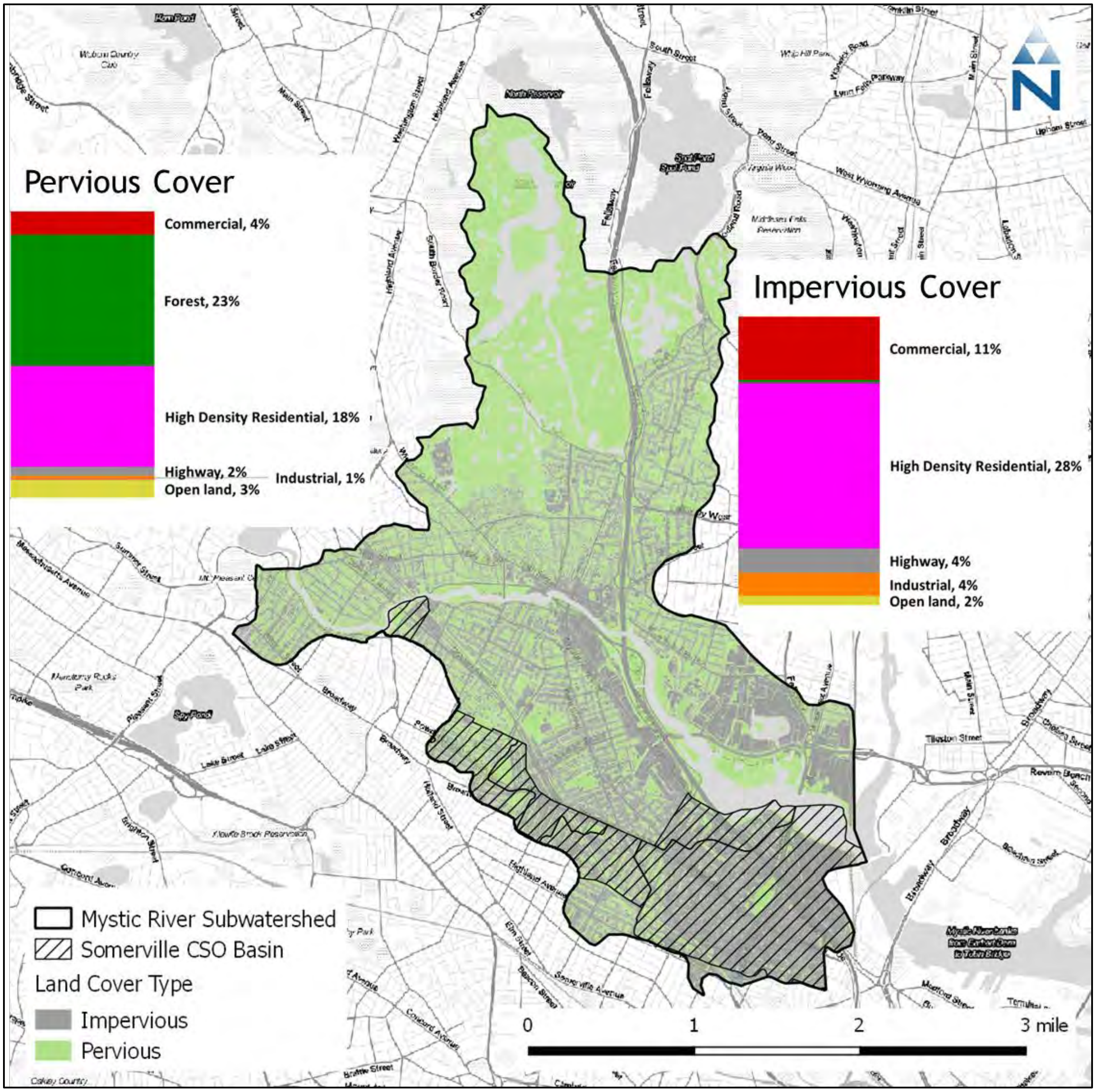



**Figure X-V. Land Cover Map of Pilot Sub-Watershed, Mystic River**

### Table X-3. Land Use Classification in Pilot Sub-Watershed, Mystic River

| Land Use Classification | Area (acres) | Percent Impervious | Percent Pervious |
|---|---|---|---|
| Commercial | 769.79 | 11% | 4% |
| Forest | 1,225.94 | 0% | 23% |
| High Density Residential | 2,370.66 | 28% | 18% |
| Highway | 294.14 | 4% | 2% |
| Industrial | 235.22 | 4% | 1% |
| Low Density Residential | 0.55 | 0% | 0% |
| Medium Density Residential | 3.09 | 0% | 0% |
| Open land | 251.20 | 2% | 3% |
| Water | 179.30 | | |
| **Total** | **5,329.89** | **49%** | **51%** |

## X.C. Technical Approach

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

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

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

### X.C.1. *Stormwater Management Categories Development*

Spatial data analyses were conducted during Phase 1 of the project to characterize watershed features and identify the corresponding stormwater management categories that were suitable for application with the Opti-Tool for the pilot study area. The GIS data used for the evaluation of stormwater management categories for the Mystic River Watershed include: municipal boundaries, watershed sub-basins, land use coverage, impervious cover, Hydrologic Soil Group (HSG), wetlands, Digital Elevation Model (DEM) for ground slopes, Activity and Use Limitation (AUL) and MGL Ch. 21E sites (for contaminated land), and property ownership. All data are from

MassGIS data layers except the watershed sub-basins, which were derived using FEMA catchments and DEM data as described earlier in this report.

The following assumptions were made to develop the stormwater management categories and estimate available BMP opportunity:

1. Areas with no depth to groundwater data were assumed to have a depth to groundwater greater than 2.5 feet.
2. Areas with no HSG identified for soils were assumed to be classified as HSG C. This was typically the predominant soil type in urban areas of the Mystic River Watershed.
3. The extent of potential contamination from AUL and/or MGL Ch. 21E sites was approximated using the parcel in which the site was located.
4. Wetland areas were not included within the management categories because they were not considered candidates for implementation of stormwater practices.
5. Both public and private land areas were assessed for identifying the GI opportunity areas based on the site suitability criteria.

Areas with impervious cover (IC) were also explored for certain management practices (i.e., porous pavement) that not only replace IC but can also treat stormwater from adjacent IC (for example, within parking lots), but at a higher unit cost. Table X-4 presents siting criteria for potential stormwater management categories (SMC), which were derived from the GIS data analysis. Table X-5 shows the maximum footprint areas of each SMC that is available in the pilot watershed and the spatial locations of those SMCs are shown in Figure X-VI.

## Table X-4. Potential Stormwater Management Categories and BMP Types in Opti-Tool

| Cover Type | Ground Slope (%) | AUL / 21E | HSG | Management Category | BMP Type(s) in Opti-Tool |
|---|---|---|---|---|---|
| Pervious Area | <= 15 | Is a AUL / 21E Site | A/B/C/D or No Data (HSG C assumed) | Shallow filtration | Biofiltration (e.g., Bioretention with underdrain option) |
| | | Not a AUL / 21E Site | A/B/C or No Data (HSG C assumed) | Infiltration | Surface Infiltration Basin (e.g., Rain Garden) |
| | | | D | Biofiltration | Biofiltration (e.g., Gravel Wetland) |
| | > 15 | - | - | Less likely for onsite BMP | - |
| Impervious Area | <= 5 | - | A/B/C/D or No Data (HSG C assumed) | Shallow filtration | Porous Pavement |
| | > 5 | - | - | Less likely for onsite BMP | - |

## Table X-5. Potential BMP Opportunity Areas (Maximum Footprints) in the Pilot Sub-Watershed, Mystic River

| Stormwater Management Category | Area (acres) | Percent Area (%) |
|---|---|---|
| Biofiltration | 437.92 | 8% |
| Shallow filtration (pervious area) | 513.13 | 10% |
| Infiltration | 1,087.20 | 20% |
| Shallow filtration (impervious area) | 1,477.06 | 28% |
| Less likely for BMP | 1,814.58 | 34% |
| **Total** | **5,329.89** | **100%** |

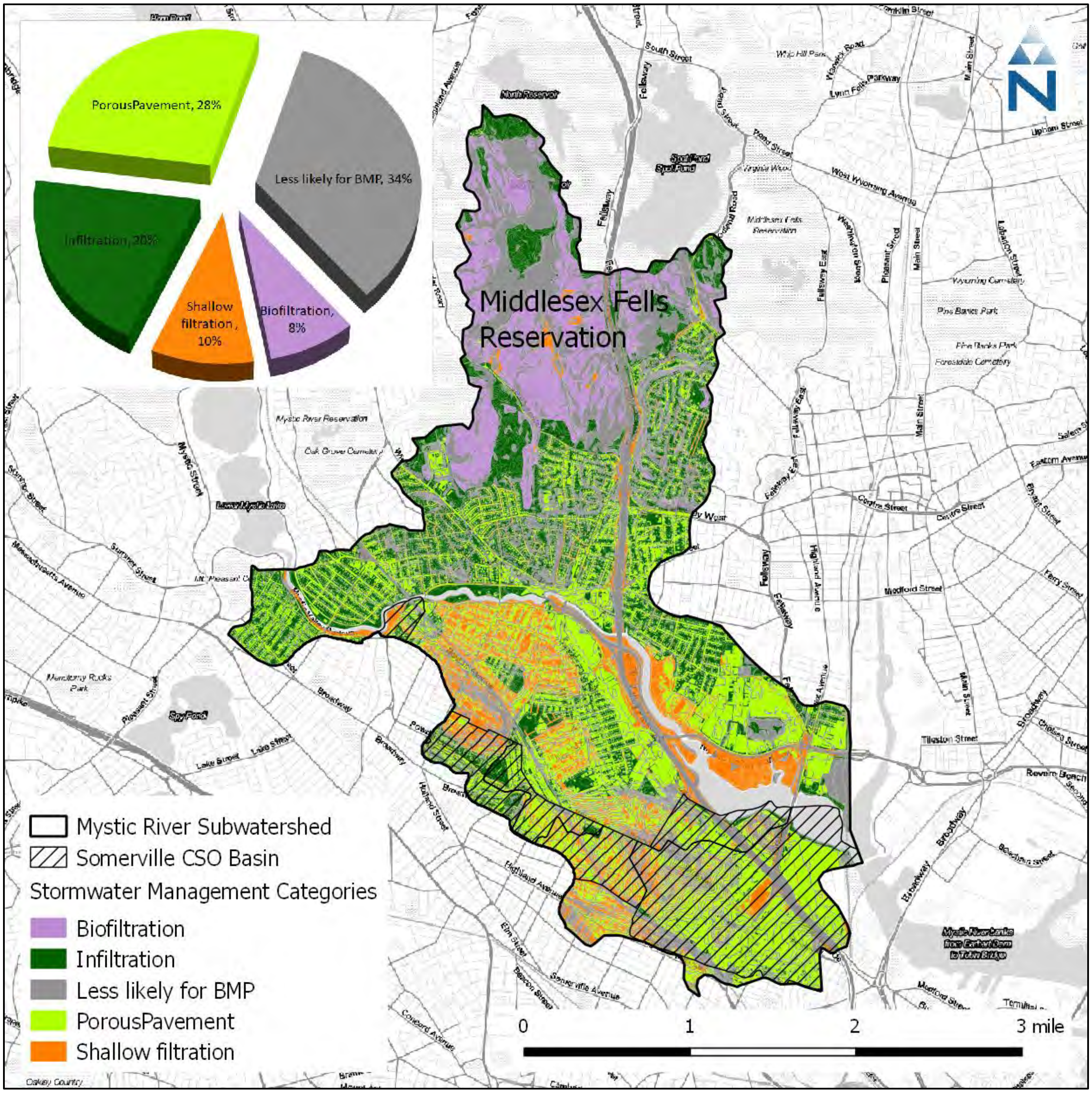



**Figure X-VI. Stormwater Management Categories Map of Pilot Sub-Watershed, Mystic River**

For this study, stormwater management siting was primarily evaluated for areas with pervious cover, outside of wetland areas, and with ground slopes of less than 15%. Porous pavement on impervious cover with ground slopes of less than 5% was also evaluated with the assumption of drainage impervious area ratio of 2:1, meaning one acre of porous pavement was assumed to treat its own footprint plus one additional acre of adjacent impervious land. Only 10% of suitable impervious land (based on the siting criterion) was identified for this practice. While removal of some impervious land cover and implementation of porous pavement are viable options within this watershed, those practices are typically costlier than stormwater practices located on pervious land. Therefore, a multiplier of 3× (unit cost) for installing porous pavement was used in the Opti-Tool to account for installing underdrains and connections to the drainage system. In comparison, a multiplier of 2× (unit cost) was used for other BMPs for installing new BMPs in developed areas.

### X.C.2. *Estimating BMP Footprints and Impervious Drainage Areas*

The distribution of the BMP opportunity areas (i.e., BMP footprints) was estimated by land use category group. This distribution represents the maximum available BMP footprint in the pilot watershed, based on GIS spatial data analysis, and does not necessarily represent the actual opportunity areas. The total impervious areas by land use group were proportionally distributed to the BMP drainage areas based on the available percentage of opportunity area of that specific BMP type by land use type as determined through the Management Category analysis (Table X-6 and Figure X-VII). For example, if the opportunity area of Bio-filtration was 20% of the total available opportunity area in commercial land, then 20% of the impervious area in the commercial land was treated by Bio-filtration practices located on commercial land. For this case study, no field verification was performed, and maximum opportunity areas were set to limit the BMP footprints needed to capture up to 1 inch of runoff from the impervious drainage areas (Table X-7).

**Table X-6. BMP-Treated Impervious Area (Drainage Area) Distribution by Land Use Category Group in the Pilot Sub-Watershed, Mystic River**

| Land Use Type | Biofiltration | Infiltration HSG-B | Infiltration HSG-C | Porous Pavement | Total (Land Use) |
|---|---|---|---|---|---|
| | (acre) | (acre) | (acre) | (acre) | (acre) |
| Commercial | 167.92 | 20.95 | 114.01 | 55.02 | **357.9** |
| High Density Residential | 9.74 | 31.78 | 714.35 | 116.01 | **871.88** |
| Highway | 86.81 | 13.67 | 46.76 | - | **147.24** |
| Industrial | - | 28.17 | 61.24 | 18.84 | **108.25** |
| Open land | 5.25 | 17.26 | 16.09 | 7.86 | **46.46** |
| **Total (BMP-treated)** | **269.72** | **111.83** | **952.45** | **197.73** | **1,531.73** |

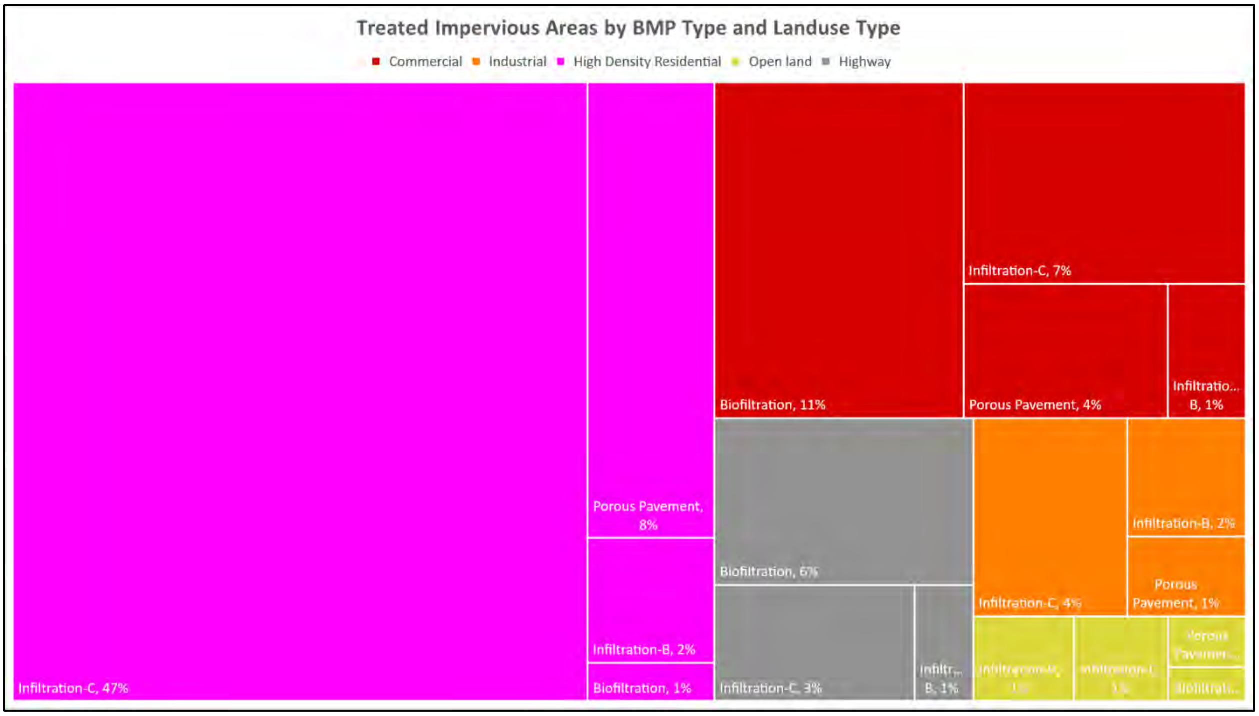



**Figure X-VII. Treated Impervious Areas by BMP Type and Land Use Type in the Pilot Sub-Watershed, Mystic River**

**Table X-7. BMP Area (Footprints) Distribution by Land Use Category Group Required to Treat 1 Inch of Runoff from the Impervious Surface in the Pilot Sub-Watershed, Mystic River**

| Land Use Type | Biofiltration | Infiltration HSG-B | Infiltration HSG-C | Porous Pavement | Total (Land Use) |
|---|---|---|---|---|---|
| | (acre) | (acre) | (acre) | (acre) | (acre) |
| Commercial | 10.00 | 0.87 | 4.75 | 27.51 | **43.13** |
| High Density Residential | 0.58 | 1.32 | 29.76 | 58.00 | **89.66** |
| Highway | 5.17 | 0.57 | 1.95 | - | **7.69** |
| Industrial | - | 1.17 | 2.55 | 9.42 | **13.14** |
| Open land | 0.31 | 0.72 | 0.67 | 3.93 | **5.63** |
| **Total (BMP-treated)** | **16.06** | **4.65** | **39.68** | **98.86** | **159.25** |

### X.C.3. *Opti-Tool Setup*[7]

The following steps were performed to set up the Opti-Tool for the pilot sub-watershed.

1. **Establish baseline condition:** The climate data was extended to develop unit-area HRU timeseries for the critical period of interest (Jan 2007 – Dec 2016), which was used as the

[7] *Opti-Tool User Guide* provides the step-by-step instructions on how to setup the Opti-Tool project.

boundary condition to the BMP simulation model. The Opti-Tool provides a utility tool that runs the SWMM models, calibrated to Region 1 specific land use average annual loading export rates, and generates the HRU hourly timeseries in the format needed for the Opti-Tool. These are the same loading HRUs being used in the watershed and water quality modeling work done as part of the Mystic River Eutrophication analysis to determine needed TP load reductions.

2. **Management objective:** Identify the most cost-effective stormwater controls (types and sizes) for achieving a wide range of TP load reductions at the watershed scale.
3. **Optimization target:** Develop cost effectiveness curve (CE-curve) for TP average annual load reduction.
4. **Land use information:** Estimate the area distribution for the major land use groups within the pilot watershed. Assign the corresponding unit-area HRU timeseries for each land use group in the model.
5. **BMP information:** Eighteen BMP types were selected on five major land use categories based on the Management Category analysis and BMP specifications were set using the default parameters and BMP cost function available in the Opti-Tool, see Appendix K). Assign impervious drainage areas to be treated by each BMP type in the model.
6. **Run optimization scenario:** Define the simulation period (2007 – 2016), the pollutant of concern (TP), the objective function (minimize cost), and create an input file for the optimization run. Run the optimization using the continuous simulation BMP model to reflect actual long-term precipitation conditions that includes a wide range of actual storm sizes to find the optimal BMP storage capacities that provide the most cost-effective solution at the watershed scale. Each optimization run generates a CE-Curve showing the optimal solutions frontier for a wide range of TP load reduction targets.

Figure X-VIII shows the main interface of the Opti-Tool, the left panel guides the user to follow steps in the chronological order. The right panel allows the user to place BMPs on the map and enter design specifications for each BMP type.

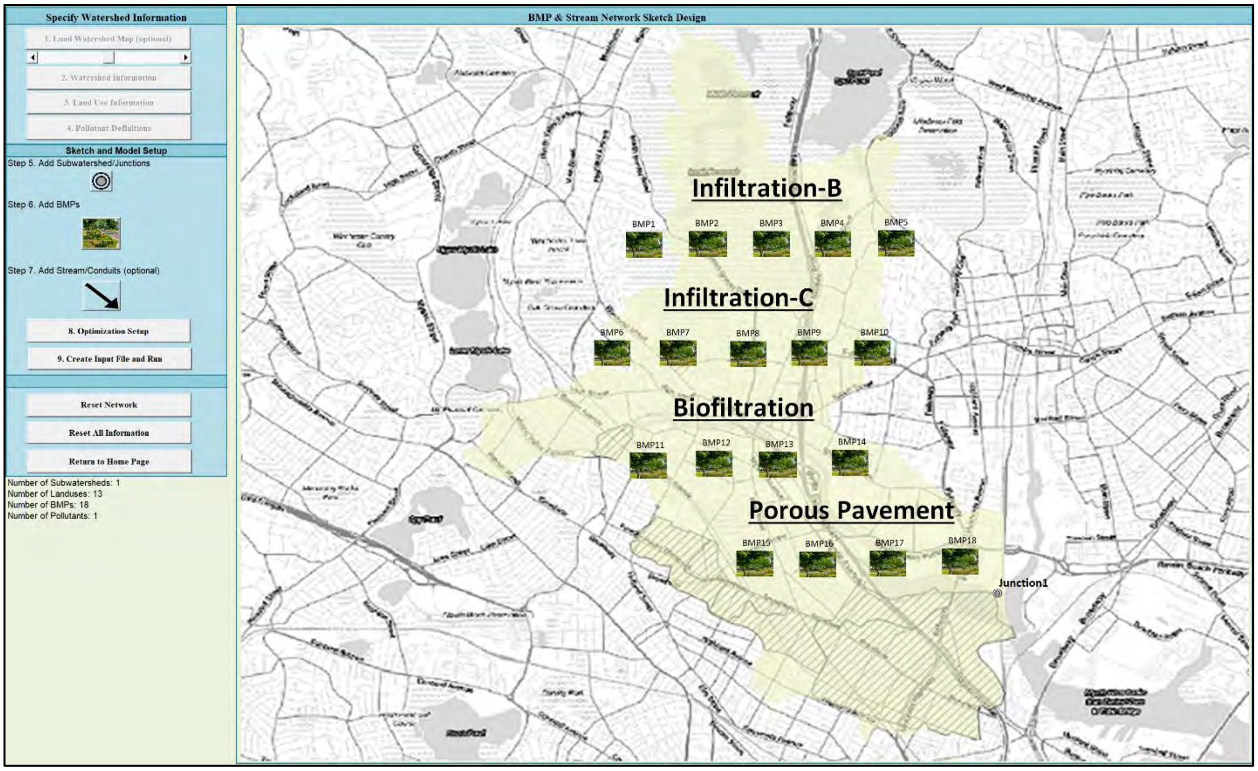



**Figure X-VIII. Opti-Tool Model of Pilot Sub-Watershed, Mystic River.**

## X.D. Management Scenarios

In this study, two management scenarios were created and optimized using the Opti-Tool. The most cost-effective solution from each scenario was selected that met the TP average annual load reduction target for the pilot watershed. Two numeric targets; 67% and 62% (load reduction target for existing condition [Section IX.A.1] and future condition 1 [Section IX.A.2], respectively) were evaluated for each management scenario. The existing condition's target requires the load reduction from stormwater only whereas the load reduction target for future condition 1 assumes additional reductions to CSO volumes that meet the long-term control plan (LTCP) estimates for the typical rainfall year and 50% sanitary sewer overflow (SSO) volume reductions for the ongoing SSO mitigation work being done within the Mystic River Watershed. The load reduction targets for future condition 2 and future condition 3 were not optimized in this study as it requires changing the baseline by shifting land areas from the CSS areas. The details on the existing and future conditions are discussed in Section IX of this report.

**Scenario 1:** Sizing the BMPs to capture one inch of surface runoff from the impervious drainage areas and spatial optimization for the strategic locations (at the land use level) in the pilot watersheds. The BMP sizes were fixed, and the optimization engine explored the best mix of BMP types and strategic locations to identify the cost-effective solutions.

**Scenario 2:** Sizing the BMPs to capture from one-tenth to an inch of surface runoff from the impervious drainage areas and spatial optimization for the strategic locations (at the land use level) in the pilot watersheds. The BMP sizes were variable (increment of one-tenth of an inch to a maximum of 1 inch) and the optimization engine explored the best mix of BMP types, sizes, and strategic locations to identify the cost-effective solutions.

### X.D.1. *Results: Scenario 1*

Figure X-IX shows the CE-Curve for *Scenario 1* from the model simulation in the Opti-Tool. The

> ***Scenario:*** *The scenario term is used to describe the BMP sizing criteria; scenario 1 captures a typical one-inch storm size (i.e., one-inch of runoff depth from the IC) whereas scenario 2 captures a range of storm sizes from one-tenth to a one-inch storm.*
> ***Condition:*** *The condition term represents the target sources; existing condition targets the stormwater load reduction only whereas future condition 1 also targets the CSO and SSO load reductions in addition to the stormwater load reduction.*
> ***Solution:*** *The solution term represents the optimized mixture of different BMP types, sizes, and locations that meet the given numeric load reduction target.*
> ***Cost:*** *The cost estimates are intended for planning level purposes and are intended to highlight relative cost differences among the scenarios.*

curve is an interactive plot showing the target solution (red triangle for the existing condition and orange triangle for the future condition 1) and all the iterations performed during the optimization process. The grey-dots on the curve are the inferior solutions and the blue-diamonds form the cost-effectiveness curve for a wide range of load reduction targets. Based on the given target reduction, Opti-Tool searches for the closest solution and provides the information on the selected BMPs under that target solution (BMP ID, BMP type, surface area, storage depth, treated the impervious area, runoff depth, annual maintenance hours, and BMP cost).

The results of *Scenario 1* (where BMPs are sized using a typical design criterion of capturing one inch of runoff from the impervious drainage area) show that it would cost **$106.37** million to meet a **67%** TP average annual load reduction target for the existing condition whereas it would cost **$66.12** million to meet a **62%** TP average annual load reduction target for the future condition 1 for the pilot watershed (Figure X-9). The cost estimates are based on regional unit cost information for the control types, a 35% add-on for engineering and contingencies and a site factor multiplier to account for anticipated difficulties associated with installations. For this analysis, a multiplier of 2X was assumed for all controls except for porous pavement for which a 3X multiplier was applied. These cost estimates can be considered conservative because they do not reflect the potential for significant cost offsets that could be achieved through the installation of SCMs as part of other development/redevelopment, urban renewal and roadwork related projects.

Though the optimization engine did not optimize the BMP sizes, it still shows a significant cost saving in optimizing the strategic locations (where to place a BMP and what BMP combination to use). Table X-8 shows the selected BMP types in the optimal solution that meet the TP load reduction target for the existing condition. Table X-9 shows the selected BMP types in the optimal solution that meet the TP load reduction target for the future condition 1. The optimizer preferred the infiltration BMPs because they provided the highest volume reduction and associated water quality benefits compared to the more expensive practices such as biofiltration and porous pavements.

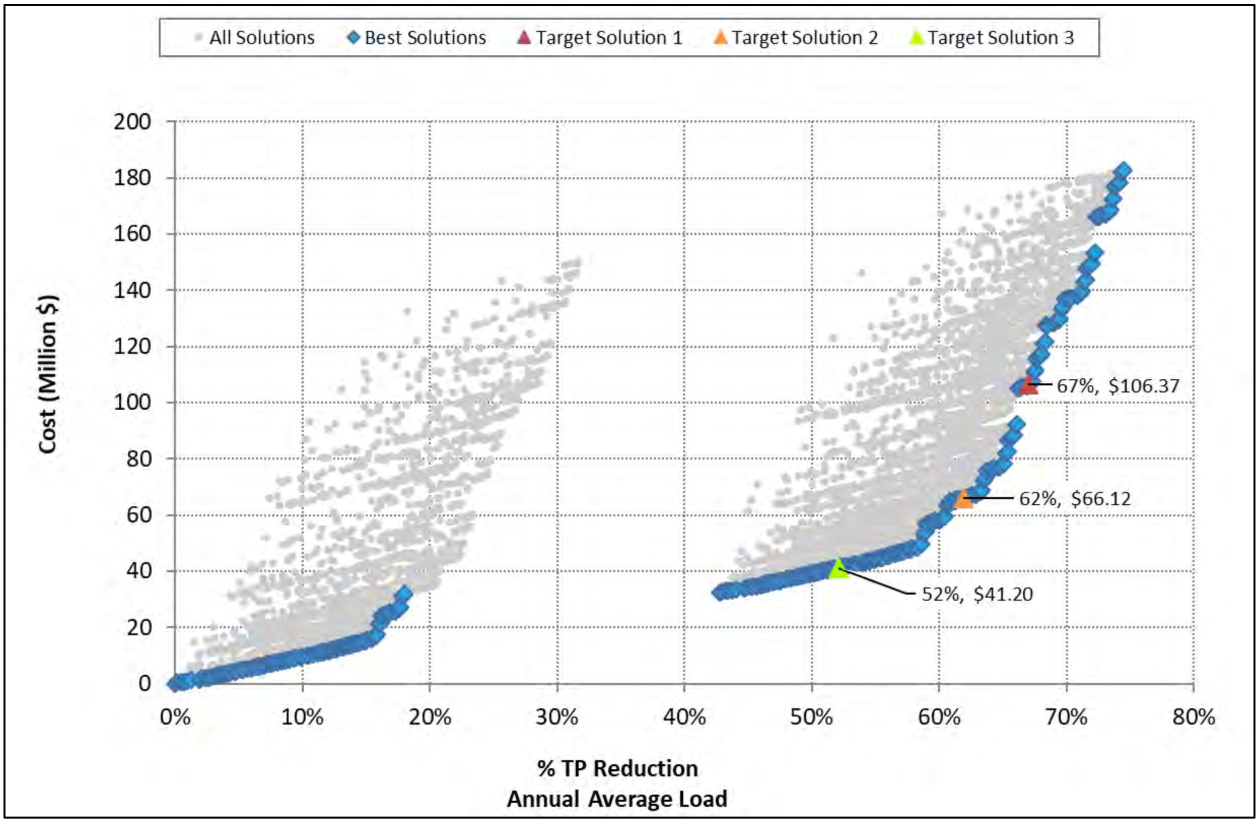



**Figure X-IX. Scenario 1: Opti-Tool Cost-Effectiveness Curve (Optimize Locations Only) of TP Annual Average Load Reduction for the Pilot Watershed**

The shape of the CE-Curve itself provides valuable information for informing strategic stormwater management planning. As indicated, the slope of the curve is relatively mild from 0% to 58% in TP reduction and then increases sharply for higher TP reductions. The incremental cost of $ 40 million to move from a TP reduction target of 62% to 67% is substantially higher than the $5 million incremental cost increase associated with the same incremental increase in percent TP reduction of 53% to 58% on the flatter part of the curve. This curve highlights the potential high value of investing in other measures including nonstructural control such as leaf litter management, high-efficiency street cleaning, catch basin cleaning and fertilizer management that could achieve TP reductions of 10-20% or higher and shift the target for the structural control retrofit program from the steep part of the curve to the flatter portion. For example, assume that a 15% TP reduction could be accomplished through nonstructural controls and that the target for structural control can be reduced from 67% to 52% resulting in an estimated cost for structural controls of approximately $40 million (less than half). Not only is it far less costly to move from the steep portion of the curve to the flatter portion but the total amount of impervious cover area requiring treatment for a 52 % reduction (909 acres) is substantially less than the 67% (1,379 acres) and 62% (1,211 acres) options as indicated in Table X-10, Table X-9, and Table X-9 respectively.

## Table X-8. Scenario 1: BMP Types and BMP Sizes for The Selected Target Solution 1 (Existing Condition) in Opti-Tool

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP1 | Infiltration-B | High Density Residential | 31.78 | 1.00 | 863,013 | $1,439,764 |
| BMP2 | Infiltration-B | Commercial | 20.95 | 1.00 | 568,931 | $949,148 |
| BMP3 | Infiltration-B | Industrial | 28.17 | 1.00 | 764,973 | $1,276,203 |
| BMP4 | Infiltration-B | Open land | 17.26 | 1.00 | 468,813 | $782,121 |
| BMP5 | Infiltration-B | Highway | 13.67 | 1.00 | 371,150 | $619,189 |
| BMP6 | Infiltration-C | High Density Residential | 714.35 | 1.00 | 19,401,598 | $32,367,663 |
| BMP7 | Infiltration-C | Commercial | 114.01 | 1.00 | 3,096,513 | $5,165,908 |
| BMP8 | Infiltration-C | Industrial | 61.24 | 1.00 | 1,663,216 | $2,774,741 |
| BMP9 | Infiltration-C | Open land | 16.09 | 1.00 | 437,036 | $729,107 |
| BMP10 | Infiltration-C | Highway | 46.76 | 1.00 | 1,270,010 | $2,118,756 |
| BMP11 | Biofiltration | High Density Residential | - | - | - | - |
| BMP12 | Biofiltration | Commercial | 167.92 | 1.00 | 4,559,847 | $18,847,683 |
| BMP13 | Biofiltration | Open land | 5.25 | 1.00 | 142,556 | $589,242 |
| BMP14 | Biofiltration | Highway | 86.81 | 1.00 | 2,357,192 | $9,743,223 |
| BMP15 | Porous Pavement | High Density Residential | - | - | - | - |
| BMP16 | Porous Pavement | Commercial | 55.03 | - | 13,573,865 | $28,963,024 |
| BMP17 | Porous Pavement | Industrial | - | - | - | - |
| BMP18 | Porous Pavement | Open land | - | - | - | - |
| | | Total | 1,379.27 | 1.00 | 49,538,712 | $106,365,771 |

## Table X-9. Scenario 1: BMP Types and BMP Sizes for the Selected Target Solution 2 (Future Condition 1) in Opti-Tool

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP1 | Infiltration-B | High Density Residential | 31.78 | 1.00 | 863,013 | $1,439,764 |
| BMP2 | Infiltration-B | Commercial | - | - | - | - |
| BMP3 | Infiltration-B | Industrial | 28.17 | 1.00 | 764,973 | $1,276,203 |
| BMP4 | Infiltration-B | Open land | 17.26 | 1.00 | 468,813 | $782,121 |
| BMP5 | Infiltration-B | Highway | 13.67 | 1.00 | 371,150 | $619,189 |
| BMP6 | Infiltration-C | High Density Residential | 714.35 | 1.00 | 19,401,598 | $32,367,663 |
| BMP7 | Infiltration-C | Commercial | 114.01 | 1.00 | 3,096,513 | $5,165,908 |
| BMP8 | Infiltration-C | Industrial | 61.24 | 1.00 | 1,663,216 | $2,774,741 |
| BMP9 | Infiltration-C | Open land | 16.09 | 1.00 | 437,036 | $729,107 |
| BMP10 | Infiltration-C | Highway | 46.76 | 1.00 | 1,270,010 | $2,118,756 |

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP11 | Biofiltration | High Density Residential | - | - | - | - |
| BMP12 | Biofiltration | Commercial | 167.92 | 1.00 | 4,559,847 | $18,847,683 |
| BMP13 | Biofiltration | Open land | - | - | - | - |
| BMP14 | Biofiltration | Highway | - | - | - | - |
| BMP15 | Porous Pavement | High Density Residential | - | - | - | - |
| BMP16 | Porous Pavement | Commercial | - | - | - | - |
| BMP17 | Porous Pavement | Industrial | - | - | - | - |
| BMP18 | Porous Pavement | Open land | - | - | - | - |
| | | Total | 1,211.24 | 1.00 | 32,896,167 | $66,121,134 |

## Table X-10. Scenario 1: BMP Types and BMP Sizes for the Selected Target Solution 3 (52% Target) in Opti-Tool

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP1 | Infiltration-B | High Density Residential | 31.78 | 1.00 | 863,013 | $1,439,764 |
| BMP2 | Infiltration-B | Commercial | 20.95 | 1.00 | 568,931 | $949,148 |
| BMP3 | Infiltration-B | Industrial | 28.17 | 1.00 | 764,973 | $1,276,203 |
| BMP4 | Infiltration-B | Open land | - | - | - | - |
| BMP5 | Infiltration-B | Highway | - | - | - | - |
| BMP6 | Infiltration-C | High Density Residential | 714.35 | 1.00 | 19,401,598 | $32,367,663 |
| BMP7 | Infiltration-C | Commercial | 114.01 | 1.00 | 3,096,513 | $5,165,908 |
| BMP8 | Infiltration-C | Industrial | - | - | - | - |
| BMP9 | Infiltration-C | Open land | - | - | - | - |
| BMP10 | Infiltration-C | Highway | - | - | - | - |
| BMP11 | Biofiltration | High Density Residential | - | - | - | - |
| BMP12 | Biofiltration | Commercial | - | - | - | - |
| BMP13 | Biofiltration | Open land | - | - | - | - |
| BMP14 | Biofiltration | Highway | - | - | - | - |
| BMP15 | Porous Pavement | High Density Residential | - | - | - | - |
| BMP16 | Porous Pavement | Commercial | - | - | - | - |
| BMP17 | Porous Pavement | Industrial | - | - | - | - |
| BMP18 | Porous Pavement | Open land | - | - | - | - |
| | | Total | 909.25 | 1.00 | 24,695,027 | $41,198,686 |

### X.D.2. *Results: Scenario 2*

The results of *Scenario 2* (where BMPs are sized to capture from one-tenth to an inch of runoff from the impervious drainage area) show that it would cost $102.83 million to meet a 67% TP average annual load reduction target for the existing condition whereas it would cost $51.13 million to meet a 62% TP average annual load reduction target for the future condition 1 for the pilot watershed (Figure X-X). For this scenario, the optimization engine optimized the BMP sizes and the strategic locations (i.e., where to place a BMP, what BMP size to pick, and what BMP combination to use). The results show more cost saving ($3.5 million for existing condition and $15 million for future condition 1) for optimizing the BMP sizes as compared to only optimizing the strategic locations. Table X-11 shows the selected BMP types in the optimal solution that meet the TP load reduction target for the existing condition. Table X-12 shows the selected BMP types in the optimal solution that meet the TP load reduction target for the future condition 1 for *Scenario 2*. However, similar to scenario 1, the TP reduction targets of 67% and 62% are located on the portion of the curve with the steeper slope indicating much higher incremental cost increases for increasing TP reduction targets. Again, assuming that nonstructural controls could achieve a 15% TP reduction, the estimated cost of achieving a 52% reduction using structural controls is $20 million and equal to ½ of the estimated cost ($40 million) for achieving the same reduction using 1-inch design capacities. Table X-13 summarizes the results of achieving 52% TP reduction for scenario 2. As indicate, optimized sizing of the structural controls for 52% are notably smaller than was determined for the 62% and 67% reductions.

The optimizer mostly picks the infiltration BMPs because they provide the highest volume reduction and water quality benefits compared to more expensive practices such as biofiltration and porous pavement. For *Scenario 2*, the optimizer picks a combination of BMP sizes ranging from 0.1 to 1.0 inches, showing that BMPs designed to manage smaller-size storms in New England region may provide more cost saving and increased feasibility for implementation in the highly urbanized watershed such as the Mystic River.

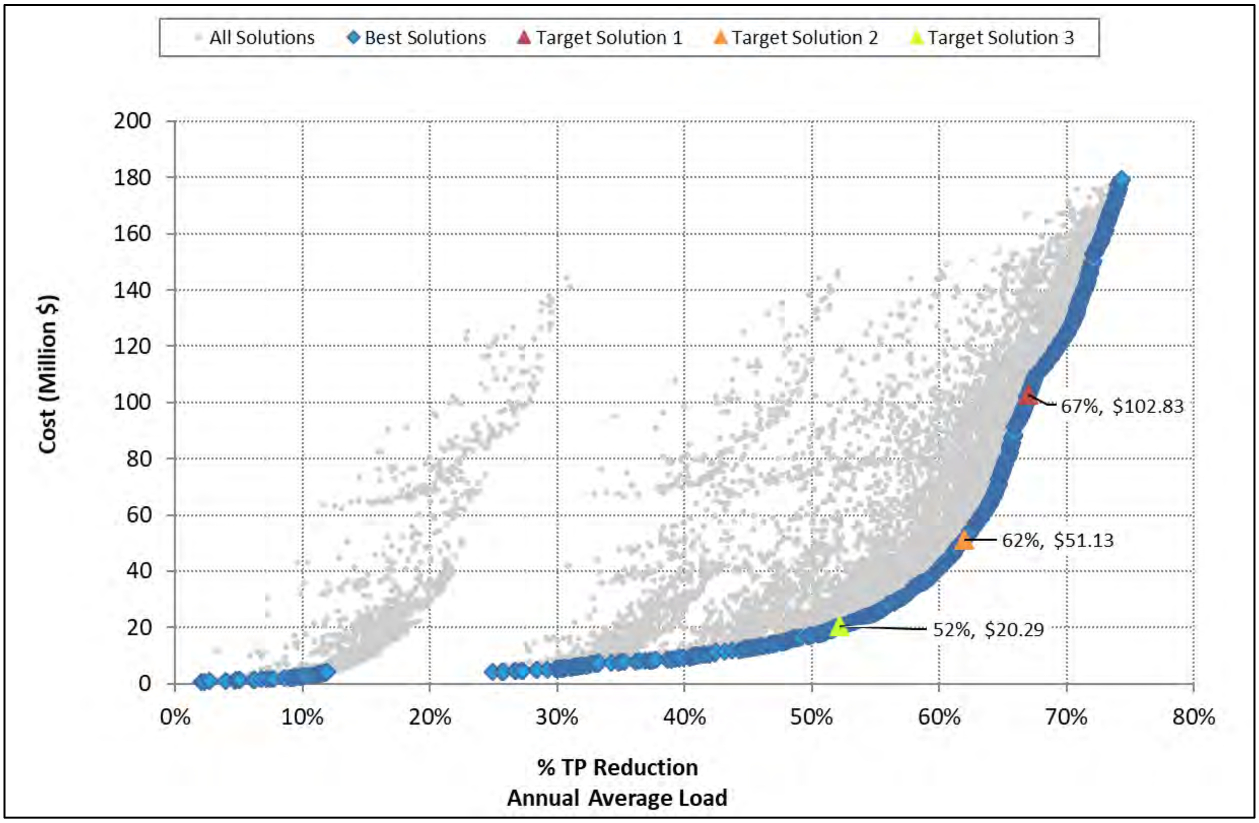



**Figure X-X. Scenario 2: Opti-Tool Cost-Effectiveness Curve (Optimize Locations and BMP Sizes) of TP Annual Average Load Reduction for the Pilot Watershed.**

**Table X-11. Scenario 2: BMP Types and BMP Sizes for the Selected Target Solution 1 (Existing Condition) in Opti-Tool**

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP1 | Infiltration-B | High Density Residential | 31.78 | 0.70 | 604,107 | $1,007,830 |
| BMP2 | Infiltration-B | Commercial | 20.95 | 0.60 | 341,364 | $569,497 |
| BMP3 | Infiltration-B | Industrial | 28.17 | 0.80 | 611,981 | $1,020,967 |
| BMP4 | Infiltration-B | Open land | 17.26 | 0.40 | 187,524 | $312,847 |
| BMP5 | Infiltration-B | Highway | 13.67 | 0.80 | 296,922 | $495,354 |
| BMP6 | Infiltration-C | High Density Residential | 714.35 | 1.00 | 19,401,581 | $32,367,635 |
| BMP7 | Infiltration-C | Commercial | 114.01 | 0.90 | 2,786,886 | $4,649,358 |
| BMP8 | Infiltration-C | Industrial | 61.24 | 0.80 | 1,330,580 | $2,219,806 |
| BMP9 | Infiltration-C | Open land | 16.09 | 0.90 | 393,340 | $656,208 |
| BMP10 | Infiltration-C | Highway | 46.76 | 0.70 | 889,019 | $1,483,150 |

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP11 | Biofiltration | High Density Residential | 9.74 | 0.80 | 211,654 | $874,853 |
| BMP12 | Biofiltration | Commercial | 167.92 | 1.00 | 4,559,847 | $18,847,683 |
| BMP13 | Biofiltration | Open land | 5.25 | 1.00 | 142,555 | $589,236 |
| BMP14 | Biofiltration | Highway | 86.81 | 0.90 | 2,121,495 | $8,768,993 |
| BMP15 | Porous Pavement | High Density Residential | - | - | - | - |
| BMP16 | Porous Pavement | Commercial | 55.03 | - | 13,573,865 | $28,963,024 |
| BMP17 | Porous Pavement | Industrial | - | - | - | - |
| BMP18 | Porous Pavement | Open land | - | - | - | - |
| | | Total | 1,389.01 | (0.4 – 1.0) | 47,452,719 | $102,826,441 |

### Table X-12. Scenario 2: BMP Types and BMP Sizes for the Selected Target Solution 2 (Future Condition 1) in Opti-Tool

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP1 | Infiltration-B | High Density Residential | 31.78 | 0.60 | 517,806 | $863,855 |
| BMP2 | Infiltration-B | Commercial | 20.95 | 0.30 | 170,682 | $284,749 |
| BMP3 | Infiltration-B | Industrial | 28.17 | 0.70 | 535,483 | $893,346 |
| BMP4 | Infiltration-B | Open land | 17.26 | 0.40 | 187,524 | $312,847 |
| BMP5 | Infiltration-B | Highway | 13.67 | 0.80 | 296,922 | $495,354 |
| BMP6 | Infiltration-C | High Density Residential | 714.35 | 0.70 | 13,581,106 | $22,657,344 |
| BMP7 | Infiltration-C | Commercial | 114.01 | 0.80 | 2,477,232 | $4,132,763 |
| BMP8 | Infiltration-C | Industrial | 61.24 | 0.50 | 831,613 | $1,387,379 |
| BMP9 | Infiltration-C | Open land | 16.09 | 0.40 | 174,818 | $291,648 |
| BMP10 | Infiltration-C | Highway | 46.76 | 0.70 | 889,019 | $1,483,150 |
| BMP11 | Biofiltration | High Density Residential | 9.74 | 0.70 | 185,198 | $765,496 |
| BMP12 | Biofiltration | Commercial | 167.92 | 0.80 | 3,647,877 | $15,078,146 |
| BMP13 | Biofiltration | Open land | 5.25 | 0.90 | 128,299 | $530,313 |
| BMP14 | Biofiltration | Highway | 86.81 | 0.20 | 471,443 | $1,948,665 |
| BMP15 | Porous Pavement | High Density Residential | - | - | - | - |
| BMP16 | Porous Pavement | Commercial | - | - | - | - |
| BMP17 | Porous Pavement | Industrial | - | - | - | - |
| BMP18 | Porous Pavement | Open land | - | - | - | - |
| | | Total | 1,333.99 | (0.2 – 0.9) | 24,095,022 | $51,125,054 |

**Table X-13. Scenario 2: BMP Types and BMP Sizes for the Selected Target Solution 3 (52% Target) in Opti-Tool**

| BMPID | BMP Type | Land Use | Treated Impervious Area (acres) | Runoff Depth (in.) | BMP Storage Capacity (gallon) | BMP Cost ($) |
|---|---|---|---|---|---|---|
| BMP1 | Infiltration-B | High Density Residential | 31.78 | 0.60 | 517,806 | $863,855 |
| BMP2 | Infiltration-B | Commercial | 20.95 | 0.30 | 170,682 | $284,749 |
| BMP3 | Infiltration-B | Industrial | 28.17 | 0.20 | 152,995 | $255,242 |
| BMP4 | Infiltration-B | Open land | 17.26 | 0.40 | 187,524 | $312,847 |
| BMP5 | Infiltration-B | Highway | 13.67 | 0.20 | 74,230 | $123,838 |
| BMP6 | Infiltration-C | High Density Residential | 714.35 | 0.40 | 7,760,632 | $12,947,054 |
| BMP7 | Infiltration-C | Commercial | 114.01 | 0.30 | 928,962 | $1,549,786 |
| BMP8 | Infiltration-C | Industrial | 61.24 | 0.50 | 831,613 | $1,387,379 |
| BMP9 | Infiltration-C | Open land | 16.09 | 0.20 | 87,409 | $145,824 |
| BMP10 | Infiltration-C | Highway | 46.76 | 0.20 | 254,005 | $423,757 |
| BMP11 | Biofiltration | High Density Residential | 9.74 | 0.10 | 26,457 | $109,357 |
| BMP12 | Biofiltration | Commercial | 167.92 | 0.10 | 455,985 | $1,884,768 |
| BMP13 | Biofiltration | Open land | - | - | - | - |
| BMP14 | Biofiltration | Highway | - | - | - | - |
| BMP15 | Porous Pavement | High Density Residential | - | - | - | - |
| BMP16 | Porous Pavement | Commercial | - | - | - | - |
| BMP17 | Porous Pavement | Industrial | - | - | - | - |
| BMP18 | Porous Pavement | Open land | - | - | - | - |
| | | Total | 1,241.93 | (0.1 – 0.6) | 11,448,300 | $20,288,455 |

## X.E. Summary

The results of this pilot study provide quantitative and qualitative technical guidance to support watershed-based GI management planning. Opti-Tool analysis results help to identify optimal stormwater controls (including categories of methods and sizing approaches) that could increase the technical and economic feasibility of retrofitting needed stormwater management strategies into developed watershed areas. This study highlights the computational power of optimization algorithms in Opti-Tool for evaluating thousands of iterations for a combination of different BMP types and BMP sizes at strategic locations. As demonstrated in *Scenario 1* (BMPs sized for a typical design storm), spatial optimization at the watershed scale can provide significant cost savings as compared to picking locations by best professional judgment. *Scenario 2* further demonstrates that when location and size are optimized, there is potential for further cost savings for the same annual average load reduction benefit. The results of both scenarios indicate that considerable cost savings or avoidance may be accomplished through investing in nonstructural controls to reduce the TP reduction target for structural controls from the steep portion of the CE-Curve to the flatter portion. Table X-14 compares the two scenarios simulated in this case study.

**Table X-14. BMP Scenarios Comparison in Opti-Tool**

| Scenario ID | Scenario Description | TP Load Reduction Target (%) | Impervious Area Treated (acre) | Runoff Depth (in.) | BMP Storage Capacity (Million gallon) | BMP Cost (Million $) |
|---|---|---|---|---|---|---|
| Scenario 1 | BMP size (1 in.) and optimize the spatial locations | 67% | 1,379 | 1.00 | 49.54 | $106.37 |
| | | 62% | 1,211 | 1.00 | 32.90 | $66.12 |
| | | 52% | 909 | 1.00 | 24.70 | $41.20 |
| Scenario 2 | Optimize BMP size (0.1 in. increment and max size 1 in.) and the spatial locations | 67% | 1,389 | (0.4 – 1.0) | 47.45 | $102.83 |
| | | 62% | 1,334 | (0.2 – 0.9) | 24.10 | $51.13 |
| | | 52% | 1,242 | (0.1 – 0.6) | 11.45 | $20.29 |

The CE-curve for both scenarios shows that the numeric targets for existing condition (67%) and future condition 1 (62%) are above the knee-of-curve where optimal solutions tend to become expensive due to the cheaper stormwater controls being exhausted. The performance curve provides clear guidance on achieving the management objectives in a most-cost effective manner. The future condition 1 load reduction target solution for *Scenario 2* provides a cost saving of $51.7 million as compared to the existing condition target solution for *Scenario 2*. By lowering 5% of load reduction target (from 67% to 62%), it can provide almost 50% of cost saving (from $102.83 to $51.13) for *Scenario 2*. The CE-curve provides optimal solutions for a range of load reduction targets, so it can also be used to pick solutions for the intermediate milestones that show progress towards meeting the final load reduction target. Additionally, the CE-Curve provides information to make a strong case for investing in nonstructural and source reduction controls to achieve TP reductions and avoid the need for installing the most expensive control in the most challenging locations.

This study provides planning level analysis with no site-specific project information but provides guidance on which land use sources to target and what type of BMPs are suitable and how to size those BMPs. For example, Scenario 2 of future condition 1 (Table X-12 and Table X-13) show recipes for meeting the 62% and 52% TP load reduction targets by implementing 14 and 12 different BMP types, respectively (combination of land use, soil, and storage capacity) in the pilot watershed. Next step would be performing the field investigation to identify the feasible sites in the watershed and selecting the BMP types and sizes based on the guidance provided in Table X-13. For example, identified suitable sites on high density residential land use should be designed as infiltration practices to capture 0.6-inch runoff depth for underlying soil B type and to capture 0.4-inch depth for underlying soil C type. For poor draining soil type D, biofiltration practices can be designed to capture 0.1-inch of runoff depth. The required BMP storage capacity reflects the storage volume of the control expressed in terms of runoff depth from the contributing impervious area.

## X.F. Example Projects

This section provides two example projects of GI implementation efforts in other locations where distributed GI practices were also found to be cost-effective stormwater management strategies.

### X.F.1. Berry Brook Project, Dover, New Hampshire

Berry Brook Project in Dover, New Hampshire is a partnership between New Hampshire Department of Environmental Services (NHDES), University of New Hampshire Stormwater Center (UNHSC) and the City. This unique partnership between regulators, academics, and committed city staff has reduced best management practice implementation costs, increased effectiveness, and led to more maintainable stormwater management systems. The project goal is to filter, infiltrate, and reduce stormwater runoff from Effective Impervious Cover (EIC) as a means for managing pollutant loading and controlling runoff volumes to Berry Brook. The project has become a prime example of how scientists and public works departments collaborated to improve water quality in an urban watershed, using Low Impact Development (LID) and Green Infrastructure (GI) retrofits, that reduced the effective impervious area in the 185-acre urban watershed from 30% down to 10%. Below is the list of BMPs implemented for this project and Figure X-11 shows their locations in the watershed. A detailed report on this project is available on UNHSC website to download.

- 12 bioretention systems,
- a tree filter,
- a subsurface gravel wetland,
- one acre of new wetland,
- 3 grass-lined swales
- 2 subsurface gravel filters
- an infiltration trench system
- 3 innovative filtering catch basin designs

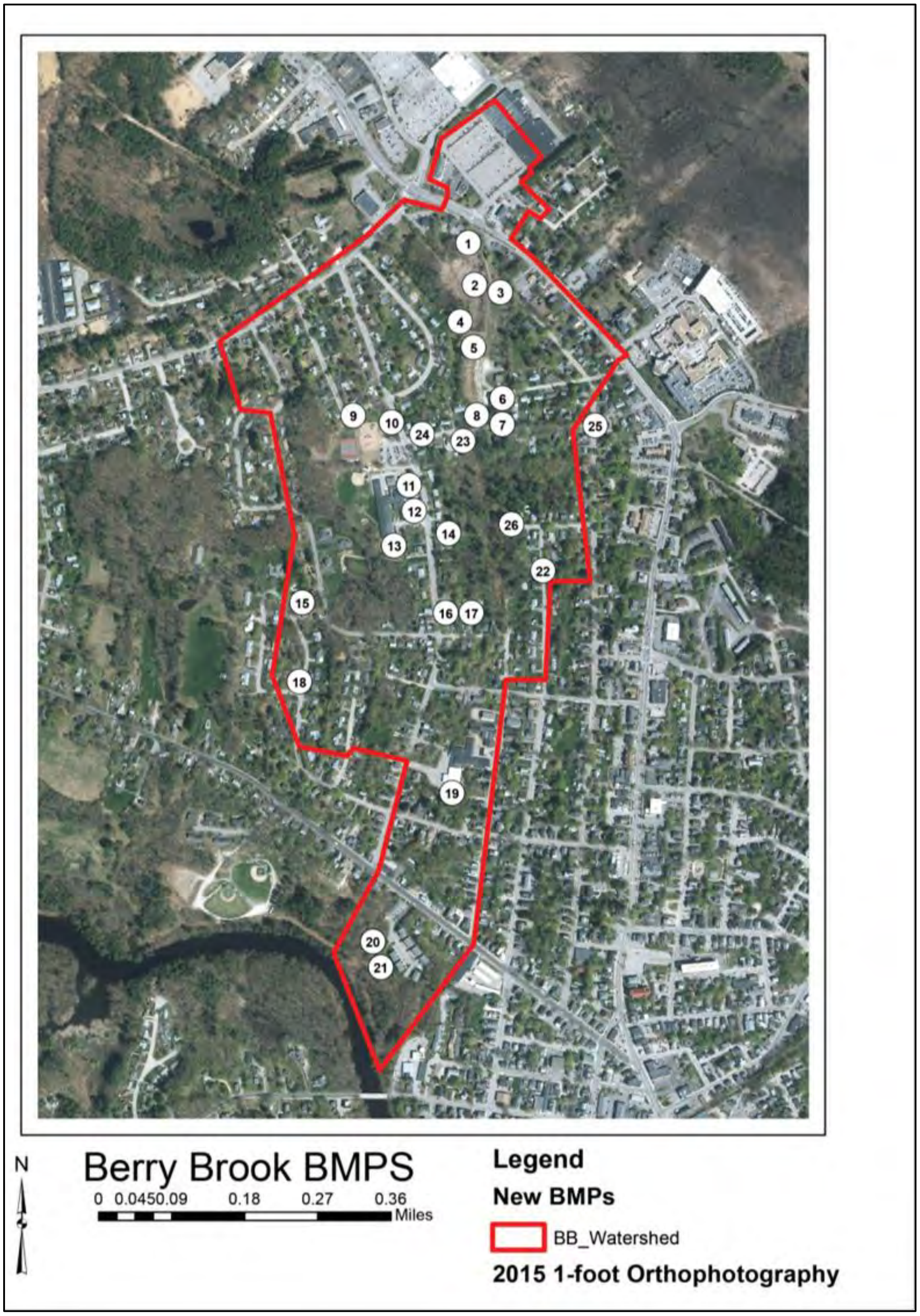



**Figure X-XI. Green Infrastructure Retrofits for Berry Brook Project in Dover, New Hampshire**

### X.F.2. The Advancing Green Infrastructure Program, New Haven, Connecticut

The Advancing Green Infrastructure Program in New Haven, Connecticut is a public-private partnership that promotes environmental protection and social justice through the construction of hundreds of right-of-way bioswales to combat water quality pollution associated with stormwater runoff and combined sewer overflows. Every year, approximately 260 million gallons of combined sewage enters the waterways surrounding New Haven, contributing to pollution in local waterways and the Long Island Sound, and negatively impacting ecosystem health and public recreation.

The bioswale program began as a pilot project in 2014, funded through the National Fish and Wildlife Long Island Sound Futures Fund, with the goal of quantifying how effective green infrastructure was at stormwater retention in the city. The project was spearheaded by the New Haven Resources Initiative (URI), a non-profit in New Haven, and made possible by the partnerships URI fostered in academia, the non-profit sector, and the city and water pollution control authority. University of Rhode Island (URI), Yale School of Forestry & Environmental Studies, the City of New Haven's Engineering Department and the Greater New Haven Water Pollution Control Authority (GNHWPCA) sited eight bioswales in the Westville neighborhood of New Haven. Considerations in siting were slope, obstacles (trees, telephone poles, driveways, underground utilities), homeowner agreement and interest, and the desire to place bioswales as close upstream of catch basins as possible.

Once bioswales were sited, outreach was conducted in the neighborhood to ask homeowners if they would be willing to adopt the bioswales, ensuring that bioswales were taken care of early in the process and maintained in the future. Each of the eight bioswales was adapted from the City of New York standard 3.05 m × 1.5 m right of way bioswale optimized for high capacity stormwater retention. These bioswales were generally smaller than typical NYC bioswales, and ranged from 8' × 5.2' (the smallest) to 16.5' × 6' (the largest). Four feet of soil was excavated, and a geo-textile was installed in the base to prevent fine soil and sediment infiltration past the base of the swale. The bioswale was backfilled with two feet of engineered soil (a mix of New Haven sandy loam and compost/mulch organic material to facilitate plant growth) and one foot of river stone or gravel. Soils in the New Haven area are highly permeable, consisting of sandy loams with infiltration rates near 0.46 m/hr. Along one end of each bioswale, 0.6 – 0.7 m wide vertical wire fenced gabions were placed in each bioswale and filled with river stones to encourage fast infiltration if ponding occurred. New Haven high school students from Common Ground High School, alongside homeowners who adopted the swales, planted native plants and shrubs, such as winterberry holly, black-eyed susans, and grasses and chose their plant pallet (see Figure X-XII). The sidewalk curbs were cut to allow water to infiltrate into the gardens.

This small pilot program turned into a citywide partnership program that recently won Harvard's prestigious Roy Award for Environmental Partnership (City of New Haven, 2018). Funding for an additional 275 bioswales has been secured, with 200 built within downtown New Haven to alleviate flooding and 75 within the combined sewer area to mitigate combined sewer overflow pollution. In small cities like New Haven that are considering sewer separation, bioswales have proven to be a cost-effective alternative to this expensive and disruptive procedure, while also improving flooding hazards and risks in urban areas. Bioretention systems are scalable to larger cities, especially those that have aging infrastructure. If sited strategically and developed with adequate maintenance, green infrastructure can serve as a long-term solution to aid in stormwater management.

**Figure X-XII. Homeowners and Common Ground High School students plant perennials in a New Haven Bioswale**

Photo taken by Kelsey Semrod, https://hixon.yale.edu/practice/bioswales.

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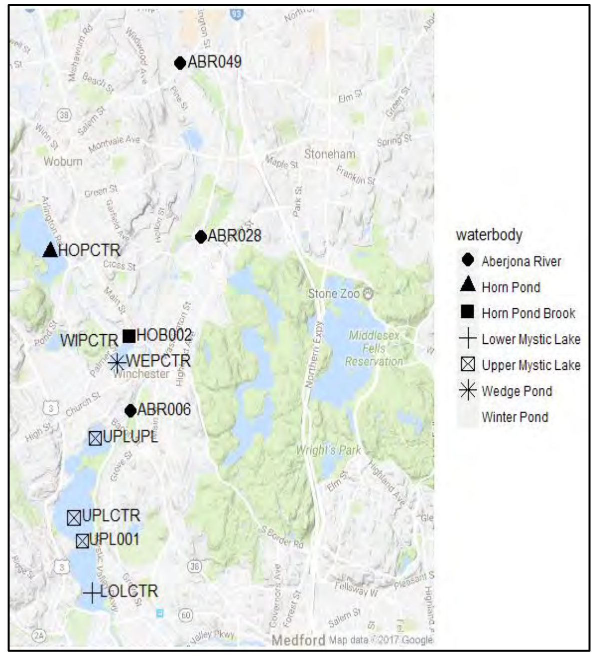
# Appendix A: Water body and Monitoring Location Summary Table

## Table A-1. Number of Days Sampled from 2000 – 2016 and Maps of Monitoring Locations.

| / Monitoring Station | Monitoring Program | | | | Total Sample No. |
|---|---|---|---|---|---|
| | Baseline | Phos. Loadin g | Bosto n Harbo r | CSO Event | |
| **Aberjona River** | **558** | **39** | **–** | **–** | **597** |
| *ABR006* | *187* | *39* | – | – | *226* |
| *ABR028* | *190* | – | – | – | *190* |
| *ABR049* | *184* | – | – | – | *184* |
| **Horn Pond** | **–** | **2** | **–** | **–** | **2** |
| *HOPCTR* | – | *2* | – | – | *2* |
| **Horn Pond Brook** | **–** | **1** | **–** | **–** | **1** |
| *HOB002* | – | *1* | – | – | *1* |
| **Winter Pond** | **–** | **5** | **–** | **–** | **5** |
| *WIPCTR* | – | *5* | – | – | *5* |
| **Wedge Pond** | **–** | **33** | **–** | **–** | **33** |
| *WEPCTR* | – | *33* | – | – | *33* |
| **Upper Mystic Lake** | **183** | **60** | **–** | **–** | **243** |
| *UPL001* | *183* | – | – | – | *183* |
| *UPLCTR* | – | *33* | – | – | *33* |
| *UPLUPL* | – | *27* | – | – | *27* |
| **Lower Mystic Lake** | **–** | **2** | **–** | **–** | **2** |
| *LOLCTR* | – | *2* | – | – | *2* |

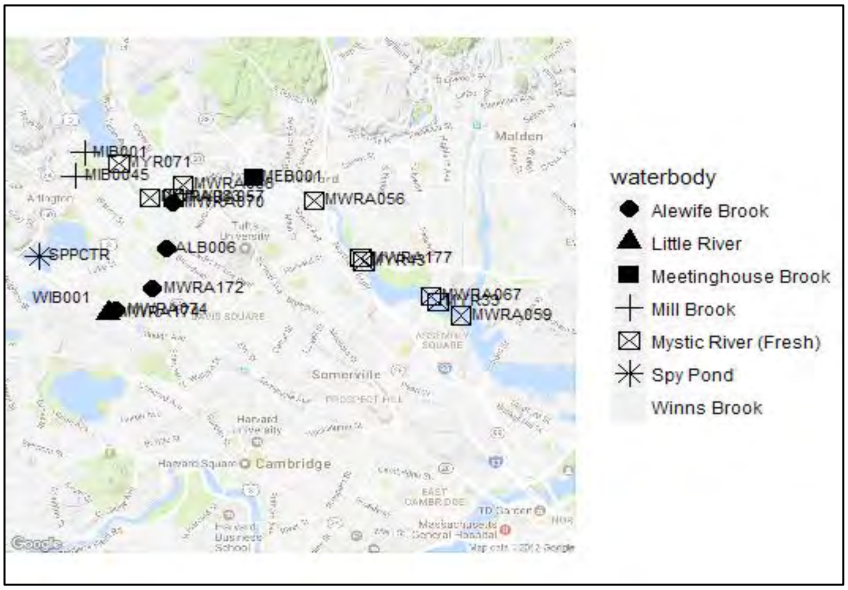


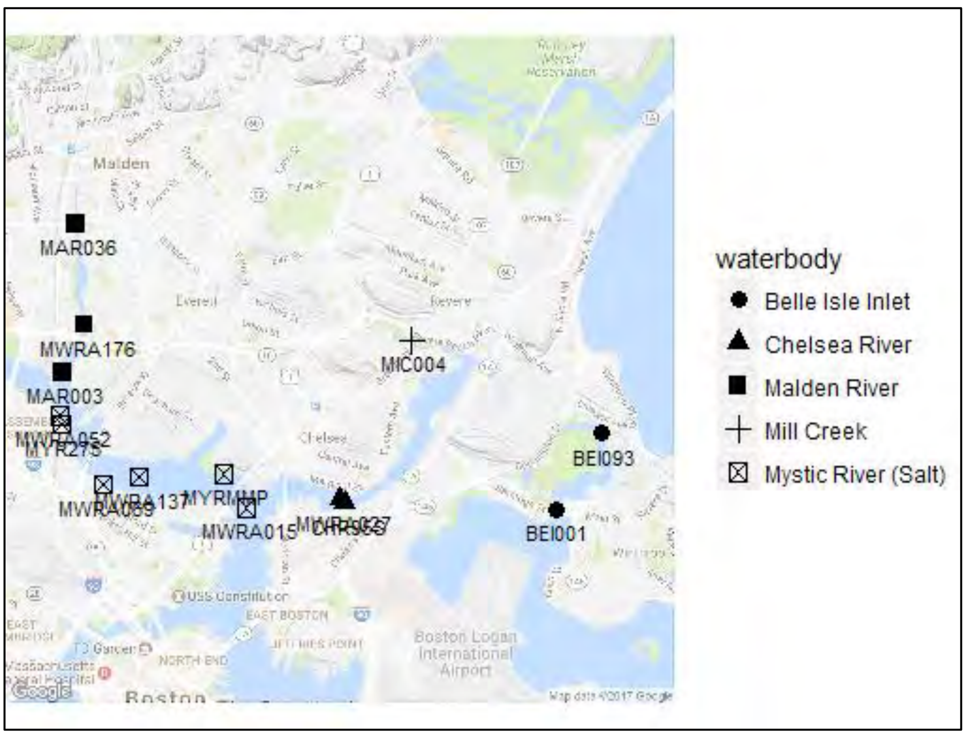

## Table A-2. Water Body/Monitoring Station and Program

| Water body/ Monitoring Station | Monitoring Program | | | | Total Monitoring Events |
|---|---|---|---|---|---|
| | Baseline | Phos. Loading | Boston Harbor | CSO Event | |
| **Mill Brook** | **188** | **38** | **–** | **–** | **226** |
| *MIB001* | **188** | – | – | – | *188* |
| *MIB0045* | – | *38* | – | – | *38* |
| **Spy Pond** | **–** | **17** | **–** | **–** | **17** |
| *SPPCTR* | – | *17* | – | – | *17* |
| **Winns Brook** | **190** | **–** | **–** | **–** | **190** |

| Water body/ Monitoring Station | Monitoring Program | | | | Total Monitoring Events |
|---|---|---|---|---|---|
| | Baseline | Phos. Loading | Boston Harbor | CSO Event | |
| *WIB001* | *190* | – | – | – | *190* |
| **Little River** | – | – | – | **442** | **442** |
| *MWRA174* | – | – | – | *442* | *442* |
| **Alewife Brook** | **192** | **39** | – | **1,393** | **1,624** |
| *ALB006* | *192* | *39* | – | | *231* |
| *MWRA070* | – | – | – | *466* | *466* |
| *MWRA074* | – | – | – | *469* | *469* |
| *MWRA172* | – | – | – | *458* | *458* |
| **Mystic River (Fresh)** | **190** | **109** | **995** | **2,053**[1] | **3,329**[1] |
| *MWRA056* | – | – | – | *365* | *365* |
| *MWRA057* | – | – | – | *373* | *373* |
| *MWRA059* | – | – | – | *367* | *367* |
| *MWRA066* | – | – | *548* | – | *548* |
| *MWRA067* | – | – | – | *370* | *370* |
| *MWRA083* | – | – | *261* | *385* | *646* |
| *MWRA177* | – | – | *186* | *194* | *365*[1] |
| *MYR071* | *190* | *38* | – | – | *228* |
| *MYR33* | – | *36* | – | – | *36* |
| *MYR43* | – | *35* | – | – | *35* |
| **Meetinghous e Brook** | **191** | **13** | – | – | **204** |
| *MEB001* | *191* | *13* | – | – | *204* |
| **Malden River** | **183** | **73** | – | **322** | **578** |
| *MAR003* | – | *36* | – | – | *36* |
| **Mystic River (Salt)** | **170**[1] | – | **459** | **1,079** | **1,708**[1] |
| *MWRA015* | – | – | – | *344* | *344* |
| *MWRA052* | – | – | – | *492* | *492* |
| *MWRA069* | – | – | – | *243* | *243* |
| *MWRA137* | – | – | *459* | – | *459* |
| *MYR275* | *82* | – | – | – | *82* |
| *MYRMMP* | *95* | – | – | – | *95* |
| **Mill Creek** | **93** | – | – | – | **93** |
| *MIC004* | *93* | – | – | – | *93* |
| **Chelsea River** | **95** | – | – | **370** | **465** |
| CHR95S | *95* | – | – | – | *95* |
| MWRA027 | – | – | – | *370* | *370* |
| **Belle Isle Inlet** | **81** | – | – | – | **81** |
| *BEI001* | *13* | – | – | – | *13* |
| *BEI093* | *68* | – | – | – | *68* |

*1.Sub-category values do not sum to this value due to sampling events at different locations or programs occur same day.*


MIB001
MYR071
MIB0045
MEB001
MWRA056
SPPCTR
ALB006
MWRA177
MWRA172
WIB001
MWRA067
MWRA059
Malden
Somerville
Cambridge
waterbody
Alewife Brook
Little River
Meetinghouse Brook
Mill Brook
Mystic River (Fresh)
Spy Pond
Winns Brook


Malden
MAR036
MWRA176
MAR003
MYR275
MIC004
BEI093
BEI001
MWRA137
MYRMMP
MWRA015
Everett
Revere
Chelsea
Boston Logan International Airport
waterbody
Belle Isle Inlet
Chelsea River
Malden River
Mill Creek
Mystic River (Salt)

# APPENDIX B: WATER QUALITY PARAMETERS INCLUDED IN MONITORING PROGRAMS

## Table B-1. Water Quality Parameters Included in Monitoring Programs

| Parameter Code | Parameter Name/Description | Speciation |
|---|---|---|
| ATTENUATION_COEFFICIENT | Light attenuation coefficient | – |
| CHLA | Chlorophyll-a | – |
| DO | Dissolved Oxygen | – |
| DO_SAT | Dissolved Oxygen, % saturation | – |
| ECOLI | Escherichia coli | – |
| ENT | Enterococcus | – |
| FCOLI | Fecal Coliform | – |
| NH3 | Ammonia | as N |
| NO2 | Nitrite | as N |
| NO23 | Nitrate + Nitrite | as N |
| NO3 | Nitrate | as N |
| PH | pH | – |
| PHAEOPHYTIN | Pheophytin a | – |
| PO4 | Orthophosphate | as P |
| SALINITY | Salinity | – |
| SECCHI | Secchi Disk Depth | – |
| SPCOND | Specific conductance | – |
| TDN | Nitrogen, total dissolved | as N |
| TDP | Dissolved Phosphorus | as P |
| TEMP_WATER | Water Temperature | – |
| TN | Total Nitrogen | as N |
| TP | Total Phosphorus | as P |
| TPC | Total Particulate Carbon | – |
| TPN | Particulate Nitrogen | as N |
| TPP | Phosphorus, Particulate Organic | as P |
| TSS | Total suspended solids | – |
| TURB | Turbidity | – |

# Appendix C: Descriptive Figures of Water Quality Data by Water body

Note that values marked as "dot" denote observations that extend above or below the nearest hinge (i.e., the 25th or 75th percentile) by a distance exceeding 1.5 times the inter-quartile range. Unusual values are marked by a red circle and additional information on these values are provided in Appendix D.

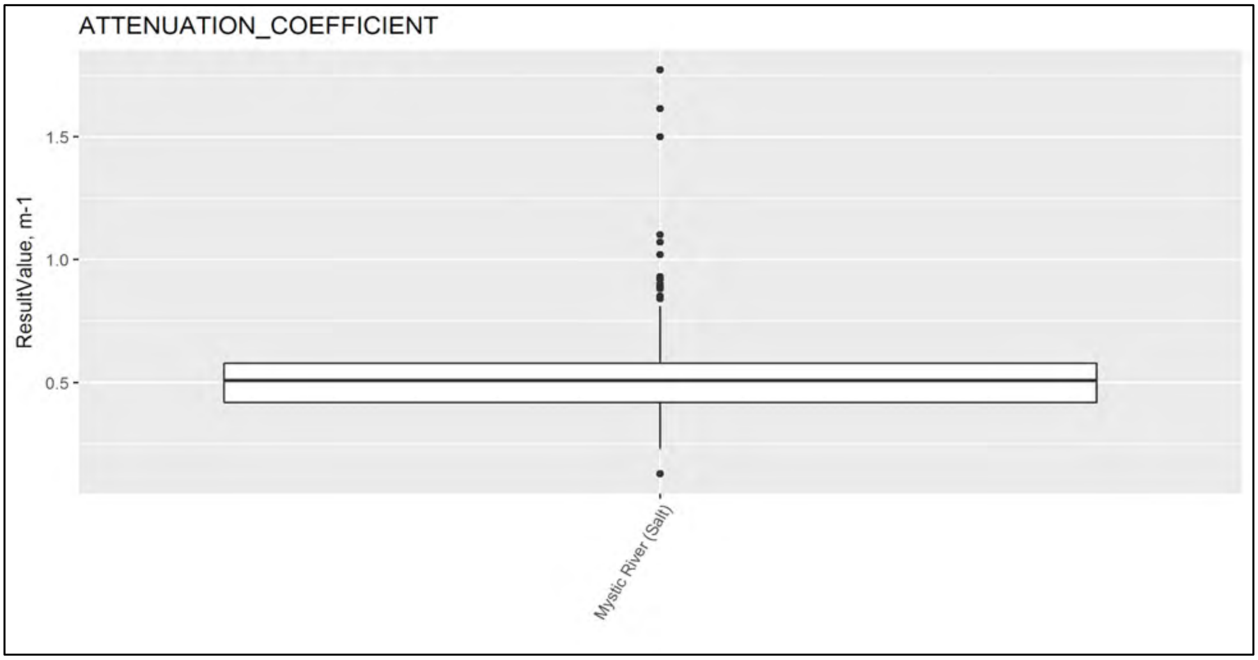



**Figure C-1. Attenuation coefficient results by water body.**

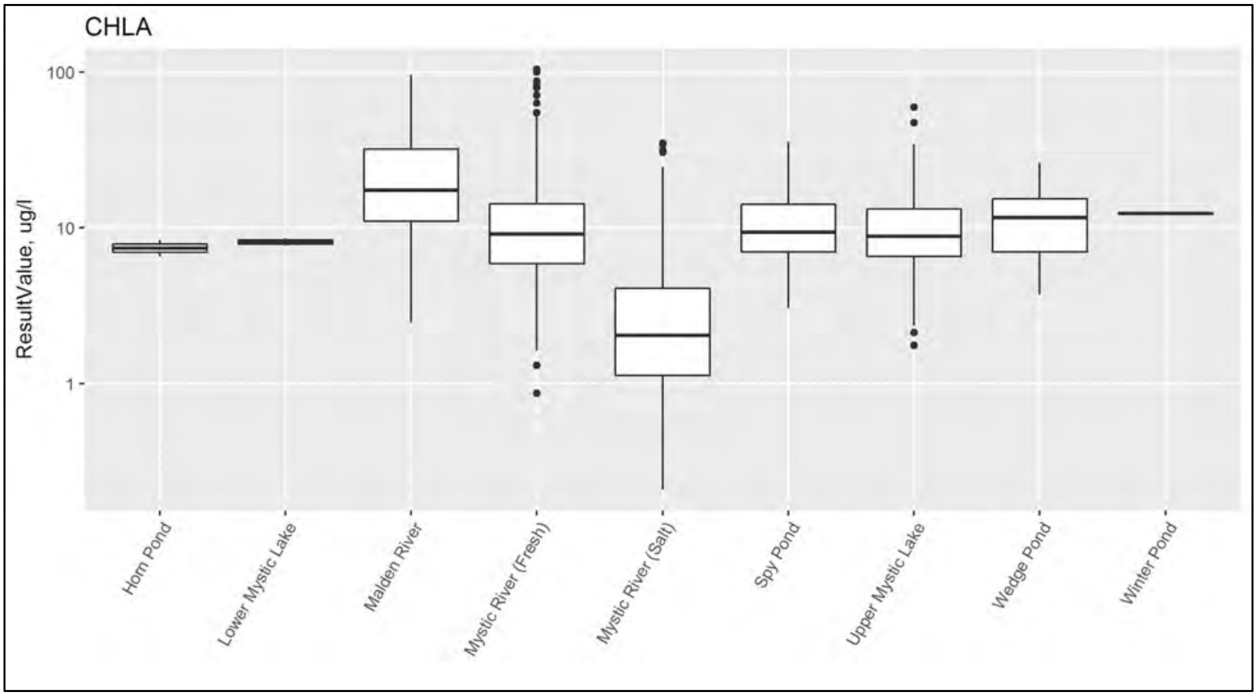



**Figure C-2. Chlorophyll-a results by water body.**

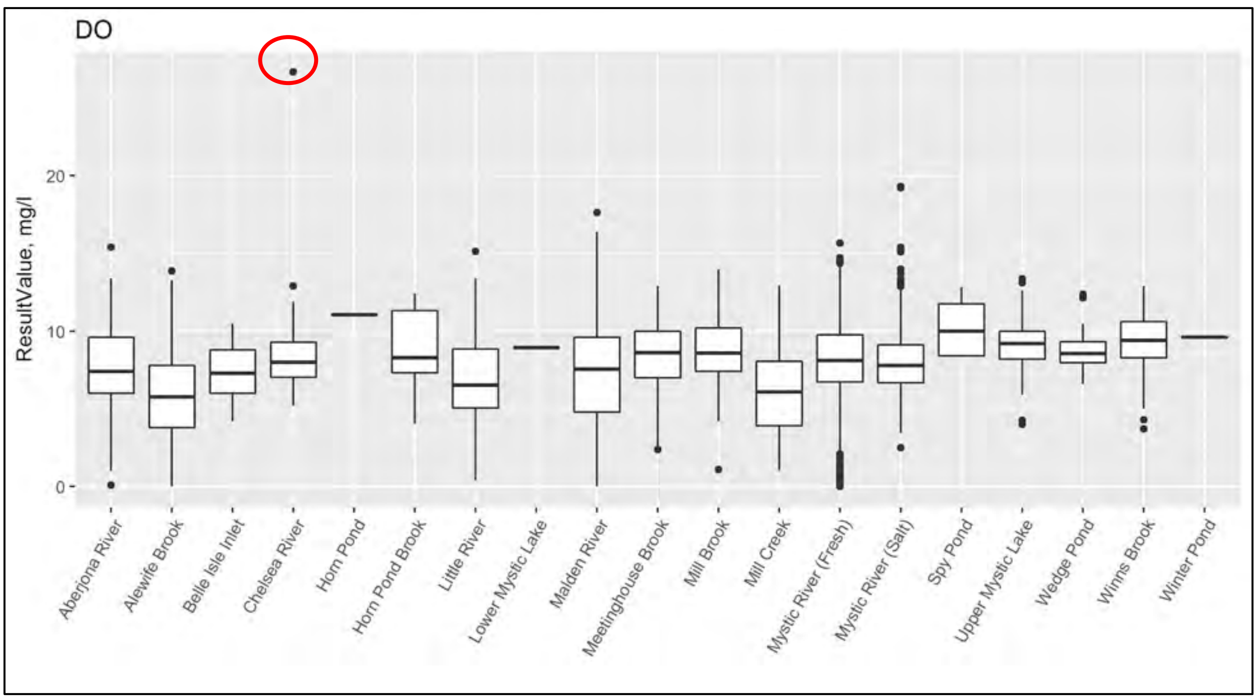



**Figure C-3. Dissolved oxygen results by water body.**

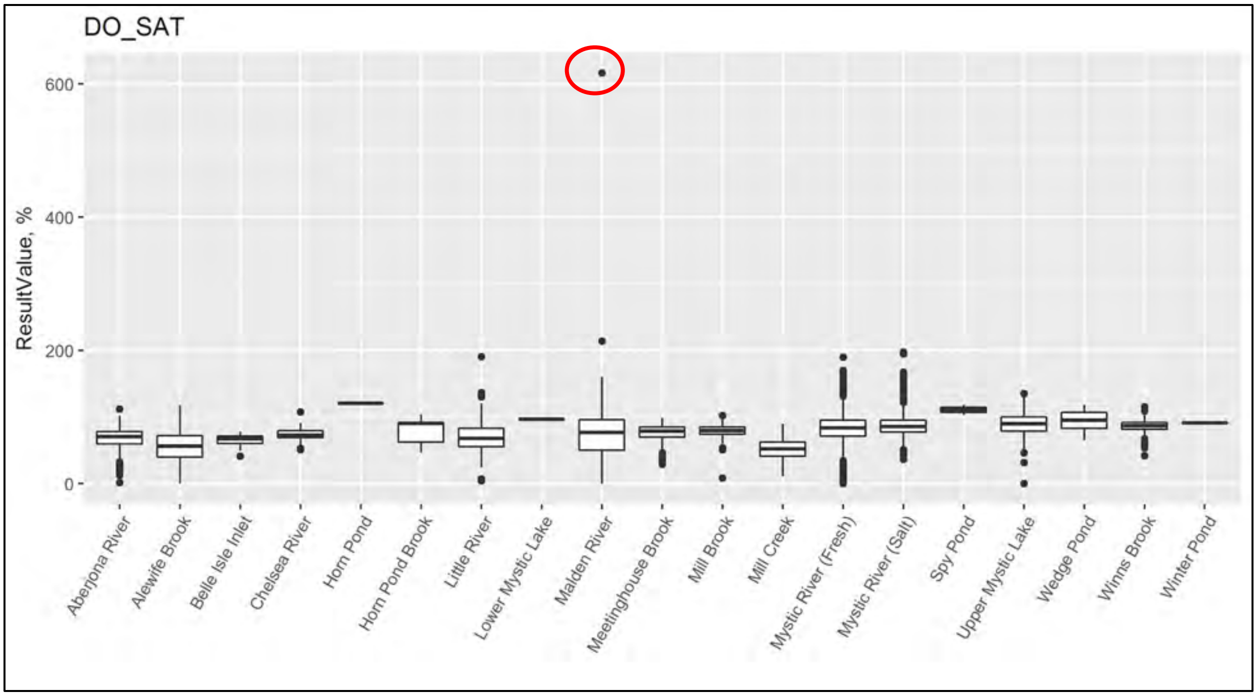



**Figure C-4. Dissolved oxygen percent saturation results by water body**

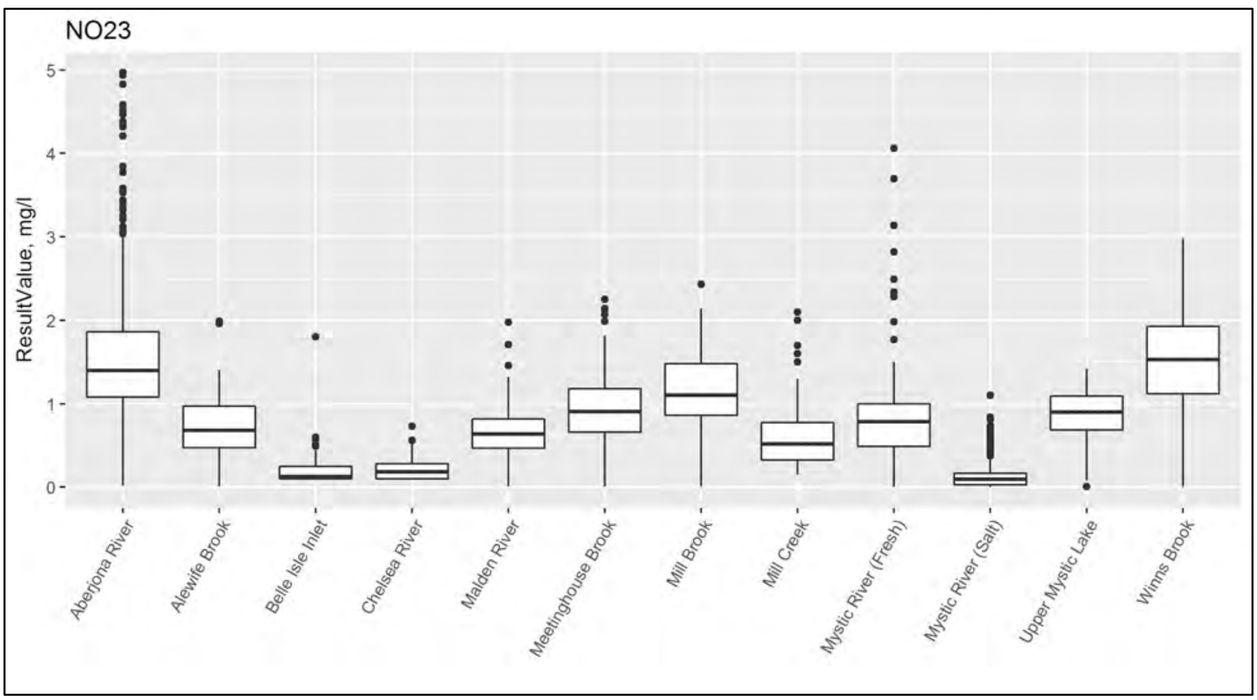



**Figure C-5. Inorganic nitrogen (nitrite plus nitrate) results by water body.**

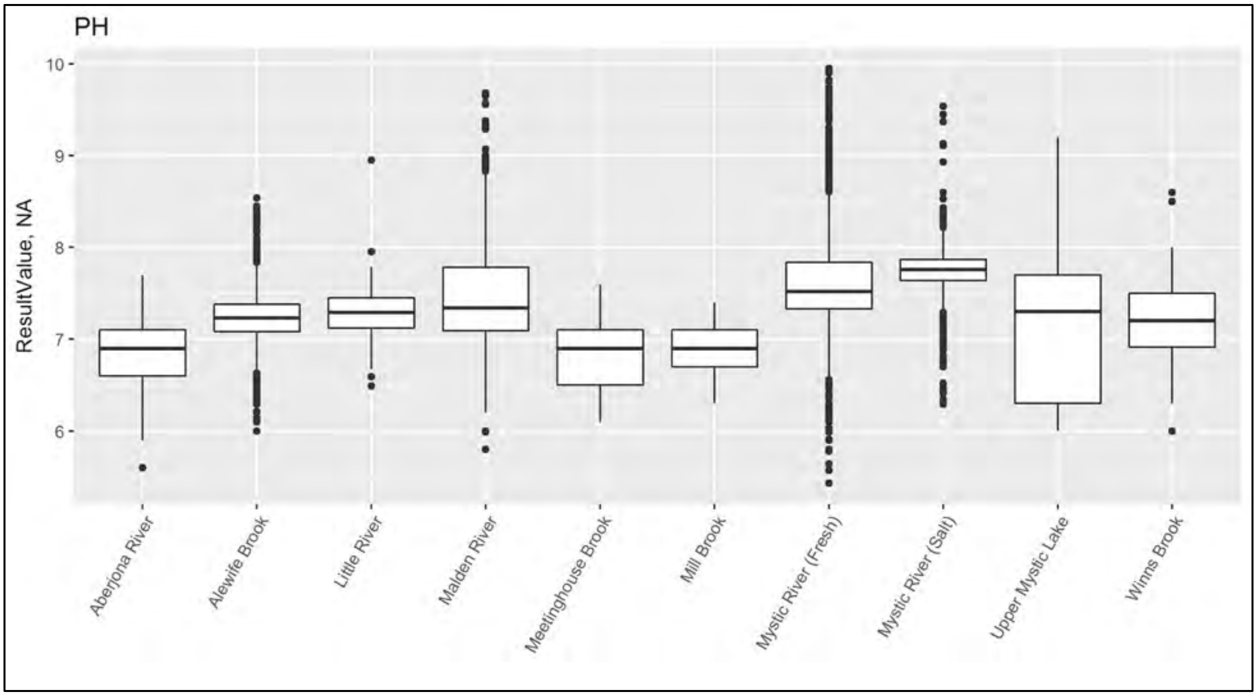



**Figure C-6. pH results by water body.**

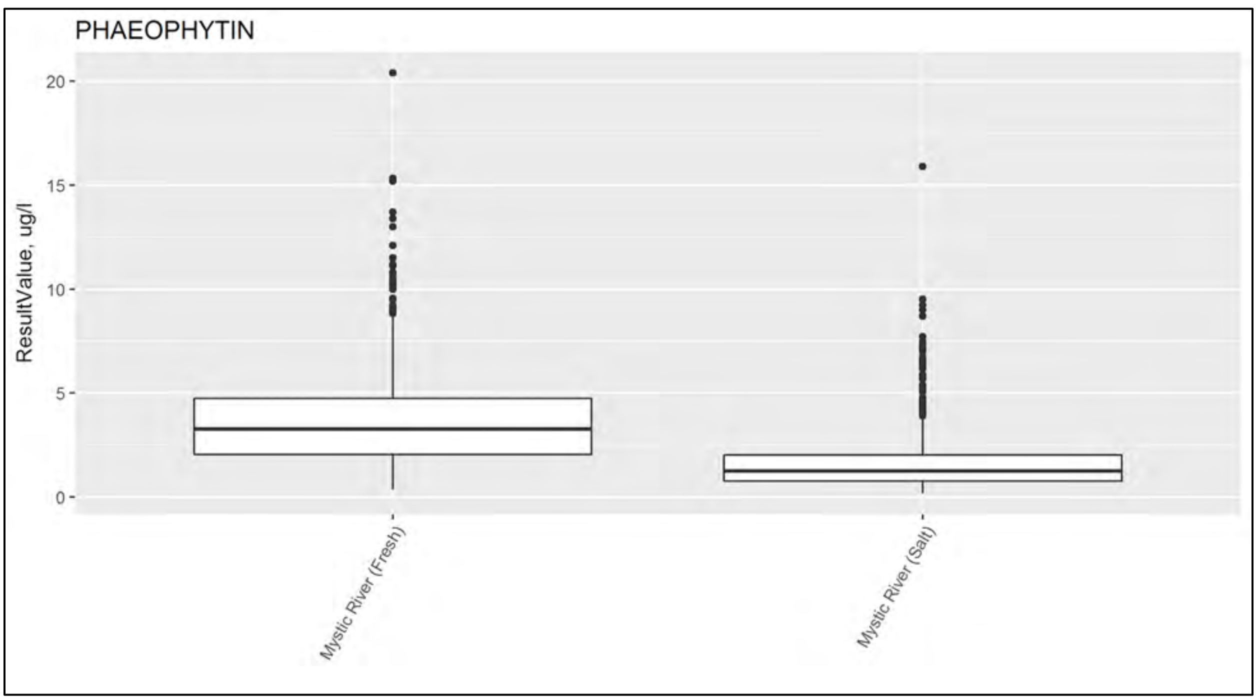



**Figure C-7. Phaeophytin results by water body.**

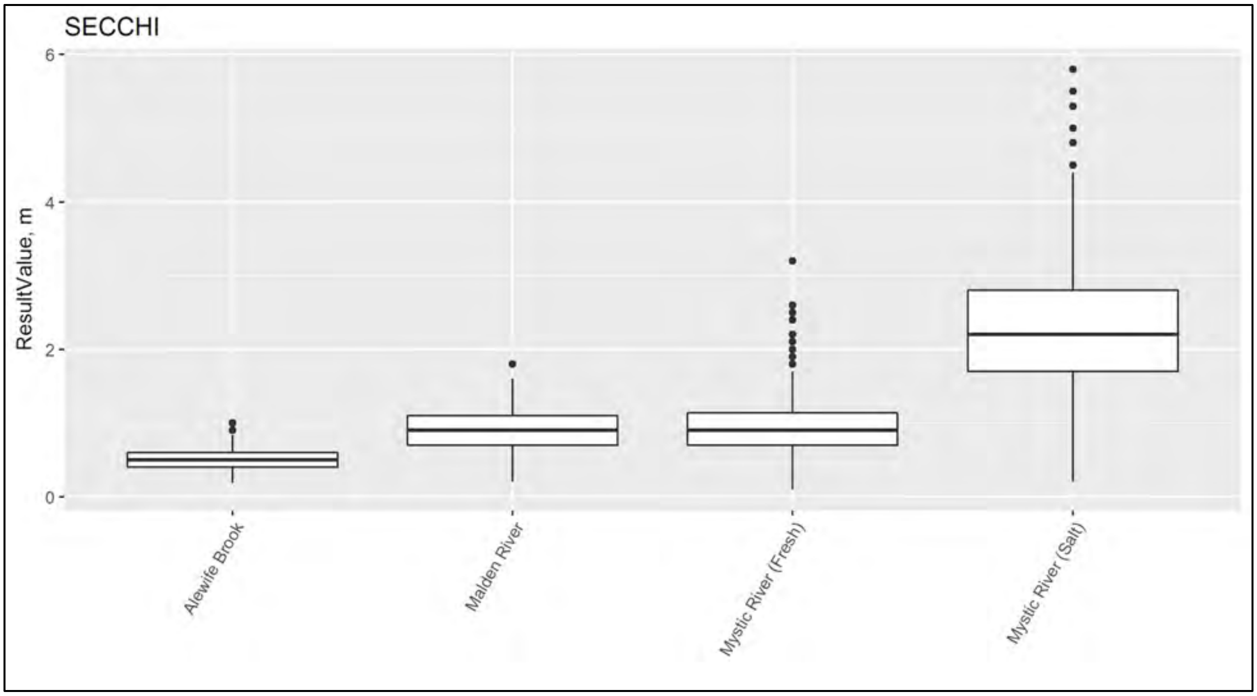



**Figure C-8. Secchi depth results by water body.**

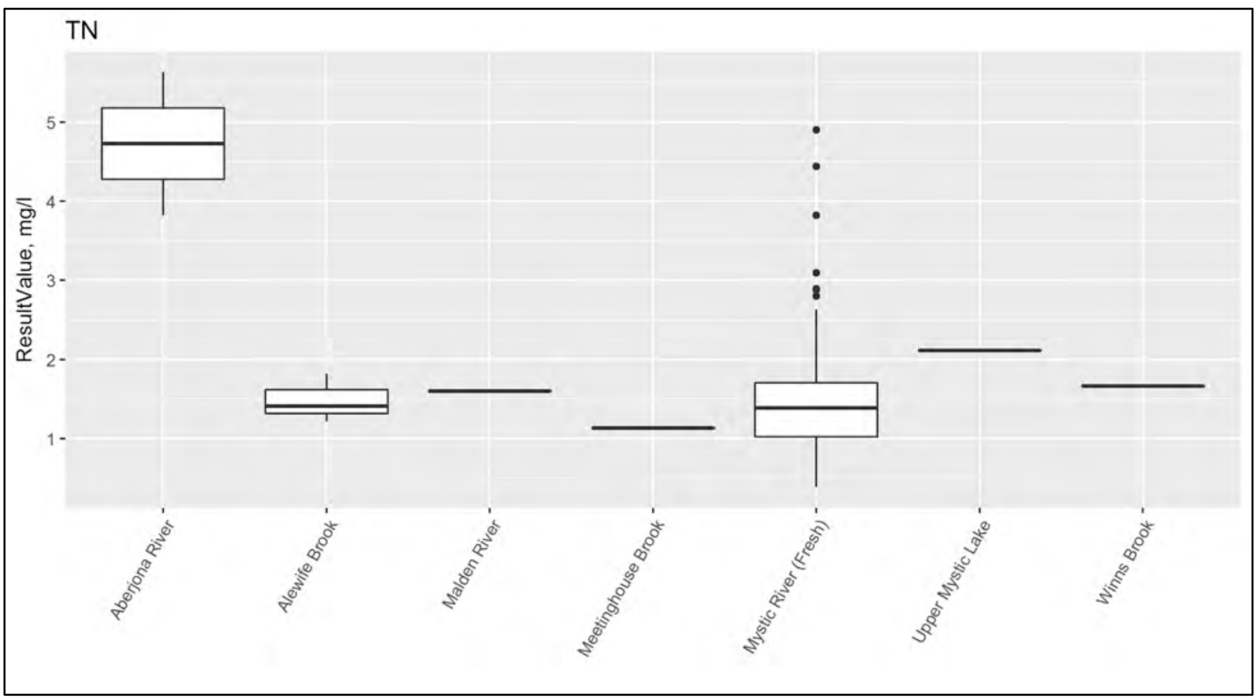



**Figure C-9. Total nitrogen results by water body.**

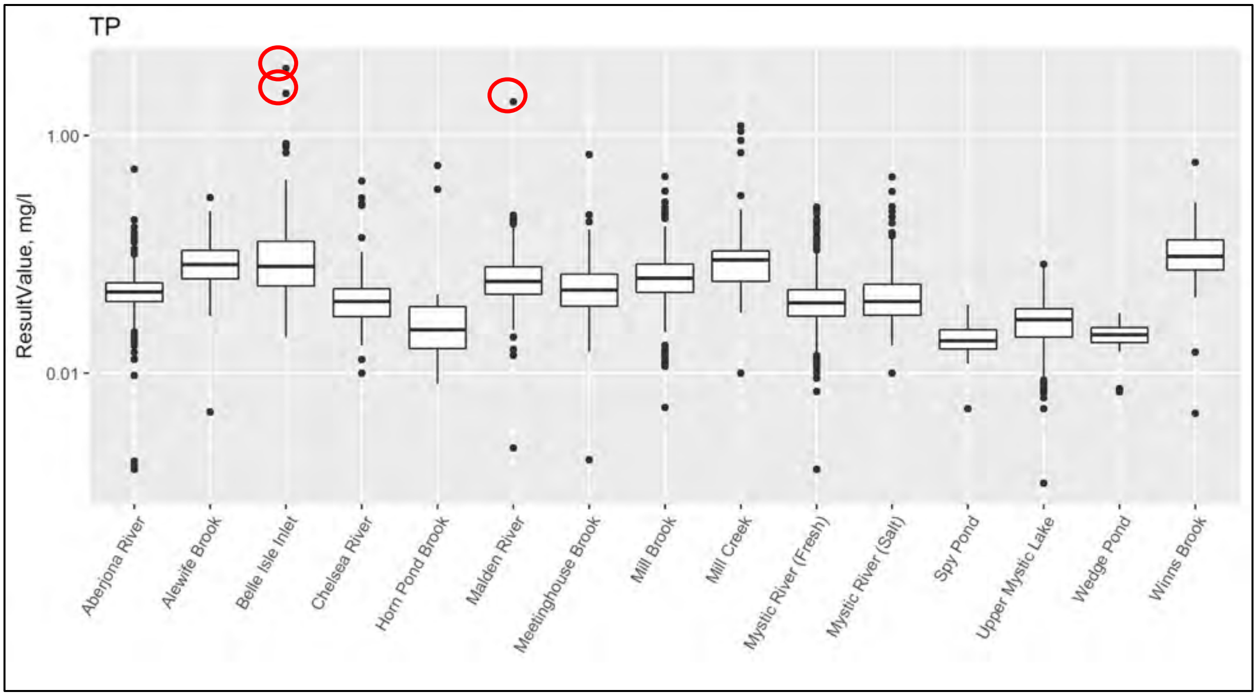



**Figure C-10. Total phosphorus results by water body.**

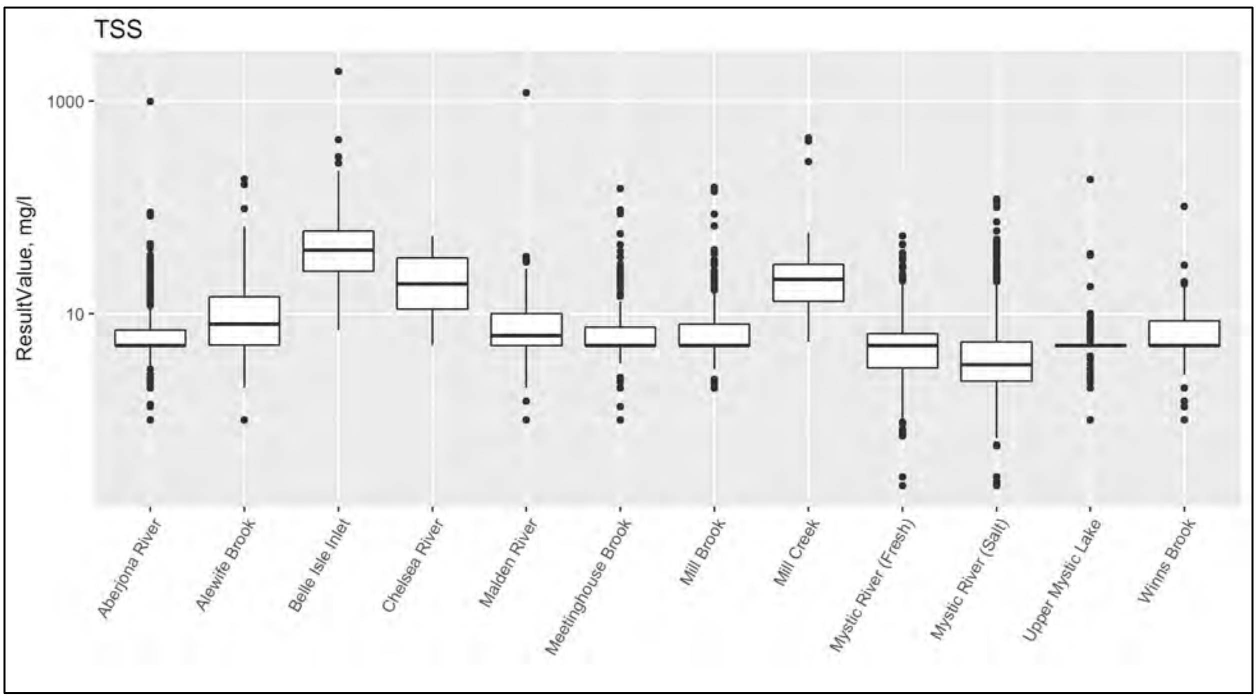



**Figure C-11. Total suspended solids results by water body.**

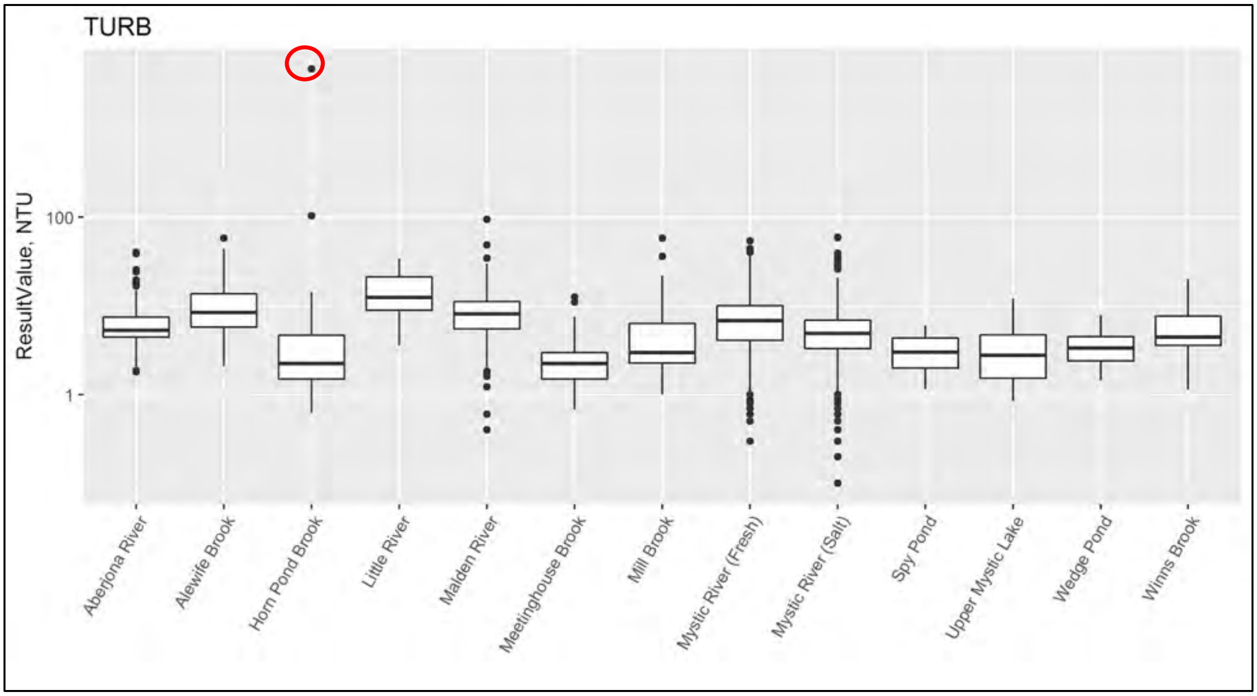



**Figure C-12. Turbidity results by water body**

# APPENDIX D: IDENTIFIED EXTREME VALUES

## Table D-1. Extreme values identified in Appendix C

| Sample Date & Time | Monitoring Program | Water body Name | Monitoring Location | Parameter Name | Sample Result | Units | Qual. | Flag ID | Flag Description | Comment | Analytical Method | Analytical Method Description |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2/2/09 7:56 | Baseline | Chelsea River | CHR95S | Dissolved Oxygen | 26.66 | mg/l | – | E | instrument error | YSI likely not calibrated correctly | D888(B) | Dissolved Oxygen by Instrumental Probe |
| 6/25/03 7:36 | CSO | Malden River | MWRA176 | Dissolved Oxygen (% Saturation) | 616.7 | % | – | – | – | – | D888(B) | Dissolved Oxygen by Instrumental Probe |
| 5/1/14 6:27 | Baseline | Belle Isle Inlet | BEI093 | Total Phos. | 3.65 | mg/l | – | – | – | – | 4500-P-E | Phosphorus in Water by Colorimetry-Ascorbic Acid Method |
| 12/16/11 7:21 | Baseline | Belle Isle Inlet | BEI093 | Total Phos. | 2.25 | mg/l | – | – | – | – | 4500-P-E | Phosphorus in Water by Colorimetry-Ascorbic Acid Method |
| 7/12/06 6:37 | Baseline | Malden River | MAR036 | Total Phos. | 1.920376 | mg/l | – | – | – | – | 4500-P-J | Persulfate Method for Simultaneous Determination of Total Nitrogen and Total Phosphorus |
| 10/13/15 10:00 | Phosphorus Loading | Horn Pond Brook | HOB002 | Turbidity | 4720 | NTU | – | – | – | – | 180.1 | Turbidity by Nephelometry |

# Appendix E: Modeled Stormwater TP Load and Rainfall-Runoff Results

## Table E-XI-1. Modeled Stormwater TP Load (lbs./year; No Calibration)

| Year | Critical Water Quality Segments | | | | Impaired Ponds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper Lobe Basin | Upper Mystic Lake | Upper Basin | Lower Basin | Blacks Nook Pond (MA71005), Cambridge | Horn Pond (MA71019), Woburn | Judkins Pond (MA71021), Winchester | Mill Pond (MA71031), Winchester | Spy Pond (MA71040), Arlington | Wedge Pond (MA71045), Winchester | Winter Pond (MA71047), Winchester |
| 1992 | 7,748 | 8,315 | 14,693 | 18,940 | 2.19 | 2,360 | 7,501 | 7,543 | 371 | 2,581 | 61 |
| 1993 | 5,428 | 5,737 | 10,408 | 13,718 | 0.73 | 1,490 | 5,260 | 5,291 | 288 | 1,646 | 36 |
| 1994 | 6,426 | 6,849 | 12,203 | 15,899 | 1.35 | 1,877 | 6,227 | 6,262 | 318 | 2,061 | 46 |
| 1995 | 5,868 | 6,276 | 11,211 | 14,556 | 1.44 | 1,726 | 5,684 | 5,716 | 294 | 1,894 | 43 |
| 1996 | 7,492 | 7,990 | 14,194 | 18,434 | 1.70 | 2,217 | 7,255 | 7,297 | 365 | 2,430 | 55 |
| 1997 | 3,749 | 3,939 | 7,327 | 9,771 | 0.28 | 951 | 3,635 | 3,657 | 218 | 1,060 | 22 |
| 1998 | 9,409 | 10,142 | 17,714 | 22,613 | 3.04 | 2,977 | 9,098 | 9,146 | 438 | 3,257 | 79 |
| 1999 | 6,852 | 7,367 | 13,067 | 16,801 | 2.02 | 2,087 | 6,628 | 6,664 | 341 | 2,292 | 55 |
| 2000 | 6,523 | 6,950 | 12,458 | 16,256 | 1.35 | 1,882 | 6,321 | 6,357 | 331 | 2,069 | 46 |
| 2001 | 4,004 | 4,218 | 7,697 | 10,193 | 0.40 | 1,073 | 3,880 | 3,904 | 218 | 1,190 | 25 |
| 2002 | 4,692 | 4,940 | 9,127 | 12,131 | 0.43 | 1,217 | 4,549 | 4,577 | 267 | 1,354 | 29 |
| 2003 | 5,449 | 5,758 | 10,419 | 13,739 | 0.68 | 1,500 | 5,282 | 5,313 | 288 | 1,659 | 35 |
| 2004 | 6,231 | 6,636 | 11,845 | 15,442 | 1.27 | 1,812 | 6,036 | 6,071 | 312 | 1,991 | 44 |
| 2005 | 5,451 | 5,763 | 10,519 | 13,878 | 0.76 | 1,478 | 5,283 | 5,314 | 295 | 1,635 | 36 |
| 2006 | 6,747 | 7,180 | 12,814 | 16,710 | 1.37 | 1,960 | 6,536 | 6,574 | 335 | 2,152 | 48 |
| 2007 | 7,376 | 7,926 | 13,968 | 17,976 | 2.16 | 2,264 | 7,141 | 7,181 | 350 | 2,475 | 58 |
| 2008 | 7,469 | 7,972 | 14,158 | 18,402 | 1.66 | 2,207 | 7,236 | 7,277 | 366 | 2,421 | 54 |
| 2009 | 5,235 | 5,521 | 10,146 | 13,454 | 0.55 | 1,381 | 5,076 | 5,106 | 293 | 1,534 | 32 |
| 2010 | 8,315 | 8,931 | 15,614 | 20,039 | 2.40 | 2,594 | 8,045 | 8,089 | 386 | 2,837 | 67 |
| 2011 | 6,559 | 6,950 | 12,543 | 16,483 | 1.02 | 1,832 | 6,356 | 6,394 | 342 | 2,022 | 44 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2012 | 5,036 | 5,322 | 9,616 | 12,675 | 0.63 | 1,392 | 4,881 | 4,910 | 265 | 1,539 | 33 |
| 2013 | 5,491 | 5,844 | 10,498 | 13,707 | 1.09 | 1,574 | 5,318 | 5,349 | 283 | 1,734 | 39 |
| 2014 | 6,141 | 6,537 | 11,747 | 15,345 | 1.24 | 1,758 | 5,950 | 5,984 | 314 | 1,933 | 43 |
| 2015 | 4,077 | 4,288 | 7,947 | 10,586 | 0.32 | 1,045 | 3,953 | 3,977 | 235 | 1,165 | 24 |
| 2016 | 3,912 | 4,115 | 7,647 | 10,202 | 0.27 | 994 | 3,795 | 3,818 | 229 | 1,110 | 23 |
| 2017 | 5,236 | 5,544 | 10,061 | 13,246 | 0.78 | 1,442 | 5,075 | 5,105 | 278 | 1,593 | 35 |
| Average Annual | 6,035 | 6,423 | 11,525 | 15,046 | 1 | 1,734 | 5,846 | 5,880 | 308 | 1,909 | 43 |

## Table E-XI-2. Modeled Groundwater TP Load (lbs./year; Concentration = 8 mg/L; No Calibration)

| Year | Critical Water Quality Segments | | | | Impaired Ponds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper Lobe Basin | Upper Mystic Lake | Upper Basin | Lower Basin | Blacks Nook Pond (MA71005), Cambridge[1] | Horn Pond (MA71019), Woburn | Judkins Pond (MA71021), Winchester | Mill Pond (MA71031), Winchester | Spy Pond (MA71040), Arlington | Wedge Pond (MA71045), Winchester | Winter Pond (MA71047), Winchester |
| 1992 | 562 | 597 | 1,102 | 1,432 | 0.15 | 168 | 544 | 547 | 32 | 184 | 4 |
| 1993 | 429 | 453 | 842 | 1,110 | 0.06 | 120 | 416 | 419 | 25 | 132 | 3 |
| 1994 | 522 | 552 | 1,021 | 1,339 | 0.10 | 151 | 506 | 509 | 30 | 165 | 4 |
| 1995 | 380 | 402 | 746 | 977 | 0.08 | 109 | 367 | 370 | 22 | 120 | 3 |
| 1996 | 634 | 673 | 1,238 | 1,612 | 0.15 | 189 | 613 | 617 | 36 | 207 | 5 |
| 1997 | 229 | 240 | 454 | 604 | 0.02 | 60 | 222 | 223 | 15 | 66 | 1 |
| 1998 | 744 | 790 | 1,450 | 1,881 | 0.19 | 226 | 719 | 723 | 42 | 247 | 6 |
| 1999 | 500 | 532 | 982 | 1,274 | 0.13 | 150 | 484 | 486 | 29 | 165 | 4 |
| 2000 | 490 | 519 | 962 | 1,259 | 0.10 | 142 | 475 | 477 | 29 | 155 | 3 |
| 2001 | 279 | 293 | 548 | 723 | 0.04 | 77 | 270 | 272 | 17 | 85 | 2 |
| 2002 | 337 | 354 | 666 | 883 | 0.04 | 90 | 327 | 329 | 21 | 99 | 2 |
| 2003 | 421 | 443 | 825 | 1,089 | 0.05 | 116 | 408 | 410 | 25 | 128 | 3 |
| 2004 | 524 | 555 | 1,024 | 1,339 | 0.11 | 153 | 507 | 510 | 30 | 168 | 4 |
| 2005 | 432 | 455 | 849 | 1,118 | 0.07 | 121 | 418 | 421 | 26 | 133 | 3 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2006 | 648 | 686 | 1,264 | 1,651 | 0.14 | 191 | 627 | 630 | 37 | 209 | 5 |
| 2007 | 442 | 467 | 864 | 1,132 | 0.08 | 128 | 427 | 430 | 26 | 140 | 3 |
| 2008 | 641 | 678 | 1,252 | 1,638 | 0.13 | 187 | 620 | 624 | 37 | 205 | 4 |
| 2009 | 374 | 393 | 739 | 979 | 0.04 | 101 | 363 | 365 | 23 | 111 | 2 |
| 2010 | 685 | 727 | 1,333 | 1,733 | 0.16 | 207 | 662 | 666 | 38 | 226 | 5 |
| 2011 | 512 | 539 | 1,004 | 1,323 | 0.07 | 143 | 496 | 499 | 30 | 157 | 3 |
| 2012 | 336 | 354 | 662 | 875 | 0.05 | 93 | 326 | 328 | 20 | 102 | 2 |
| 2013 | 427 | 450 | 835 | 1,096 | 0.07 | 122 | 413 | 415 | 25 | 134 | 3 |
| 2014 | 492 | 520 | 965 | 1,266 | 0.09 | 141 | 477 | 479 | 29 | 155 | 3 |
| 2015 | 270 | 283 | 534 | 710 | 0.02 | 71 | 262 | 263 | 17 | 79 | 2 |
| 2016 | 251 | 263 | 497 | 662 | 0.02 | 65 | 243 | 245 | 16 | 73 | 1 |
| 2017 | 385 | 405 | 757 | 999 | 0.05 | 106 | 373 | 375 | 23 | 117 | 2 |
| Average Annual | 459 | 486 | 901 | 1,181 | 0 | 132 | 445 | 447 | 27 | 145 | 3 |

1. All results rounded to the nearest pound. Groundwater loads for Blacks Nook Pond are non-zero but below the rounding level.

### Table E-XI-3. Modeled Total Streamflow TP Load (lbs./year) from Stormwater and Groundwater (No Calibration and No Attenuation)

| Year | Critical Water Quality Segments | | | | Impaired Ponds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper Lobe Basin | Upper Mystic Lake | Upper Basin | Lower Basin | Blacks Nook Pond (MA71005), Cambridge | Horn Pond (MA71019), Woburn | Judkins Pond (MA71021), Winchester | Mill Pond (MA71031), Winchester | Spy Pond (MA71040), Arlington | Wedge Pond (MA71045), Winchester | Winter Pond (MA71047), Winchester |
| 1992 | 8,310 | 8,913 | 15,795 | 20,372 | 2.34 | 2,528 | 8,045 | 8,090 | 403 | 2,764 | 65 |
| 1993 | 5,857 | 6,189 | 11,250 | 14,828 | 0.79 | 1,610 | 5,676 | 5,710 | 314 | 1,779 | 38 |
| 1994 | 6,948 | 7,401 | 13,224 | 17,238 | 1.45 | 2,028 | 6,732 | 6,771 | 348 | 2,226 | 49 |
| 1995 | 6,247 | 6,678 | 11,957 | 15,532 | 1.51 | 1,836 | 6,051 | 6,086 | 316 | 2,014 | 46 |
| 1996 | 8,126 | 8,663 | 15,432 | 20,046 | 1.86 | 2,407 | 7,869 | 7,914 | 401 | 2,637 | 60 |
| 1997 | 3,978 | 4,179 | 7,781 | 10,375 | 0.29 | 1,011 | 3,857 | 3,881 | 233 | 1,127 | 24 |
| 1998 | 10,152 | 10,932 | 19,165 | 24,494 | 3.24 | 3,203 | 9,816 | 9,869 | 480 | 3,503 | 84 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1999 | 7,352 | 7,899 | 14,049 | 18,075 | 2.15 | 2,237 | 7,112 | 7,150 | 370 | 2,457 | 59 |
| 2000 | 7,014 | 7,469 | 13,420 | 17,516 | 1.45 | 2,023 | 6,795 | 6,834 | 360 | 2,224 | 50 |
| 2001 | 4,283 | 4,511 | 8,245 | 10,916 | 0.44 | 1,150 | 4,150 | 4,175 | 235 | 1,275 | 27 |
| 2002 | 5,029 | 5,294 | 9,793 | 13,015 | 0.47 | 1,307 | 4,876 | 4,906 | 288 | 1,453 | 31 |
| 2003 | 5,870 | 6,201 | 11,243 | 14,828 | 0.73 | 1,616 | 5,689 | 5,723 | 313 | 1,787 | 38 |
| 2004 | 6,755 | 7,190 | 12,869 | 16,781 | 1.37 | 1,965 | 6,543 | 6,581 | 342 | 2,159 | 48 |
| 2005 | 5,883 | 6,219 | 11,368 | 14,996 | 0.83 | 1,599 | 5,701 | 5,735 | 321 | 1,767 | 38 |
| 2006 | 7,394 | 7,866 | 14,079 | 18,361 | 1.51 | 2,151 | 7,163 | 7,204 | 372 | 2,361 | 53 |
| 2007 | 7,818 | 8,393 | 14,832 | 19,108 | 2.24 | 2,392 | 7,569 | 7,611 | 375 | 2,614 | 61 |
| 2008 | 8,110 | 8,650 | 15,411 | 20,040 | 1.80 | 2,394 | 7,856 | 7,900 | 403 | 2,626 | 59 |
| 2009 | 5,609 | 5,914 | 10,884 | 14,433 | 0.59 | 1,482 | 5,438 | 5,471 | 316 | 1,645 | 35 |
| 2010 | 9,000 | 9,657 | 16,947 | 21,771 | 2.56 | 2,801 | 8,707 | 8,755 | 424 | 3,063 | 72 |
| 2011 | 7,070 | 7,490 | 13,547 | 17,806 | 1.09 | 1,975 | 6,852 | 6,892 | 373 | 2,179 | 47 |
| 2012 | 5,373 | 5,677 | 10,278 | 13,550 | 0.67 | 1,484 | 5,207 | 5,238 | 285 | 1,641 | 35 |
| 2013 | 5,917 | 6,294 | 11,333 | 14,803 | 1.16 | 1,696 | 5,731 | 5,764 | 308 | 1,867 | 42 |
| 2014 | 6,633 | 7,057 | 12,712 | 16,611 | 1.34 | 1,900 | 6,426 | 6,464 | 343 | 2,088 | 47 |
| 2015 | 4,347 | 4,571 | 8,481 | 11,296 | 0.34 | 1,116 | 4,215 | 4,241 | 252 | 1,243 | 26 |
| 2016 | 4,163 | 4,379 | 8,143 | 10,863 | 0.29 | 1,059 | 4,039 | 4,063 | 245 | 1,182 | 24 |
| 2017 | 5,621 | 5,950 | 10,818 | 14,245 | 0.83 | 1,549 | 5,448 | 5,480 | 302 | 1,710 | 37 |
| Average Annual | 6,495 | 6,909 | 12,425 | 16,227 | 1 | 1,866 | 6,291 | 6,327 | 335 | 2,054 | 46 |

**Table E-XI-4. Modeled Stormwater Rainfall-Runoff (in-acre/year) Results Attributable to Stormwater (No Calibration)**

| Year | Critical Water Quality Segments | | | | Impaired Ponds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper Lobe Basin | Upper Mystic Lake | Upper Basin | Lower Basin | Blacks Nook Pond (MA71005), Cambridge | Horn Pond (MA71019), Woburn | Judkins Pond (MA71021), Winchester | Mill Pond (MA71031), Winchester | Spy Pond (MA71040), Arlington | Wedge Pond (MA71045), Winchester | Winter Pond (MA71047), Winchester |
| 1992 | 163,532 | 172,857 | 299,273 | 386,996 | 34 | 48,984 | 158,337 | 159,243 | 7,458 | 53,541 | 1,201 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 124,957 | 131,132 | 228,531 | 299,548 | 15 | 35,074 | 121,200 | 121,922 | 5,923 | 38,533 | 811 |
| 1994 | 151,887 | 159,854 | 277,229 | 361,607 | 23 | 43,887 | 147,257 | 148,122 | 7,020 | 48,090 | 1,026 |
| 1995 | 110,439 | 116,346 | 202,510 | 263,692 | 18 | 31,888 | 107,023 | 107,645 | 5,206 | 34,979 | 764 |
| 1996 | 184,500 | 194,666 | 336,333 | 435,720 | 35 | 55,105 | 178,670 | 179,708 | 8,282 | 60,185 | 1,334 |
| 1997 | 66,630 | 69,539 | 122,938 | 162,806 | 4 | 17,386 | 64,691 | 65,087 | 3,386 | 19,230 | 396 |
| 1998 | 216,286 | 228,638 | 394,132 | 508,494 | 45 | 65,734 | 209,281 | 210,472 | 9,710 | 71,879 | 1,618 |
| 1999 | 145,562 | 154,019 | 266,821 | 344,342 | 31 | 43,804 | 140,861 | 141,655 | 6,735 | 47,978 | 1,089 |
| 2000 | 142,610 | 150,205 | 261,067 | 340,099 | 23 | 41,244 | 138,230 | 139,038 | 6,647 | 45,187 | 980 |
| 2001 | 81,045 | 84,916 | 148,487 | 195,056 | 9 | 22,396 | 78,615 | 79,087 | 3,896 | 24,633 | 519 |
| 2002 | 98,038 | 102,569 | 180,500 | 238,187 | 8 | 26,240 | 95,165 | 95,740 | 4,882 | 28,956 | 599 |
| 2003 | 122,371 | 128,239 | 223,592 | 293,853 | 12 | 33,921 | 118,729 | 119,439 | 5,854 | 37,342 | 771 |
| 2004 | 152,491 | 160,591 | 278,158 | 361,786 | 25 | 44,629 | 147,742 | 148,606 | 6,987 | 48,869 | 1,064 |
| 2005 | 125,609 | 131,889 | 230,356 | 301,812 | 16 | 35,190 | 121,833 | 122,558 | 5,993 | 38,640 | 821 |
| 2006 | 188,424 | 198,535 | 343,313 | 445,967 | 33 | 55,633 | 182,546 | 183,616 | 8,494 | 60,793 | 1,329 |
| 2007 | 128,454 | 135,124 | 234,544 | 305,637 | 19 | 37,152 | 124,466 | 125,196 | 5,968 | 40,747 | 883 |
| 2008 | 186,341 | 196,318 | 340,070 | 442,459 | 30 | 54,472 | 180,579 | 181,632 | 8,558 | 59,652 | 1,291 |
| 2009 | 108,768 | 113,884 | 200,147 | 263,889 | 10 | 29,298 | 105,583 | 106,218 | 5,392 | 32,316 | 668 |
| 2010 | 199,181 | 210,309 | 362,159 | 468,354 | 38 | 60,157 | 192,826 | 193,935 | 8,871 | 65,750 | 1,455 |
| 2011 | 148,835 | 156,207 | 272,223 | 357,113 | 17 | 41,628 | 144,398 | 145,255 | 7,090 | 45,772 | 953 |
| 2012 | 97,844 | 102,650 | 179,543 | 235,965 | 10 | 26,972 | 94,958 | 95,523 | 4,748 | 29,693 | 616 |
| 2013 | 124,104 | 130,387 | 226,509 | 295,882 | 16 | 35,490 | 120,288 | 120,998 | 5,811 | 38,976 | 833 |
| 2014 | 143,166 | 150,681 | 262,035 | 341,763 | 22 | 41,170 | 138,785 | 139,599 | 6,695 | 45,131 | 973 |
| 2015 | 78,511 | 82,072 | 144,666 | 191,383 | 5 | 20,705 | 76,244 | 76,705 | 3,965 | 22,898 | 465 |
| 2016 | 72,989 | 76,278 | 134,516 | 178,297 | 4 | 19,059 | 70,913 | 71,341 | 3,724 | 21,118 | 420 |
| 2017 | 111,957 | 117,413 | 205,258 | 269,529 | 12 | 31,009 | 108,617 | 109,266 | 5,391 | 34,106 | 715 |
| Average Annual | 133,636 | 140,589 | 244,420 | 318,855 | 20 | 38,393 | 129,532 | 130,292 | 6,257 | 42,115 | 908 |

## Table E-XI-5. Modeled Groundwater Flow (in-acre/year) Results

| Year | Critical Water Quality Segments | | | | Impaired Ponds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper Lobe Basin | Upper Mystic Lake | Upper Basin | Lower Basin | Blacks Nook Pond (MA71005), Cambridge | Horn Pond (MA71019), Woburn | Judkins Pond (MA71021), Winchester | Mill Pond (MA71031), Winchester | Spy Pond (MA71040), Arlington | Wedge Pond (MA71045), Winchester | Winter Pond (MA71047), Winchester |
| 1992 | 310,282 | 329,668 | 608,065 | 790,428 | 80 | 92,834 | 300,072 | 301,790 | 17,708 | 101,464 | 2,269 |
| 1993 | 237,057 | 249,894 | 465,018 | 612,652 | 35 | 66,473 | 229,692 | 231,061 | 14,063 | 73,023 | 1,532 |
| 1994 | 288,158 | 304,720 | 563,690 | 739,100 | 54 | 83,174 | 279,075 | 280,713 | 16,668 | 91,133 | 1,939 |
| 1995 | 209,530 | 221,810 | 411,823 | 539,012 | 43 | 60,434 | 202,825 | 204,004 | 12,361 | 66,287 | 1,443 |
| 1996 | 350,059 | 371,192 | 683,395 | 890,007 | 83 | 104,434 | 338,607 | 340,574 | 19,664 | 114,054 | 2,520 |
| 1997 | 126,394 | 132,440 | 250,595 | 333,477 | 10 | 32,949 | 122,600 | 123,350 | 8,040 | 36,442 | 747 |
| 1998 | 410,390 | 436,066 | 800,564 | 1,038,307 | 106 | 124,578 | 396,619 | 398,876 | 23,055 | 136,215 | 3,056 |
| 1999 | 276,195 | 293,776 | 542,123 | 703,279 | 74 | 83,018 | 266,953 | 268,457 | 15,991 | 90,922 | 2,056 |
| 2000 | 270,564 | 286,351 | 530,850 | 695,146 | 55 | 78,165 | 261,968 | 263,499 | 15,783 | 85,633 | 1,851 |
| 2001 | 153,749 | 161,796 | 302,272 | 399,084 | 20– | 42,445 | 148,987 | 149,883 | 9,250 | 46,680 | 979 |
| 2002 | 185,977 | 195,396 | 367,697 | 487,619 | 19 | 49,730 | 180,353 | 181,443 | 11,593 | 54,874 | 1,132 |
| 2003 | 232,145 | 244,344 | 455,090 | 601,152 | 28 | 64,287 | 225,010 | 226,356 | 13,899 | 70,766 | 1,457 |
| 2004 | 289,316 | 306,154 | 565,466 | 739,317 | 59 | 84,581 | 279,994 | 281,631 | 16,590 | 92,610 | 2,009 |
| 2005 | 238,295 | 251,350 | 468,759 | 617,306 | 38 | 66,691 | 230,892 | 232,267 | 14,230 | 73,226 | 1,552 |
| 2006 | 357,496 | 378,515 | 697,750 | 911,177 | 78 | 105,436 | 345,956 | 347,984 | 20,167 | 115,211 | 2,515 |
| 2007 | 243,707 | 257,573 | 476,959 | 624,767 | 46 | 70,411 | 235,882 | 237,266 | 14,171 | 77,219 | 1,668 |
| 2008 | 353,536 | 374,279 | 691,310 | 904,163 | 72 | 103,235 | 342,228 | 344,224 | 20,319 | 113,047 | 2,442 |
| 2009 | 206,333 | 216,968 | 407,645 | 540,156 | 23 | 55,525 | 200,096 | 201,300 | 12,802 | 61,242 | 1,262 |
| 2010 | 377,926 | 401,058 | 735,670 | 956,458 | 91 | 114,009 | 365,440 | 367,542 | 21,063 | 124,605 | 2,754 |
| 2011 | 282,354 | 297,679 | 553,937 | 730,413 | 40 | 78,893 | 273,658 | 275,283 | 16,834 | 86,742 | 1,802 |
| 2012 | 185,615 | 195,606 | 365,464 | 482,757 | 25 | 51,118 | 179,961 | 181,031 | 11,273 | 56,270 | 1,164 |
| 2013 | 235,449 | 248,509 | 460,735 | 604,953 | 39 | 67,260 | 227,965 | 229,310 | 13,797 | 73,861 | 1,573 |
| 2014 | 271,616 | 287,239 | 532,893 | 698,638 | 52 | 78,025 | 263,020 | 264,564 | 15,897 | 85,527 | 1,840 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2015 | 148,931 | 156,333 | 294,781 | 391,900 | 12 | 39,241 | 144,494 | 145,368 | 9,415 | 43,394 | 879 |
| 2016 | 138,452 | 145,290 | 274,137 | 365,152 | 9 | 36,120 | 134,392 | 135,202 | 8,841 | 40,020 | 793 |
| 2017 | 212,390 | 223,734 | 417,794 | 551,403 | 29 | 58,768 | 205,847 | 207,077 | 12,800 | 64,634 | 1,351 |
| Average Annual | 253,535 | 267,990 | 497,095 | 651,836 | 47 | 72,763 | 245,484 | 246,925 | 14,857 | 79,811 | 1,714 |

## Table E-XI-6. Modeled Total Streamflow (in-acre/year; Stormflow + Groundwater) Results

| Year | Critical Water Quality Segments | | | | Impaired Ponds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper Lobe Basin | Upper Mystic Lake | Upper Basin | Lower Basin | Blacks Nook Pond (MA71005), Cambridge | Horn Pond (MA71019), Woburn | Judkins Pond (MA71021), Winchester | Mill Pond (MA71031), Winchester | Spy Pond (MA71040), Arlington | Wedge Pond (MA71045), Winchester | Winter Pond (MA71047), Winchester |
| 1992 | 473,814 | 502,525 | 907,338 | 1,177,424 | 114 | 141,818 | 458,409 | 461,033 | 25,166 | 155,005 | 3,470 |
| 1993 | 362,014 | 381,026 | 693,550 | 912,199 | 50 | 101,547 | 350,892 | 352,982 | 19,986 | 111,556 | 2,343 |
| 1994 | 440,045 | 464,573 | 840,920 | 1,100,707 | 76 | 127,061 | 426,332 | 428,835 | 23,688 | 139,223 | 2,965 |
| 1995 | 319,969 | 338,156 | 614,333 | 802,704 | 61 | 92,322 | 309,847 | 311,649 | 17,567 | 101,265 | 2,207 |
| 1996 | 534,559 | 565,859 | 1,019,728 | 1,325,728 | 118 | 159,539 | 517,277 | 520,282 | 27,947 | 174,239 | 3,855 |
| 1997 | 193,024 | 201,978 | 373,533 | 496,283 | 14 | 50,335 | 187,291 | 188,437 | 11,426 | 55,672 | 1,143 |
| 1998 | 626,677 | 664,704 | 1,194,696 | 1,546,801 | 151 | 190,312 | 605,899 | 609,347 | 32,765 | 208,095 | 4,674 |
| 1999 | 421,756 | 447,794 | 808,944 | 1,047,621 | 105 | 126,822 | 407,813 | 410,112 | 22,725 | 138,900 | 3,145 |
| 2000 | 413,174 | 436,556 | 791,917 | 1,035,245 | 78 | 119,408 | 400,198 | 402,537 | 22,430 | 130,820 | 2,830 |
| 2001 | 234,794 | 246,713 | 450,759 | 594,140 | 29 | 64,841 | 227,602 | 228,970 | 13,147 | 71,313 | 1,498 |
| 2002 | 284,014 | 297,965 | 548,197 | 725,806 | 28 | 75,969 | 275,518 | 277,183 | 16,475 | 83,830 | 1,731 |
| 2003 | 354,516 | 372,583 | 678,682 | 895,005 | 40 | 98,208 | 343,739 | 345,795 | 19,753 | 108,108 | 2,228 |
| 2004 | 441,808 | 466,744 | 843,624 | 1,101,102 | 84 | 129,210 | 427,736 | 430,237 | 23,577 | 141,479 | 3,073 |
| 2005 | 363,904 | 383,239 | 699,115 | 919,117 | 54 | 101,881 | 352,725 | 354,825 | 20,224 | 111,866 | 2,373 |
| 2006 | 545,920 | 577,050 | 1,041,063 | 1,357,145 | 110 | 161,069 | 528,502 | 531,600 | 28,660 | 176,004 | 3,844 |
| 2007 | 372,161 | 392,697 | 711,503 | 930,404 | 65 | 107,563 | 360,348 | 362,462 | 20,140 | 117,966 | 2,551 |
| 2008 | 539,877 | 570,597 | 1,031,380 | 1,346,621 | 103 | 157,707 | 522,808 | 525,856 | 28,876 | 172,699 | 3,733 |

| Year | Critical Water Quality Segments | | | | Impaired Ponds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Upper Lobe Basin | Upper Mystic Lake | Upper Basin | Lower Basin | Blacks Nook Pond (MA71005), Cambridge | Horn Pond (MA71019), Woburn | Judkins Pond (MA71021), Winchester | Mill Pond (MA71031), Winchester | Spy Pond (MA71040), Arlington | Wedge Pond (MA71045), Winchester | Winter Pond (MA71047), Winchester |
| 2009 | 315,101 | 330,853 | 607,792 | 804,045 | 33 | 84,823 | 305,679 | 307,517 | 18,195 | 93,558 | 1,930 |
| 2010 | 577,106 | 611,367 | 1,097,829 | 1,424,813 | 129 | 174,166 | 558,267 | 561,477 | 29,934 | 190,354 | 4,209 |
| 2011 | 431,189 | 453,885 | 826,160 | 1,087,526 | 57 | 120,521 | 418,056 | 420,539 | 23,924 | 132,514 | 2,755 |
| 2012 | 283,459 | 298,256 | 545,007 | 718,721 | 35 | 78,090 | 274,919 | 276,554 | 16,021 | 85,964 | 1,780 |
| 2013 | 359,552 | 378,896 | 687,244 | 900,835 | 55 | 102,750 | 348,254 | 350,308 | 19,609 | 112,837 | 2,406 |
| 2014 | 414,783 | 437,920 | 794,928 | 1,040,401 | 74 | 119,195 | 401,805 | 404,163 | 22,592 | 130,658 | 2,814 |
| 2015 | 227,442 | 238,405 | 439,447 | 583,284 | 18 | 59,946 | 220,738 | 222,073 | 13,381 | 66,293 | 1,344 |
| 2016 | 211,442 | 221,568 | 408,654 | 543,449 | 13 | 55,179 | 205,305 | 206,543 | 12,565 | 61,138 | 1,213 |
| 2017 | 324,347 | 341,148 | 623,052 | 820,932 | 42 | 89,777 | 314,464 | 316,343 | 18,191 | 98,740 | 2,067 |
| Average Annual | 387,170 | 408,579 | 741,515 | 970,692 | 67 | 111,156 | 375,016 | 377,217 | 21,114 | 121,926 | 2,622 |

# Appendix F: Baseflow Estimates for Aberjona River and Alewife Brook

Table F-XI-7. Baseflow Estimates for Aberjona River and Alewife Brook

| Year | Aberjona River (1992 – 2016) | | | Alewife Brook (2006 – 2016) | | |
|---|---|---|---|---|---|---|
| | Streamflow (in-acre/year) | Baseflow (in-acre/year) | Baseflow Fraction | Streamflow (in-acre/year) | Baseflow (in-acre/year) | Baseflow Fraction |
| 1992 | 242,453 | 160,274 | 0.66 | – | – | – |
| 1993 | 287,207 | 193,927 | 0.68 | – | – | – |
| 1994 | 302,226 | 203,394 | 0.67 | – | – | – |
| 1995 | 199,736 | 145,786 | 0.73 | – | – | – |
| 1996 | 430,248 | 270,572 | 0.63 | – | – | – |
| 1997 | 223,833 | 162,732 | 0.73 | – | – | – |
| 1998 | 431,381 | 268,083 | 0.62 | – | – | – |
| 1999 | 233,642 | 155,263 | 0.66 | – | – | – |
| 2000 | 300,981 | 193,870 | 0.64 | – | – | – |
| 2001 | 316,739 | 195,302 | 0.62 | – | – | – |
| 2002 | 243,445 | 155,279 | 0.64 | – | – | – |
| 2003 | 360,401 | 238,359 | 0.66 | – | – | – |
| 2004 | 336,903 | 208,603 | 0.62 | – | – | – |
| 2005 | 386,938 | 266,063 | 0.69 | – | – | – |
| 2006 | 491,444 | 299,860 | 0.61 | 101,411 | 65,492 | 0.65 |
| 2007 | 293,250 | 184,530 | 0.63 | 70,514 | 47,048 | 0.67 |
| 2008 | 471,436 | 297,944 | 0.63 | 92,796 | 59,443 | 0.64 |
| 2009 | 394,291 | 266,786 | 0.68 | 76,214 | 54,396 | 0.71 |
| 2010 | 482,776 | 269,709 | 0.56 | 106,148 | 64,646 | 0.61 |
| 2011 | 444,306 | 290,130 | 0.65 | 102,179 | 71,934 | 0.70 |
| 2012 | 224,915 | 131,197 | 0.58 | 77,111 | 57,112 | 0.74 |
| 2013 | 255,365 | 189,513 | 0.74 | 70,244 | 53,077 | 0.76 |
| 2014 | 381,277 | 248,166 | 0.65 | 85,295 | 61,040 | 0.72 |
| 2015 | 261,463 | 179,430 | 0.69 | 73,946 | 54,779 | 0.74 |
| 2016 | 210,791 | 142,541 | 0.68 | 69,169 | 52,276 | 0.76 |
| 2017 | 312,960 | 210,840 | 0.67 | 95,648 | 72,209 | 0.75 |
| **Avg.** | **327,668** | **212,591** | **0.65** | **85,056** | **59,454** | **0.70** |
| **CV** | **0.28** | **0.25** | **0.065** | **0.16** | **0.12** | **0.069** |

# APPENDIX G: MAPS DEPICTING CSO DRAINAGE BASINS

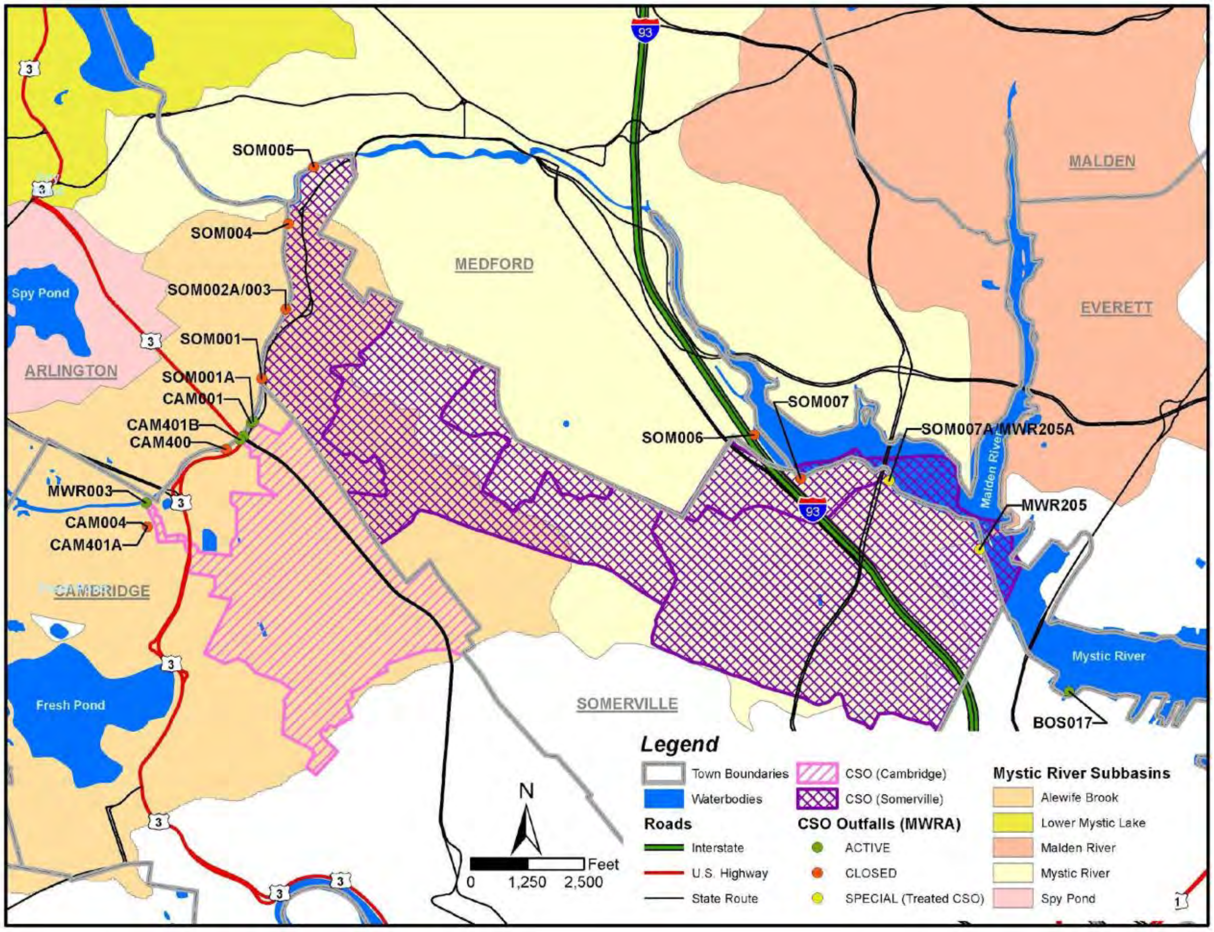



**Figure G-XI-1.** MWRA CSO Map (updated in September 2015).

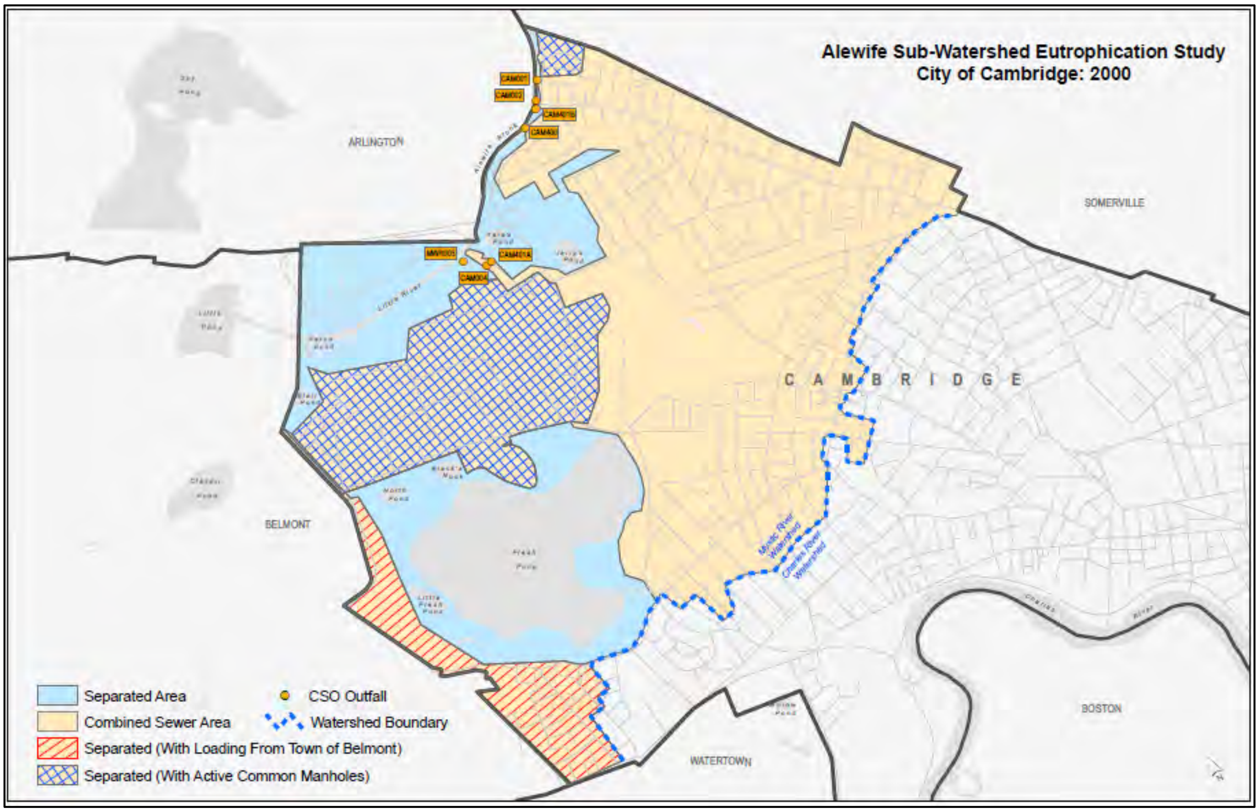



Figure G-XI-2. City of Cambridge CSO Drainage Basins (2000).

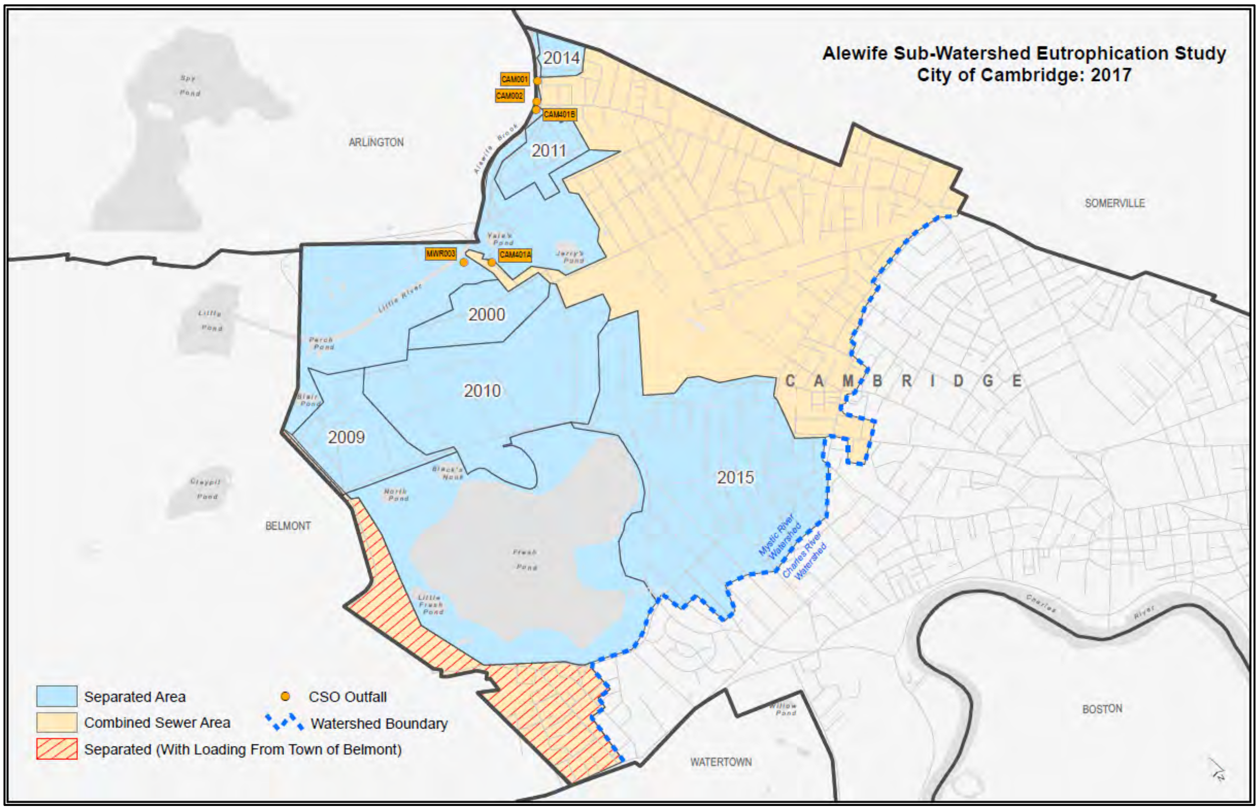
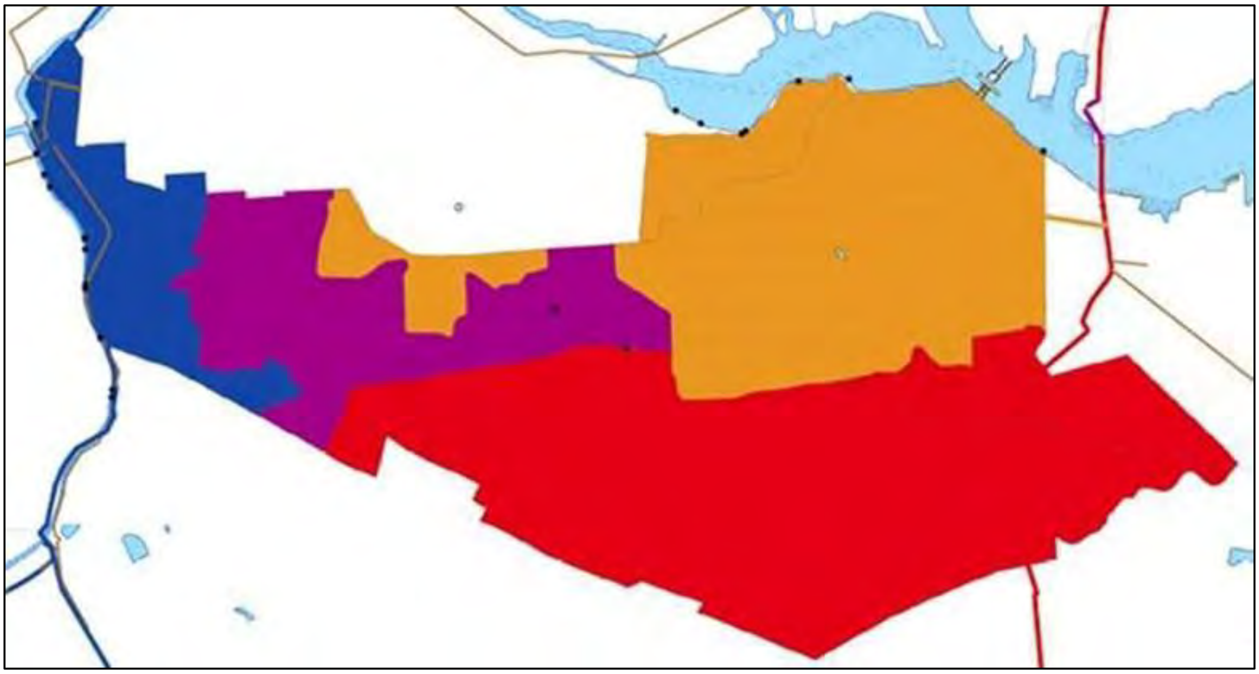



**Figure G-XI-3. City of Cambridge CSO Drainage Basins (2017).**



**Legend**

| Area | MWRA Connection | Combined Sewer Overflow |
|---|---|---|
| (orange) | Somerville Marginal Interceptor (SMI) | Mystic River |
| (blue) | Alewife Brook Conduit (ABC) | Alewife Brook |
| (red) | Cambridge Branch Sewer (CBS) | Interactions with SMI and McGrath system |
| (purple) | Primary to CBS with overflows to ABC | Alewife Brook, plus interactions with CBS |

**Figure G-XI-4. City of Somerville CSO Drainage Basins (2017).**

# Appendix H: Water Quality Data Used in Calibration and Validation of the Bathtub Model

| Year | Segment | WQ Site ID | TP | Chl-a |
|---|---|---|---|---|
| 2010 | Upper Lobe | UPLUPL | | |
| 2014 | Upper Lobe | UPLUPL | | |
| 2015 | Upper Lobe | UPLUPL | 0.052 | 16.790 |
| 2016 | Upper Lobe | UPLUPL | 0.060 | 17.103 |
| 2017 | Upper Lobe | UPLUPL | 0.053 | 13.351 |
| 2010 | Upper Lake | UPLCTR | | |
| 2010 | Upper Lake | UPL001 | 0.029 | |
| 2014 | Upper Lake | UPLCTR | | |
| 2014 | Upper Lake | UPL001 | 0.038 | |
| 2015 | Upper Lake | UPLCTR | 0.035 | 8.929 |
| 2015 | Upper Lake | UPL001 | 0.029 | |
| 2016 | Upper Lake | UPLCTR | 0.037 | 8.709 |
| 2016 | Upper Lake | UPL001 | 0.022 | |
| 2017 | Upper Lake | UPLCTR | 0.036 | 13.257 |
| 2017 | Upper Lake | UPL001 | | |
| 2010 | Lower Lake | MYR071 | 0.036 | |
| 2014 | Lower Lake | MYR071 | 0.034 | |
| 2015 | Lower Lake | MYR071 | 0.036 | |
| 2016 | Lower Lake | MYR071 | 0.036 | |
| 2017 | Lower Lake | MYR071 | 0.038 | |
| 2010 | Upper Basin | MWRA083 | 0.036 | 7.158 |
| 2010 | Upper Basin | MWRA066 | 0.050 | 7.015 |
| 2014 | Upper Basin | MWRA083 | 0.044 | 8.379 |
| 2014 | Upper Basin | MWRA066 | 0.045 | 9.023 |
| 2015 | Upper Basin | MYR43 | 0.056 | 17.944 |
| 2016 | Upper Basin | MYR43 | 0.072 | 21.273 |
| 2017 | Upper Basin | MYR43 | 0.062 | 22.476 |
| 2010 | Lower Basin | MYR33 | | |
| 2010 | Lower Basin | MAR003 | | |
| 2010 | Lower Basin | MWRA167 | 0.054 | 14.582 |
| 2014 | Lower Basin | MYR33 | | |
| 2014 | Lower Basin | MAR003 | | |
| 2014 | Lower Basin | MWRA167 | 0.047 | 15.574 |
| 2015 | Lower Basin | MYR33 | 0.064 | 23.771 |
| 2015 | Lower Basin | MAR003 | 0.059 | 22.881 |
| 2015 | Lower Basin | MWRA167 | 0.054 | 23.951 |
| 2016 | Lower Basin | MYR33 | 0.092 | 29.825 |
| 2016 | Lower Basin | MAR003 | 0.094 | 26.699 |
| 2016 | Lower Basin | MWRA167 | 0.080 | 35.384 |

| Year | Segment | WQ Site ID | TP | Chl-a |
|---|---|---|---|---|
| 2017 | Lower Basin | MYR33 | 0.072 | 26.674 |
| 2017 | Lower Basin | MAR003 | 0.065 | 24.750 |
| 2017 | Lower Basin | MWRA167 | 0.062 | 30.367 |

# APPENDIX I: BATHTUB MODEL INPUTS FOR CALIBRATION

## Calculation Input Worksheet (English units)

| Type | Parameter | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|
| Atmospheric | Precipitation (in/yr.) | 34.8 | 34.8 | 34.8 | 34.8 | 34.8 |
| Atmospheric | Lake Evaporation (in/yr.) | 37.7 | 37.7 | 37.7 | 37.7 | 37.7 |
| Atmospheric | Total P Load (lb./ac/yr.) | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| Atmospheric | Inorg P Fraction (-) | 50% | 50% | 50% | 50% | 50% |
| Atmospheric | Inorg P Load (lb./ac/yr.) | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Atten* External | Area (mi2) | 24.72 | - | - | 5.87 | 10.28 |
| Atten* External | Flow (ac-in/yr.) | 226,408 | - | - | 95,529 | 123,300 |
| Atten* External | Flow (in/yr.) | 14.31 | - | - | 25.43 | 18.74 |
| Atten* External | P Load (lb./yr.) | 2,701 | - | - | 1,108 | 2,312 |
| Atten* External | P Load (lb./ac/yr.) | 0.17 | - | - | 0.29 | 0.35 |
| Sub-basin* | Area (mi2) | 0.21 | 1.90 | 6.59 | 5.50 | 0.97 |
| Sub-basin* | Flow (ac-in/yr.) | 1,034 | 10,963 | 49,212 | 56,766 | 20,881 |
| Sub-basin* | Flow (in/yr.) | 7.69 | 9.02 | 11.67 | 16.13 | 33.64 |
| Sub-basin* | P Load (lb./yr.) | 21 | 225 | 996 | 1,150 | 623 |
| Sub-basin* | P Load (lb./ac/yr.) | 0.16 | 0.18 | 0.24 | 0.33 | 1.00 |
| Ext* + Sub-basin | Area (mi2) | 24.93 | 1.90 | 6.59 | 11.37 | 11.25 |
| Ext* + Sub-basin | Flow (ac-in/yr.) | 227,442 | 10,963 | 49,212 | 152,295 | 144,181 |
| Ext* + Sub-basin | Flow (in/yr.) | 14.26 | 9.02 | 11.67 | 20.93 | 20.03 |
| Receiving Water | P Load (lb./yr.) | 2,722 | 225 | 996 | 2,257 | 2,935 |
| Ext* + Sub-basin | P Load (lb./ac/yr.) | 0.17 | 0.18 | 0.24 | 0.31 | 0.41 |
| Ext* + Sub-basin | P Conc (mg/L) | 0.05 | 0.09 | 0.09 | 0.07 | 0.09 |
| Ext* + Sub-basin | Inorg P Fraction (-) | 60% | 60% | 50% | 50% | 50% |
| Ext* + Sub-basin | Inorg P Conc (mg/L) | 0.03 | 0.05 | 0.04 | 0.03 | 0.04 |
| Ext* + Sub-basin | Org P Conc (mg/L) | 0.02 | 0.04 | 0.04 | 0.03 | 0.04 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Receiving Water | Surface Area (ac) | 35.6 | 140.9 | 92.8 | 56.9 | 124.2 |
| Receiving Water | Depth (ft) | 10.0 | 42.5 | 30.8 | 3.8 | 4.5 |
| Receiving Water | Length (mi) | 0.36 | 0.8 | 0.6 | 3.6 | 1.3 |
| Receiving Water | Epi Depth (ft) | 10.0 | 10.0 | 10.0 | 3.8 | 4.5 |
| Receiving Water | Hypo Depth (ft) | 0.0 | 32.5 | 20.8 | 0.0 | 0.0 |
| Receiving Water | Volume (ac-ft) | 177.9 | 5987.5 | 2861.5 | 215.9 | 553.5 |
| Receiving Water | Cum Flow (ac-in/yr.) | 227,442 | 238,405 | 287,617 | 439,912 | 584,093 |
| Receiving Water | Retention Time (d) | 3.4 | 110.0 | 43.6 | 2.1 | 4.2 |
| Receiving Water | Total P Conc (mg/L) | 0.05 | 0.03 | 0.04 | 0.06 | 0.06 |
| Receiving Water | Inorg P Fraction (-) | 60% | 60% | 60% | 60% | 60% |
| Receiving Water | Inorg P Conc (mg/L) | 0.03 | 0.02 | 0.02 | 0.03 | 0.04 |
| Receiving Water | Org P Conc (mg/L) | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 |
| Receiving Water | Chl-a Avg Conc (µg/L) | 16.8 | 8.9 | 4.7 | 17.9 | 23.5 |
| Receiving Water | Non-algal Turbidity (1/ft) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| Receiving Water | Internal TP load (lb./ac/yr.) | 19.5 | 3.3 | 3.3 | 13.0 | 13.0 |

* Atten = attenuated, Ext = external, Sub-basin = unattenuated local sub-basin

# Model Input Worksheet (Metric units)

| | |
|---|---|
| Case Title | Mystic River Alternative TMDL - Final Calibration |

| | |
|---|---|
| Number of Segments | 5 |
| Number of Tributaries | 5 |
| Number of Channels | 0 |

| **Global Variables** | Mean | CV |
|---|---|---|
| Averaging Period (yrs.) | 1 | 0 |
| Precipitation (m) | 0.90 | 0 |
| Evaporation (m) | 1 | 0 |
| Storage Increase (m) | 0 | 0 |

| **Atmos. Loads ($kg/km^2$-yr)** | Mean | CV |
|---|---|---|
| Total P | 30 | 0.5 |
| Ortho P | 15 | 0.5 |

**Segment Data**

| Segment Number | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Segment Name | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
| Outflow Segment Number | 2 | 3 | 4 | 5 | 0 |
| Segment Group Number | 1 | 1 | 1 | 1 | 1 |
| Segment Morphometry | | | | | |
| Surface Area ($km^2$) | 0.14 | 0.57 | 0.38 | 0.23 | 0.50 |
| Mean Depth (m) | 1.52 | 12.95 | 9.40 | 1.16 | 1.36 |
| Length (km) | 0.58 | 1.29 | 0.97 | 5.79 | 2.09 |
| Mixed Depth (m) | 1.52 | 3.05 | 3.05 | 1.16 | 1.36 |
| Hypol. Depth (m) | 0.00 | 9.91 | 6.35 | 0.00 | 0.00 |
| Observed Water Quality | | | | | |
| Non-Algal Turb (1/m) | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 |
| Conservative Subst | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total P (ppb) | 52.00 | 32.00 | 36.00 | 56.00 | 59.00 |
| Chlorophyll-a (ppb) | 16.80 | 8.90 | 4.70 | 17.90 | 23.50 |
| Total P - Ortho P (ppb) | 31 | 19 | 22 | 34 | 35 |
| Segment Calibration Factors | | | | | |
| Dispersion Rate | 1 | 1 | 1 | 1 | 1 |
| Total P | 1 | 1 | 1 | 1 | 1 |
| Chlorophyll-a | 1 | 1 | 1 | 1 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| Total P - Ortho P (ppb) | 1 | 1 | 1 | 1 | 1 |
| Internal Loading Rates (mg/m2-day) | | | | | |
| Total P | 6 | 1 | 1 | 4 | 4 |

**Tributary Data**

| | | | | | |
|---|---|---|---|---|---|
| Tributary Number | 1 | 2 | 3 | 4 | 5 |
| Tributary Name | Upper Lobe | Upper Mystic | Lower Mystic | Upper Basin | Lower Basin |
| Segment Number | 1 | 2 | 3 | 4 | 5 |
| Tributary Type Code | 1 | 1 | 1 | 1 | 1 |
| Drainage Area ($km^2$) | 64.57 | 4.92 | 17.07 | 29.45 | 29.14 |
| Flow (hm3/yr.) | 23.40 | 1.10 | 5.10 | 15.70 | 14.80 |
| Total P (ppb) | 53 | 90 | 89 | 65 | 90 |
| Ortho P (ppb) | 32 | 54 | 45 | 33 | 45 |

**NonPoint Source Areas ($km^2$)**

| | | | | | |
|---|---|---|---|---|---|
| Not used | 0 | 0 | 0 | 0 | 0 |

**Non-Point Source Export Coefficients**

| | | | | | |
|---|---|---|---|---|---|
| Not used | 0 | 0 | 0 | 0 | 0 |

**Transport Channels**

| | | | | | |
|---|---|---|---|---|---|
| Not used | 0 | 0 | 0 | 0 | 0 |

**Model Coefficients (Mean, CV)**

| | | |
|---|---|---|
| Dispersion Rate | 0.20 | 0.70 |
| Total Phosphorus | 1 | 0.45 |
| Chl-a Model | 0.60 | 0.26 |
| TP-OP Model | 1 | 0.15 |
| HODv Model | 1 | 0.15 |
| MODv Model | 1 | 0.22 |
| Minimum Qs (m/yr.) | 0.10 | 0 |
| Chl-a Flushing Term | 1 | 0 |
| Chl-a Temporal CV | 0.62 | 0 |
| Availability Factor - Total P | 0.33 | 0 |
| Availability Factor - Ortho P | 1.93 | 0 |

**Model Options**

| | |
|---|---|
| Phosphorus Balance | 1 |
| Chlorophyll-a | 2 |
| Dispersion | 1 |

| | |
|---|---|
| Phosphorus Calibration | 1 |
| Error Analysis | 1 |
| Availability Factors | 0 |
| Mass-Balance Tables | 1 |
| Output Destination | 2 |

# APPENDIX J: BATHTUB MODEL INPUTS AND OUTPUTS FOR SCENARIOS

### Table J-XI-8. Detailed BATHTUB Model Inputs and Outputs for Average Annual Data

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| Input | Atten Trib Flow (ac-in/yr.) | 1 - 1 | 371,417 | | | 148,218 | 192,965 |
| | | 1a - 7 | 371,417 | | | 148,218 | 192,965 |
| | | 2 - 9 | 371,386 | | | 147,525 | 192,963 |
| | | 2a - 14 | 371,386 | | | 147,525 | 192,963 |
| | | 3 - 16 | 371,386 | | | 157,040 | 192,963 |
| | | 3a - 21 | 371,386 | | | 157,040 | 192,963 |
| | | 4 - 23 | 371,386 | | | 185,594 | 192,963 |
| | | 4a - 28 | 371,386 | | | 185,594 | 192,963 |
| | Sub-basin Flow (ac-in/yr.) | 1 - 1 | 1,856 | 20,243 | 84,185 | 90,239 | 30,380 |
| | | 1a - 7 | 1,856 | 20,243 | 84,185 | 90,239 | 30,380 |
| | | 2 - 9 | 1,855 | 20,238 | 84,159 | 90,202 | 30,185 |
| | | 2a - 14 | 1,855 | 20,238 | 84,159 | 90,202 | 30,185 |
| | | 3 - 16 | 1,855 | 20,238 | 84,159 | 90,331 | 31,315 |
| | | 3a - 21 | 1,855 | 20,238 | 84,159 | 90,331 | 31,315 |
| | | 4 - 23 | 1,855 | 20,238 | 84,159 | 90,719 | 34,701 |
| | | 4a - 28 | 1,855 | 20,238 | 84,159 | 90,719 | 34,701 |
| | Total Flow (ac-in/yr.) | 1 - 1 | 373,272 | 20,243 | 84,185 | 238,457 | 223,345 |
| | | 1a - 7 | 373,272 | 20,243 | 84,185 | 238,457 | 223,345 |
| | | 2 - 9 | 373,241 | 20,238 | 84,159 | 237,727 | 223,148 |
| | | 2a - 14 | 373,241 | 20,238 | 84,159 | 237,727 | 223,148 |
| | | 3 - 16 | 373,241 | 20,238 | 84,159 | 247,371 | 224,278 |
| | | 3a - 21 | 373,241 | 20,238 | 84,159 | 247,371 | 224,278 |
| | | 4 - 23 | 373,241 | 20,238 | 84,159 | 276,314 | 227,664 |
| | | 4a - 28 | 373,241 | 20,238 | 84,159 | 276,314 | 227,664 |
| | Atten Trib P Load (lb./yr.) | 1 - 1 | 3,873 | | | 1,637 | 3,130 |
| | | 1a - 7 | 1,476 | | | 872 | 1,186 |
| | | 2 - 9 | 3,858 | | | 1,352 | 3,128 |

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| | | 2a - 14 | 1,640 | | | 644 | 1,329 |
| | | 3 - 16 | 3,858 | | | 1,442 | 3,128 |
| | | 3a - 21 | 1,676 | | | 667 | 1,358 |
| | | 4 - 23 | 3,858 | | | 1,603 | 3,128 |
| | | 4a - 28 | 1,748 | | | 733 | 1,416 |
| | Sub-basin P Load (lb./yr.) | 1 - 1 | 34 | 416 | 1,558 | 1,661 | 719 |
| | | 1a - 7 | 14 | 161 | 625 | 681 | 421 |
| | | 2 - 9 | 34 | 410 | 1,526 | 1,616 | 579 |
| | | 2a - 14 | 15 | 175 | 663 | 710 | 303 |
| | | 3 - 16 | 34 | 410 | 1,526 | 1,618 | 577 |
| | | 3a - 21 | 15 | 178 | 677 | 725 | 294 |
| | | 4 - 23 | 34 | 410 | 1,526 | 1,624 | 570 |
| | | 4a - 28 | 16 | 186 | 705 | 757 | 264 |
| | Total P Load (lb./yr.) | 1 - 1 | 3,907 | 416 | 1,558 | 3,298 | 3,849 |
| | | 1a - 7 | 1,490 | 161 | 625 | 1,553 | 1,608 |
| | | 2 - 9 | 3,892 | 410 | 1,526 | 2,968 | 3,707 |
| | | 2a - 14 | 1,655 | 175 | 663 | 1,354 | 1,632 |
| | | 3 - 16 | 3,892 | 410 | 1,526 | 3,033 | 3,704 |
| | | 3a - 21 | 1,691 | 178 | 677 | 1,393 | 1,652 |
| | | 4 - 23 | 3,892 | 410 | 1,526 | 3,227 | 3,697 |
| | | 4a - 28 | 1,763 | 186 | 705 | 1,490 | 1,680 |
| | P Sediment load (lb./yr.) | 1 - 1 | 695 | 459 | 302 | 741 | 1,619 |
| | | 1a - 7 | 466 | 307 | 202 | 497 | 1,084 |
| | | 2 - 9 | 695 | 459 | 302 | 741 | 1,619 |
| | | 2a - 14 | 480 | 317 | 209 | 512 | 1,117 |
| | | 3 - 16 | 695 | 459 | 302 | 741 | 1,619 |
| | | 3a - 21 | 480 | 317 | 209 | 512 | 1,117 |
| | | 4 - 23 | 695 | 459 | 302 | 741 | 1,619 |
| | | 4a - 28 | 494 | 326 | 215 | 526 | 1,149 |
| | N conc (mg/L) | 1 - 1 | 0.78 | 1.35 | 1.31 | 1.00 | 1.15 |
| | | 1a - 7 | 0.78 | 1.35 | 1.31 | 1.00 | 1.15 |
| | | 2 - 9 | 0.78 | 1.35 | 1.31 | 1.00 | 1.15 |
| | | 2a - 14 | 0.78 | 1.35 | 1.31 | 1.00 | 1.15 |
| | | 3 - 16 | 0.78 | 1.35 | 1.31 | 0.96 | 1.15 |
| | | 3a - 21 | 0.78 | 1.35 | 1.31 | 0.96 | 1.15 |
| | | 4 - 23 | 0.78 | 1.35 | 1.31 | 0.85 | 1.14 |
| | | 4a - 28 | 0.78 | 1.35 | 1.31 | 0.85 | 1.14 |
| | Inorg. N conc (mg/L) | 1 - 1 | 0.47 | 0.81 | 0.78 | 0.60 | 0.69 |
| | | 1a - 7 | 0.47 | 0.81 | 0.78 | 0.60 | 0.69 |

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| | | 2 - 9 | 0.47 | 0.81 | 0.78 | 0.60 | 0.69 |
| | | 2a - 14 | 0.47 | 0.81 | 0.78 | 0.60 | 0.69 |
| | | 3 - 16 | 0.47 | 0.81 | 0.78 | 0.58 | 0.69 |
| | | 3a - 21 | 0.47 | 0.81 | 0.78 | 0.58 | 0.69 |
| | | 4 - 23 | 0.47 | 0.81 | 0.78 | 0.51 | 0.68 |
| | | 4a - 28 | 0.47 | 0.81 | 0.78 | 0.51 | 0.68 |
| | P conc (mg/L) | 1 - 1 | 0.05 | 0.09 | 0.08 | 0.06 | 0.08 |
| | | 1a - 7 | 0.02 | 0.04 | 0.03 | 0.03 | 0.03 |
| | | 2 - 9 | 0.05 | 0.09 | 0.08 | 0.06 | 0.07 |
| | | 2a - 14 | 0.02 | 0.04 | 0.04 | 0.03 | 0.03 |
| | | 3 - 16 | 0.05 | 0.09 | 0.08 | 0.05 | 0.07 |
| | | 3a - 21 | 0.02 | 0.04 | 0.04 | 0.03 | 0.03 |
| | | 4 - 23 | 0.05 | 0.09 | 0.08 | 0.05 | 0.07 |
| | | 4a - 28 | 0.02 | 0.04 | 0.04 | 0.02 | 0.03 |
| | Inorg. P Conc (mg/L) | 1 - 1 | 0.03 | 0.05 | 0.04 | 0.03 | 0.04 |
| | | 1a - 7 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 |
| | | 2 - 9 | 0.03 | 0.05 | 0.04 | 0.03 | 0.04 |
| | | 2a - 14 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 |
| | | 3 - 16 | 0.03 | 0.05 | 0.04 | 0.03 | 0.04 |
| | | 3a - 21 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 |
| | | 4 - 23 | 0.03 | 0.05 | 0.04 | 0.03 | 0.04 |
| | | 4a - 28 | 0.01 | 0.02 | 0.02 | 0.01 | 0.02 |
| | Stormwater load reduction (%) | 1 - 1 | 0 | | | | |
| | | 1a - 7 | 67 | | | | |
| | | 2 - 9 | 0 | | | | |
| | | 2a - 14 | 62 | | | | |
| | | 3 - 16 | 0 | | | | |
| | | 3a - 21 | 61 | | | | |
| | | 4 - 23 | 0 | | | | |
| | | 4a - 28 | 61 | | | | |
| | P sediment load reduction (%) | 1 - 1 | 0 | | | | |
| | | 1a - 7 | 33 | | | | |
| | | 2 - 9 | 0 | | | | |
| | | 2a - 14 | 31 | | | | |
| | | 3 - 16 | 0 | | | | |
| | | 3a - 21 | 31 | | | | |
| | | 4 - 23 | 0 | | | | |
| | | 4a - 28 | 29 | | | | |
| **Output** | | 1 - 1 | 43.4 | 33.1 | 33.6 | 46.2 | 57.7 |

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| | Predicted P conc (µg/L) | 1a - 7 | 20.8 | 18.6 | 19.4 | 25.3 | 31.1 |
| | | 2 - 9 | 43.3 | 33.0 | 33.3 | 44.2 | 55.8 |
| | | 2a - 14 | 22.4 | 19.8 | 20.4 | 24.9 | 31.1 |
| | | 3 - 16 | 43.3 | 33.0 | 33.3 | 44.2 | 55.6 |
| | | 3a - 21 | 22.7 | 20.0 | 20.6 | 24.9 | 31.1 |
| | | 4 - 23 | 43.2 | 32.9 | 33.2 | 43.4 | 54.5 |
| | | 4a - 28 | 23.4 | 20.4 | 21.1 | 25 | 31.1 |
| | Predicted chl-a conc (µg/L) | 1 - 1 | 13.9 | 7.6 | 7.7 | 16.4 | 19.4 |
| | | 1a - 7 | 5.9 | 4.1 | 4.3 | 8.1 | 10.0 |
| | | 2 - 9 | 13.9 | 7.6 | 7.7 | 15.6 | 18.8 |
| | | 2a - 14 | 6.5 | 4.4 | 4.6 | 7.9 | 9.9 |
| | | 3 - 16 | 13.8 | 7.6 | 7.6 | 15.6 | 18.7 |
| | | 3a - 21 | 6.6 | 4.5 | 4.6 | 7.9 | 9.9 |
| | | 4 - 23 | 13.8 | 7.5 | 7.6 | 15.3 | 18.3 |
| | | 4a - 28 | 6.9 | 4.6 | 4.7 | 7.9 | 9.9 |

## Table J-XI-9. Detailed BATHTUB Model Inputs and Outputs for Wet and Dry Year Data

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| **Input** | Atten Trib Flow (ac-in/yr.) | 1a - 7 (Wet) | 574,239 | | | 218,660 | 285,460 |
| | | 1a - 7 (Dry) | 210,500 | | | 88,880 | 115,436 |
| | | 2a - 14 (Wet) | 574,105 | | | 216,564 | 285,449 |
| | | 2a - 14 (Dry) | 210,499 | | | 89,101 | 115,436 |
| | | 3a - 21 (Wet) | 574,105 | | | 230,094 | 285,449 |
| | | 3a - 21 (Dry) | 210,499 | | | 95,041 | 115,436 |
| | | 4a - 28 (Wet) | 574,105 | | | 270,695 | 285,449 |
| | | 4a - 28 (Dry) | 210,499 | | | 112,870 | 115,436 |
| | Sub-basin Flow (ac-in/yr.) | 1a - 7 (Wet) | 3,137 | 34,308 | 135,055 | 135,664 | 42,401 |
| | | 1a - 7 (Dry) | 942 | 10,127 | 45,401 | 52,853 | 19,407 |
| | | 2a - 14 (Wet) | 3,133 | 34,284 | 134,942 | 135,512 | 41,679 |
| | | 2a - 14 (Dry) | 942 | 10,127 | 45,401 | 52,853 | 19,488 |
| | | 3a - 21 (Wet) | 3,133 | 34,284 | 134,942 | 135,703 | 43,217 |
| | | 3a - 21 (Dry) | 942 | 10,127 | 45,401 | 52,930 | 20,221 |
| | | 4a - 28 (Wet) | 3,133 | 34,284 | 134,942 | 136,277 | 47,825 |

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| | | 4a - 28 (Dry) | 942 | 10,127 | 45,401 | 53,161 | 22,418 |
| | Total Flow (ac-in/yr.) | 1a - 7 (Wet) | 577,376 | 34,308 | 135,055 | 354,324 | 327,860 |
| | | 1a - 7 (Dry) | 211,442 | 10,127 | 45,401 | 141,733 | 134,842 |
| | | 2a - 14 (Wet) | 577,238 | 34,284 | 134,942 | 352,077 | 327,128 |
| | | 2a - 14 (Dry) | 211,442 | 10,127 | 45,401 | 141,953 | 134,923 |
| | | 3a - 21 (Wet) | 577,238 | 34,284 | 134,942 | 365,797 | 328,666 |
| | | 3a - 21 (Dry) | 211,442 | 10,127 | 45,401 | 147,970 | 135,657 |
| | | 4a - 28 (Wet) | 577,238 | 34,284 | 134,942 | 406,972 | 333,274 |
| | | 4a - 28 (Dry) | 211,442 | 10,127 | 45,401 | 166,031 | 137,854 |
| | Atten Trib P Load (lbs./yr.) | 1a - 7 (Wet) | 2,127 | | | 1,607 | 1,579 |
| | | 1a - 7 (Dry) | 960 | | | 350 | 827 |
| | | 2a - 14 (Wet) | 2,303 | | | 818 | 1,752 |
| | | 2a - 14 (Dry) | 1,082 | | | 482 | 932 |
| | | 3a - 21 (Wet) | 2,351 | | | 854 | 1,789 |
| | | 3a - 21 (Dry) | 1,106 | | | 492 | 953 |
| | | 4a - 28 (Wet) | 2,448 | | | 955 | 1,864 |
| | | 4a - 28 (Dry) | 1,155 | | | 518 | 995 |
| | Sub-basin P Load (lbs./yr.) | 1a - 7 (Wet) | 27 | 301 | 1,089 | 1,151 | 865 |
| | | 1a - 7 (Dry) | 7 | 79 | 353 | 410 | 170 |
| | | 2a - 14 (Wet) | 25 | 304 | 1,053 | 1,066 | 371 |
| | | 2a - 14 (Dry) | 8 | 90 | 398 | 462 | 244 |
| | | 3a - 21 (Wet) | 26 | 310 | 1,073 | 1,085 | 365 |
| | | 3a - 21 (Dry) | 9 | 92 | 407 | 473 | 232 |
| | | 4a - 28 (Wet) | 27 | 322 | 1,112 | 1,124 | 343 |
| | | 4a - 28 (Dry) | 9 | 96 | 425 | 496 | 193 |
| | Total P Load (lbs./yr.) | 1a - 7 (Wet) | 2,153 | 301 | 1,089 | 2,758 | 2,445 |
| | | 1a - 7 (Dry) | 968 | 79 | 353 | 760 | 998 |
| | | 2a - 14 (Wet) | 2,328 | 304 | 1,053 | 1,884 | 2,124 |
| | | 2a - 14 (Dry) | 1,090 | 90 | 398 | 944 | 1,177 |
| | | 3a - 21 (Wet) | 2,377 | 310 | 1,073 | 1,939 | 2,155 |
| | | 3a - 21 (Dry) | 1,115 | 92 | 407 | 965 | 1,186 |

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| | | 4a - 28 (Wet) | 2,474 | 322 | 1,112 | 2,079 | 2,206 |
| | | 4a - 28 (Dry) | 1,164 | 96 | 425 | 1,015 | 1,188 |
| | P Sediment load (lb./yr.) | 1a - 7 (Wet) | 466 | 307 | 202 | 497 | 1,084 |
| | | 1a - 7 (Dry) | 466 | 307 | 202 | 497 | 1,084 |
| | | 2a - 14 (Wet) | 480 | 317 | 209 | 512 | 1,117 |
| | | 2a - 14 (Dry) | 480 | 317 | 209 | 512 | 1,117 |
| | | 3a - 21 (Wet) | 480 | 317 | 209 | 512 | 1,117 |
| | | 3a - 21 (Dry) | 480 | 317 | 209 | 512 | 1,117 |
| | | 4a - 28 (Wet) | 494 | 326 | 215 | 526 | 1,149 |
| | | 4a - 28 (Dry) | 494 | 326 | 215 | 526 | 1,149 |
| | N conc (mg/L) | 1a - 7 (Wet) | 0.506 | 0.794 | 0.814 | 0.673 | 0.782 |
| | | 1a - 7 (Dry) | 1.383 | 2.691 | 2.422 | 1.683 | 1.900 |
| | | 2a - 14 (Wet) | 0.507 | 0.795 | 0.815 | 0.677 | 0.783 |
| | | 2a - 14 (Dry) | 1.383 | 2.691 | 2.422 | 1.680 | 1.899 |
| | | 3a - 21 (Wet) | 0.507 | 0.795 | 0.815 | 0.650 | 0.782 |
| | | 3a - 21 (Dry) | 1.383 | 2.691 | 2.422 | 1.607 | 1.894 |
| | | 4a - 28 (Wet) | 0.507 | 0.795 | 0.815 | 0.579 | 0.777 |
| | | 4a - 28 (Dry) | 1.383 | 2.691 | 2.422 | 1.420 | 1.878 |
| | Inorg N conc (mg/L) | 1a - 7 (Wet) | 0.304 | 0.477 | 0.489 | 0.404 | 0.469 |
| | | 1a - 7 (Dry) | 0.830 | 1.614 | 1.453 | 1.010 | 1.140 |
| | | 2a - 14 (Wet) | 0.304 | 0.477 | 0.489 | 0.406 | 0.470 |
| | | 2a - 14 (Dry) | 0.830 | 1.614 | 1.453 | 1.008 | 1.139 |
| | | 3a - 21 (Wet) | 0.304 | 0.477 | 0.489 | 0.390 | 0.469 |
| | | 3a - 21 (Dry) | 0.830 | 1.614 | 1.453 | 0.964 | 1.137 |
| | | 4a - 28 (Wet) | 0.304 | 0.477 | 0.489 | 0.348 | 0.466 |
| | | 4a - 28 (Dry) | 0.830 | 1.614 | 1.453 | 0.852 | 1.127 |
| | P conc (mg/L) | 1a - 7 (Wet) | 0.016 | 0.039 | 0.036 | 0.034 | 0.033 |
| | | 1a - 7 (Dry) | 0.020 | 0.035 | 0.034 | 0.024 | 0.033 |
| | | 2a - 14 (Wet) | 0.018 | 0.039 | 0.034 | 0.024 | 0.029 |
| | | 2a - 14 (Dry) | 0.023 | 0.039 | 0.039 | 0.029 | 0.038 |
| | | 3a - 21 (Wet) | 0.018 | 0.040 | 0.035 | 0.023 | 0.029 |

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| | | 3a - 21 (Dry) | 0.023 | 0.040 | 0.040 | 0.029 | 0.039 |
| | | 4a - 28 (Wet) | 0.019 | 0.041 | 0.036 | 0.023 | 0.029 |
| | | 4a - 28 (Dry) | 0.024 | 0.042 | 0.041 | 0.027 | 0.038 |
| | Inorg P Conc (mg/L) | 1a - 7 (Wet) | 0.010 | 0.023 | 0.018 | 0.017 | 0.016 |
| | | 1a - 7 (Dry) | 0.012 | 0.021 | 0.017 | 0.012 | 0.016 |
| | | 2a - 14 (Wet) | 0.011 | 0.023 | 0.017 | 0.012 | 0.014 |
| | | 2a - 14 (Dry) | 0.014 | 0.023 | 0.019 | 0.015 | 0.019 |
| | | 3a - 21 (Wet) | 0.011 | 0.024 | 0.018 | 0.012 | 0.014 |
| | | 3a - 21 (Dry) | 0.014 | 0.024 | 0.020 | 0.014 | 0.019 |
| | | 4a - 28 (Wet) | 0.011 | 0.025 | 0.018 | 0.011 | 0.015 |
| | | 4a - 28 (Dry) | 0.015 | 0.025 | 0.021 | 0.013 | 0.019 |
| | Stormwater load reduction (%) | 1a - 7 (Wet) | 67 | | | | |
| | | 1a - 7 (Dry) | 67 | | | | |
| | | 2a - 14 (Wet) | 62 | | | | |
| | | 2a - 14 (Dry) | 62 | | | | |
| | | 3a - 21 (Wet) | 61 | | | | |
| | | 3a - 21 (Dry) | 61 | | | | |
| | | 4a - 28 (Wet) | 59 | | | | |
| | | 4a - 28 (Dry) | 59 | | | | |
| | P sediment load reduction (%) | 1a - 7 (Wet) | 33 | | | | |
| | | 1a - 7 (Dry) | 33 | | | | |
| | | 2a - 14 (Wet) | 31 | | | | |
| | | 2a - 14 (Dry) | 31 | | | | |
| | | 3a - 21 (Wet) | 31 | | | | |
| | | 3a - 21 (Dry) | 31 | | | | |
| | | 4a - 28 (Wet) | 29 | | | | |
| | | 4a - 28 (Dry) | 29 | | | | |
| **Output** | Predicted P conc (µg/L) | 1a - 7 (Wet) | 18.9 | 17.9 | 19.8 | 26.2 | 30.5 |
| | | 1a - 7 (Dry) | 24.9 | 20.3 | 20.1 | 26.3 | 35.0 |
| | | 2a - 14 (Wet) | 20.0 | 18.7 | 20.2 | 23.2 | 27.4 |
| | | 2a - 14 (Dry) | 26.9 | 21.4 | 21.2 | 29.0 | 38.4 |

| Model Input/ Output | Parameter | Scenario - Run | Upper Lobe | Upper Lake | Lower Lake | Upper Basin | Lower Basin |
|---|---|---|---|---|---|---|---|
| | | 3a - 21 (Wet) | 20.4 | 19.0 | 20.4 | 23.3 | 27.5 |
| | | 3a - 21 (Dry) | 27.2 | 21.6 | 21.4 | 28.9 | 38.3 |
| | | 4a - 28 (Wet) | 21.0 | 19.5 | 21.0 | 23.4 | 27.7 |
| | | 4a - 28 (Dry) | 28.1 | 22.0 | 21.8 | 28.7 | 37.9 |
| | Predicted Chl-a conc (µg/L) | 1a - 7 (Wet) | 5.2 | 3.8 | 4.3 | 8.3 | 9.5 |
| | | 1a - 7 (Dry) | 7.5 | 4.7 | 4.6 | 8.6 | 11.6 |
| | | 2a - 14 (Wet) | 5.6 | 4.0 | 4.4 | 7.1 | 8.4 |
| | | 2a - 14 (Dry) | 8.3 | 5.0 | 4.9 | 9.7 | 12.9 |
| | | 3a - 21 (Wet) | 5.7 | 4.1 | 4.4 | 7.2 | 8.4 |
| | | 3a - 21 (Dry) | 8.4 | 5.0 | 5.0 | 9.7 | 12.9 |
| | | 4a - 28 (Wet) | 5.9 | 4.2 | 4.5 | 7.2 | 8.5 |
| | | 4a - 28 (Dry) | 8.7 | 5.1 | 5.1 | 9.6 | 12.7 |

# APPENDIX K. BMP DESIGN PARAMETERS USED IN THE PILOT WATERSHED

| General Information | BMP Parameters | Biofiltration | Infiltration-B | Infiltration-C | Porous Pavement |
|---|---|---|---|---|---|
| BMP Dimensions | Surface Area (ac) | Table X-7 | Table X-7 | Table X-7 | Table X-7 |
| Surface Storage Configuration | Orifice Height (ft) | 0 | 0 | 0 | 0 |
| | Orifice Diameter (in.) | 0 | 0 | 0 | 0 |
| | Rectangular or Triangular Weir | Rectangular | Rectangular | Rectangular | Rectangular |
| | Weir Height (ft)/Ponding Depth (ft) | 0.5 | 2 | 2 | 0.2 |
| | Crest Width (ft) | 100 | 100 | 100 | 100 |
| Soil Properties | Depth of Soil (ft) | 2.5 | 0 | 0 | 2.67 |
| | Soil Porosity (0-1) | 0.2 | 0.4 | 0.4 | 0.23 |
| | Vegetative Parameter A | 0.9 | 0.9 | 0.9 | 0.1 |
| | Soil Infiltration (in/hr.) | 2.5 | 2.41 | 0.52 | 17.42 |
| Underdrain Properties | Consider Underdrain Structure? | Yes | No | No | Yes |
| | Storage Depth (ft) | 1 | 0 | 0 | 1.75 |
| | Media Void Fraction (0-1) | 0.4 | 0 | 0 | 0.4 |
| | Background Infiltration (in/hr.) | 0 | 2.41 | 0.52 | 0 |
| Cost Parameters | Storage Volume Cost ($/ft3) | $15.46 | $6.24 | $6.24 | $5.32 |
| Cost Function Adjustment | BMP Development Type | New BMP in Developed Area | New BMP in Developed Area | New BMP in Developed Area | Difficult Installation in Highly Urban Settings |
| | Cost Adjustment Factor | 2 | 2 | 2 | 3 |
| Decay Rates | TP (1/hr.) | 0.13 | 0.27 | 0.27 | 0.0051 |
| Underdrain Removal Rates | TP (%, 0-1) | 0.43 | 0 | 0 | 0.1 |