

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.

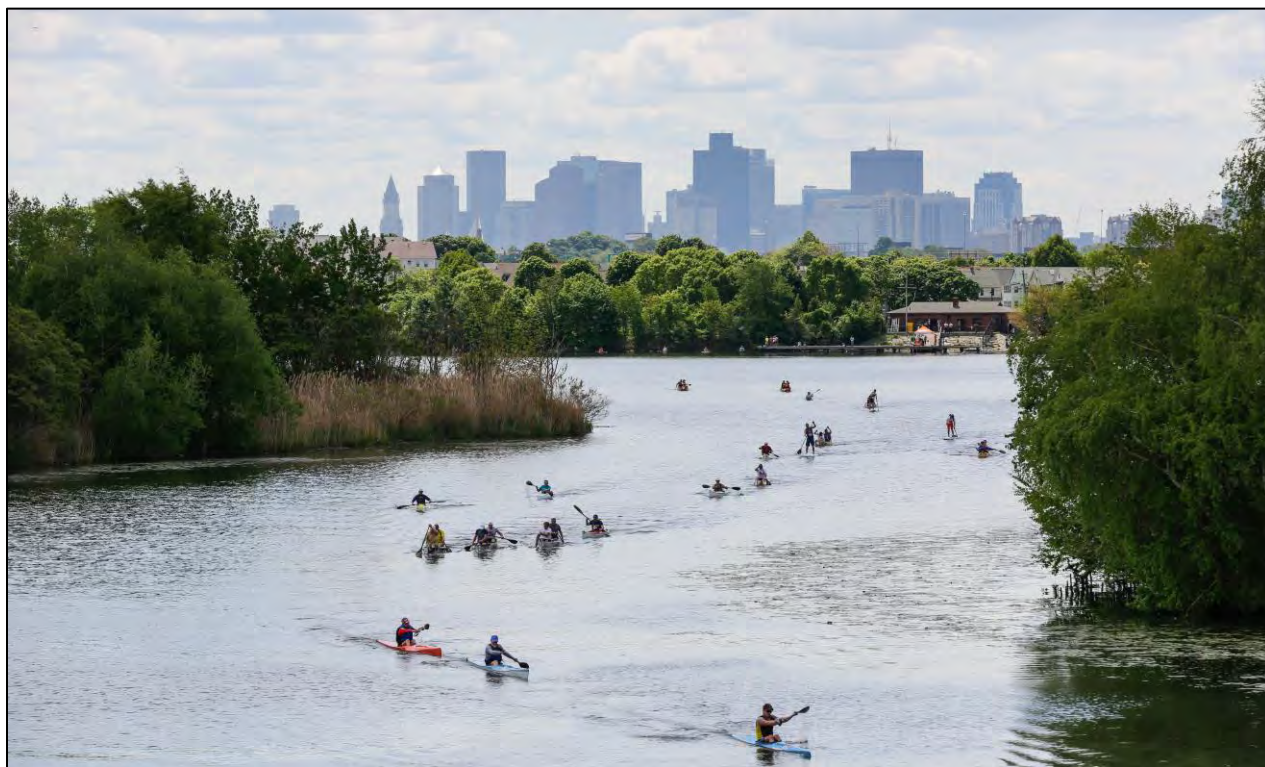


Photo Above: The Mystic River Run and Paddle (May 2016). This annual race celebrates the return of the river herring and draws the public to the Mystic River. This image looks downstream from Route 16 to the Blessing of the Bay Boathouse in Somerville with the Boston skyline in the background. Photo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

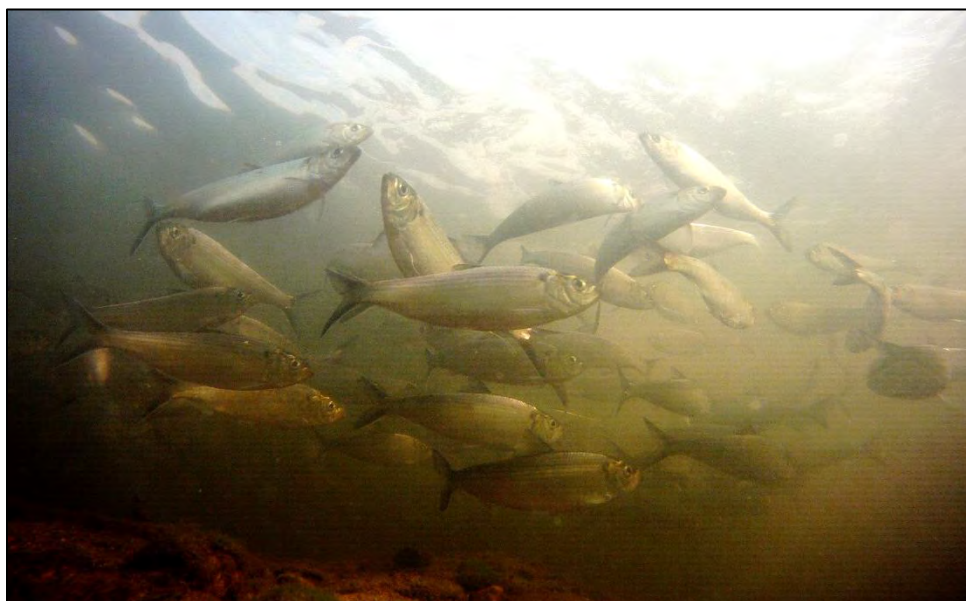


Photo Left: River herring above the fish ladder in Upper Mystic Lake in 2012. This was the first year since the late 1800s that had significant passage of anadromous fish into the Upper Mystic Lake. Photo credit: Patrick Herron, Mystic River Watershed Association.

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 predictable 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.

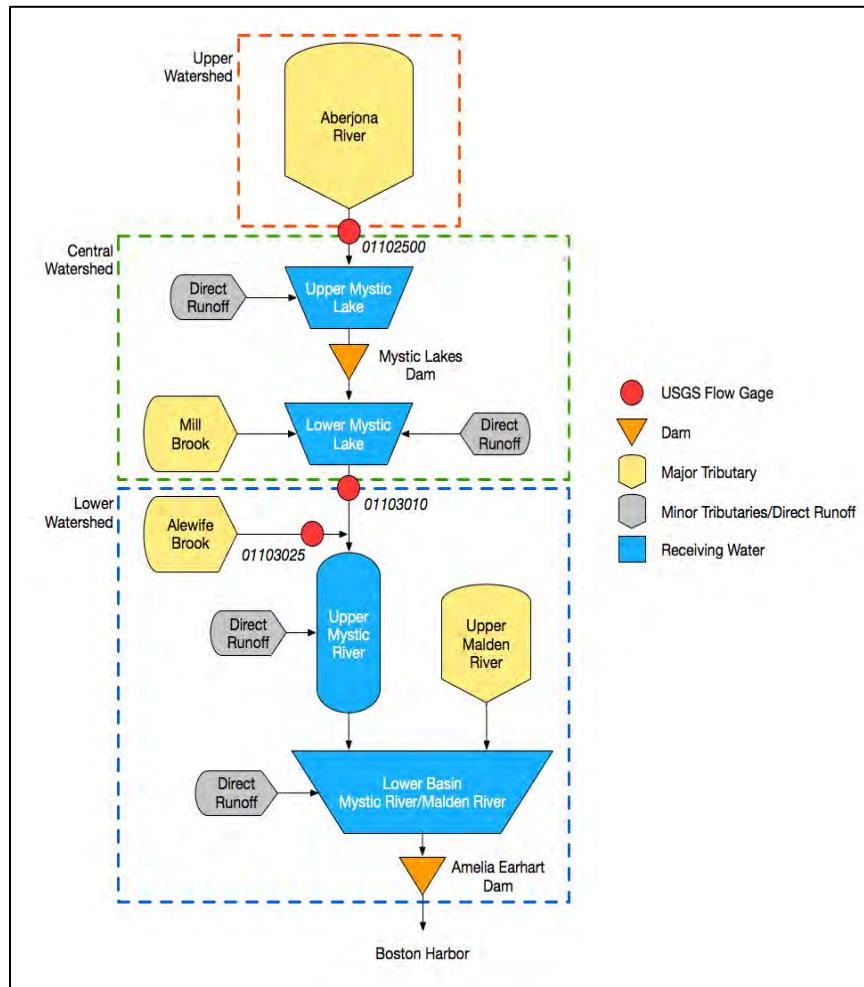
II. CONCEPTUAL MODEL OF THE HYDROLOGY AND NUTRIENT DYNAMICS IN THE MYSTIC RIVER BASIN

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.

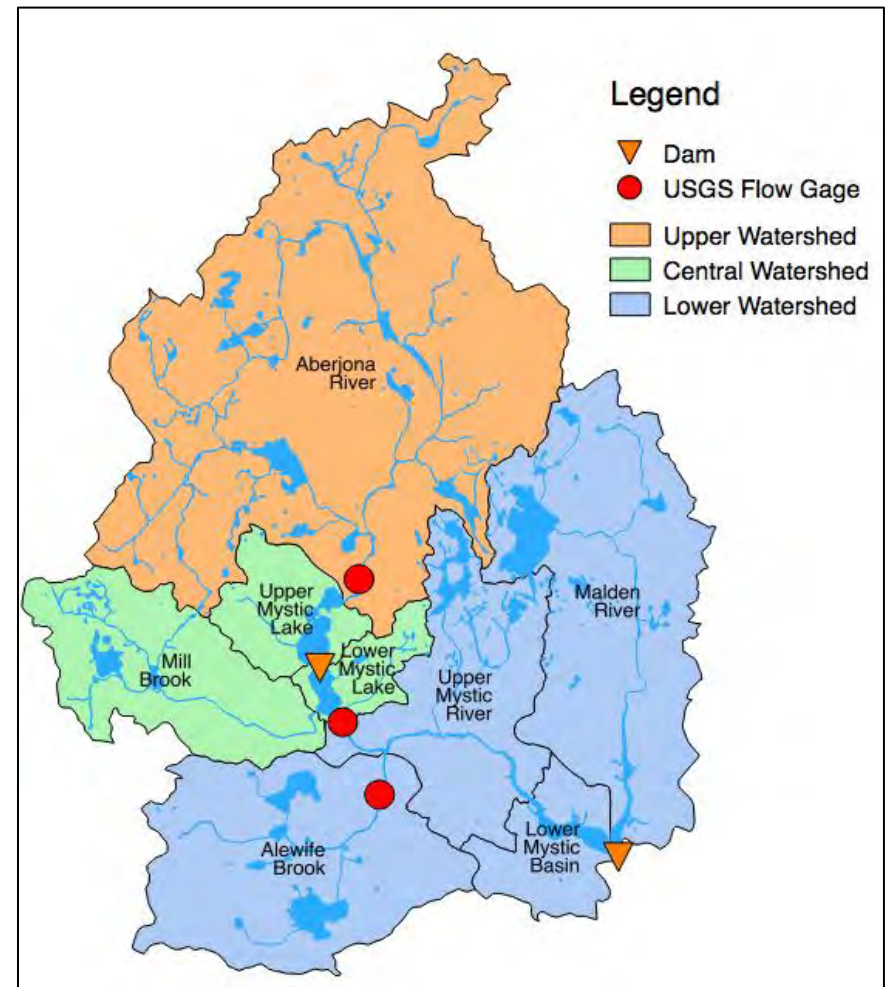


Figure II-I Schematic Diagram and Map of Mystic River Watershed

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.

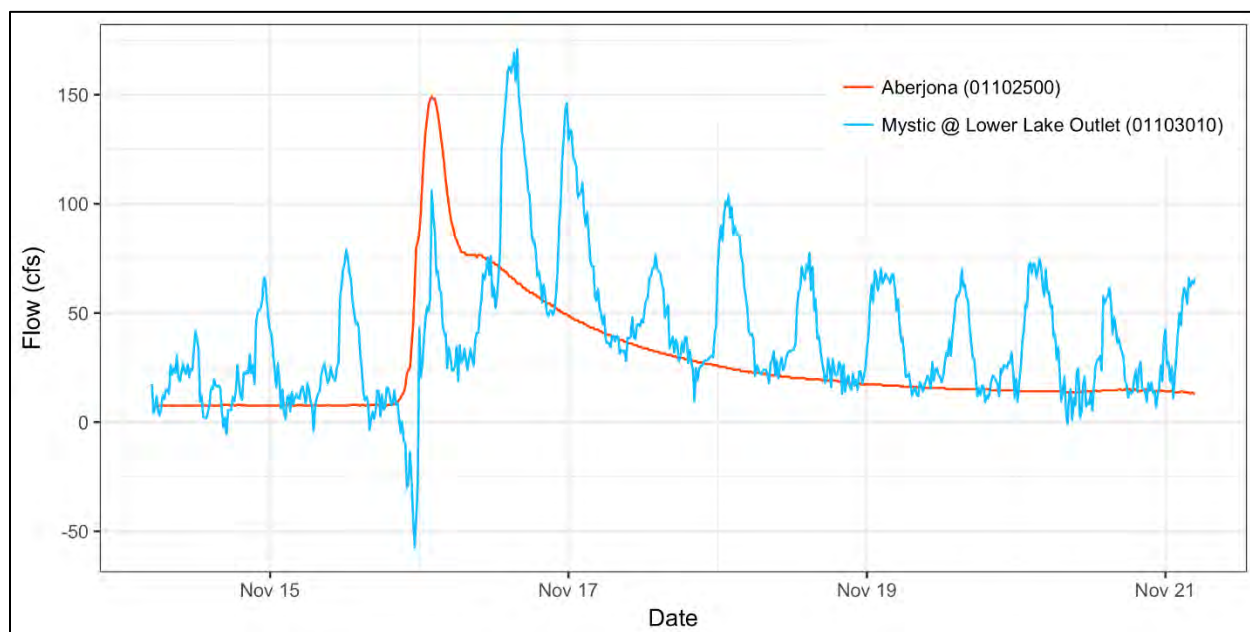


Figure II-II Instantaneous Streamflow Above and Below Mystic Lakes

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.

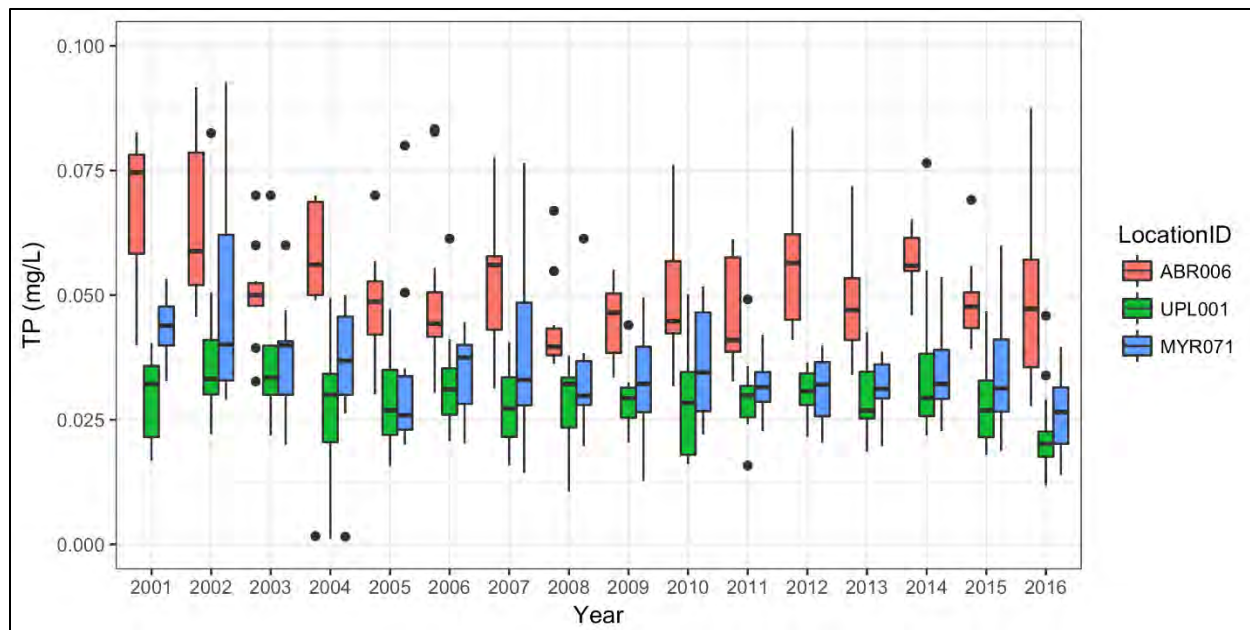


Figure II-III Annual Distributions of Monthly TP Concentrations at the Aberjona River Outlet (ABR006), Mystic Lake Dam (UPL001), and Start of the Mystic River Mainstem (MYR071)¹

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.

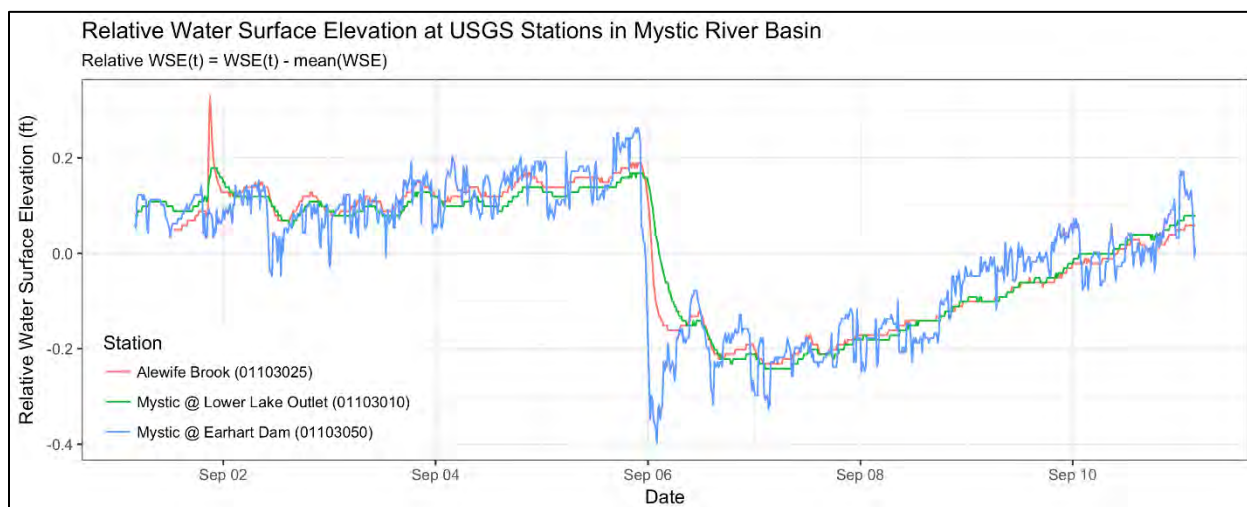


Figure II-IV Relative Water Surface Elevation at USGS Gages on Alewife Brook and Mystic River (Sept. 1 – 10, 2016)

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.

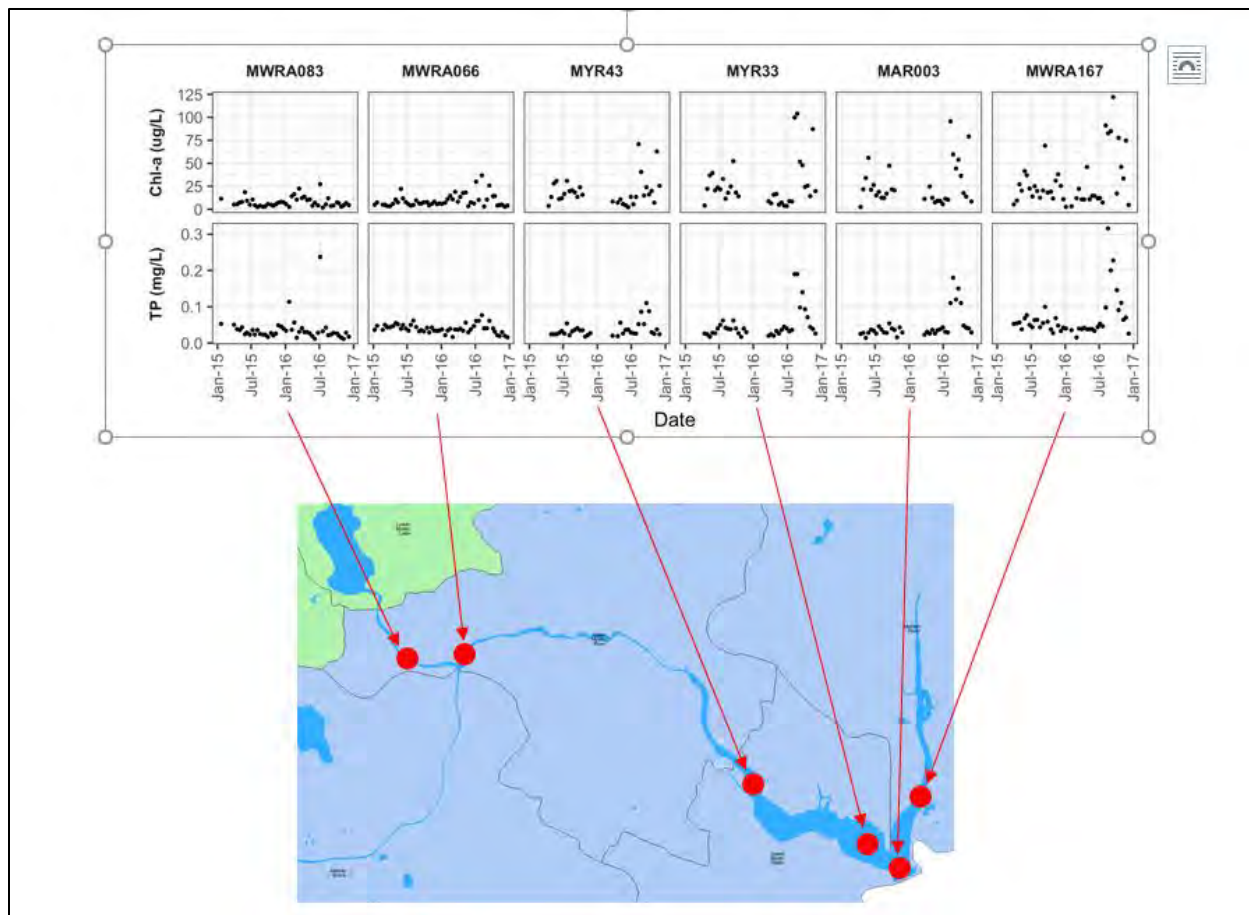


Figure II-V Chlorophyll-a and TP Concentrations Along the Mystic and Malden Rivers, 2015 – 2016

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 90th 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, 90th 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.

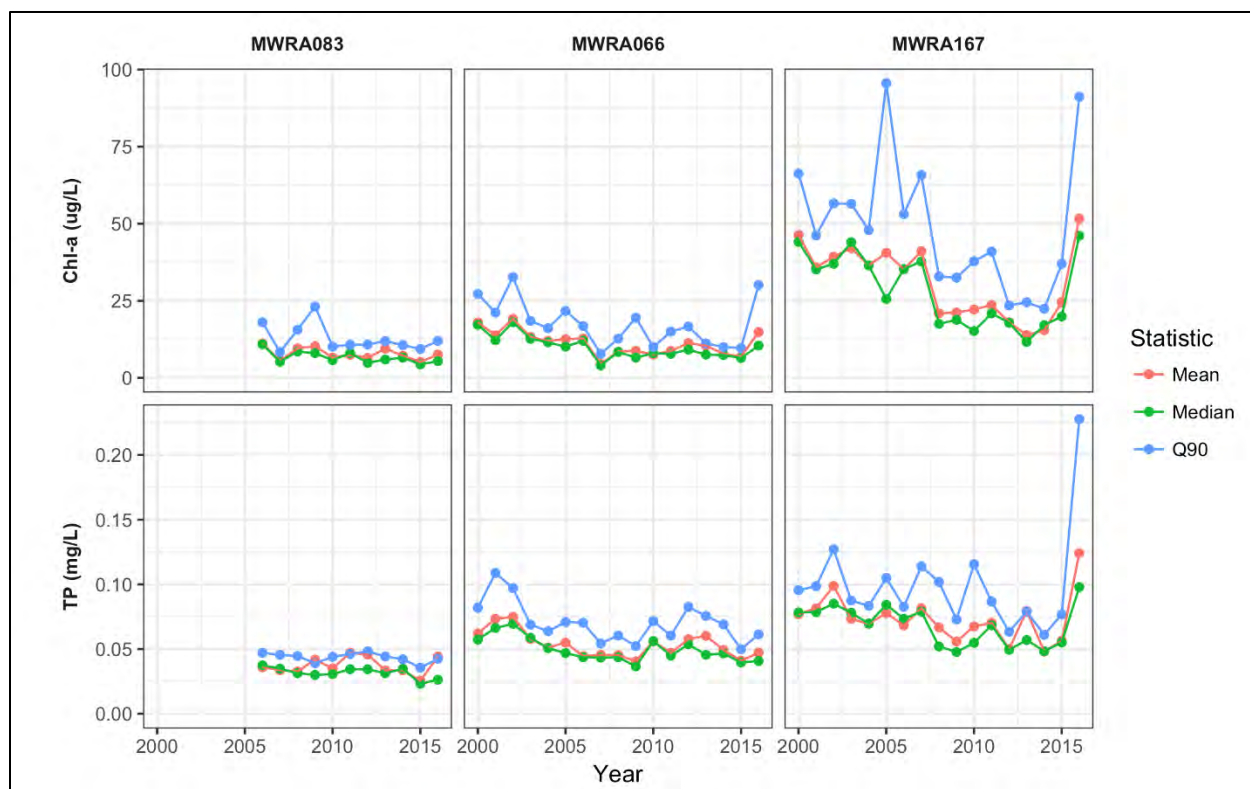


Figure II-VI Annual Mean, Median, 90th Percentile of Chlorophyll-a and TP at Three Stations on the Mystic River, 2000 – 2016 (June – Oct. only)

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 ($<100 \mu\text{g/L}$), 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 Program²

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-basins⁵. 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.

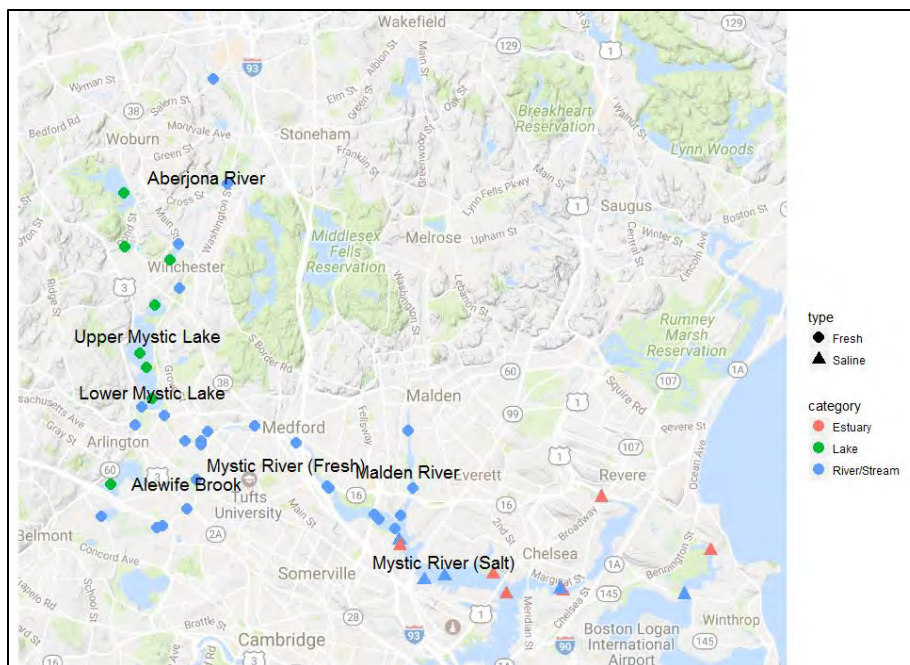


Figure III-I. Mystic River Watershed Drainage Basins and Monitoring Locations

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).

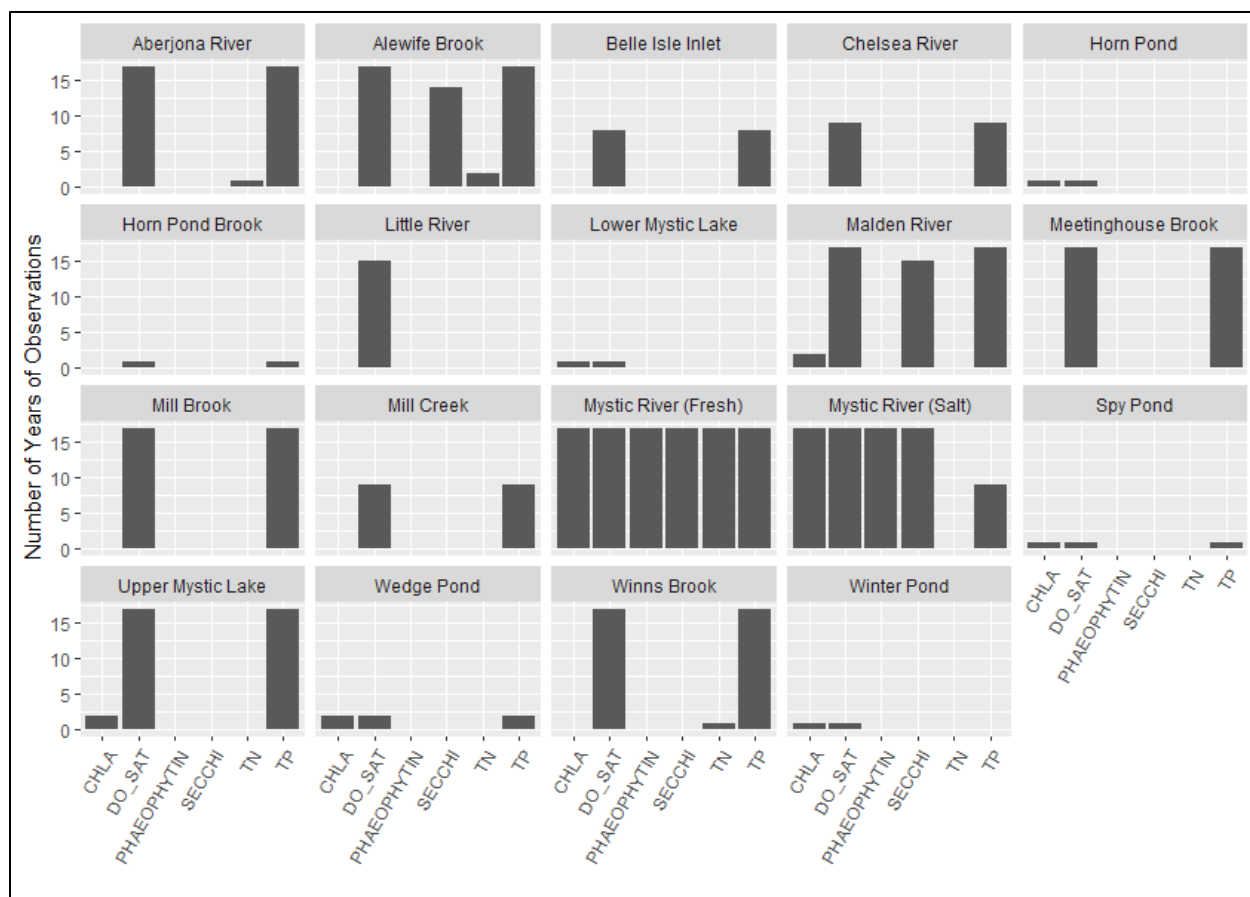
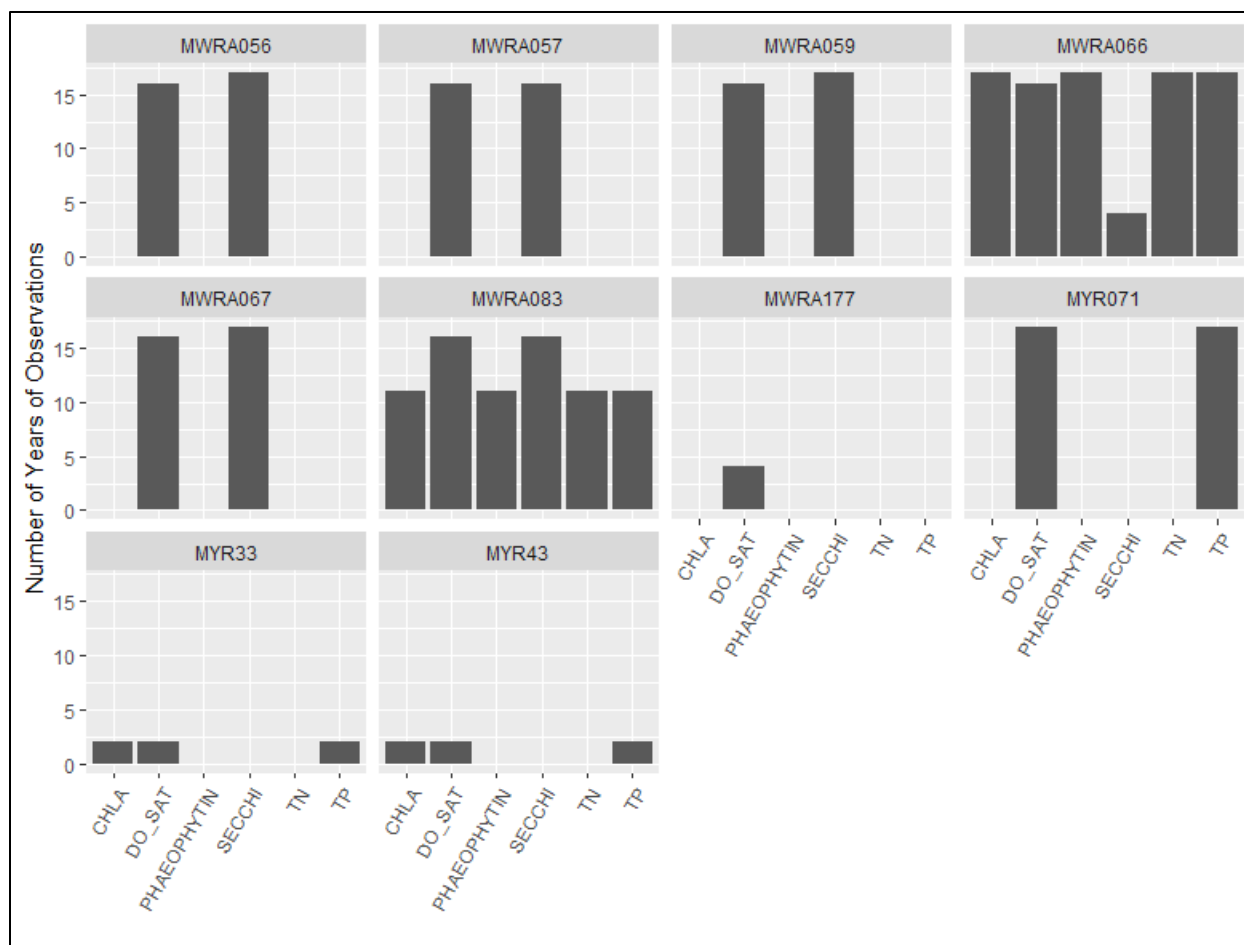


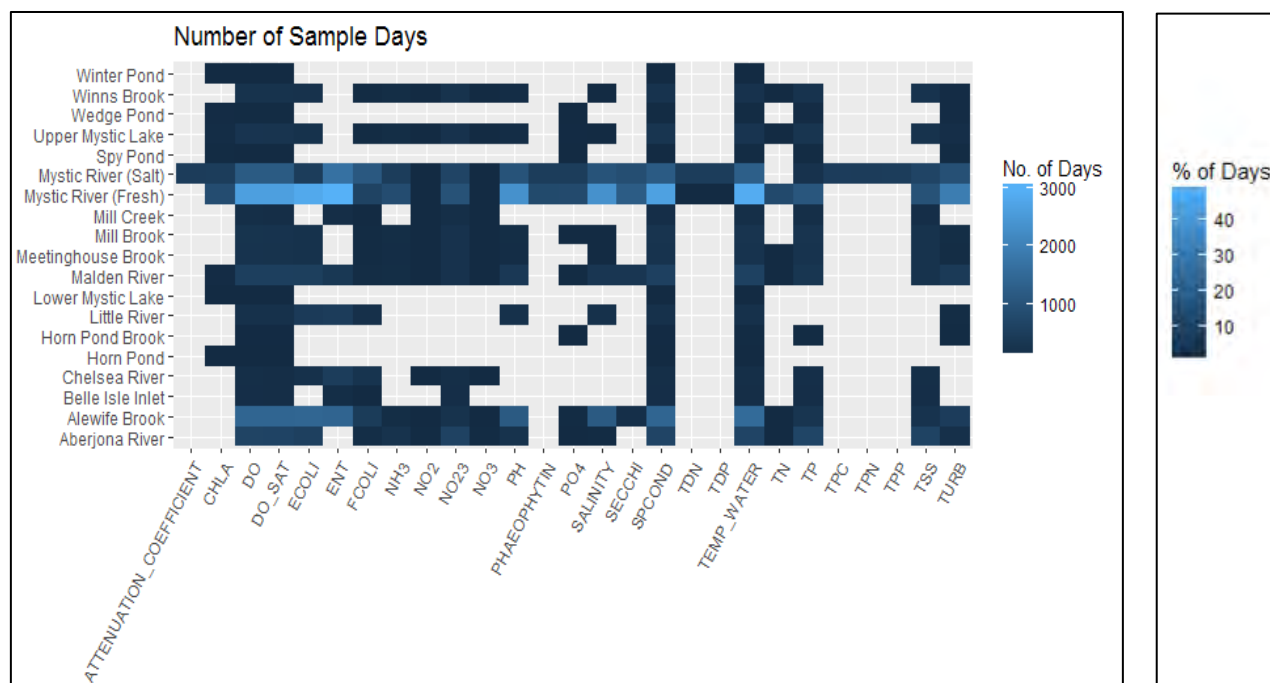
Figure III-II. Number of Years in Which Observations Were Made for Eutrophication Related Parameters in the Watershed



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 ($N \leq 3$) Samples were Collected for a Waterbody-Parameter Combination

Parameter	No. of Seasons with $n \leq 3$ ¹	
	Jun-Oct	Nov-May
<i>Alewife Brook</i>		
Secchi Depth	3	9
Turbidity	–	5
<i>Little River</i>		
Dissolved Oxygen	7	7
Dissolved Oxygen (% Saturation)	7	7
pH	7	5
Specific Conductivity	8	7
Water Temperature	7	7
Turbidity	2	3
<i>Malden River</i>		
Dissolved Oxygen	1	19
Dissolved Oxygen (% Saturation)	–	10
pH	–	9
Secchi Depth	–	12
Specific Conductivity	–	13
Water Temperature	–	12
Turbidity	2	20
<i>Mystic River (Fresh)</i>		
Secchi Depth	–	2
Total Dissolved Nitrogen	1	4
Total Dissolved Phosphorus	1	4
Turbidity	–	1
<i>Mystic River (Salt)</i>		
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
Alewif 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
Alewif 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	<u>Massachusetts Office of Geographic Information (MassGIS) or Multi-Resolution Land Characteristics Consortium (MLCD)</u>	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	<u>MassGIS</u>	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)	<u>MassGIS</u>	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	<u>MassGIS (NRCS SSURGO) or NRCS Web Soil Survey</u>	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 75th 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 25th 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.

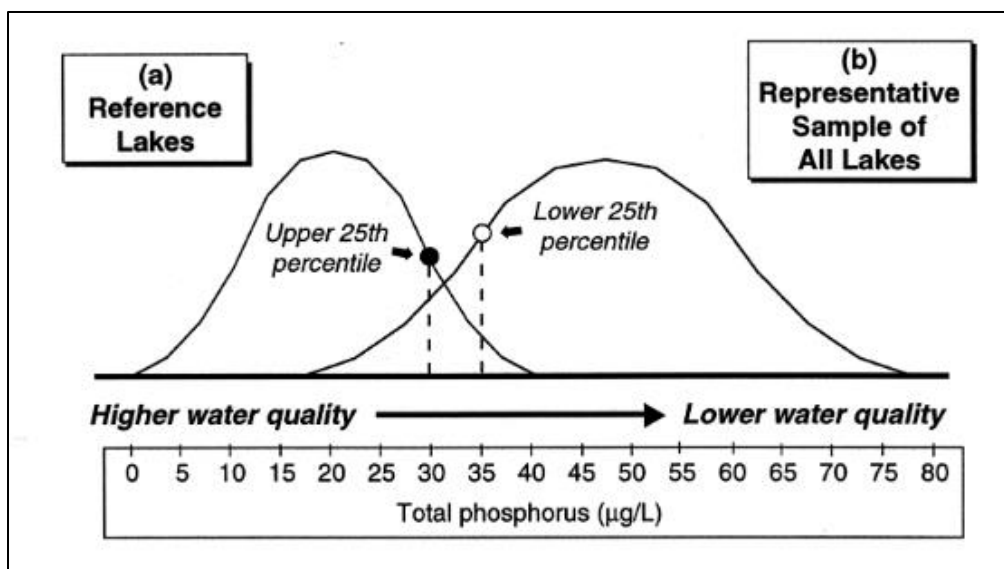


Figure IV-I. Reference Condition Approach for Establishing Numeric Water Quality Targets (EPA, 1998)

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 25th 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 25th 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 25th percentile observational values ranging from 20 µg/L - 34 µg/L for total phosphorus 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)
<i>Eco-region XIV, Sub-region 59</i>					
Rivers & Streams	23.75	0.59	0.44 ²	–	1.68 ³
<i>Mystic River Watershed 25th Percentile Observations (2000 – 2016)</i>					
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.

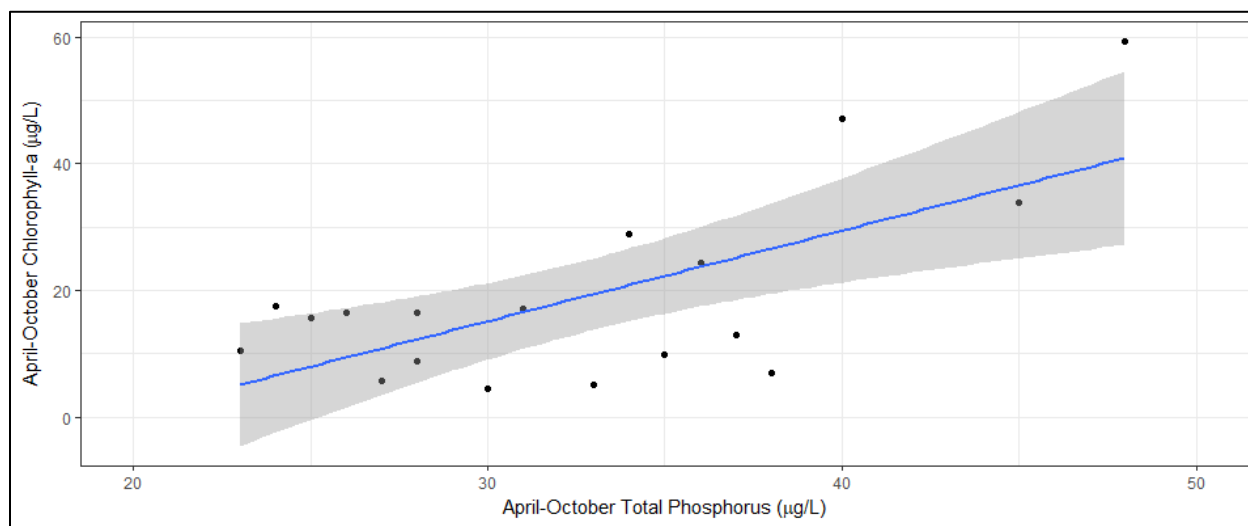


Figure IV-II. April – October Total Phosphorus vs. Chlorophyll-a Concentrations in the Upper Lobe of the Upper Mystic Lake (Monitoring Station UPLUPL)

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-a¹

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 90 th 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.

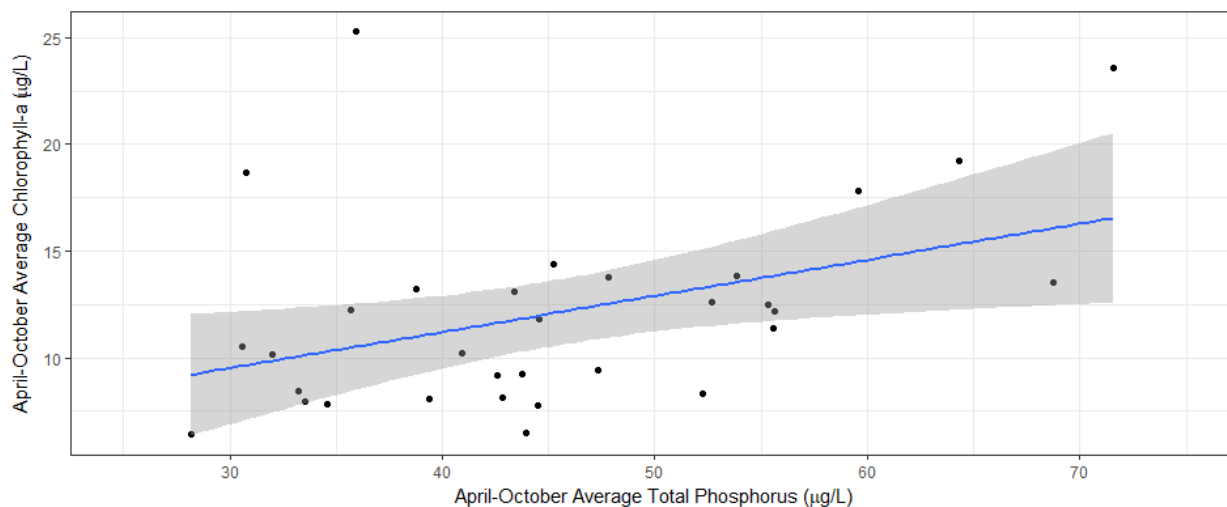


Figure IV-III. April – October Average Total Phosphorus vs. Average Chlorophyll-a Concentrations in the Mystic River

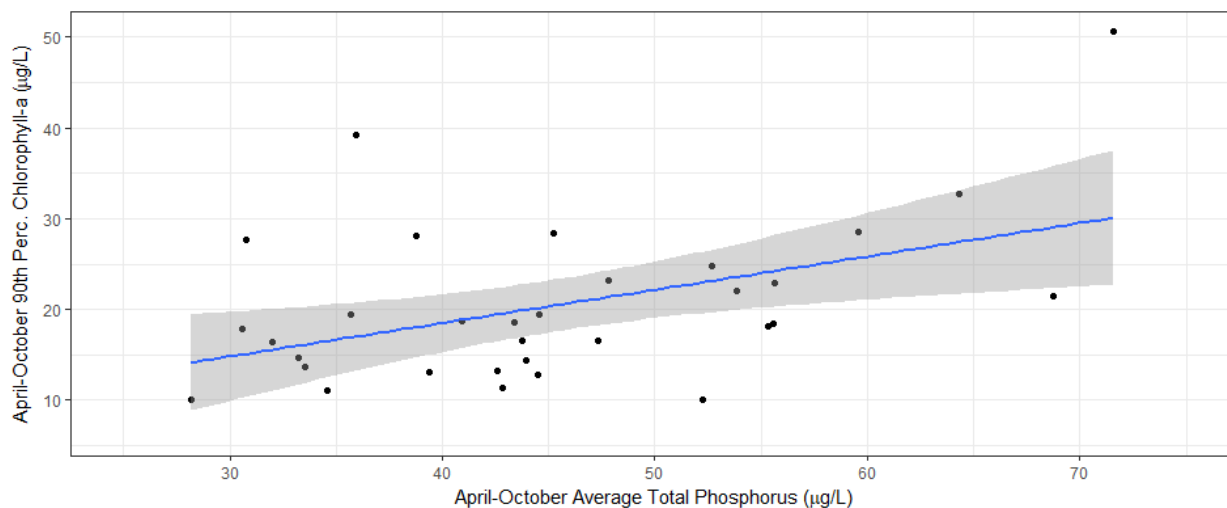


Figure IV-IV. April – October Average Total Phosphorus vs. 90th Percentile Chlorophyll-a Concentrations in the Mystic River

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://landscape.team.maps.arcgis.com/apps/SimpleViewer/index.html?appid=4dbfec52f1442eeb368c435251591ec
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.

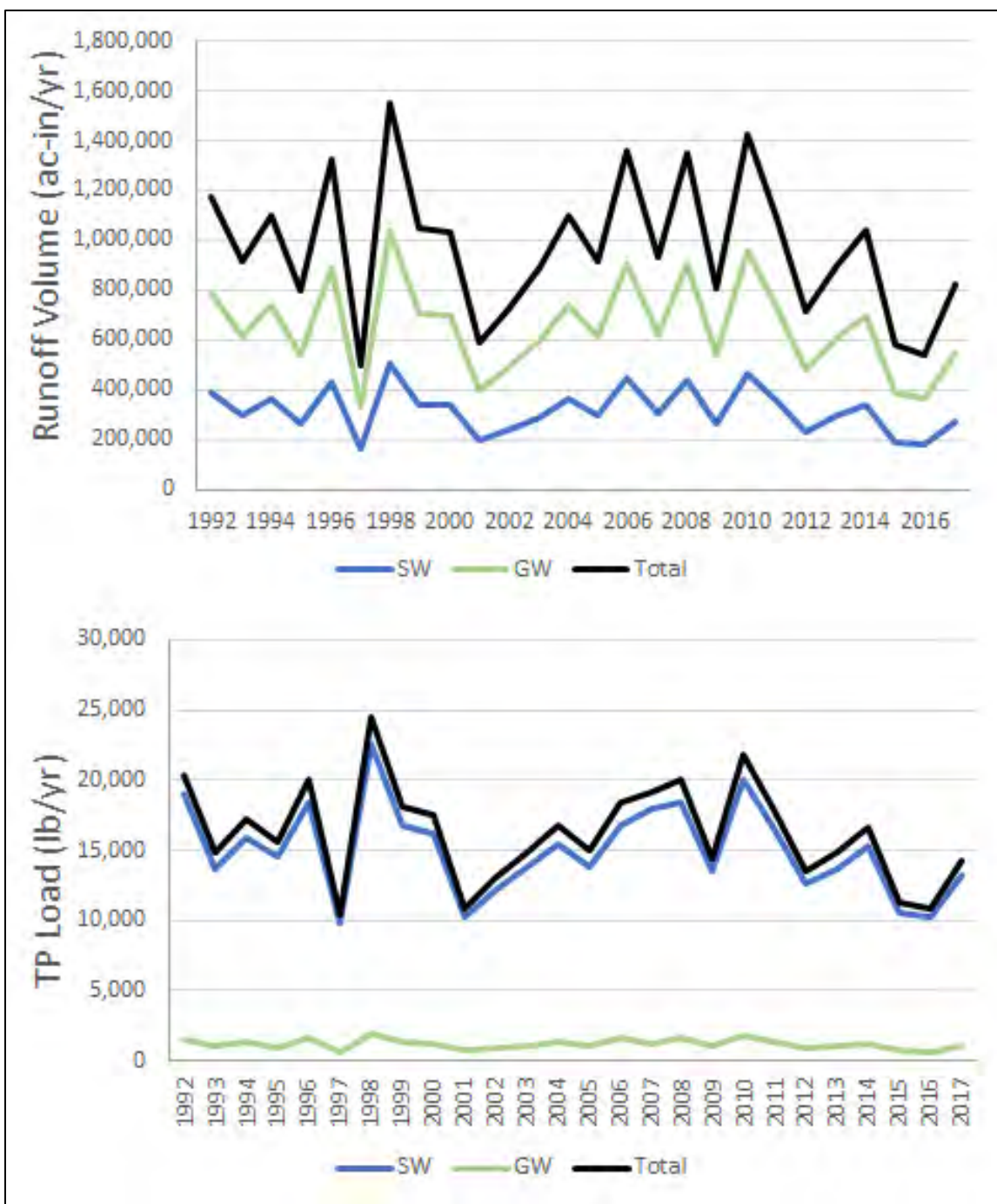


Figure V-I. Estimated Annual Runoff Volume and TP Load for the Mystic River

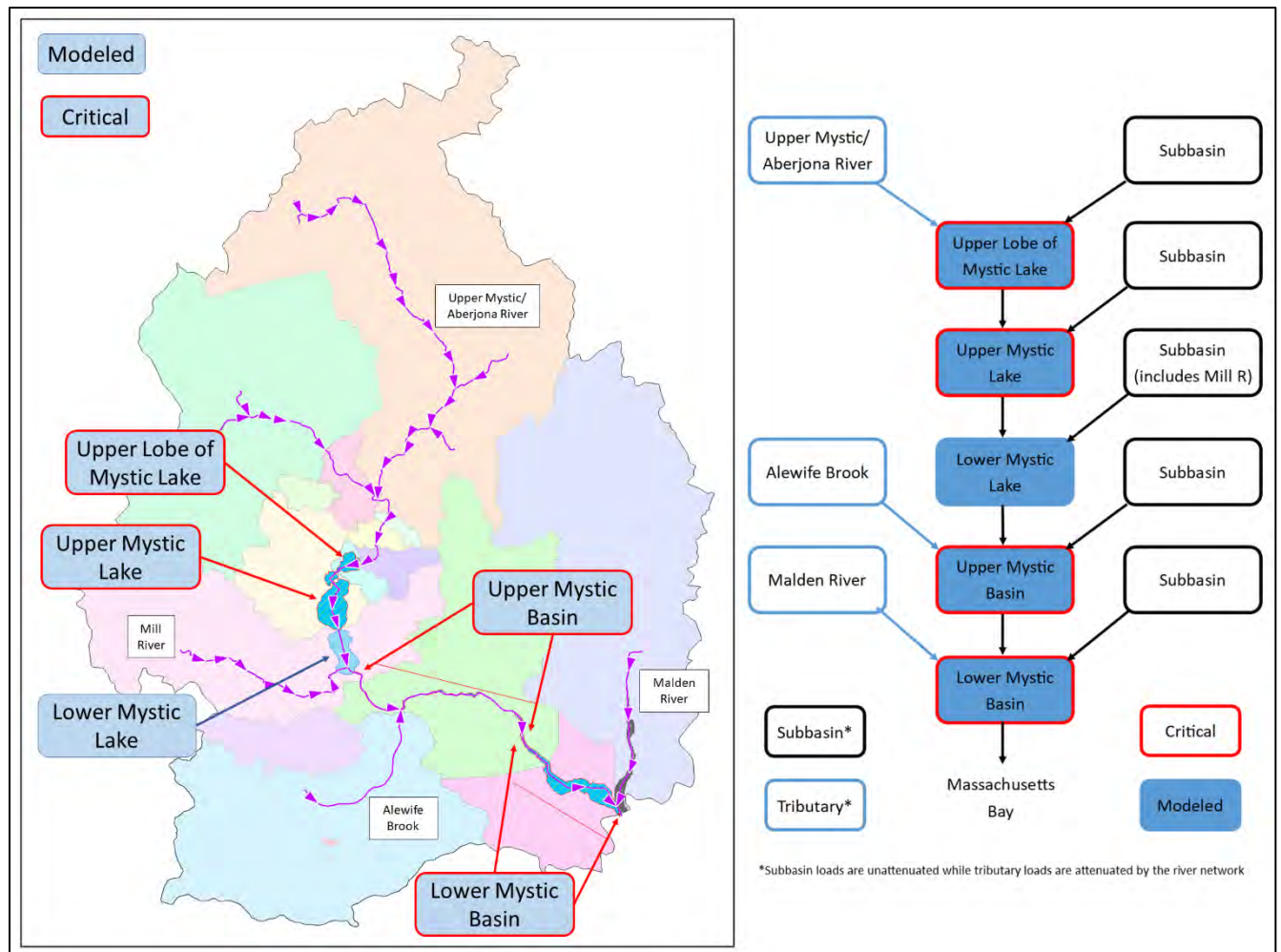


Figure V-II. Mystic River Watershed Sub-Basin Delineation and Schematic Diagram for Final Model

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.

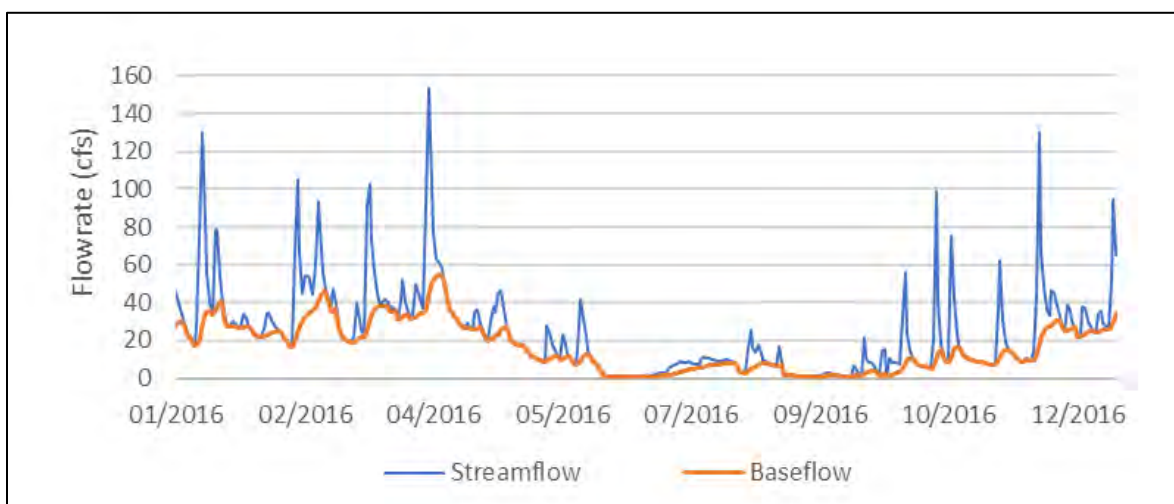


Figure V-III. Baseflow Estimates and Streamflow Measurements at Aberjona River for 2016 (USGS Gage 01102500)

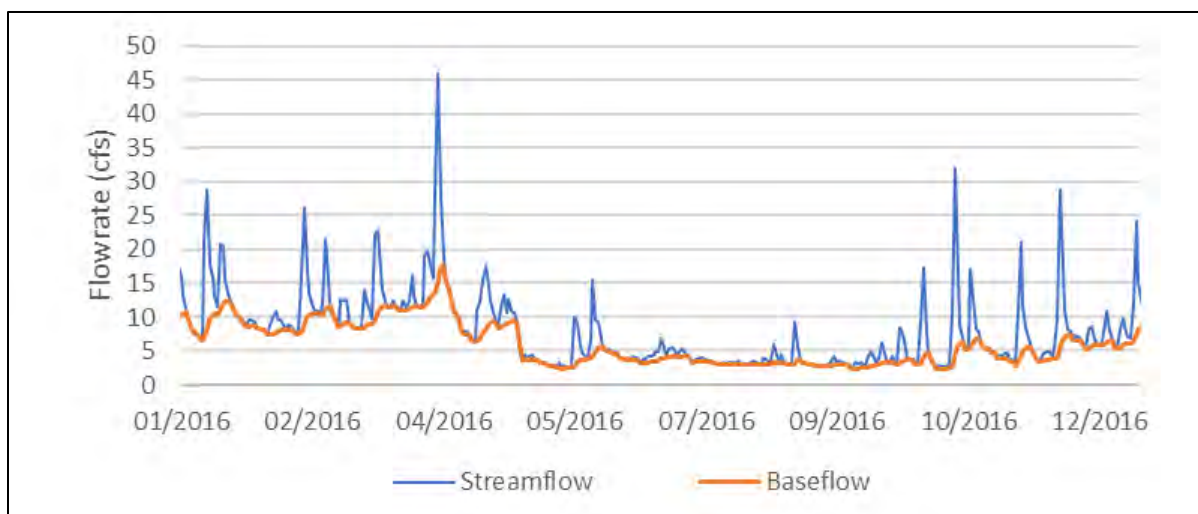


Figure V-IV. Baseflow Estimates and Streamflow Measurements at Alewife Brook for 2016 (USGS Gage 01103025)

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:

$$\text{Groundwater Flow} = (f \times \text{Stormwater Flow}) / (1 - f)$$

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.

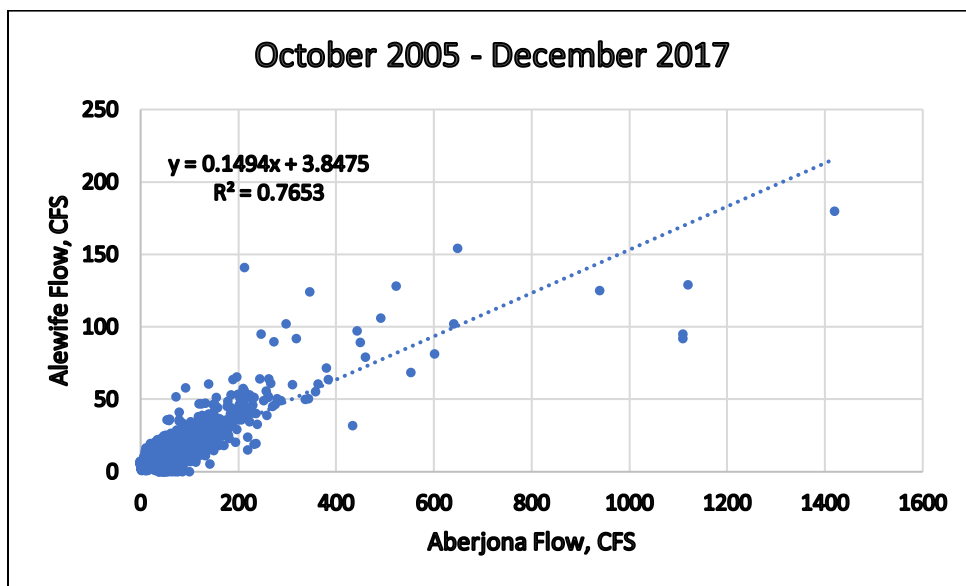


Figure V-V. Regression of Flow Measurements at Aberjona River (01102500) and Alewife Brook (01103025) USGS Stations

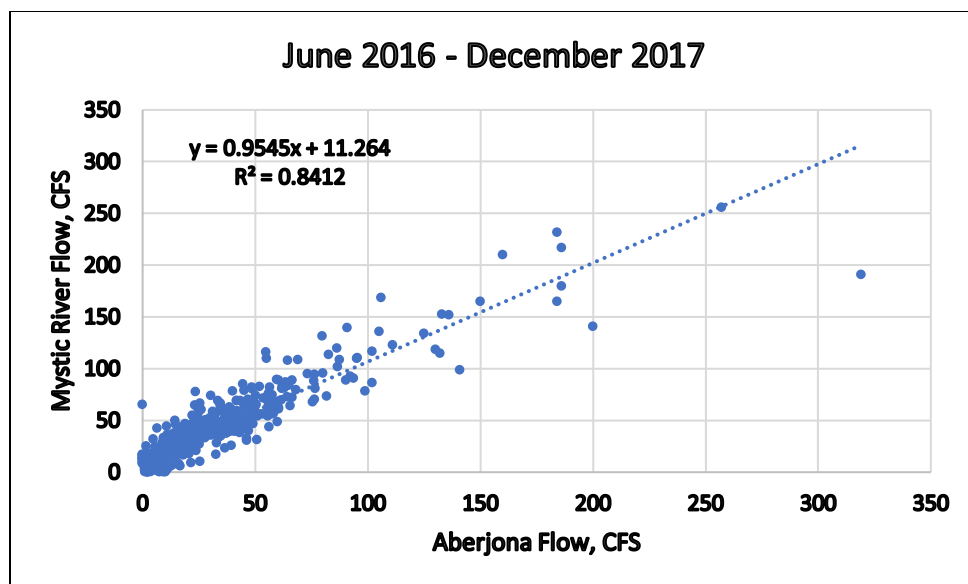


Figure V-VI. Regression of Flow Measurements at Aberjona River (01102500) and Alewife Brook (01103025) USGS Stations

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 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).

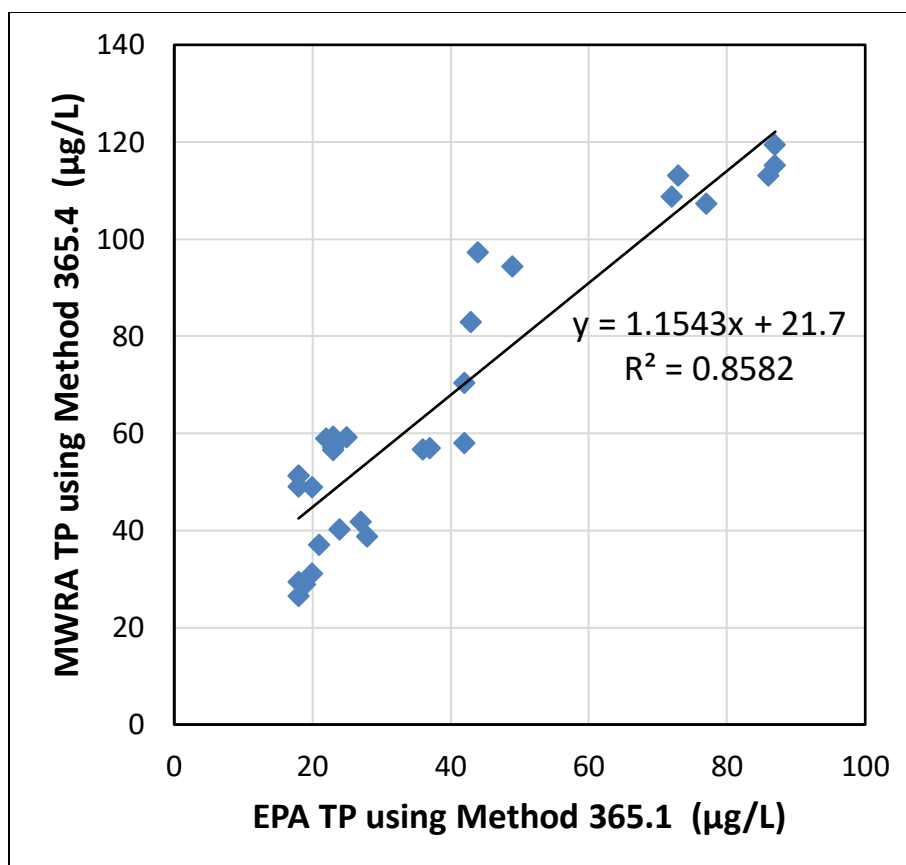


Figure V-VII. Correction of TP Values from Method 365.1 to 365.4

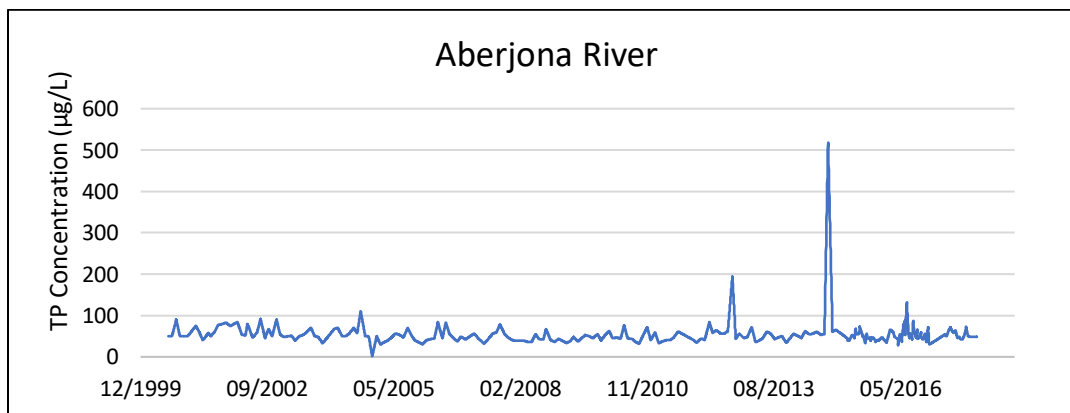


Figure V-VIII. Adjusted Total Phosphorus Concentrations in the Aberjona River

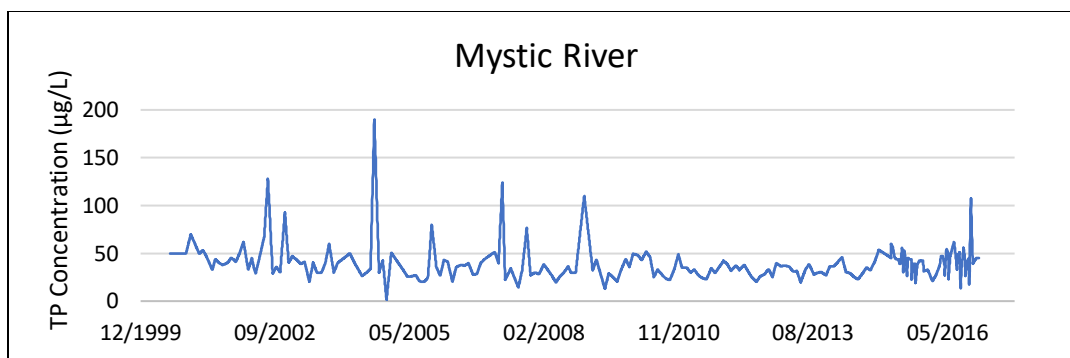


Figure V-IX. Adjusted Total Phosphorus Concentrations in the Mystic River

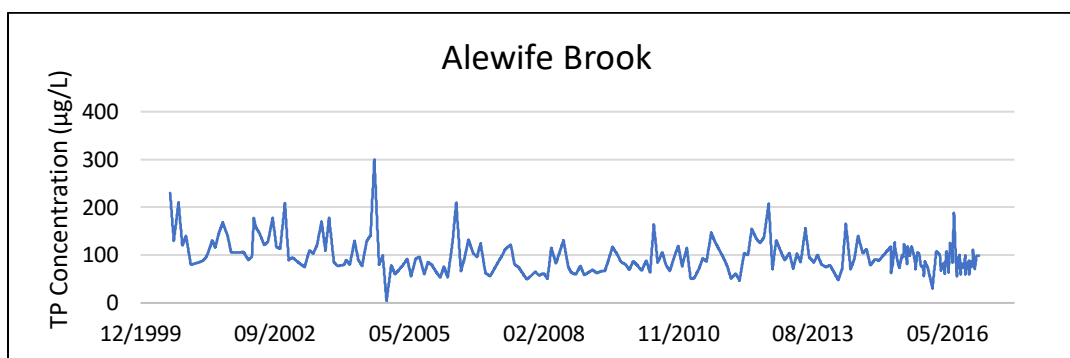


Figure V-X. Adjusted Total Phosphorus Concentrations in Alewife Brook.

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:

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

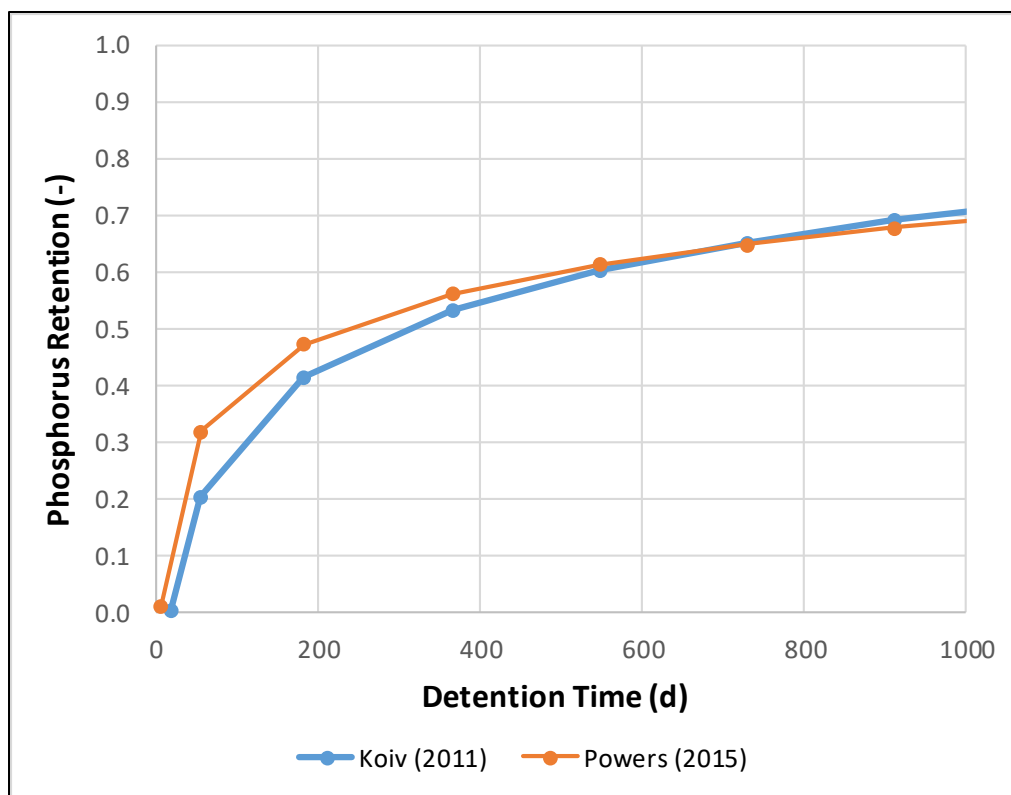


Figure V-XI. Phosphorus Attenuation Curves

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 (m³)	Cumulative Reach Flow (m³/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
Alewif Brook	-	17,560,488	-	0.05	0.48
Calibration Site is USGS Streamflow Gauge at Alewife Brook (1103025)					

¹ From land loading model

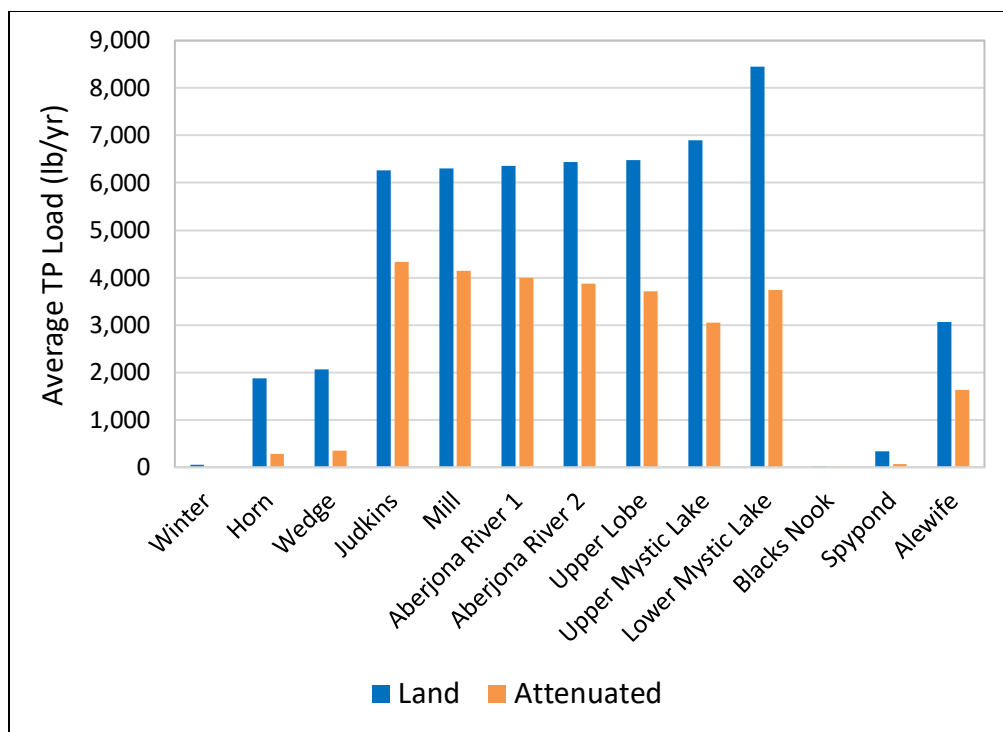


Figure V-XII. Modeled Land vs. Attenuated Reach Phosphorus Loads (2007-2016)

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 ($p\text{-value} < 0.05$). 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.

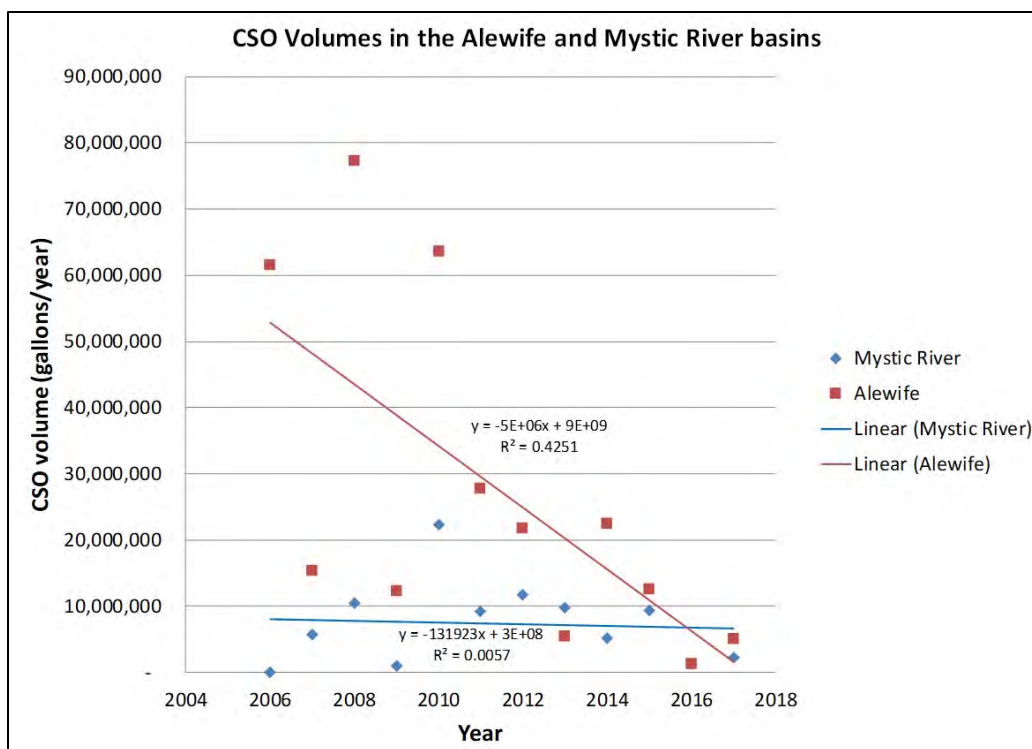


Figure VI-I. Annual CSO Volumes over Time

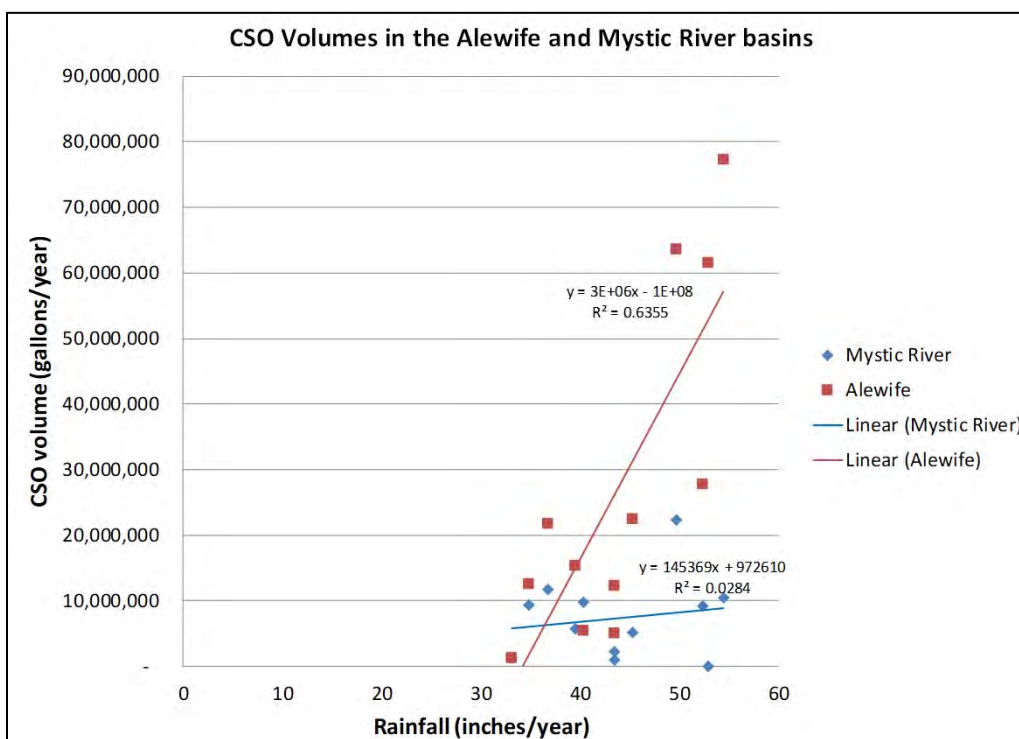


Figure VI-II. Annual CSO Volumes versus Annual Rainfall

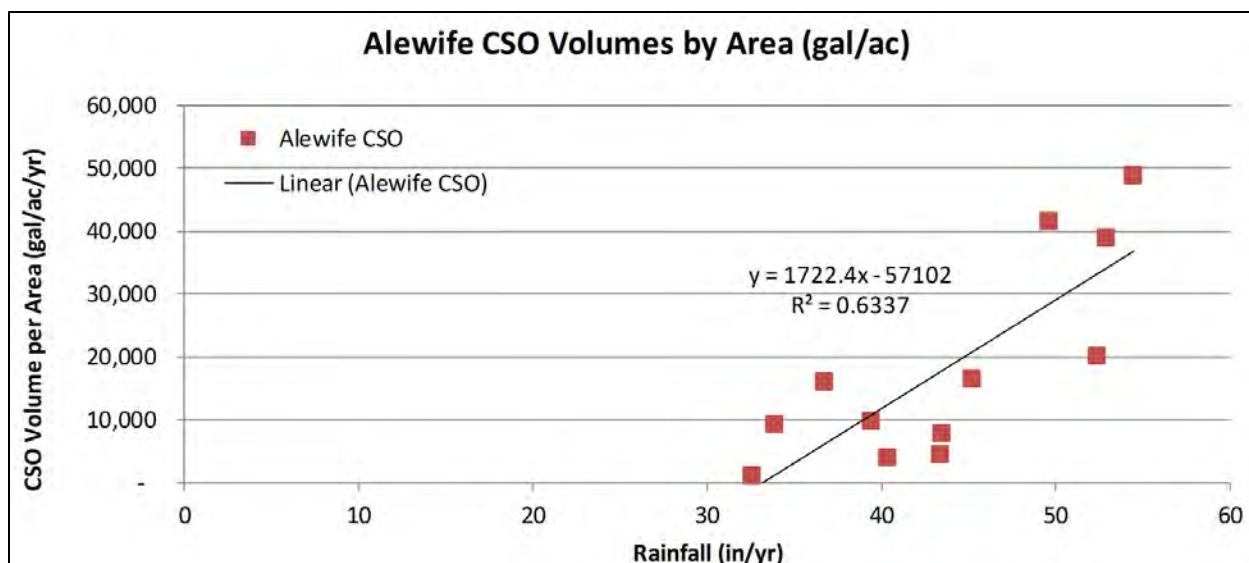


Figure VI-III. Normalized Alewife Annual CSO Volumes versus Annual Precipitation

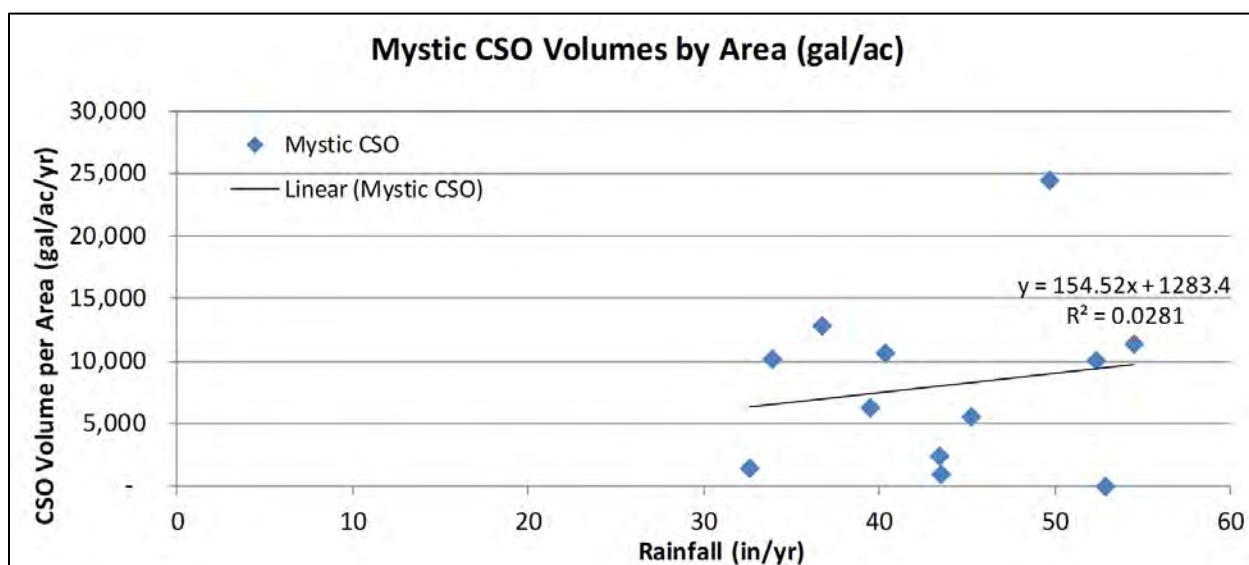


Figure VI-IV. Normalized Mystic Annual CSO Volumes versus Annual Precipitation

Table VI-2. Statistical Outlier Analysis for CSO Datasets

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

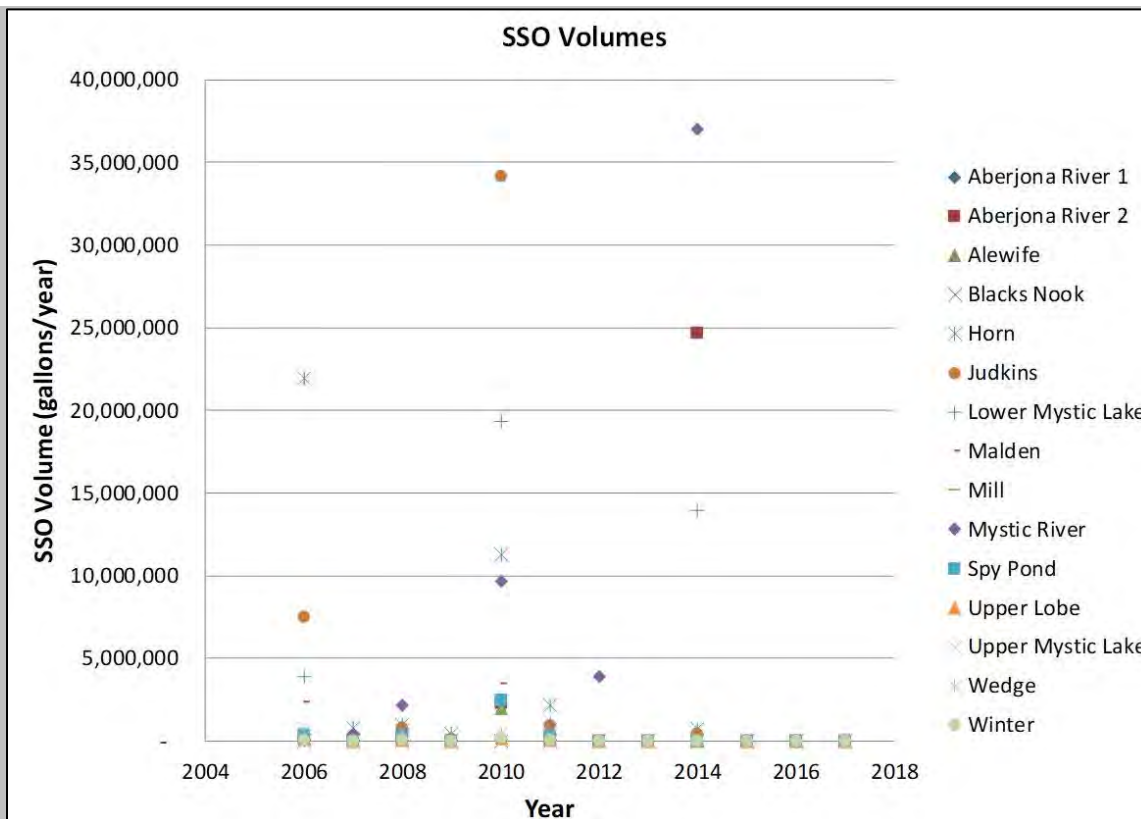


Figure VI-V. Annual SSO Discharge Volumes by Sub-watershed versus Time

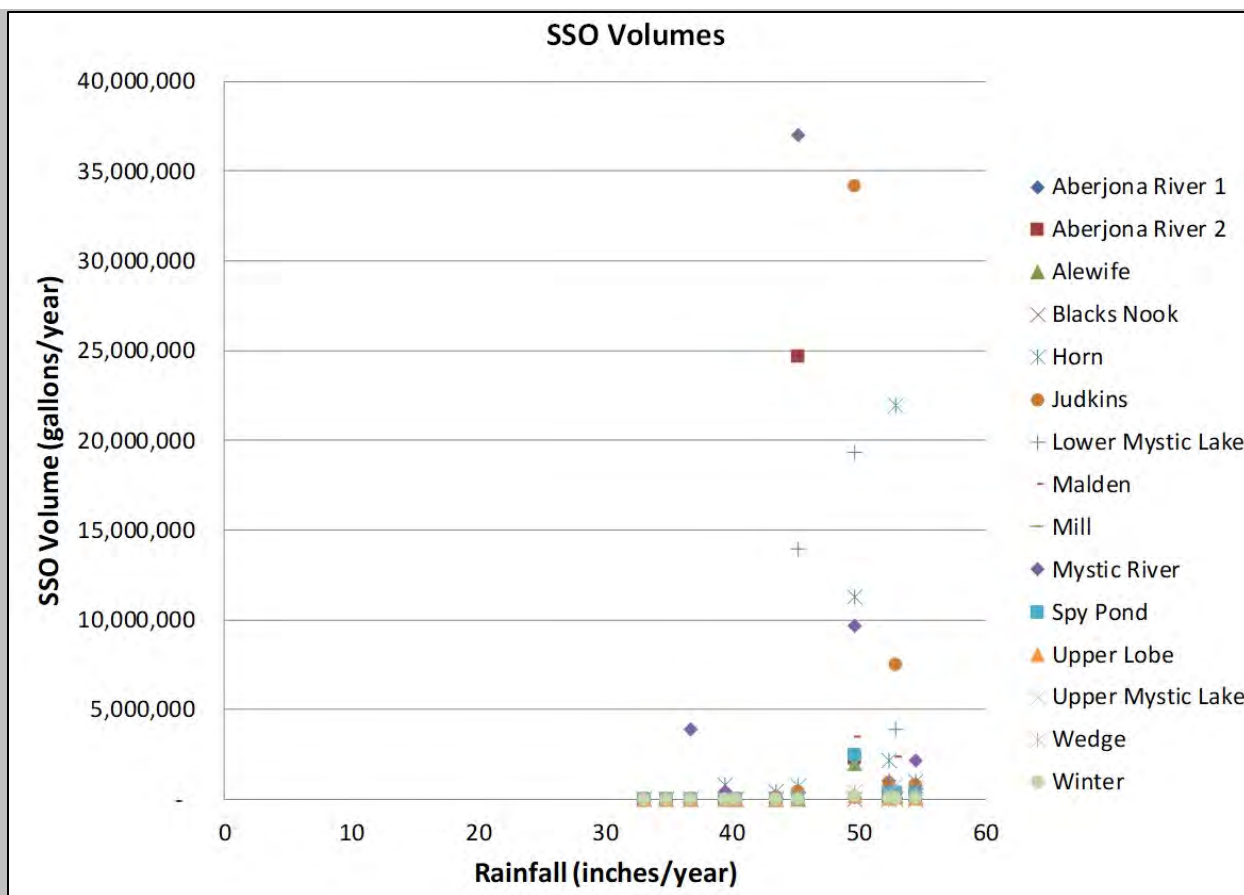


Figure VI-VI. Annual SSO Discharge Volumes by Sub watershed versus Rainfall

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
<i>1st quartile (25%)</i>	273	8,622	0	0	0	912	460	3,296	213	0	0	0	0	0	0
<i>3rd quartile (75%)</i>	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
<i>Interquartile range</i>	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
<i>Upper bound (Q3+1.5*IQR)</i>	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
<i>Mean (all data)</i>	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
<i>Mean (w/o outliers)</i>	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 Mystic 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

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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
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 and 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 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.

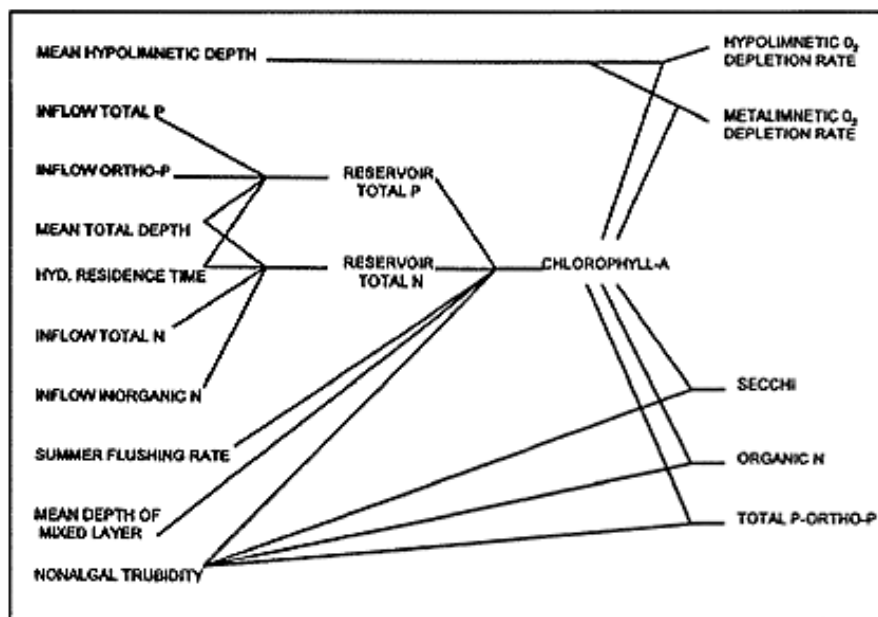


Figure VII-I. BATHTUB Model Schematic

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).

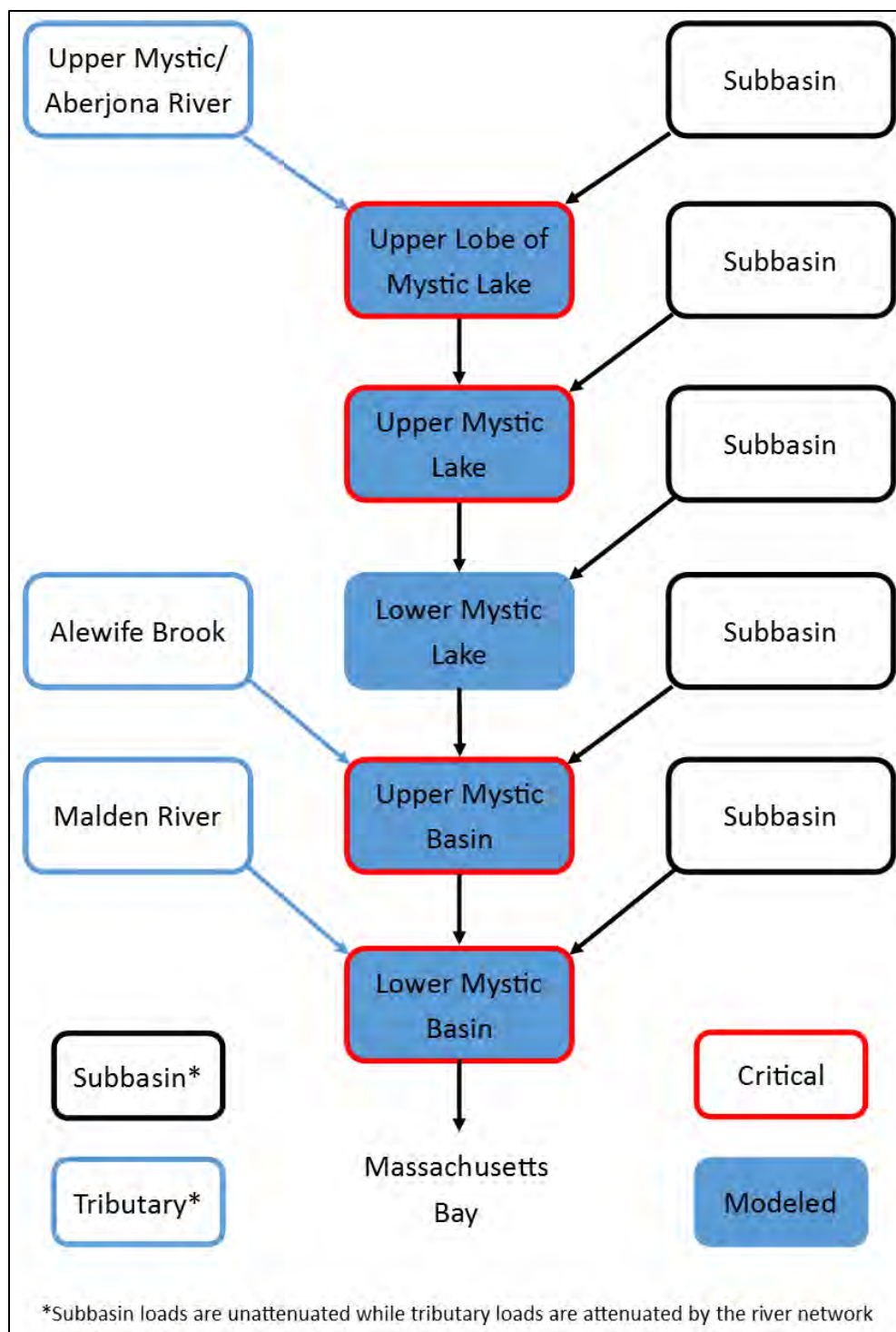


Figure VII-II. BATHTUB Segmentation for the Mystic River.

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	2 nd 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 ($PETW = 41.06 - 0.0952 \cdot PREC$, $R^2=0.2$) 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).

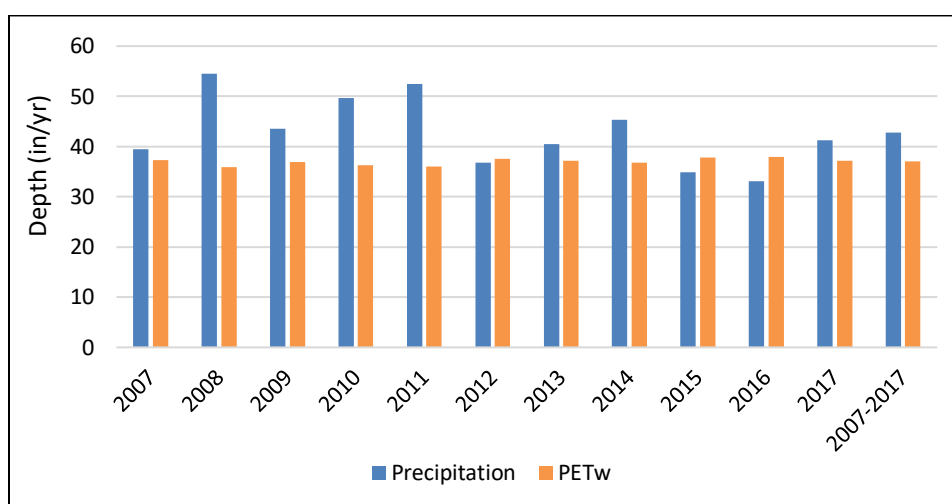


Figure VII-III. Annual Precipitation and Lake Evaporation

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 mi²) was split into the Upper (6.08 mi²) and Lower Basins (2.55 mi²) 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/m²/d. TP values were set to a maximum of 6 mg/m²/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/m²/d) while those with no sediments or no data (e.g. Upper Lake and Upper Lobe) were assigned a low value (1 mg/m²/d). As part of the calibration process, these internal loads were adjusted with the expected range (0-6 mg/m²/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).

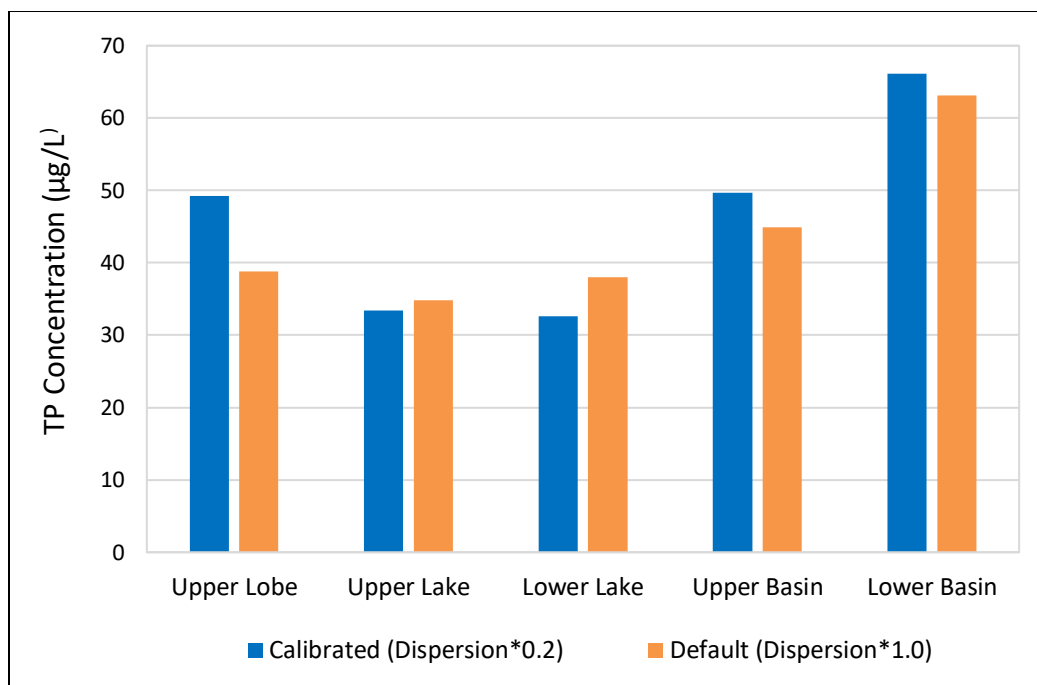


Figure VII-IV. Dispersion Effect on Modeled Phosphorus Concentrations

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, $\mu\text{g/L}$) 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 $\mu\text{g/L}$, and an R^2 and RMSE for chl-a of 0.84 and 1.5 $\mu\text{g/L}$, 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.

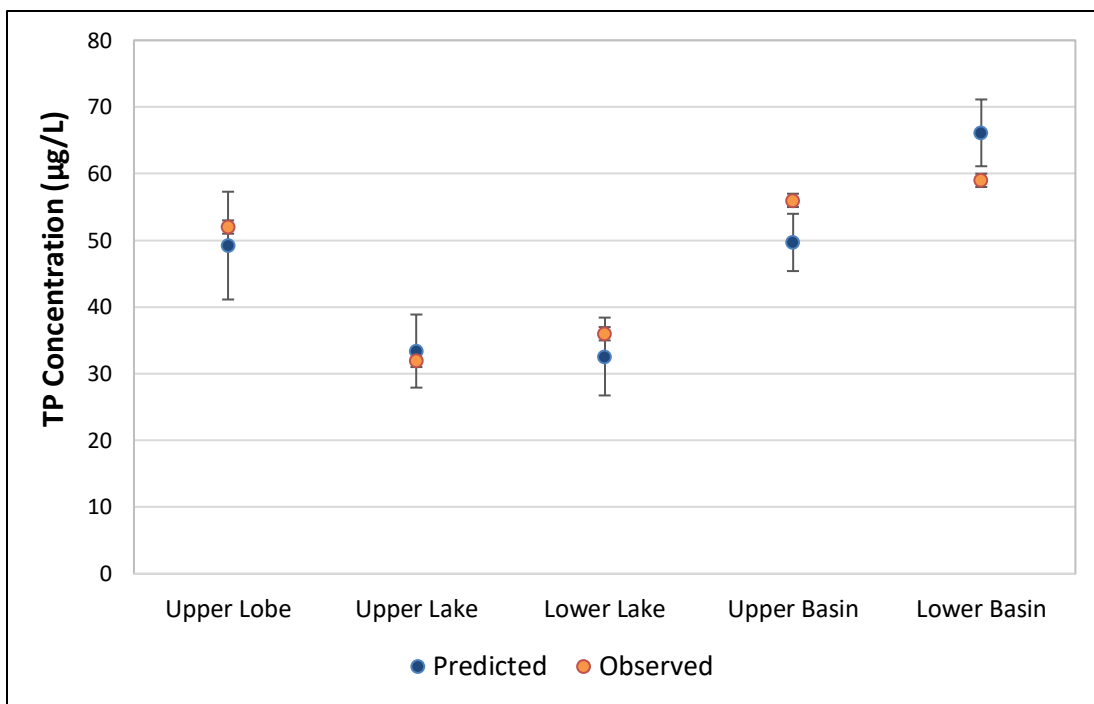


Figure VII-V. Predicted vs. Observed TP by Segment for Calibration Period

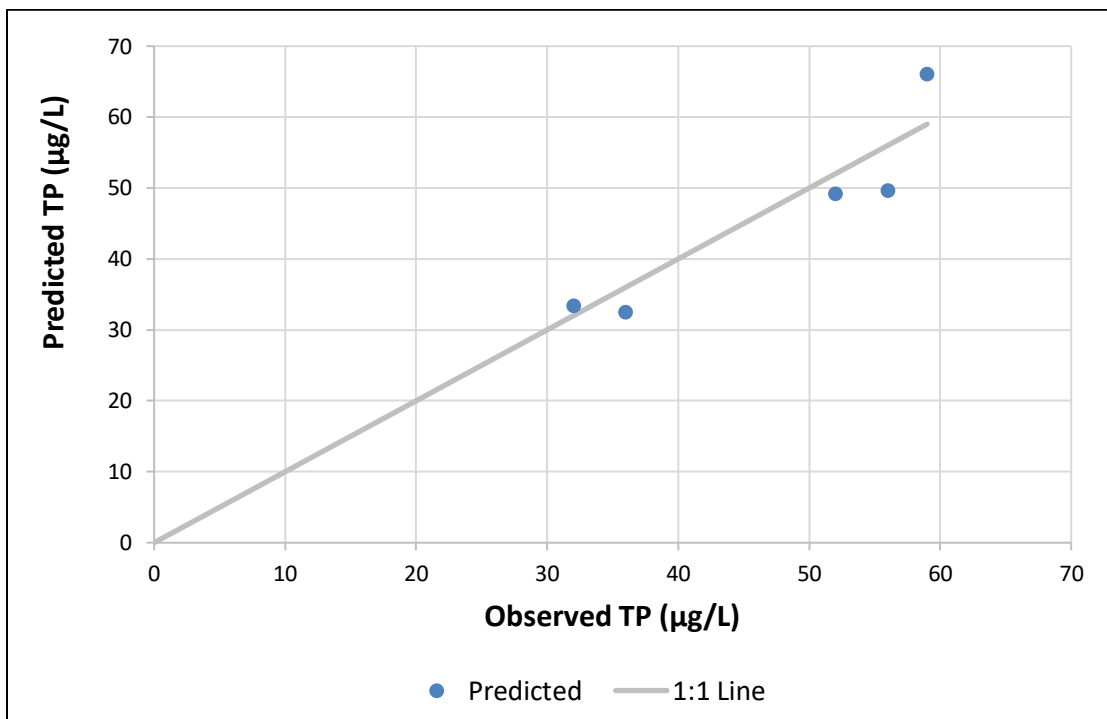


Figure VII-VI. Predicted vs. Observed TP Relationship for Calibration Period

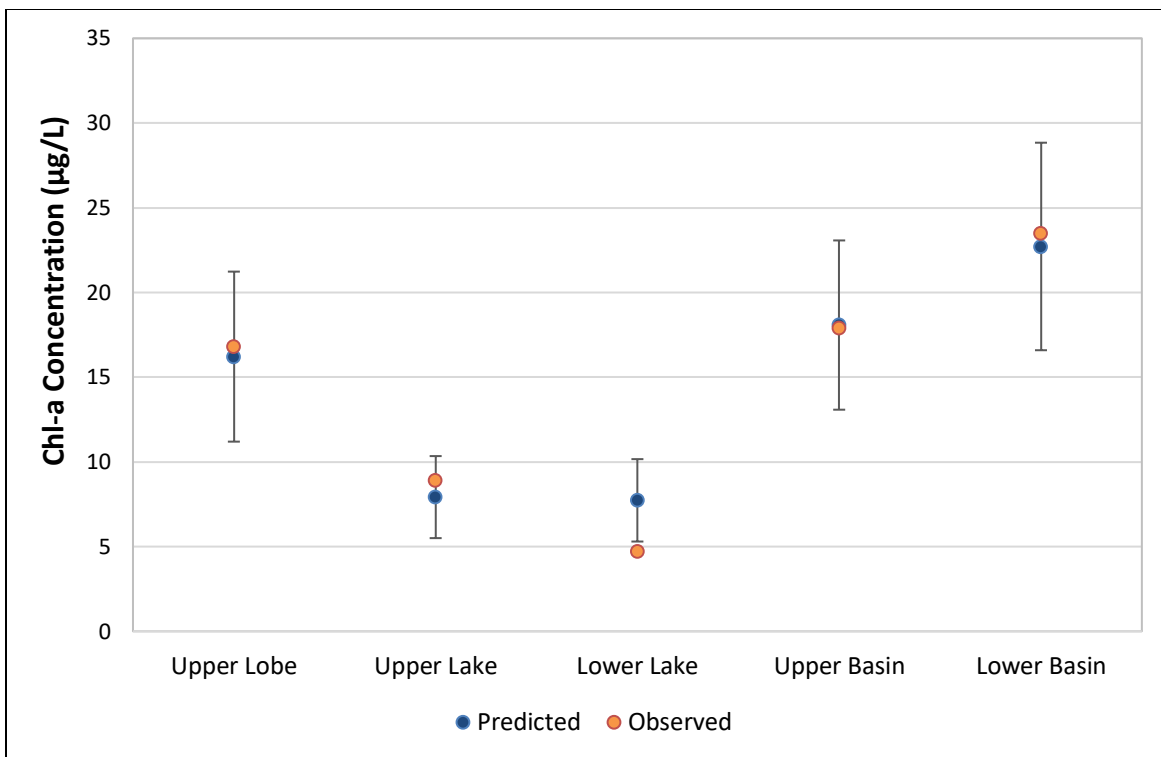


Figure VII-VII. Predicted vs. Observed Chl-a by Segment for Calibration Period

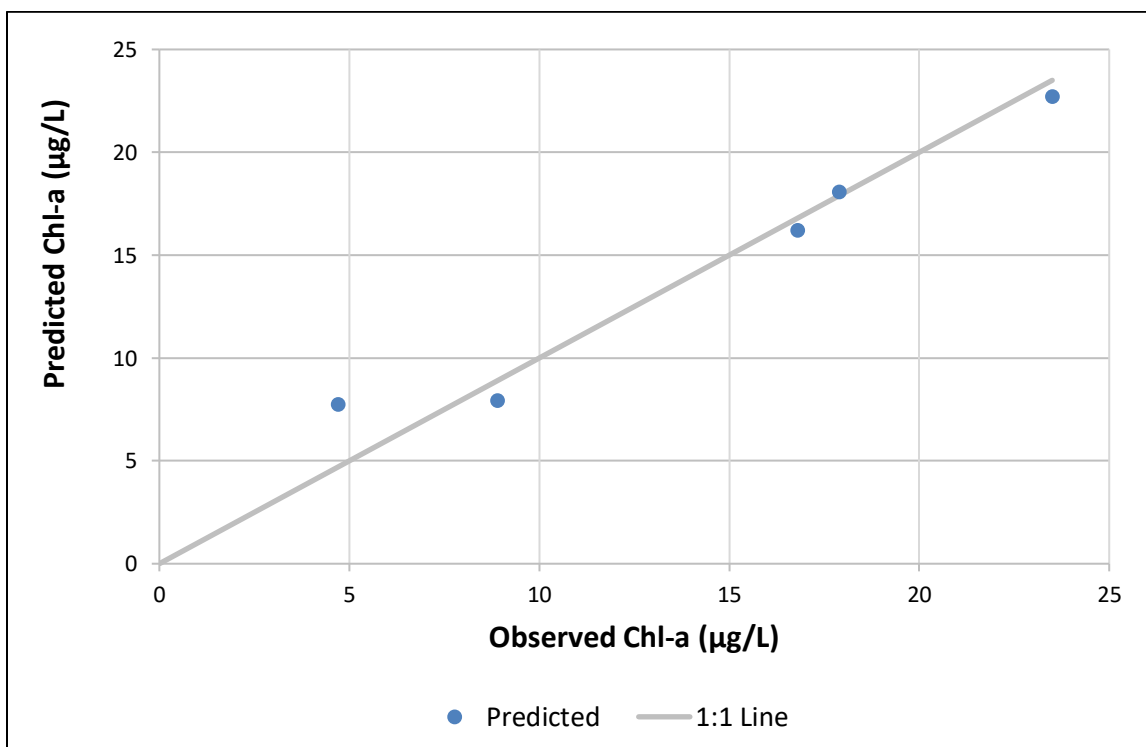


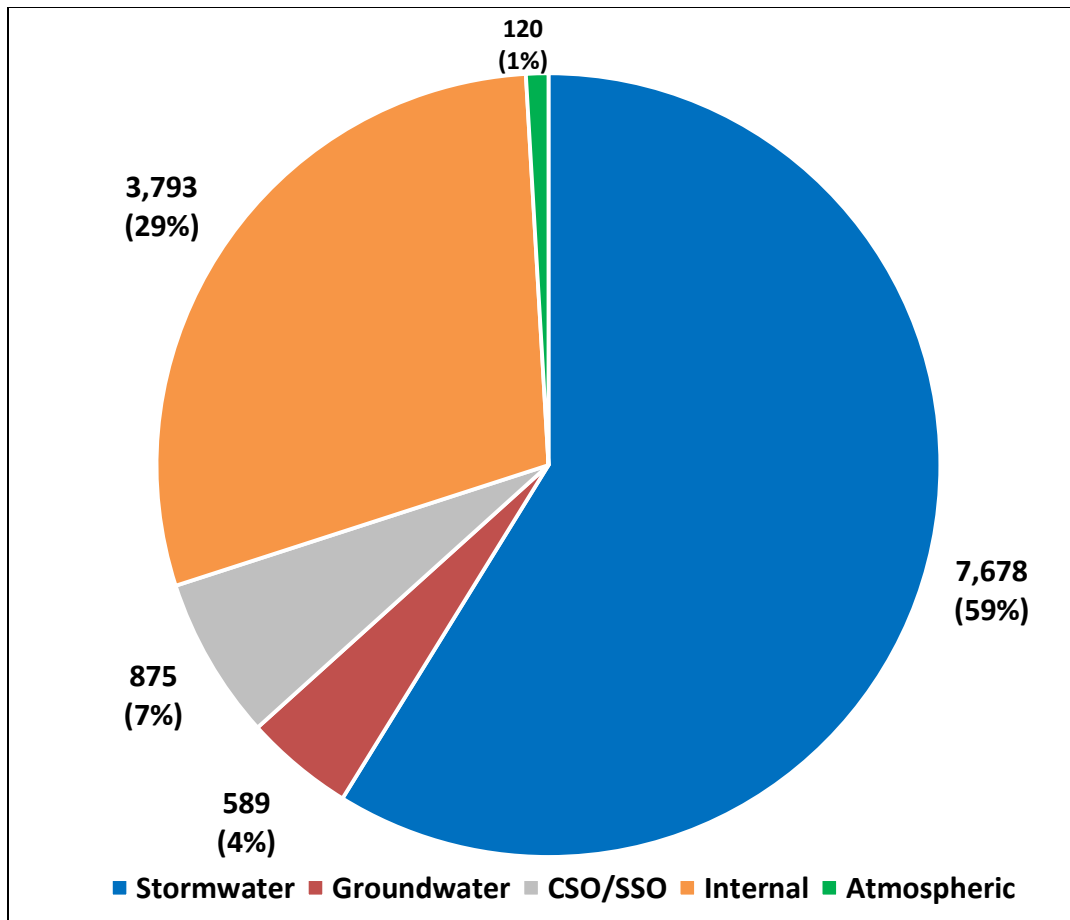
Figure VII-VIII. Predicted vs. Observed Chl-a Relationship for Calibration Period

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 $\mu\text{g/L}$ for TP and chl-a, respectively. (Figure VII-VIII and Figure VII-IX). In 2017, the predicted values were higher than observed values in the most segments but much larger in the Upper and Lower Basin than in 2016, in the range of 9-13 $\mu\text{g/L}$ for TP and 8-11 $\mu\text{g/L}$ 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 $\mu\text{g/L}$), while when outliers were included gave higher than observed TP values (3.1 to 8.1 $\mu\text{g/L}$) (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 $\mu\text{g/L}$), while with outliers included gave higher than observed TP values (-1.9 to 14.7 $\mu\text{g/L}$) (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.

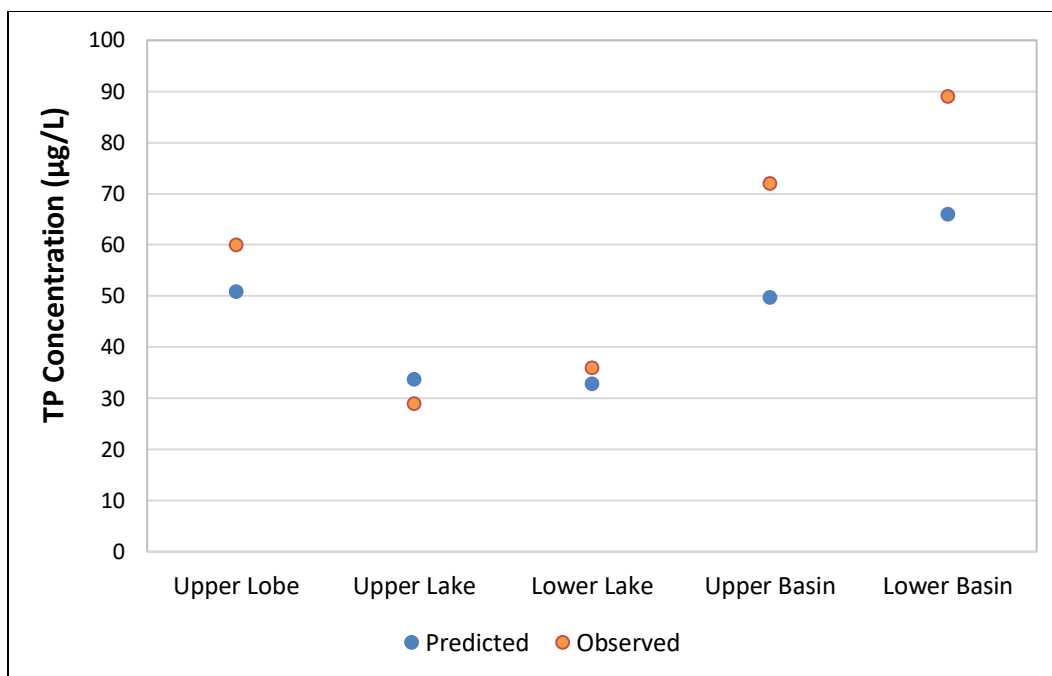


Figure VII-X. Validation 2016 - Predicted vs. Observed TP by Segment

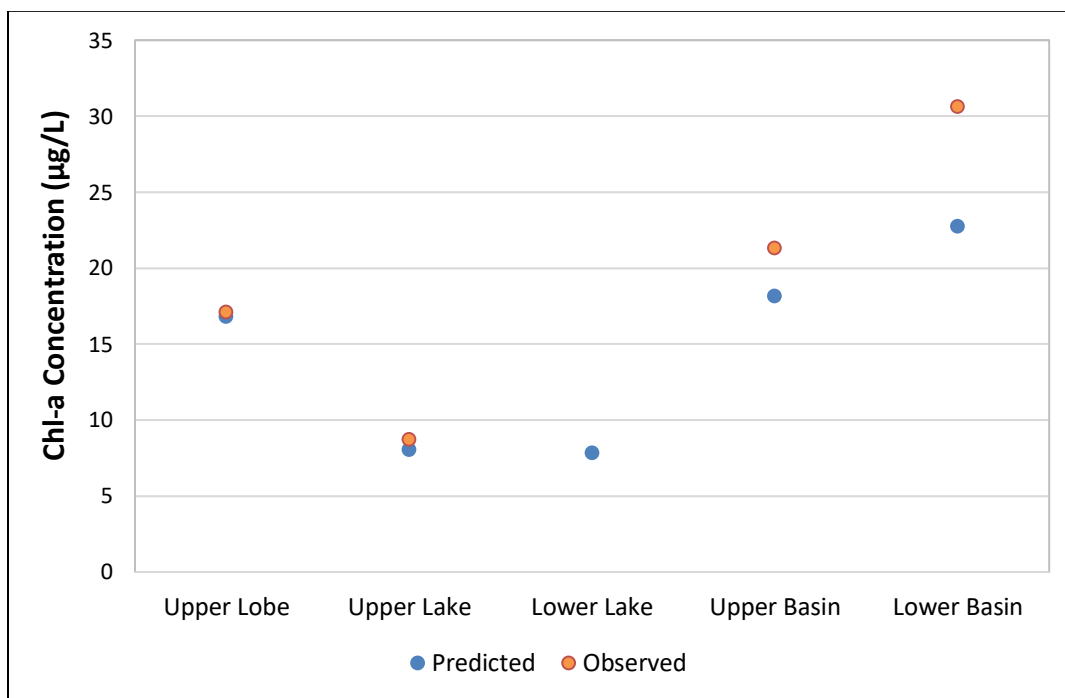


Figure VII-XI. Validation 2016 - Predicted versus Observed Chl-a by Segment

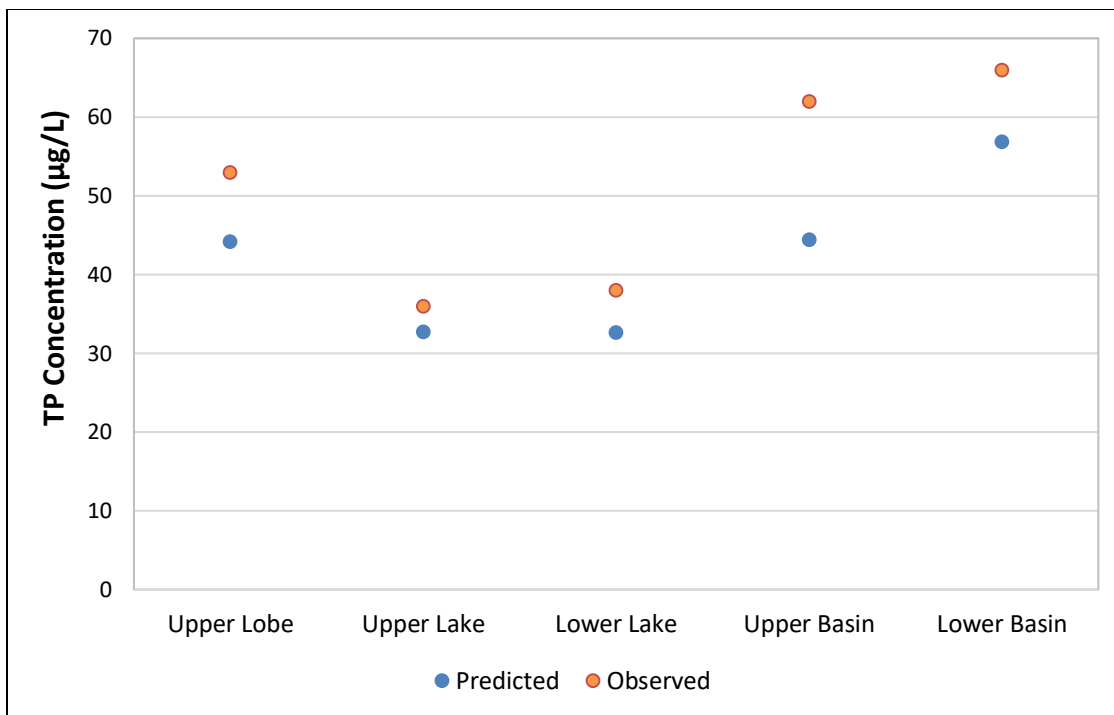


Figure VII-XII. Validation 2017 - Predicted vs. Observed TP by Segment

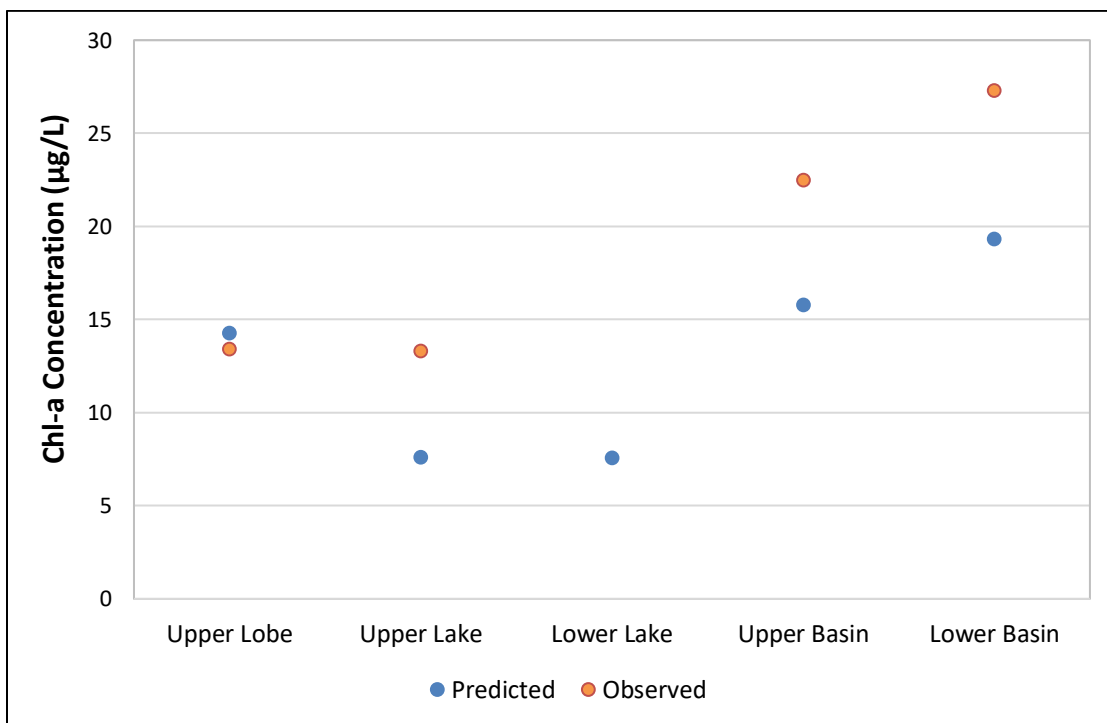


Figure VII-XIII. Validation 2017 - Predicted vs. Observed Chl-a by Segment

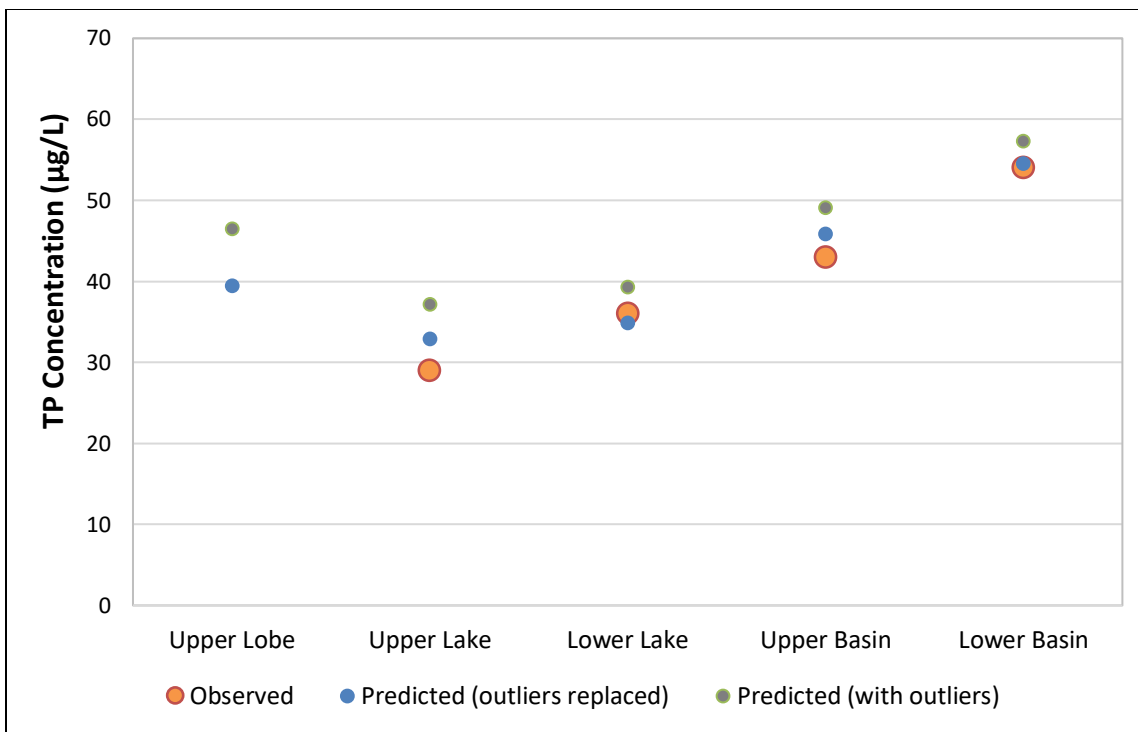


Figure VII-XIV. SSO Outlier Replacement 2010 - Predicted versus Observed TP

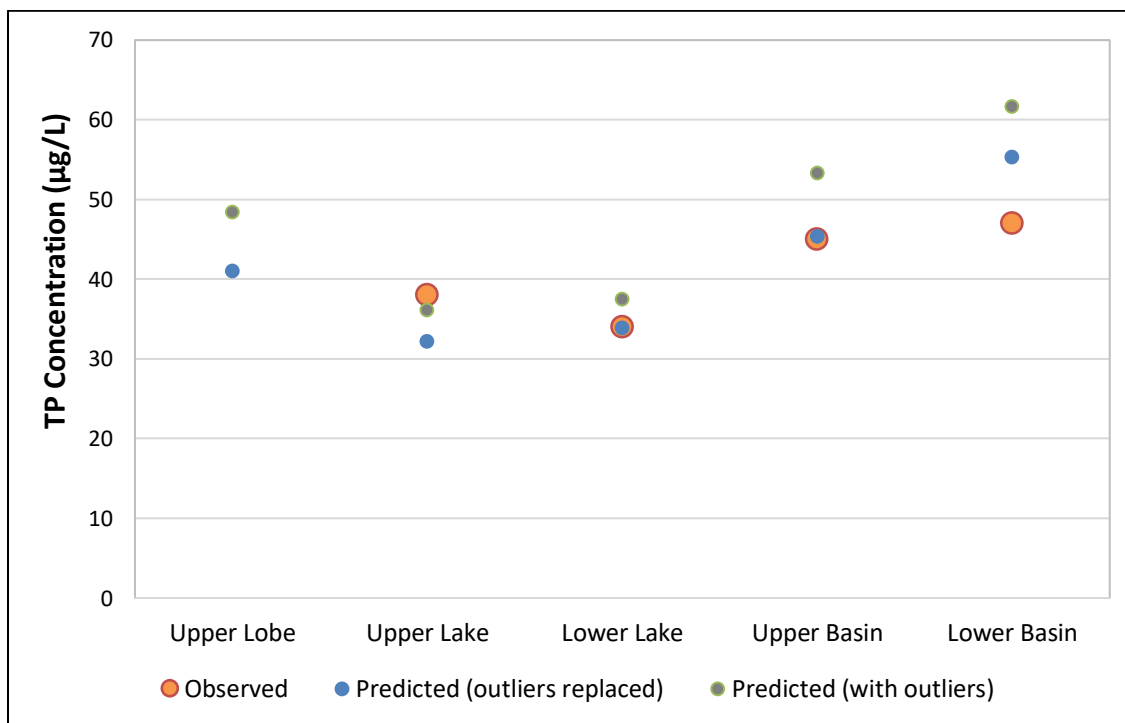


Figure VII-XV. SSO Outlier Replacement 2014 - Predicted versus Observed TP

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

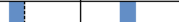







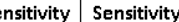

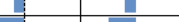



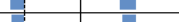



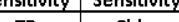

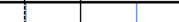

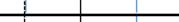



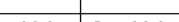



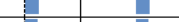

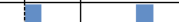

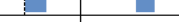

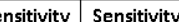



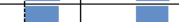

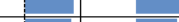

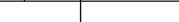

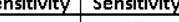



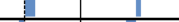

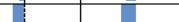







This analysis provides confirmation that several professional judgements made in calibrating the BATHTUB model consistently chose the correct approach:

- 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, 1993). 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
<i>2 and above</i>	Extremely wet
<i>1.5 to 1.99</i>	Severely wet
<i>1.0 to 1.49</i>	Moderately wet
<i>-0.99 to 0.99</i>	Near normal
<i>-1.0 to -1.49</i>	Moderately dry
<i>-1.5 to -1.99</i>	Severely dry
<i>-2.0 and less</i>	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

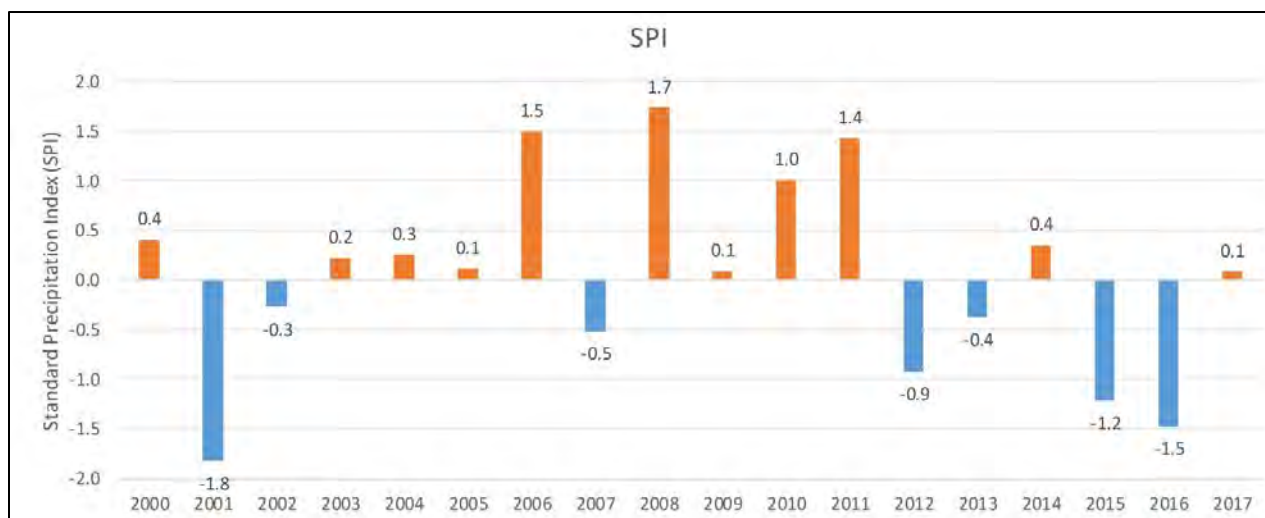


Figure VIII-I. Standard Precipitation Index (SPI) between 2000-2017

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 10th and 90th 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 10th percentile rainfall depth is 34.1 inches, while the 90th percentile rainfall depth is 52.6 inches. Comparatively, over a longer term, from 1990-2016, the 10th percentile rainfall depth is 34.4 inches and the 90th 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.

CSO Loads

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.

SSO Loads

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.

Stormwater Loads from Combined Sewer Separation

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 10th and 90th 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.

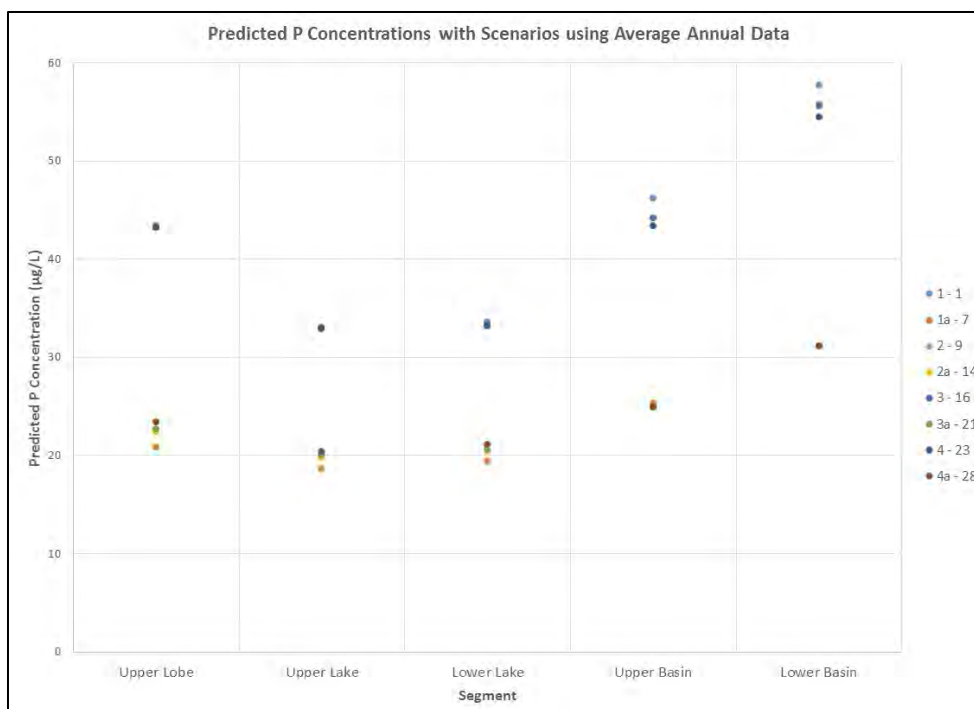


Figure IX-I. Predicted Phosphorus Concentrations with Average Annual Data

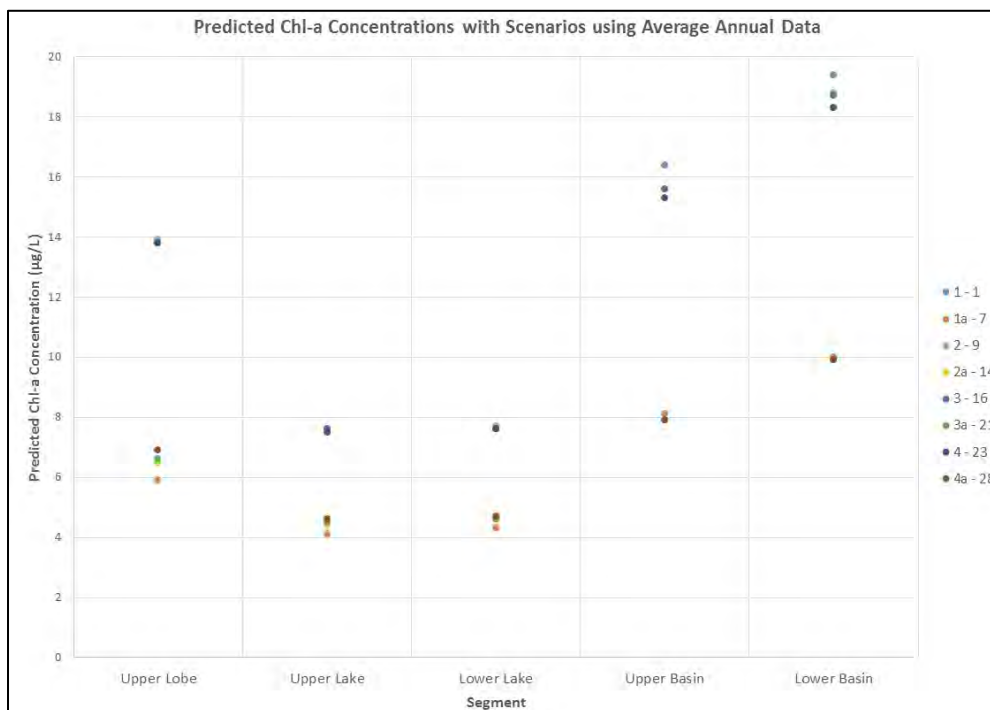


Figure IX-II. Predicted Chlorophyll-a Concentrations with Average Annual Data

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.

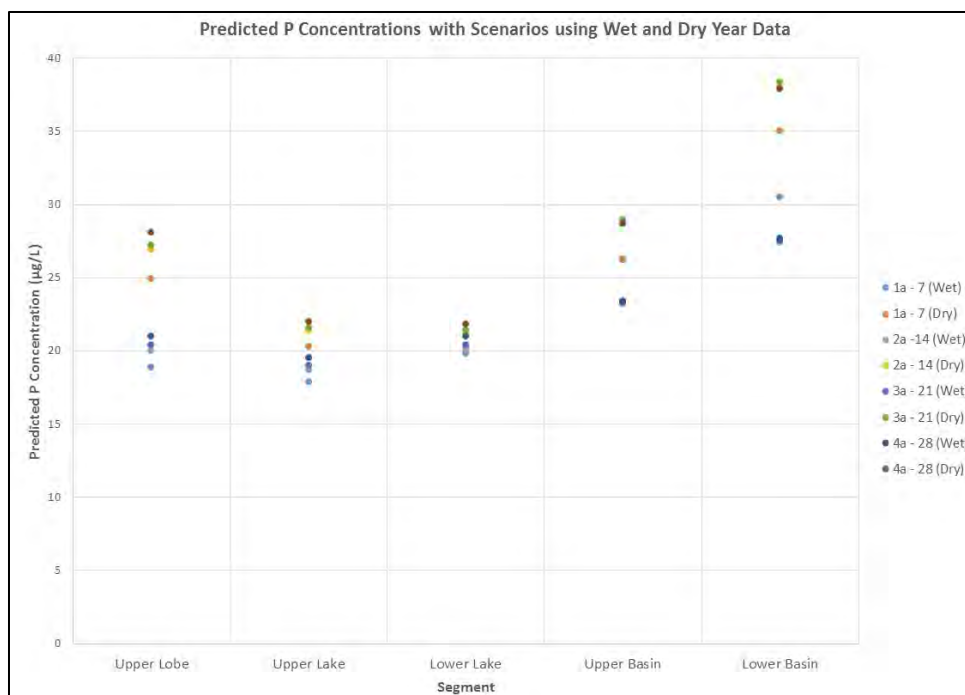


Figure IX-III. Predicted Phosphorus Concentrations with Wet and Dry Year Data

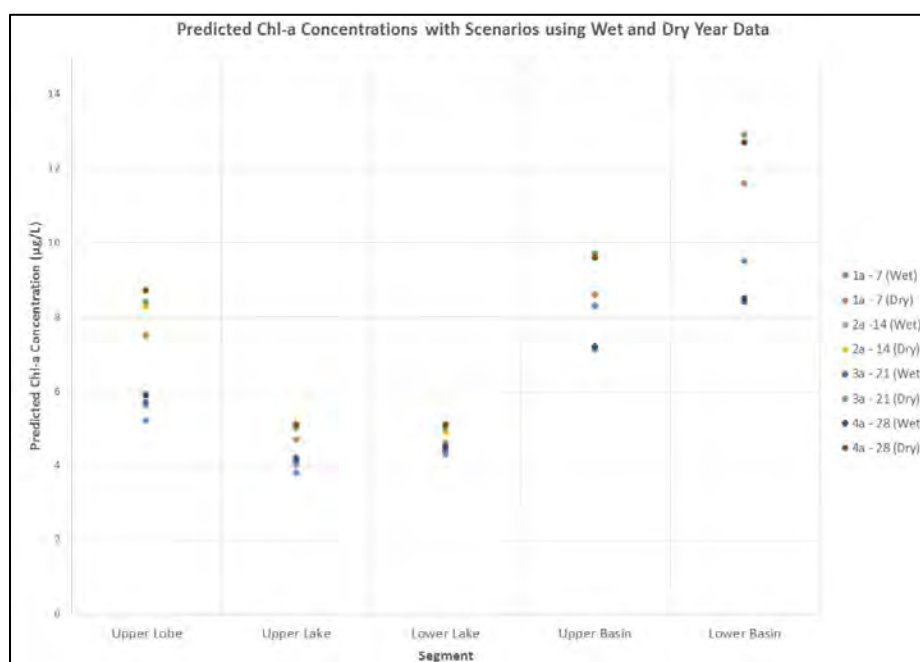


Figure IX-IV. Predicted Chlorophyll-a Concentrations with Wet and Dry Year Data

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 10th 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.

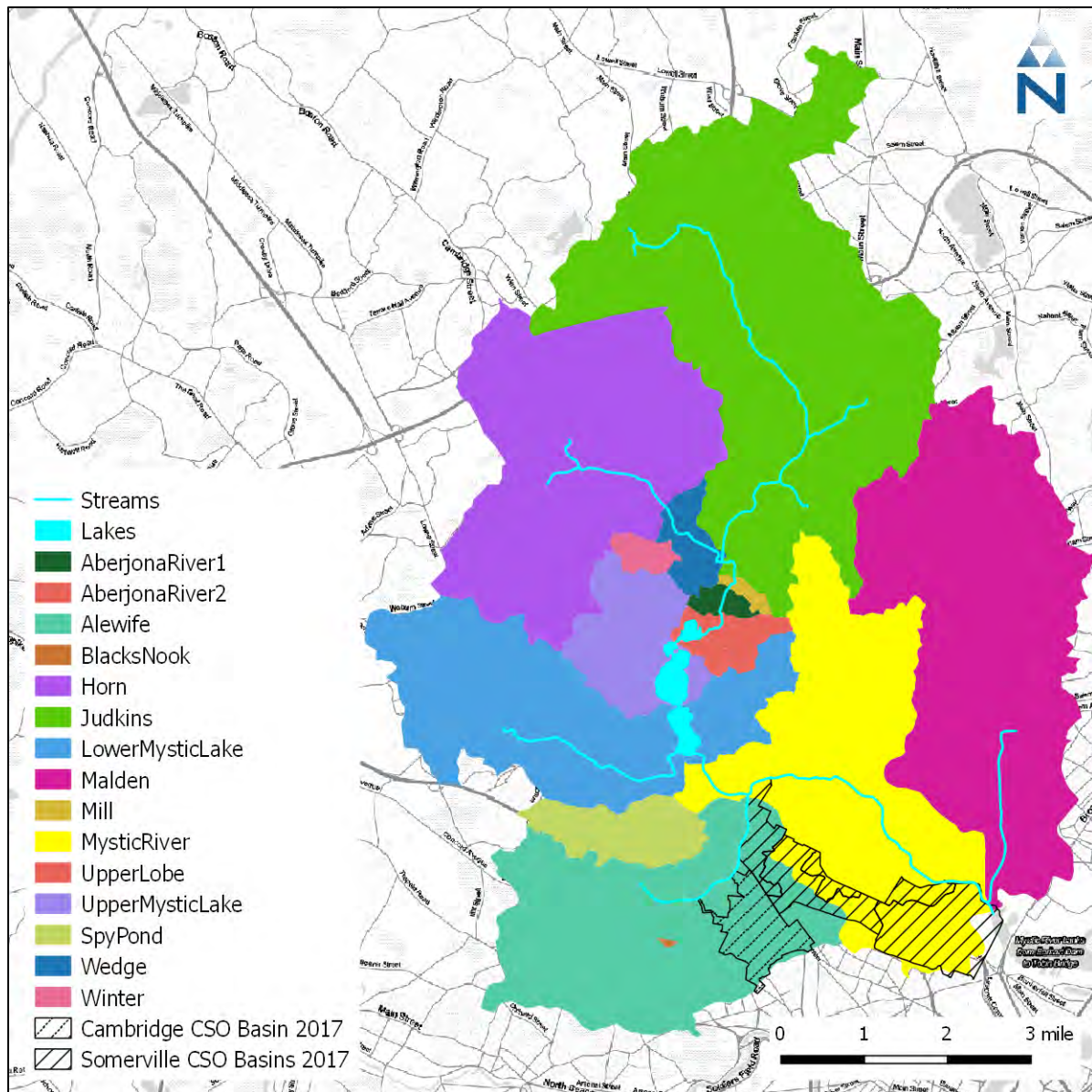


Figure X-I. Location Map of Pilot Sub-Watershed, Mystic River (Highlighted in Yellow)

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

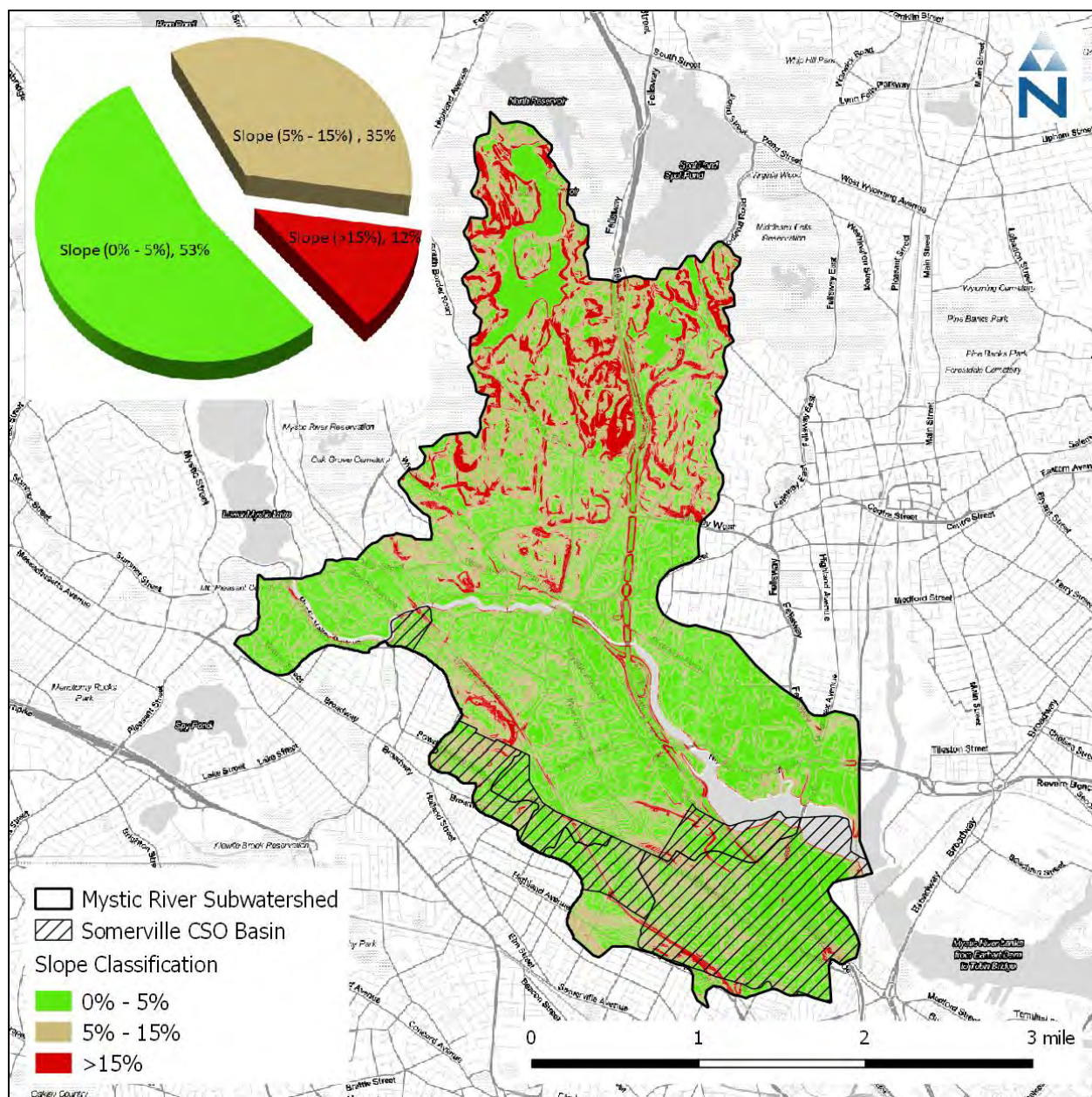


Figure X-II. Ground Slope Map of Pilot Sub-Watershed, Mystic River

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

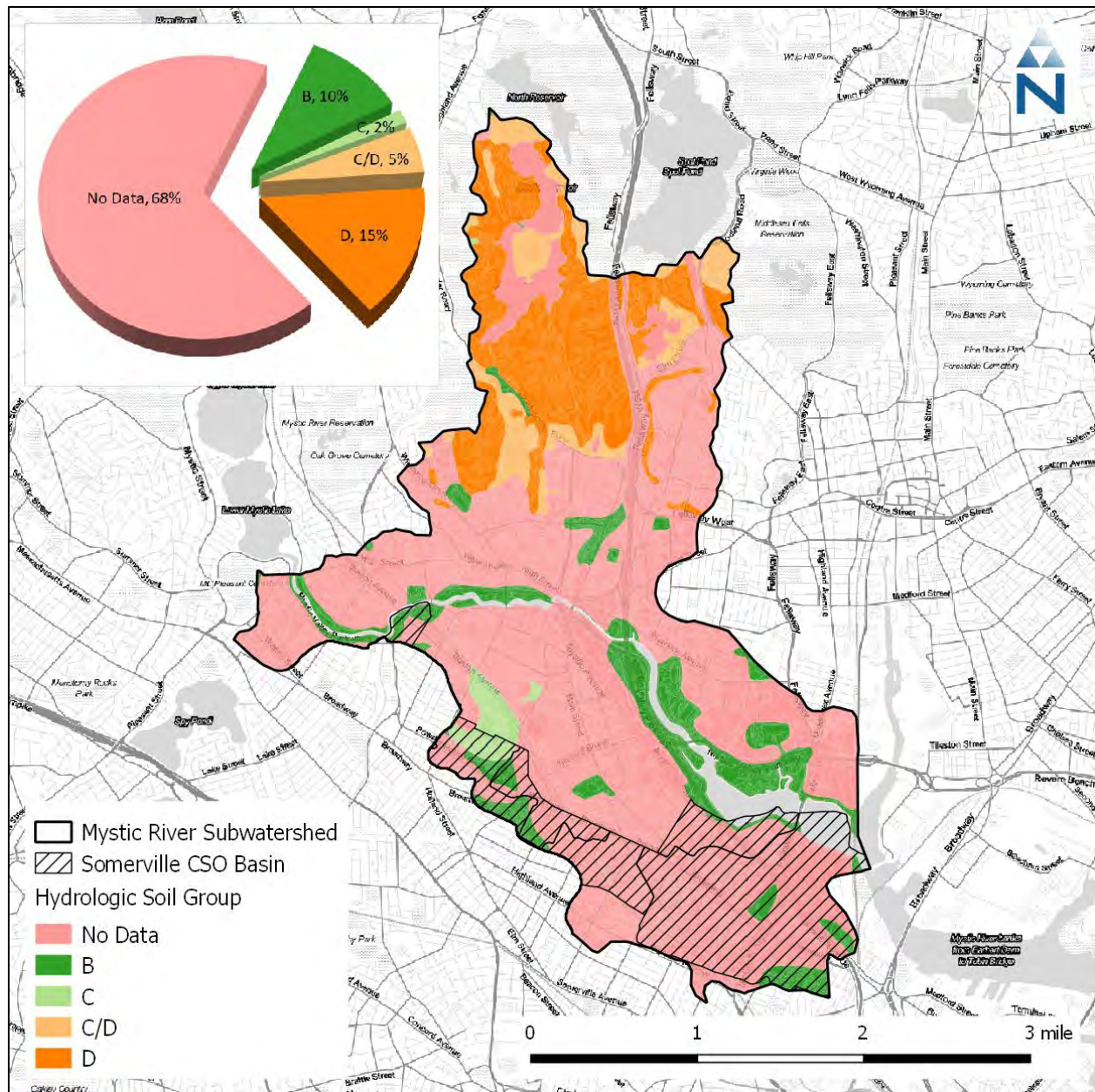


Figure X-III. Soil Map (Hydrologic Soil Group) of Pilot Sub-Watershed, Mystic River

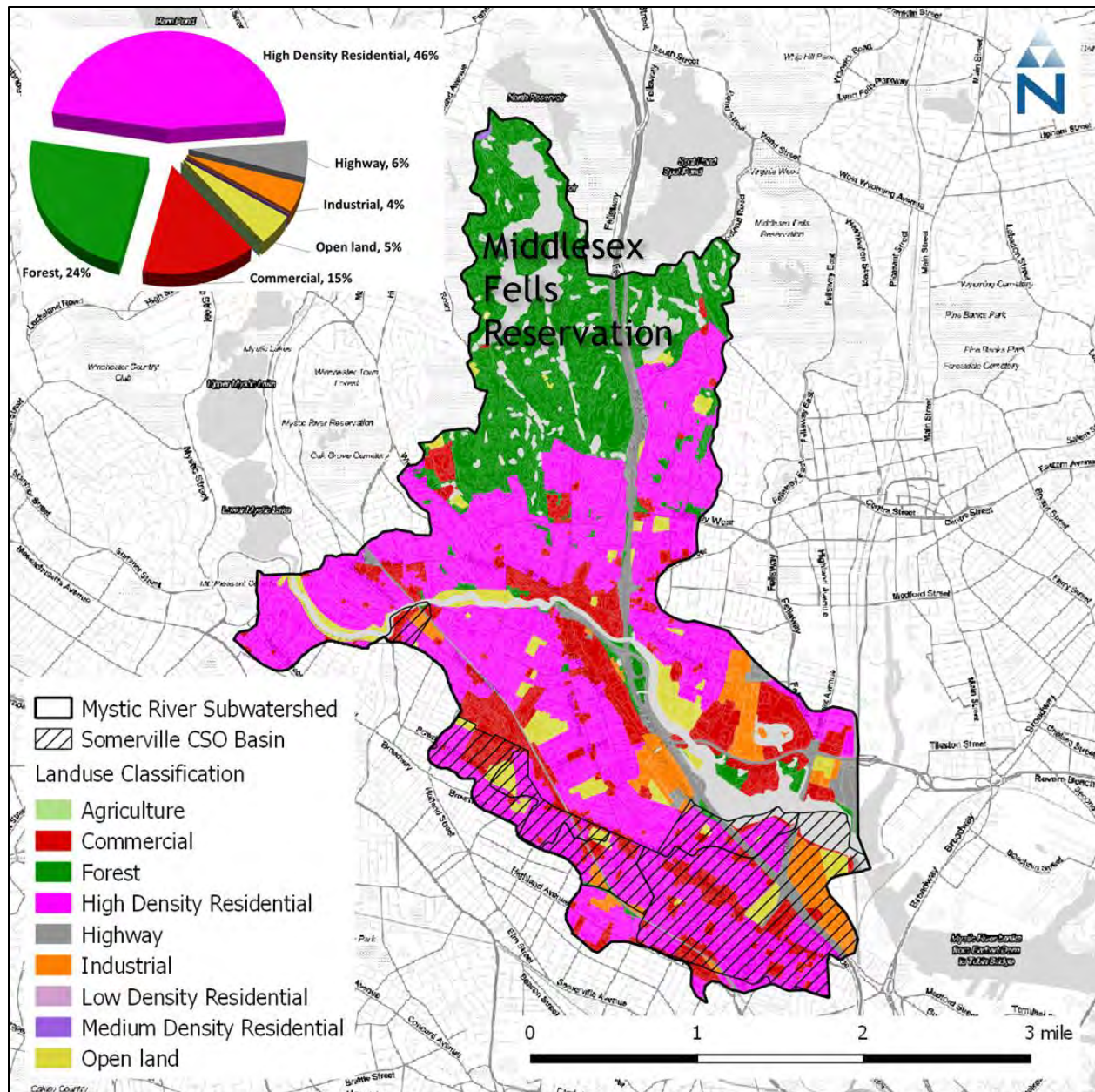


Figure X-IV. Land Use Map of Pilot Sub-Watershed, Mystic River

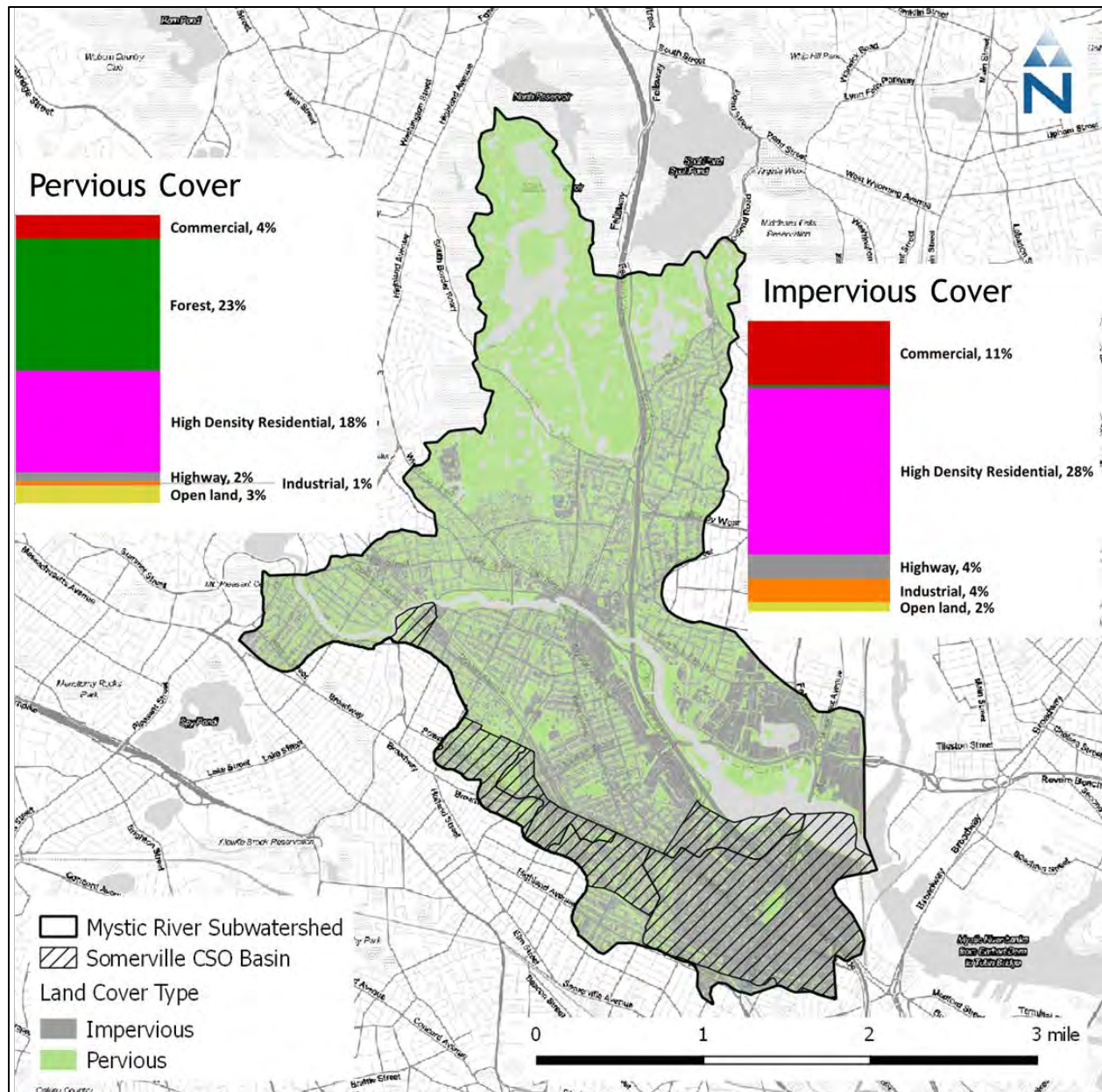


Figure X-V. Land Cover Map of Pilot Sub-Watershed, Mystic River

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%

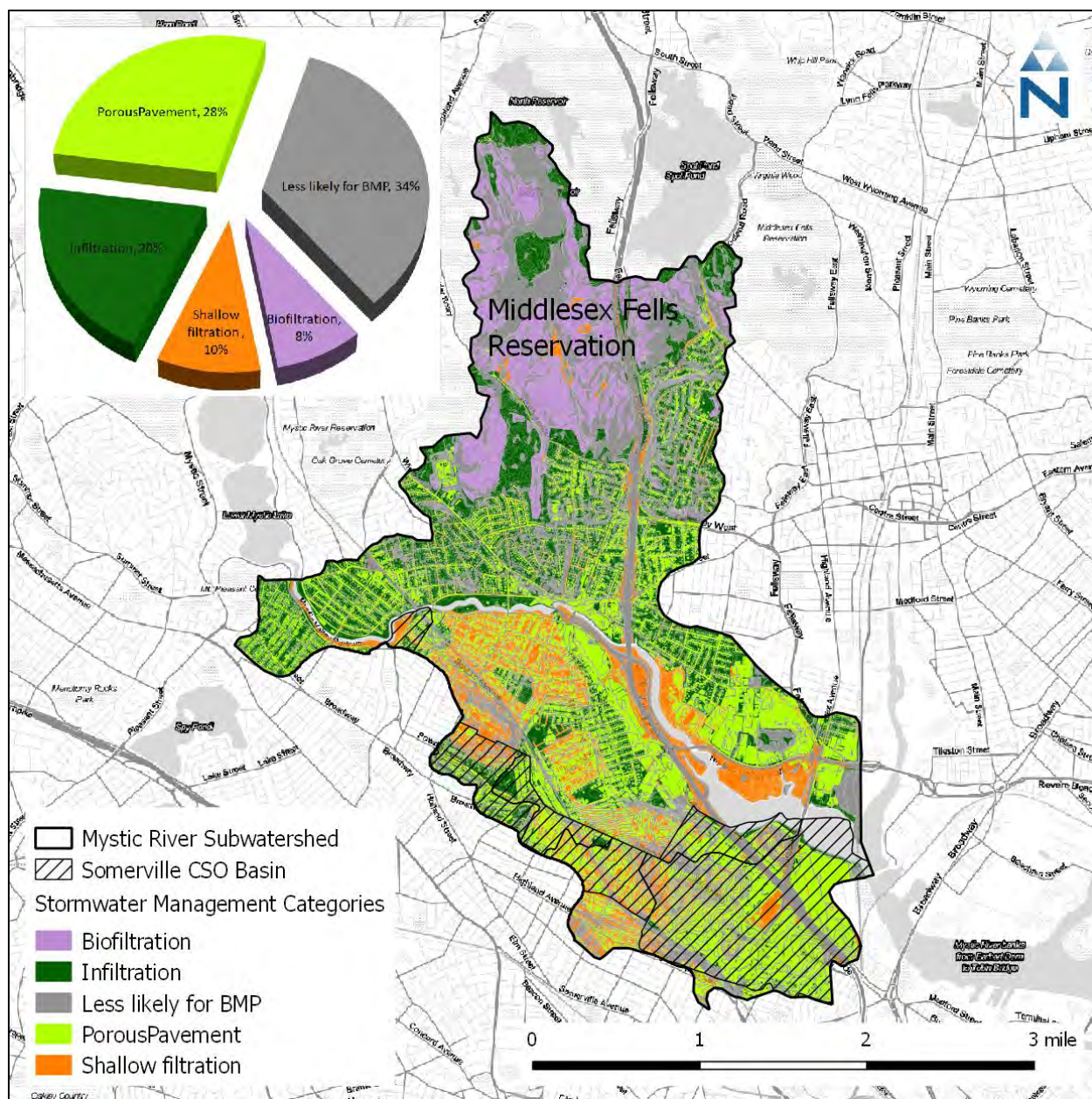


Figure X-VI. Stormwater Management Categories Map of Pilot Sub-Watershed, Mystic River

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 $3\times$ (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

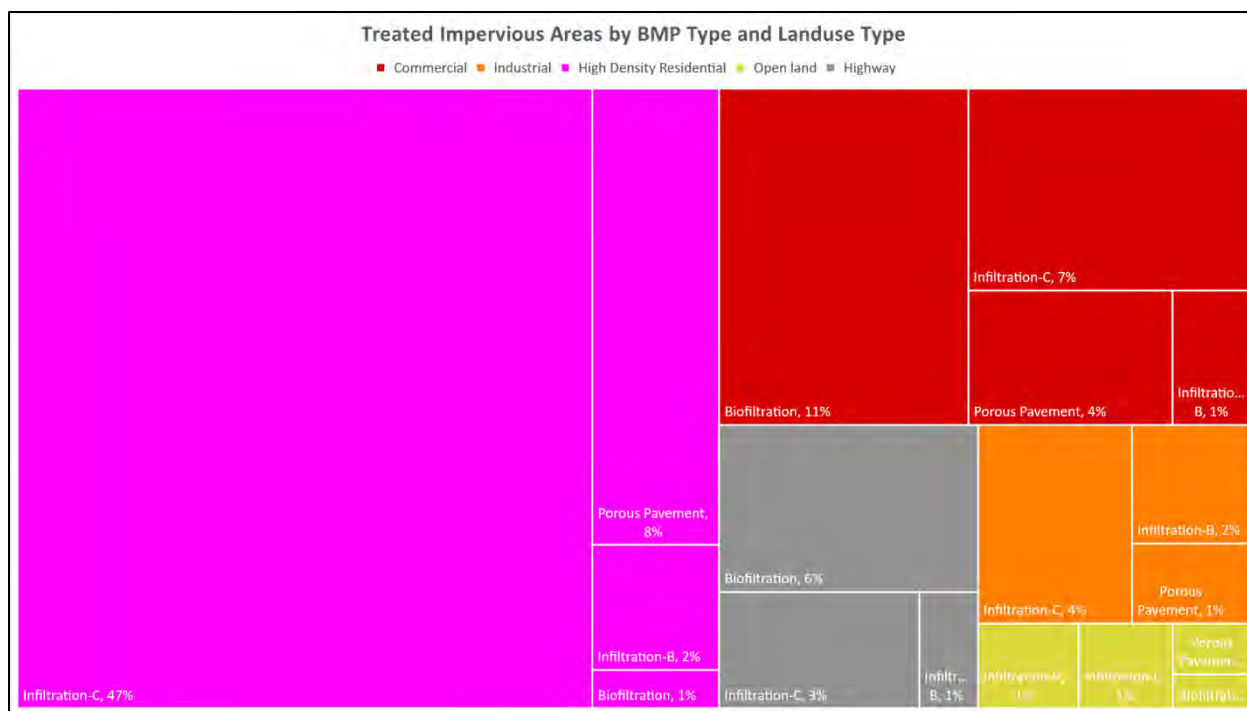


Figure X-VII. Treated Impervious Areas by BMP Type and Land Use Type in the Pilot Sub-Watershed, Mystic River

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 Setup⁷

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.

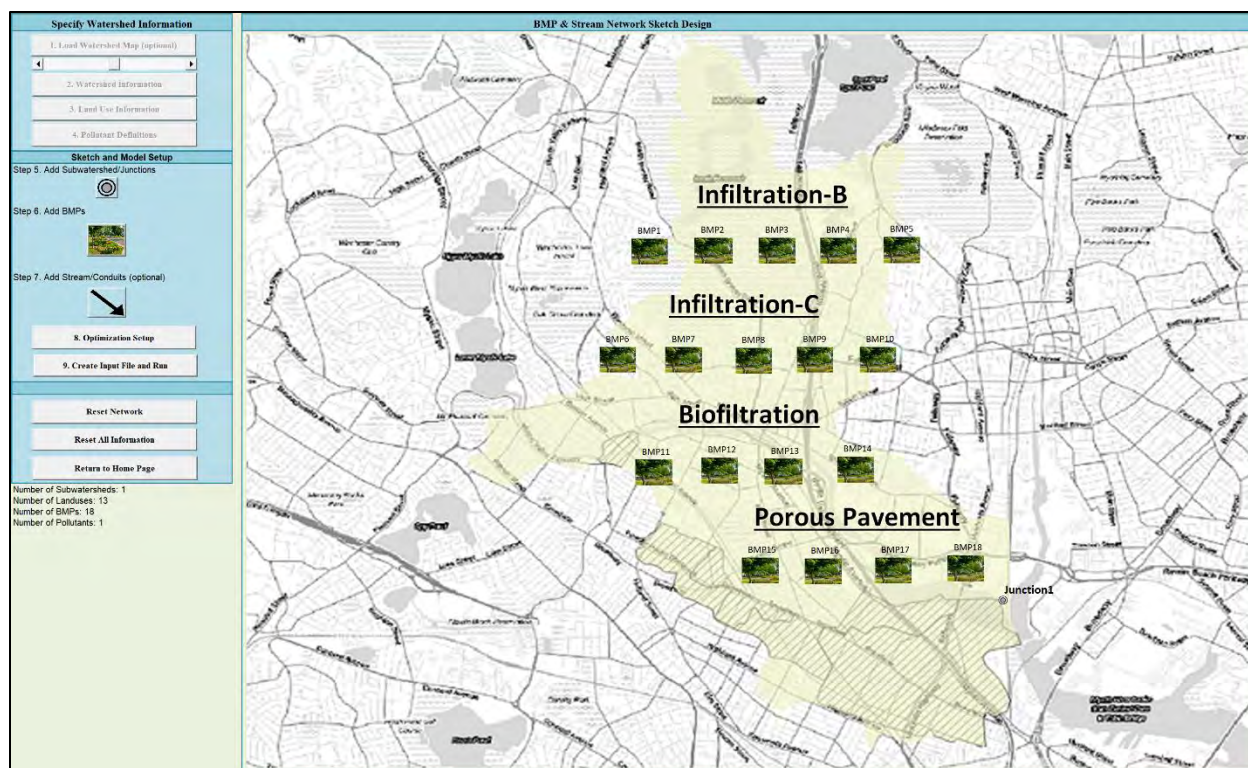


Figure X-VIII. Opti-Tool Model of Pilot Sub-Watershed, Mystic River.

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.

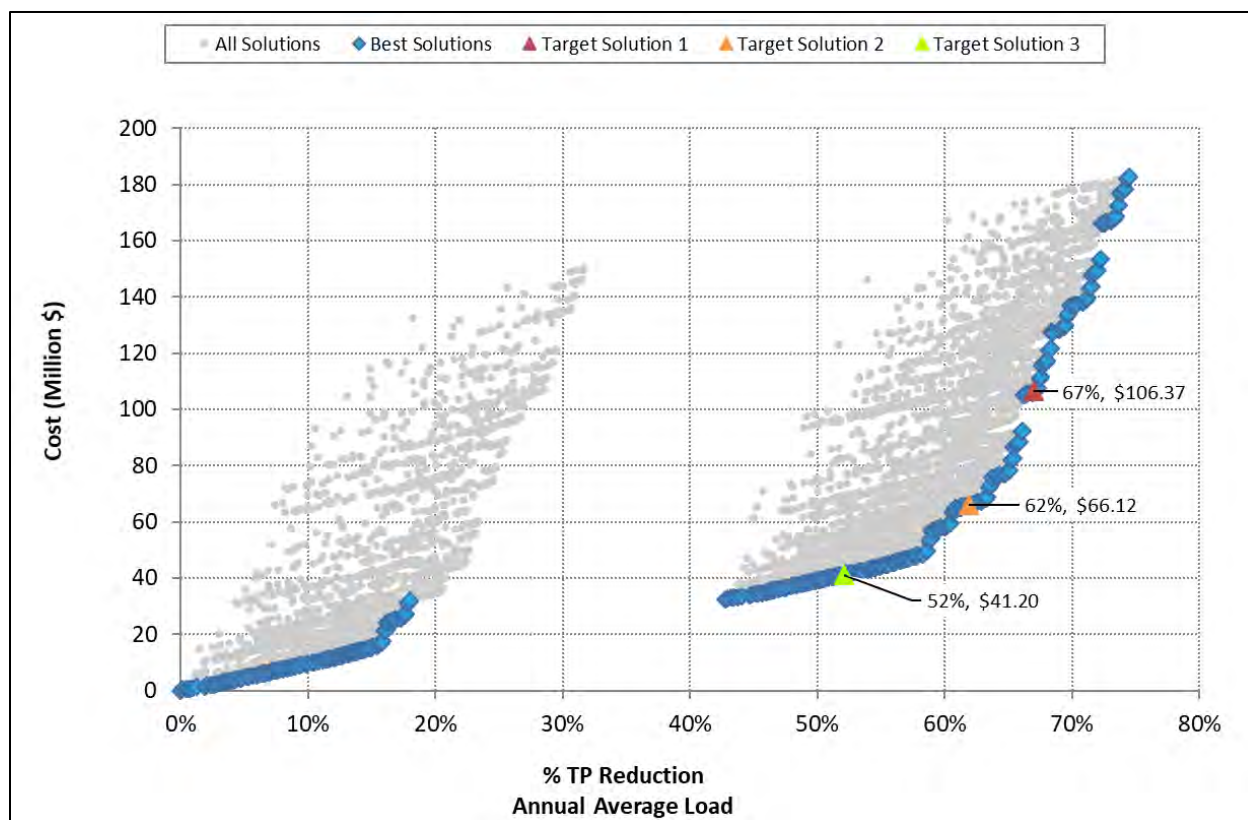


Figure X-IX. Scenario 1: Opti-Tool Cost-Effectiveness Curve (Optimize Locations Only) of TP Annual Average Load Reduction for the Pilot Watershed

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.

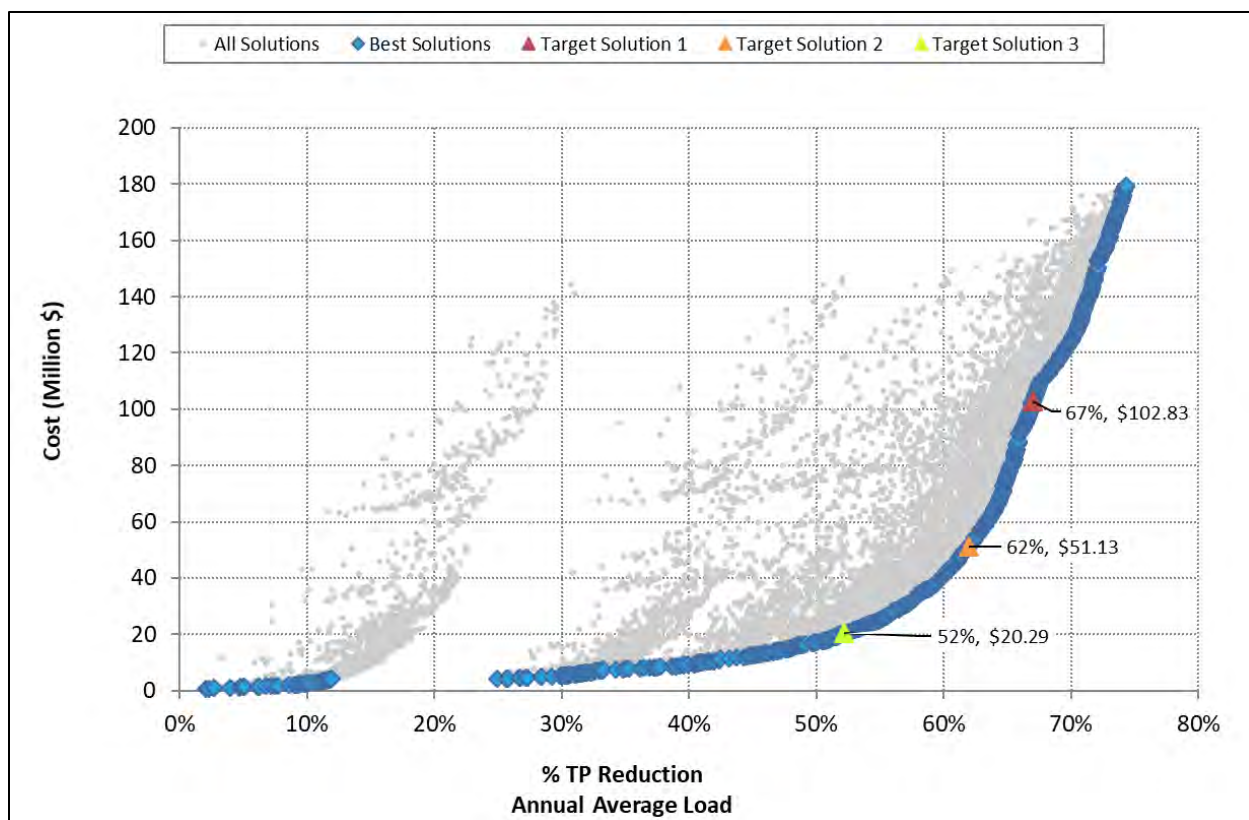


Figure X-X. Scenario 2: Opti-Tool Cost-Effectiveness Curve (Optimize Locations and BMP Sizes) of TP Annual Average Load Reduction for the Pilot Watershed.

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>.

XI. REFERENCES

- Arnold JG and PM Allen, 1999. Automated methods for estimating baseflow and groundwater recharge from streamflow records. *J Am Water Resource Assoc*, 35(2), 411-424.
- Arnold, JG, PM Allen, R Muttiah, and G Bernhardt, 2005. Automated base flow separation and recession analysis techniques. *Ground Water*, 33(6): 1010-1018.
- Berry Brook Project. (2017). Berry Brook Watershed Management Plan –Implementation Projects Phase III. Prepared for: The New Hampshire Department of Environmental Services, NH. Prepared by: The City of Dover and University of New Hampshire Stormwater Center, NH. December 2017.
- Breault, RF, Sorenson, JR and Weiskel, PK, 2002, *Streamflow., Water Quality and Contaminant Loads in the Lower Charles River Watershed, Massachusetts, 1999-2000*. Water Resources Investigations Report 02-4137, 139 p. U.S. Geological Survey, Westborough, Massachusetts.
- City of New Haven. (2018). New Haven’s “Advancing Green Infrastructure Program” Wins Harvard’s Roy Award for Environmental Partnership Promoting environmental protection, climate resilience, and social justice in New Haven, CT. Accessed November 9: <https://www.newhavenct.gov/news/displaynews.htm?NewsID=516&TargetID=67>
- Clough JS, 2014. AQUATOX (Release 3.1 plus). Modeling Environmental Fate and Ecological Effects in Aquatic Ecosystems. Volume 1: User’s Manual. US Environmental Protection Agency, Office of Science and Technology, Washington DC.
- Demonstration of Opti-Tool: Buzzards Bay Watershed Case Study. Prepared for: U.S. EPA Region 1, Boston, MA. Prepared by: Tetra Tech, Inc. Fairfax, VA. December 30, 2016.
- DEP, 2010. Draft Total Maximum Daily Loads of Phosphorus for Selected Boston Harbor (Mystic Basin) Lakes. Department of Environmental Protection, Division of Watershed Management, MA.
- DEP-EPA, 2011. Total Maximum Daily Load for Nutrients in the Upper/Middle Charles River, Massachusetts. Control Number: CN 272.0. Massachusetts Department of Environmental Protection, Worcester, MA and US Environmental Protection Agency, Boston, MA. Prepared by Charles River Watershed Association, Weston, MA and Numeric Environmental Services, Beverly Farms, MA.
- DFW (no date). Various Bathymetry Maps. Department of Fish and Game, MA.
- Dodds, WK, & Oakes, RM. 2004. A technique for establishing reference nutrient conditions across watersheds affected by humans. *Limnol. Oceanogr.: Methods* 2, 2004, pgs. 333–341.
- ENSR, 2000. Diagnostic/Feasibility Study of Winter Pond, Winchester, Massachusetts. Prepared for The Town of Winchester and the Friends of Winter Pond Association.
- EPA, 2016. Phosphorus TMDLs for Vermont Segments of Lake Champlain. U.S. Environmental Protection Agency, Region 1, Boston, MA.
- EPA, 2018. Bathymetric Depths and Soft Sediment Presence Measurements in the Mystic River. Personal communication with Mark Voorhees and Monique Dulac of EPA Region 1.
- Filstrup, CT and Downing, JA, 2017. Relationship of chlorophyll to phosphorus and nitrogen in nutrient-rich lakes, *Inland Waters*, 7(4), p385-400, DOI:10.1080/20442041.2017.1375176.

- Fischer, HB, List, EJ, Koh, RCY, Imberger, J and Brooks. NH, 1979. Mixing in inland and coastal waters. Academic Press, New York, N.Y.
- Flanagan, SA, DL Montgomery, and JD Ayotte, 2001. Shallow Ground-water Quality in Boston, Massachusetts Metropolitan Area. USGS Water-Resources Investigations Report 01-4042.
- HW, 2015, Stump Brook / Monponsett Pond Hydrologic and Water Quality Assessment. Prepared for the Massachusetts Division of Ecological Restoration, MA by Horsley Witten Group, Sandwich, MA.
- IDEQ, 2015. Lower Boise River TMDL. Total Phosphorus Addendum. Idaho Department of Environmental Quality, Boise, ID.
- Knight, E. (2016). Aberjona River: Historical Background. Prepared by Ellen Knight, PhD for the Town of Winchester's Flood Mitigation Program. Updated 6/25/2016.
<https://www.winchester.us/DocumentCenter/View/1745> (Accessed June 28, 2017)
- Kõiv T, Nõges T, and Laas A, 2011. Phosphorus retention as a function of external loading hydraulic turnover time, area and relative depth in 54 lakes and reservoirs. *Hydrobiologia* 660, p105–115. DOI 10.1007/s10750-010-0411-8.
- Ludlam, S. D., & Duval, B. (2001). Natural and Management-Induced Reduction in Monimolimnetic Volume and Stability in a Coastal, Meromictic Lake. *Lake and Reservoir Management*, 17(2), 71–81.
- Massachusetts Department of Environmental Protection & U.S. EPA. 2007. Final – Total Maximum Daily Load for Nutrients in the Lower Charles River Basin, Massachusetts. CN 301.0.
- Massachusetts Department of Environmental Protection. 2016. Massachusetts Consolidated Assessment and Listing Methodology Guidance Manual for the 2016 Reporting Cycle. CN 445.0.
- McKee, T.B., Doesken N.J, and Kliest J. 1993. The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th Conference of Applied Climatology*, 17-22 January, Anaheim, CA. American Meteorological Society, Boston, MA. 179-184.
- MWRA, 2018. CSO Discharge Estimates and Rainfall Analyses for Calendar Year 2017. Technical Memorandum. April 30, 2018.
- MWRA, 2016. *Industrial Waste Report*. Number 32. October 2016, variously paged. Massachusetts Water Resources Authority, Boston, Massachusetts.
- NADP, 2016. Nitrogen from the Atmosphere. ISWS Miscellaneous Publication 207 and NADP Brochure 2016-01. National Atmospheric Deposition Program, University of Wisconsin, Madison, WI. <http://nadp.slh.wisc.edu/lib/brochures/nitrogenAtmos.pdf>.
- NADP, 2018a. Map of Nitrate Ion Wet Deposition, 2015. National Atmospheric Deposition Program, University of Wisconsin, Madison, WI.
http://nadp.slh.wisc.edu/maplib/pdf/2015/NO3_dep_2015.pdf.
- NADP, 2018b. Map of Ammonium Ion Wet Deposition, 2015. National Atmospheric Deposition Program, University of Wisconsin, Madison, WI.
http://nadp.slh.wisc.edu/maplib/pdf/2015/NH4_dep_2015.pdf.
- NADP, 2018c. Map of Total Nitrogen Deposition, 2015. National Atmospheric Deposition Program, University of Wisconsin, Madison, WI.
http://nadp.slh.wisc.edu/committees/tdep/tdepmaps/preview.aspx#n_tw.

NCEI, 2018. National Centers for Environmental Information, formerly the National Climatic Data Center. <https://www.ncdc.noaa.gov/data-access>.

NOAA, 2018. Hourly/Sub-Hourly Data Observation Map. <https://gis.ncdc.noaa.gov/maps/ncei/cdo/hourly>. Accessed May 2018. National Oceanic and Atmospheric Administration, Washington, DC.

Opti-Tool for Stormwater and Nutrient Management: User's Guide. Prepared for: U.S. EPA Region 1, Boston, MA. Prepared by: Tetra Tech, Inc. Fairfax, VA. June 30, 2016.

Park RA and Clough JS, 2014. AQUATOX (Release 3.1 plus). Modeling Environmental Fate and Ecological Effects in Aquatic Ecosystems. Volume 1: Technical Documentation. US Environmental Protection Agency, Office of Science and Technology, Washington DC.

Paul, M.J., J. Robbiani, L. Zheng, T. Rafi, S. Bai, and P. von Loewe. 2011. Development of Nutrient Endpoints for the Northern Piedmont Eco-region of Pennsylvania: TMDL Application Follow-up Analysis. Prepared by Tetra Tech, Inc., Owings Mills, MD for United States Environmental Protection Agency, Region 3.

Powers SM, Tank JL, and Robertson DM, 2015. Control of nitrogen and phosphorus transport by reservoirs in agricultural landscapes. *Biogeochemistry* 124, p417–439. DOI 10.1007/s10533-015-0106-3.

Sloto RA and MY Crouse, 1996. HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis. Water-Resources Investigations Report 96-4040. US Geological Survey, Lemoyne, PA.

TetraTech, 2015. Lake Champlain BATHTUB Model Calibration Report. Prepared for the U.S. Environmental Protection Agency, Region 1, Boston, MA.

Tipping, E, Benham, S, Boyle, J F, Crow, P, Davies, J, Fischer, U, Guyatt, H, Helliwell, R, Jackson-Blake, L, Lawlor, AJ, Monteith, DT, Roweg, EC, and Tobermanac, H, 2014. Atmospheric deposition of phosphorus to land and freshwater. *Environ. Sci.: Processes Impacts*, 2014 (16), 1608–1617. <https://doi.org/10.1039/c3em00641g>.

U.S. EPA, 1986. Quality Criteria for Water.

U.S. EPA, 1998. Level III eco-regions of the continental United States (revision of Omernik, 1987).

U.S. EPA, 2001. Using Stressor-response Relationships to Derive Numeric Nutrient Criteria. EPA-820-S-10-001.

Wagner K, 2009. LLRM – Lake Loading Response Model. Users Guide and Quality Assurance Project Plan. Water Resource Services, Wilbraham, MA.

Walker, W, 1982. An empirical analysis of phosphorus, nitrogen, and turbidity effects on reservoir chlorophyll-a levels, *Canadian Water Resources Journal*, 7(1), 88-107,

<https://doi.org/10.4296/cwrj0701088>. Published online 2013.

Walker, W, 1985. Empirical Methods for Predicting Eutrophication in Impoundments - Report 3: Model Refinements", Technical Report E-81-9, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MI.

Walker W, 1996. Simplified Techniques for Eutrophication Assessment & Prediction: User Manual. Instruction Report W-96-2. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MI. Updated September 1999.

Walker W, 2004. BATHTUB-Model Version 6.1. Simplified Techniques for Eutrophication Assessment & Prediction. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MI.

WH, 1987. Clean Lakes Program: Diagnostic/Feasibility Studies of Black Nooks Pond. Whitman and Howard, MA.

WH, 1988. Clean Lakes Program: Diagnostic/Feasibility Studies of Wedge Pond. Whitman and Howard, MA.

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. Loading	Boston Harbor	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

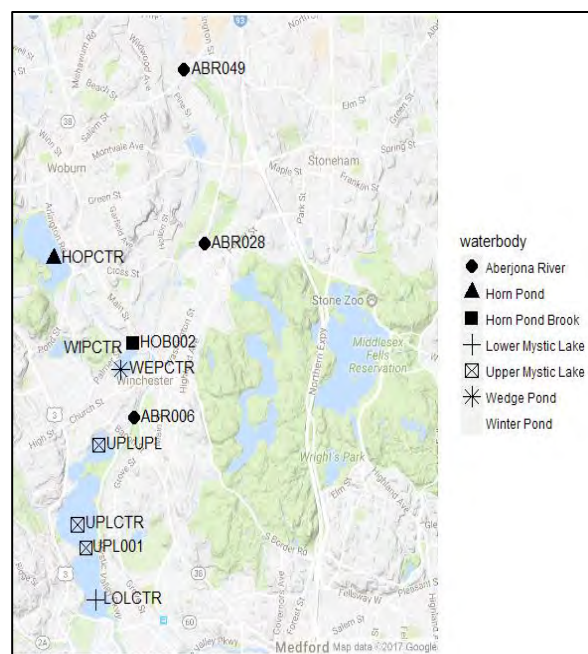
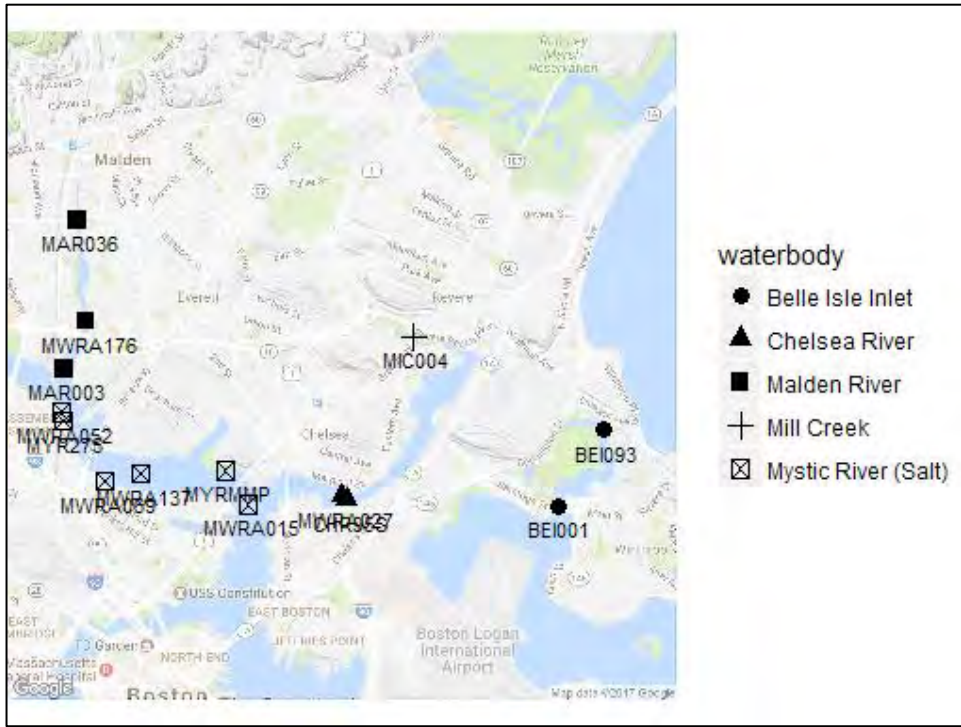
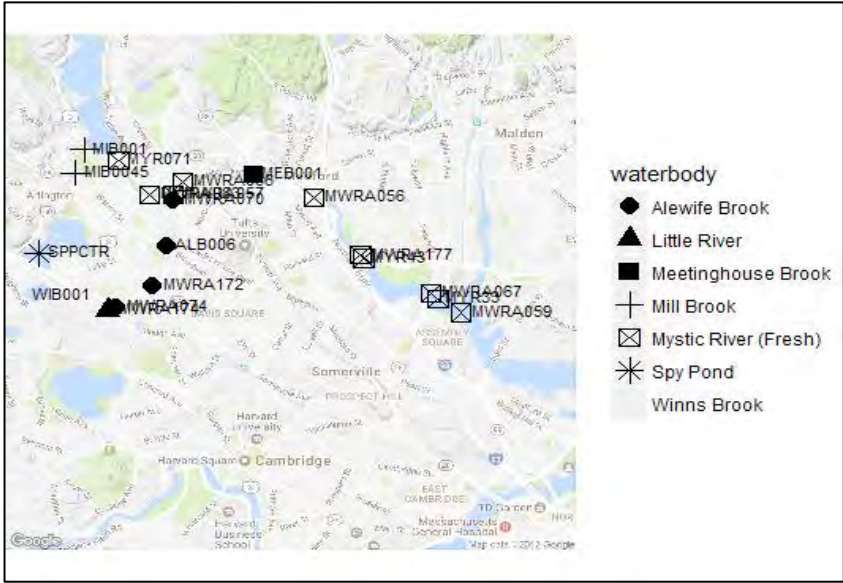


Table A-2. Water Body/Monitoring Station and Program

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	
<i>WIB001</i>	190	–	–	–	190
Little River	–	–	–	442	442
<i>MWRA174</i>	–	–	–	442	442
Alewife Brook	192	39	–	1,393	1,624
<i>ALB006</i>	192	39	–		231
<i>MWRA070</i>	–	–	–	466	466
<i>MWRA074</i>	–	–	–	469	469
<i>MWRA172</i>	–	–	–	458	458
Mystic River (Fresh)	190	109	995	2,053¹	3,329¹
<i>MWRA056</i>	–	–	–	365	365
<i>MWRA057</i>	–	–	–	373	373
<i>MWRA059</i>	–	–	–	367	367
<i>MWRA066</i>	–	–	548	–	548
<i>MWRA067</i>	–	–	–	370	370
<i>MWRA083</i>	–	–	261	385	646
<i>MWRA177</i>	–	–	186	194	365 ¹
<i>MYR071</i>	190	38	–	–	228
<i>MYR33</i>	–	36	–	–	36
<i>MYR43</i>	–	35	–	–	35
Meetinghouse Brook	191	13	–	–	204
<i>MEB001</i>	191	13	–	–	204
Malden River	183	73	–	322	578
<i>MAR003</i>	–	36	–	–	36
Mystic River (Salt)	170¹	–	459	1,079	1,708¹
<i>MWRA015</i>	–	–	–	344	344
<i>MWRA052</i>	–	–	–	492	492
<i>MWRA069</i>	–	–	–	243	243
<i>MWRA137</i>	–	–	459	–	459
<i>MYR275</i>	82	–	–	–	82
<i>MYRMMP</i>	95	–	–	–	95
Mill Creek	93	–	–	–	93
<i>MIC004</i>	93	–	–	–	93
Chelsea River	95	–	–	370	465
<i>CHR95S</i>	95	–	–	–	95
<i>MWRA027</i>	–	–	–	370	370
Belle Isle Inlet	81	–	–	–	81
<i>BEI001</i>	13	–	–	–	13
<i>BEI093</i>	68	–	–	–	68

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



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.

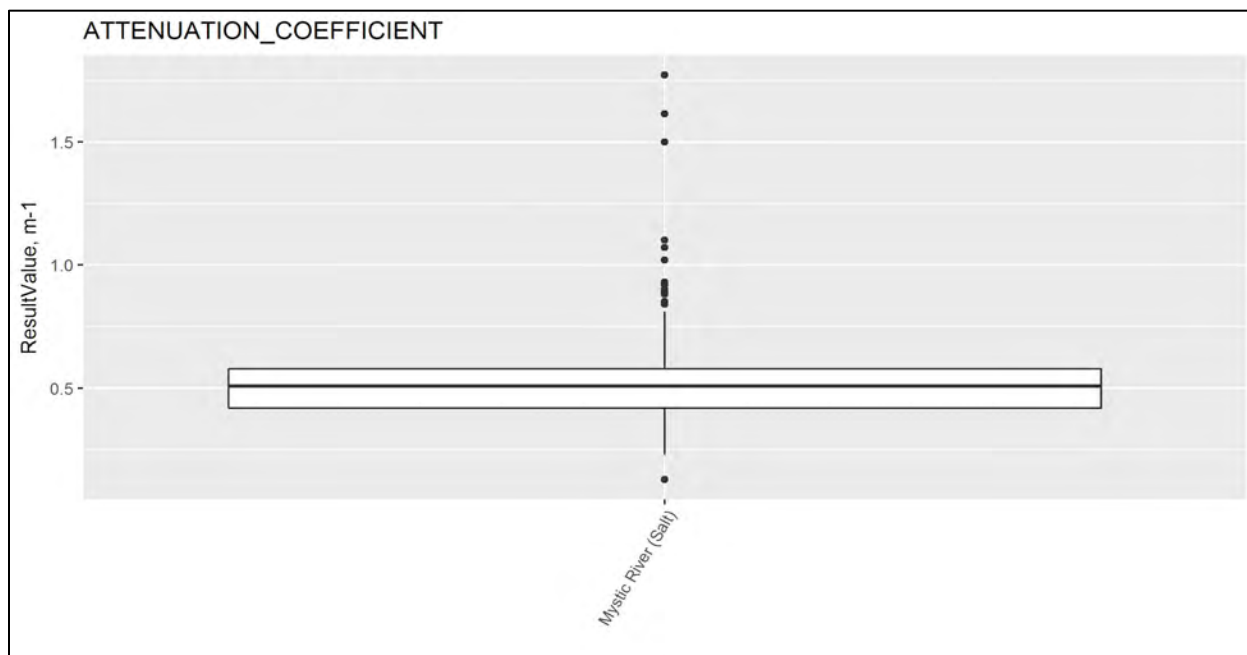


Figure C-1. Attenuation coefficient results by water body.

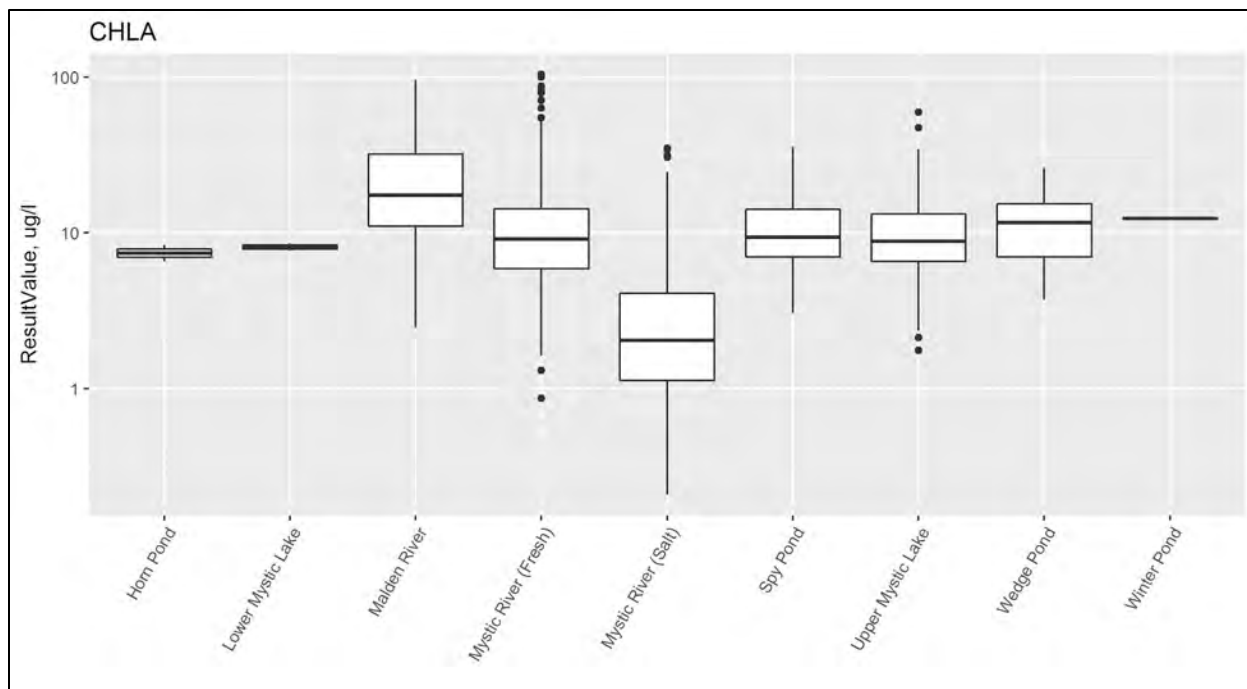


Figure C-2. Chlorophyll-a results by water body.

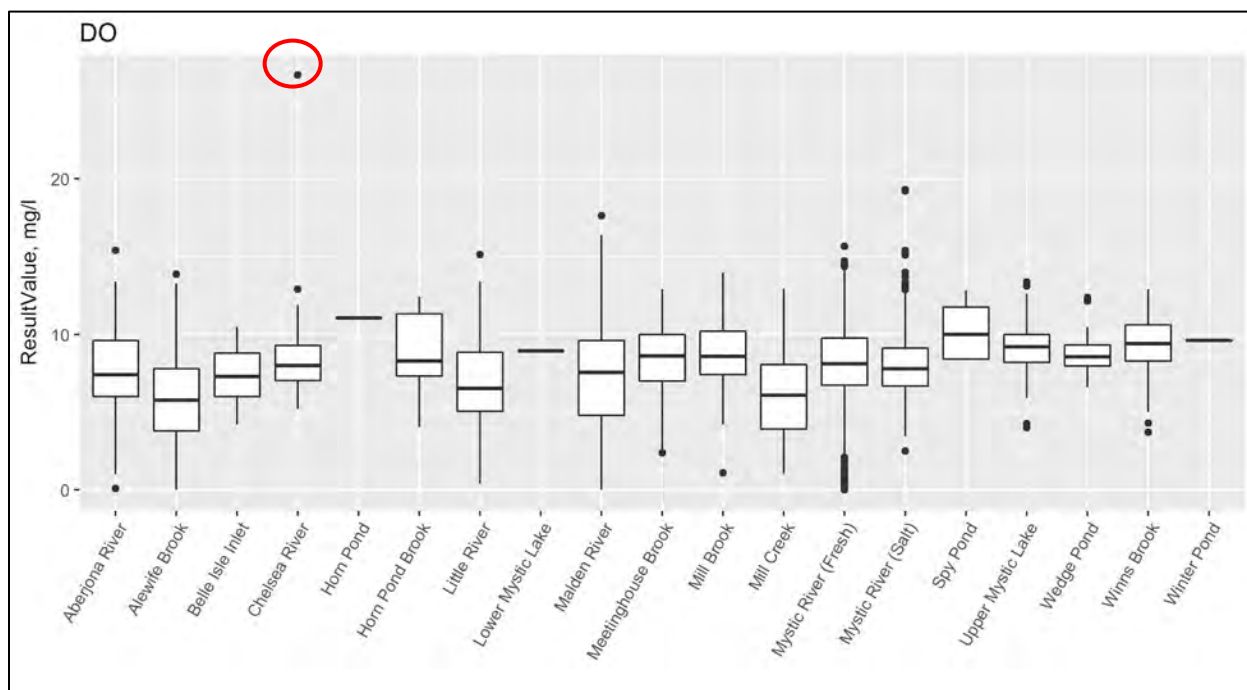


Figure C-3. Dissolved oxygen results by water body.

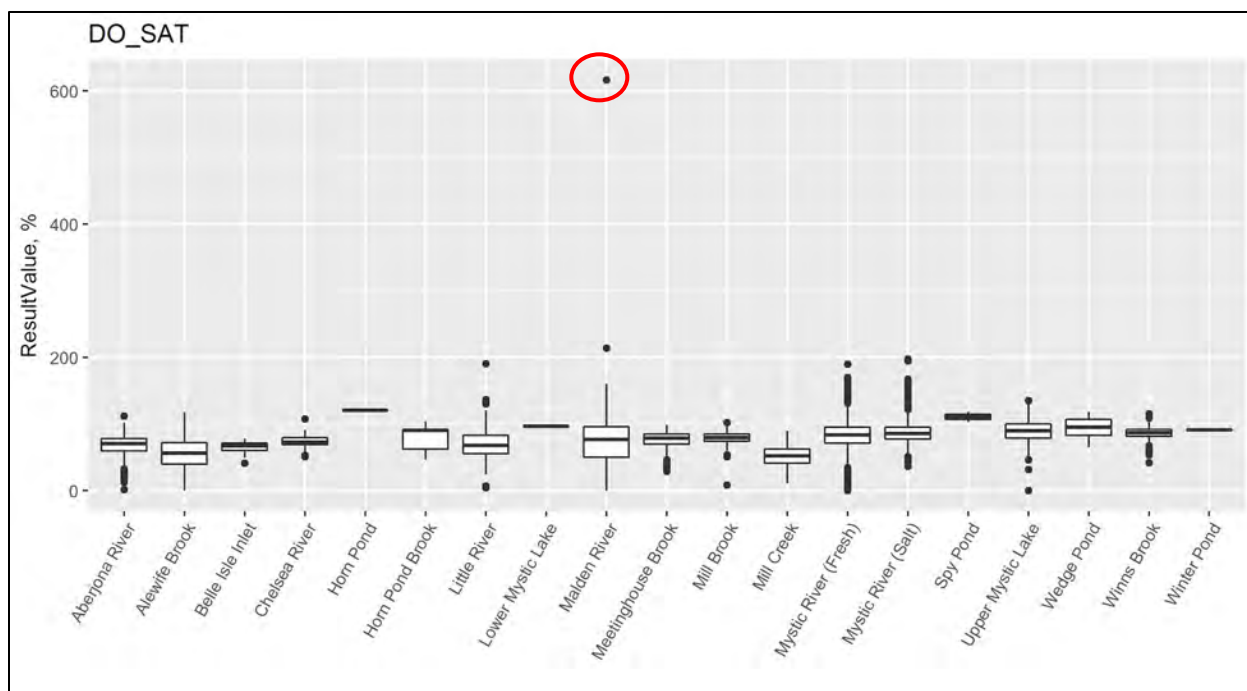


Figure C-4. Dissolved oxygen percent saturation results by water body

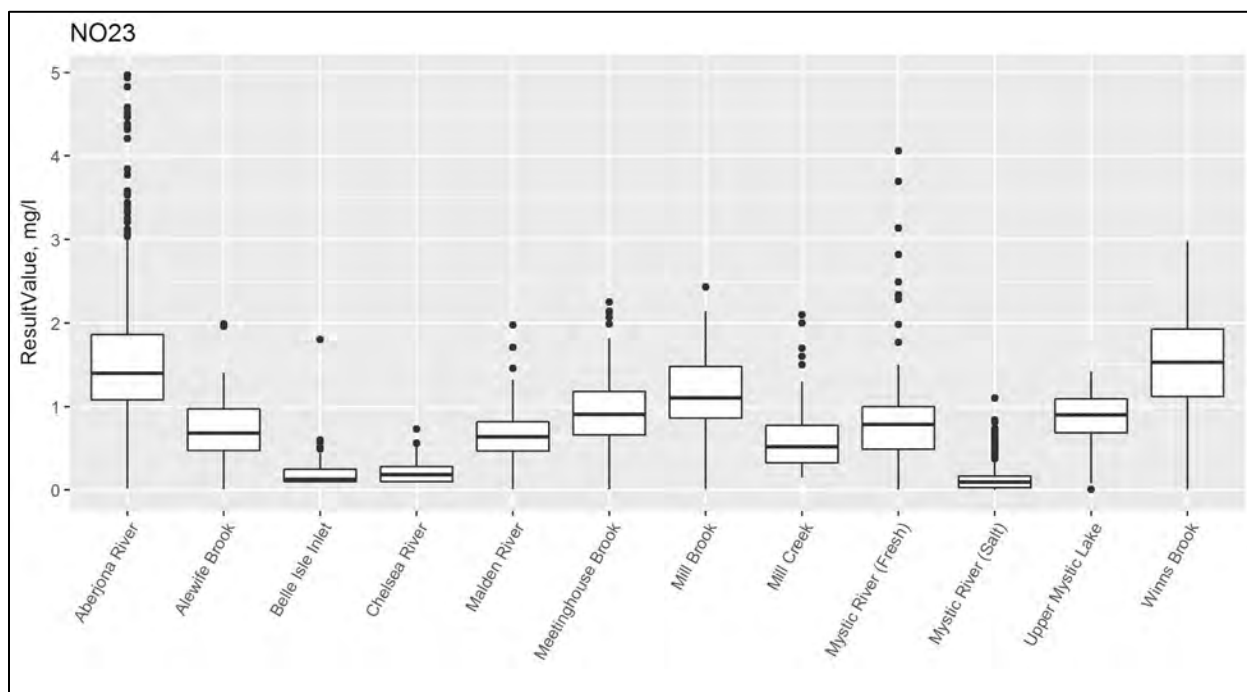


Figure C-5. Inorganic nitrogen (nitrite plus nitrate) results by water body.

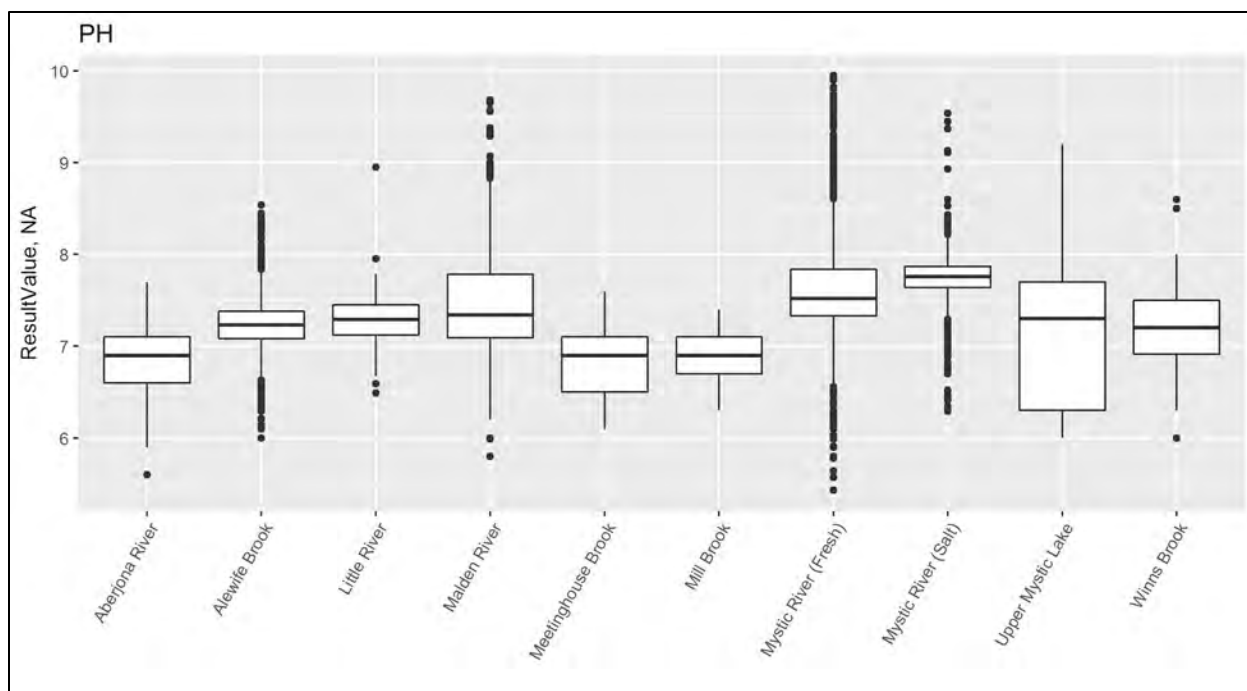


Figure C-6. pH results by water body.

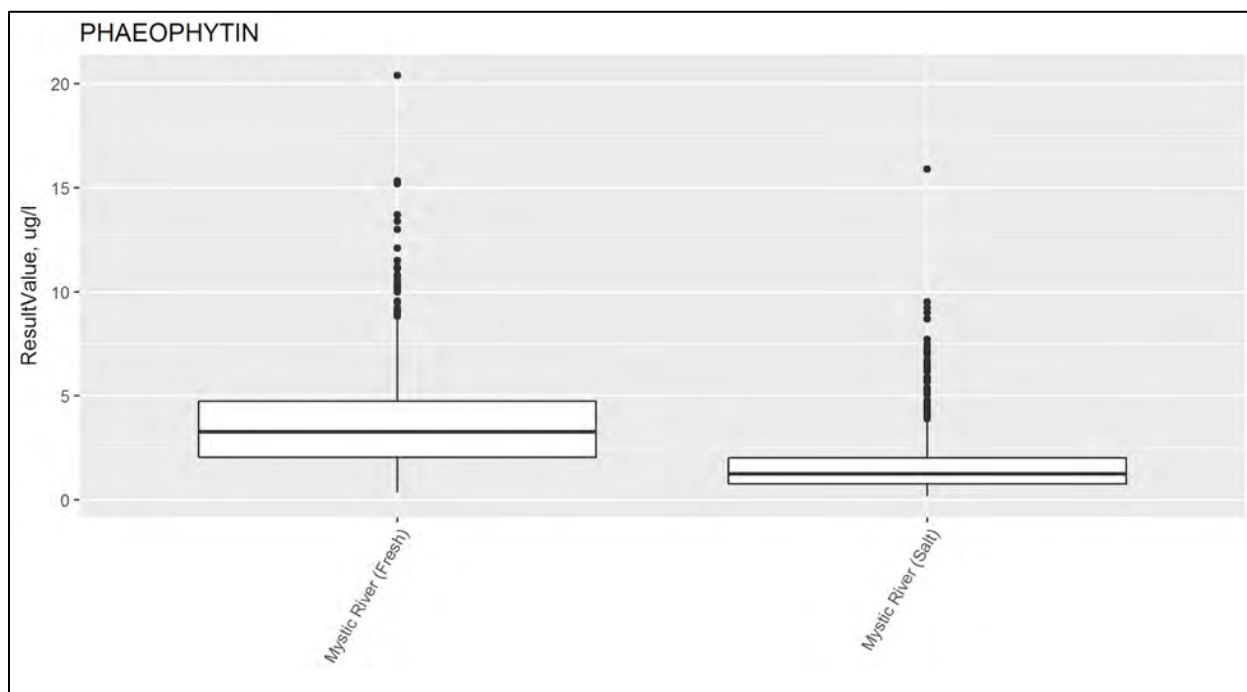


Figure C-7. Phaeophytin results by water body.

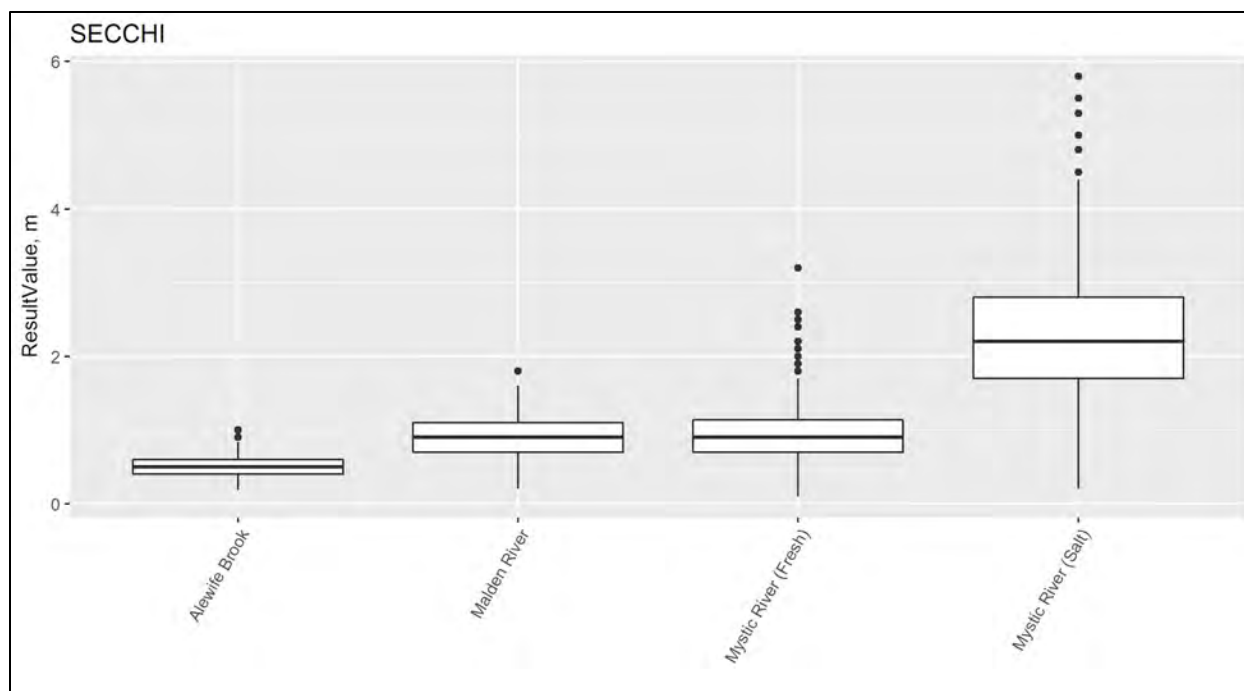


Figure C-8. Secchi depth results by water body.

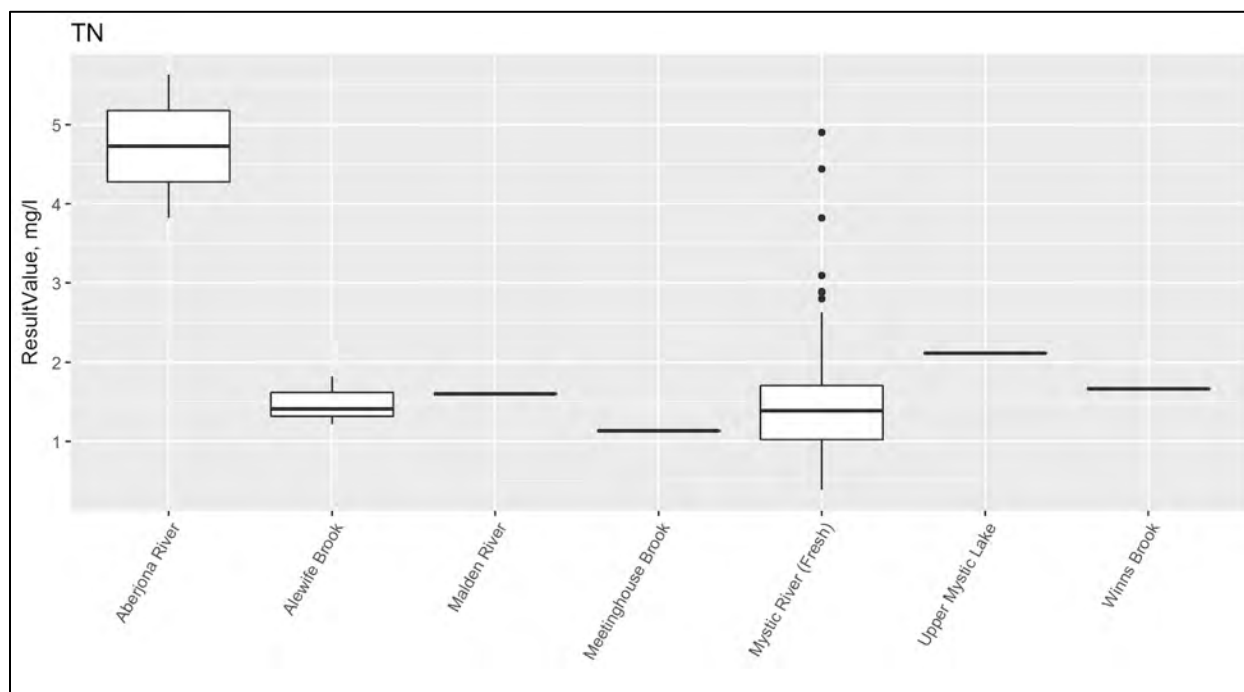


Figure C-9. Total nitrogen results by water body.

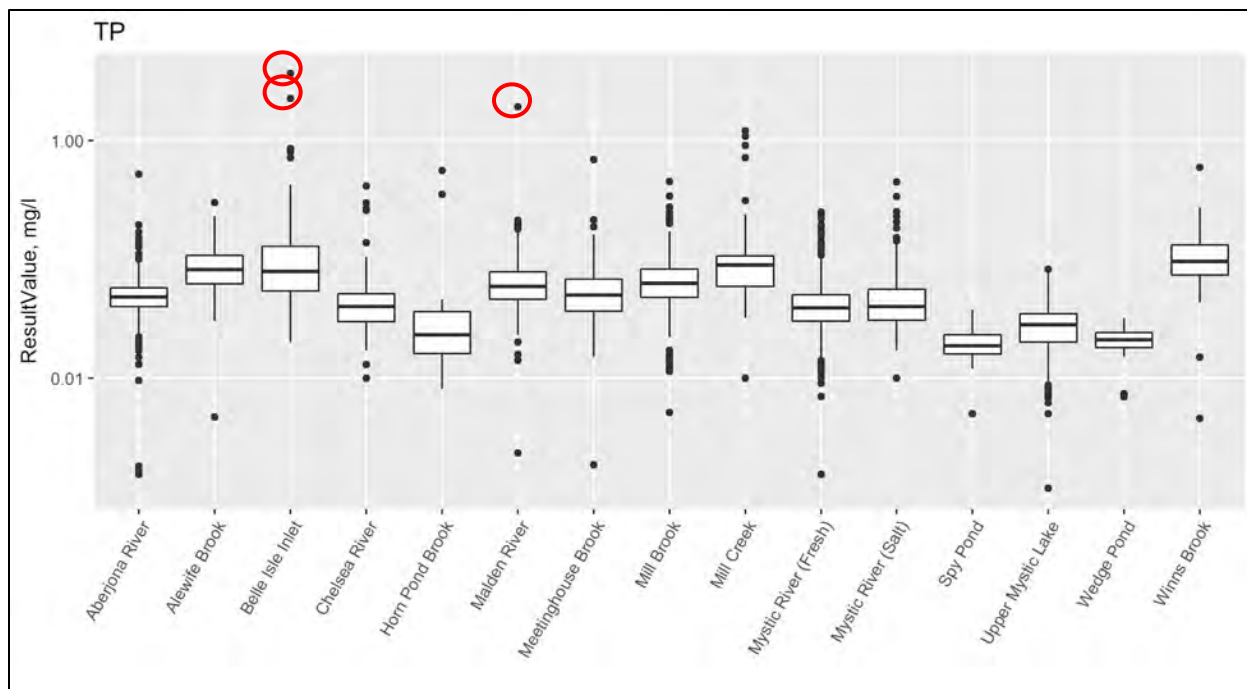


Figure C-10. Total phosphorus results by water body.

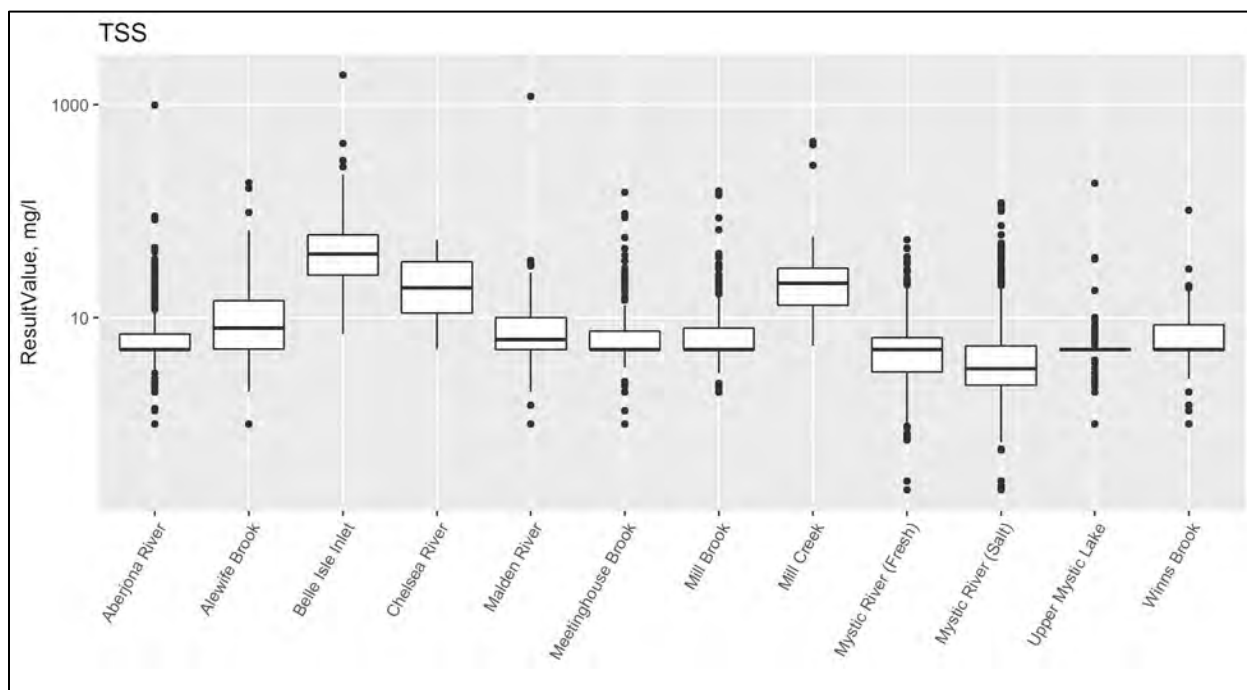


Figure C-11. Total suspended solids results by water body.

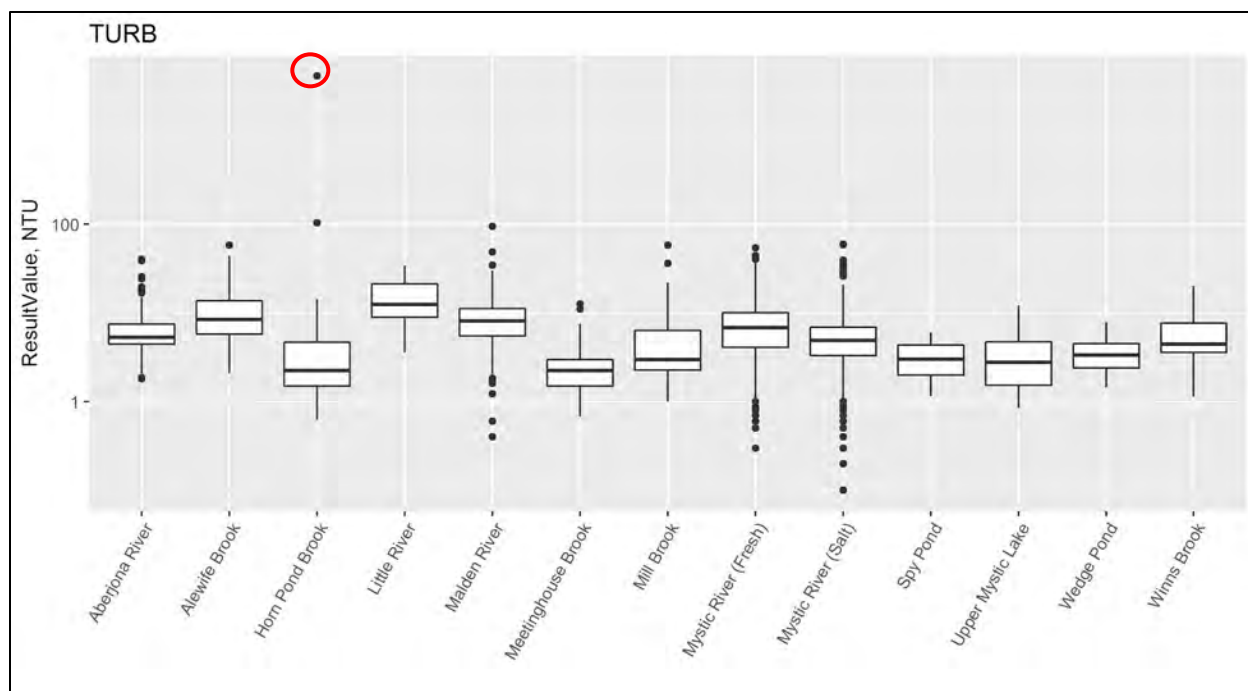


Figure C-12. Turbidity results by water body

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

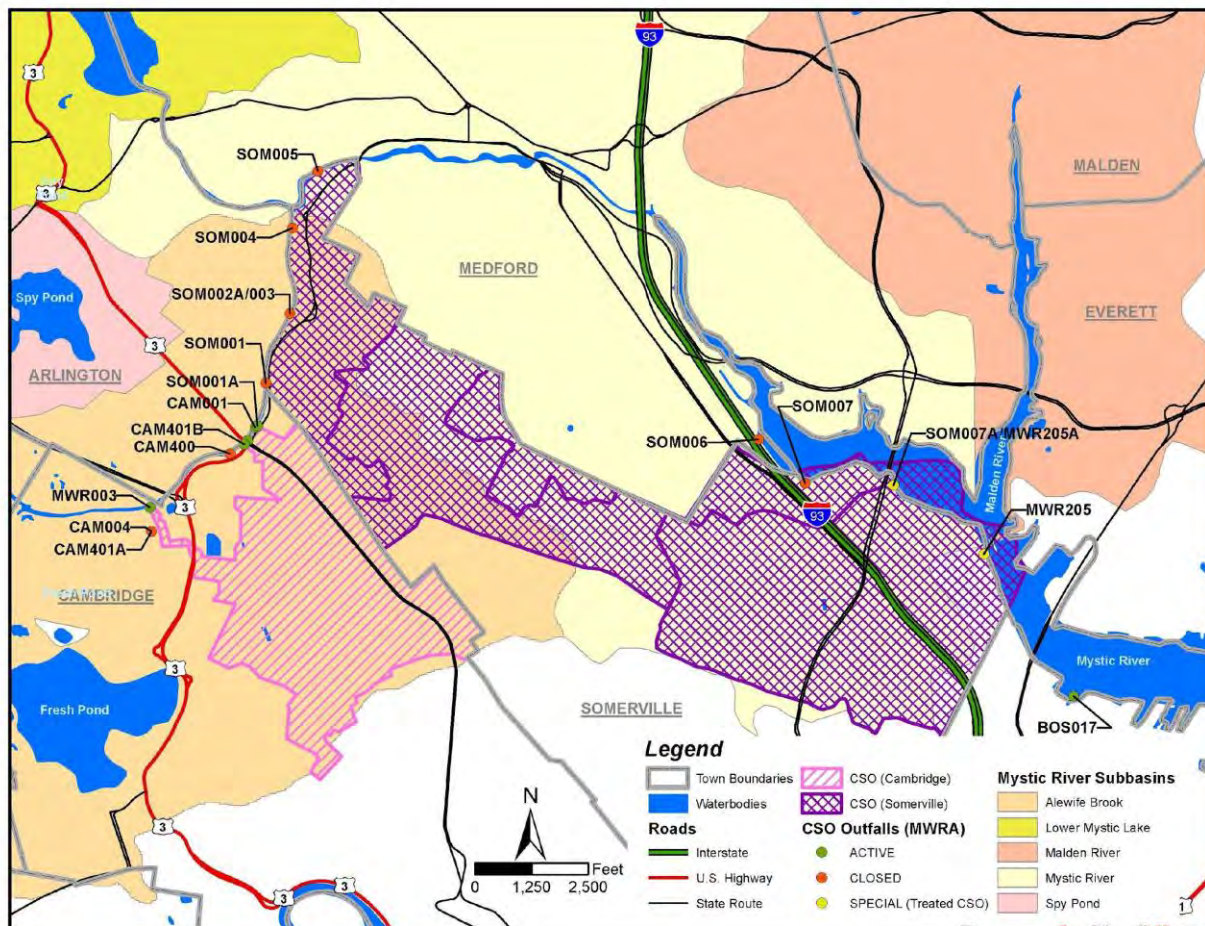


Figure G-XI-1. MWRA CSO Map (updated in September 2015).

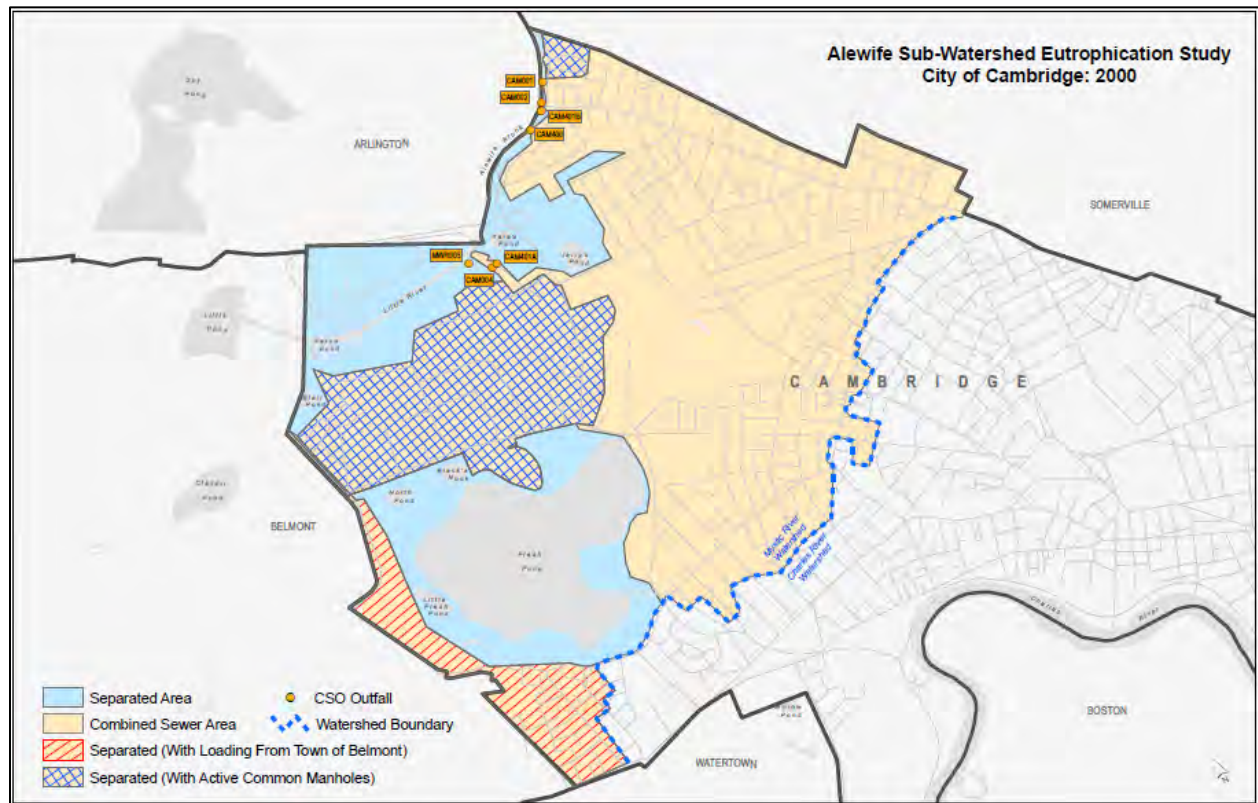
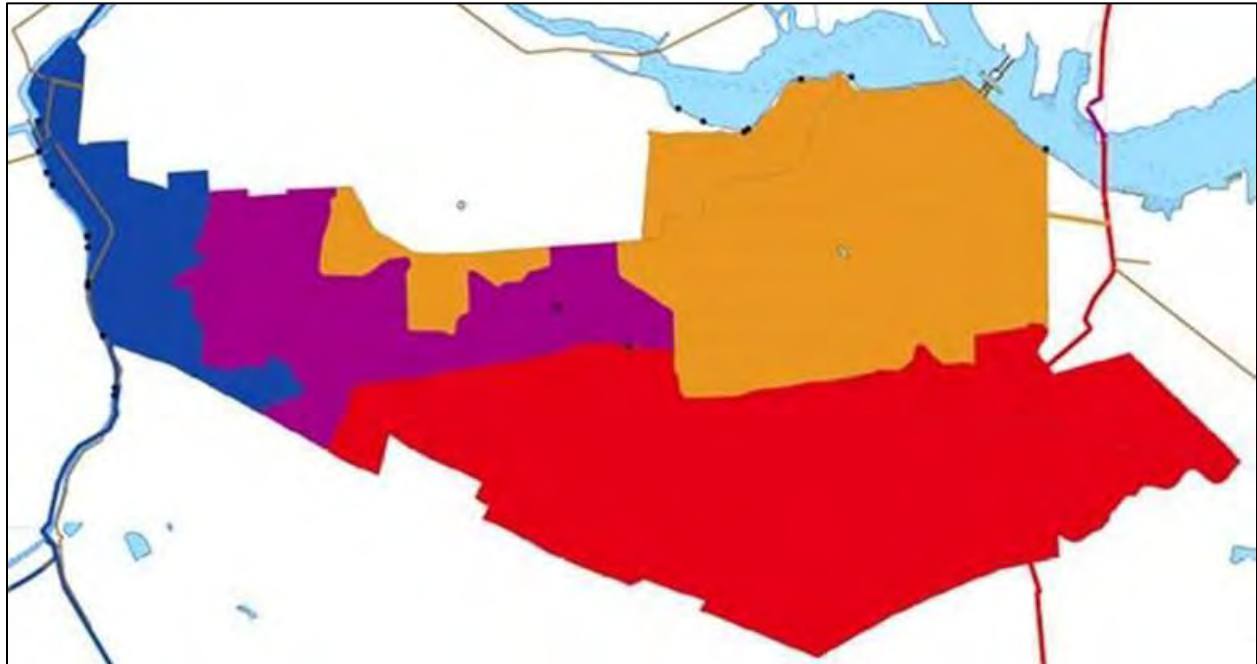


Figure G-XI-2. City of Cambridge CSO Drainage Basins (2000).



Legend

Area	MWRA Connection	Combined Sewer Overflow
	Somerville Marginal Interceptor (SMI)	Mystic River
	Alewife Brook Conduit (ABC)	Alewife Brook
	Cambridge Branch Sewer (CBS)	Interactions with SMI and McGrath system
	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
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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	1	2	3	4	5
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	1	2	3	4	5
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	1	2	3	4	5
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	1	2	3	4	5
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
<u>Internal Loading Rates (mg/m2-day)</u>					
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 (hm ³ /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 (km²)

Not used	0	0	0	0	0
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Non-Point Source Export Coefficients

Not used	0	0	0	0	0
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Transport Channels

Not used	0	0	0	0	0
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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
Soil Properties	Crest Width (ft)	100	100	100	100
	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 (\$/ft ³)	\$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