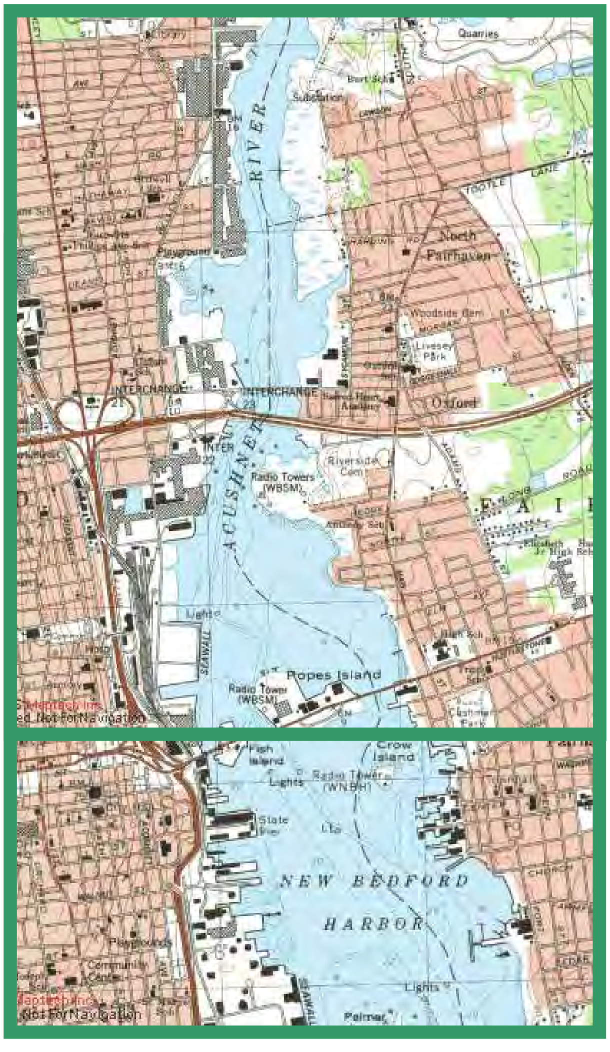
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the New Bedford Inner Harbor Embayment System, New Bedford, MA



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

UPDATED FINAL REPORT – November 2015

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Brian Howes
Roland Samimy
David Schlezinger
Ed Eichner

John Ramsey
Trey Ruthven

Contributors:

US Geological Survey

Don Walters and John Masterson

Applied Coastal Research and Engineering, Inc.

Elizabeth Hunt and Sean W. Kelley

Massachusetts Department of Environmental Protection

Charles Costello and Brian Dudley (DEP project manager)

SMAST Coastal Systems Program

Jennifer Benson, Michael Bartlett, Sara Sampieri and Elizabeth White

M A E, Inc.

Maisy McDarby-Stanovich

Massachusetts Department of Environmental Protection

SMAST
University of Massachusetts Dartmouth
The School for Marine Science and Technology

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Executive Summary

1. Project Overview

This updated report (revised to Final based on two rounds of comments from the MassDEP {Dec. 2013 and Aug. 2014} and comments from the Town of Fairhaven consultant {Feb. 2014}) builds on the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach which was applied to the Acushnet River – New Bedford Inner Harbor embayment system and first completed in December 2008. This updated report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Acushnet River – New Bedford Inner Harbor embayment system, a coastal embayment within the City of New Bedford and the Town of Fairhaven, Massachusetts.

Analyses of the New Bedford Harbor embayment system was originally performed to assist the City and the Town with nitrogen management decisions associated with current and future wastewater planning efforts, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and harbor maintenance programs. The present update incorporates information obtained subsequent to the completion of the original analysis (2008) and addresses clarifications requested by the Buzzards Bay Project. Minor editorial comments provided to the MEP Technical Team by the Coalition for Buzzards Bay were also integrated into this updated report. The key underlying refinement in the present report involves an update to the land-use database used by the Towns and provided to the MEP. The updating of the parcel database included reformatting GIS files and cross-checks as well as a re-evaluation of water use and sewershed linkages, updates related to developed versus undeveloped and developable parcels, in addition to new wetland survey information and the treatment of cranberry bogs, all of which has been conducted over the past several years by the Buzzards

Bay Project, MassDEP and MEP/SMAST staff. The refinements to the land-use database have been used by the MEP to reconstruct the watershed nitrogen loading model, which then required a recalibration of the water quality model and associated assessments. In support of the revision of the loading models, additional data on nitrogen sources/strength were integrated into the update of the MEP threshold analysis. As a result of the refinements to the land-use database, the MEP/SMAST Technical Team completed a new build-out nitrogen loading projection for the present report update which will greatly enhance on-going nutrient management planning associated with these estuaries. In addition to the updates made to the watershed nitrogen loading module, water quality was re-evaluated to include monitoring that has taken place throughout the harbor since completion of the original MEP threshold analysis. Benthic regeneration (nutrient cycling from sediments) was re-evaluated as well in the summer of 2012 in order to capture potential changes in sediment nutrient flux rates which may have resulted from nutrient load reductions to the harbor between 2002 and 2012. In the fall of 2012, additional sediment cores were collected for the purpose of reassessing the benthic infaunal populations and how they may have changed over the ten years since the original infaunal assessment was completed.

As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the City of New Bedford and the Town of Fairhaven resource planning and decision-making process. The primary products of this effort are: (1) a current quantitative assessment of the nutrient related health of the New Bedford Harbor embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the City and the Town) for the restoration of the New Bedford Harbor embayment system.

As increasing numbers of people occupy coastal watersheds, the associated coastal waters receive increasing pollutant loads. Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The elevated nutrients levels are primarily related to the land use impacts associated with the increasing population within the coastal zone over the past half-century.

The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities. The primary nutrient causing the increasing impairment of our coastal embayments is nitrogen, with its primary sources being wastewater disposal, and nonpoint source runoff that carries nitrogen (e.g. fertilizers) from a range of other sources. Nitrogen related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters. Coastal embayments, because of their shallow nature and large shoreline area, are generally the first coastal systems to show the effect of nutrient pollution from terrestrial sources.

In particular, the New Bedford Harbor embayment system within the City of New Bedford and the Town of Fairhaven is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater and surface water from the increasingly developed watershed to this coastal system as well as the single point discharge of treated effluent directly to the inner harbor from the Town of Fairhaven Wastewater Treatment Facility. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The City of New Bedford and the Town of Fairhaven, as the primary stakeholders to the New Bedford Inner Harbor embayment system, have been concerned over the quality of this local coastal resource. The community has worked to implement controls on direct stormwater discharges, PCB clean-up, and institute an aggressive program for controlling nutrient inputs to the Harbor from combined sewer overflows (CSOs) as well as upgrading the New Bedford Wastewater Treatment Facility to secondary treatment (85 - 90 percent reduction of the influent biochemical oxygen demand and suspended solids). The Town of Fairhaven has also completed and implemented wastewater planning and sewering in other regions of the Town not associated with the Acushnet River – New Bedford Inner Harbor embayment system. The Town has nutrient management activities related to their tidal embayments, which have been associated with the MEP effort in the Little Bay and Nasketucket Bay embayment system. In addition, the Town of Acushnet has been expanding its sewer system thereby capturing nutrient load that would otherwise discharge directly into the Acushnet River. This wastewater flow is being sent to the New Bedford Wastewater Treatment Facility for treatment and eventual discharge to Buzzards Bay via ocean outfall.

In addition, the City of New Bedford and the Town of Fairhaven have supported the Coalition for Buzzards Bay's Water Quality Monitoring Program which has been collecting data on nitrogen related water quality within the Inner Harbor System since 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of the embayment and outer New Bedford harbor. The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay and determine the relationship between observed water quality and habitat health.

The City of New Bedford and the Town of Fairhaven and Acushnet have recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion of the multi-step nutrient management process has been taking place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the City and Towns. The modeling tools developed as part of this program provide the quantitative information necessary for the City and Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios. The present MEP effort is the necessary "next step" in the restoration of the New Bedford Inner Harbor System by providing quantitative restoration targets for nitrogen for on-going efforts by the City of New Bedford, Town of Fairhaven and the Coalition for Buzzards Bay.

This report also presents the results of specific scenarios developed by the New Bedford Harbor Trustee Council (NBHTC). Results were obtained using the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Acushnet River – New Bedford Inner

Harbor embayment system. Further analysis of the Acushnet River – New Bedford Inner Harbor embayment system was performed to assist the NBH Trustee's in decisions related to proposed restoration alternatives related to enhancing tidal exchange by placing culverts in the New Bedford Hurricane Barrier. This restoration alternative, Hurricane Barrier Box Culvert, was determined to have potential merit by the Trustees (NBHTC RP/EIS) in the early round of solicitations for restoration alternatives related to the restoration fund, established as a result of settlements between the Federal Government, the Commonwealth of Massachusetts, and companies responsible for releasing PCBs into New Bedford Harbor.

The Hurricane Barrier Box Culvert restoration alternative focused on ameliorating perceived restrictions to tidal flushing or Harbor circulation stemming from the construction of the Hurricane Barrier by the Army Corps of Engineers (ACOE) in the 1960's. The concept was that if there were reduced tidal flushing of the Inner Harbor, it would exacerbate the on-going nitrogen enrichment from the watershed, and further impair harbor habitats through the effects of eutrophication. Therefore, analysis of the Hurricane Barrier Box Culvert restoration alternative required the use of the full MEP Linked Watershed-Embayment Model for the New Bedford Inner Harbor System. The completion of the MEP analysis allowed the NBHTC to efficiently leverage its effort, through use of the MEP's calibrated and validated models to assess various Hurricane Barrier Box Culvert sizes and placements. Since the NBHTC box culvert alternatives rely upon the MEP analysis, this report presents both the necessary MEP information and model descriptions as well as the model results relating specifically to the box culvert scenarios selected by that projects Technical Group which included NOAA, ACOE and EPA experts.

2. Background Massachusetts Estuaries Project Analysis of Inner Harbor

Approach: Realizing the need for scientifically defensible management tools has resulted in a focus on determining the aquatic system's assimilative capacity for nitrogen. The highest-level approach is to directly link the watershed nitrogen inputs with embayment hydrodynamics to produce water quality results that can be validated by water quality monitoring programs. This approach when linked to state-of-the-art habitat assessments yields accurate determination of the "allowable N concentration increase" or "threshold nitrogen concentration". These determined nitrogen concentrations are then directly relatable to the watershed nitrogen loading, which also accounts for the spatial distribution of the nitrogen sources, not just the total load. As such, changes in nitrogen load from differing parts of the embayment watershed can be evaluated relative to the degree to which those load changes drive embayment water column nitrogen concentrations toward the "threshold" for the embayment system. To increase certainty, the "Linked" Model is independently calibrated and validated for each embayment.

The Massachusetts Department of Environmental Protection (DEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including Applied Coastal Research and Engineering (ACRE) and the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool to communities throughout southeastern Massachusetts (the Linked Watershed-Embayment Management Model) for nutrient management in their coastal embayment systems. Ultimately, use of the Linked Watershed-Embayment Management Model tool by municipalities in the region results in effective screening of nitrogen reduction approaches and eventual restoration and protection of valuable coastal resources. The MEP provides technical guidance in support of policies on nitrogen loading to embayments, wastewater management decisions, and establishment of nitrogen Total Maximum Daily Loads (TMDLs). A TMDL represents the greatest amount of a pollutant that a waterbody can accept and still meet water quality standards for protecting public health and maintaining the designated beneficial uses of those waters for drinking, swimming, recreation and fishing. The MEP modeling approach assesses available options for meeting selected nitrogen goals that are protective of embayment health and achieve water quality standards.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach, which links watershed inputs with embayment circulation and nitrogen characteristics.

The Linked Model builds on well-accepted basic watershed nitrogen loading approaches such as those used in the Buzzards Bay Project, the CCC models, and other relevant models. However, the Linked Model differs from other nitrogen management models in that it:

- requires site-specific measurements within each watershed and embayment;
- uses realistic "best-estimates" of nitrogen loads from each land-use (as opposed to loads with built-in "safety factors" like Title 5 design loads);
- spatially distributes the watershed nitrogen loading to the embayment;
- accounts for nitrogen attenuation during transport to the embayment;
- includes a 2D or 3D embayment circulation model depending on embayment structure;
- accounts for basin structure, tidal variations, and dispersion within the embayment;
- includes nitrogen regenerated within the embayment;
- is validated by both independent hydrodynamic, nitrogen concentration, and ecological data;
- is calibrated and validated with field data prior to generation of "what if" scenarios.

The Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

For a comprehensive description of the Linked Model, please refer to the *Full Report: Nitrogen Modeling to Support Watershed Management: Comparison of Approaches and Sensitivity Analysis*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. A more basic discussion of the Linked Model is also provided in Appendix F of the *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. The Linked Model suggests which management solutions will adequately protect or restore embayment water quality by enabling towns to test specific management scenarios and weigh the resulting water quality impact against the cost of that approach. In addition to the management scenarios modeled for this report, the Linked Model can be used to evaluate additional management scenarios and may be updated to reflect future changes in land-use within an embayment watershed or changing embayment characteristics. In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries. Unlike many approaches, the Linked Model accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics and accommodates the spatial distribution of these processes. For an overview of several management scenarios that may be employed to restore embayment water quality, see *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm.

Application of MEP Approach to New Bedford Inner Harbor: The Linked Model was applied to the Acushnet River – New Bedford Inner Harbor embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Coalition for Buzzards Bay in partnership and with technical guidance from the Coastal Systems Program at SMAST (see Chapter 2). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the City of New Bedford, the Towns of Fairhaven and Acushnet Planning Departments, and watershed boundaries delineated by USGS and CSP-SMAST scientists. This land-use data was used to determine watershed nitrogen loads within the Acushnet River – New Bedford Inner Harbor embayment system and each of the systems sub-basins as appropriate (current and build-out loads are summarized in Chapter IV of the MEP Threshold Report). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the overall embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Buzzards Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Acushnet River – New Bedford Inner Harbor embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

MEP Nitrogen Thresholds Analysis: The threshold nitrogen level for an embayment represents the average water column concentration of nitrogen that will support the habitat quality being sought. The water column nitrogen level is ultimately controlled by the watershed nitrogen load and the nitrogen concentration in the inflowing tidal waters (boundary condition). The water column nitrogen concentration is modified by the extent of sediment regeneration. Threshold nitrogen levels for the embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. High habitat quality was defined as supportive of eelgrass and infaunal communities. Dissolved oxygen and chlorophyll a were also considered in the assessment.

The nitrogen thresholds developed in the MEP Threshold Report were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and/or infaunal habitats in the overall system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station chosen for the Acushnet River – New Bedford Inner Harbor system. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Acushnet River – New Bedford Inner Harbor embayment system in the City of New Bedford and the Towns of Fairhaven and Acushnet. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. The MEP analysis has initially focused upon nitrogen loads from on-site septic systems and the Fairhaven Wastewater Treatment Facility as a test of the potential for achieving the level of total nitrogen reduction for restoration of each embayment system. The concept was that since septic system and WWTF nitrogen loads generally represent 85% - 90% of the controllable watershed load to the Acushnet River – New Bedford Inner Harbor embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through these sources is a good gauge of the feasibility for restoration of the system.

3. Problem Assessment (Current Conditions) as Presented in MEP Threshold Report

A habitat assessment was conducted throughout the Acushnet River – New Bedford Inner Harbor system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. At present, the New Bedford Inner Harbor System is showing variations in nitrogen enrichment and habitat quality among its various component basins. In general the upper component system is showing moderately impaired benthic habitat within the upper tidal reach. As a wetland dominated basin, impairment is only moderate resulting mainly from the patches of drift macroalgal accumulation and to high chlorophyll-a levels and a preponderance of stress tolerant species. The middle basin is depositional with sediments consisting of organic rich mud. Organic enrichment appears to result from the moderate to high chlorophyll levels, as macroalgae are generally sparse to absent. The infaunal community is consistent with a moderate level of impairment, as consistent to the tidally averaged nitrogen levels of 0.51-0.62 mg N L^{-1} across this basin. Finally, the lower basin is generally slightly too moderately impaired by nitrogen enrichment, with significant impairment only in localized areas of physical disturbance or altered flushing. While the lower basin still exhibits moderate oxygen depletions and elevated chlorophyll-a, drift algae are not common, although attached forms can be found. The moderate level of nitrogen enrichment (tidally average generally 0.47 to 0.51 mg N L^{-1}) is consistent with the infaunal community within the lower main basin, with larger and deep burrowing forms evident. All of the habitat indicators are consistent with this evaluation of the whole of system (Chapter VII of the MEP Threshold Report).

The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the upper tidal reach of the Acushnet River / New Bedford Inner Harbor system is nitrogen and organic matter enriched. However, this basin is also influenced by its bordering wetlands, and to some extent is naturally organic matter rich. The relationship of watershed nitrogen loading versus ecosystem function (wetland/tidal river) also suggests impairment of habitat within this basin, but at a lower level than based upon the water quality indicators alone.

Overall, the dissolved oxygen records indicate a gradient in oxygen depletion and chlorophyll a levels from the upper to the lower basins of the Acushnet River / New Bedford Inner Harbor system. Consistent with estuarine response to over-enrichment from nitrogen, the extent of bottom water oxygen depletion parallels the levels of phytoplankton biomass (e.g. chlorophyll a). Based upon the basin type and configuration, oxygen depletion and organic matter enrichment indicates infaunal habitat impairment at a moderate level within the upper tidal river basin and within the lower basin, but at slightly higher levels within the depositional middle basin. All moorings showed periodic oxygen depletions below 5 mg L^{-1} and generally to <4 mg L^{-1}. The exceptional depletion at the Popes Island site in the lower basin, was apparently associated with the semi-isolated marina basin and not a larger spatial phenomenon. The embayment specific results are presented in Chapter VII of the Massachusetts Estuaries Project Report.

All of the available information on eelgrass relative to New Bedford Inner Harbor indicates that this embayment has not supported eelgrass over the past 2 decades and likely has not supported eelgrass for over a century. No eelgrass was detected in the 1985 survey and subsequent field surveys. The MassDEP analysis indicates that eelgrass habitat was not present within the Inner Harbor in 1951 which is consistent with the bathymetry of the Harbor basins (see below) and consistent with a recent reconstruction of the ecological history of the Inner Harbor (Pesch et al. 2002). This reconstruction strongly suggests that the harbor is unlikely to have supported eelgrass over the past century, even if the structure of the basins could have supported it. It appears that while long-term and present watershed and harbor activities would likely contribute to an impairment of eelgrass habitat, the depth of the basins plays the major role. Specifically, the large lower basin of the Inner Harbor sustains depths of 5-10 meters, deeper than eelgrass habitat within the other sub-embayments of Buzzards Bay (Westport Rivers to Quissett Harbor), which do not appear to have supported eelgrass habitat at these depths over the past 60 years.

It should be noted that while no eelgrass habitat could be documented within the Acushnet River/New Bedford Inner Harbor Estuary, the adjacent region of the Outer Harbor of the overall New Bedford Harbor system does support eelgrass habitat. As eelgrass habitat could not be documented to exist, either historically or presently, within New Bedford Inner Harbor, the thresholds analysis for this system should focus on restoration of the impaired infaunal animal habitats. However, it is likely that nitrogen management within the Inner Harbor will improve eelgrass and infaunal habitat within the down-gradient basins of the Outer Harbor.

The Infauna Study indicated that the New Bedford Inner Harbor Estuary is presently supporting a range of habitat quality for infaunal animal communities. However, each of the 3 major basins contains significant regions where the habitat is impaired by nitrogen enrichment. These impairments are associated with organic enrichment by phytoplankton blooms and periodic oxygen depletion, with the addition of macroalgal accumulations within the upper basin.

The habitat quality of the upper basin of New Bedford Inner Harbor, relative to nitrogen enrichment, is generally reflective of its function as a tidal river with bordering wetlands. This upper reach of the estuary appears to be influenced by freshwater inflows from the Acushnet River. This upper basin is clearly nitrogen enriched, with high total nitrogen levels, high chlorophyll levels and frequent depletions of oxygen. Significantly, this basin also had accumulations of drift algae, further evidence of a significant level of nitrogen enrichment. The infaunal community within the upper basin was distributed among a relatively few species, primarily those tolerant of organic rich sediments and tolerant of periodic oxygen depletion.

The middle reach of the New Bedford Inner Harbor Estuary is a moderately "deep" basin formed between the narrows of the upper basin and Popes Island. The middle basin functions as a classic sub-embayment basin and does not typically undergo large salinity variations. However, the waters are nitrogen enriched, have moderate to high chlorophyll levels and frequent depletions of oxygen. The infaunal community within the middle basin was generally diverse with high evenness. The dominant species were those associated with moderate levels of organic matter and nitrogen enrichment.

The lower reach of the New Bedford Inner Harbor Estuary contains a range of infaunal habitat quality, primarily resulting from nitrogen enrichment effects and localized disturbances. The lower basin is formed by Popes Island to the north and the Hurricane Barrier at its southern limit. The thresholds analysis necessarily focused upon the nitrogen enrichment effects, although the other factors were noted. For example, infaunal communities directly adjacent the recently dredged channel had few organisms, with opportunistic species being the initial re-colonizers of the substrate in these areas. In contrast, the greater main basin generally showed only slight nutrient related habitat impairment, consistent with the moderate levels of chlorophyll and oxygen depletion and tidal velocities that reduce organic matter deposition, thereby reducing sediment organic enrichment in some areas. In addition, the lower basin did not appear to support significant habitat for macroalgae or accumulations of drift algae. Habitat quality throughout most of the lower basin appears to be structured by nitrogen related processes with transport of low oxygen and high chlorophyll waters from the upper basins also playing a likely role.

4. Conclusions of the MEP Analysis of New Bedford Inner Harbor

The threshold nitrogen level for an embayment represents the average watercolumn concentration of nitrogen that will support the habitat quality being sought. The watercolumn nitrogen level is ultimately controlled by the integration of the watershed nitrogen load, the nitrogen concentration in the inflowing tidal waters (boundary condition) and dilution and flushing via tidal flows. The water column nitrogen concentration is modified by the extent of sediment regeneration and by direct atmospheric deposition.

Threshold nitrogen levels for this embayment system were developed to restore or maintain SB waters and habitat quality consistent with this systems classification as a working port. In this system, habitat quality consistent with the systems classification as a working port was defined as supportive of diverse benthic animal communities. Dissolved oxygen and chlorophyll *a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the City of New Bedford and the Towns of Fairhaven and Acushnet overall embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 60% - 70% of the controllable watershed nitrogen load to the embayment was from wastewater.

The threshold nitrogen levels for the Acushnet River – New Bedford Inner Harbor embayment system were determined as follows:

Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the New Bedford Inner Harbor Estuary does not include eelgrass habitat. However, the estuary is presently supporting moderately impaired infaunal habitat within its 3 three main basins, with the critical focus for nitrogen management on the depositional middle basin. Impairments result from watershed nitrogen inputs that exceed the tolerance of these basins, resulting in the loss of diversity and larger, deep burrowing forms. The stress to infaunal communities is by organic enrichment through phytoplankton blooms, macroalgal accumulations and periodic oxygen depletion. The threshold nitrogen loading represents the target for lowering nitrogen levels and the associated habitat impacts, and to restore the impaired infaunal habitats throughout the Inner Harbor Basins.

- The target total nitrogen concentration for restoration of infaunal habitat within the New Bedford Inner Harbor Estuary, is $\leq$0.50 mg TN L^{-1} (tidally averaged) at the sentinel location (head of the middle basin, just below the entrance to the channel to the upper basin) as depicted in Figure VIII-1. As the present TN level at this site is ~0.6 mg TN L^{-1}, watershed nitrogen management will be required for restoration of the estuarine habitats within this system. As nitrogen management alternatives are implemented and the nitrogen threshold is attained, a consequence will also be a lowering of nitrogen enrichment in both the upper and lower basins. Nitrogen levels within the lower basin will likely be significantly reduced compared to present conditions.

- Two model runs were made under the MEP to asses the impact of removing loads to the harbor system: (1) changes in water quality from continued Combined Sewer Outflows (CSOs) improvements and (2) from the modification of the Fairhaven wastewater treatment facility (FTF) outfall. The focus of the model runs was whether either change to TN loads to the harbor system would achieve the requirements of the threshold. An 8.3% reduction in the total watershed load to the harbor system is possible by removing all CSO inputs. A 49.2% reduction in total watershed load is possible by removing both CSO and FTF discharges to the harbor. Based on the results from the Linked Watershed-Embayment Model, it is seen that neither of these scenarios alone will meet the threshold requirements of a 0.50 mg/L TN concentration at the upper 1/3 of the mid Harbor basin. Therefore, some additional load (e.g., septic load), would need to be removed to meet the threshold.

Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, “planned” use of natural systems has to be done carefully and with the full analysis to ensure that degradation of these systems will not occur. One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

5. Conclusions of the Analysis of the Hurricane Barrier Box Culvert Alternatives

The objective of evaluating modifications to the New Bedford Harbor Hurricane Barrier is to assess potential improvements to the water quality within the harbor. Existing data show that the opening in the barrier is large enough to only cause a delay of approximately 5 minutes in water elevation between the entrance of the harbor and the northern end of the harbor during an incoming tide. It appears that the present opening is providing good volumetric exchange between the inner and outer harbor regions. However, water quality within the inner harbor is not just influenced by total volume exchange, but also circulation or mixing of waters within the harbor. At present, the Hurricane Barrier results in circulation cells around the inlet with depositional areas located west of Palmer Island and possibly east of the inlet on the Fairhaven side of the system.

The specific hydrodynamic alternatives were selected based on discussions representatives from the U.S Army Corps of Engineers, NOAA, and the U.S. EPA. The results of the initial selection process were outlined in a memorandum (Memo #NBHM-03) dated May 31, 2007. The following is a list of the alternative scenarios modeled to date:

- *Model Scenario NB-01*: Existing Conditions (described in Chapters V and VI)
- *Model Scenario NB-02*: Hurricane Barrier Removed
- *Model Scenario NB-03*: 24-ft Wide Culvert between Locations 5 and 6 (Figure IX-1)

The modeling results focused on quantifying the effects of installing additional openings in the Hurricane Barrier to both tidal circulation and water quality in Inner New Bedford Harbor. Since total nitrogen is the primary “pollutant” responsible for eutrophication in Massachusetts estuaries, modeling of nitrogen concentrations was utilized to assess water quality improvements.

The overall conclusion relating to the modeling effort is that the Hurricane Barrier is currently presenting only a very minor restriction to tidal exchange between the Inner New Bedford and Outer New Bedford Harbor waters (Tables ES-3,4,5). Therefore, installing a 24' box culvert would have negligible effect on volumetric exchange and tidal flushing, hence water or habitat quality within the Inner Harbor. The only potential effect might stem from a localized circulation enhancement at the mouth of the culvert, but the areal extent of this improvement is likely minor.

A. Results of *Model Scenario NB-01*: Existing Conditions

The computed flushing rates for the harbor show that as a whole, the system flushes well. A flushing time of 1.5 days for the entire harbor indicates that on average, water is resident in the system for approximately a day and a half. The system residence time for the upper portions of the harbor lags behind with a residence time of approximately a week. However, the local residence times show that the water passes rather quickly into the lower portions of the harbor from the Acushnet River and then past Popes Island into the outer harbor.

Generally, possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle.

For regions where a strong littoral drift exists, this assumption is valid. Since littoral drift in Buzzards Bay is typically strong because the local winds and tidal currents induce mixing within the regional estuarine systems, the “strong littoral drift” assumption only will cause minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the “strong littoral drift” assumption are within 10% to 15% of “true” residence times

B. Results of *Model Scenario NB-02*: Hurricane Barrier Removed

Comparing the tidal prisms and residence times with and without the barrier shows very minor differences, less than a half of percent of improvement in tidal prisms and flushing times. The minor improvements are not unexpected. The tidal constituent analysis in Table IX-1 revealed that the system had very minor attenuation through the barrier and into the upper reaches of the system. Therefore, only a minor improvement to the tidal propagation into the system will be achieved by removing the barrier. This lack of tidal attenuation indicates that the Hurricane Barrier does not cause large-scale degradation of inner harbor water quality.

While removal of the barrier does not lead to significant system-wide changes, it does have significant impacts on circulation in the vicinity of the barrier. Relative to quantitative changes to total nitrogen concentrations at various sites within the model domain, only a minor improvement in total nitrogen concentrations would result from removal of the Hurricane Barrier. Due to the relative hydrodynamic efficiency of the Hurricane Barrier main channel, tidal attenuation across the barrier is minor. This lack of tidal attenuation indicates that the Hurricane Barrier does not cause large-scale degradation of inner harbor water quality. Model results do indicate a marked improvement in the region southwest of Palmer Island, where total nitrogen reductions would be on the order of 4% or 0.2 mg/L as a result of enhanced circulation.

C. Results of *Model Scenario NB-03*: 24-ft. Wide Culvert between Locations 5 and 6

Comparing the tidal prisms and residence times with and without the 24-ft culvert shows negligible differences, less than 0.1% improvement in tidal prisms and flushing times. While addition of the 24-ft culvert does not lead to measurable system-wide changes, it does have impacts on circulation in the vicinity of the culvert. Specifically, the area immediately adjacent to the culvert experiences an increase in depth-averaged current speeds of over 0.2 feet per second, as a result of the proposed culvert. Relative to quantitative changes to total nitrogen concentrations at various sites within the model domain under scenario NB-03, only a minor improvement in total nitrogen concentrations would result from installation of the 24-ft culvert, and this area would be limited to the region south of Popes Island. The region southwest of Palmer Island indicated the largest water quality improvement, where total nitrogen reductions were on the order of 1% or 0.06 mg/L. As such, there may be some merit in improving tidal circulation within this enclosed basin immediately north of the western segment of the Hurricane Barrier.

It should be noted, however, that small improvements in flushing created by the additional culvert may actually reduce water quality within the upper regions of the system. Based on the water quality model results, total nitrogen concentrations show a very slight increase (~0.5%) within the upper reaches of the estuary as a result of the 24-ft culvert. Since the existing configuration of the estuary creates relatively efficient flushing, the addition of the 24-ft culvert actually redirects a small portion of the incoming tidal flow into the basin to the southwest of Palmer Island. However, the slight change in tidal circulation and the shape of the tidal signal relative to existing conditions causes an increase in mean volume of the upper portions of the estuary, allowing total nitrogen levels within this region to increase between 0.002 and 0.004 mg/L.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Acushnet River system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Acushnet River system include both upper watershed regions contributing to the major surface water inputs.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
ACUSHNET RIVER SYSTEM										
Upper Basin	1.855	40.337	7.562	-	47.899	2.836	45.081	95.815	0.62-0.79	--
Mid Basin	0.964	15.463	2.137	-	17.600	3.614	-28.561	-7.347	--	--
Lower Basin	1.088	159.540	5.973	145.3233	165.512	7.011	52.147	224.670	0.48-1.20	--
Acushnet River (fresh water)	8.833	61.164	38.279	-	99.444	-	-	99.444	0.70-1.38	--
Acushnet River System Total	12.740	276.504	53.951	145.3233	330.455	13.460	68.667	412.582	**0.48-1.38**	**0.5000**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing unattenuated wastewater treatment facility (Town of Fairhaven) discharges to lower basin of harbor
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of data collected between 2000 and 2006, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.
[8] benthic infauna threshold for sentinel site located at the head of the middle basin, just below the entrance to the channel to the upper basin.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Acushnet River system.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
ACUSHNET RIVER SYSTEM						
Upper Basin	47.899	22.948	2.668	45.081	70.697	-52.1%
Mid Basin	17.600	12.219	3.403	-28.561	-12.939	-30.6%
Lower Basin	165.512	62.668	6.674	52.147	121.490	-62.1%
Acushnet River (fresh water)	99.444	68.820	-	-	68.820	-30.8%
Acushnet River System Total	330.455	166.656	12.745	68.667	248.068	-49.6%

(1) Composed of combined natural background, fertilizer, runoff, WWTF, CFOs, and septic system loadings.
(2) Target threshold watershed load is the load from the watershed needed to meet the embayment threshold concentration identified in Table ES-1.
(3) Projected future flux (present rates reduced approximately proportional to watershed load reductions).
(4) Sum of target threshold watershed load, atmospheric deposition load, and benthic flux load.

Table ES-3. Embayment mean volumes and average tidal prism during simulation period for the Acushnet River system. Values in () under volumes represent the % change from existing conditions.

	Scenario NB01 (Present Conditions)		Scenario NB02 (Hurricane barrier removed)		Scenario NB03 (New 24 foot-wide culvert through hurricane barrier)	
Basin	Mean Volume (ft3)	Tide Prism Volume (ft3)	Mean Volume (ft3)	Tide Prism Volume (ft3)	Mean Volume (ft3)	Tide Prism Volume (ft3)
New Bedford Harbor (entire embayment)	602,576,038 (--)	184,051,554 (--)	608,514,944 (1.0%)	189,108,626 (2.7%)	602,559,842 (0.0%)	184,051,131 (0.0%)
Above Popes Island	207,498,930 (--)	91,615,362 (--)	207,345,624 (-0.1%)	92,815,067 (1.3%)	207,499,653 (0.0%)	91,621,613 (0.0%)
Acushnet River	43,307,006 (--)	38,317,453 (--)	43,278,417 -0.1%)	38,839,247 (1.4%)	43,306,975 (0.0%)	38,319,754 (0.0%)

Table ES-4. Computed System and Local residence times for embayments in the Acushnet River system.

	Scenario NB01 (Present Conditions)		Scenario NB02 (Hurricane barrier removed)		Scenario NB03 (New 24 foot-wide culvert through hurricane barrier)	
Basin	System Residence Time (days)	Local Residence Time (days)	System Residence Time (days)	Local Residence Time (days)	System Residence Time (days)	Local Residence Time (days)
New Bedford Harbor (entire embayment)	1.70	1.70	1.67	1.67	1.70	1.70
Above Popes Island	3.42	1.18	3.41	1.16	3.42	1.18
Acushnet River	8.18	0.59	8.15	0.58	8.18	0.59

Table ES-5. Comparison of model average total N concentrations from present conditions and Scenarios NB02 and NB03, with percent change, for the New Bedford Harbor system. The locations of stations A through E in the southwest lower basin are indicated in Figure VII-9. Change (%) relate to present conditions.

		NB01 (Present Conditions)	Scenario NB02 (no hurricane barrier)		Scenario NB03 (new 24' culvert)	
Sub-Embayment	monitoring station (MEP ID)	Total N (mg/L)	Total N (mg/L)	% change	Total N (mg/L)	% change
Estuary Upper Basin	2	0.754	0.756	0.30%	0.758	0.60%
Coggeshall Bridge	3	0.621	0.621	0.10%	0.623	0.40%
Popes Island East Bridge	6	0.505	0.503	-0.30%	0.505	0.00%
Lower Basin (North)	7	0.496	0.495	-0.30%	0.496	-0.10%
Lower Basin (Mid)	8	0.485	0.482	-0.50%	0.484	-0.20%
Lower Basin South of FTP	12	0.474	0.471	-0.50%	0.472	-0.30%
Lower Basin-Inside Inlet	9	0.458	0.455	-0.70%	0.457	-0.20%
Southwest Lower Basin - A	-	0.473	0.452	-4.30%	0.467	-1.20%
Southwest Lower Basin - B	-	0.473	0.454	-4.10%	0.469	-0.90%
Southwest Lower Basin - C	-	0.473	0.455	-3.80%	0.47	-0.70%
Southwest Lower Basin - D	-	0.475	0.459	-3.20%	0.471	-0.70%
Southwest Lower Basin - E	-	0.475	0.462	-2.80%	0.472	-0.60%

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First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by members of the Coalition for Buzzards Bay's BayWatcher, Water Quality Monitoring Program. These individuals gave of their time to consistent and sound nutrient related water quality from this system for over a decade. These data were enhanced by short-term intensive water quality monitoring efforts by the Coastal Systems Program at SMAST-UMD. These multiple efforts have resulted in a solid water quality database for this urban estuary, without which the present analysis would not have been possible.

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I. INTRODUCTION

The Acushnet River-New Bedford Inner Harbor Estuarine System is located within the City of New Bedford to the west and the Town of Fairhaven to the east, in the region referred to as southeastern Massachusetts. The estuary is bounded to the south by a constructed hurricane barrier that periodically (under storm surge conditions) closes off the mouth of the embayment system from outer New Bedford Harbor and Buzzards Bay (Figure I-1). The watershed for this embayment system is also distributed almost entirely within the City of New Bedford and the Town of Fairhaven with the uppermost portions of the watershed extending into the Towns of Rochester, Freetown and Lakeville. The Acushnet River-New Bedford Inner Harbor System is one of the region's and the Nation's significant marine resources in that it is a major active port, at the top of the nations annual commercial fish landings and supports one of the country's largest fishing fleets (Harbor Master Plan Committee 2000). The Acushnet River Estuary and associated harbor of New Bedford, Massachusetts is located on the northwestern shore of Buzzards Bay and is the major urban harbor within southeastern Massachusetts. As a historically active seaport, the harbor environment has been significantly altered by dredging, filling of wetlands and construction of piers and bulkheads to support marine industries. However, there remain major areas of this embayment where high quality marine resources can be supported.

The Acushnet River flowing seaward from the Towns of Lakeville and Freetown in the upper portions of the Acushnet River watershed provides steady freshwater flow to the headwaters of New Bedford Harbor, which is actually the estuarine reach of the Acushnet River. Freshwater flows from throughout the Acushnet River watershed ultimately discharge to Buzzards Bay through the hurricane barrier. Together, the estuary and the associated port are a complex coastal marine environment that forms the basis for numerous natural, social, cultural, and economic resources of the region. In the absence of comprehensive management, the system has suffered as development in the watershed has increased over the centuries.

Since their development as coastal communities, New Bedford and Fairhaven have supported port activities and industry associated with the Acushnet River and the lower Inner Harbor estuary. As a result the estuarine reach of the River has undergone numerous transformations. Each developmental transformation has had associated impacts on the condition of the estuarine environment. Generally accepted historical research has established that the development of the Acushnet River watershed progressed in four distinct phases: agricultural (1659 – 1780), whaling (1750 – 1900), textile (1880 – 1940) and post-textile (1940 to present). The post textile period was marked by the emergence of a mature and productive commercial fishing fleet as well as an assortment of industries, including electronic parts manufacturers. Each development phase of the watershed could be characterized by related environmental impacts to the estuarine system.

The environmental impacts of the agricultural period were associated most notably with land clearing in the watershed with some alteration of the water resources of the estuarine system, both by structures and a changing nutrient and sediment load. During the whaling period wharfs and the New Bedford-Fairhaven bridge (across Popes Island) were built, altering the hydrodynamic circulation as well as introducing contaminants such as biological wastes, lye, and caustic cleaning solutions. Additionally, peripheral industries serving the whaling fleet such as foundries, machine shops, casting, plating and metal working businesses, would have likely contributed environmental contaminants such as metals, solvents, acids, oils and greases.

Figure I-1. Acushnet River-New Bedford Inner Harbor study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters from Outer New Bedford Harbor and Buzzards Bay enter the Inner Harbor Estuary through the Hurricane Barrier. Freshwaters enter from the watershed primarily through the Acushnet River (up-gradient of Tar Kiln Road), direct groundwater discharge and to a lesser extent through the Fairhaven WWTF outfall and New Bedford Combined Sewer Overflows along the western shore, although this latter input has been reduced by ca. 90% over the past decade.

As the whaling industry declined and textile production took over as the main economic focus, wetlands were filled in throughout the estuary and mills were built on the newly available land. Loss of the wetlands translated into decreased habitat for terrestrial and aquatic resources as well as diminished natural filtration capacity for attenuating anthropogenically generated contaminant, nutrient, and bacterial inputs. The significant growth in the population within the watershed resulted in dramatic increases in sewage discharges to the estuary and harbor system as well as contamination of local shellfish resources.

More recently, during the post-textile period, industries and human activity introduced a host of new contaminants, Polychlorinated biphenols (PCBs), metals, effluent from fish processing plants and sewage treatment facilities, and others. During this period a major structural alteration of the estuary was put in place, the Hurricane Barrier, which was constructed in 1963-64. The result has been alteration of sedimentation and circulation patterns within the lower Harbor Basin.

Ultimately, the culmination of environmental contamination that occurred during the post-textile period prompted action by the United States Environmental Protection Agency (USEPA). In 1983 the EPA listed the Acushnet River Estuary/New Bedford Harbor as the first marine Superfund site, thereby necessitating remediation activities. In association with the EPA, the United States Army Corps of Engineers (USACE) has been supporting efforts to characterize and remediate the harbor since the mid-1980s. In 1990 a Record of Decision (ROD) was signed to begin cleanup activities in a five acre portion within the upper estuary. This initial remediation effort focused on reduction of PCB contamination within surficial sediments containing extremely high levels of total PCB's, 4,000 ppm to 200,000 ppm. A revised ROD was signed in 1999 modifying the effort to allow for a variety of alternative treatment/disposal options for processing the volume of removed contaminated sediment. Prior to the revised ROD of 1999, the EPA signed a different ROD in 1998 to address the cleanup of all of the harbor basins. Cleanup levels of 1 ppm, 10 ppm, 25 ppm, and 50 ppm were established for various zones within the estuary and provided for confined disposal facilities (CDFs) along the Harbor shoreline.

With the listing of New Bedford Harbor as a Superfund site, much attention has been directed towards the overall health and end use of the Acushnet River / New Bedford Harbor embayment system beyond the effects of PCB and organic contamination. Consideration for overall system health requires that managers (municipal) reconcile intended future uses of the natural resource with the ongoing environmental assaults to the system. Within the New Bedford Inner Harbor System, with PCB remediation underway, the major remaining impairment relative to full utilization as a recreational and socioeconomic resource is nutrient over-enrichment (nitrogen) and associated habitat and aesthetics impacts. This management challenge is further complicated by the need to develop the relationship between nutrient enrichment in the embayment under investigation and critical ecological parameters that can be used as measures for whether the embayment system is pristine (healthy / not stressed) versus impaired (unhealthy / stressed).

Nutrient related water quality decline represents one of the most serious and current threats to the ecological health of the near shore coastal waters of the Commonwealth. Coastal embayments like the Acushnet River Estuary / New Bedford Harbor embayment system, because of their shallow nature and large shoreline area, are generally the first indicators of nutrient pollution from terrestrial sources. For the Acushnet / New Bedford system nutrient impacts are compounded by the fact that the watershed draining to the system is the most heavily developed in all of the Buzzards Bay watershed. It is a commercial port with a host of marine related business such as boatyards, ferry terminal, fish processing facilities and ships chandleries. The Harbor is also important for recreation and supports approximately 400 moorings, the City of New Bedford's marina on Pope's Island, the Town of Fairhaven's public marina (near the Rt. 6 bridge), the Fairhaven Boatyard and a variety of other boat works.

Similar to other embayments in southeastern Massachusetts and on Cape Cod, the Acushnet River / New Bedford Inner Harbor is a eutrophic to mesotrophic (highly to moderately nutrient impacted) shallow coastal estuarine system. However, this embayment is unique in that it has been heavily altered over the course of history. For example, the typical measure of embayment habitat health, namely eelgrass bed coverage, does not apply to this estuary as this portion of the system has not had documented eelgrass for over half a century. This system is also unique in southeastern Massachusetts for its variety of wastewater discharges. The largest point source discharge within the Inner Harbor is from the Fairhaven Wastewater Treatment Facility (WWTF) at Arcene Street. Also, CSO discharges from the City of New Bedford are still operating after major rain events, although their flows have been reduced by ~90% through an aggressive remediation program over the past 10-15 years. Similarly, concern over direct discharges from boats has lead to installation of pump-out facilities by the City of New Bedford. So, while significant nitrogen discharges remain, the level of nitrogen loading to this system has been declining in recent decades over historic levels. However, this may be changing as development within the watershed is continuing.

Continuing development of the watershed, particularly for residential housing, is offsetting some of the gains in nitrogen loading reduction (mainly through CSO remediation). Like almost all embayments in southeastern Massachusetts, these new loads result primarily from on-site disposal of wastewater (septic systems). Fortunately, the City of New Bedford operates a recently upgraded WWTP which receives wastewater from a large portion of the highly urbanized section of the lower watershed to the system and similarly, the Town of Fairhaven also has sewered a large section of the residential area of the lower watershed to the Inner Harbor. Although this latter WWTF discharges to the Inner Harbor waters, the nitrogen load is somewhat reduced over on-site septic treatment and disposal. Within the upper watershed, the Town of Acushnet has completed a small sewering project and that wastewater flow is sent to the New Bedford WWTP. The unsewered areas of the upper watershed contribute to the nitrogen loading of the Acushnet River-New Bedford Inner Harbor System, both through transport in direct groundwater discharges to estuarine waters and through surface water flow to the headwaters of the estuary. For the purpose of the MEP analysis, 'direct groundwater discharge' refers to the portion of fresh water that enters an estuary as groundwater seepage into the estuary itself, as opposed to the portion of fresh water that enters as surface water inflow from streams, which receive much of their water from groundwater base flow.

The City of New Bedford and the Town of Fairhaven, as the primary stakeholders to the New Bedford Inner Harbor embayment system, have been concerned over the quality of this focal coastal resource. The community has worked to implement controls on direct stormwater discharges, PCB clean-up, and combined sewer overflows (CSOs) just to name a few remediation actions. In addition, the City of New Bedford and the Town of Fairhaven have supported the Coalition for Buzzards Bay's Water Quality Monitoring Program which has been collecting data on nitrogen related water quality within the Inner Harbor System since 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of the embayment and outer New Bedford harbor. The BayWatchers is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD. The common focus of the Coalition for

Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay and determine the relationship between observed water quality and habitat health. The present MEP effort is the necessary "next step" in the restoration of the New Bedford Inner Harbor System by providing quantitative restoration targets for nitrogen for on-going efforts by the City of New Bedford, Town of Fairhaven and the Coalition for Buzzards Bay.

In conjunction with the City of New Bedford and the Town of Fairhaven efforts, the Southeastern Regional Planning and Economic Development District (SRPEDD) has been able to assist the municipalities in enhancing available GIS tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that ongoing effort. Based on the wealth of information obtained over the many years of study of the Acushnet River-New Bedford Inner Harbor System, this embayment was originally included in the first round prioritization at the outset of the Massachusetts Estuaries Project to provide state-of-the-art analysis and modeling. Over the years, the analysis and report has been revised and updated per new information developed after the report was initially completed in 2008, much in the spirit of the MEP reports being living documents, available to be updated as funds and need dictates.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to update/refine wastewater master plans and nitrogen management alternatives development needed by the City of New Bedford and the Town of Fairhaven, as well as the Town of Acushnet. It should be noted that the MEP approach includes high-order, watershed and sub-watershed scale modeling necessary to develop critical nitrogen targets for portions of a given embayment systems or a singular target (threshold) at a sentinel station located at a strategic point in the system. The models, data, and assumptions used in this process are specifically intended for the purposes stated below in the MEP Report. As such, the MEP's Linked Model process does not contain the type of data or level and scale of analysis necessary to predict the fate and transport of nitrogen through groundwater from specific sources. In addition, any determinations related to direct and immediate hydrologic connection to surface waters are beyond the scope of the MEP's Linked Model process.

While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of City and Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for each municipality to develop and evaluate the most cost effective nitrogen management alternatives to restore this valuable coastal resource currently being degraded by nitrogen overloading.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over this assimilative capacity, which begins to cause declines in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities. At its higher levels, enhanced loading from surrounding watersheds causes aesthetic degradation and inhibits even recreational uses of coastal waters. In addition to nutrient related ecological declines, an increasing number of embayments are being closed to swimming, shellfishing and other activities as a result of bacterial contamination. While bacterial contamination does not generally degrade the habitat, it restricts human uses. However like nutrients, bacterial contamination is related to changes in land-use as watersheds become more developed. The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities.

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Bourne) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

Municipalities are seeking guidance on the assessment of nitrogen sensitive embayments, as well as available options for meeting nitrogen goals and approaches for restoring impaired systems. Many of the communities have encountered problems with "first generation" watershed based approaches, which do not incorporate estuarine processes. The appropriate method must be quantitative and directly link watershed and embayment nitrogen conditions. This "Linked" Modeling approach must also be readily calibrated, validated, and implemented to support planning. Although it may be technically complex to implement, results must be understandable to the regulatory community, town officials, and the general public.

The Massachusetts Estuaries Project represents the newest generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the MassDEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

In appropriate estuaries, TMDLs for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing). However, the goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation. As part of the overall effort, the evaluation and modeling approach will be used to assess available options for meeting selected nitrogen goals, protective of embayment health.

The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment model available to address future regulatory needs.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach. This approach represents the "next generation" of nitrogen management strategies. It fully links watershed inputs with embayment circulation and nitrogen characteristics. The Linked Model builds on and refines well accepted basic watershed nitrogen loading approaches such as those used in the Buzzards Bay Project, the CCC models, and other relevant models. However, the Linked Model differs from other nitrogen management models in that it:

- requires site specific measurements within each watershed and embayment;
- uses realistic "best-estimates" of nitrogen loads from each land-use (as opposed to loads with built-in "safety factors" like Title 5 design loads);
- spatially distributes the watershed nitrogen loading to the embayment;
- accounts for nitrogen attenuation during transport to the embayment;
- includes a 2D or 3D embayment circulation model depending on embayment structure;
- accounts for basin structure, tidal variations, and dispersion within the embayment;
- includes nitrogen regenerated within the embayment;
- is validated by both independent hydrodynamic, nitrogen concentration, and ecological data;
- is calibrated and validated with field data prior to generation of "what if" scenarios.

The Linked Model has been applied for watershed nitrogen management in ca. 60 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

The Linked Watershed-Embayment Model when properly parameterized, calibrated and validated for a given embayment becomes a nitrogen management planning tool, which fully supports TMDL analysis. The Model suggests "solutions" for the protection or restoration of nutrient related water quality and allows testing of "what if" management scenarios to support evaluation of resulting water quality impact versus cost (i.e., "biggest ecological bang for the buck"). In addition, once a model is fully functional it can be "kept alive" and corrected for continuing changes in land-use or embayment characteristics (at minimal cost). In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries.

Linked Watershed-Embayment Model Overview: The Model provides a quantitative approach for determining an embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold loading levels (TMDL) and (3) response to changes in loading rate. The approach is fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-2). This methodology integrates a variety of field data and models, specifically:

- Monitoring - multi-year embayment nutrient sampling
- Hydrodynamics -
  - embayment bathymetry
  - site specific tidal record
  - current records (in complex systems only)
  - hydrodynamic model
- Watershed Nitrogen Loading
  - watershed delineation
  - stream flow (Q) and nitrogen load
  - land-use analysis (GIS)
  - watershed N model
- Embayment TMDL - Synthesis
  - linked Watershed-Embayment N Model
  - salinity surveys (for linked model validation)
  - rate of N recycling within embayment
  - D.O record
  - Macrophyte survey
  - Infaunal survey

I.2 SITE DESCRIPTION

The Acushnet River Estuary / New Bedford Harbor embayment system is situated within the Buzzards Bay Basin. The Buzzards Bay Basin is located in southeastern Massachusetts and is comprised of portions of Plymouth, Bristol, and Barnstable Counties. Overall, the Buzzards Bay Basin is sparsely developed with land uses ranging from open land to agriculture (cranberry bogs and farmland) and residential. The most notable exceptions are the City of Fall River and the City of New Bedford, both of which are heavily populated and supportive of a broad range of land uses including high density residential and commercial classifications.

The Buzzards Bay Basin and associated Acushnet River / New Bedford Harbor embayment system exist within the Lowlands physiographic province of New England. The topography of the area is generally considered flat to gently rolling with coastal lands west of the Sippican River sub-basin regarded as low relief valley and ridge land forms following south flowing rivers (USGS WRI 95-4234). Based on the geologic setting described by the U.S. Geological Survey, the Buzzards Bay Basin and its sub-watershed are underlain by granitic (igneous) and metamorphic rock at a depth of between 100 and 200 feet below land surface (bls) depending on the location within the basin.

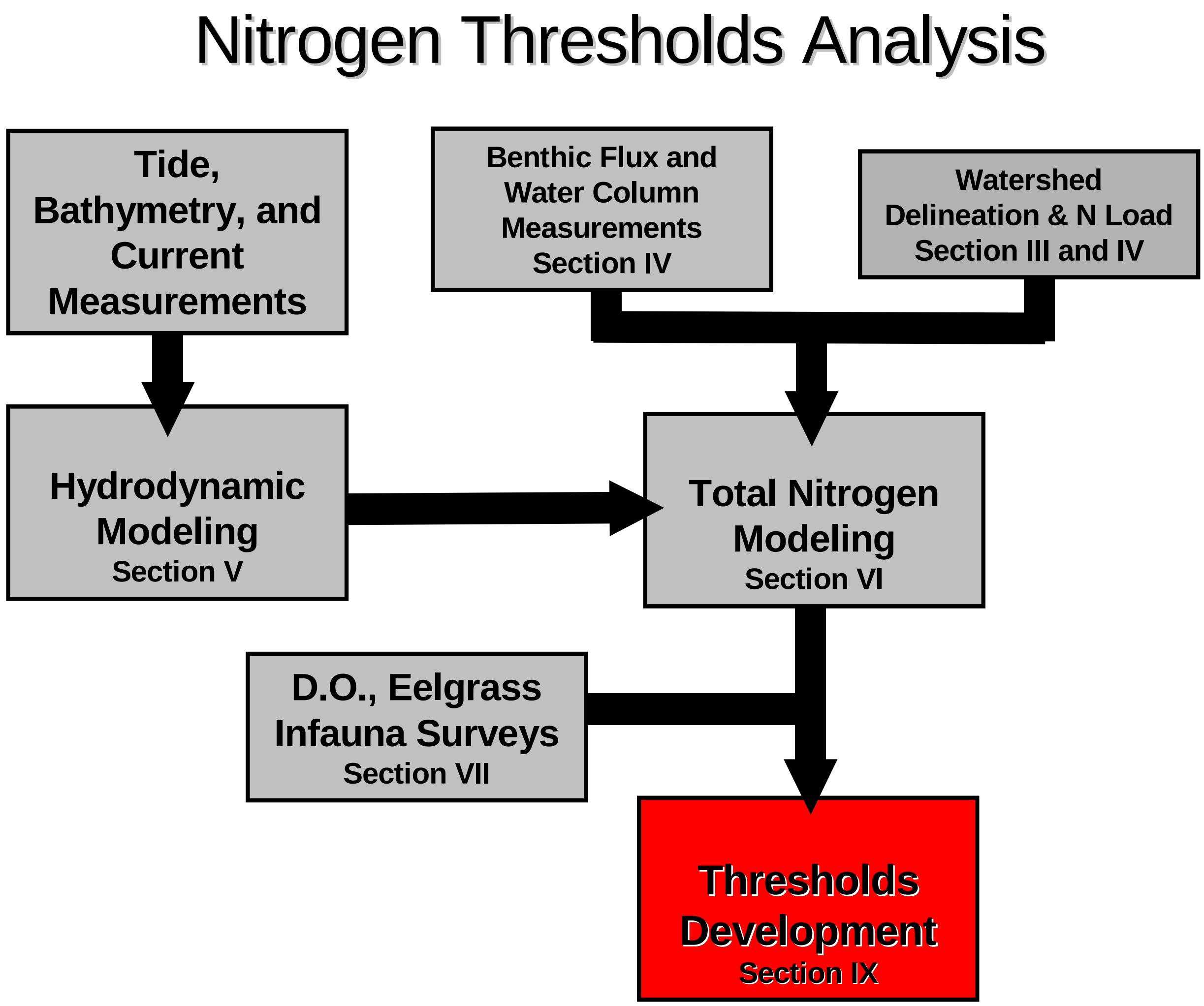


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

The watershed to the New Bedford Inner Harbor Estuary is geologically complex, characterized by glacial processes that defined the surficial geology of the region during the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~15,000 years ago. The basin is underlain primarily by granitic and metamorphic bedrock at depths ranging from outcrops at the land surface to approximately 100 to 200 feet below land surface depending on the location (Bent, 1995). Most of the surficial deposits in the Buzzards Bay Basin were deposited during the retreat of the glaciers during the last glacial period and are primarily composed of till and stratified drift deposits. Till was deposited over bedrock during the retreat of the glaciers and characterizes much of the Buzzards Bay Basin. The till is generally overlain by stratified drift deposits. As described by Melvin and others (Melvin, 1992) the till deposits in southern New England are relatively sandy and in areas overlain by stratified drift deposits the thickness of till layers can be less than 10 feet. In areas not overlain by stratified drift deposits the thickness of the till layer can be as much as 30 feet. Unlike till, stratified drift deposits are composed of

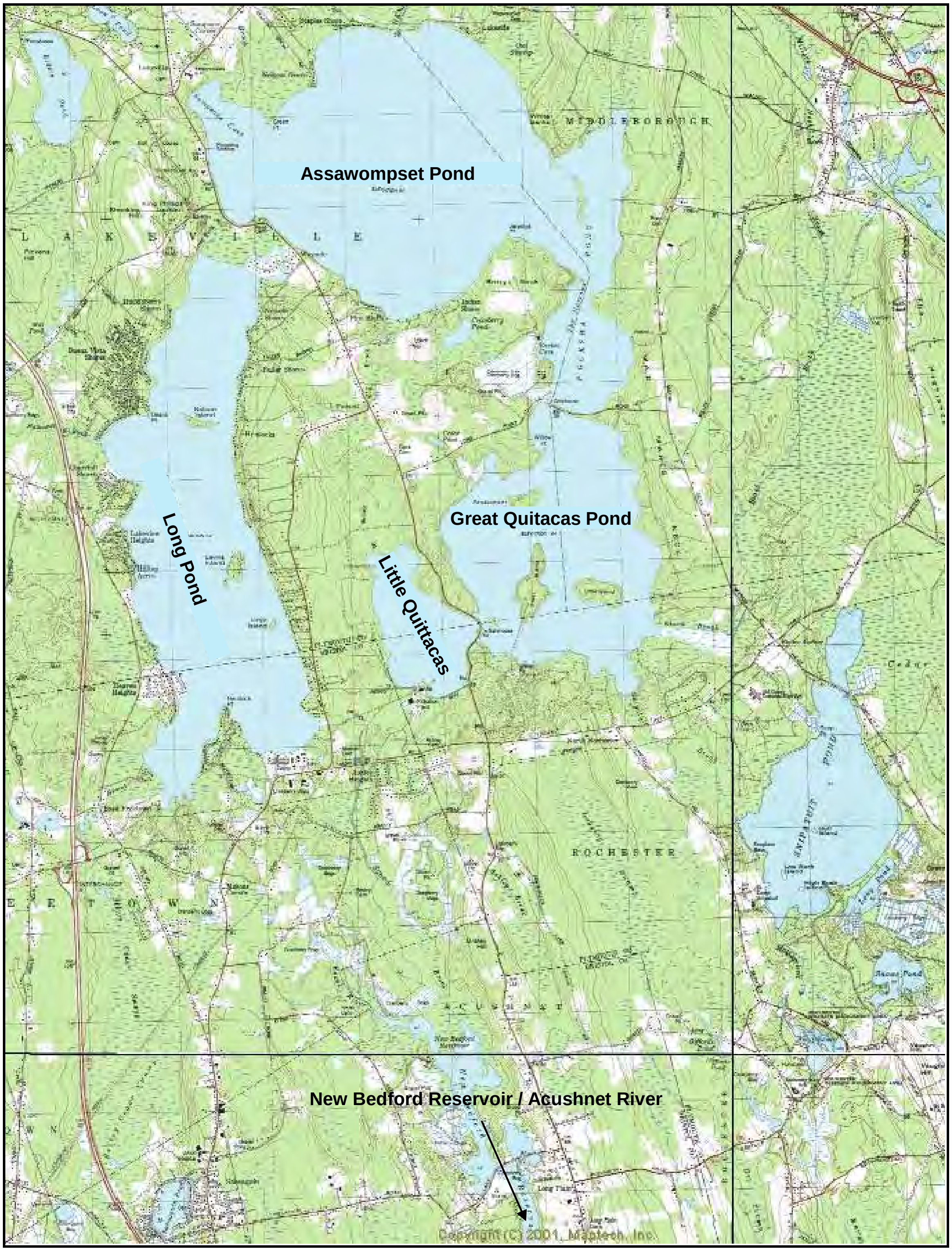


Figure I-3. Assawompset Pond network depicting the headwater region of the Acushnet River. Freshwater enters from the watershed primarily through 1 surface water discharge (Acushnet River up-gradient of Tar Kiln Road) and direct groundwater discharge

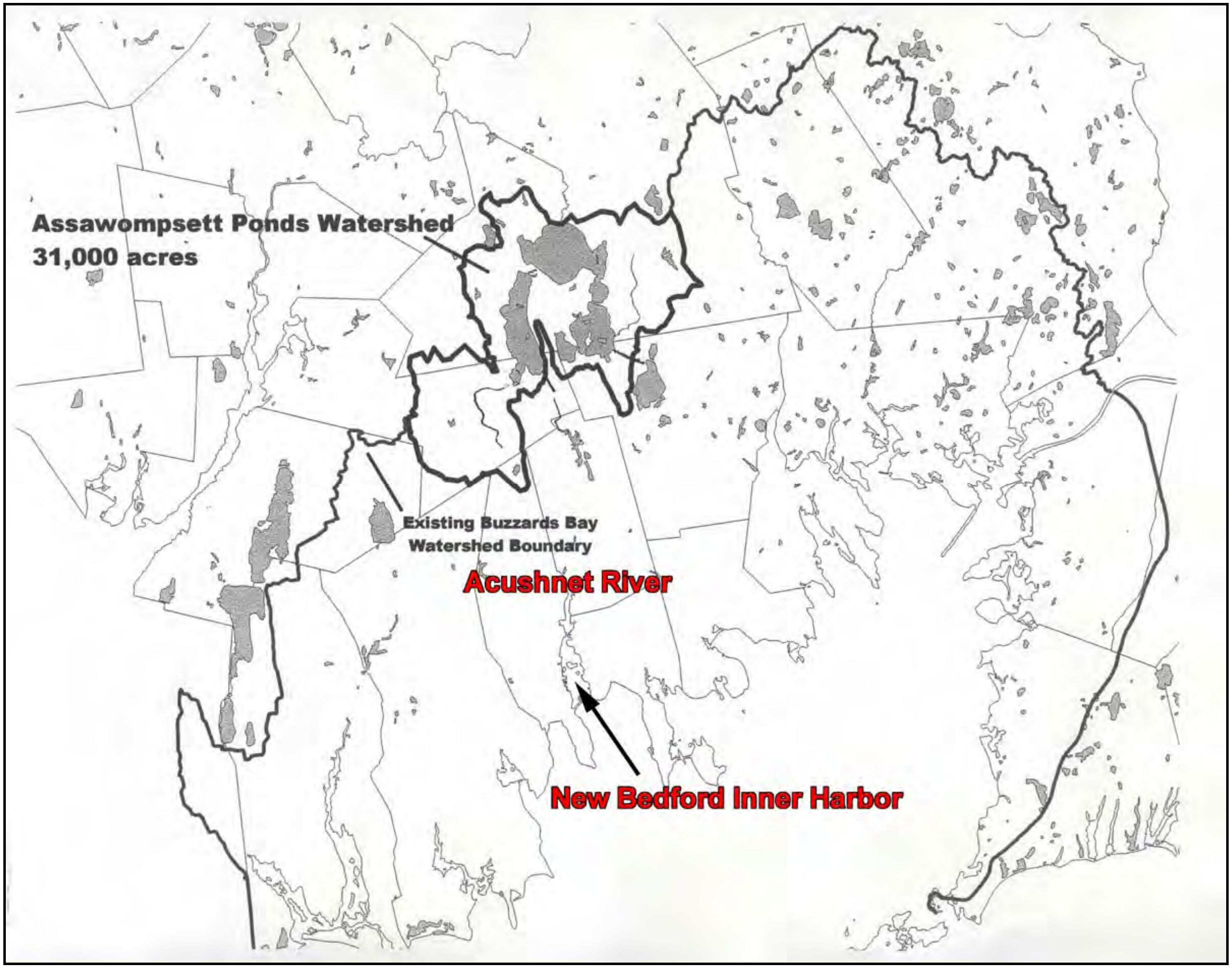


Figure I-4. Assawompset Pond sub-watershed flowing into the Taunton River relative to the Acushnet River and New Bedford Inner Harbor.

glaciofluvial and glacial lacustrine deposits of all grain sizes ranging from cobbles to clay (inclusive of silts, sands and gravels). The glaciofluvial deposits were generated mainly by glacial meltwater streams in outwash plains and river valleys (Stone and Peper, 1982). Glaciolacustrine deposits were generated during the presence of glacial lakes formed during the retreat of the ice sheet in southern New England and are comprised mainly of silts and clays as well as fine sands (Hansen and Lapham, 1992).

Within the watershed to New Bedford Inner Harbor, stratified drift deposits mainly follow a north-south trend consistent with the direction of river valleys and range in thickness from 0 feet to 200 feet (Williams and Tasker, 1978). In the upper watershed soils are composed predominantly of stratified drift deposits (sorted and layered glaciofluvial and glaciolacustrine deposits) whereas the lower watershed containing the Acushnet River / New Bedford Harbor embayment system appears to be a mix of till and bedrock deposits with stratified drift limited to the low relief valleys containing southerly flowing rivers such as the Acushnet River. Stratified drift deposits can range from 0 to 200 feet bls.

The varying surficial deposits lead to differing rates of groundwater recharge within the Buzzards Bay Basin. The National Weather Service (NWS) maintains a climatological station in New Bedford, MA, Based on climate data for the period 1951 to 1980, average annual precipitation ranges from 1.12 to 1.23 m/year (43.9 to 48.6 in./year). Precipitation is considered uniformly distributed through the year with the summer months of June and July being the driest (total precipitation for two months < 0.08 m). NWS rainfall records indicate that December is typically the wettest month with an average precipitation equal to 0.127 m for the month. This results in an annual mean groundwater recharge rate for the Acushnet River watershed of 27.25 inches, as estimated by the US Geological Survey.

The New Bedford Harbor embayment system is an estuary with a relatively large river originating south of the Assawompset Pond network located in the most up-gradient region of the watershed. A site survey was conducted to confirm flows within the complex. The Assawompset Pond complex consists of Long Pond to the west and south (flowing into Assawompset Pond), Little Quittacas connected to Great Quittacas, also flowing into Assawompset Pond but located south of Assawompset Pond and east of Long Pond. Fall Brook flows into Long Pond from the West. Long Pond in turn flows north into Assawompset Pond that flows into the Taunton River as a sub-watershed to the broader Taunton River watershed. In addition, Little Quittacas Pond is directly connected to Great Quitticas Pond that flows into Assawompset Pond via Pocksha Pond. (Figure I-3). Adjacent to the Assawompset Pond watershed and to the south is the New Bedford Reservoir watershed which is the uppermost subwatershed of the New Bedford Inner Harbor Watershed (Figure I-4). The headwaters of the Acushnet River appear to be located south of Long Pond and Little Quittacas Pond and water within the Acushnet River flows south through the New Bedford Reservoir ultimately discharging into the estuarine portion of the Acushnet River, herein called, New Bedford Inner Harbor. The New Bedford Inner Harbor Estuarine System acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Buzzards Bay, however, the salinity characteristics of the system varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with Buzzards Bay.

The Acushnet River Estuary is a drown river valley estuary on the northwestern shore of Buzzards Bay, from which it receives flood tidal waters through an artificial structure, the New Bedford Hurricane Barrier (built in 1963-64). The estuarine basin falls within the City of New Bedford and the Town of Fairhaven, with upper watershed areas including parts of the Towns of Acushnet and Rochester. The Estuary currently has relatively good tidal flushing, due to its relatively large tide range. The upper watershed contributes freshwater and nitrogen primarily through the Acushnet River. There are no significant tributary sub-embayments within this system. The estuary can be partitioned into an upper (north of Rt. 195), middle (Rt. 195 to Popes Island) and lower region (Popes Island to Hurricane Barrier).

The Acushnet River estuary was the nation's first marine Super-Fund Site, due to PCB contamination from manufacturing activities in the near shore region of New Bedford. It is clear that for ecological restoration of this estuary, the remediation of PCB contamination is necessary, but not sufficient. Nutrient management also will be required. In addition to current Super-Fund activities the lower region of the harbor is currently being dredged for navigational purposes (i.e. to maintain the port functions). Other large projects affecting this system include the opening of the new wastewater treatment facility for New Bedford, which discharges through an outfall offshore from the tip of Clarks Point, and the upgrading of the CSO system. Also, Fairhaven is currently in the process of wastewater planning as part of the permit renewal for its existing wastewater treatment facility which discharges through an outfall to the lower basin.

The New Bedford Inner Harbor is a shallow eutrophic to mesotrophic (highly to moderately nutrient impacted) coastal estuarine system.. For the MEP analysis, the Inner Harbor embayment was analyzed as a stand-alone system, which will be linked to the Outer New Bedford Harbor model at a future date. Similar to other embayments in the region (e.g. Westport River, West Falmouth Harbor and others), New Bedford Inner Harbor has focused freshwater input at the headwaters via the Acushnet River and exchanges tidal water with the higher quality waters of the Outer Harbor and Buzzards Bay. The habitat quality of the Acushnet River-New Bedford Inner Harbor system is tightly coupled to its watershed nitrogen inputs and to the level of tidal flushing through its inlet (hurricane barrier) to Buzzards Bay, which exhibits a moderate tide range of about 5 ft. Since the water elevation difference between the Bay and Harbor is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft). The Acushnet River-New Bedford Inner Harbor is a true estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from Buzzards Bay. Salinity in the harbor ranges from approximately 30 ppt. at the inlet to less than 10 ppt. at the uppermost estuarine reach. However, salinities throughout all of the basins is generally >27 ppt.

Given the present hydrodynamic characteristics of the Acushnet River-New Bedford Inner Harbor embayment system, it appears that estuarine habitat quality is mostly dependent on the level of nutrient loading to embayment waters as opposed to tidal characteristics, although both aspects are analyzed as part of the MEP Approach. In the Inner Harbor, minimal enhancements to tidal flushing may be achieved via modification of the hurricane barrier or channel dredging in the harbor thereby resulting in some mediation of the nutrient loading impacts from the watershed. The details of such are a part of the MEP analysis described later in this report.

I.3 NITROGEN LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In glacially dominated aquifers with a mix of sandy outwash, till and stratified drift, such as in the watershed to the Acushnet River-New Bedford Inner Harbor embayment system and others in the region, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since rivers in the region are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems, especially the case on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Tidal reaches within the Acushnet River-New Bedford Inner Harbor system follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

Nutrient related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters. Coastal embayments, because of their enclosed basins, shallow waters and large shoreline area, are generally the first indicators of nutrient pollution from terrestrial sources. By nature, these systems are highly productive environments, but nutrient over-enrichment of these systems worldwide is resulting in the loss of their aesthetic, economic and commercially valuable attributes.

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. As nearshore coastal salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the water body itself, can have chronic and long lasting impacts on these fragile coastal environments.

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the “allowable N concentration increase” or “threshold nitrogen concentration” used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the New Bedford Inner Harbor Estuary monitored by the Coalition for Buzzards Bay BayWatchers Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to “tune” general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, within the New Bedford Inner Harbor Estuary, the upper most basin (north of I-195) appears to be beyond its ability to assimilate additional nutrients without impacting ecological health. However, nitrogen levels are elevated throughout the estuary and there are presently no eelgrass beds, although eelgrass can be found at the margins of the Outer Harbor basin. The result is that nitrogen management of the system is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, it is considered "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within a given embayment system could potentially occur without human influence and must be considered in the nutrient threshold analysis. While this finding would not change the need for restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a "pristine" system.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" for water quality modeling of the New Bedford Inner Harbor estuarine system; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within the system. Therefore, water quality modeling of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the Acushnet River-New Bedford Inner Harbor System and each of its basins: Upper, Middle and Lower. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by the USGS and field verification by the MEP. Virtually all nitrogen entering the embayment system is transported by freshwater, predominantly groundwater, either through direct discharge or after discharging to a stream flowing to estuarine waters. Concentrations of total nitrogen and salinity of Buzzards Bay source waters and throughout the inner harbor system was taken from the Coalition for Buzzards Bay BayWatchers Monitoring Program (associated with the Coastal Systems Program at SMAST) and from additional sampling efforts within the inner harbor system and Buzzards Bay nearshore waters by MEP staff. Measurements of nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the New Bedford Inner Harbor Estuarine System for the City of New Bedford, the Town of Fairhaven and the Town of

Acushnet. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from SRPEDD data and offshore water column nitrogen values were derived from an analysis of monitoring stations in Buzzards Bay (Section IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section IV. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of each embayment was performed that included a review of existing water quality information, temporal changes in eelgrass distribution, dissolved oxygen records and the results of a benthic infaunal animal analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration in a given estuarine basin. This latter assessment represents only one of many solutions and is produced to assist the municipalities that reside in the overall watershed to develop a variety of alternative nitrogen management options for the Acushnet River-New Bedford Inner Harbor System. Finally, analyses of the system was relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of the effects of dredging options to improve nitrogen related water quality in the overall system. The results of the nitrogen modeling for each scenario have been presented (Section IX).

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

Nutrient additions to aquatic systems cause shifts in a series of biological processes that can result in impaired nutrient related habitat quality. Effects include: 1) excessive plankton and macrophyte growth leading to reduced water clarity, 2) organic matter enrichment of waters and sediments, with the concomitant resulting increased rates of oxygen consumption and periodic depletion of dissolved oxygen (especially in bottom waters), and 3) the limitation of the growth of desirable species such as eelgrass. Even without changes to water clarity and bottom water dissolved oxygen, the increased organic matter deposition to the sediments generally results in a decline in habitat quality for benthic infaunal communities (animals living in the sediments). This habitat change causes a shift in infaunal communities from high diversity deep burrowing forms (which include economically important species), to low diversity shallow dwelling organisms. This shift alone causes significant degradation of the resource and a loss of productivity to the local shell fisherman, the sport-fishery and offshore fin fishery, all of which are dependent upon these highly productive estuarine systems as a habitat and food resource during migration or during different life cycle phases. This process is generally termed "eutrophication" and in embayment systems, unlike in shallow lakes and pond, it is not a necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the New Bedford Inner Harbor System, bordered by the City of New Bedford and the Town of Fairhaven, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds as well as the resultant concentrations of water column nitrogen. Additional development of the approach generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2002).

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions (based upon watershed nitrogen loading and embayment recycling) and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Acushnet River – New Bedford Inner Harbor System. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of "data mining" and to gather additional information on an estuary's habitat quality or unique features.

New Bedford Inner Harbor has been the subject of a wide range of data collection efforts and studies related both to its PCB contamination and clean-up, restoration of its PCB damaged resources and identifying and quantifying sources of watershed nutrient and bacterial loadings to the estuary. While the purpose of much of the PCB related study was aimed at determining impacts of PCB's, fate and transport and later planning for PCB "clean-up" under the Super Fund effort, some information was found to be directly relevant to the nutrient related health of the Inner Harbor and therefore, the present MEP assessment and modeling effort. The MEP Technical Team reviewed key prior studies (a) focused on nutrients and related water and habitat quality and (b) related to the Superfund effort, but which contained information related to aspects of the MEP assessment and modeling approach.

Nutrient and Habitat Studies

Concern over the health of Buzzards Bay's tributary embayments has resulted in a number of studies relating to the nutrient related health of the New Bedford Inner Harbor System over the past 2 decades. These investigations include both habitat assessments and studies relating to nitrogen loading, hydrodynamics and habitat health. While none of the previous studies was able to link watershed nitrogen loading and attenuation processes with quantitative hydrodynamics of the estuary, some did focus on developing nitrogen thresholds for the restoration of this estuary. These studies provide useful information to the present MEP effort. Other earlier efforts were generally survey studies to evaluate this estuary and its watershed within the larger regional system or to examine aquifer properties.

An initial watershed land-use and nitrogen loading analysis was conducted by the Buzzards Bay Project (BBP 1996) as part of a survey of all of the tributary embayments to Buzzards Bay. This survey used Mass GIS 1984 land-use coverage. The results indicated that the system appeared to be receiving nitrogen inputs more than 2 times that which would maintain high quality waters (Massachusetts SB Classification). While the overall watershed based nitrogen loads developed by the BBP have basically held true, the analysis is insufficient to simulate changes in nitrogen within the estuary under different management alternatives. In addition, as the land use models did not account for nitrogen attenuation by the wetland ecosystems (no data available), the models would have overestimated the role of nitrogen sources in upper (inland most) sub-watersheds compared to the direct groundwater watersheds to the estuary. While watershed delineation and nitrogen loading data from earlier efforts were considered by the MEP, direct use of the modeling results was problematic. Since the BBP land use model was based upon watershed delineations which have been updated by the MEP in collaboration with the USGS, the contributing areas are slightly different (Chapter III). In addition, improved modeling of the CSO inputs to the Harbor and parcel specific nitrogen loads throughout the watershed, as well as MEP refined watershed nitrogen loading model (e.g. to incorporate attenuation and new nitrogen source information), results in a more quantitative approach and therefore the MEP analysis supersedes earlier studies.

The City of New Bedford as one of the primary stakeholders to the New Bedford Inner Harbor System has been concerned over the declining quality of this coastal resource. The community has worked to implement controls on stormwater discharges (and specifically CSO discharges) and has recently completed an upgrade to its WWTF that collects wastewater from much of the lower watershed to the Harbor basin. The closing off of CSOs discharging to the Inner Harbor has resulted in a significant reduction in what was once the single major nitrogen input to this basin (approximately 90% reduction). While CSO remediation efforts continue, other sources have now become dominant. The City of New Bedford, along with its wastewater consultant (Camp Dresser and McKee Inc.) has conducted a detailed investigation and modeling effort related to the CSO discharges. This effort expanded upon the previous models and was of sufficient quality to be integrated into the MEP nitrogen loading analysis (Chapter IV), to provide this critical nitrogen loading information (CDM, 2006).

The MEP hydrodynamic modeling of the Inner Harbor System benefited from a prior effort examining the role of the Hurricane Barrier and how it affects hydrodynamics in the Harbor (Abdelrhman, 2002). This study developed a two-dimensional model to simulate circulation patterns and gradients in conservative constituents, to determine changes related to the construction of the Hurricane Barrier. Another hydrodynamic study related to tidal exchange and nitrogen/salinity transport through the Hurricane Barrier (inlet to the Inner Harbor), was conducted by the Coastal Systems Program at SMAST, with assistance from ACRE engineers.

This research project measured volumetric flow and exchanges of salt and nutrients between the Inner Harbor and offshore waters. These data provide for an additional level of validation of the MEP Water Quality Model (Chapter VI). Hydrodynamic analysis has also been conducted relative to determining the fate and transport of nutrient discharges from the Fairhaven WWTF, directly to Harbor waters through an outfall in the nearshore area of the eastern side of the lower basin (ASA, 2002). This analysis provided some considerations as to circulation within the Harbor basins, but as a result of various technical difficulties, did not provide quantitative information to the present effort.

Finally, the MEP analysis requires high quality water quality data in order to complete its assessment and modeling approach. The Coalition for Buzzards Bay's Water Quality Monitoring Program has been collecting data on nutrient related water quality throughout the New Bedford Harbor System for more than a decade. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of each of Buzzards Bay's embayments and harbors. The BayWatchers is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD. The program has a USEPA and MassDEP approved Quality Assurance Project Plan (QAPP), which was operational over the entire period of 2000-2006 (data period for this MEP analysis).

The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay to support evaluations of observed water quality and habitat health. The BayWatcher Water Quality Monitoring Program in the New Bedford Inner Harbor Embayment System developed a data set that elucidated the long-term water quality of this system (Costa et al. 1996. Howes et al. 1999).

In addition to the BayWatcher water quality data, the Coastal Systems Program at SMAST-UMass Dartmouth has periodically conducted intensive nutrient related system-wide sampling of New Bedford Inner Harbor as part of a partnership project with the New Bedford Oceanarium and as part of its research programs. These data were collected and analyzed consistent with the MEP QAPP protocols and are comparable to other MEP water quality data. In addition to water quality data, the Coastal Systems Program has conducted a variety of estuarine research projects related to nitrogen transport and habitat quality within the Inner Harbor System. These efforts collected records of dissolved oxygen, vertical structure of the harbor waters and detailed small scale variation in harbor nutrient gradients.

The BayWatcher Program (integrated with the other smaller efforts noted above) provided the quantitative watercolumn nitrogen data (2000-2006) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon the previous watershed delineation and land-use analyses, river transport and attenuation data, and embayment water quality and eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Acushnet River – New Bedford Inner Harbor System. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the New Bedford Inner Harbor System.

PCB Contamination and Restoration:

Numerous studies have been performed regarding the degraded state of the Acushnet River-New Bedford Inner Harbor system. A wide variety of projects have been undertaken and numerous more projects have been proposed, of which a portion have been funded and in some cases implemented. A Restoration Plan and Environmental Impact Statement (EIS) was developed by the New Bedford Harbor Trustee Council (NBHTC or Council) as well as a harbor management plan to guide remediation activities. Additionally, the New Bedford/Fairhaven Harbor Master Plan was funded several years ago to address, in part, issues concerning wastewater treatment plant discharges to New Bedford Inner Harbor from the Town of Fairhaven.

Though clean-up of the Acushnet River Estuary - New Bedford Harbor system is underway under the supervision of the EPA, attention is gradually turning towards restoration of the aquatic habitat. As such the Council is working to coordinate restoration with clean-up. Restoration actions not directly dependent on the progress of the clean-up are being evaluated for near term implementation. The trustees are working with citizens, businesses, academic institutions, state and local governments, and non-profit organizations to develop and select restoration alternatives for the New Bedford Harbor environment.

Priorities for restoration include marshes and wetlands, recreational areas, water quality, living resources, habitats, and shellfish and endangered species. The trustees have identified a number of potential restoration actions that address those priorities. Collectively, these actions will begin to restore an ecosystem severely degraded by long-term contaminant releases, industrial development and shoreline modification. Some of the Round I restoration activities that are funded for study and in some cases implementation include:

- **Hurricane Barrier Box Culvert -** Install an additional opening in the Hurricane Barrier at the mouth of the Acushnet River to increase tidal exchange between the Harbor and Buzzards Bay. (Army Corps of Engineers to study feasibility)
- **Eelgrass Habitat Restoration -** Survey eelgrass within the harbor, identify eelgrass habitat, select priority areas for restoration, and plant eelgrass in these areas to provide fish and shellfish habitat. (Funded for two years, completed)
- **Restoration and Management of the New Bedford Area Shellfishery -** Restore shell fishing in the Harbor by purchasing and planting adult and seed quahogs, relaying contaminated adult quahogs to clean areas for depuration, and purchasing and spreading bay scallop and soft shell clam seed. (First year completed, applied for second year funding)
- **New Bedford/Fairhaven Harbor Master Plan -** Assist in the development of open space planning and use through the comprehensive New Bedford/Fairhaven Harbor Master Plan. (Funded)
- **Wetlands Inventory -** Study wetlands within the New Bedford Harbor Environment to identify and plan for future wetlands restoration. (Funded)

Additionally, several years ago the Council's second round of requests for restoration ideas was closed. Thirty five ideas requesting approximately $35 million were received. To date, the Council has considered all comments and recommendations and has issued a final decision on the received ideas. Some of the Round II Restoration Actions included funding to be provided for the following:

- **Marsh Island Restoration** - Restoration of the salt marsh at Marsh Island, Fairhaven.
- **Marine Fish Stock Enhancement** - A feasibility study to determine whether a facility to raise species that have been injured by PCB contamination for replacement of species injured or to provide a clean food source for the food chain can meet the Trustees goals. If justified by the study then funding would be provided for design and construction of the facility.
- **Regional Shellfish Grow Out System** - Shellfish would be restored through the construction and startup of a shellfish grow out up-well system or through funding of an existing facility to provide shellfish seed for transplant.
- **Upper Sconticut Neck Shellfish/Sewer Installation*** - A study to determine the sources impacting closed shellfish beds in Outer New Bedford Harbor. Results of the study could provide justification for the Council to release additional funds to assist in design and engineering to correct the problem.

A number of studies and data collection efforts of particular note related to the Superfund effort yielded significant information to the present MEP effort. Key among these was a synthesis of the ecological history of the Harbor, since the early agricultural period, 1650 to present day (Pesch et al. 2001). This history provides significant insight into the highly altered nature of New Bedford Inner Harbor, the regions main urban embayment, and what its undisturbed environs may have been like.

Another integrative study of the shellfish resources and their management was undertaken as part of the Trustee's Restoration Action. The City of New Bedford and Towns of Fairhaven and Dartmouth, working with Coastal Systems Program staff located at SMAST-UMass Dartmouth, recently completed a Regional Shellfish Management Plan for the Town's waters. The overall goal of the effort was to: 1) improve the management of the region's shell fisheries, 2) provide information helpful for the restoration of the shell fishery in the New Bedford Harbor area that has experienced reduction in PCB contamination and 3) elucidate issues related to nutrient related habitat decline, bacterial contamination and over-fishing. It will take a similar type of collaborative effort to develop and implement nitrogen management plans for the New Bedford Inner Harbor Estuary.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Acushnet River Estuary/New Bedford Inner Harbor watershed is located along the northern edge of the Buzzards Bay watershed basin. The Buzzards Bay Basin is the result of glacial processes that defined the surficial geology of the region during the retreat of the Cape Cod Lobe of the Laurentide Ice sheet approximately 18,000 years ago. The underlying granitic and metamorphic bedrock is located at depths ranging from surface outcrops to approximately 100 to 200 feet below land surface depending on one's location in the basin (Bent, 1995). Most of the surficial deposits in the Buzzards Bay Basin were deposited during the retreat of the glaciers during the last glacial period and are primarily composed of till and stratified drift deposits. The till is generally overlain by the stratified drift deposits, but is found at the land surface more frequently in the western portion of the basin. As described by Melvin and others (1992), the till deposits in southern New England are relatively sandy. In areas not overlain by stratified drift deposits, the thickness of the till layer can be as much as 30 feet. Unlike till, stratified drift deposits are composed of sorted and layered glaciofluvial and glacial lacustrine deposits of all grain sizes ranging from cobbles to clay (inclusive of silts, sands and gravels). The glaciofluvial deposits were generated mainly by glacial meltwater streams in outwash plains and river valleys (Stone and Peper, 1982), while glaciolacustrine deposits were generated during the presence of glacial lakes. The fluvial deposits tend to have coarser materials (*e.g.*, sands and gravels), while the lacustrine deposits tend to be finer materials (*e.g*., silts and clays). Stratified drift deposits in the Mattapoisett River valley and westward along Buzzards Bay tend to follow north-south river valleys and range in thickness up to 200 feet within the Buzzards Bay Basin (Williams and Tasker, 1978). As these materials are heterogeneous throughout the Buzzards Bay Basin and are characterized by varying permeabilities and hydraulic conductivities, direct rainwater run-off is typically higher than for the sandy outwash sediments along the eastern shore of Buzzards Bay (*i.e.*, Cape Cod). Therefore, freshwater inflow from northern Buzzards Bay rivers leading to the estuarine systems tends to be a significant transport mechanism along with usual direct groundwater discharge to the estuarine receiving water.

III.2 WATERSHED DELINEATION APPROACH

A watershed divide or boundary can be described as the line from which rainwater or snowmelt flows on the surface and through groundwater towards one stream, river or estuary, while rainfall and groundwater on the other side of the divide flows away to another water body. In addition, the water table, or the surface of the saturated sediments (aquifer), also tends to reflect the changes in surface elevation within bedrock and till dominated landscapes, but can be modified by layers of low hydraulic conductivity sediments within the aquifer. The technique of topographic inspection begins with developing an understanding of the watershed stratigraphy and hydrogeology to determine the validity of this method of watershed delineation. In the case of the Acushnet River Estuary/New Bedford Inner Harbor the surficial till on high elevation areas and outwash in valleys and the dominance of bedrock in forming the watershed supports the use of this method. Analysis focuses on determining the pattern of lines of local maximum elevation upon a US Geological Survey 1:25,000 topographic map and draws watershed divides based upon the tendency of surface water and groundwater to flow downhill perpendicularly to the topographic contour lines. Divides drawn upon topographic maps can be confirmed by observing general patterns of groundwater flow and surface water flow during rainfall or snow melt or by measuring the flow of water in streams over a hydrologic cycle.

The initial watershed delineation for the Acushnet River Estuary/New Bedford Inner Harbor was conducted in 1991 by the US Geological Survey as part of determining the watersheds for all the sub-embayments to Buzzard Bay for the Buzzards Bay Project, now the Buzzards Bay National Estuary Program (BBP, 1991). The boundaries were determined by the method of topographic inspection and focused on the outer boundary of each sub-embayment. MEP staff reviewed the delineation for the Acushnet River Estuary/New Bedford Inner Harbor and generally found it to be sufficient for advancing a land-use analysis of this system. In order to complete the MEP assessment, however, subwatershed delineations were developed to address the major freshwater features in the estuary watershed (*e.g.*, New Bedford Reservoir and Acushnet River gauge) and to provide nitrogen loadings at spatial scales matching the sub-embayment segmentation of the MEP tidal hydrodynamic model (*e.g.,* Middle Acushnet River and Lower Acushnet River on either side of the I-195 crossing of the estuary).

Six (6) subwatersheds were delineated based mostly on topographic inspection for the MEP analysis of the Acushnet River Estuary/New Bedford Inner Harbor (Figure III-1). Portions of the subwatershed delineations in the City of New Bedford were adjusted to match the city's stormwater collection system (discussed below). The delineations allow proper distribution of watershed nitrogen loads in the MEP water quality modeling. The subwatersheds include contributing areas to the freshwater portion of the Acushnet River. Delineation of this subwatershed allows direct comparison between the expected discharge flows and nitrogen loads from the delineated area and measured data from MEP stream gauge. This effort also supported quantification of nitrogen attenuation prior to discharge to estuarine waters. Attenuation is a critical element in the development of the inputs to the estuary water quality model (see section IV.2).

Based upon the delineated sub-watersheds and annual recharge, freshwater streamflow and direct groundwater input were determined for the Acushnet River Estuary/New Bedford Inner Harbor estuary system (Table III-1). The streamflow estimate determined by this method is compared to measured streamflows collected by the MEP (see Section IV). Annual recharge was based on a review of available precipitation data for the region. The National Oceanic and Atmospheric Administration (NOAA) maintains a long-term precipitation gauge in New Bedford. Annual average precipitation at this site between 1961 and 2000 is 47.8 inches (CDM, 2006), while the average between 1971 and 2000 is 50.8 inches (NOAA, 2004). Review of NOAA data from this site between 2002 and 2006, the period associated with the MEP analysis, shows an average annual precipitation of 50.3 inches. Given good agreement between the long-term precipitation rate and precipitation during the MEP stream measurement period, MEP staff assessed that the near long term average at New Bedford (50.77 in/yr) was most appropriate annual precipitation rate for further analysis.

A portion of precipitation is utilized by plants on the land surface (transpiration) and a portion is evaporated back into the atmosphere. USGS recharge rates used in groundwater modeling on Cape Cod are approximately 60% of long-term precipitation rates (*e.g.*, Walter and Whealan, 2005). USGS modeling of recharge in the Charles River basin, which is more similar to the geology of the Acushnet River Estuary/New Bedford Inner Harbor watershed, has found recharge variations of 43 to 56% of precipitation with a strong reliance on measured streamflows for the development of the model (DeSimone, *et al.*, 2002). Given the uncertainty in many of the factors for developing the percentage of recharge, MEP staff conservatively assumed 60% of precipitation or 30.5 inches per year is an appropriate recharge rate in the Acushnet River Estuary/New Bedford Inner Harbor watershed. It should be noted that this rate provides reasonable agreement between measured and estimated streamflows in other stream watersheds reviewed by the MEP. This recharge rate is used to develop the long-term freshwater inflows in Table III-1 and is also used in the watershed nitrogen loading estimates (see Section IV). It should also be noted that this recharge analysis is used for comparison of

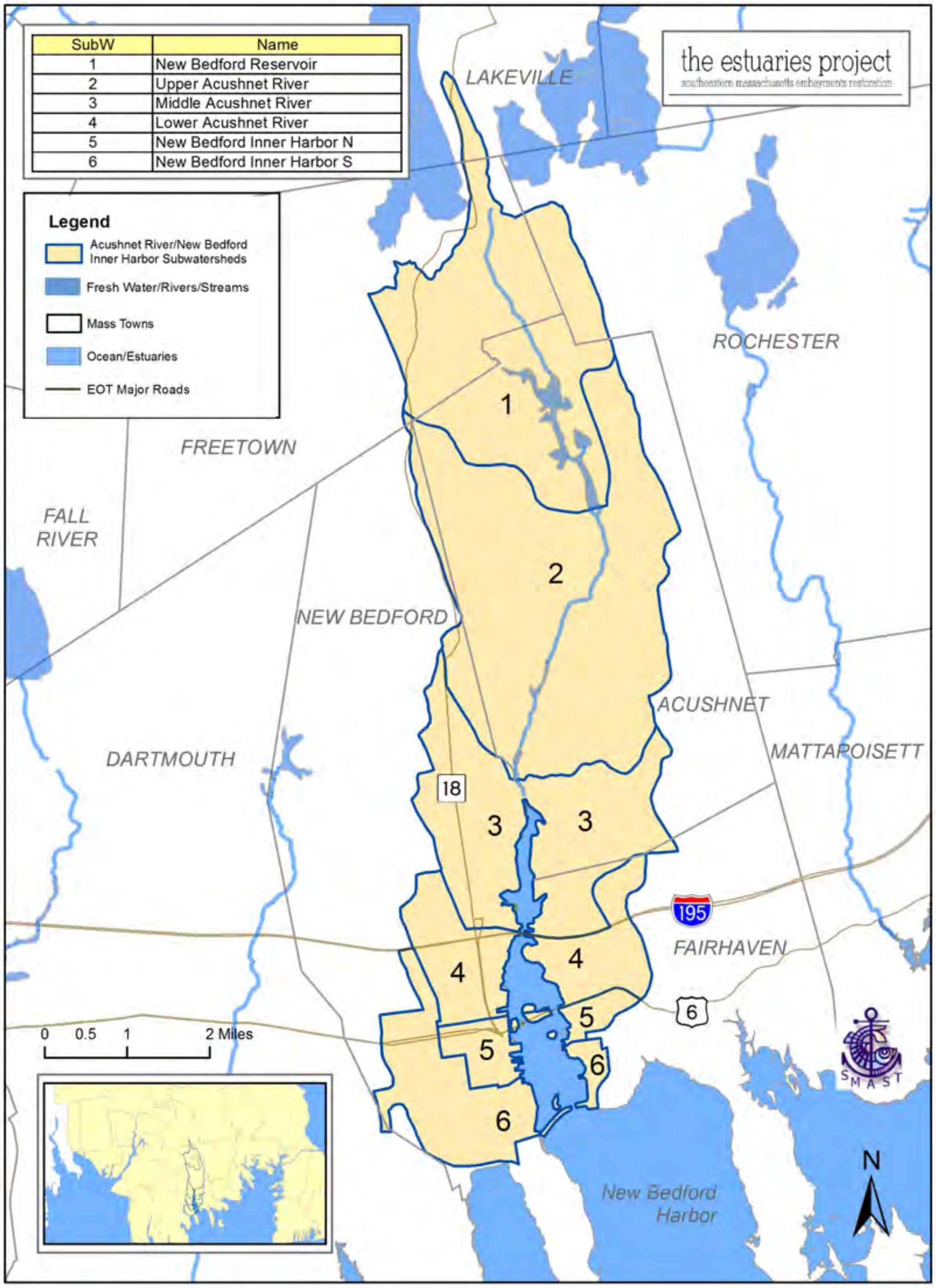


Figure III-1. Watershed and sub-watershed delineations for the Acushnet River/New Bedford Inner Harbor estuary system. Outer watershed boundary is based on USGS/BBP (1991) topographic delineation with adjustments in the lower eastern boundary to reflect the collection area of the City of New Bedford stormwater system. Interior subwatershed delineations were completed by MEP staff using the same topographic examination techniques; interior subwatershed delineations were completed to match natural watershed or estuary features (*e.g.*, New Bedford Reservoir or basins on either side of I-195 crossing) or key measurement points (*e.g.*, MEP stream gauge at Tar Kiln Road).

Table III-1. Acushnet River/New Bedford Inner Harbor MEP Subwatershed Areas and Estimated Long-Term Freshwater Recharge.

Watershed Name	#	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
New Bedford Reservoir	1	4,735	40,617	1,434,371
Upper Acushnet River	2	6,431	55,170	1,948,294
Middle Acushnet River	3	3,265	28,006	989,036
Lower Acushnet River	4	1,834	15,731	555,529
New Bedford Inner Harbor North	5	612	5,249	185,376
New Bedford Inner Harbor South	6	1,623	13,921	491,601
ACUSHNET RIVER/NEW BEDFORD HARBOR SYSTEM TOTAL		18,499	158,693	5,604,207

Notes:
1) discharge volumes are based on 30.46 inches of annual recharge over the watershed;
2) recharge is based on 60% of annual precipitation of 50.77 inches (1971-2000 average at New Bedford NOAA gauge);
3) area does not include the surface of the estuary
4) flows do not include precipitation on the surface of the estuary;
5) totals may not match due to rounding.

measured and modeled annual stream flow and for providing an independent check on stream watershed areas, but does not directly influence the nitrogen loading analysis for this system (Section IV).

Storm Drain and Sewer Networks

In more urbanized areas much of the precipitation falls on impervious surfaces and flows into municipal storm drain networks. In the City of New Bedford and Town of Dartmouth portions of the Acushnet River/New Bedford Inner Harbor estuary watershed, these municipal networks may cause surface drainage that may not agree with the watershed boundaries determined by topographic inspection. In portions of the Acushnet River Estuary/New Bedford Harbor watershed within the City of New Bedford, this relationship is more complicated because the municipal storm drain system contains sections that mix stormwater with sewage/wastewater. These sections were built during a time when it was thought that this mixing would be more cost effective (CDM, 2006). The design of these portions of the system include structures that keep sewage flowing toward the City's wastewater treatment facility, but also pressure relief points to prevent sewage surcharge into basements or city streets. These pressure relief points are combined sewer overflows (CSOs) and they discharge into New Bedford Harbor and the Acushnet River. Details on their discharge locations and the measured loads are included in Section IV, but key portions of the collection areas for the stormwater system cause adjustments in the watershed boundary delineation to the Acushnet River Estuary/New Bedford Inner Harbor estuary system. The USGS/BBNEP watershed boundaries were adjusted to reflect the pattern of the storm drain networks in only one area, the divide along the eastern, common divide between the Slocums River watershed and the Acushnet River-New Bedford Harbor watershed. In this specific area, the watershed delineation was shifted to reflect the New Bedford storm drain-sewer network. The net effect of the boundary adjustments for storm drains in the Slocums River watershed was a 310 acre decrease in the Slocums River basin area.

Confirmation of the Upper Watershed Delineations in the Vicinity of Long Pond

MEP staff also reviewed and confirmed the boundary of the USGS/BBNEP watershed delineations in the upper portions of the watershed for the Acushnet River/New Bedford Inner Harbor (Figure III-2). Limited field reconnaissance on the part of others (*e.g.*, Coalition for Buzzards Bay) had raised questions regarding whether or not there was a hydraulic connection between Long Pond and New Bedford Reservoir (sub-watershed to the Acushnet River). Long Pond is located in the Assawompset Ponds watershed, which is part of the larger Taunton River watershed according to USGS watershed delineations. The main concern raised was that that water and associated nutrients from Long Pond are discharging into the Acushnet River/New Bedford Harbor/Buzzards Bay system rather than the Taunton River system.

The Assawompset Pond complex consists of Long Pond to the west and south (flowing into Assawompset Pond), Little Quittacas connected to Great Quittacas, also flowing into Assawompset Pond but located south of Assawompset Pond and east of Long Pond. Fall Brook flows into Long Pond from the West. Long Pond in turn flows north into Assawompset Pond that flows into the Taunton River as a sub-watershed to the broader Taunton River watershed. In addition, Little Quittacas Pond is directly connected to Great Quittacas Pond that flows into Assawompset Pond via Pocksha Pond (see Figure III-2).

Adjacent to the Assawompset Pond watershed and to the south is the New Bedford Reservoir watershed which is a sub-watershed of the broader Acushnet River/New Bedford Inner Harbor Watershed. The 1978 Assawompset Pond USGS Quadrangle map shows a direct connection from Long Pond to the bogs north of Squam Brook flowing into the New Bedford Reservoir (headwater to the Acushnet River). Field reconnaissance by MEP staff confirmed the presence of a creek flowing south towards the bogs north of Squam Brook, however, the creek did not appear connected to Long Pond at the time of the two site visits conducted on November 18, 2002 and February 12, 2003. The southerly flow in the creek was traced upgradient to try and identify the source water and it did not appear to be Long Pond. A small channel (approximately 1.0 meter wide) leaving Long Pond was observed paralleling a public boat landing parking lot (Figure III-3). The channel was partially dry on the November 18, 2002 visit to the site, despite a strong northerly wind blowing down the main fetch of Long Pond. The wind direction should have potentially stacked water up at the southern end of the pond where the small channel was identified and facilitated flow from the pond. However, although the channel did contain a small amount of water, it did not show flow from the pond. The channel appeared to cross under the road (Lakeside Avenue) leading to the public boat launch via a 12-inch culvert. The culvert drains the small volume of water in the channel to the east side of Lakeside Avenue that is characterized as a dying red maple swamp. There is no discrete channel conveying water through the swampland. Based on the field reconnaissance, it is likely that the flow found in the small creek connecting to Squam Brook discharging to the New Bedford Reservoir originates in the swamp land located to the east of Lakeside Avenue, rather than from water flowing from Long Pond.

Considering the local topography, Lakeside Avenue appears to serve as a hydraulic divide between Long Pond and nearby lowlands. It is assumed that the culvert passing under Lakeside Avenue exists as a means to pass water under the road under extreme meteorological conditions, but does not conduct daily flow. The observed southerly flow in the un-named creek flowing to Squam Brook was calculated using velocity measurements at one cross-section located downgradient of the culvert that passes flow in the creek under Morton Road in Ashley Heights (East Freetown). It should be noted that these observations were taken during a period that is currently being considered near drought conditions, however, there are no obvious signs that water levels in Long Pond are unusually low. Using velocity measurements taken on November 18, 2002, flow in the un-named creek was calculated to be 0.017 m^3/s (0.61 cfs). This flow rate converts to approximately 0.39 mgd which is a relatively small flow compared to the Acushnet River discharge (average of 20.23 mgd over the period March 2002 to December 2002).

Given the relative differences between the flows, modification of the existing watershed delineation for the New Bedford Reservoir to include Long Pond did not seem warranted. If the watershed delineation to the New Bedford reservoir were modified to include Long Pond, a significant amount of additional land area and potential flow would be added to the New Bedford Reservoir/Acushnet River watershed based on only minimal measured flow. Field observations were forwarded to the USGS and reviewed with hydrologists familiar with the watershed. As a result of the field observations and subsequent discussions, there was general agreement that the watershed delineation should not be altered. No changes were made to the upper watershed delineation as it was originally developed by Frimpter (1974) and as presented in this report.

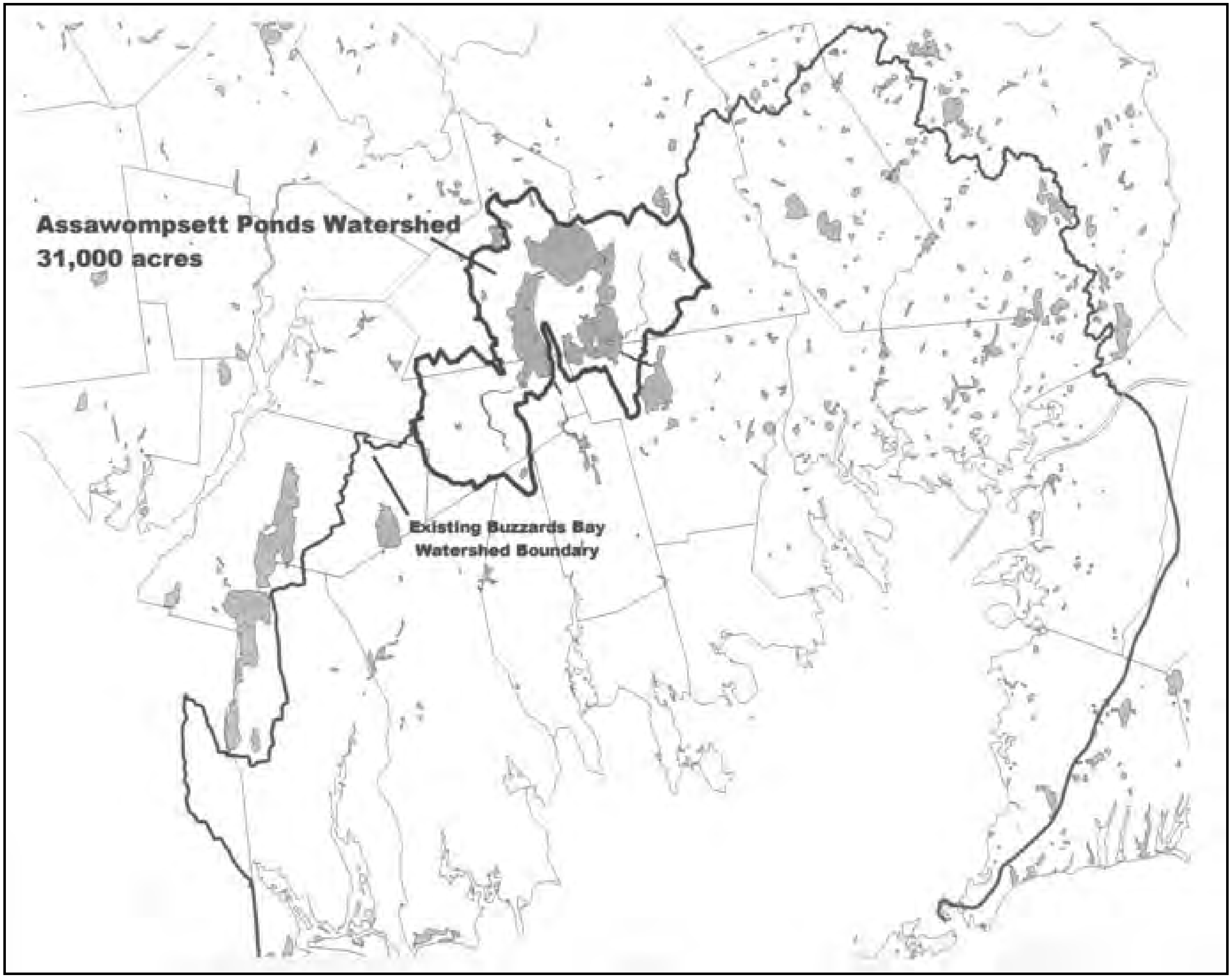


Figure III-2. Watershed delineation for Assawompset Pond and Buzzards Bay. MEP staff conducted field investigations that confirmed the USGS/BBNEP watershed boundary in the Assawompset Pond area.

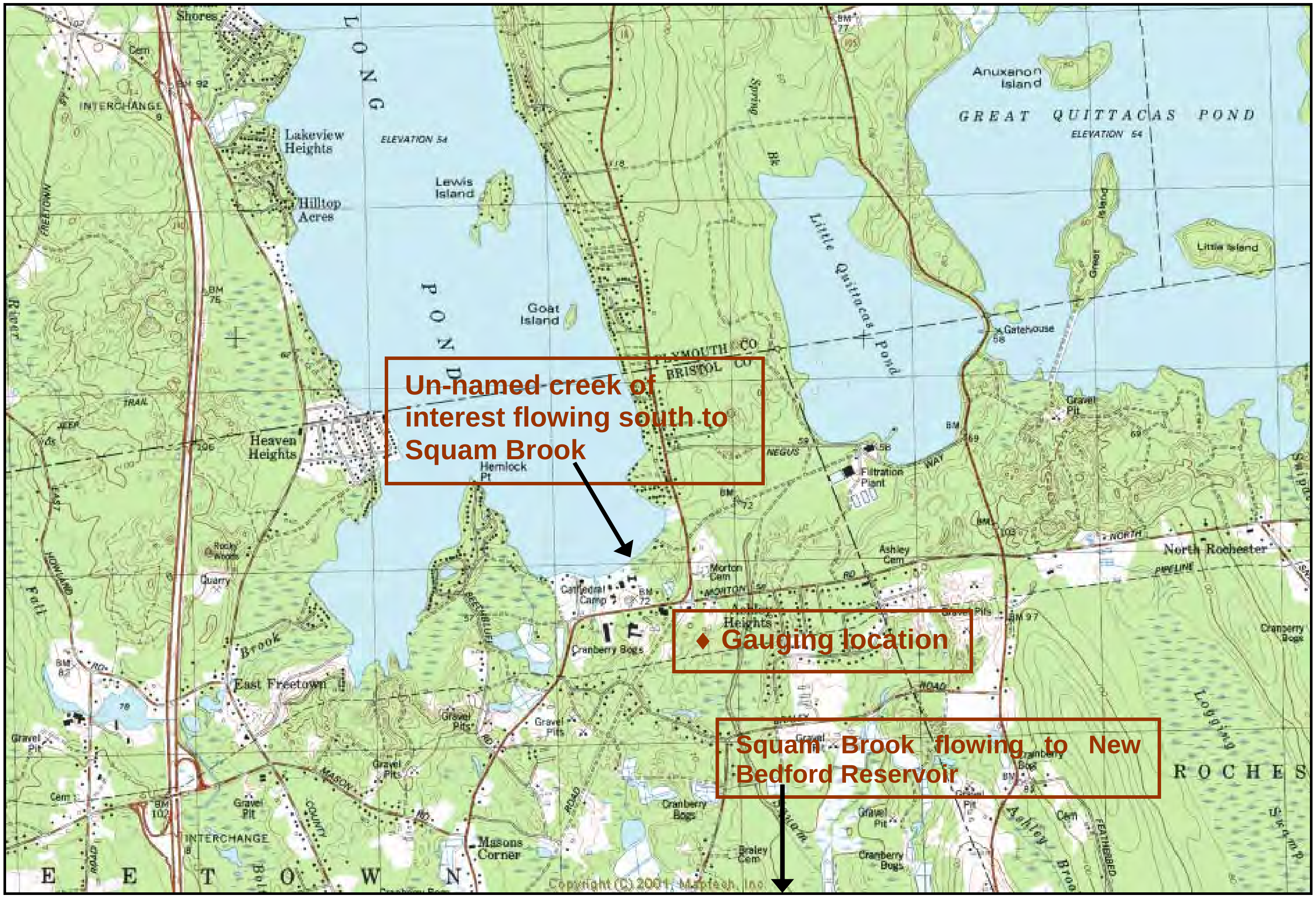


Figure III-3. Southern portion of Assawompset Pond system.

IV. WATERSHED NITROGEN LOADING TO EMBAYMENT: LAND USE, STREAM INPUTS, AND SEDIMENT NITROGEN RECYCLING

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

Management of nutrient related water quality and habitat health in coastal waters requires determination of the amount of nitrogen transported by freshwaters (surface water flow, groundwater flow) from the surrounding watershed to the receiving embayment of interest. In southeastern Massachusetts, the nutrient of management concern for estuarine systems is nitrogen and this is true for the Acushnet River/New Bedford Inner Harbor system as well. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that the transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes. This latter natural attenuation process results from biological processes that naturally occur within ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Permanent burial of nitrogen is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom. Failure to include the nitrogen balance of estuarine sediments generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters.

In order to determine watershed nitrogen loading inputs to the Acushnet River/New Bedford Inner Harbor estuary system, the MEP Technical Team developed nitrogen loading rates (Section IV.1) to each component of the estuary and its watersheds (Section III). This effort was coordinated with staff from the towns and city in the watershed, as well as the Buzzards Bay National Estuary Program (BBNEP). The Acushnet River/New Bedford Inner Harbor sub-watersheds were delineated to define contributing areas to the two main freshwater features (*i.e.*, Acushnet River and New Bedford Reservoir) and to each major portion of the estuary. A total of six sub-watershed areas were delineated within the Acushnet River/New Bedford Inner Harbor study area (see Section III). Freshwater inflow to the Acushnet River/New Bedford Inner Harbor Estuary is predominately river input; discharge from the Acushnet River accounts for approximately 60% of the watershed inputs to the estuary (see Chapter III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This generally involves a temporal review of land use changes, review of data at natural collection points, such as streams and ponds, and, in groundwater dominated systems, the time of groundwater travel provided by a USGS groundwater model. The Acushnet River/New Bedford Inner Harbor watershed system is a stream-dominated system because of its underlying geology, so this portion of the review focused heavily on land use development and data from stream gauges. Comparison of subwatershed nitrogen loads to the overall system estimates show that 64% of the unattenuated load is in the lower portion of the watershed, which was evident once the land use map was reviewed. In addition, the distance from the edges of the watershed to the Acushnet River, its tributaries, or adjacent wetlands is generally less than 0.6 km (~2,000 ft) often with wetlands or feeder streams extending to within hundreds of meters of the watershed boundaries. If it is assumed that groundwater discharge is the only mechanism for transfer of nitrogen and water to the main stem of each stream and that groundwater travels at approximately 1 ft/d (a common assumption in porous outwash or till materials), the areas furthest from the primary stream channels (close to the sub-watershed boundaries) would take less than six years to reach the main stem. Since the groundwater system is constrained by underlying bedrock and USGS quadrangles show extensive tributaries feeding into the Acushnet, flow to the Acushnet River in the northern portions of the watershed must be 10 years or less from the outer edges of the watershed. In the southern, more urban, portion of the watershed, extensive wastewater and stormwater collection systems ensure that discharge to the estuary from the edges of the watershed generally occurs within months. Given that other MEP reviews in groundwater-dominated systems have shown that if most development is within 10 years or less, then the watershed and nitrogen loads are in relative balance with the estuary nitrogen concentrations, the MEP has a high level of confidence that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuaries (after accounting for natural attenuation discussed below).

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used to develop nitrogen loads from most areas, while information developed from other detailed site-specific studies is applied to the remaining portions of the watershed. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon sub-watershed specific land uses and pre-determined nitrogen loading rates based on detailed source studies in southeastern Massachusetts. For the Acushnet River/New Bedford Inner Harbor Embayment System, the model uses land-use data from the City of New Bedford and the Towns of Fairhaven, Acushnet, Rochester, Lakeville, and Freetown. This land-use data is transformed to nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel-by-parcel water use). Determination of the nitrogen loads required obtaining watershed-specific information regarding wastewater (including municipal sewer connections), fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” or unattenuated nitrogen load to each receiving embayment, since attenuation during transport is included at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea within the Acushnet River/New Bedford Inner Harbor watershed was determined based upon site-specific measurements of stream flow at a gauge on the Acushnet River. A subwatershed to this stream discharge point allowed comparison between field-collected data from the river and estimates from the nitrogen-loading sub-model. Stream flow and associated surface water attenuation is included in the MEP nitrogen attenuation and freshwater flow investigation, presented in Section IV.2. If smaller aquatic features that have not been included in this MEP analysis were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources within the watershed.

Based upon the evaluation of the watershed system, the MEP Technical Team used the watershed Nitrogen Loading Model to estimate nitrogen loads for the sub-watersheds that directly discharge groundwater to the estuary without flowing through one of these interim stream measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Acushnet River/New Bedford Inner Harbor Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Since the watershed to the Acushnet River/New Bedford Inner Harbor includes portions of the City of New Bedford and the Towns of Fairhaven, Acushnet, Rochester, and Freetown, Estuaries Project staff obtained the most up-to-date, digital parcel and tax assessor's data from these municipalities to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data for Acushnet, Rochester, and New Bedford are from 2010, while the Fairhaven data are from 2009 and the Freetown data are from 2005. Fairhaven data were developed as part of buildout assessment completed by the BBNEP (Rockwell, 2010). Additional assistance was subsequently provided by BBNEP to link available water use and sewer account databases to the respective parcels. These land use databases contain traditional information regarding land use classification based on MassDOR (2012) land use codes. Significant effort was made to reconcile and link all of the databases, including QA/QC by MEP staff to review incomplete entries in the datasets.

Figure IV-1 shows the land uses within the Acushnet River/New Bedford Inner Harbor estuary watershed areas. Land uses in the study area are grouped into ten land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) undeveloped, 6) agricultural, 7) recreational, 8) forest (Chapter 61 properties), 9) public service/government, including road rights-of-way, and 10) freshwater features (*e.g.* ponds and streams). These land use categories, except the freshwater features, are aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2012). These categories are common to each town in the watershed. "Public service" properties in the MassDOR coding system are tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, open space, roads) and private non-profit groups like churches and colleges.

In the overall Acushnet River/New Bedford Inner Harbor System watershed, the predominant land use based on area is residential, which accounts for 39% of the overall watershed area (Figure IV-2). This percentage is similar in most of the system sub-watersheds, which range from 28% (New Bedford Inner Harbor North) to 43% (New Bedford Inner Harbor South). Public service/ROW areas account for the second largest area (24% of the overall watershed area), followed by parcels classified as undeveloped (12%). Other land use categories are less than 10% of the total area. Public service/ROW areas range from 14% to 49% of the subwatershed land areas.

Parcel counts present a different perspective; residential parcels are the majority of parcels in almost all of the sub-watersheds and in all the groupings in Figure IV-2. Residential parcels are 83% of all parcels in the overall watershed and range between 64% and 89% of the total parcel counts in the six subwatersheds. Undeveloped parcels are the second highest percentage of the watershed parcel counts, accounting for 6% of the parcel count for the entire watershed. This type of information provides a sense of how many potential land owners exist in each subwatershed portion and how information on watershed management strategies might be tailored to address predominant land uses and concerns. Review of average undeveloped lot size shows that the average undeveloped watershed parcel is 1.4 acres, but average parcels are much larger in the upper, river watershed (2.1 acres in the two upper subwatersheds) and generally less than 0.6 acre in the lower watersheds. This finding suggests that the majority of the undeveloped parcels in the lower, urban portion of the watershed are likely already subdivided and surrounded by developed parcels, while parcels in the upper, more rural portion of the watershed could be subdivided further. Single-family residences (MassDOR land use code 101) are 52% to 94% of residential parcels in the individual sub-watersheds with the highest percentages (>90%) in the upper, freshwater river subwatersheds. These parcels are also the majority of the area of residential development; 78% of overall watershed lands classified by town assessors as residential are single family residences. Analysis of these numbers also shows that higher percentages exist in the upper, river subwatersheds and lower (generally <65%) in the lower, estuarine subwatersheds.

MEP analyses generally use water use as a proxy for wastewater flows and these loads are adjusted for any sewer collection systems. In the Acushnet River/New Bedford Inner Harbor watershed, the Towns of Fairhaven, Freetown, and Acushnet and the City of New Bedford provided municipal water use databases for individual parcels. Developed parcels in the portions of the watershed in the Towns of Rochester and Lakeville rely on private wells for drinking water. Sewer billing records in New Bedford, Fairhaven, and Acushnet were used to identify parcels with sewer connections. With the help of the BBNEP, these databases were linked to the town parcel GIS coverages and used in the watershed nitrogen loading model to provide subwatershed-specific wastewater nitrogen loads. Review of the resulting databases showed a number of properties, mostly government or other 900's land use code, that did not have water use or sewer billing. Given that most of these were within New Bedford sewered areas and the New Bedford wastewater is treated and discharged outside of the Acushnet River/New Bedford Inner Harbor watershed, efforts were not undertaken to clarify the water use from these parcels. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the average water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2). Project staff also obtained facility performance data from MassDEP for the Town of Fairhaven wastewater treatment facility, which does discharge within the watershed. There are other permitted discharges in the watershed, however, according to MassDEP they do not contribute a significant flow or nitrogen load.

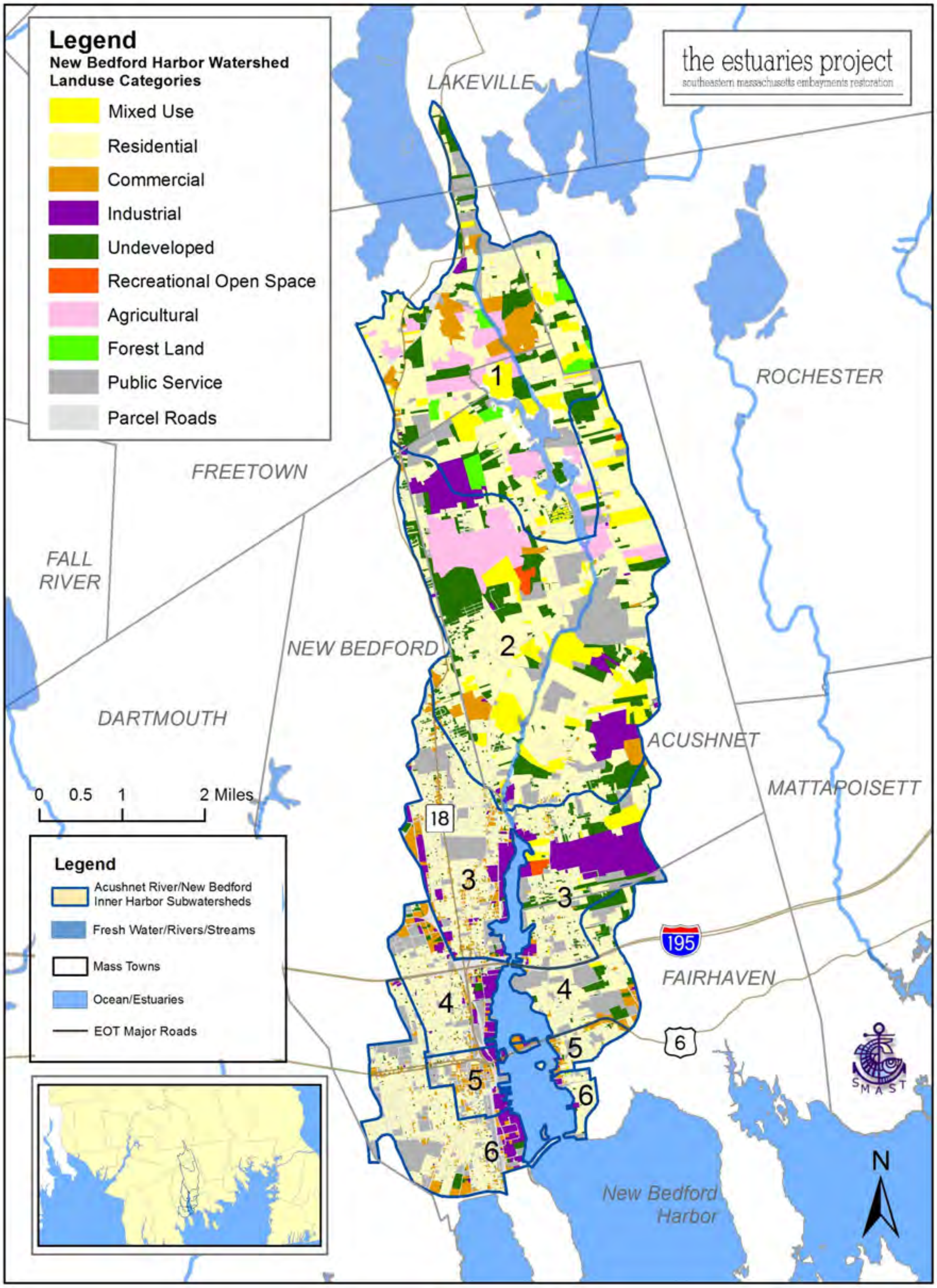


Figure IV-1. Land-use in the Acushnet River/New Bedford Inner Harbor watershed. The watershed is split among the Towns of Fairhaven, Acushnet, Freetown, Rochester and Lakeville and the City of New Bedford. Land use classifications are based on municipal assessors' records.

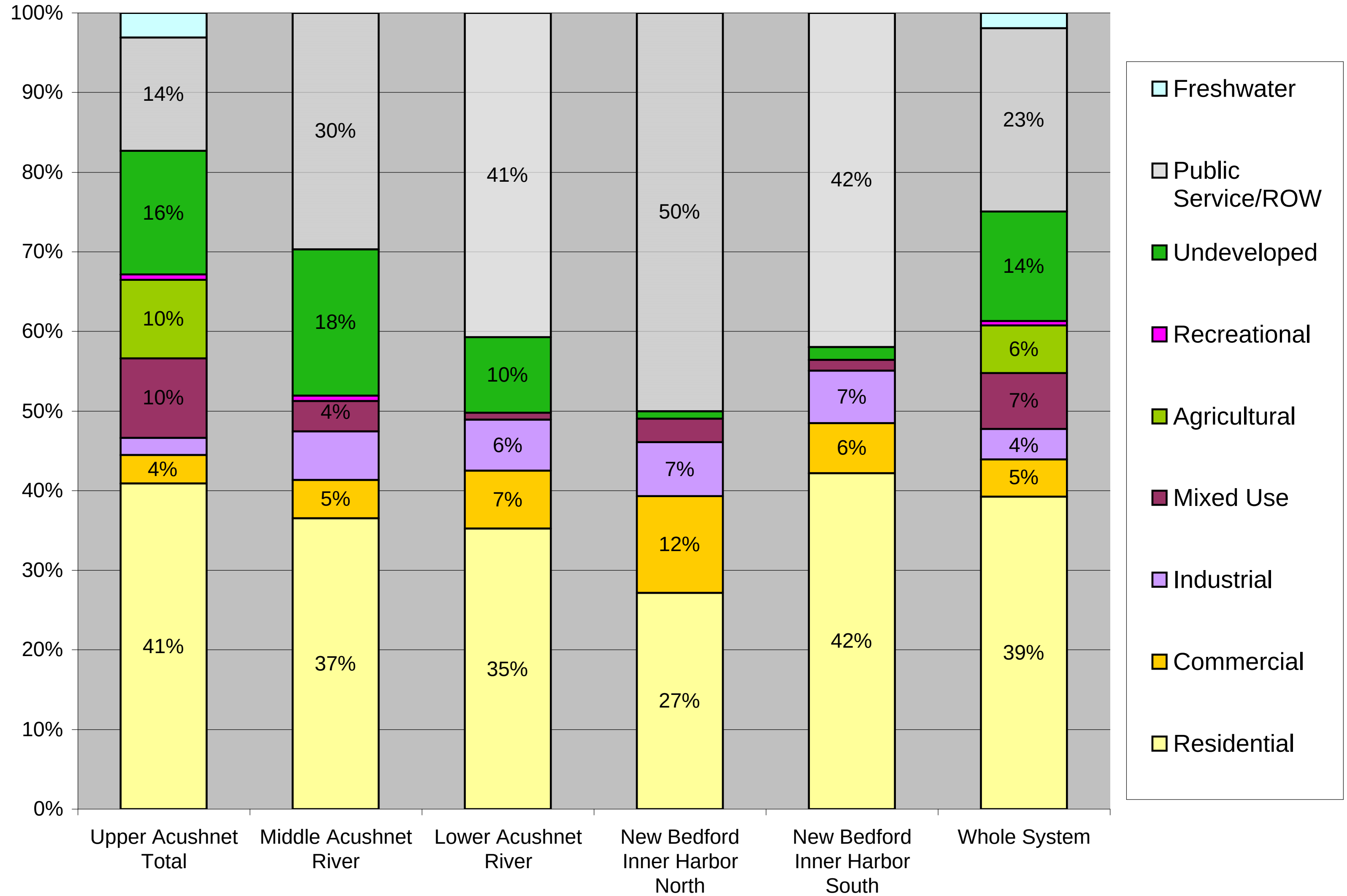


Figure IV-2. Distribution of land-uses within the major sub-watersheds and whole watershed to the Acushnet River/New Bedford Inner Harbor estuary system. Only percentages greater than or equal to 4% are shown.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

The Massachusetts Estuaries Project septic system nitrogen loading rate is fundamentally based upon a per capita nitrogen load to the receiving aquatic system. Specifically, the MEP septic system wastewater nitrogen loading is based upon a number of studies and additional information that directly measured septic system and per capita loads on Cape Cod or in similar geologic settings (Nelson *et al.*1990, Weiskel & Howes 1991, 1992, Koppelman 1978, Frimpter *et al.* 1990, Brawley *et al.* 2000, Howes and Ramsey 2000, Costa *et al.* 2001). Variation in per capita nitrogen load has been found to be relatively small, with average annual per capita nitrogen loads generally between 1.9 to 2.3 kg person-yr^{-1}.

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP Technical Team employs a water-use approach. The water-use approach is applied on a parcel-by-parcel basis within a watershed, where annual water meter data is linked to assessor's parcel information using GIS techniques. The parcel specific water use data is converted to septic system nitrogen discharges (to the receiving aquatic systems) by adjusting for consumptive use (*e.g.,* irrigation) and applying a wastewater nitrogen concentration. The water use approach focuses on the nitrogen load, which reaches the aquatic receptors downgradient in the aquifer.

All nitrogen losses within a septic system are incorporated into the MEP analysis. For example, information developed on Title 5 septic systems at the MassDEP Massachusetts Alternative Septic System Test Center at the Massachusetts Military Reservation have shown nitrogen removals between 21% and 25%. Multi-year monitoring from the Test Center has revealed that nitrogen removal within the septic tank was small (1% to 3%), with most (20 to 22%) of the removal occurring within five feet of the soil adsorption system (Costa *et al.* 2001). Downgradient studies of septic system plumes indicate that further nitrogen loss during aquifer transport is negligible (Robertson *et al.* 1991, DeSimone and Howes 1996).

In its application of the water-use approach to septic system nitrogen loads, the MEP Technical Team has ascertained for the Estuaries Project region that while the per capita septic load is well constrained by direct studies, the consumptive use and nitrogen concentration data are less certain. As a result, the Technical Team has derived a combined term for an effective N Loading Coefficient (consumptive use times N concentration) of 23.63, to convert water (per volume) to nitrogen load (N mass). This coefficient uses a per capita nitrogen load of 2.1 kg N person-yr^{-1} and is based upon direct measurements and corrects for changes in concentration that result from per capita shifts in water-use (*e.g.* due to installing low plumbing fixtures or high versus low irrigation usage).

The nitrogen loads developed using this approach have been validated in a number of long and short term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Further, modeled and measured nitrogen loads were determined for a small subwatershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes, manuscript in review) where measured nitrogen discharge from the aquifer was within 5% of the modeled N load. Another evaluation was conducted by surveying nitrogen discharge to the Mashpee River in reaches with swept sand channels and in winter when nitrogen attenuation is minimal. The modeled and observed loads showed a difference of less than 8%, easily attributable to the low rate of attenuation expected at that time of year in this type of ecological situation (Samimy and Howes, unpublished data).

While census based population data has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, which covers large areas and have significant year-round populations, the septic nitrogen loading based upon the census data is within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller areas of any given town, have shown up to a 13% difference in average occupancy from town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

Overall, the MEP water use approach for determining septic system nitrogen loads has been both calibrated and validated in a variety of watershed settings. The approach: (a) is consistent with a suite of studies on per capita nitrogen loads from septic systems in sandy outwash aquifers; (b) has been validated in studies of the MEP Watershed “Module”, where there has been excellent agreement between the nitrogen load predicted and that observed in direct field measurements corrected to other MEP Nitrogen Loading Coefficients (e.g., stormwater, lawn fertilization); (c) the MEP septic nitrogen loading coefficient agrees in specific studies of consumptive water use and nitrogen attenuation between the septic tank and the discharge site; and (d) the watershed module provides estimates of nitrogen attenuation by freshwater systems that are consistent with a variety of ecological studies. It should be noted that while points b-d support the use of the MEP Septic N Coefficient, they were not used in its development. The MEP Technical Team has developed the septic system nitrogen load over many years, and the general agreement among the number of supporting studies has greatly enhanced the certainty of this critical watershed nitrogen loading term.

The independent validation of the water quality model (Section VI) and the reasonableness of the freshwater attenuation (Section IV.2) add additional weight to the nitrogen loading coefficients used in MEP analyses and a variety of other MEP embayments. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%) needed to lower embayment nitrogen levels to a nitrogen target (*e.g*. nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to the how the septic system nitrogen mass compares to the nitrogen loads from all other sources that reach the estuary (*i.e.* attenuated loads).

Previous evaluations of watersheds with available water use and sewer service areas have shown that water use provides a reasonable estimate of wastewater generation. In order to provide an independent validation of the average residential water use within the Acushnet River/New Bedford Inner Harbor watershed, MEP Technical Team reviewed US Census population and housing values for the City of New Bedford and Towns of Fairhaven, Acushnet, Freetown, Rochester and Lakeville. The state on-site wastewater design regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within the municipalities ranges from 2.44 (Fairhaven) to 2.98 people per housing unit (Lakeville) and these varied slightly during the 2010 Census (Table IV-1). Seasonal properties are a small component of the housing stock in each town, so potential variability associated with seasonal fluctuations should not be a significant concern. Year-round occupancies in each of the municipalities ranged from 90% to 98% during the 2000 Census and 89% to 96% during the 2010 Census. Based on the watershed water use data, the average single family residence water use is 138 gpd. If this flow is then divided by 55 gpd, the average estimated occupancy based on the water use in the study area is 2.51 people per household. This occupancy is within the range of the town-wide averages. An alternative comparison, based on a housing unit weighted average of the occupancies in the towns, results in an average water use of 139 gpd for the 2000 Census figures and a 138 average for the 2010 Census results. These comparisons provide confidence in the water use information and show that water use is an appropriate basis for determining septic system wastewater nitrogen loads within Acushnet River/New Bedford Inner Harbor watershed.

Table IV-1. Town Occupancy Data from the 2000 and 2010 US Censuses used to evaluate potential per capita water use in the Acushnet River/New Bedford Inner Harbor Watershed.

Town/City	Occupied Housing Units		Average Occupancy (People per occupied housing unit)		Seasonal Properties (% of total housing units)		Estimated Title 5 flow per housing unit (gallons per day)	
	2000 Census	2010 Census	2000 Census	2010 Census	2000 Census	2010 Census	2000 Census	2010 Census
New Bedford	38,178	38,761	2.46	2.45	0%	0%	135	135
Fairhaven	6,622	6,672	2.44	2.38	6%	6%	134	131
Acushnet	3,793	3,934	2.68	2.62	0%	1%	147	144
Freetown	2,932	3,162	2.89	2.81	1%	2%	159	154
Rochester	1,575	1,813	2.91	2.89	1%	1%	160	159
Lakeville	3,292	3,725	2.98	2.85	8%	8%	164	157
				Weighted average			139	138

Notes:

a. Estimated Title 5 flow per housing unit is based on average occupancy multiplied by 55 gpd. Title 5 assumes 2 people per bedroom and a wastewater flow of 110 gpd per bedroom.

b. Weighted average flows are based on number of housing units in each town.

Municipal Wastewater Treatment Facilities

NEW BEDFORD WASTEWATER POLLUTION CONTROL FACILITY (WPCF) AND COMBINED SEWER OVERFLOWS (CSO)

The New Bedford Wastewater Pollution Control Facility (WPCF) is located at the end of Clarks Point and discharges treated effluent into Buzzards Bay through an outfall pipe located off the end of the point and outside of the Acushnet River/New Bedford Inner Harbor MEP study area. The sewer collection system includes properties in New Bedford and Acushnet. Because of the older design of the wastewater collection system, the WPCF also receives stormwater runoff that is mixed with the sewage. During periods of heavy rains, these combined pipes overflow and discharge at discrete locations along the New Bedford shoreline, into New Bedford Harbor, the Acushnet River estuary, and Clarks Cove (Figure IV-3). Discharges into the Acushnet River/New Bedford Inner Harbor estuary occur between the hurricane barrier and as far up the system as the Tar Kiln Road bridge crossing over the Acushnet River. Separating the stormwater from wastewater has been a long-term commitment for New Bedford and, as such, the discharges and contaminant concentrations from the Combined Sewer Overflow (CSO) system have been monitored, modeled (CDM, 2006) and steadily reduced through system improvements over the past 15 years.

Since 1990, the City of New Bedford has embarked on an aggressive program to shut down CSO discharges to the Acushnet River-New Bedford Inner Harbor system and the MEP confirmed the shutting down of specific CSOs to the inner harbor through numerous discussions with the City of New Bedford Department of Public Works, Wastewater Division. CSO closures summarized by the Wastewater Division provided the MEP independent confirmation of the active CSOs discharging to the inner harbor as described in the 2006 CDM report. CDM estimates that system overflows have gone from 3 billion gallons in 1990 to 470 million gallons in 2005.

The 2006 modeling effort undertaken by CDM for the City of New Bedford builds upon the City's phased CSO facilities plan also developed by CDM in the 1980s and 1990s. The earlier estimates of CSO flows determined by CDM were based on the USEPA SWMM (Storm Water Management Model) and STORM (Storage Treatment Overflow Runoff Model) models, originally developed by the U.S. Army Corps of Engineers. The estimates developed by CDM for the 1990 analysis of the New Bedford CSO system were calibrated to field data and used to estimate CSO volumes, durations, and frequencies as well as discharge concentrations and loads of specific constituents. Once calibrated the 2006 system SWMM-5 model was then used by CDM to assess the future impact of proposed changes in the CSO system.

In order to generate a total CSO discharge volume to the inner harbor, CDM utilized the NetSTORM software to identify design rainfall amounts across a range of intervals. Rainfall amounts were subsequently utilized in SWMM-5 to generate CSO volumes at specific discharge points in the inner harbor. As described by CDM in its 2006 report, "NetSTORM uses methodologies comparable with those used by the National Weather Service and presented in its Atlas 14 (2003) that reports precipitation statistics for the mid-Atlantic, Midwest, and Southwest. NetSTORM produces more pertinent statistics than are available in the 1962 National Weather Service publication TP-40. That report was based on data collected prior to 1960 and did not report rainfall statistics for return periods shorter than one year. The NetSTORM analysis is based on the full digital hourly record and produces statistics for return periods from 2 weeks to 100 years." Based on the NetSTORM and SWMM-5 modeling undertaken by CDM, the 2005 CSO volume discharged to the Acushnet River-New Bedford Inner Harbor system is approximately 1.26 million m^3/yr (334 MG/yr).

As a basic check of the CDM CSO volume, the MEP utilized precipitation data obtained from the NOAA National Weather Service Meteorological Station located at the New Bedford Regional Airport (Location: Lat 41.41N; Lon 70.58W) in order to calculate CSO flows to the Acushnet River-New Bedford Inner Harbor system over two hydrologic years (September to August, 2002-2003 and 2003-2004). Analysis focused on 2002 to 2004, since most of the MEP initial data collection was obtained during this period. The MEP utilized modeled flow rates developed by CDM for specific CSOs under a variety of “storm events”. This information combined with an evaluation of which CSOs flowed under the specified rainfall conditions resulted in estimates of CSO volumetric discharge to the MEP system of 1.40 million m^3/yr (370 MG/yr) and 1.12 million m^3/yr (297 MG/yr) for the two hydrologic years, respectively.

The primary reason for the difference between the CSO volumes in the two hydrologic years was variation in precipitation. For the first hydrologic year, New Bedford precipitation was 129 cm (50.8 inches), while it was 97.9 cm (38.5 inches) during the second hydrologic year. The average of the CSO volumes calculated by the MEP for the period 2002 to 2004 was 1.262 million m^3/yr (333 MG/yr) compares well with the CDM CSO 2005 volume of 1.264 million m^3/yr (334 MG/yr). Based on the similarity between the CDM CSO analysis and the cross check completed by the MEP, the CDM volumes were utilized in both the MEP hydrodynamic and water quality modeling for the Acushnet River-New Bedford Inner Harbor system.

In order to develop nitrogen loads into the harbor from the CSOs, the developed volumes must be paired with an estimate of total nitrogen concentration. In CDM (1990), nitrogen concentrations collected 14 samples from CSOs discharging both inside and outside of the inner harbor, as well as to nearby Clarks Cove, during three wet weather events. Average Total Kjeldahl Nitrogen (TKN) concentration in these samples was 7.22 mg/l. CDM (2006) utilized an average TKN concentration of 6.7 mg/l for New Bedford CSOs and showed that compared well with CSOs in the City of Hartford, CT (6.2 mg/l) and Manchester, NH (7.6 mg/l).

TKN only includes a portion of the nitrogen forms that would be expected to be in CSO flows. Total nitrogen includes oxidized forms of nitrogen (nitrates and nitrites) in addition to the organic and ammonia forms that are included in TKN analyses. Since no nitrate+nitrite data was available for New Bedford CSOs, MEP staff reviewed available data from other communities. The City of Hartford, CT, whose TKN CSO concentrations compared favorably to New Bedford, reported average nitrate+nitrite concentrations of 0.457 mg/l. Adding this concentration to the TKN average for New Bedford CSOs (7.22 mg/l) results in the total nitrogen concentration in CSO effluent of 7.68 mg/l. This concentration, and previously described flows, was used as the basis for calculating existing New Bedford CSO nitrogen loads in the combined MEP models of New Bedford Harbor (Table IV-2). The annual existing MEP CSO nitrogen load to the Acushnet River-New Bedford Inner Harbor system is 9,706 kg.

Table IV-2 aggregates the MEP CSO total nitrogen loads by embayment segment under current conditions and buildout conditions. Buildout conditions for the CSOs are based on CDM (2006) projected configuration and the resultant flows for the CSO system in 2030. CDM projects that the CSO flow within the Acushnet River-New Bedford Inner Harbor system will decline to 0.84 million m^3/yr (223.2 MG/yr). Using the same estimated TN concentration, this flow will result in a reduced TN load of 6,486 kg/yr. This load is included in the buildout scenario evaluated in this report. Since nearly all of the New Bedford properties in the Harbor watershed are connected to the sewer system and the New Bedford WPCF discharges through an outfall pipe outside of the Harbor study area, the only wastewater nitrogen loads from the New Bedford portion of the watershed is the portion included in the CSO nitrogen loads.

Table IV-2. New Bedford CSO flows and nitrogen loads in the New Bedford Harbor MEP study area.

Watershed	watershed #	Total Existing Flow	Total 2030 Flow	TN Load Existing	TN Load 2030
		MG/y	MG/y	kg/y	kg/y
Middle Acushnet River	3	246.9	131.1	7,175	3,810
Lower Acushnet River	4	48.8	41.0	1,418	1,191
New Bedford Inner Harbor North	5	1.2	2.3	35	67
New Bedford Inner Harbor South	6	37.1	48.8	1,078	1,418
WHOLE SYSTEM		334.0	223.2	9,706	6,486

Notes:
a. Flow data from CDM (2006)
b. total nitrogen loads based on estimated total nitrogen concentration of 7.677 mg/l, which is sum of CDM TKN average sampled concentration of 7.22 mg/l and 0.457 mg/l nitrate+nitrite average from Hartford, CT CSO sampling

FAIRHAVEN WASTEWATER TREATMENT FACILITY

The Fairhaven Wastewater Treatment Facility (WWTF) is located on Arsene Street in Fairhaven. The WWTF has a National Pollutant Discharge Elimination System (NPDES) permit from US Environmental Protection Agency (USEPA) and MassDEP that allows direct discharge into New Bedford Harbor (outfall location shown in Figure IV-3) and limits total flow to 5 million gallons per day (www.epa.gov/region1/npdes/permits/fairhavenpermit.pdf). Nitrogen limits are not specified, although it is anticipated that a TMDL will be developed for New Bedford Harbor/Acushnet River. The sewer collection system connected to the WWTF receives wastewater flow from the Towns of Fairhaven and Mattapoisett (approximately 0.25-0.30 MGD).

Monthly effluent flow and total nitrogen concentration data was provided to MEP staff by MassDEP staff for 2010 through 2012 (B. Dudley, personal communication). During this time period, effluent flow from the WWTF averaged 3.04 million gallons per day (MGD) with a range of 2.0 to 5.7 MGD based on 36 monthly measurements (Figure IV-4). Effluent total nitrogen concentration averaged 13.4 milligrams per liter (mg/l) with a range of 7.0 to 24.0 mg/l based on 36 monthly measurements. Using the flow and concentration data, MEP staff determined monthly loads and summed these to determine an annual load for each of the three years. The average of the three years is 53,043 kg with a 7,143 kg difference between the highest year (2012) and the lowest year (2010). Review of previous MassDEP data (2004-2006) shows an increase of 13,808 kg to the average 2010-2012 load. The 2010-2012 average was used as the basis for the nitrogen load from the Fairhaven WWTF in the MEP watershed nitrogen loading model as those data were most reliable. Properties within the Acushnet River-New Bedford Inner Harbor watershed that were identified through town parcel information as having sewer connections were not assigned a wastewater nitrogen load. All other properties were assumed to utilize on-site septic systems and were assigned a wastewater load based on the assigned average water use.

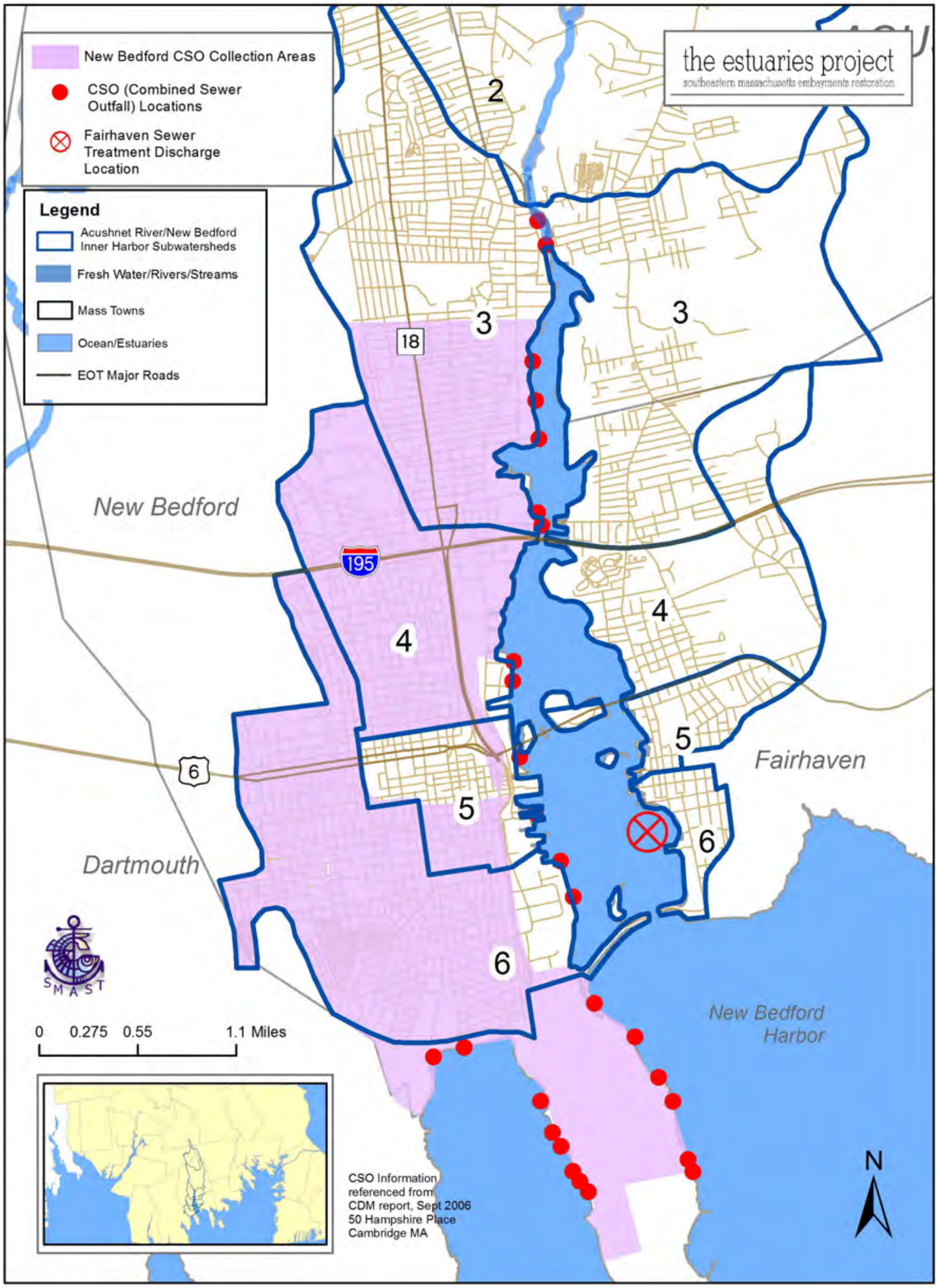
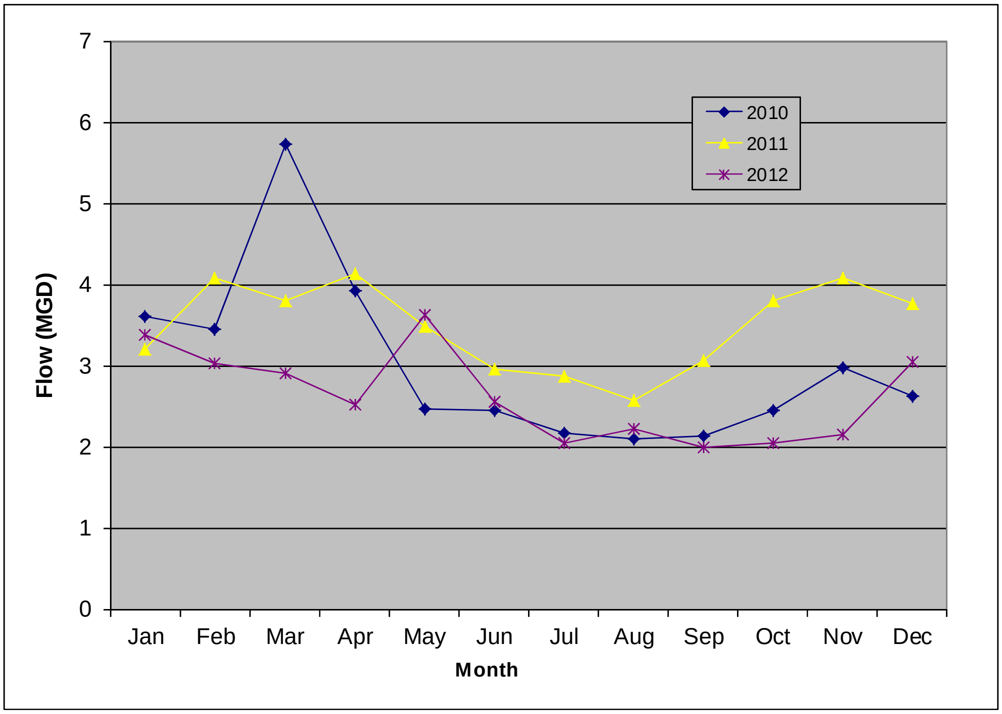


Figure IV-3. New Bedford Combined Sewer Overflow (CSO) discharge locations and the combined system collection area. Also shown is the location of the Fairhaven Wastewater Treatment Facility outfall within the Acushnet River-New Bedford Inner Harbor estuary system.



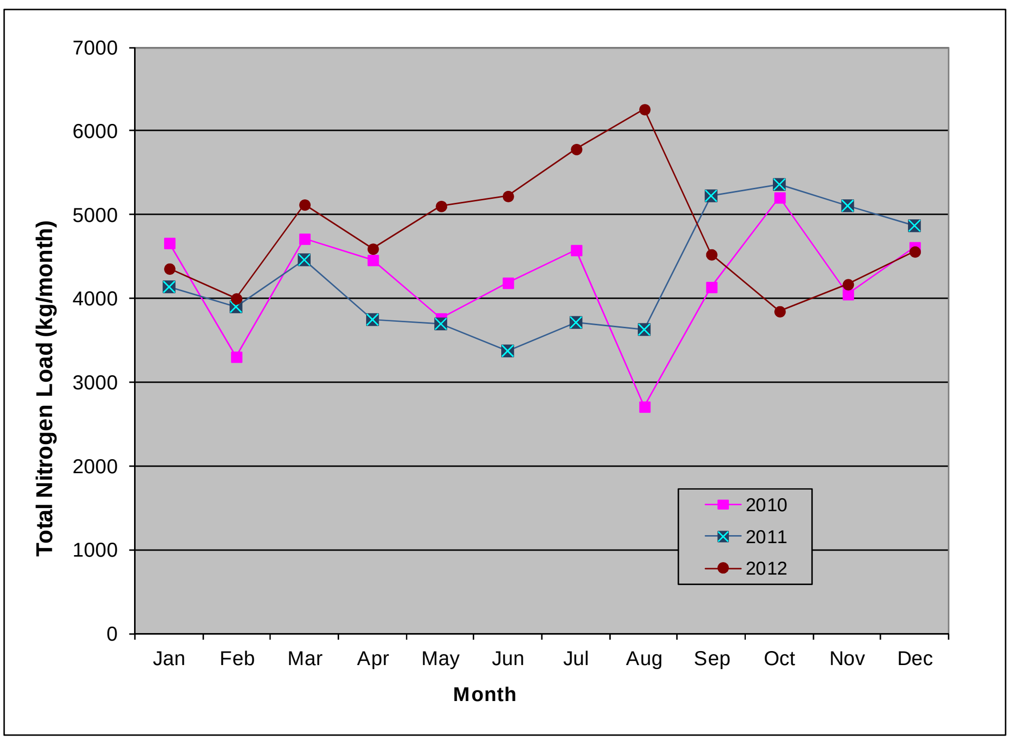


Figure IV-4. Average monthly effluent flow and nitrogen load at the Town of Fairhaven Wastewater Treatment Facility (2010-2012). This WWTF discharges at an outfall within the Acushnet River-New Bedford Inner Harbor estuary. Data supplied by MassDEP. Average monthly flow was 3.04 million gallons per day, while average monthly load was 4,420 kg. Existing annual average load was 53,043 kg.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and agricultural land uses (*e.g.*, cranberry bogs, crops, and animals). Residential lawns are usually the predominant source within this category. In order to add this source to the watershed nitrogen loading model for the Acushnet River-New Bedford Inner Harbor, MEP staff reviewed available information about residential lawn fertilizing practices and incorporated site-specific information to determine nitrogen loading from other fertilization applications in the watershed. Within the watershed, MEP staff reviewed available regional information about residential lawn fertilizing practices. The primary site-specific information in this watershed is for crop and farm animal nitrogen loads, which were determined based on previous studies conducted in southeastern Massachusetts. In addition, there is one golf course in the watershed (Acushnet River Valley Golf Course) and loads for the course were based on information gathered from other golf courses in previous MEP reviews.

Residential lawn fertilizer use has rarely been directly measured in watershed-based nitrogen loading investigations. Instead, lawn fertilizer nitrogen loads have historically been estimated based upon a number of assumptions: a) each household applies fertilizer, b) cumulative annual applications are 3 pounds per 1,000 sq. ft., c) each lawn is 5000 sq. ft., and d) only 25% of the nitrogen applied reaches the groundwater (leaching rate). Because many of these assumptions had not been rigorously reviewed in over a decade, at the outset of the MEP, the MEP Technical Staff undertook an assessment of lawn fertilizer application rates and a review of leaching rates for inclusion among the standard factors used in the Watershed Nitrogen Loading Sub-Model.

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. The assessment accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are used in the MEP nitrogen loading calculations. It should also be noted that a recent data review of lawn fertilizer leaching in settings similar to those on Cape Cod confirmed that the 20% leaching rate is appropriate (HWG, 2009) as opposed to the historical leaching rate of 25% mentioned above. It is likely that these loading rates still represents a conservative estimate of nitrogen load from residential lawns. It should also be noted that professionally maintained lawns in the three town survey were found to have the higher rate of fertilizer application and hence higher estimated annual contribution to groundwater of 3 lb/lawn/yr.

As noted in the land use review above, agricultural areas are a significant percentage of the land area within the Acushnet River/New Bedford Inner Harbor watershed (6% of the overall watershed area and 10% of the watershed above the MEP Acushnet River gauge). During the parcel-by-parcel assignment of the nitrogen loads for agricultural crops, MEP staff reviewed aerial photos of the parcels classified as agricultural land use by the town assessors. This review found that on average approximately 85% of agricultural parcels were used for crop production. This value was generally used to assign nitrogen loads for agricultural parcels after the removal of wetland areas; field areas for selected individual parcels were determined by review of aerial photographs. Wetland areas were determined based on MassDEP 1:12000K wetland GIS coverage (MassGIS, 2009). The crop areas are assigned nitrogen application rates based on rates determined for various Massachusetts land use codes [previously used in the Slocum River MEP assessment (Howes, *et al*., 2007)]. Based on the land use analysis, MEP staff determined that there are 834 acres of fertilized agricultural land is in the Upper Acushnet River subwatersheds.

Cranberry bogs are a significant agricultural land use within the Acushnet River/New Bedford Inner Harbor watershed. Bog areas in the MEP watershed nitrogen loading model are based on a GIS coverage maintained by MassDEP for Water Management Act purposes; this coverage identifies the surface areas of the bogs (personal communication, Jim McLaughlin, MassDEP). Cranberry bogs total 257 acres within the watershed and are located exclusively in the freshwater Acushnet River sub-watersheds (subwatersheds 1 and 2). Based on a review of studies of nitrogen export from regional cranberry bogs (*e.g.*, Howes and Teal, 1995; DeMoranville and Howes, 2009), MEP staff have refined the nitrogen loading factors assigned to cranberry bogs based on whether water continuously flows through a bog or is pumped or diverted onto the bog (non-flow through bogs) from an outside source of water. The reason for the refinement was recent quantitative work on local bogs which indicated that non-flow through bogs lose less nitrogen to downgradient systems, since they only periodically have outflow. The recent study consisted of 6 non-flow through bogs including both those in inorganic and organic soils, measured over 3 years by researchers at the Cranberry Experiment Station and at SMAST-UMass Dartmouth. The finding of DeMoranville and Howes (2009) were updated by the authors to better account for nitrogen losses through drainage and infiltration, with the result that each hectare on average loses 6.95 $\pm$ 1.14 kg/ha/yr (mean$\pm$S.E.; N=6) to downgradient waters. This is lower than the loss from continuously flowing or flow through bogs of 23.1 kg/ha/yr. MEP staff reviewed current aerial photos and classified bogs as either flow through or non-flow through and assigned the appropriate nitrogen load based on the bog area. Non-flow through bogs typically have stream bypasses. Nitrogen loads from the cranberry bogs in the watershed nitrogen loading model are based on these classifications and loads; details are contained in the MEP Data Disk that accompanies this report.

The Upper Acushnet River sub-watersheds also contain the one golf course identified in the Acushnet River/New Bedford Inner Harbor watershed: the municipally owned Acushnet River Valley Golf Course. MEP staff was unsuccessful in contacting a staff person at the course who could provide course-specific fertilizer application rates, so the watershed nitrogen loading model utilized averages from 19 other courses contacted through a number of previous MEP watershed analyses. MEP staff reviewed aerial photographs of the golf course and digitized the tees, greens, fairways, and rough areas using GIS techniques and determined a total nitrogen load for the course based on a 20% leaching rate and the following nitrogen application averages to these areas: greens, 3.6 lbs per 1,000 square feet; tees, 3.3 lbs per 1,000 square feet; fairways, 3.3 lbs per 1,000 square feet and roughs, 2.5 lbs per 1,000 square feet.

Nitrogen Loading Input Factors: Freshwater Wetlands

The data collected at the MEP gauge site in the Acushnet River freshwater watershed generally produced measured nitrogen loads that were higher than what the preliminary MEP watershed nitrogen loading model indicated. Since the MEP assessment approach is data-driven, MEP staff began the process of exploring the cause of these higher nitrogen loads by re-reviewed all of the data leading to the preliminary watershed loads, including the watershed delineations, the nitrogen loading inputs, and re-reviewing the streamflow and concentration data (see Section IV.2). These steps confirmed the evaluations and suggested that there was another nitrogen source in the Acushnet River/New Bedford Inner Harbor watershed that was not included in the preliminary model. A similar approach was taken in the Slocums River, Westport River, and Nasketucket Bay systems, where MEP staff identified extensive wetland and swamp lands surrounding most of the streams and rivers feeding into the estuaries as the most likely cause of the high nitrogen loads.

The nitrogen load assigned to freshwater wetlands bordering the freshwater portion of the Acushnet River and its tributaries is consistent with the nitrogen loading assigned to the freshwater wetlands bordering the Slocums/Paskamansett River (Howes, *et al.*, 2008) and the Westport River (Howes, *et al.*, 2012). It was clear from both the Westport River and Paskamansett River measurements that attenuation of nitrogen in their riverine wetlands was relatively low, with added nitrogen being transformed, but not removed. Specifically, the indication of wetland "N saturation" is based up atmospheric N deposition being only partially removed. This determination for the Acushnet River/New Bedford Inner Harbor streams is reasonable based on the available similarly determined measurements for the two larger rivers, as well as observation developed during the assessment of other smaller freshwater systems in similar settings.

The Westport River, Paskamansett River, and Acushnet River have similar geology, are structurally similar, have significant associated freshwater wetlands (especially the Acushnet River stream), and are highly nitrogen-enriched (TN's of 1.3 mg/L, 1.2 mg/L and 1.1 mg/L, respectively). The geology of these systems (particularly the Westport and Paskamansett Rivers) differs from those on Cape Cod and the Islands in that the watersheds tend to be topographically defined and have exposed bedrock and till, whereas the systems from the Wareham River and to the east are primarily glacial sands and moraines with watersheds defined by differences in water table elevations within the porous matrix. As such, based on site-specific analysis that is the foundation of the MEP, some of the factors associated with surface water systems in the Westport River, Paskamansett River, and Acushnet River watersheds are different than those developed for the Cape Cod and the Islands watersheds.

In most of the Cape Cod streams, application of the MEP N loading approach has produced very good agreement with measured stream nitrogen loads. These sandy aquifer-dominated systems typically support limited freshwater wetland areas and much lower stream flows than found in western Buzzards Bay streams. In these Cape Cod systems, nitrogen attenuation rates of 20% to 30% are typical, possibly due to higher watershed retention times. In contrast, the rivers along the northwestern edge of the Buzzards Bay watershed are underlain by bedrock and till, have comparatively high stream flows, and extensive bordering freshwater wetlands. In these western Buzzards Bay systems, nitrogen contact time in the wetlands will be shorter and, like freshwater ponds with short residence times, they should attenuate less nitrogen. In addition, reviews of river wetlands have indicated that they have threshold effects like those seen in estuaries and ponds. This means that these freshwater wetlands can become nearly completely loaded with nitrogen and once in that condition act as transformers of nitrogen (changing nitrate+nitrite to organic forms), but not attenuators of nitrogen (*e.g.*, USDA, 2011). This change appears to be related to the amount of nitrogen received, as well as inter-related factors such as hydraulic residence time, temperature, plant surface coverage, and plant density (*e.g.*, Hagg *et al.*, 2011; Kröger, *et al.*, 2009; Alexander, *et al.*, 2008).

It is important to note that the wetlands are not actually a nitrogen source, but they merely have a lower rate of nitrogen removal of the nitrogen deposited upon them, than in the smaller, low flow wetlands. The result is a low total combined attenuation of all nitrogen sources the Acushnet River being 15%. The river/wetland systems of the Westport River and Paskamansett River are operating in a similar manner.

The MEP results are also consistent with studies by other researchers that found the ability of river wetlands to attenuate nitrogen is directly related to their hydraulic residence time with longer residence times resulting in greater nitrogen reduction (*e.g.*, Jansson, *et al.*, 1994; Perez, *et al.*, 2011; Toet, *et al.*, 2005). Direct data in the overall MEP study area generally confirms this relationship with lower flow/longer residence time streams on the eastern portion of the overall MEP study area having greater nitrogen attenuation, as well as attenuation in ponds and lakes, which have even longer residence times, having nitrogen attenuation rates of 50% or higher (*e.g.*, Howes, *et al.*, 2006).

In order to incorporate the nitrogen loading from the wetland areas in the Acushnet River/New Bedford Inner Harbor watershed, MEP staff assigned the water surface nitrogen loading factor to the wetland areas identified in a MassGIS/MassDEP wetland coverage (Figure IV-5). The wetlands are interpreted from 1:12,000 scale, stereo color-infrared photography captured over a series of years between 1990 and 2000 (MassGIS, 2009). For the purposes of the MEP assessment, the treatment of these wetlands as water surfaces is appropriately conservative without further data to refine the spatial differences in residence times, plant communities/densities and the role of seasonal impacts along the various streams and rivers in the Acushnet River/New Bedford Inner Harbor watershed system.

Nitrogen Loading Input Factors: Other

In addition to fertilizers and wastewater, other factors add nitrogen loads to a watershed. A previous analysis of the New Bedford watershed (Costa, 2000) had identified an annual load of 1,300 kg from the Fairhaven landfill. The landfill is located in the Lower Acushnet River sub-watershed. According to discussions with Town of Fairhaven staff, the landfill stopped receiving solid waste in 1997 and was closed with an impervious cap and leachate collection system in 1999. Monitoring of seven wells and the leachate collection system for nitrate-nitrogen is a required component of the closure. The leachate collection system flows are treated at the Fairhaven WWTF. Monitoring data from 2002 to 2006 was provided to MEP staff. A review of the monitoring data shows that the average nitrate-nitrogen concentration in downgradient monitoring wells (n=89) is 0.07 mg/l, while the average concentration in the leachate collection system (n=18) is 0.7 mg/l. Multiplying the average down gradient well nitrate-nitrogen concentration times the recharge over the 36 acre landfill surface (a standard method for determining a nitrogen load) results in an estimated annual nitrogen load of 7 kg from the Fairhaven landfill. Given the small impact of such a load, MEP staff did not add it to the Acushnet River/New Bedford Inner Harbor watershed nitrogen loading model.

MEP staff also assigned nitrogen loads based on the number of farm animals within the watersheds. Counts of farm animals were obtained from: Town of Fairhaven (personal communication, Lisa Moniz, 7/12), Town of Acushnet (personal communication, Rebekah Tomlinson, Animal Inspector, 2/13), Town of Rochester (personal communication, Mike Cahill, Director, Massachusetts Division of Animal Health, 2/13), and Town of Freetown (personal communication, Lisa Podielsky, Animal Control Officer, 3/13). All farm animal counts, except for Fairhaven, were only available as town-wide counts. MEP staff reviewed aerial maps to evaluate the potential distribution of lots that appeared to have farm animals present and decided to assign farm animal loads on the basis of the percentage of town area within the watershed. For the purposes of these assignments, 70% of Acushnet is within the watershed, 9% of Freetown, and 2% of Rochester. Fairhaven has only one property with farm animals within the watershed. Details of the animal counts are available in the MEP Data Disk that accompanies this report.

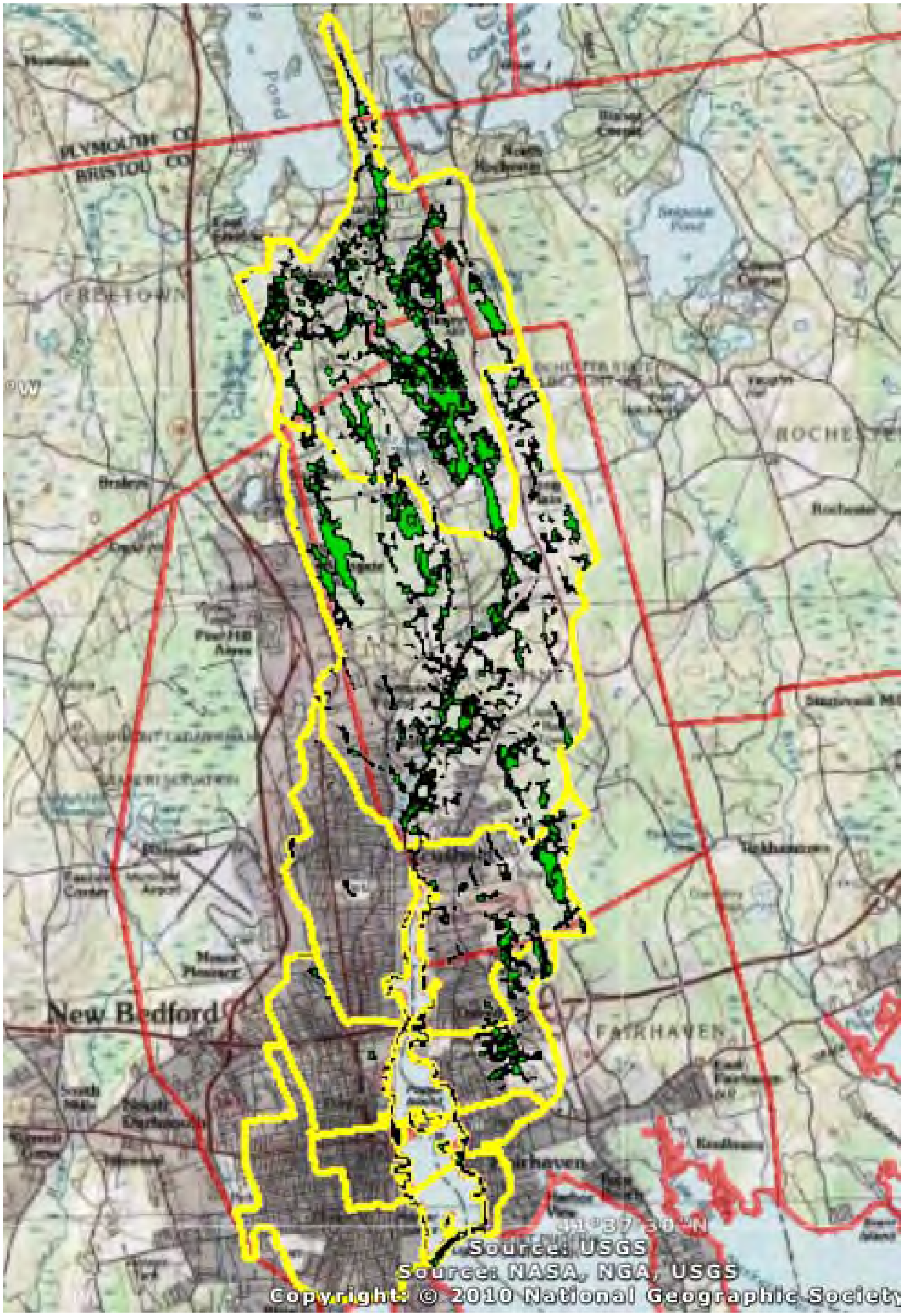


Figure IV-5. Wetland areas in the Acushnet River/New Bedford Inner Harbor watersheds. All areas colored in green are freshwater wetlands areas delineated by MassGIS/MassDEP 1:12,000K coverage. Most of these areas are associated with freshwater streams that discharge into the Bay. All these areas were assigned a surface water nitrogen load in the MEP watershed nitrogen loading model.

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas in the Acushnet River/New Bedford Inner Harbor assessment are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and the MassDEP Nitrogen Loading Computer Model Guidance Document (1999). The recharge rate for natural areas and lawn areas is the same as utilized in the watershed modeling effort (Section III). Factors used in the MEP nitrogen loading analysis for the Acushnet River/New Bedford Inner Harbor watershed are summarized in Table IV-3.

For impervious surfaces, MEP reviewed a number of different sources and selected the most reliable sources. Road areas are based on MassHighway GIS information, which provides road width for various road segments. MEP staff utilized the GIS to sum these segments and their various widths by sub-watershed. Project staff also checked this information against parcel-based rights-of-way. Town assessor's databases for both watershed towns include parcel-specific building footprint information. MEP impervious surface nitrogen loading factors were applied to these road and roof areas.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the initial assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each sub-watershed based on the watershed delineations and the sum of the area of the parcels within each sub-watershed.

The review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Acushnet River/New Bedford Inner Harbor estuary. The assignment effort was undertaken to better define sub-estuary loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, sub-watershed modules were generated for each of the six sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. The individual sub-watershed modules were then integrated to create an Acushnet River/New Bedford Inner Harbor Watershed Nitrogen Loading module with summaries for each of the individual sub-embayments and sub-estuaries. The sub-embayments represent the functional embayment units for the Linked Watershed-Embayment Model's estuary water quality component.

Table IV-3. Primary Nitrogen Loading Factors used in the Acushnet River/New Bedford Inner Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from watershed-specific data.

Nitrogen Concentrations:	mg/l
Road Run-off	1.5
Roof Run-off	0.75
Direct Precipitation on Embayments and Ponds	1.09
Natural Area Recharge	0.072
Wastewater Coefficient	23.63
Fertilizers:	
Average Residential Lawn Size (sq ft)[1]	5,000
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08
Nitrogen leaching rate	20%
Crops	kg/ha/yr
Hay, Pasture	5
Hay, Pasture leaching rate	100%[7]
Corn, Vegetables, Vineyard, Fruit	34
Crop N leaching rate	30%
Cranberry Bogs export – flow through (kg/ha/yr)	23.1
Cranberry Bogs export – non-flow through(kg/ha/yr)	6.95
Farm Animals	kg/yr/animal
Horse	32.4
Cow/Steer	55.8
Goats/Sheep	7.3
Hogs	14.5
Chickens	0.4
Animal N leaching rate	40%

Recharge Rates:[2]	in/yr
Impervious Surfaces	45.7
Natural and Lawn Areas	30.46
Water Use/Wastewater:	
Existing developed parcels wo/water accounts and buildout single family residence parcels	138 gpd[3]
Multi-family residential parcels	315 gpd[4]
Existing developed parcels w/water accounts:	Measured annual water use
Commercial, Industrial, and 900s Buildings buildout additions[5]	
Commercial	
Wastewater flow (gpd/1,000 ft2 of building):	87
Building lot coverage:	14%
Industrial	
Wastewater flow (gpd/1,000 ft2 of building):	126
Building lot coverage:	15%
Public Service (900s)	
Wastewater flow (gpd/1,000 ft2 of building):	110
Building lot coverage:	16%
Existing Building Size (watershed average; sq ft)	Parcel specific
New Bedford CSOs	
Flows	CDM, 2006
New Bedford CSO TN concentration (mg/L)[6]	7.677

Notes:
1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
2) Based on precipitation rate of 50.77 inches per year (1971-2000 NOAA average for closest long-term precipitation gauge (New Bedford))
3) Acushnet River/New Bedford Inner Harbor watershed average from single-family residences with water use accounts
4) Acushnet River/New Bedford Inner Harbor watershed average from other residential properties with water use accounts
5) Based on characteristics of respective land uses within the watershed: existing water use and building coverage for similarly classified properties; buildout for properties in the 900 land use code (public service properties) only occurs within the portion of the watershed in Fairhaven; BBNEP buildout was used in Fairhaven and includes development of all 900 properties; MEP buildout in other municipalities in the watershed assume 900 properties will continue to be used as they currently are
6) Based on CDM (2006) CSO monitoring of TKN and nitrate+nitrite average from Hartford, CT CSO sampling
7) Hay, Pasture leaching rate is 100% because the assigned nitrogen loading rate already incorporates a leaching rate

For management purposes, the aggregated watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Acushnet River/New Bedford Inner Harbor study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), wastewater treatment facilities (Fairhaven WWTF), fertilizers, farm animals, freshwater wetlands, impervious surfaces, the New Bedford combined sewer overflows, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-4). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-6 a-b). The annual watershed nitrogen input is then reduced by natural nitrogen attenuation in the Acushnet River during transport and the estuary receives this reduced load. The nitrogen loads used in the MEP embayment water quality sub-model are a combination of the estimated loads in Table IV-4 and the measured loads from the rivers discussed in Section IV.2.

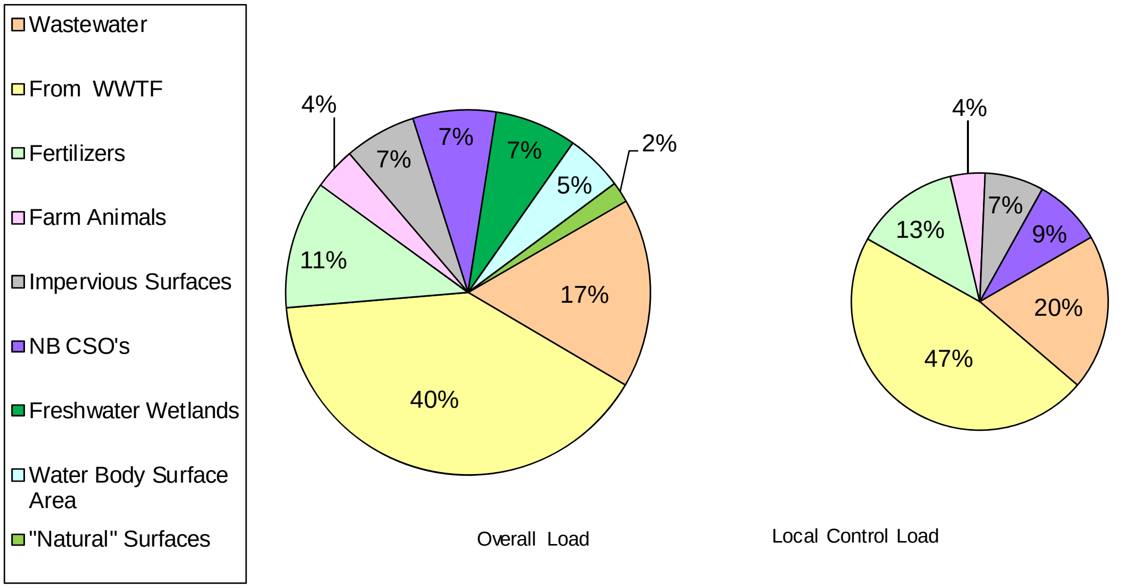
Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watersheds. The MEP buildout is relatively straightforward and is completed in four steps: 1) each residential parcel classified by the town assessor as developable is identified and divided by minimum lot sizes specified in town zoning and the resulting number of new residential units is rounded down, 2) parcels classified as developable commercial and industrial parcels by the town assessor are identified, and 3) residential, commercial and industrial parcels with existing development and lot areas greater than twice zoning's minimum lot size are identified, divided by the minimum lot size and the resulting number of new units is rounded down. Local knowledge and insights regarding future sewer connections, other land use restrictions, or future development are also incorporated into the MEP buildout scenario.

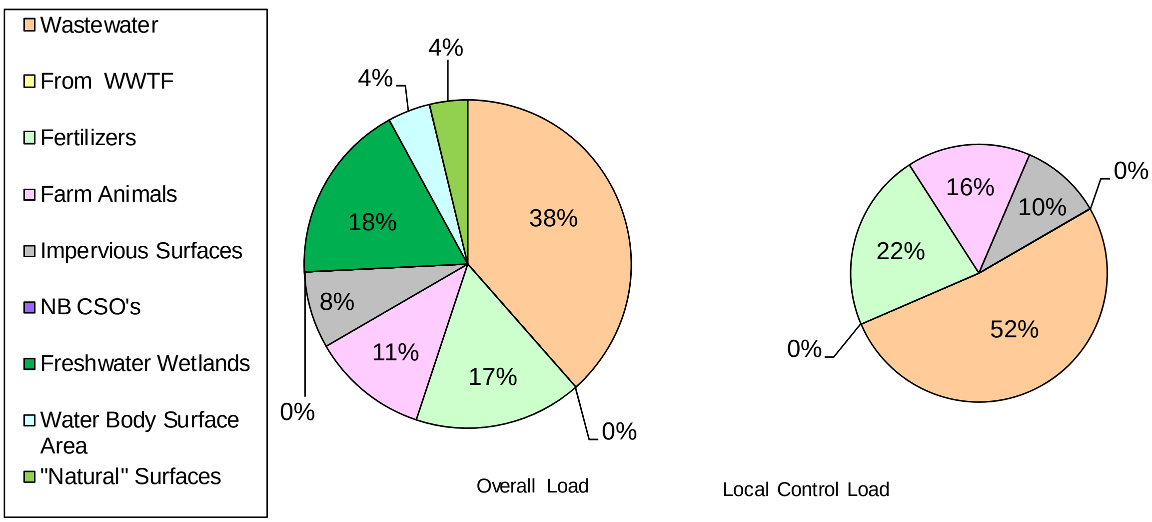
It should be noted that the initial MEP buildout approach is relatively simple and does not include any modifications/refinements for lot line setbacks, road construction, frontage requirements, parcel shape requirements, or other more detailed zoning provisions. The MEP buildout approach also does not include potential impacts associated with the higher densities usually associated with Chapter 40B affordable housing projects. The Acushnet River/New Bedford Inner Harbor watershed initial MEP buildout did, however, include, a removal of wetland areas (based on a MassDEP/MassGIS coverage) prior to applying the minimum lot size calculations. Properties classified by the town assessors as "undevelopable" (*e.g.*, MassDOR land use codes 132, 392, and 442) are not assigned any development at buildout (unless revised by a town review).

Table IV-4. Acushnet River/New Bedford Inner Harbor Watershed Nitrogen Loads. Attenuation of system nitrogen loads occurs within the Upper Acushnet River (freshwater) system as nitrogen moves through upgradient ponds and streams during transport to the estuary. Attenuation factors related to the freshwater inflows from the Upper Acushnet River was based upon MEP stream measurements. All values are kg N yr^{-1}.

		New Bedford Harbor N Loads by Input (kg/y):										***Present N Loads***			***Buildout N Loads***		
Name	**Watershed ID#**	**Wastewater**	**From WWTF**	**Fertilizers**	**Farm Animals**	**Impervious Surfaces**	**NB CSO's**	**Freshwater Wetlands**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
New Bedford Harbor System		22158	53043	14957	4933	8408	9706	9594	6709	2424	14932	131932		125527	146865		138472
Middle Acushnet River	3	2760	0	2731		3247	7175	1194	0	376	-2111	17483		17483	15372		15372
Lower Acushnet River	4	780	0	2630		703	1418	708	0	184	806	6424		6424	7229		7229
New Bedford Inner Harbor North	5	1048	0	449	1	867	35	20	0	72	128	2491		2491	2620		2620
New Bedford Inner Harbor South	6	1132	53043	2056		354	1078	72	0	186	2861	57921		57921	60782		60782
Upper Acushnet River		16438	0	7090	4932	3238	0	7600	1798	1605	13248	42702	15%	36297	55950	15%	47557
New Bedford Reservoir	1	5563	0	2514		926		2784	1716	688	3586	14192		14192	17779		17779
Upper Acushnet River	2	10875	0	4576		2312		4816	82	917	9661	23578		23578	33239		33239
adjusted town-wide	Acushnet, Rochester, Freetown				4932							4932		4932	4932		4932
Middle Acushnet River Estuary Surface									1035			1035		1035	1035		1035
Lower Acushnet River Estuary Surface									1319			1319		1319	1319		1319
New Bedford Inner Harbor North Estuary Surface									1127			1127		1127	1127		1127
New Bedford Inner Harbor South Estuary Surface									1432			1432		1432	1432		1432



a. New Bedford Harbor/Acushnet River Whole System Watershed



b. Freshwater Acushnet River subwatershed

Figure IV-6 (a-b).Land use-specific unattenuated nitrogen load (by percent) to the (a) overall Acushnet River/New Bedford Inner Harbor Estuary System watershed and (b) Freshwater Acushnet River sub-watershed (subwatersheds #1 and #2). "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control. WWTF and CSO nitrogen loads are exclusively in the southern portion of the watershed. Farm animal loads are almost exclusively in the northern portion of the watershed.

As an example of how the MEP approach might apply to an individual parcel, assume an 81,000 square foot lot is classified by the town assessor as a developable residential lot (land use code 130). Current zoning specifies that this lot is in an area where the minimum lot size is 40,000 square foot. For the MEP buildout, this lot is divided by a 40,000 square foot minimum lot size specified in town zoning and the result is rounded down to two. As a result, two additional residential lots would be added to the sub-watershed in the MEP buildout scenario. Under the buildout, each of these lots would have the addition of nitrogen loads from wastewater, lawn fertilizers, and impervious surfaces (*i.e.*, roof and driveway). This addition could then be modified during discussion with town staff and incorporation of other factors, such as whether sewering is expected in the area.

In the MEP buildout, commercial and industrial properties classified as developable are not subdivided; the area of each parcel and zoning factors are used to determine a building size and wastewater flow for these properties. Pre-existing lots classified by the town assessor as developable are also treated as developable even if they are less than the minimum lot size specified in zoning; so, for example, a 10,000 square foot lot classified by the town assessor as a developable residential property (130 land use code) will be assigned an additional residential dwelling in the MEP buildout scenario even though the minimum lot size in the area is 40,000 square feet. Most town zoning bylaws have a lower minimum lot size for pre-existing lots (usually 5,000 square feet) that will minimize instances of regulatory takings. Existing developed residential properties that are larger than zoning's minimum lot sizes are also assigned additional development potential only if enough area is available to accommodate at least one additional lot as specified by the zoning minimum. Also in MEP buildouts, agricultural lands, Chapter 61 open space, town preserved open space, recreational areas and most other land uses other than residential, commercial and industrial properties are assumed to remain under their current use unless this is modified through discussions with town staff.

Discussions with town planners, boards, and/or wastewater consultants can generate some additional insights on planned development, and often include discussion of developments planned for government or public service parcels, and updates to assessor classifications, including lands purchased by the town as open space. Refinements of the MEP buildout can continue as the Towns conduct nitrogen management planning and could include updates on parcels initially identified as developable or undevelopable and application of more detailed zoning provisions. As planning proceeds the Towns may request additional refined buildout scenarios to account for specific land-use shifts or projects that may be deemed likely within the watershed.

In the Acushnet River/New Bedford Inner Harbor watershed, the MEP buildout approach was used within the City of New Bedford and the towns of Towns of Acushnet, Freetown, Rochester and Lakeville, but another approach was used for the buildout within the Town of Fairhaven. In the Town of Fairhaven, the BBNEP completed a buildout assessment in 2010. At the prompting of MEP staff, further discussions were arranged between BBNEP staff, the Board of Public Works Superintendent and the Town Planner to review the BBNEP estimates. The BBNEP buildout included more detailed procedures, including frontage calculations, but also included allowances for development on parcels that MEP typically excludes from future development [*e.g.*, current agricultural properties (700 land use codes) and government-owned properties (900s)]. The Fairhaven buildout also includes assignment of future sewer connections for buildout additions. Town staff completed a 2012 review of the BBNEP draft and removed a number of government properties from the initial buildout estimates and this version was included in the MEP buildout assessment of the Acushnet River/New Bedford Inner Harbor watershed. The final Fairhaven buildout includes some future development on properties with land use categories that are excluded from additional development in the other municipalities in the watershed.

The MEP buildout also includes connection of additional properties to the Town of Fairhaven and City of New Bedford WWTFs. Since almost all properties in the City of New Bedford portion of the Acushnet River/New Bedford Inner Harbor watershed are connected to the municipal sewer system, all additional New Bedford properties estimated from the buildout analysis were assumed to be connected to the sewer system. Properties with identified buildout potential within the Acushnet and Fairhaven sewered areas were also assumed to be connected to the sewer systems in the buildout scenario. Wastewater for any buildout properties that are connected to the Fairhaven WWTF sewage collection system was assumed to be added to the WWTF flow; the buildout effluent TN concentration in the Fairhaven WWTF was assumed to be equal to the 2010-2012 average (13.41 mg/L). The increase in flow due to buildout at the Fairhaven WWTF is 0.13 MGD (details are included in the MEP Data Disk that accompanies this report). Buildout additions to the Fairhaven WWTF also included portions of Fairhaven within the Nasketucket Bay MEP watershed (Howes, *et al*., 2013). The 2030 CSO scenario developed by CDM (2006) was also included in the buildout assessment; projected loads in Table IV-2 were part of the buildout load. It should be noted that the projected improvements in the 2030 CSO loads reduced the buildout load in the Middle Acushnet River (subwatershed #3) below existing conditions so a negative number is shown for this sub-watershed in the buildout column in Table IV-4.

All the parcels with additional buildout potential within the Acushnet River/New Bedford Inner Harbor watershed under the MEP buildout scenario are shown in Figure IV-7 and details for individual parcels are included in the MEP Data Disk that accompanies this report. The MEP buildout scenario for the Acushnet River/New Bedford Inner Harbor watershed includes 3,108 additional residential units (1,113 with sewer connections), 440,895 square feet of commercial buildings, 1.0 million square feet of industrial buildings, and 580,204 square feet of public service (government/non-profit) buildings (all in Fairhaven). Each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces minus the sewer corrections to the WWTFs. All properties not connected to the sewers are assumed to utilize Title 5 on-site septic systems for wastewater treatment. Residential additions also include lawn fertilizer nitrogen additions. Cumulative unattenuated and attenuated buildout loads are indicated in separate columns in Table IV-4. Buildout additions within the Acushnet River/New Bedford Inner Harbor system watershed will increase the unattenuated nitrogen loading rate by 11%; 89% of the additional load associated with buildout is in the freshwater Acushnet River subwatershed (subwatersheds #1 and #2).

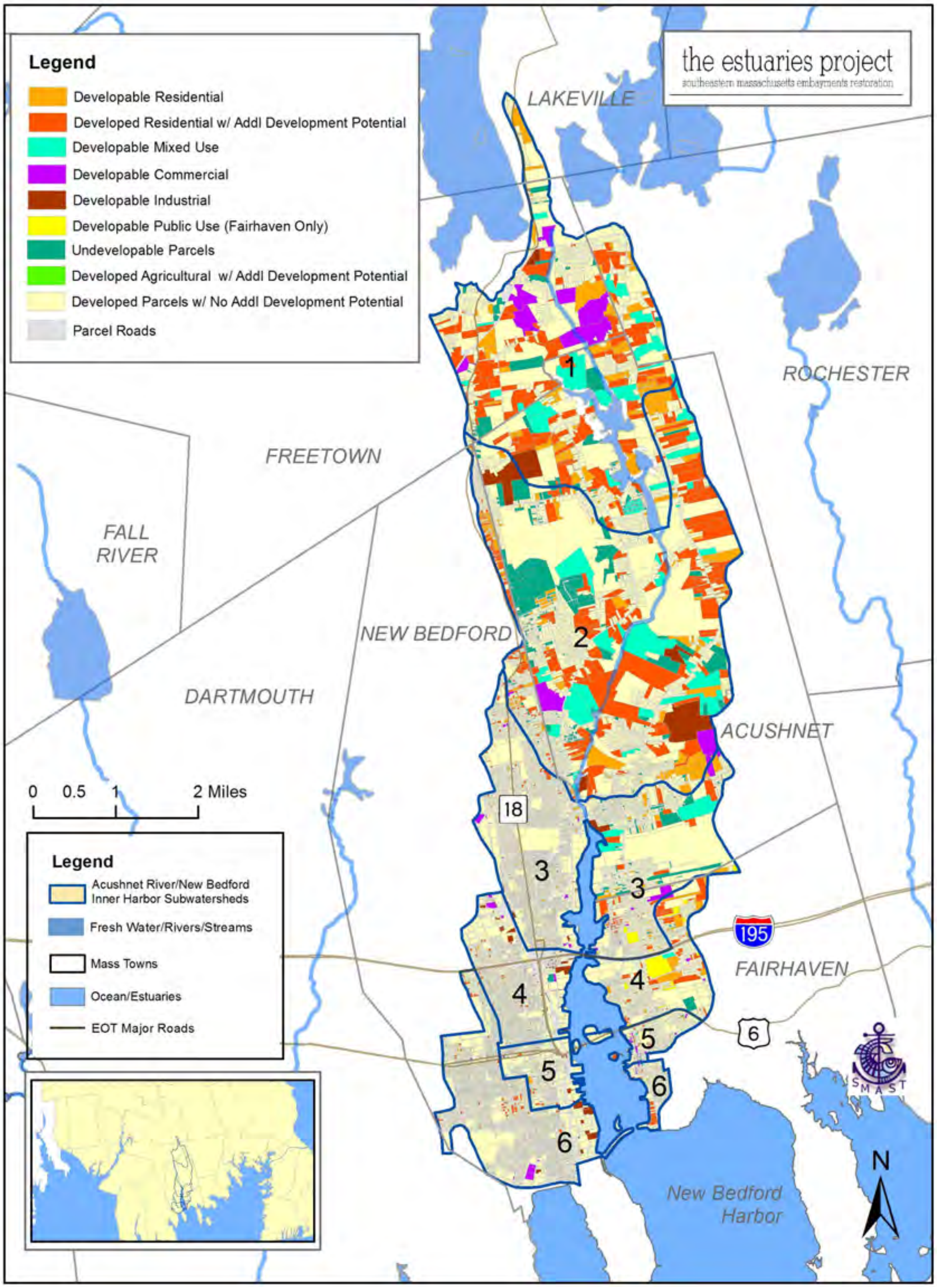


Figure IV-7. Developable Parcels in the Acushnet River/New Bedford Inner Harbor watershed. Parcels that are shown are either parcels with no existing development but classified by the respective town assessors as developable or parcels with existing development, but potential for additional development based on minimum lot sizes specified in respective town zoning regulations. Buildout assessments were completed by MEP staff except for Town of Fairhaven, which was completed by BBNEP staff using more liberal development potential assumptions.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Acushnet River-New Bedford Inner Harbor System being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1). If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such being the case in the developed region of southeastern Massachusetts but more so on Cape Cod). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the case of the Acushnet River-New Bedford Inner Harbor embayment system watersheds, a portion of the freshwater flow and transported nitrogen passes through a surface water system (Acushnet River via the New Bedford reservoir) prior to entering the Acushnet River estuary, producing the opportunity for significant nitrogen attenuation.

Failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 2001). Similarly, MEP analysis of the Quashnet River indicates that in the upland watershed, which has natural attenuation predominantly associated with riverine processes, the integrated attenuation was 39% (Howes et al. 2004). In addition, a preliminary study of Great, Green and Bournes Ponds in Falmouth, measurements indicated a 30% attenuation of nitrogen during stream transport (Howes and Ramsey 2001). An example where natural attenuation played a significant role in nitrogen management can be seen relative to West Falmouth Harbor (Falmouth, MA), where ~40% of the nitrogen discharge to the Harbor originating from the groundwater effluent plume emanating from the WWTF was attenuated by a small salt marsh prior to reaching Harbor waters. Clearly, proper development and evaluation of nitrogen management options requires determination of the nitrogen loads reaching an embayment, not just loaded to the watershed.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the head of the embayment system (estuarine reach of the Acushnet River) in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). This additional site-specific study was conducted in the 1 major surface water flow system, the freshwater portion of the Acushnet River originating in the area south of the Assawompset Pond network and discharging to the head of the tidal portion of Acushnet River.

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater reach of the Acushnet River (at Tar Kiln Road) provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up-gradient from the gauging site. Flow and nitrogen load were measured at the Acushnet River freshwater stream site starting in April of 2002 and continued into 2006/2007 for a full 4 years of continuous record (Figure IV-8). To date 4 complete hydrologic years are available for use in this analysis. During the study period, velocity profiles were completed on the Acushnet River every month to two months. The summation of the products of stream subsection areas of the stream cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

Determination of stream flow was calculated and based on the measured values obtained for stream cross sectional area and velocity. Stream discharge was represented by the summation of individual discharge calculations for each stream subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire stream cross section were not averaged and then applied to the total stream cross sectional area.

The formula that was used for calculation of stream flow (discharge) is as follows:

$$Q = \Sigma(A * V)$$

where by:

Q = Stream discharge (m^3/s)
A = Stream subsection cross sectional area (m^2)
V = Stream subsection velocity (m/s)

Thus, each stream subsection will have a calculated stream discharge value and the summation of all the sub-sectional stream discharge values will be the total calculated discharge for the stream.

Periodic measurement of flows over the entire stream gauge deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the detailed record of stage measured by the continuously recording stream gauges. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river. These hourly stages values where then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The two low tide stage values for any given day were averaged and the average stage value for a given day was then entered into the stage – discharge relation in order to compute daily flow. Four complete annual records of stream flow (365 days) were generated for the surface water discharge flowing into the estuarine portion of the Acushnet River.

Each annual flow record for the surface water flow was merged with the nutrient data set generated through the weekly water quality sampling to determine nitrogen loading rates to the head (tidally influenced) of the estuarine portion of the Acushnet River. Nitrogen discharge from the stream was calculated using the paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through the gauging site. For the Acushnet River gauging location, weekly water samples were (and continue to be) collected at low tide for a tidally influenced stage in order to determine nutrient concentrations from which nutrient load was calculated. In order to pair daily flows with daily nutrient concentrations, interpolation between weekly nutrient data points was necessary. These data are expressed as nitrogen mass per unit time (kg/d) and can be summed in order to obtain weekly, monthly, or annual nutrient load to the embayment system as appropriate. Comparing these measured nitrogen loads based on stream flow and water quality sampling to predicted loads based on the land use analysis allowed for the determination of the degree to which natural biological processes within the watershed to each pond currently reduces (percent attenuation) nitrogen loading to the embayment system.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge to the Acushnet River-New Bedford Inner Harbor System

The New Bedford Reservoir located up-gradient of the Acushnet River gauge site is a essentially a large freshwater pond and unlike many of the freshwater ponds in southeastern Massachusetts and Cape Cod, this pond/reservoir has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. This stream outflow, the Acushnet River, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and streambed associated with the freshwater portion of the Acushnet River. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Acushnet River above the gauge site and the measured annual discharge of nitrogen to the tidal portion of the Acushnet River, Figure IV-8.

Figure IV-8. Location of Stream gauge (red triangle) in the Acushnet River-New Bedford Inner Harbor embayment system.

At the Acushnet River (up-gradient Tar Kiln Road) gauge site, a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater portion of the Acushnet River that carries the flows and associated nitrogen load to the head of the upper portion of the estuarine reach of the Acushnet River. As the Acushnet River is tidally influenced the gauge was located above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average low tide salinity was determined to be <0.2 ppt (Acushnet River estuarine reach averages 27 ppt). Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked monthly. The gauge on the Acushnet River was installed in April 2002 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection has continued uninterrupted until 2006 for a total deployment of 62 months. The four hydrologic years (12-month uninterrupted record from low flow conditions in one year to low flow conditions in the next year) used in this analysis encompasses the summer 2003 field season as well as the summers of 2004, 2005 and 2006 (Figure IV-9).

River flow (volumetric discharge) was initially measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter for a period of approximately 18 months. A rating curve was developed for the Acushnet River site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume over the following three years until the gage was removed from the river. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of the Acushnet River (**Figure IV-10, 11, 12,13 and Table IV-5**). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gauge site.

Table IV-5. Comparison of water flow and nitrogen discharges from Acushnet River (freshwater) discharging to estuarine reach of Acushnet River. The "Stream" data is from the MEP stream gauging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	2002-2003 Acushnet Discharge[a]	2003-2004 Acushnet Discharge[a]	2004-2005 Acushnet Discharge[a]	2005-2006 Acushnet Discharge[a]	Data Source
Total Days of Record	365[b]	365[b]	365[b]	365[b]	(1)
Flow Characteristics					
Stream Average Discharge (m3/day) **	85415	50972	85149	102622	(1)
Contributing Area Average Discharge (m3/day)	95786	95786	95786	95786	(2)
Discharge Stream (MEP) relative to Long-term Discharge	11%	47%	11%	7%	
Nitrogen Characteristics					
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.602	0.594	0.617	0.577	(1)
Stream Average Total N Concentration (mg N/L)	1.109	1.185	1.109	1.055	(1)
Nitrate + Nitrite as Percent of Total N (%)	54%	50%	56%	55%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	94.73	60.4	94.44	108.3	(1)
TN Average Contributing UN-attenuated Load (kg/day)	116.38	116.38	116.38	116.38	(3)
Attenuation of Nitrogen in Pond/Stream (%)	19%	48%	19%	7%	(4)

(a) Flow and N load to streams discharging to Acushnet River-New Bedford Inner Harbor system includes apportionments of Pond contributing areas.
(b) September to August starting in 2002 and continuing through to 2006
** Flow is an average of annual flow for each given year

(1) MEP gage site data
(2) Calculated from MEP watershed delineations to ponds upgradient of specific gages; the fractional flow path from each sub-watershed which contribute to the flow in the Acushnet River; and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates as applicable.
(4) Calculated based upon the measured TN discharge from the river vs. the unattenuated watershed load.

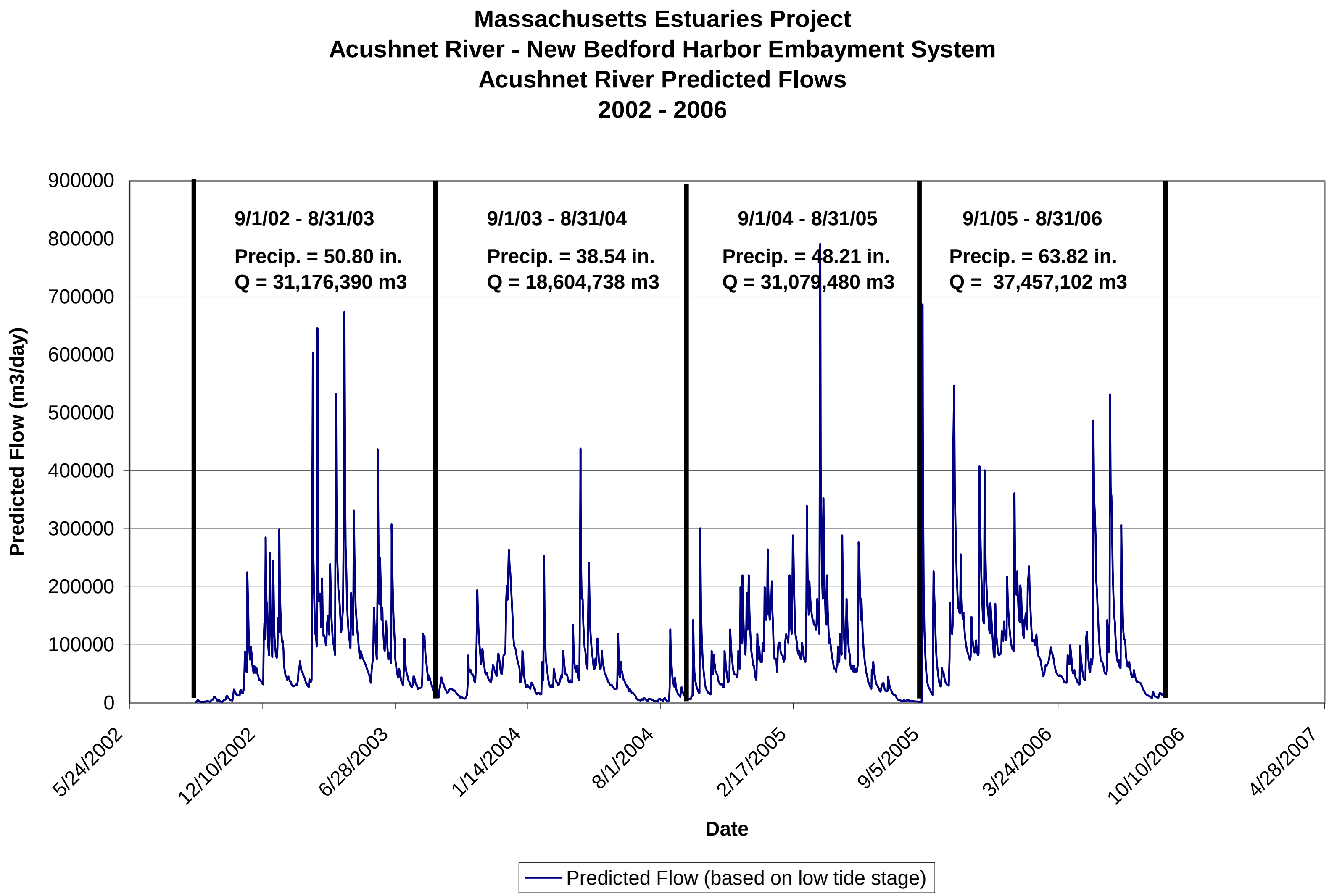


Figure IV-9. Acushnet River discharge (solid blue line) predicted from 2002 to 2006 for determination of annual volumetric discharge from the upper watershed to the Acushnet River Estuary-New Bedford Inner Harbor (Table IV-5)

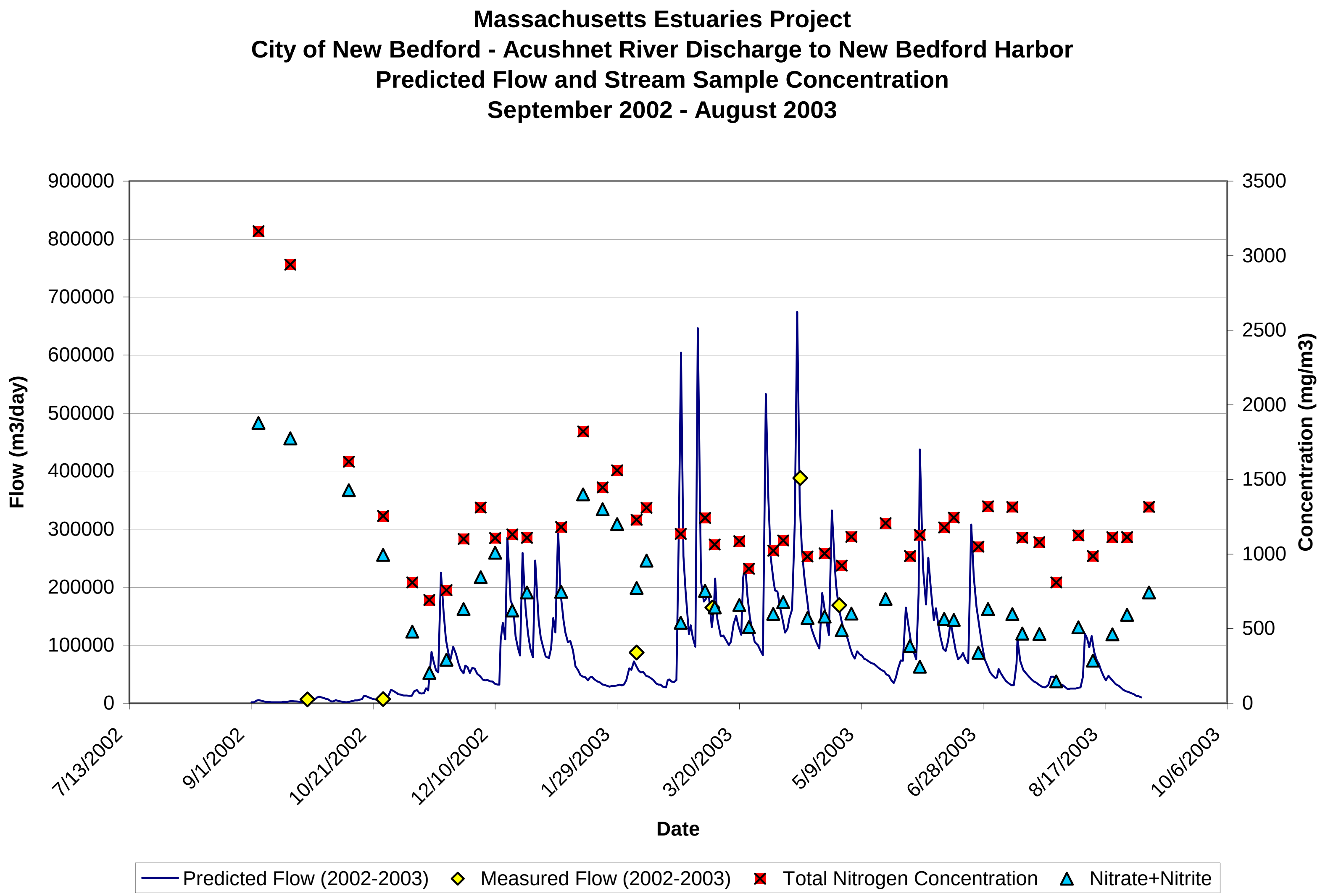


Figure IV-10. Acushnet River discharge (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (red box) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Acushnet River Estuary (Table IV-5).

Massachusetts Estuaries Project
City of New Bedford - Acushnet River Discharge to New Bedford Harbor
Predicted Flow and Stream Sample Concentration
September 2003 - August 2004

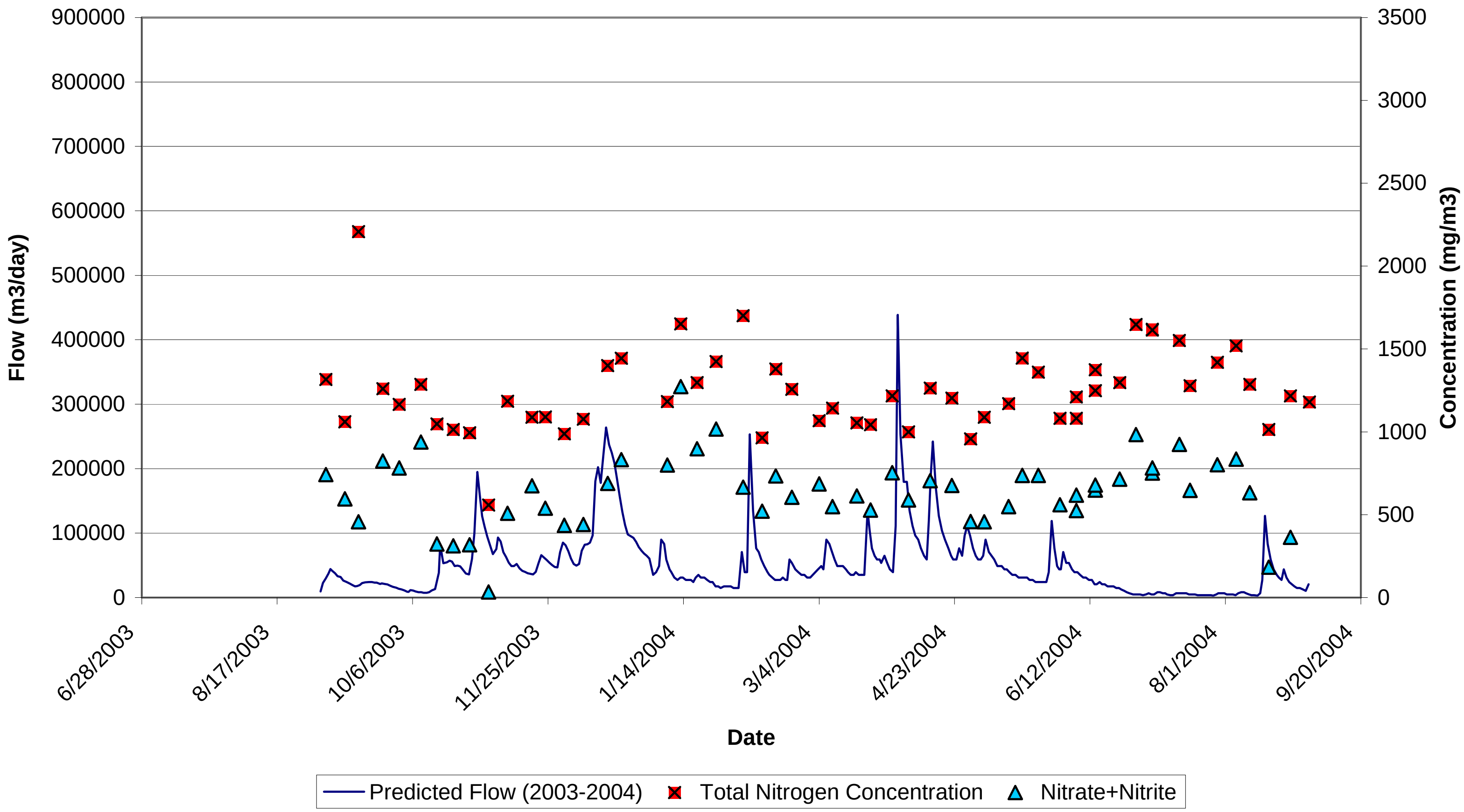


Figure IV-11. Acushnet River discharge (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (red box) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Acushnet River Estuary (Table IV-5)

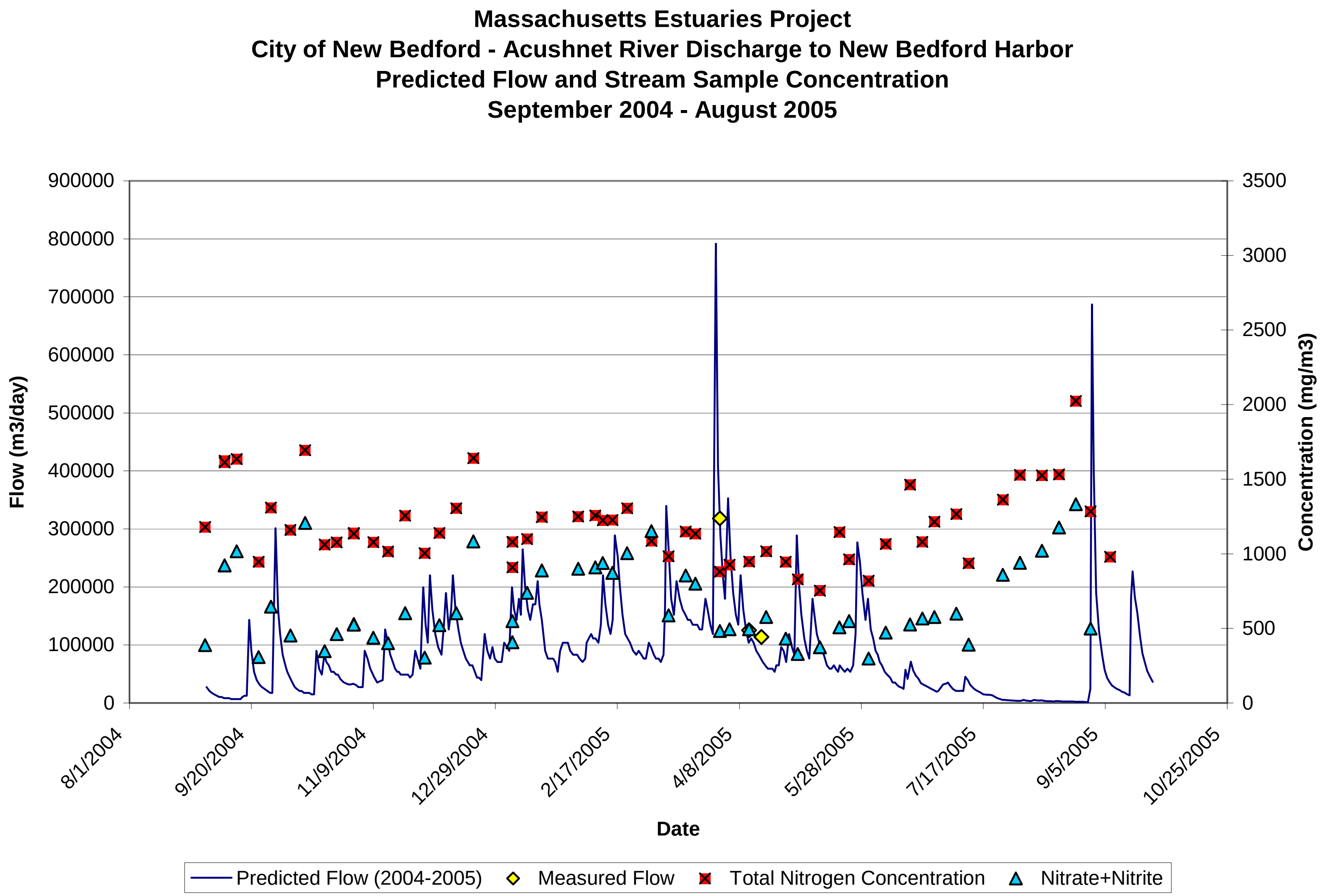


Figure IV-12. Acushnet River discharge (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (red box) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Acushnet River Estuary (Table IV-5)

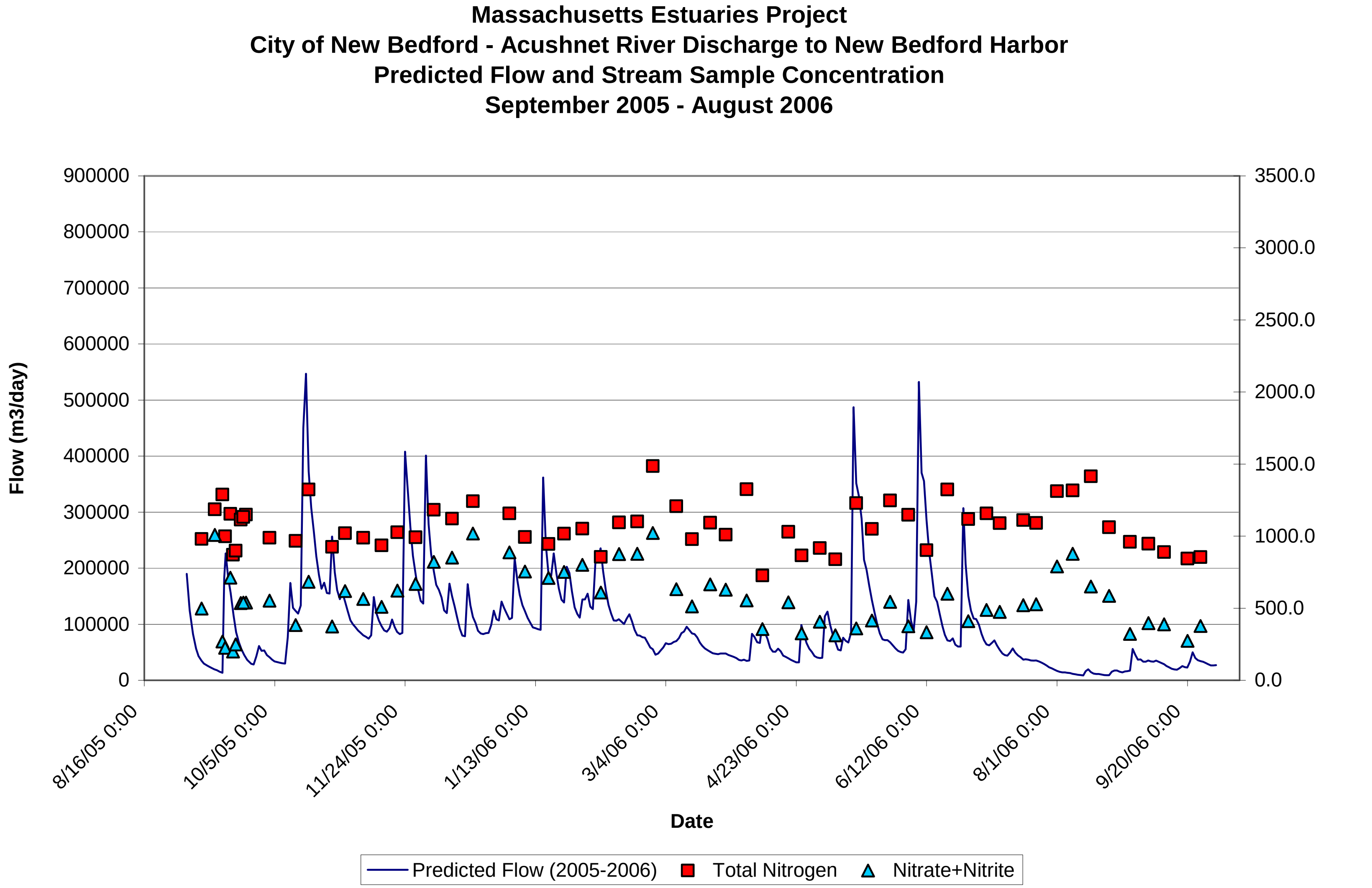


Figure IV-13. Acushnet River discharge (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (red box) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Acushnet River Estuary (Table IV-5)

The annual freshwater flow record for the Acushnet River measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from the Acushnet River was between 7% and 11% (average 10%) different than the long-term average modeled flows. The difference may in part be due to the recharge rate utilized over the watershed area as well as the yearly variations in rainfall. Based on the glaciofluvial and glaciolacustrine dominated sediments composed mainly of a combination of stratified drift sediments and till, the generalized recharge rate may be a slight overestimate for the western Buzzards Bay Basin. In addition, measured stream flows in the Acushnet River vary annually as a function of the precipitation in any given year thus causing annual differences in the measured flow and that calculated using the recharge rate over the watershed area (long term estimate). Based on 14 years of annual precipitation data obtained from the NOAA-National Weather Service which operates a meteorological station at the New Bedford Regional Airport (Location: Lat 41.41N; Lon 70.58W), the average rainfall in the vicinity of the Acushnet River is 50.3 inches. Over the deployment period utilized for the MEP analysis annual precipitation varied as follows: 50.80 inches (2002-2003), 38.54 inches (2003-2004), 48.21 inches (2004-2005) and 63.82 inches (2005-2006). Given the good agreement between the long-term precipitation rate and precipitation during the MEP stream measurement period, MEP staff assessed that the near long term average at New Bedford (50.77 in/yr) was most appropriate annual precipitation rate for further analysis. This variation in rainfall is clearly manifest in the flow record obtained at the stream gage. This is significant relative to measured flow in the Acushnet River surface water system as it is essentially a groundwater fed feature. As precipitation and therefore flow for the hydrologic period 2003-2004 were significantly below average conditions, this hydrologic year was dropped from the overall calculation of average daily flow and average daily load. Based upon the rainfall and groundwater levels associated with the three years of stream flow record (suggesting a lower average flow than the long-term average) and the only slightly different stream discharge predicted (10%) it appears that the stream gauge is capturing the up-gradient recharge (and loads) accurately.

Based on three years of flow and nutrient concentration data at the Acushnet River stream gage, total nitrogen concentrations within the Acushnet River outflow were relatively high averaging 1.09 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 99.16 kg/day (based on three year record) and a measured total annual TN load of 36,192 kg/yr (based on three year record). In the Acushnet River, nitrate was slightly more than half of the total nitrogen pool (55%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond or stream ecosystems. The concentration of inorganic nitrogen in the out-flowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is not nitrogen limited. In addition, the nitrate level in the Acushnet River flow suggests the possibility for additional uptake by freshwater systems might be accomplished in this system either within the impounded water behind the dam immediately up-gradient from the gage location or along the freshwater reach of the Acushnet River further up in the watershed.

From the measured nitrogen load discharged by the Acushnet River to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the Bay. Based upon lower nitrogen load (36,192 kg yr^{-1}) discharged from the freshwater Acushnet River compared to that added by the various land-uses to the associated watershed (42,702 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 15% (i.e. 15% of nitrogen input to watershed does not reach the estuary). This level of attenuation is consistent with the integrated attenuation rate determined from the watershed nitrogen model of 15% (Table IV-4). The relatively low attenuation of nitrogen occurring in the Acushnet River watershed up gradient of the gage is expected given the small number of aquatic systems such as ponds and wetlands up-gradient of the Acushnet River stream gage location. The directly measured nitrogen loads from the river was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

An additional analysis of the Acushnet River flows and loads was completed for the 2013 update of the MEP nutrient threshold analysis in order to get a sense for how the average Acushnet River flows and loads (based on 2002-2005 data collection) compared to the updated 2013 modeled nitrogen loads and potential variations in flow based on available long term records of precipitation at the New Bedford Airport as well as long term records of flow collected by the USGS on the adjacent Paskamanset River. Given the geologic characteristics of both the Acushnet River and Paskamanset River watersheds, there does appear to be a clear response in river flows to increases and decreases in precipitation (Figure IV-14). Furthermore, plotting measured flows in the Acushnet River obtained by the MEP against measured USGS flows in the Paskamanset River, a relationship exists between both flows (Figure IV-15) which enabled an estimate of Acushnet River flows based on the historic USGS flow record for the Paskamanset River (1995-2002 and 2006-2012). Based on the four year water quality record obtained by the MEP for the Acushnet River, average monthly total nitrogen concentrations were calculated at the gaging location in order to calculate an average monthly loads for years in which flow in the Acushnet River was determined based on measured flows in the Paskamanset River (Figure IV-16). Considering variations in total nitrogen loads in the Acushnet River based on the historic record of Paskamanset River flow, it appears that the MEP nitrogen load (36,192 kg yr^{-1}) for the Acushnet River is a reasonable representation of average annual loading conditions. Average total nitrogen load in the Acushnet River based on the long term record was (36,840 kg yr^{-1}).

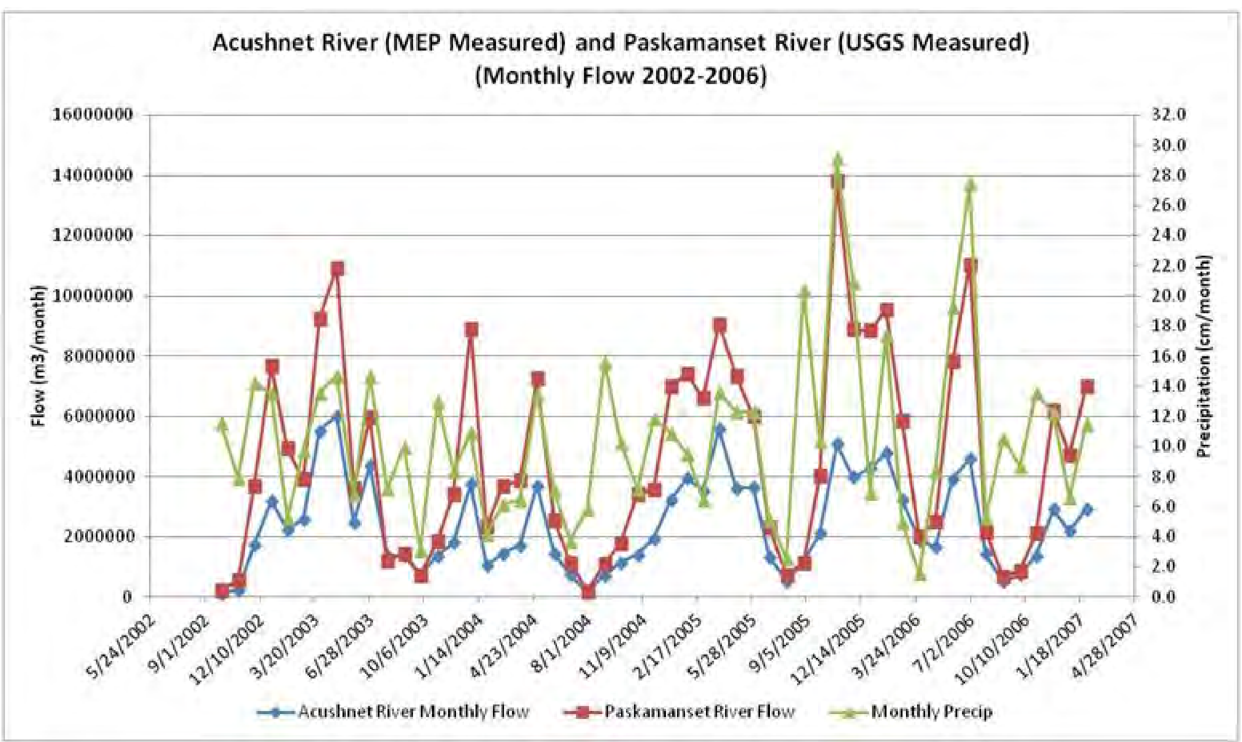


Figure IV-14. Acushnet (solid blue line) and Paskamanset River (red line) discharge (solid blue line), compared to monthly precipitation from New Bedford Airport.

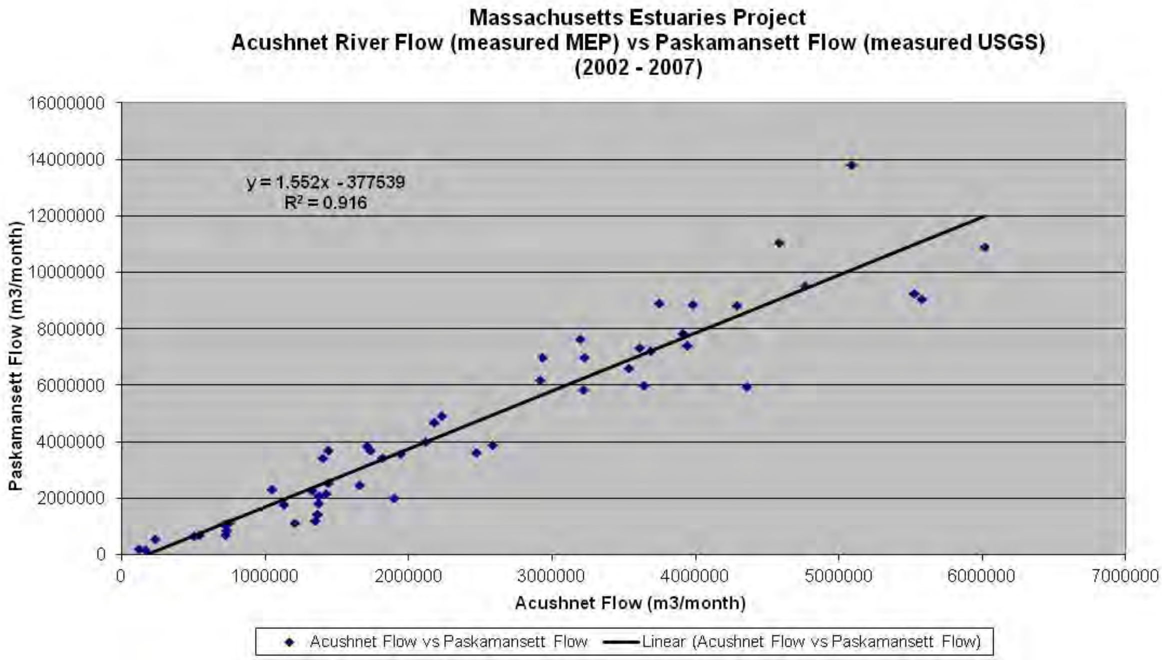


Figure IV-15. Acushnet River discharge plotted relative to Paskamanset measured flows obtained from the USGS. Relationship used to calculate Acushnet River flows based on historic Paskamanset flow from the USGS.

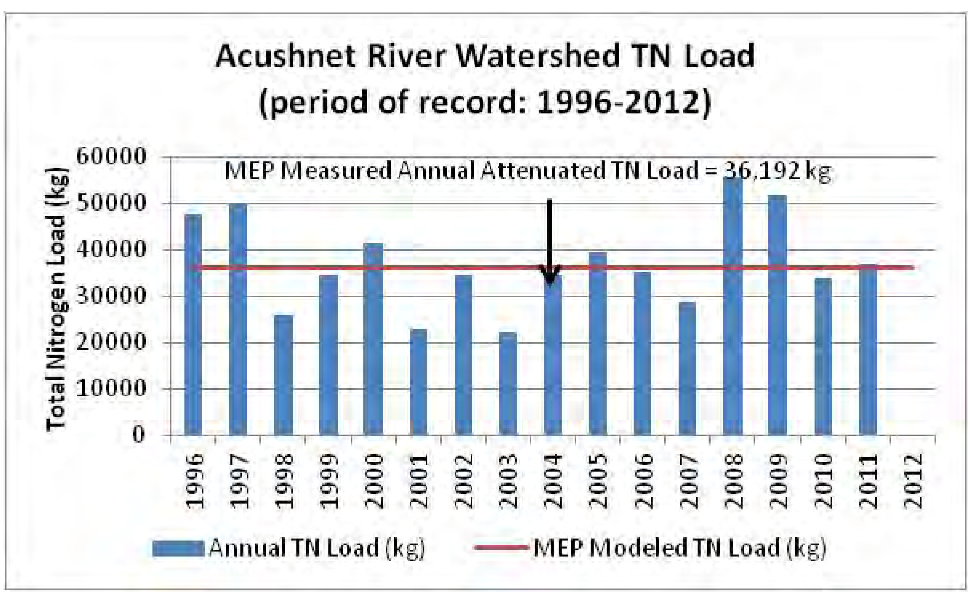


Figure IV-16. Average monthly nitrogen loads in the Acushnet River based on predicted flows and average total nitrogen concentrations based on MEP water quality data collection (2002-2006).

Table IV-6. Summary of annual volumetric discharge and nitrogen load (nitrate+nitrite and total nitrogen) from the Acushnet River (freshwater) discharging to the head of the estuarine reach of Acushnet River based upon the data presented in Figures IV-10, 11, 12, 13 and Table IV-5.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Acushnet River Stream Gage (Tar Kiln Rd)	**September 1, 2002 to August 31, 2003**	**31176390**	**18778**	**34577**
Acushnet River Stream Gage (Tar Kiln Rd)	**September 1, 2003 to August 31, 2004**	**18604738**	**11059**	**22047**
Acushnet River Stream Gage (Tar Kiln Rd)	**September 1, 2004 to August 31, 2005**	**31079480**	**19168**	**34471**
Acushnet River Stream Gage (Tar Kiln Rd)	**September 1, 2005 to August 31, 2006**	**37457102**	**21607**	**39528**
Acushnet River Stream Gage (Tar Kiln Rd)	**Four Year Average**	**29579428**	**17653**	**32656**
Acushnet River (Freshwater) CCC	Based on Watershed Area and Recharge	**34961890**	**--**	**--**

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the benthic nutrient flux surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters throughout the New Bedford Inner Harbor Embayment System (Acushnet River Estuary bounded by the Hurricane Barrier). The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the New Bedford Inner Harbor Embayment System predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton "particles". Most of these "particles" remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Buzzards Bay). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen "load" become incorporated into the surficial sediments of the bays.

In general the fraction of the phytoplankton population which enters the surficial sediments of a shallow embayment: (1) increases with decreased hydrodynamic flushing, (2) increases in low velocity settings, (3) increases within enclosed tributary basins, particularly if they are deeper than the adjacent embayment. To some extent, the settling characteristics can be evaluated by observation of the grain-size and organic content of sediments within an estuary.

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found within Lewis Bay, Crooked River in the Wareham River and the lower reach of the Pleasant Bay System. In contrast, regions of enhanced deposition typically support organic rich sediments and moderate to high levels of nitrogen release during summer months. These areas frequently occur in the upper reaches of estuaries where watershed nutrients are focused (frequently due to river inflows) and sediments become organic and nutrient enriched, for example in the estuarine reach of the Agawam and Wankinko Rivers in the Wareham River Estuary.

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the New Bedford Inner Harbor Embayment System. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the New Bedford Inner Harbor Embayment System in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from 15 sites, **(Figure IV-17)** in July-August 2002 and 2012, with a total of 16 sediment cores collected in each survey. Thirteen of the sites were the same in both surveys. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site **(Figure IV-17)** per incubation are as follows:

New Bedford Inner Harbor Embayment System Benthic Nutrient Regeneration Cores (2002/2012)

- Upper Basin-14 3/2 cores (Basin)
- Middle Basin-9 1/1 core (Basin)
- Middle Basin-10 1/1 core (Basin)
- Middle Basin-11 1/1 core (Basin)
- Middle Basin-12 1/1 core (Basin)
- Middle Basin-13 1/1 core (Basin)
- Middle Basin-15 0/1 core (Basin)
- Lower Basin North-4 1/1 core (Basin)
- Lower Basin North-5 1/1 core (Basin)
- Lower Basin North-6 1/1 core (Basin)
- Lower Basin North-7 1/1 core (Basin)
- Lower Basin North-8 1/1 core (Basin)
- Lower Basin South-1 1/1 core (Basin)
- Lower Basin South-2 1/1 core (Basin)
- Lower Basin South-3 1/1 core (Basin)

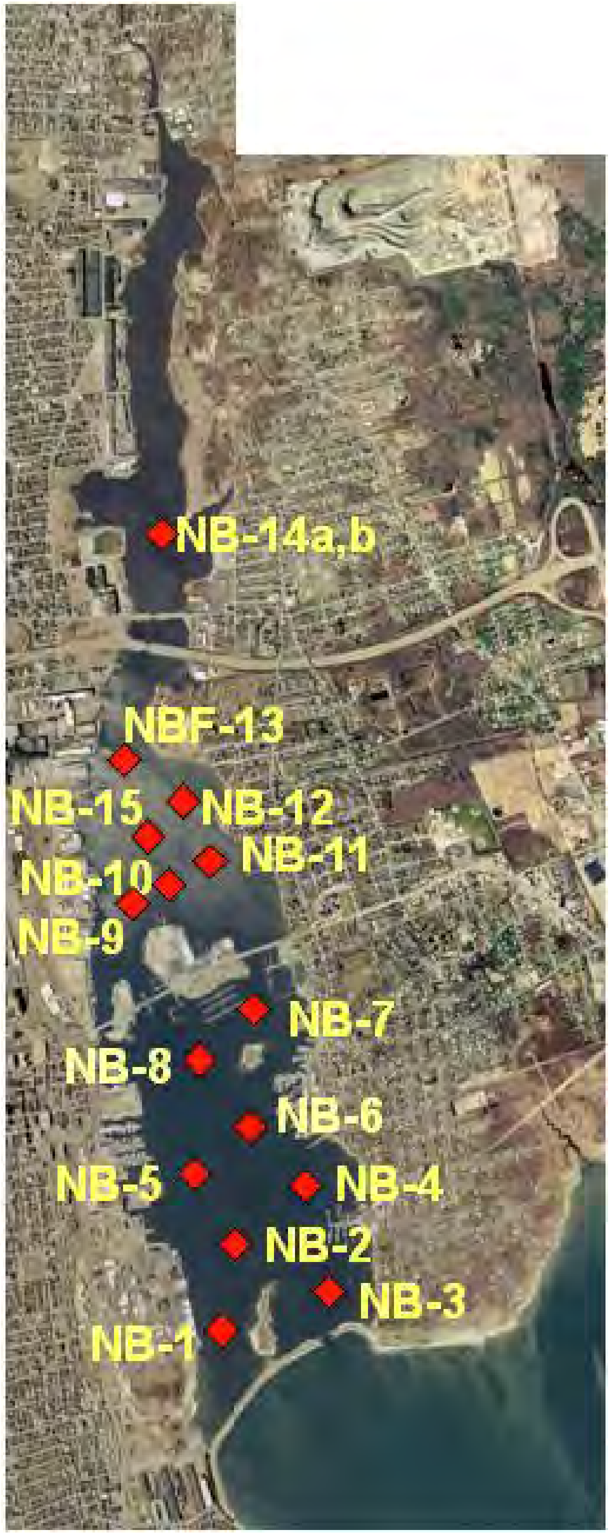


Figure IV-17. Acushnet River-New Bedford Inner Harbor embayment system sediment sampling sites (red symbols) for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-6. Station 15 was only sampled in 2012.

Sampling was distributed throughout the primary embayment sub-basins of this system: the upper basin, above the Route 195 bridge, middle basin, between Popes Island and the Route 195 bridge, Lower Basin between Popes Island and the Hurricane Barrier (partitioned into northern and southern regions). The results for each site were combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory (Harbormasters Office) the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and ortho-phosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20^{o}C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA. The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Water column nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (water column and benthic), and uptake (e.g. photosynthesis). As stated above, during the warmer summer months the sediments of shallow embayments typically act as a net source of nitrogen to the overlying waters and help to stimulate eutrophication in organic rich systems. However, some sediments may be net sinks for nitrogen and some may be in “balance” (organic N particle settling = nitrogen release). Sediments may also take up dissolved nitrate directly from the water column and convert it to dinitrogen gas (termed “denitrification”), hence effectively removing it from the ecosystem. This process is typically a small component of sediment denitrification in embayment sediments, since the water column nitrogen pool is typically dominated by organic forms of nitrogen, with very low nitrate concentrations. However, this process can be very effective in removing nitrogen loads in some systems, particularly in streams, ponds and salt marshes, where overlying waters support high nitrate levels.

In addition to nitrogen cycling, there are ecological consequences to habitat quality of organic matter settling and mineralization within sediments, these relate primarily to sediment and water column oxygen status. However, for the modeling of nitrogen within an embayment it is the relative balance of nitrogen input from water column to sediment versus regeneration which is critical. Similarly, it is the net balance of nitrogen fluxes between water column and sediments during the modeling period that must be quantified. For example, a net input to the sediments represents an effective lowering of the nitrogen loading to down-gradient systems and net output from the sediments represents an additional load.

The relative balance of nitrogen fluxes (“in” versus “out” of sediments) is dominated by the rate of particulate settling (in), the rate of denitrification of nitrate from overlying water (in), and regeneration (out). The rate of denitrification is controlled by the organic levels within the sediment (oxic/anoxic) and the concentration of nitrate in the overlying water. Organic rich sediment systems with high overlying nitrate frequently show large net nitrogen uptake throughout the summer months, even though organic nitrogen is being mineralized and released to the overlying water as well. The rate of nitrate uptake, simply dominates the overall sediment nitrogen cycle.

In order to model the nitrogen distribution within an embayment it is important to be able to account for the net nitrogen flux from the sediments within each part of each system. This requires that an estimate of the particulate input and nitrate uptake be obtained for comparison to the rate of nitrogen release. Only sediments with a net release of nitrogen contribute a true additional nitrogen load to the overlying waters, while those with a net input to the sediments serve as an "in embayment" attenuation mechanism for nitrogen.

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-18).

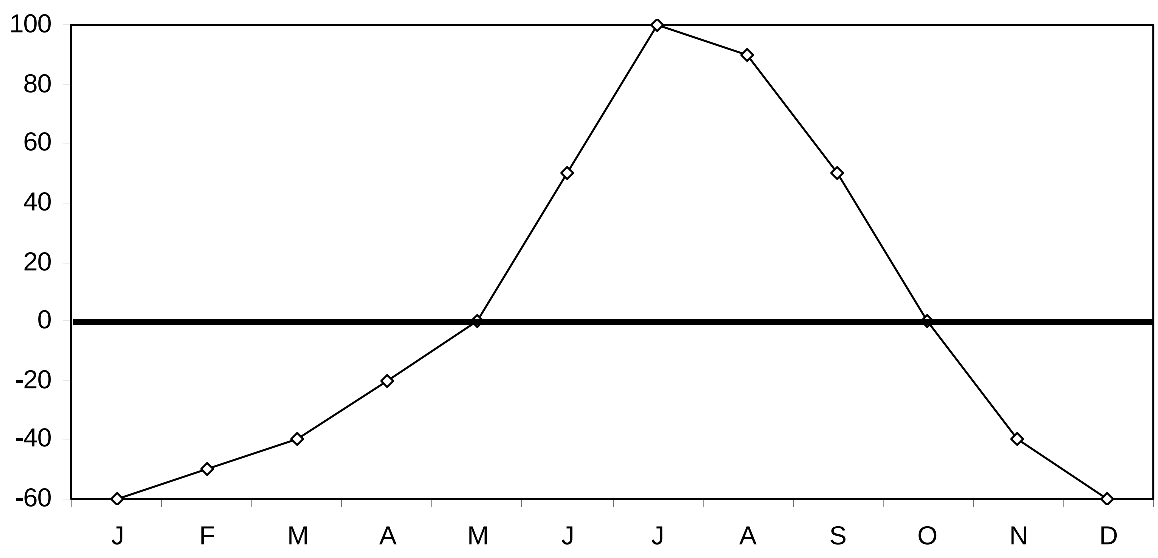


Figure IV-18. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Unfortunately, the tendency for net release of nitrogen during warmer periods coincides with the periods of lowest nutrient related water quality within temperate embayments. This sediment nitrogen release is in part responsible for poor summer nutrient related health. Other major factors causing the seasonal water quality decline are the lower solubility of oxygen during summer, the higher oxygen demand by marine communities, and environmental conditions supportive of high phytoplankton growth rates.

In order to determine the net nitrogen flux between water column and sediments, all of the above factors were taken into account. The net input or release of nitrogen within a specific embayment was determined based upon the measured total dissolved nitrogen uptake or release, and estimate of particulate nitrogen input.

Sediment sampling was conducted throughout the primary embayment sub-basins of this system: the upper basin, middle basin, and lower basin (northern and southern regions). in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). Two levels of settling were used. If the sediments were organic rich and fine grained, and the hydrodynamic data showed low tidal velocities, then a water column particle residence time of 8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). If the sediments indicated coarse-grained sediments and low organic content and high velocities, then half this settling rate was used. Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas which are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham embayments) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism), which would be accounted for by daily particulate carbon settling. This analysis indicated that sediment metabolism in the highly organic rich sediments of the wetlands and depositional basins is driven primarily by stored organic matter (ca. 90%). Also, in the more open lower portions of larger embayments, storage appears to be low and a large proportion of the daily carbon requirement in summer is met by particle settling (approximately 33% to 67%). This range of values and their distribution is consistent with ecological theory and field data from shallow embayments. Additional, validation has been conducted on deep enclosed basins (with little freshwater inflow), where the fluxes can be determined by multiple methods. In this case the rate of sediment regeneration determined from incubations was comparable to that determined from whole system balance.

Net nitrogen release or uptake from the sediments within the New Bedford Inner Harbor Embayment System measured in 2002 and 2012 were not significantly different ($p<0.05$). In fact for each of the 4 basin areas, the difference was less than 1 standard deviation (s.d.) which shows a high degree of similarity ($r=0.73$). As a result, the data were combined to provide a more robust estimate of sediment regeneration within the Harbor than available from the 2002 or 2012 measurements alone. Overall the rates were generally comparable to other similar embayments in southeastern Massachusetts. However, the presence of the Hurricane Barrier, depth of the lower basin and urban nature of the Harbor have likely influenced the nitrogen dynamics of this system. A clear gradient in nitrogen release rates was observed from the upper to lower basins, with a moderate net nitrogen release in the upper basin (59.7 mg N m^{-2} d^{-1}) to a net uptake in the mid and eastern portion of the lower basin (-26.2 and -10.9 mg N m^{-2} d^{-1}, respectively), while there was net release (41.0 mg N m^{-2} d^{-1}) in the depositional region of the lower basin (western portion), associated with the shipping lane. The rates measured within the upper and middle basins of the Inner Harbor rates are typical of embayment sediments throughout the region. For example in the nearby Wareham River Estuary, the primary estuarine reach (south of the Rt. 6 Bridge) showed rates ranging from -4.9 and 37.0 mg N m^{-2} d^{-1} and 11.1 mg N m^{-2} d^{-1} and 10.5 mg N m^{-2} d^{-1} in Broad Marsh River and Marks Cove, respectively. Similar rates have also been measured by the MEP Technical Team within other Buzzards Bay estuaries, as previously reported (e.g. Phinneys Harbor, and Slocums River). The lower basin of New Bedford Inner Harbor is relatively deep (6 m) compared to other embayments to Buzzards Bay and contains "urban" nitrogen sources (CSO's, WWTF outfall) in addition to river and groundwater inflows. The sediments of the mid and eastern lower basin show net nitrogen uptake (-10.9 to -26.2 mg N m^{-2} d^{-1}) typical of larger systems like lower Pleasant Bay (-7.0 to -18.1 mg N m^{-2} d^{-1}), the main basin of Waquoit Bay (-16.4 to -31.9 mg N m^{-2} d^{-1}) or Boston Harbor (c.f. MWRA HOM Program), but are much lower than the deep basin of a non-tidal coastal salt pond, Sesachacha Pond, Nantucket (-244 mg N m^{-2} d^{-1}). Further, the eutrophic basins of Hamblin Pond (9.3 mg N m^{-2} d^{-1}) and Jehu Pond (51.9 mg N m^{-2} d^{-1}) in Waquoit Bay, with similar depths showed similar net release as for the lower western area and the upper basin of New Bedford Inner Harbor. The overall range of nitrogen exchange was also similar to another tidal river, Bass River (-30.0 to 80.9 mg N m^{-2} d^{-1}) and the adjacent Nasketucket Bay which ranges from 16.9 in the upper tributary basins to -20.3 N m^{-2} d^{-1}) in the deeper lower basins which have less nitrogen loading. The Inner Harbor rates are consistent with the depositional nature of these basins and their nutrient enriched waters. The finding of higher rates of summer nitrogen release in upper regions of estuaries is common in southeastern Massachusetts estuaries.

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the New Bedford Inner Harbor Embayment System (Chapter VI) are presented in Table IV-7. There was a clear spatial pattern of sediment nitrogen flux, with nitrogen release by the sediments of the upper estuary. The sediments within the New Bedford Inner Harbor Embayment System showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and its relatively high flushing rate.

Table IV-7. Rates of net nitrogen return from sediments to the overlying waters of the New Bedford Inner Harbor Embayment System (Acushnet River Estuary). These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July-August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d. *
	Mean	S.E.	N	
New Bedford Inner Harbor Embayment System				
Upper Basin	59.7	10.9	5	NB 14a,b,c
Middle Basin	-26.2	13.4	11	NB 9-13
Lower Basin - East	-10.9	16.7	10	NB 3,4,6,7
Lower Basin - West	41.0	14.4	6	NB 1,2,5,8

* Station numbers refer to Figure IV-17.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

A hydrodynamic study was performed for the Acushnet River system. The system is located along the southern coast of Massachusetts in New Bedford, along the western coastline of Buzzards Bay. A site map showing the general study area is shown in Figure V-1. The estuarine system has been divided into smaller embayments with the construction of bridges to Popes Island, the Interstate 195 bridge, and hurricane barrier at the head of the harbor. In general, flow between Buzzards Bay and the system is restricted by the hurricane barrier at the entrance of New Bedford Harbor. Although the bridges and overpass restrict tidal flow, they do not significantly hinder flow to the upper reaches of the estuary.

Acushnet River is a moderately sized estuary which discharges into Buzzards Bay. The system is generally a shallow tidal estuary, with mean water depth of only 2.5 feet and deeper sections resulting from navigational dredging and scour through the hurricane barrier. The system is comprised of a small overall area of salt marsh (approximately 230 acres), which accounts for 37 percent of the estuary surface area.

Circulation in the Acushnet River is dominated by tidal exchange with Buzzards Bay. From measurements made in the course of this study, the average tide range at the entrance to New Bedford Harbor is approximately 3.1 feet. By flow restrictions caused by narrowing of channels, bridge abutments, restrictions and frictions losses, the tide range in upper Acushnet River is slightly smaller, or approximately 3.0 feet.

The hydrodynamic study consisted of two major components. In the first portion of the study, bathymetry, Acoustic Doppler Current Profile (ADCP) measurements, and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the hydrodynamic modeling portion of the study. The bathymetry survey of the Acushnet River was performed to determine the variation of embayment and channel depths throughout the system. This survey addressed the previous lack of adequate bathymetry data for this area. In addition to the survey, tides were recorded for 33 days at three locations within the Acushnet River, and at an offshore gage. This tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of the Acushnet River system was developed in the second portion of this study. Using the bathymetry survey data, a finite element model grid was generated for use with the RMA-2 hydrodynamic code. The tide data from the offshore gage was used to define the open boundary condition that drives the circulation of the model, and data from the three locations within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system. In addition to the calibration process, the ADCP current measurements supplied the data needed as an independent verification of the hydrodynamic model results.

The calibrated computer model of the Acushnet River system was used to compute the flushing rates of each of the sub-embayments of the system. Though water quality in an embayment cannot be directly inferred by use of the computed flushing rate alone, it can serve as a useful indicator of an embayments flushing performance relative to other similar systems. The ultimate utility of this hydrodynamic model is as input into a constituent transport model, where water quality constituents like nitrogen are modeled to determine the water quality dynamics of a system. This next level of modeling is planned as part of the Massachusetts Estuaries Project, a Massachusetts DEP program focused on the restoration of coastal embayments in southeastern Massachusetts (http://www.state.ma.us/dep/smerp/smerp.htm).

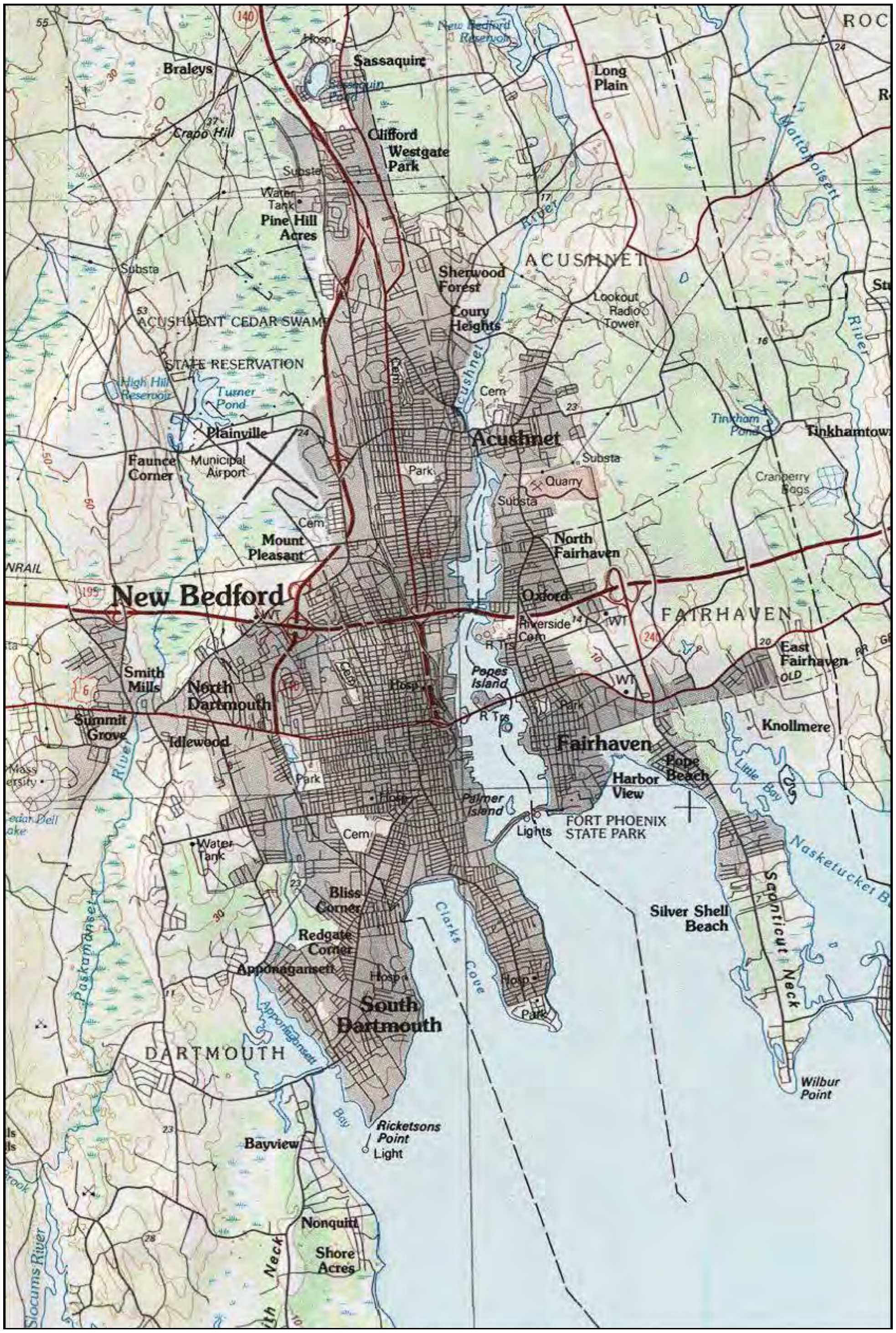


Figure V-1. Site map of the region around the Acushnet River and New Bedford.

Figure V-2. Aerial photograph of the Acushnet River in New Bedford, MA.

V.2 FIELD DATA COLLECTION AND ANALYSIS

A precise description of embayment geometries and hydrodynamic forcing processes is required for the development of numerical hydrodynamic models. To support hydrodynamic and future water quality modeling efforts in Acushnet River estuary, tidal currents, water elevation variations, and bathymetry of the embayments were measured. Cross-channel current measurements were surveyed through a complete tidal cycle at entrance to New Bedford Harbor along the channel opening in the hurricane barrier. Tidal elevation measurements at selected points along the river were used for both forcing conditions and to evaluate tidal attenuation through the system. Bathymetry data were collected in detail necessary for evaluation of tidal hydrodynamics. The bathymetric data collection effort was focused on areas of flow constrictions: near inlets and narrow sections of the estuaries. This bathymetric information was utilized to develop the computational grid of the system for the hydrodynamic modeling effort.

V.2.1 Data Acquisition

V.2.1.1 Water Elevation

Changes in water surface elevation were measured using internal recording tide gages. These tide gages were installed on fixed platforms (such as pier pilings or screw anchors secured to the seabed) to record changes in water pressure over time. Variations in the water surface can be due to tides, wind set-up, or other low frequency oscillations of the sea surface. The tide gages were installed in 4 locations in Acushnet River estuary (Figure V-3) in early April 2003 and recovered mid-May 2003. Data records span at least 29 days to yield an adequate time period for resolving the primary tidal constituents.

The tide gages used for the study consisted of Brancker TG-205 and Brancker XR-420 instruments. Data were set for 10-minute intervals, with each 10-minute observation resulting from an average of 60 1-second pressure measurements. Each of these instruments uses strain gage transducers to sense variations in pressure, with resolution on the order of 1 cm (0.39 inches) head of water. Each gage was calibrated prior to installation to assure accuracy.

Once the data were downloaded from each instrument, the water pressure readings were corrected for variations in atmospheric pressure. Hourly atmospheric readings were obtained from the NOAA buoy in Buzzards Bay (site BUZM3), interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in water pressure above the instrument. Further, a (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gage). Several of the sensors were surveyed into local benchmarks to provide vertical rectification of the water level; these survey values were used to adjust the water surface to a known vertical datum. The result from each gage is a time series representing the variations in water surface elevation relative to NGVD29. Figure V-4 presents the water levels at each gage location.

Figure V-3. Tide gage and ADCP transect locations in Acushnet River estuary. The yellow circles represent the tide gage locations. The red line is the ADCP transect location.

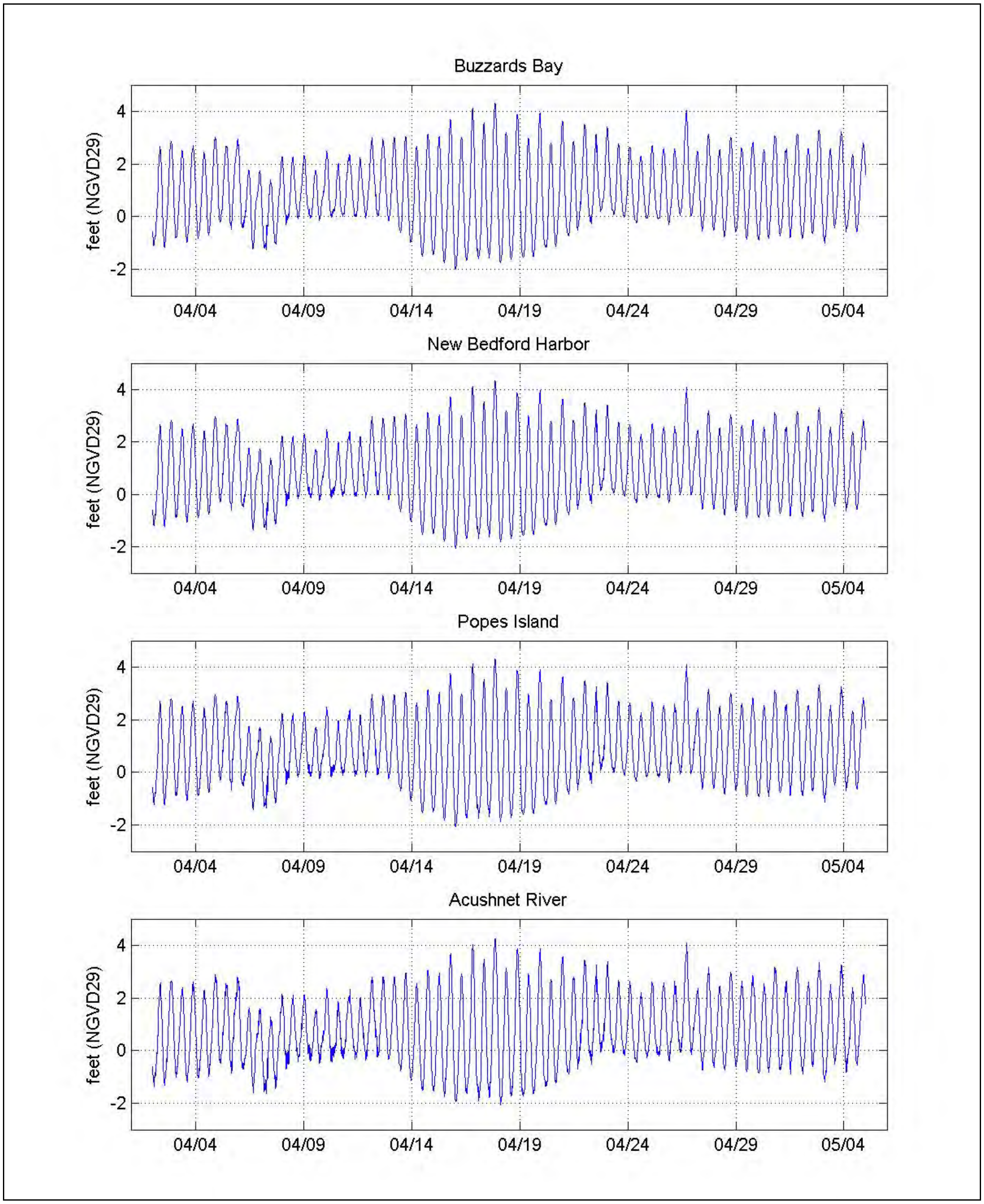


Figure V-4. Tidal elevation observations for Acushnet River estuary (offshore, New Bedford Harbor, Popes Island, and Acushnet River).

V.2.1.2 Bathymetry

The bathymetry for the Acushnet River was collected between two bathymetric surveys. The collected data was supplemented with bathymetry from NOAA GEODAS database for the offshore Buzzards Bay portions of the modeling domain.

The survey of Acushnet River above Popes Island was designed by Applied Coastal and conducted by CR Environmental in April 2003. The survey was completed using a small vessel equipped with a precision fathometer interfaced to a differential GPS receiver. The fathometer has a depth resolution of approximately 0.1 foot and the differential GPS provides x-y position measurements accurate to approximately 1-3 feet. Digital data output from both the echosounder and GPS were logged to a laptop computer in Hypack. GPS positions and echosounder measurements were merged to produce data sets consisting of water depth as a function of x-y horizontal position (in Massachusetts Mainland State Plane, 1983). The data were combined with water surface elevations to obtain the vertical elevation of the bottom (z) relative to the NGVD 1929 vertical datum (NGVD29).

Bathymetry in the lower portion of the Acushnet River from Popes Island to the hurricane barrier was collected in April 2003, by Applied Coastal. The survey employed a bottom tracking Acoustic Doppler Current Profiler (ADCP) mounted on a small vessel. Positioning data were collected using a differential GPS. The survey paths are shown in Figure V-5. The resulting bathymetric data was tide corrected, and referenced to the NGVD 1929.

The resulting xyz files (Figure V-6) were input to mapping software to calculate depth contours for the system shown in Figure V-7. The surface was created by interpolating the data to a finite element mesh.

V.2.1.3 Current Measurements

The measurements were collected using an Acoustic Doppler Current Profiler (ADCP) mounted aboard a small survey vessel. The boat repeatedly navigated a pre-defined set of transect lines through the area, approximately every 60 minutes, with the ADCP continuously collecting current profiles. This pattern was repeated for an approximate 11-hour duration to capture measurements over a tidal cycle. The results of the data collection effort are high-resolution observations of the spatial and temporal variations in tidal current patterns throughout the survey area.

Measurements were obtained with a BroadBand 1200 kHz Acoustic Doppler Current Profiler (ADCP) manufactured by RD Instruments (RDI) of San Diego, CA. The ADCP was mounted to a specially constructed mast, which was rigidly attached to the rail of the survey vessel. The ADCP was oriented to look downward into the water column, with the sensors located approximately 1 foot below the water surface. The mounting technique assured no flow disturbance due to vessel wake.

The ADCP emits individual acoustic pulses from four angled transducers (at 20° from the vertical) in the instrument. The instrument then listens to the backscattered echoes from discrete depth layers in the water column. The difference in time between the emitted pulses and the returned echoes, reflected from ambient sound scatters (plankton, debris, sediment, etc.), is the time delay. BroadBand ADCPs measure the change in travel times from successive pulses. As particles move further away from the transducers sound takes longer to travel back and forth. The change in travel time, or propagation delay, corresponds to a change in distance between the transducer and the sound scatterer, due to a Doppler shift. The propagation delay, the time lag between emitted pulses, and the speed of sound in water are used to compute the velocity of the particle relative to the transducer. By combining the velocity components for at least three of the four directional beams, the current velocities are transformed using the unit's internal compass readings to an orthogonal earth coordinate system in terms of east, north, and vertical components of current velocity.

Figure V-5. Bathymetry points collected in the Acushnet River. The yellow points represent the data collected by CR Environmental, and the purple points represent the data collected by Applied Coastal.

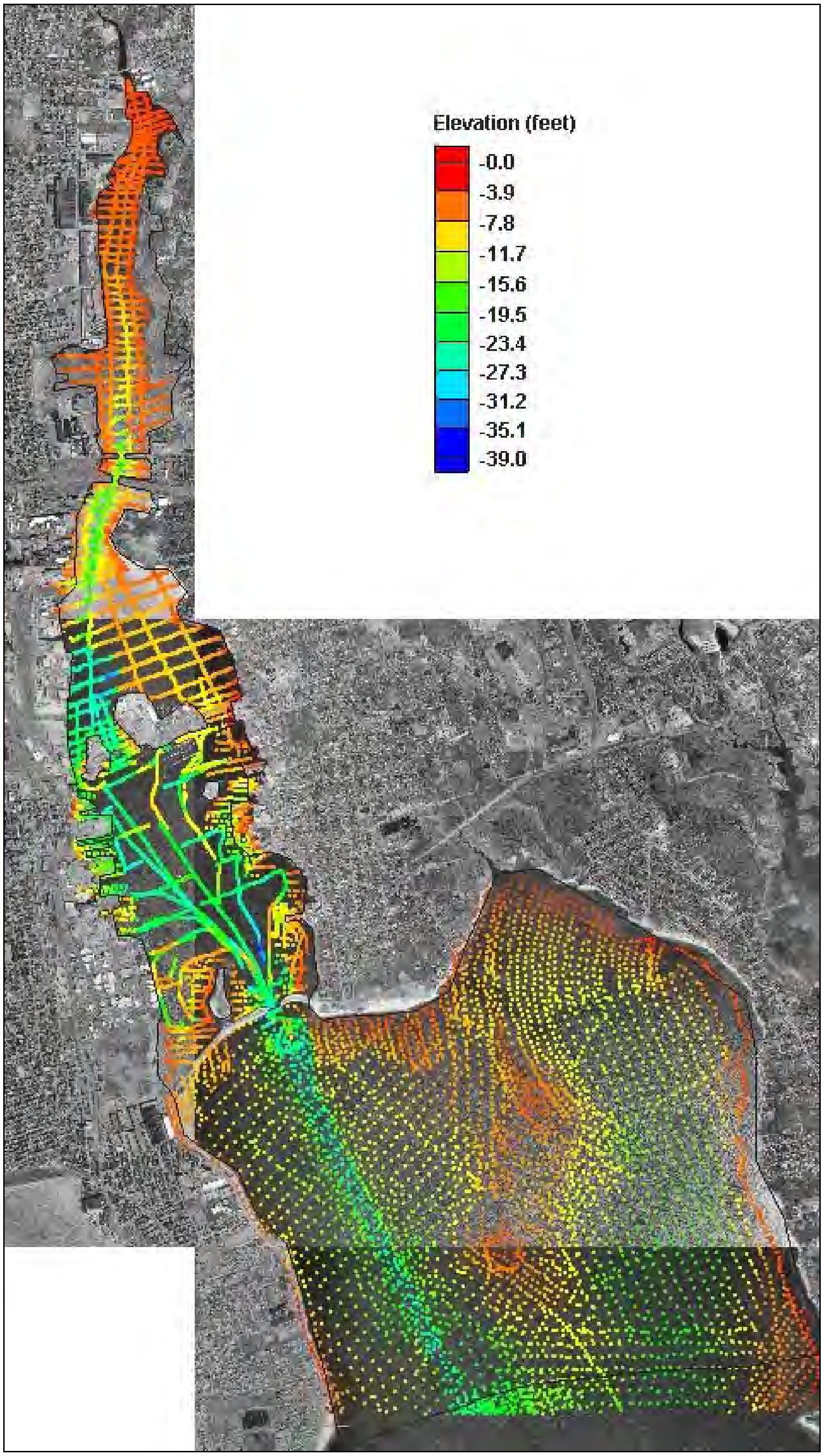


Figure V-6. XYZ bathymetry points collected for the model of Acushnet River estuary. Point colors indicate depth relative to the NGVD 29 vertical datum.

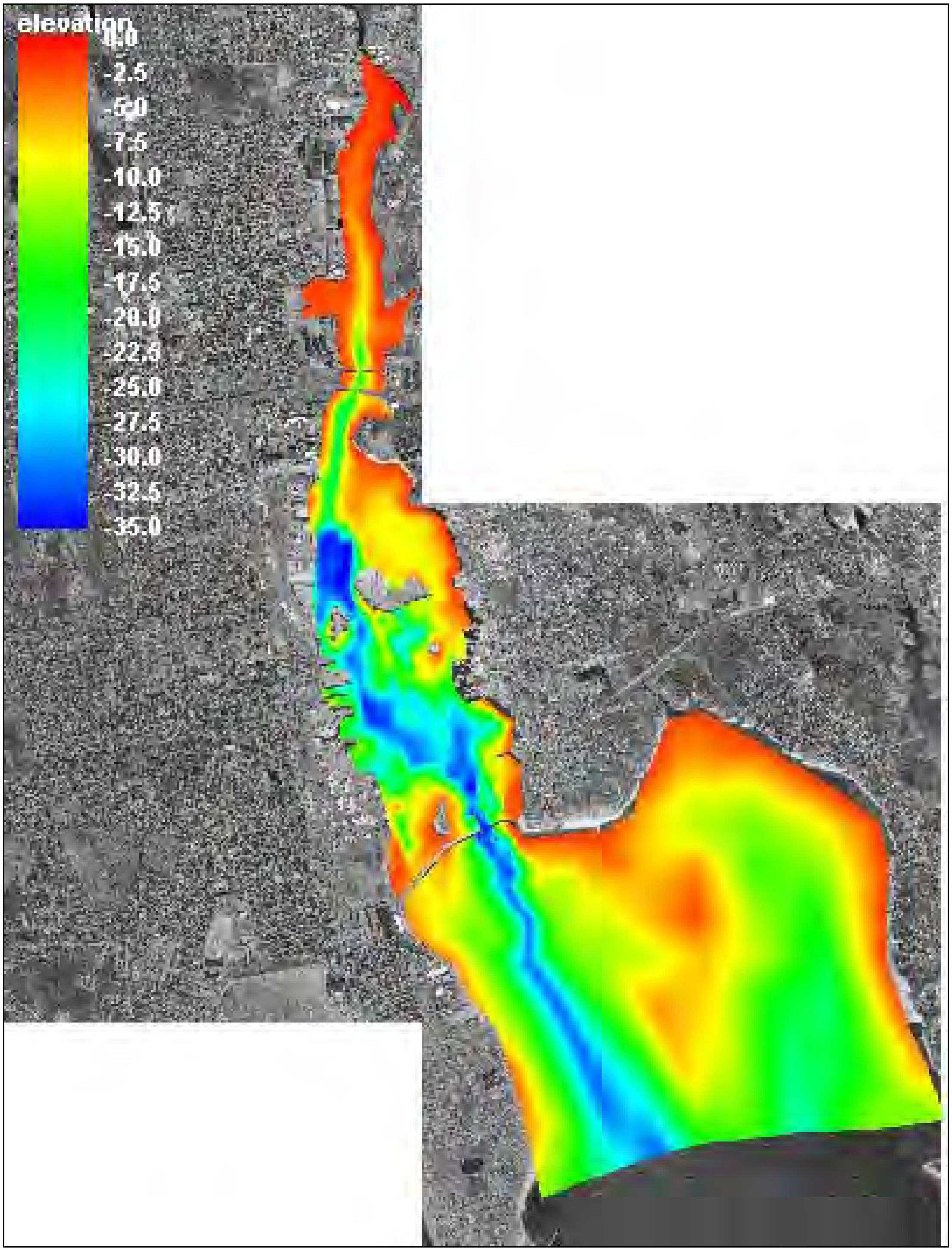


Figure V-7. Bathymetry map from model of Acushnet River estuary. Color contours indicate depth relative to the NGVD 29 vertical datum.

Vertical structure of the currents is obtained using a technique called 'range-gating'. Received echoes are divided into successive segments (gates) based on discrete time intervals of pulse emissions. The velocity measurements for each gate are averaged over a specified depth range to produce a single velocity at the specified depth interval ('bin'). A velocity profile is composed of measurements in successive vertical bins.

The collection of accurate current data with an ADCP requires the removal of the speed of the transducer (mounted to the vessel) from the estimates of current velocity. ‘Bottom tracking’ is the strongest echo return from the emission of an additional, longer pulse to simultaneously measure the velocity of the transducer relative to the bottom. Bottom tracking allows the ADCP to record absolute versus relative velocities beneath the transducer. In addition, the accuracy of the current measurements can be compromised by random errors (or noise) inherent to this technique. Improvements in the accuracy of the measurement for each bin are achieved by averaging several velocity measurements together in time. These averaged results are termed ‘ensembles’; the more pings used in the average, the lower the standard deviation of the random error.

For this study, the standard deviation (or accuracy) of current estimates (resulting from an ensemble average of 8 individual pulses) was approximately 0.30 ft/sec. Each ensemble took approximately 5-6 seconds to collect. Averaging parameters resulted in a horizontal resolution of approximately 10 feet along the transect line. For example, ADCP transect A1 (Figure V-3) near Acushnet River Inlet was approximately 700 feet across, resulting in approximately 65 to 70 independent velocity profiles per transect. The vertical resolution was set to 0.82 ft, or one velocity observation per every 9.8 inches of water depth. The first measurement bin was centered 2.9 feet from the surface, allowing for the transducer draft as well as an appropriate blanking distance between the transducer and the first measurement.

Position information was collected by Hypack, an integrated navigation software package running on a PC computer, linked to a differential GPS. The position data were read from the device in the WGS-84 coordinate system, and transformed to NAD 1983 Massachusetts Mainland State Plane coordinates. Position updates were available every 1 second. Clock synchronization between the GPS and ADCP laptop computers allowed each ADCP ensemble to be assigned an accurate GPS position during post-processing.

Current measurements were collected by the ADCP as the vessel navigated repeatedly a pre-defined transect line across the entrance to New Bedford Harbor (Figure V-3). The line-cycle was repeated every hour throughout the survey. The first cycle was begun at 05:49 hours (Eastern Daylight Time, EDT) and the final cycle was completed at 16:51 hours (EDT), for a survey duration of approximately 11.0 hours on April 21, 2003.

The transect line was designed to measure as accurately as possible the volume flux through the constriction into New Bedford Harbor during a complete tidal cycle. The line ran across the opening of hurricane barrier at the entrance to New Bedford Harbor.

V.2.1.4 Stream Flow Measurements

The stream flow entering the system from the upper Acushnet River was measured by SMAST. The station provided daily mean stream discharges throughout the deployment. A plot of the stream discharges is shown in Figure V-8. The average discharge for the deployment was 90 cfs.

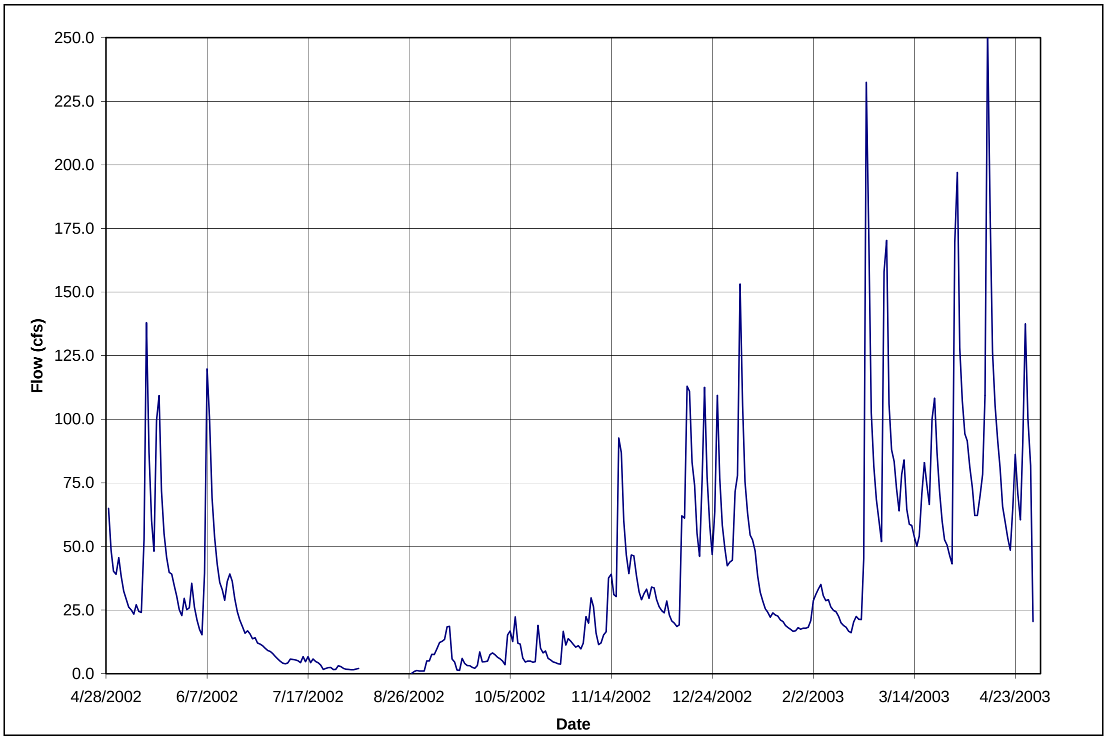


Figure V-8. Daily mean discharge along the upper portions of Acushnet River.

V.2.2 Data Processing Techniques

Data processing consisted of the following:

- Convert raw ADCP (binary) files to engineering units
- Merge ADCP vertical profile data with GPS position data
- QA/QC procedures to verify the accuracy of both ADCP and position data
- Manipulate the ADCP data to calculate spatial averages and cross section discharge values

The data files were converted from raw binary format to engineering ASCII values using RDI's BBLIST conversion program. The command set for this conversion process is described in greater detail in the RDI ADCP manual, and consists of developing a user-defined output file format, through which all conversions are defined.

The output data file from this procedure consists of multiple ensemble data 'packets'. The ensemble 'packet' consists of a single line containing the time of the profile, the ensemble number, and the measured water temperature (measured by the ADCP's internal temperature sensor) followed by consecutive rows and columns of the profile data. Each row of profile data corresponds to one bin, or depth layer, with succeeding columns representing east and north components of velocity, error velocity, speed, direction, echo amplitudes (for 4 beams), and correlation magnitudes (for 4 beams). Each ensemble, collected approximately every 5-6 seconds, has 30 rows corresponding to each discrete depth layer, starting at 2.9 feet. A single data file consists of multiple ensembles, as few as 25-30 to as many as 100. A single data file was recorded for each transect.

The next step in the processing was the assignment of an accurate x-y position pair to each ensemble. This was accomplished using the time stamp of both the ADCP data file and the position data file. Prior to the survey, the clocks used for each system were synchronized to assure this operation was valid. The procedure finds the time of each ADCP ensemble, then searches the position data file for the nearest corresponding time. When the nearest time is found, subject to a 'neighborhood' limit of 1 second, the x-y pair for that time is assigned to the ADCP ensemble. This method produces some inaccuracies; however for this survey the error in position definition was less than approximately 3.5 feet (calculated as vessel speed of 2 knots times the neighborhood value of 1 second for this survey). If no time is found within 1 second of the ADCP time, then a position is calculated using the ADCP bottom track velocity for that ensemble, and the time interval between ensembles.

Once each ensemble was assigned a valid x-y position, the data were reduced to calculate vertical averages as well as total discharge. A mean value of each east and north component of velocity is calculated for each vertical profile. These component mean values are then used to determine the mean speed and mean direction.

The total discharge time series represents the total volumetric flow through a waterway cross-section over the duration of the tidal cycle. Discharge calculations were performed on velocity components normal and tangential to the transect azimuth, which in most cases was perpendicular to the channel axis. To determine accurately the discharge normal to the channel cross-section (i.e. along-stream), the east and north velocity components were rotated into normal (along-stream) and tangential (cross-stream) components. Only the along-stream component was used to calculate total discharge.

The discharge through a cross section, Q_t, is the product of the upstream velocity, $V_{upstream}$, multiplied by the cross sectional area, A_{cs}, or

$$\Sigma Q_t = \Sigma_{i=1...N} (V_{upstream} * A_{cs})$$

where the cross sectional area is the water depth times the lateral (cross-stream) distance from the previous ensemble profile. The summation occurs over i, where i represents each individual ensemble profile from 1 to N, with 1 representing the top (surface) bin and N representing the deepest (near-bottom) bin.

Data recorded for the bottom-most bins in the water column can be contaminated by side lobe reflections from the transducer. At times, the measurements can be invalid. Validity of the bottom bin measurements is determined by comparing the standard deviation of bottom values to the standard deviation of mid-column measurements. If the standard deviation at the bottom was more than twice the standard deviation of mid-column measurements, the bottom bin was discarded from the discharge calculation. If the bottom value was within the limits defined by adjacent measurements, the value was included in the calculation.

The total discharge calculations assume a linear extrapolation of velocity from the surface to the first measurement bin (centered at 2.9 feet). Since the ADCP cannot directly measure the surface velocity, it is assumed the surface layer discharge is equivalent to the discharge in the first depth layer. The same linear assumption was applied to bottom bins when the bin measurement was declared invalid; that is, the bottom bin value was assumed equivalent to the overlying bin velocity value.

V.2.3 Results of Data Analysis

V.2.3.1 Tidal Harmonic Analysis

Analyses of the tide and bathymetric data provided insight into the hydrodynamic characteristics of each system. Harmonic analysis of the tidal time series produced tidal amplitude and phase of the major tidal constituents, and provided assessments of hydrodynamic ‘efficiency’ of each system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system.

Figure V-4 shows the tidal elevation for the period April 2 through May 5, 2003 at four locations in Acushnet River: Offshore New Bedford Harbor in Buzzards Bay, inside hurricane barrier in New Bedford Harbor, Popes Island, and Upper Acushnet River. The curves have a predominant 12.42-hour variation around the lunar semi-diurnal (twice-a-day), or M_2, tidal constituent. There was also a strong modulation of the lunar and solar tides, resulting in the familiar spring-neap fortnightly cycle. The spring (maximum) tide range was approximately 6 feet, and occurred on April 16. The neap (or minimum) tide range was 2 feet, occurring April 9.

Harmonic analyses were performed on the time series from each gage location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 known tidal constituents result from this procedure. Table V-1 presents the amplitudes of the eight largest tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 1.63 feet in Buzzards Bay (offshore Acushnet River). The range of the M_2 tide is twice the amplitude, or 3.26 feet. The diurnal tides, K_1 and O_1, possess amplitudes of approximately 0.24 feet and 0.17 feet respectively, throughout the system. Other semi-diurnal tides strongly contribute to the observed tide; the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides both have amplitudes of 0.46 and 0.49 feet through the system.

Table V-1 also shows how the constituents vary as the tide propagates into the upper reaches of the tidal river. Note the slight reduction in the M_2 amplitude from Buzzards Bay to the upper portions of Acushnet River. The decrease in the amplitude of M_2 constituent is evidence of frictional damping. Usually, a portion of the energy lost from the M_2 tide is transferred to higher harmonics (i.e., the M_4 and M_6), and is observed as an increase in amplitude of these constituents over the length of an estuary. However, since the lower portions of the Acushnet River are relatively deep as a result of dredging and development, the effect of frictional damping is minimal.

Table V-2 presents the phase delay of the M_2 tide at all tide gage locations compared to the offshore gage in Buzzards Bay. Phase delay is another indication of tidal damping, and results with a later high tide at inland locations. The greater the frictional effects, the longer the delay between locations.

In addition to the tidal analysis, the data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. These other processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large. This analysis calculated the energy (or variance) of the original water elevation time series, and compared these energy values to that of the purely tidal signal (re-created by summing the contributions from the 23 known harmonic constituents). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. The results of this analysis for the Acushnet River are posted in Table V-3.

Table V-1. Tidal Constituents, Acushnet River, New Bedford, April-May 2003

AMPLITUDE (feet)								
M2	**M4**	**M6**	**S2**	**N2**	**K1**	**O1**	**Msf**	
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Offshore	1.63	0.21	0.01	0.46	0.49	0.24	0.17	0.12
New Bedford Hbr	1.63	0.22	0.01	0.45	0.49	0.24	0.17	0.11
Popes Island	1.64	0.22	0.01	0.46	0.49	0.25	0.16	0.11
Acushnet River	1.62	0.22	0.01	0.44	0.48	0.25	0.18	0.10

Table V-2. M_2 Tidal Attenuation, Acushnet River, New Bedford, April-May 2003 (Delay in minutes relative to Offshore).

Location	Delay (minutes)
Offshore	--
New Bedford Harbor	4.41
Popes Island	4.74
Acushnet River	10.23

Table V-3. Percentages of Tidal versus Non-Tidal Energy, Acushnet River, New Bedford, April to May 2003

	Total Variance ($ft^2 \cdot sec$)	Tidal (%)	Non-tidal (%)
Offshore	1.69	94.9	5.1
New Bedford Hbr	1.71	94.7	5.3
Popes Island	1.71	94.7	5.3
Acushnet River	1.68	93.7	6.3

Table V-3 shows that the percentage of tidal energy was largest in the offshore signal in Buzzards Bay; as should be expected given the tidal attenuation through the system. In general, the energy of the signal decreases with distance from the offshore gage, with the lowest energy found in upper regions of the estuarine systems. The analysis also shows that tides are responsible for approximately 94% of the water level changes in Acushnet River. Meteorological effects in this data set were significant (approximately 5-6%) contributors to the total observed water level changes. However, the change in the non-tidal variance from offshore to the systems' upper reaches (approximately 2%) indicates that the offshore tide is adequate for use as the forcing time series of the computer hydrodynamic model of these systems. This relative increase in non-tidal energy within this system is likely due to the decrease in tidal energy as a result of frictional forces rather than actual growth of residual forces.

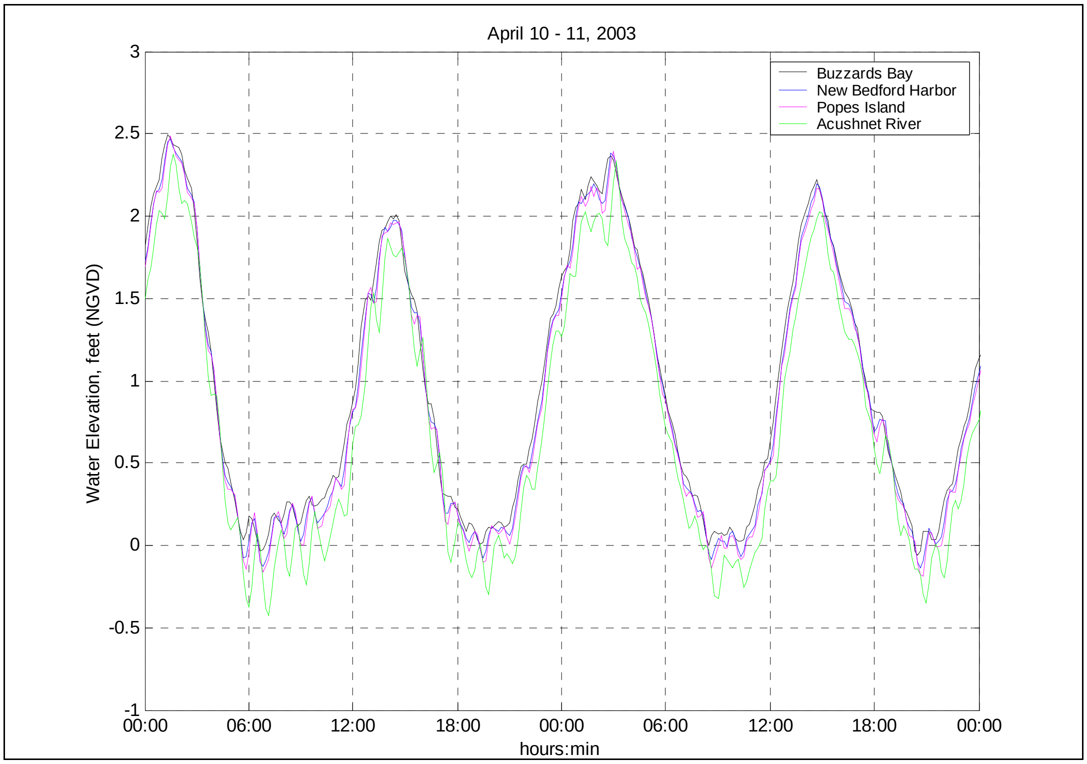


Figure V-9. Water elevation variations for a 2-day period in the Acushnet River estuary.

V.2.3.2 Current Measurements

Current measurements in New Bedford Harbor, surveyed on April 21, 2003, provided observation of the temporal and spatial variability of the flow regime during a tidal cycle. The survey was designed to observe tidal flow through the entrance to New Bedford Harbor, and attenuation by frictional damping through upstream constrictions at hourly intervals. The current measurements observed during the flood and ebb tides can be seen in Figures V-10 through V-11. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. At the inlet to New Bedford Harbor, positive along-channel is in the direction of northwest, and positive cross-channel is in the direction of northeast. In the lower left panel of the figures, the mean current or average currents across the channel are shown relative to the shoreline. The lower right panel indicates the stage of the tide during the transect illustrated (shown by a vertical line through the water elevation curve).

Flow into New Bedford Harbor is constricted to a small inlet through a break in the northeastern side of the hurricane barrier. Tidal currents tend to be vertically coherent during all stages of the tide, due to the large volume of water being directed through the narrow channel. Measured currents at the entrance to New Bedford Harbor reached maximum speeds of approximately 4.2 ft/sec directed into the estuary. On the ebb tide currents were biased to the southwest side of the channel, flowing almost due south just outside the hurricane barriers. Flood tidal currents were focused along the northeastern edge of the channel. Maximum volume flux through New Bedford harbor inlet during flood tide was 10,363 ft^3/sec, while the maximum flux during ebb conditions was slightly less, -9,737 ft^3/sec.

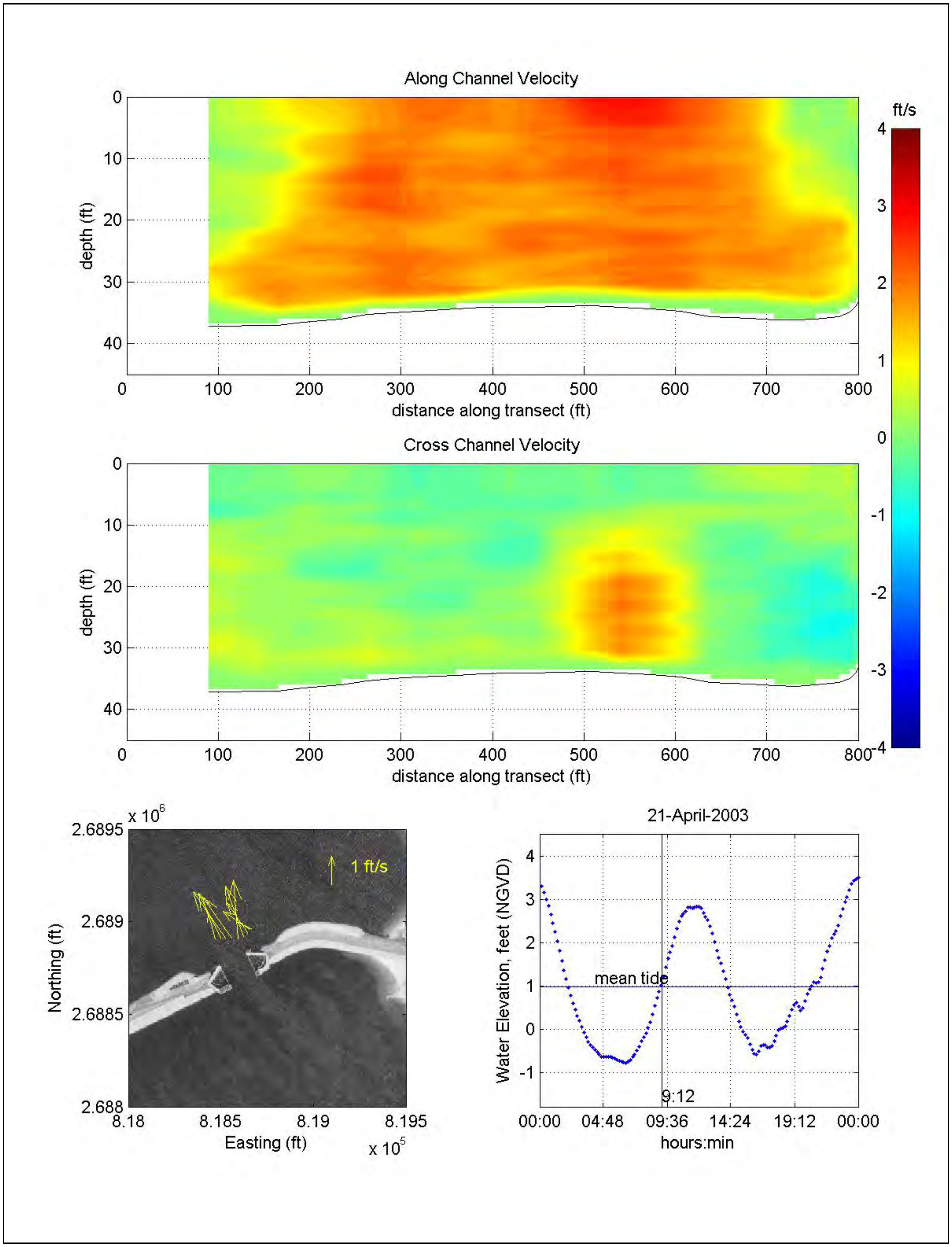


Figure V-10. Color contour plots of along-channel and cross-channel velocity components for the transect line across the hurricane barrier measured at 9:12 on April 21, 2003 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

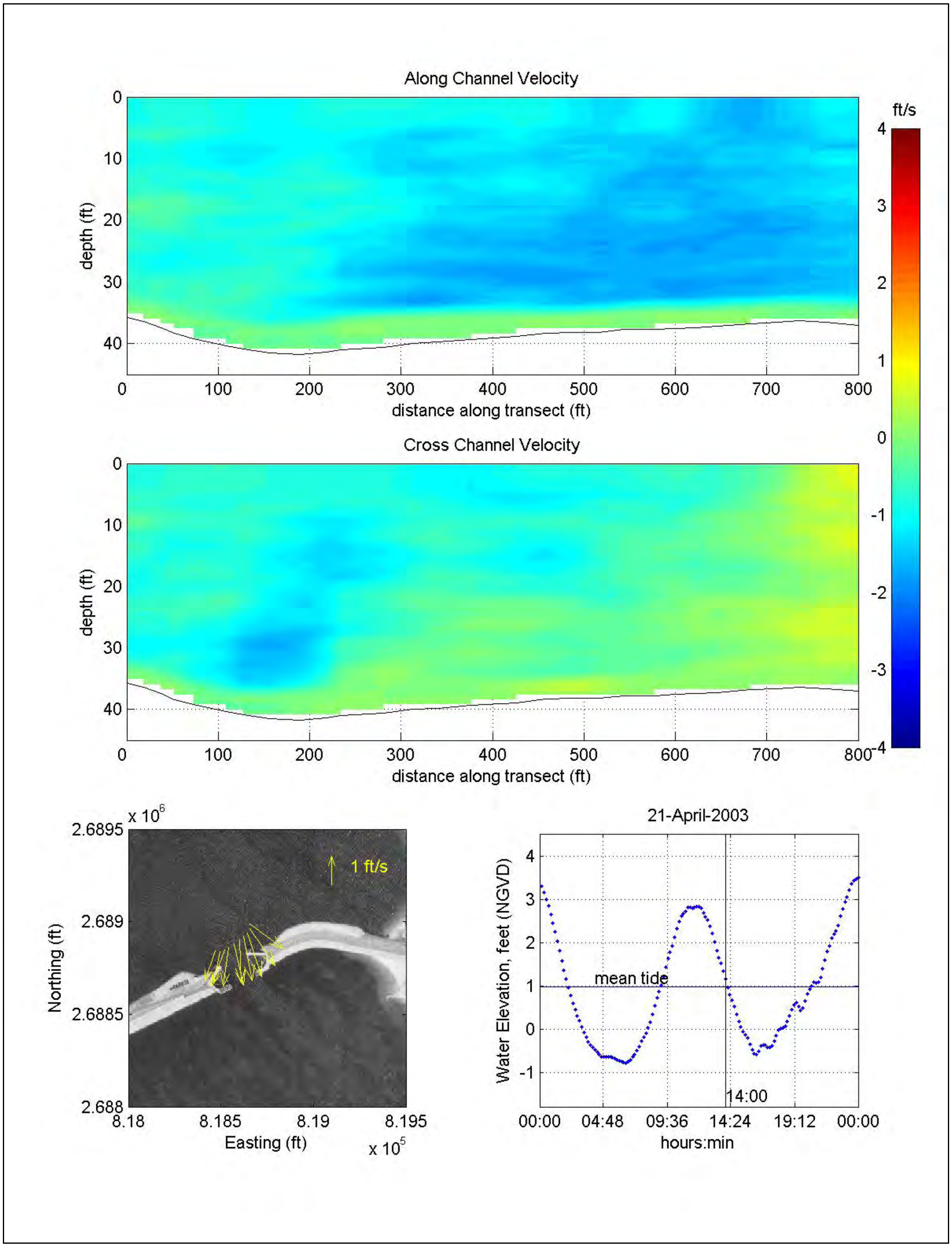


Figure V-11. Color contour plots of along-channel and cross-channel velocity components for the transect line across the hurricane barrier measured at 14:00 on April 21, 2003 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

V.3. HYDRODYNAMIC MODELING

For the modeling of the Acushnet River system, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in the system. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. RMA-2 operates under the hydrostatic assumption; meaning accelerations in the vertical direction are negligible. As a two-dimensional model in the horizontal plane, vertically stratified flow effects are beyond the capabilities of RMA-2. The model is widely accepted and tested for analyses of estuaries or rivers.

V.3.1 Model Theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

RMA-2 is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All the coefficients associated with these terms may vary from element to element. The model utilizes quadrilaterals and triangles to represent the prototype system. Element boundaries may either be curved or straight.

The time dependence of the governing equations is incorporated within the solution technique needed to solve the set of simultaneous equations. This technique is implicit; therefore, unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.

V.3.2 Model Setup

There are three main steps required to implement RMA-2:

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using 1994 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified within the larger embayment south of hurricane barrier at the entrance to New Bedford Harbor, on Buzzards Bay. The boundary condition was based on the tide gauge data collected along the western shore of the embayment. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite hydrodynamic information for future detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. A 2009 digital aerial orthophoto and the bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the embayments and waterways within the estuary. The aerial photograph was used to determine the land boundary of the system, as well as determine the surface coverage of salt marsh. The bathymetry data was interpolated to the developed finite element mesh of the system. The completed grid consists of 8,984 nodes, which describe 3,918 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth was -39 ft (NGVD 29), through the inlet in the hurricane barrier. The completed grid mesh of the Acushnet River system is shown in Figures V-12 and V-13.

The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties of the system. Fine resolution was required to simulate the numerous channel constrictions that significantly impact the estuarine hydrodynamics, such as the bridge abutments, as well as the hurricane barrier. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary.

Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution was employed where complex flow patterns were expected. For example, smaller node spacing in constrictions and channels was designed to provide a more detailed analysis in these regions of rapidly varying flow. Widely spaced nodes were often employed in areas where flow patterns are not likely to change dramatically, such as in the outer portion of Buzzards Bay, along the channels, and on the marsh plain. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

V.3.2.2 Boundary Condition Specification

Three types of boundary conditions were employed for the RMA-2 model of the Acushnet River system: 1) "slip" boundaries 2) tidal elevation boundaries, and 3) flow boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified at the offshore boundary of the bay. TDR measurements provided the required data. The rise and fall of the tide in Buzzards Bay is the primary driving force for estuarine circulation in this system. Dynamic (time-varying) model simulations specified a new water surface elevation at the boundary to the bay every model time step (10 minutes). A flow boundary was utilized at the upper model boundary of Acushnet River to account for the freshwater moving along the river. Data from a School for Marine Sciences and Technology at the University of Massachusetts Dartmouth (SMAST) flow recording station, located along the river at the upper limit of the finite element grid, was used to specify the flow values along the river boundary. Although freshwater also enters the river via groundwater, the rate of inflow can be considered negligible relative to the tidal flow that dominates the hydro dynamic processes.

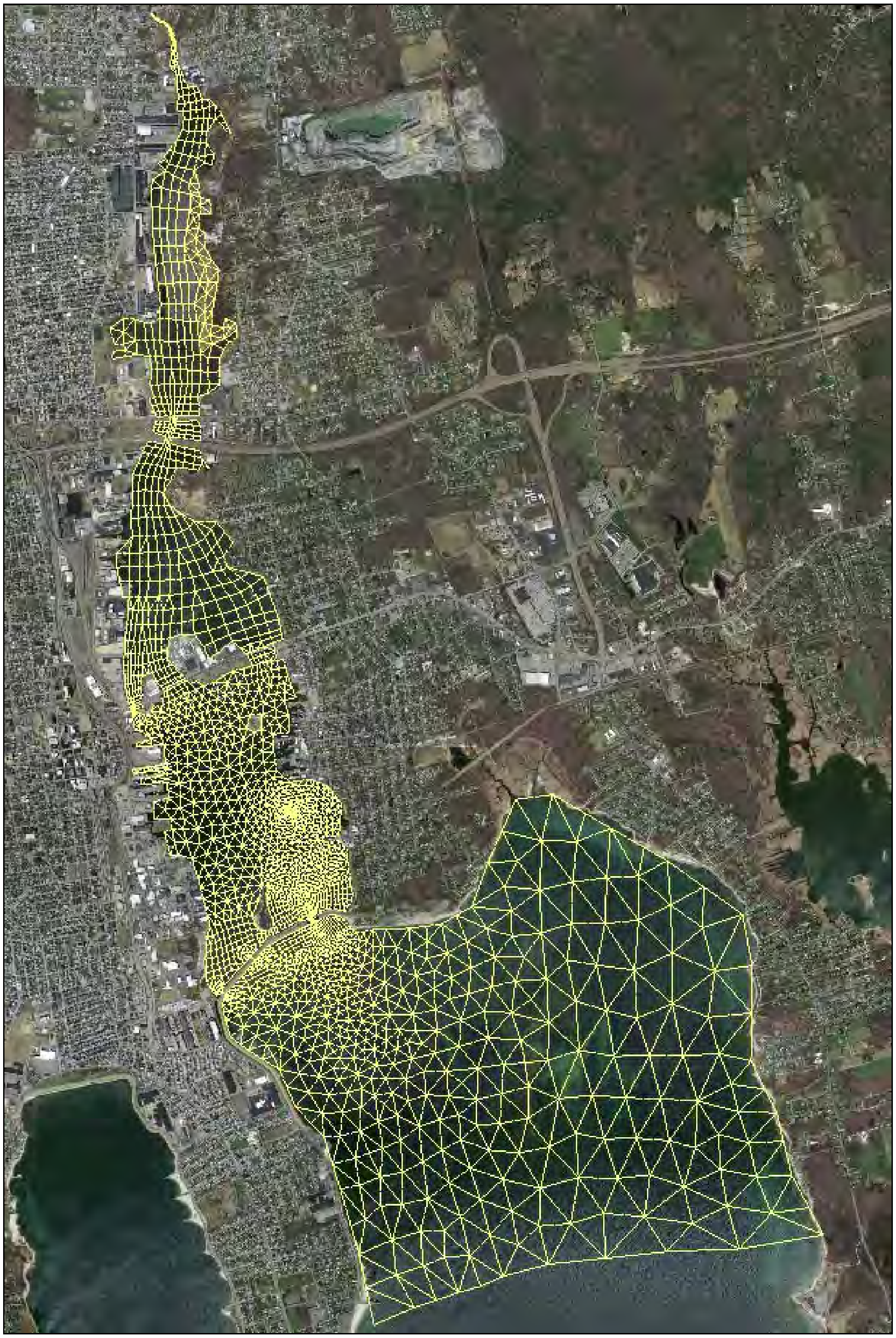


Figure V-12. Plot of hydrodynamic model grid mesh for the Acushnet River system overlaid on 2009 Mass GIS aerial orthophotos of the area.

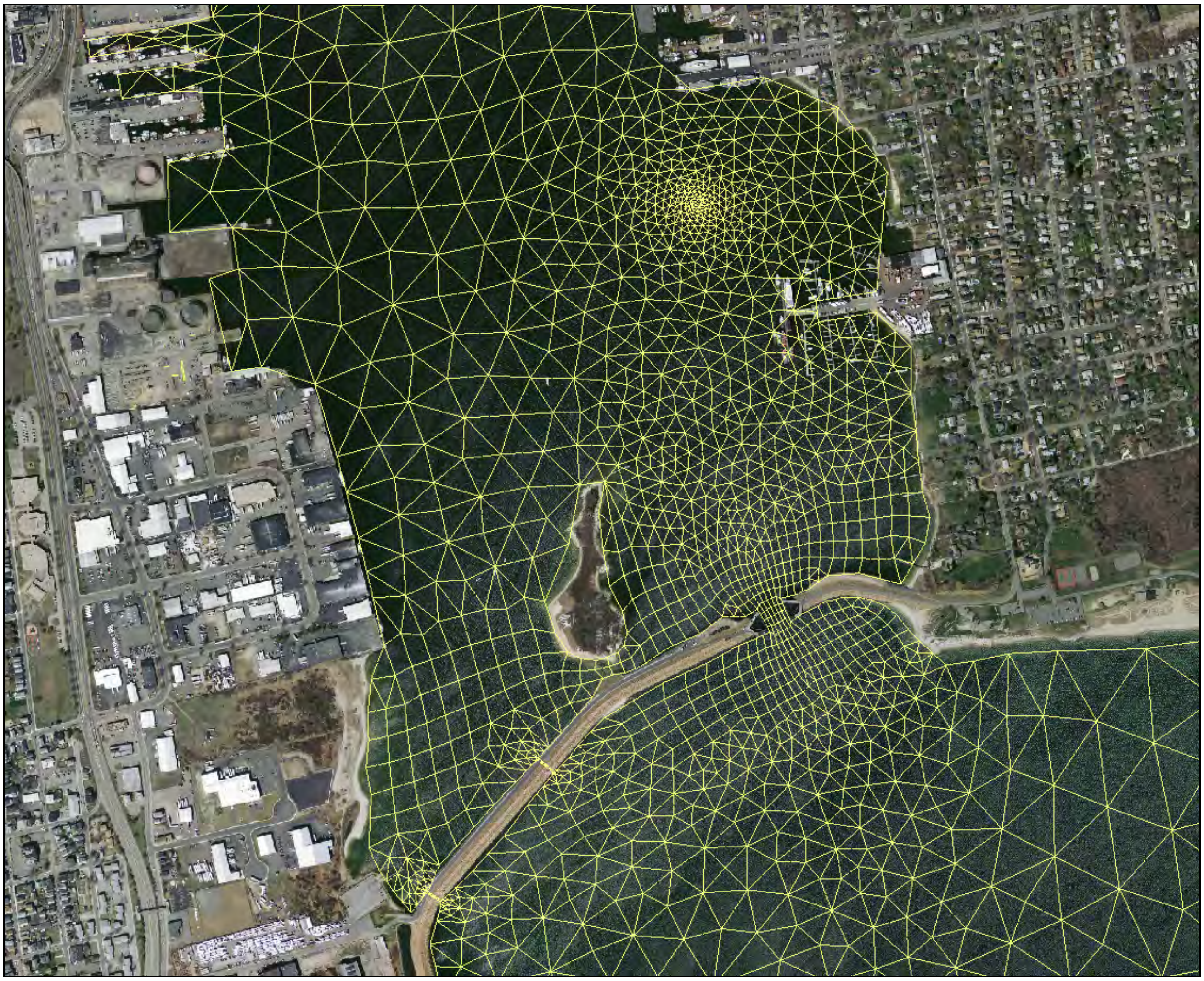


Figure V-13. Plot of hydrodynamic model grid mesh for the Acushnet River system in the vicinity of the Hurricane Barrier and Fairhaven outfall, overlaid on 2009 Mass GIS aerial orthophotos of the area.

V.3.2.3 Calibration

After developing the finite element grid, and specifying boundary conditions, the model for the Acushnet River system was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Numerous model simulations are required for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, an approximate seven-day period (14 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section 2. The seven-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents

The calibration was performed for a seven-day period beginning April 13, 2003 at 17:00 EDT, representing the transition from spring to neap tide conditions, or a period of average tidal conditions for forcing conditions for use in model verification and flushing analysis.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events.

V.3.2.3.a Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of tidal signals. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.026 and 0.035 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning’s coefficients were matched to bottom type. For example, lower friction coefficients were specified for the smooth sandy channels found in the lower portion of the Acushnet River, versus the winding channels shallow channels in upper portion of the Acushnet River, which provide greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-4.

Table V-4. Manning’s Roughness coefficients used in model simulations. These delineations correspond to the material type areas shown in Figure V-14.

System Embayment	Bottom Friction
Offshore	0.026
New Bedford Harbor	0.028
Popes Island	0.029
Acushnet River	0.035
Marsh Plain	0.035
Culverts	0.035

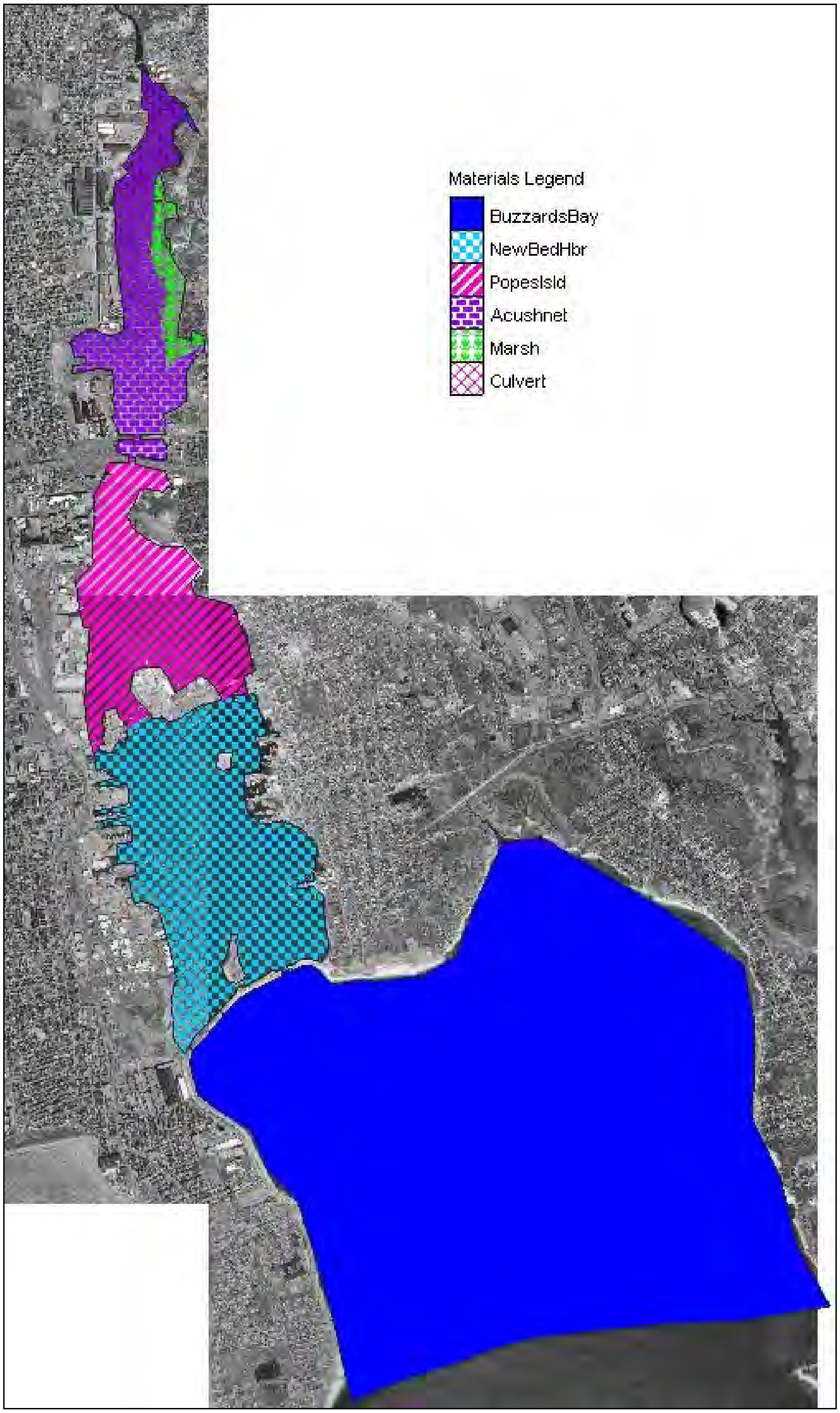


Figure V-14. Hydrodynamic model grid material properties. Color patterns designate the different model material types used to vary model calibration parameters and compute flushing rates.

V.3.2.3.b Turbulent Exchange Coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 25 and 30 lb-sec/ft^2.

V.3.2.3.c Marsh Porosity Processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain included in the model within upper sections of the Acushnet River. Cyclically wet/dry areas of the marsh will tend to store waters as the tide begins to ebb and then slowly release water as the water level drops within the creeks and channels. This store-and-release characteristic of these marsh regions was partially responsible for the distortion of the tidal signal, and the elongation of the ebb phase of the tide. On the flood phase, water rises within the channels and creeks initially until water surface elevation reaches the marsh plain, when at this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water. Marsh porosity is a feature of the RMA-2 model that permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RMA-2 to vary the ability of an element to hold water, like squeezing a sponge. The marsh porosity feature of RMA-2 is typically utilized in estuarine systems where the marsh plain has a significant impact on the hydrodynamics of a system.

V.3.2.3.d Comparison of Modeled Tides and Measured Tide Data

A best-fit of model predictions for the first TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-15 though V-17 illustrate the seven-day calibration simulation along with 48-hour sub-section, for upper New Bedford Harbor gage, Popes Island gage, and Upper Acushnet River gage. Modeled (dashed line) and measured (solid line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Table V-5 for the calibration period differ from those in Table V-2 because constituents were computed for only the seven-day section of the 39-days represented in Table V-2. Table V-5 compares tidal constituent height and time lag for modeled and measured tides at the TDR locations. Table V-5 compares tidal constituent height and phase for modeled and measured tides at the TDR locations.

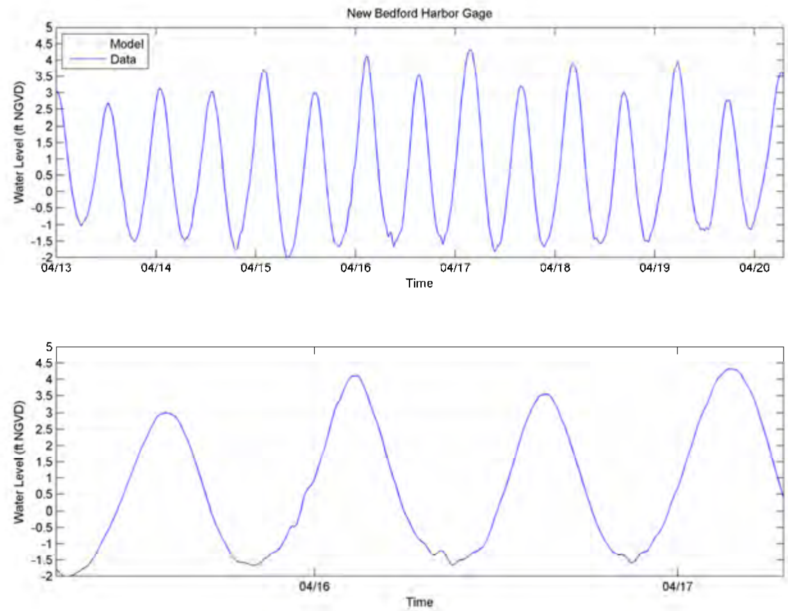


Figure V-15. Comparison of model output and measured tides for the TDR location in New Bedford Harbor. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

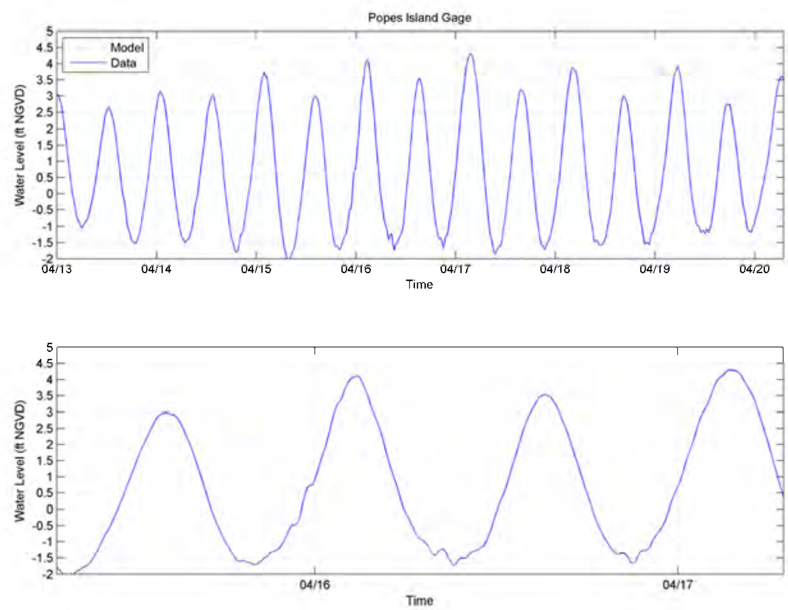


Figure V-16. Comparison of model output and measured tides for the TDR location at Popes Island. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

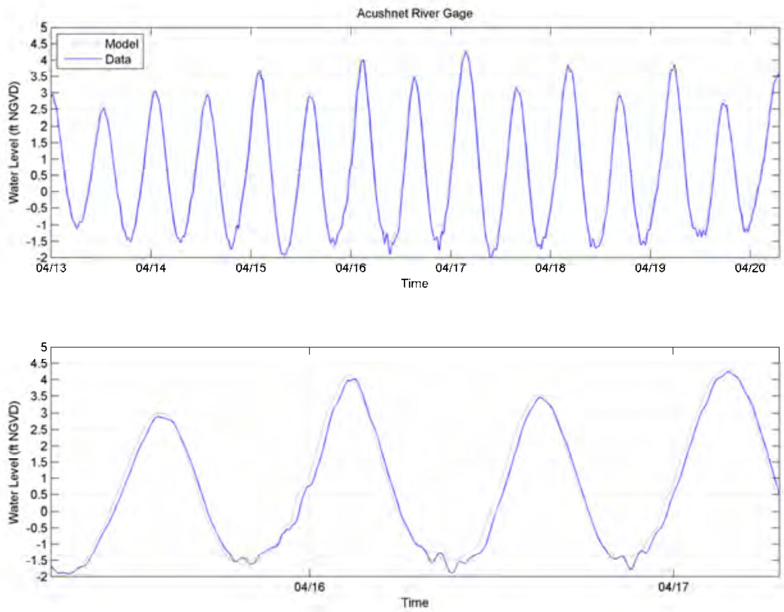


Figure V-17. Comparison of model output and measured tides for the TDR location at upper Acushnet River. The bottom plot is a 48-hour sub-section of the total modeled time period, shown in the top plot.

Table V-5. Tidal constituents for measured water level data and calibrated model output for northern embayments.

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (rad)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
New Bedford Harbor	2.41	0.31	0.03	0.35	-0.29	-0.27
Popes Island	2.40	0.31	0.03	0.35	-0.29	-0.27
Acushnet River	2.40	0.31	0.03	0.35	-0.35	-0.41
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (rad)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
New Bedford Harbor	2.40	0.32	0.02	0.36	-0.26	-0.19
Popes Island	2.41	0.32	0.02	0.36	-0.26	-0.19
Acushnet River	2.36	0.31	0.03	0.37	-0.20	-0.10
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
New Bedford Harbor	-0.01	0.01	-0.01	0.01	3.6	4.7
Popes Island	-0.01	0.01	-0.01	0.01	3.6	4.7
Acushnet River	-0.04	0.00	0.00	0.02	17.8	18.4

The constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.01 ft, which is of the same order of the accuracy of the tide gages (0.032 ft). Time lag errors were typically less than the time increment resolved by the model (0.10 hours or 10 minutes), indicating good agreement between the model and data. The largest errors were in upper Acushnet, where the influence of fresh water inflow may have influenced the gage readings.

V.3.2.4 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Acushnet River system. Using model inputs of bathymetry and tide data, current velocities and flow rates can be determined at any point in the model domain. This is a very useful feature of a hydrodynamic model, where a limited amount of collected data can be expanded to determine the physical attributes of the system in areas where no physical data record exists.

Examining the results from the model run shows flood velocities in the channels are slightly larger than velocities during maximum ebb. The highest velocities occur at the entrance to New Bedford Harbor where the channel passes through the Hurricane Barrier, where the estuary width is heavily constrained by the barrier. Higher velocities also occur at other constrictions within the harbor for instance the between the bridge abutments to Interstate 195 and Howland Street. The maximum velocities at the Hurricane Barrier peak at approximately 5.6 feet/sec during the flood tide, while maximum ebb velocities are about 4.7 feet/sec. A close-up of the model output is presented in Figure V-18, showing contours of velocity magnitude, along with velocity vectors that indicate the magnitude and direction of flow, for a single model time-step, at the portion of the tide cycle where flood velocities peak at the entrance to New Bedford Harbor.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. For the flushing analysis in the next section, flow rates were computed across a number of separate transects in the system. The variation of flow as the tide floods and ebbs is seen in the plot of channel flow rates in Figure V-19. Maximum flow rates occur during flood tides in this system, an indication that this estuary system is flood dominant, and likely a sediment sink (a system that accumulates sediment). The maximum flood flow rates reach approximately 28,920 ft^3/sec at the hurricane barrier. Maximum ebb flow rates are slightly less, or about 24,640 ft^3/sec.

A verification of the model was conducted by comparing flow rates computed from ADCP measurements to flow rates extracted from the hydrodynamic model. The hydrodynamic model was run for the period of April 17, 2003 to April 25, 2003 to simulate the time period when the ADCP measurements were taken (April 21, 2003). This time period was not included in the initial calibration period described above. Flow measurements were extracted from the model along the Hurricane Barrier transect which corresponds to the ADCP measurement transect (see Figure V-3 for transect location). A comparison of the modeled and measured flow rates for the transect is shown in Figure V-20. The graphs show that the model follows the trends and characteristics of the ADCP data. However, the model slightly over-predicts the volume of water flow across the transect line. To quantify the error, an R square error analysis was performed on the results. The results, shown in Table V-6, indicate that the error in the flows rates was approximately 9 percent.

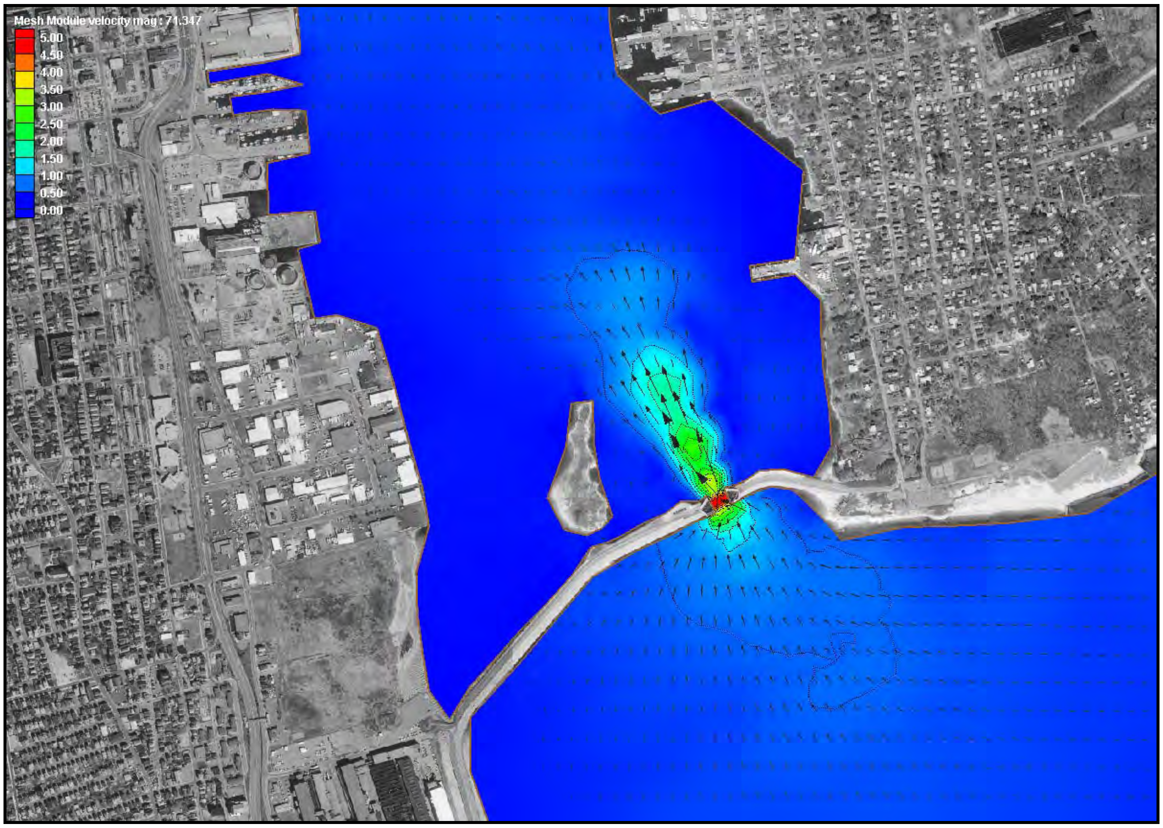


Figure V-18. Example of hydrodynamic model output for a single time step where maximum flood velocities occur for this tide cycle. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

There are several possible reasons for the model over-predicting the flow measurements. The primary limitation of the ADCP measurements was the ADCP is unable to measure velocities in the first 1 to 2 feet of the water column, due to the ADCP transducer being suspended below the water surface and signal blanking across the first measurement cell. The ADCP cannot take measurements across the first measurement cell since a time gap is required between the transmission and receipt of the acoustic signal (this allows measurement of the Doppler shift). To account for the unmeasured portion of the water column, velocities from second measurement cell were used to represent the portion of water column above. This resulted in a slight under prediction in surface currents and thus adds to the under-prediction of flow rates. The second reason is the unaccounted flow through the hurricane barrier structure that is not captured in the model. Although the measured flow rates were approximately 9 percent less than the modeled flows, the current measurement limitations provide a reasonable explanation for this magnitude of error. Therefore, the ADCP measurements within Acushnet River provided adequate measurements to verify the results of the hydrodynamic model.

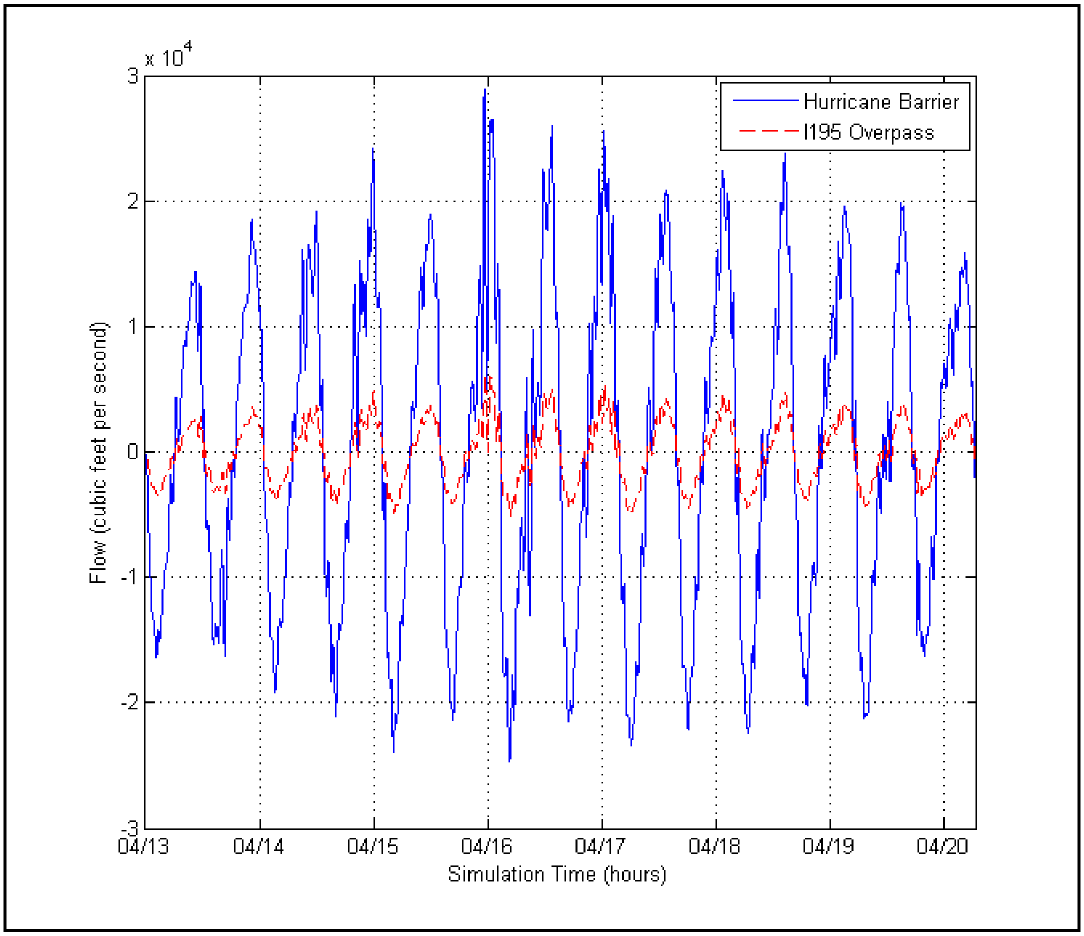


Figure V-19. Time variation of computed flow rates for two transects in the Acushnet River system. Model period shown corresponds to period between spring and neap tide conditions, where the tide range is average. Plotted time period represents four tide cycles (12.42 h cycle). Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

Table V-6. R square error results on the flow analysis for Acushnet River.

Transect	R Square Error	Error as Percent of Max flow
Hurricane Barrier	0.94	15.5

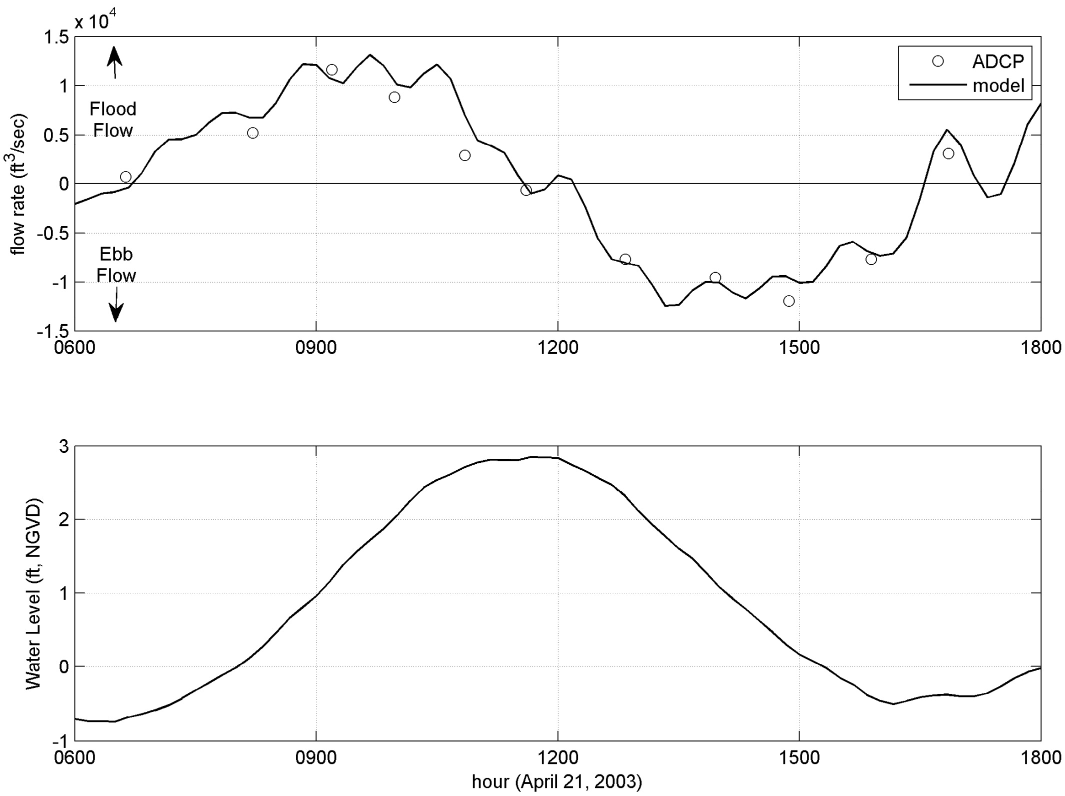


Figure V-20. Comparison of computed flow rates to the ADCP transect. Model period shown corresponds to transition from low to high tide. Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

V.4. FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller than the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within the modeled Acushnet River system is tidal exchange. A rising tide offshore in Buzzards Bay creates a slope in water surface from the ocean into the modeled systems. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of Buzzards Bay on an ebbing tide. This exchange of water between the system and the Bay is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of each system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of an estuary from points within the system. For this study, **system residence times** were computed as the average time required for a water parcel to migrate from a point within the each embayment to the entrance of the system. System residence times are computed as follows:

$$T_{system} = \frac{V_{system}}{P} t_{cycle}$$

where T_{system} denotes the residence time for the system, V_{system} represents volume of the (entire) system at mean tide level, P equals the tidal prism (or volume entering the system through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days). To compute system residence time for a sub-embayment, the tidal prism of the sub-embayment replaces the total system tidal prism value in the above equation.

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using upper Acushnet River as an example, the **system residence time** is the average time required for water to migrate from upper Acushnet River, through the hurricane barrier, and into Buzzards Bay, where the **local residence time** is the average time required for water to migrate from upper Acushnet River through the bridge opening, and into region around Popes Island (not all the way to the bay). Local residence times for each sub-embayment are computed as:

$$T_{local} = \frac{V_{local}}{P} t_{cycle}$$

where T_{local} denotes the residence time for the local sub-embayment, V_{local} represents the volume of the sub-embayment at mean tide level, P equals the tidal prism (or volume entering the local sub-embayment through a single tidal cycle), and t_{cycle} the period of the tidal cycle (again, 0.52 days).

Residence times are provided as a first order evaluation of estuarine water quality. Lower residence times generally correspond to higher water quality; however, residence times may be misleading depending upon pollutant/nutrient loading rates and the overall quality of the receiving waters. As a qualitative guide, **system residence times** are applicable for systems where the water quality within the entire estuary is degraded and higher quality waters provide the only means of reducing the high nutrient levels. For the Acushnet River system this approach is applicable, since it assumes the main system has relatively low quality water relative to Buzzards Bay.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the estuary is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the system.

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in the system, model results were used to compute residence times. Residence times were computed for the estuarine system, as well as selected sub-embayments within the system. In addition, **system** and **local residence times** were computed to indicate the range of conditions possible for each system. Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet.

Residence times were averaged for the tidal cycles comprising a representative 7.25 day period (14 tide cycles), and are listed in Table V-8. The modeled time period used to compute the flushing rates was different from the modeled calibration period, and included the transition from spring to neap tide conditions. Model divisions used to define the system sub-embayments include 1) the entire New Bedford Harbor system, 2) the upper portion harbor above Popes Island 3) the Acushnet River system north of Interstate 195. The model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the 7.25-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

Table V-7. Embayment mean volumes and average tidal prism during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
New Bedford Harbor (entire embayment)	601,698,540	208,042,981
Above Popes Island	208,817,089	106,941,268
Acushnet River	45,843,708	48,668,122

Table V-8. Computed System and Local residence times for embayments in the Acushnet River system.

Embayment	System Residence Time (days)	Local Residence Time (days)
New Bedford Harbor (entire embayment)	1.504	1.504
Above Popes Island	2.926	1.015
Acushnet River	6.429	0.490

The computed flushing rates for the harbor shows that as a whole, the system flushes well. A flushing time of 1.5 days for the entire harbor shows that on average, water is resident in the system for approximately a day and a half. The system residence time for the upper portions of the harbor lags behind with the resident time of approximately a week. However, the local residence times show that the water passes rather quickly into the lower portions of the harbor from the Acushnet River and then past Popes Island into the outer harbor.

Generally, possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the "strong littoral drift" assumption would lead to an under-prediction of residence time. Since littoral drift in Buzzards Bay is typically strong because the local winds and tidal currents induce mixing within the regional estuarine systems, the "strong littoral drift" assumption only will cause minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the "strong littoral drift" assumption are within 10% to 15% of "true" residence times.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the New Bedford Harbor system. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the New Bedford Harbor system. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic model output used for the water quality model calibration was the 7.2 day (14 tide cycle) period beginning April 12, 2003 0330 EST. This period corresponds to that used in the flushing analysis presented in Section V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to sub-embayments are recognized in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. Additionally, there is a fourth load to the New Bedford Harbor system’s sub-embayments, consisting of the background concentrations of total nitrogen in the waters entering from Buzzards Bay. This load is represented as a constant concentration along the seaward boundary of the model grid.

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Seven years of data (collected between 2000 and 2006) were available for some stations (i.e., MEP stations 3, 6, 12 and outer harbor). These data were provided by the BayWatcher Monitoring Program, the New Bedford Oceanarium monitoring project and studies by SMAST scientists. Integration of the results of these efforts provided a detailed spatial and temporal picture of water quality within New Bedford Inner Harbor. Data from the BayWatchers was also available from 2007-2012 for a sub-set of the stations and generally only for surface water. These data were used to assess any trend in total nitrogen from the earlier period. No significant differences were found in TN between the 2 sampling periods ($p<0.05$), more importantly differences were small, less than

9% and generally less than +/-5%, averaging <4% difference (relative percent difference). These small differences (in both directions) need to be evaluated relative to the Coefficient of Variation (s.d./mean x 100%), which ranges from 16% to 27%, underscoring the lack of a difference between the 2 sampling periods. Therefore, the 2000-2006 data was used for the modeling, with the 2006-2012 data available for key stations supporting the contention that this was appropriate for the 2000-2012 period. The reason for this approach was to allow better spatial coverage of the Harbor basins to produce a more accurate calibration and verification of the water quality model.

Table VI-1. Measured data and modeled Nitrogen concentrations for the New Bedford Harbor estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in the summers of 2000 through 2006.

Sub-Embayment	MEP monitoring station	data mean	s.d. all data	N	model min	model max	model average
Estuary Upper Basin	2	0.789	0.128	14	0.629	1.060	0.754
Coggeshall Bridge	3	0.624	0.155	50	0.549	0.764	0.621
Popes Island East Bridge	6	0.553	0.110	27	0.499	0.515	0.505
Lower Basin (North)	7	0.544	0.127	19	0.490	0.506	0.496
Lower Basin (Mid)	8	0.493	0.083	29	0.475	0.493	0.485
LowBasin South of FTP	12	0.519	0.129	27	0.452	0.488	0.474
FTP - Fairhaven WWTF	FTP	1.200	0.320	23	-	-	-
LowBasin-Inside Inlet	9	0.484	0.084	17	0.429	0.482	0.458
Outer Harbor - Boundary	PT1,NB5,NB3,11	0.388	0.017	108	-	-	-

VI.2 MODEL DESCRIPTION AND APPLICATION

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of nitrogen loading in the New Bedford Harbor estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of New Bedford Harbor. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. The MEP Technical Team has utilized this model in water quality studies of other Cape Cod embayments, including systems other Massachusetts estuarine systems such as Falmouth (Howes *et al*., 2005); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

The overall approach involves modeling total nitrogen as a non-conservative constituent, where bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. This modeling represents summertime conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the Cape Cod Commission watershed loading analysis, as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model of the New Bedford Harbor system.

Figure VI-1. Estuarine water quality monitoring station locations in the New Bedford Harbor estuary system. Station labels correspond to those provided in Table VI-1.

VI.2.1 Model Formulation

The formulation of the model is for two-dimensional depth-averaged systems in which concentration in the vertical direction is assumed uniform. The depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in the modeled sub-embayments. The governing equation of the RMA-4 constituent model can be most simply expressed as a form of the transport equation, in two dimensions:

$$\left(\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y}\right) = \left(\frac{\partial}{\partial x}D_x\frac{\partial c}{\partial x} + \frac{\partial}{\partial y}D_y\frac{\partial c}{\partial y} + \sigma\right)$$

where c in the water quality constituent concentration; t is time; u and v are the velocities in the x and y directions, respectively; D_x and D_y are the model dispersion coefficients in the x and y directions; and σ is the constituent source/sink term. Since the model utilizes input from the RMA-2 model, a similar implicit solution technique is employed for the RMA-4 model.

The model is therefore used to compute spatially and temporally varying concentrations c of the modeled constituent (i.e., total nitrogen), based on model inputs of 1) water depth and velocity computed using the RMA-2 hydrodynamic model; 2) mass loading input of the modeled constituent; and 3) user selected values of the model dispersion coefficients. Dispersion coefficients used for each system sub-embayment were developed during the calibration process. During the calibration procedure, the dispersion coefficients were incrementally changed until model concentration outputs matched measured data.

The RMA-4 model can be utilized to predict both spatial and temporal variations in total for a given embayment system. At each time step, the model computes constituent concentrations over the entire finite element grid and utilizes a continuity of mass equation to check these results. Similar to the hydrodynamic model, the water quality model evaluates model parameters at every element at 10-minute time intervals throughout the grid system. For this application, the RMA-4 model was used to predict tidally averaged total nitrogen concentrations throughout the sub-embayments of the New Bedford Harbor system.

VI.2.2 Water Quality Model Setup

Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient. Because the RMA-4 model is part of a suite of integrated computer models, the finite-element meshes and the resulting hydrodynamic simulations previously developed for New Bedford Harbor also were used for the water quality constituent modeling portion of this study.

For each model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 7 tidal-day (174 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the New Bedford Harbor model.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed and direct atmospheric deposition loads for the Mid-Harbor basin were evenly distributed at grid cells that formed the perimeter of the sub-embayment. Benthic regeneration loads were distributed among another sub-set of grid cells which are in the interior portion of each basin.

The loadings used to model present conditions in the New Bedford Harbor system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For some areas of New Bedford Harbor (e.g., the mid harbor basin, between the Coggeshall Street bridge and Popes Island), the net benthic flux is negative which indicates a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in the Buzzards Bay region offshore the Harbor was set at 0.388 mg/L, based on SMAST data collected during seven summers between 2000 and 2006, at five separate stations in the outer harbor, between the hurricane barrier and open Buzzards Bay.

Table VI-2. Sub-embayment and surface water loads used for total nitrogen modeling of the New Bedford Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions** for the listed sub-embayments.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Basin	47.899	2.836	45.081
Mid Basin	17.600	3.614	-28.561
Lower Basin	165.512	7.011	52.147
Acushnet River – fresh water	99.444	-	-
System Total	330.455	13.460	68.667

VI.2.4 Model Calibration

Calibration of the total nitrogen model of New Bedford Harbor proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by setting different values of *E* for each grid material type, as designated in Section V. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent estuarine embayments encircling Buzzards Bay require values of *E* that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of *E* in these calmer areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of *E* used in each sub-embayment of the modeled system are presented in Table VI-3. These values were used to develop the “best-fit” total nitrogen model calibration. For the case of TN modeling, “best fit” can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

Comparisons between calibrated model output and measured nitrogen concentrations are shown in plots presented in Figures VI-2 and VI-3. In these plots, means of the water column data and a range of two standard deviations of the annual means at each individual station are plotted against the modeled maximum, mean, and minimum concentrations output from the model at locations which corresponds to the MEP monitoring stations.

For model calibration, the mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each water-quality monitoring station. The calibration target would fall near the modeled mean because the monitoring data are collected, as a rule, during mid ebb tide.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the New Bedford Harbor estuary system.

Embayment Division	E m^2/sec
Outer Harbor	20.0
Hurricane Barrier Culverts	20.0
Lower Basin (Inner Harbor)	20.0
Mid Basin (Pope Is. to Coggeshall bridge)	20.0
Upper Basin - south	20.2
Upper Basin - north	20.0
Upper Basin marsh	1.0
Uppermost Acushnet River	0.1

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system. Computed root mean squared (rms) error is less than 0.03 mg/L, with a R^2 correlation of 0.93, both of which demonstrate the exceptional fit between modeled and measured data for this system.

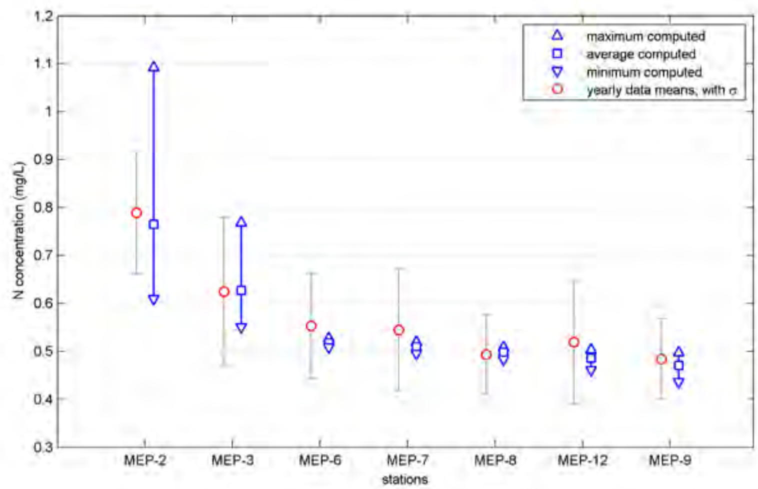


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the New Bedford Harbor system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset

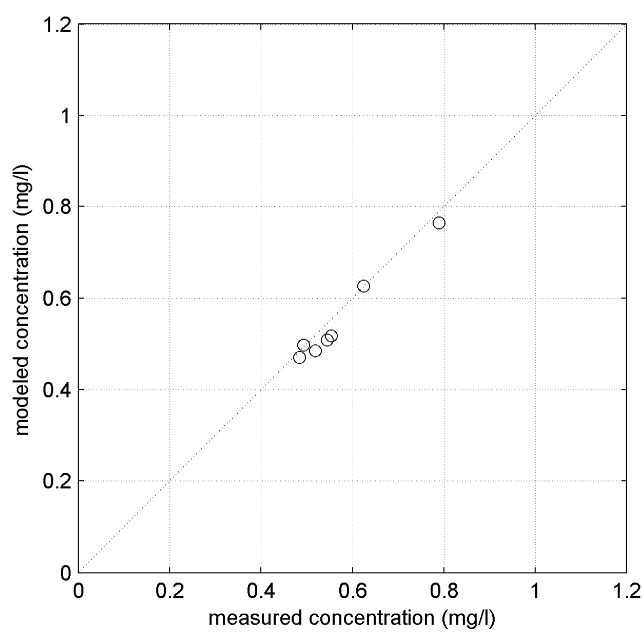


Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are 0.93and 0.03 mg/L respectively.

A contour plot of calibrated model output is shown in Figures VI-4. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average total nitrogen concentrations, computed using the full 7-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the New Bedford Harbor system using salinity data collected at the same stations as the nitrogen data. Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The rms error of the model is 1.78 ppt.

The only required inputs into the RMA4 salinity model of the system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, and groundwater inputs. The open boundary salinity was set at 30.6 ppt. The average annual surface water discharge (33.12 ft^3/sec or 81,000 m^3/day) of the Acushnet River was included in the model. Groundwater input salinities were set at 0 ppt. Groundwater inputs used for the model were 11.16 ft^3/sec (27,300 m^3/day) for the upper Harbor basin watershed, 6.34 ft^3/sec (15,500 m^3/day) for the mid Harbor basin and 7.88 ft^3/sec (19,300 m^3/day) for the lower harbor basin. Groundwater flows were distributed evenly in the model through the use of several 1-D element input points positioned along the model's land boundary. The Fairhaven Treatment Plant outfall discharge was also specified in the model. An average summer discharge of 3.04 MGD was applied to the model grid element that contains the outfall discharge location. This rate was determined using data provided by MassDEP (B. Dudley, personal communication) for 2010, 2011 and 2012.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the New Bedford Harbor, the standard “build-out” and “no-load” water quality modeling scenarios were run. These runs included a “build-out” scenario, based on potential development (described in more detail in Section IV), and a “no anthropogenic load” or “no load” scenario assuming only atmospheric deposition on the watershed and sub-embayment, as well as a natural forest within each watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-4. Loads are presented in kilograms per day (kg/day) in this Section, since it is inappropriate to show benthic flux loads in kilograms per year due to seasonal variability.

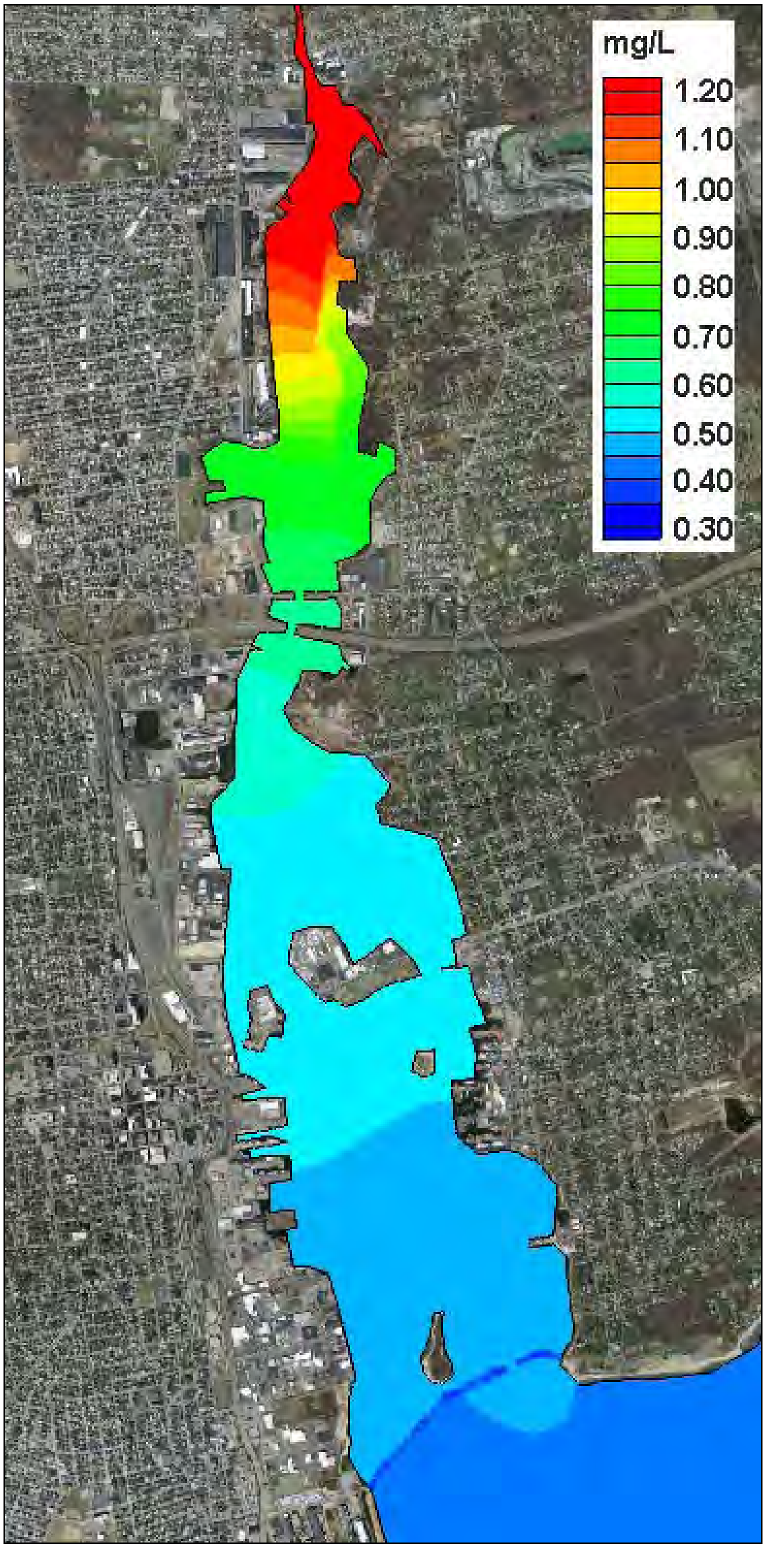


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the New Bedford Harbor system.

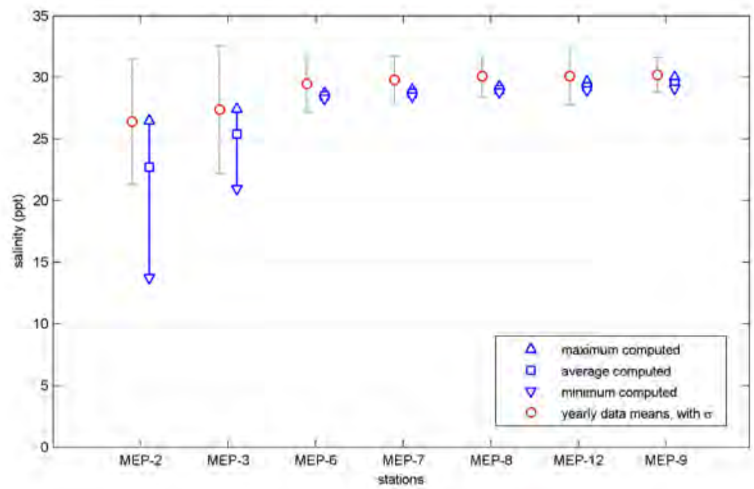


Figure VI-5. Comparison of measured and calibrated model output at stations in New Bedford Harbor. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset.

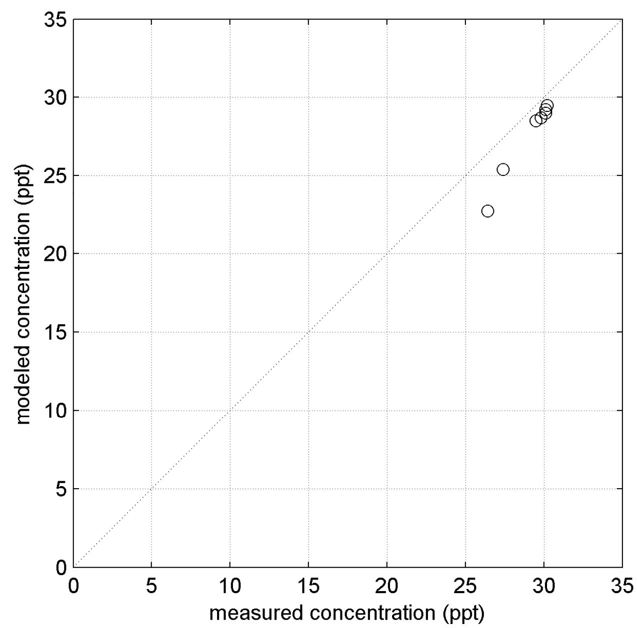


Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. RMS error for this model verification run is 1.78 ppt or 5.9% of measurements max range.

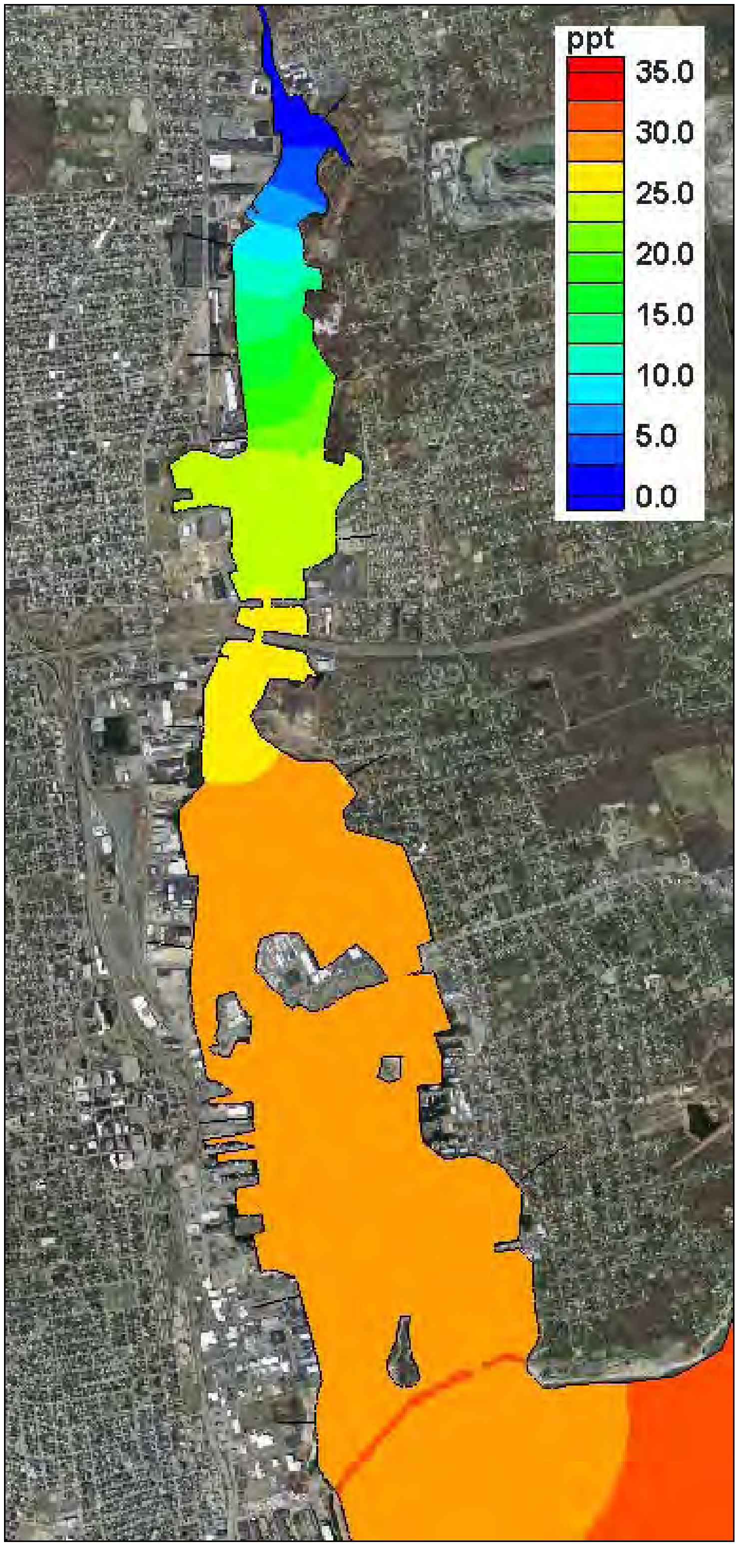


Figure VI-7. Contour Plot of average modeled salinity (ppt) in the New Bedford Harbor system.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the New Bedford Harbor system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	Build-out (kg/day)	build-out % change	no load (kg/day)	no load % change
Upper Basin	47.899	42.115	-12.1%	1.855	-96.1%
Mid Basin	17.600	19.805	+12.5%	0.964	-94.5%
Lower Basin	165.512	173.704	+4.9%	1.088	-99.3%
Acushnet River – fresh water	99.444	130.293	+31.0%	8.833	-91.1%
System Total	330.455	365.918	+10.7%	12.740	-96.1%

VI.2.6.1 Build-Out

A breakdown of the total nitrogen load entering each sub-embayment is shown in Table VI-5 for the modeled build-out scenario. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vice versa*.

Projected benthic fluxes (for both the build-out and no load scenarios) are based upon projected PON concentrations and watershed loads, determined as:

$$(Projected\ N\ flux) = (Present\ N\ flux) * [PON_{projected}]/[PON_{present}]$$

where the projected PON concentration is calculated by,

$$[PON_{projected}] = R_{load} * \Delta PON + [PON_{(present\ offshore)}],$$

using the watershed load ratio,

$$R_{load} = (Projected\ N\ load) / (Present\ N\ load),$$

and the present PON concentration above background,

$$\Delta PON = [PON_{(present\ flux\ core)}] - [PON_{(present\ offshore)}].$$

Table VI-5. **Build-out** scenario sub-embayment and surface water loads used for total nitrogen modeling of the New Bedford Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Basin	42.115	2.836	47.874
Mid Basin	19.805	3.614	-29.869
Lower Basin	173.704	7.011	53.543
Acushnet River – fresh water	130.293	-	-
System Total	365.918	13.460	71.548

Following development of the nitrogen loading estimates for the build-out scenario, the water quality models of the system was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. For build-out, the increase in modeled TN concentrations is greatest in the upper basin, where TN concentrations increase more than 12%. A contour plot showing average TN concentrations throughout the Harbor is presented in Figure VI-8 for the model of build-out loading.

Table VI-6. Comparison of model average total N concentrations from present loading and the **build-out scenario**, with percent change, for the New Bedford Harbor system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
Estuary Upper Basin	2	0.764	0.856	12.0%
Coggeshall Bridge	3	0.626	0.677	8.0%
Popes Island East Bridge	6	0.517	0.538	4.1%
Lower Basin (North)	7	0.509	0.528	3.7%
Lower Basin (Mid)	8	0.498	0.514	3.3%
LowBasin South of FTP	12	0.485	0.499	2.8%
LowBasin-Inside Inlet	9	0.470	0.482	2.5%

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load (“no load”) scenarios is shown in Table VI-7. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in §VI.2.6.1). Compared to the modeled present conditions and build-out scenario, atmospheric deposition directly to each sub-embayment becomes a greater percentage of the total nitrogen load as the watershed load and related benthic flux decrease.

Table VI-7. “**No anthropogenic loading**” (“no load”) sub-embayment and surface water loads used for total nitrogen modeling of the New Bedford Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Basin	1.855	2.836	19.935
Mid Basin	0.964	3.614	-16.461
Lower Basin	1.088	7.011	39.953
Acushnet River – fresh water	8.833	-	-
System Total	12.740	13.460	43.428

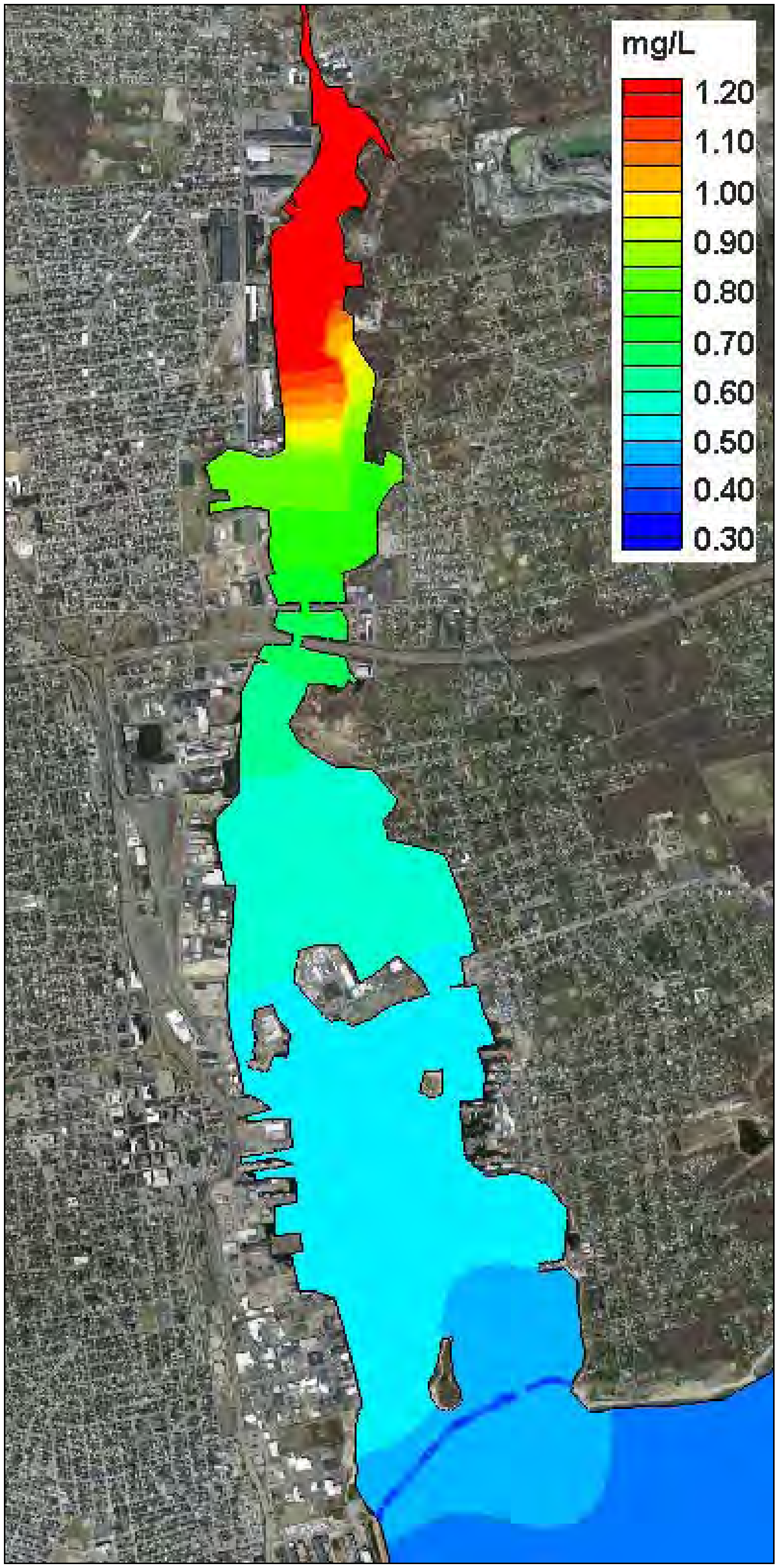


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the New Bedford Harbor system, for projected build-out scenario loading conditions.

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Again, total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was large, with some areas of the system experiencing reductions greater than 48%. A contour plot showing TN concentrations throughout the system is shown pictorially in Figure VI-9.

Table VI-8. Comparison of model average total N concentrations from present loading and the "**No anthropogenic loading**" ("no load"), with percent change, for the New Bedford Harbor system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	no-load (mg/L)	% change
Estuary Upper Basin	2	0.764	0.388	-49.2%
Coggeshall Bridge	3	0.626	0.398	-36.5%
Popes Island East Bridge	6	0.517	0.398	-23.0%
Lower Basin (North)	7	0.509	0.398	-21.8%
Lower Basin (Mid)	8	0.498	0.398	-20.0%
LowBasin South of FTP	12	0.485	0.397	-18.1%
LowBasin-Inside Inlet	9	0.470	0.396	-15.7%

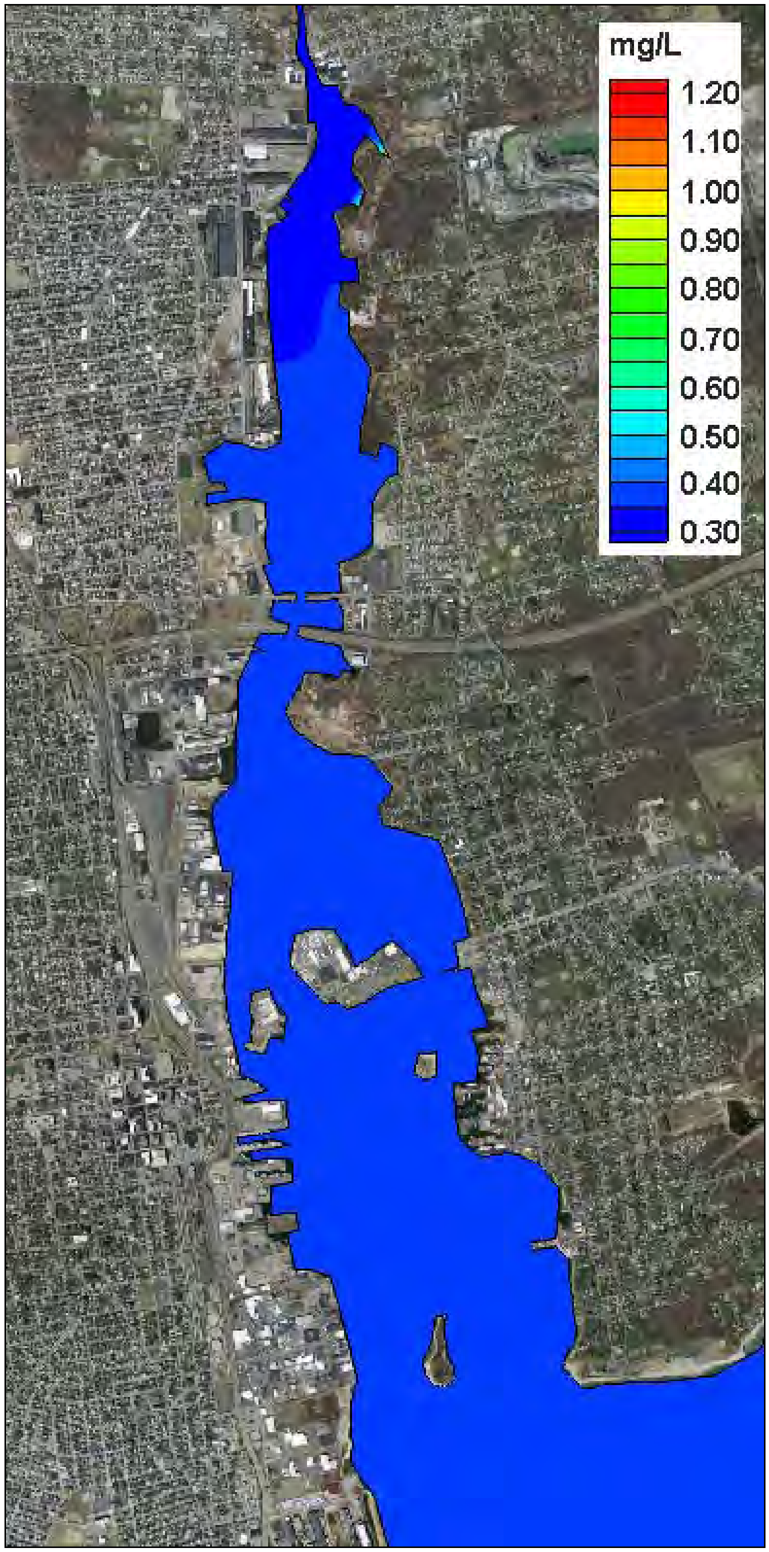


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in New Bedford Harbor, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Acushnet River / New Bedford Inner Harbor embayment system in the City of New Bedford and the Town of Fairhaven, MA, our assessment is based upon data from the water quality monitoring database developed by the Coalition for Buzzards Bay, as supplemented by surveys by the New Bedford Oceanarium and the Coastal Systems Program at SMAST-UMass-Dartmouth, and MEP/SMAST surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen records conducted during the summer of 2002 and the fall of 2003. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for these systems (Section VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

There are a variety of indicators that can be used in concert with water quality monitoring data for evaluating the ecological health of embayment systems. The best biological indicators are those species which are non-mobile and which persist over relatively long periods, if environmental conditions remain constant. The concept is to use species which integrate environmental conditions over seasonal to annual intervals. The approach is particularly useful in environments where high-frequency variations in structuring parameters (e.g. light, nutrients, dissolved oxygen, etc.) are common, making adequate field sampling difficult.

As a basis for a nitrogen thresholds determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the upper, middle and lower basins of the Inner Harbor System to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the overall New Bedford system (inner and outer) was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Acushnet River / New Bedford Inner Harbor system, temporal changes in eelgrass distribution could not provide a basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet or additional culverts) in nutrient enrichment as there has not been eelgrass in the inner harbor for at least a half a century. The presence of eelgrass in the outer portion of the New Bedford Harbor system (seaward of the hurricane barrier) may provide a basis for linking nutrient enrichment to habitat impairment in that specific area.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from “healthy” (low organic matter loading, high D.O.) to “highly stressed” (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they exist. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Woods Hole Oceanographic Institution) and New Bedford (SMAST), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H’) and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 3.8 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SB (moderate quality) waters maintain oxygen levels above 5 mg L^{-1}. The tidal waters of the Acushnet River / New Bedford Inner Harbor Estuary, as an active port, are currently listed under this Classification as SB while the outer portion of New Bedford Harbor (seaward of the hurricane barrier) is classified as SA (able to maintain oxygen levels above 6 mg L^{-1}. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (by example, Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Acushnet River / New Bedford Inner Harbor system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the

Acushnet River / New Bedford Inner Harbor embayment system was collected during the summer of 2002.

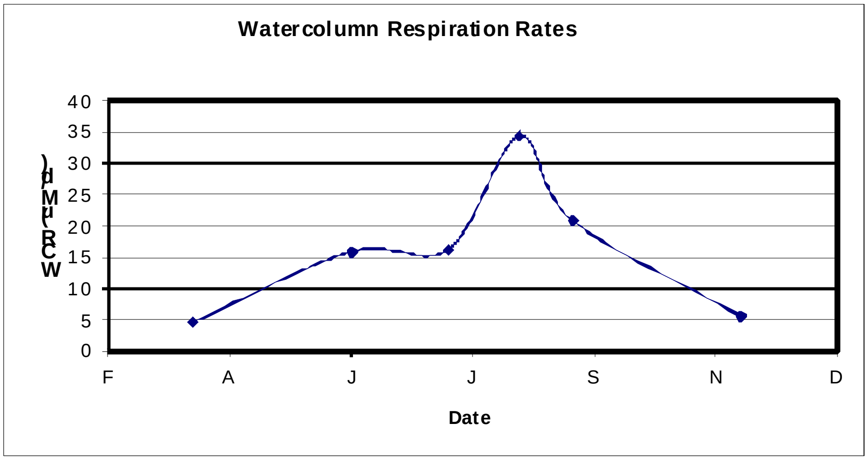


Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability. This figure is an example of one embayment respiration rate.

Similar to other embayments in southeastern Massachusetts, the Acushnet River / New Bedford Inner Harbor system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site, underscores the need for continuous monitoring within these systems.

Dissolved oxygen and chlorophyll a records were examined both for temporal trends and to determine the percent of the 34-42 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate nutrient enriched waters and some impairment of infaunal habitat quality at all mooring sites within each estuarine basin (Figures VII-3 through VII-10). The oxygen data parallels the level of organic matter enrichment from phytoplankton production (chlorophyll a levels) indicative of moderate to high nitrogen loading rates. The oxygen records further indicate that the upper tidal basin has the largest daily oxygen excursion, which further supports the assessment of a high degree of nutrient enrichment. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the upper tidal reach of the Acushnet River / New Bedford Inner Harbor system is nitrogen and organic matter enriched. However, this basin is also influenced by its bordering wetlands, and to some extent is naturally organic matter rich. The relationship of watershed nitrogen loading versus ecosystem function (wetland/tidal river) also suggests impairment of habitat within this basin, but at a lower level than based upon the water quality indicators alone (Sections VII.2, VII.3).

Overall, the dissolved oxygen records indicate a gradient in oxygen depletion and chlorophyll a levels from the upper to the lower basins of the Acushnet River / New Bedford Inner Harbor system (Table VII-1). Consistent with estuarine response to over-enrichment from nitrogen, the extent of bottom water oxygen depletion parallels the levels of phytoplankton biomass (e.g. chlorophyll a, Table VII-2). Based upon the basin type and configuration, oxygen depletion and organic matter enrichment indicates infaunal habitat impairment at a moderate level within the upper tidal river basin and within the lower basin, but at slightly higher levels within the depositional middle basin. All moorings showed periodic oxygen depletions below 5 mg L^{-1} and generally to <4 mg L^{-1}. The exceptional depletion at the Popes Island site in the lower basin, was apparently associated with the semi-isolated marina basin and not a larger spatial phenomenon. The embayment specific results are as follows:

Upper Basin **(Figures VII-3 and VII-7):**

The mooring in the upper basin was placed one-third of the distance from I-195 and the head of the estuarine reach in 2.3 m of water. The relatively shallow upper basin, bordered by fringing marshes to the east and industrialized watershed on the west, is separated from the middle basin by a narrow reach crossed by two bridges. Dissolved oxygen was frequently depleted to below 5 mg L^{-1} (27% of time), but to ~4 mg L^{-1} (<1% of time Table VII-1). Oxygen levels were generally depleted below air equilibration (6.5 to 7.5 mg L^{-1}) throughout much of the record. Organic enrichment, particularly of sediments, appear to be the mechanism for the observed oxygen depletion, with sediment oxygen uptake rates averaging 3500 mg m^{-2} d^{-1} during this period (D. Schlezinger personal communication). It appears that the shallowness of the water allows ventilation with the atmosphere to prevent anoxia in this basin. Maximum oxygen levels and maximum diurnal variation was observed during the phytoplankton bloom during the third week of deployment. Organic loading from phytoplankton, macroalgae and adjacent marshes stimulating oxygen demand provide the mechanism for the observed oxygen depletion within this shallow basin.

Middle Basin **(Figures VII-4 and VII-8):**

The middle basin of the Inner Harbor System is formed below the narrows of the upper basin at the I-195 cross-over point and Popes Island to the south. The mooring was located in 2.0 meters of water at about the geographical center of the basin. Oxygen levels within the middle basin were similar to those in the upper basin, generally below air equilibration with diurnal variation usually less than 3 mg L^{-1} on any given day. Dissolved oxygen dropped to <5 mg L^{-1} 31% of the time infrequently to <4mg L^{-1} for brief periods (Table VII-1). Poor water clarity appears to play a role in influencing dissolved oxygen levels in this basin (Secchi depth 1.3 m). Although sediment oxygen uptake was not as high as that observed within the upper basin, chlorophyll a concentrations remained high for significantly longer periods of time (>15, >20,

>25 ugL^{-1} for 67%, 47% and 32% of the time respectively; Table VII-2). The record is consistent with that seen within the upper basin. The mooring data indicate organic matter enrichment, primarily through nutrient enrichment and phytoplankton production (see below) and likely impairment of infaunal habitat throughout this basin, particularly the prolonged oxygen in the 4-5 mg L^{-1} and declines to <4 mg L^{-1}.

***Lower Basin: Pope's Island* (Figures VII-5 and VII-9):**

The lower basin is bounded by Popes Island and the Hurricane Barrier. A mooring was placed at the head of the lower basin on the breakwater of the Popes Island Marina. Oxygen concentrations showed little tidal variation and inconsistent diurnal variation. It appears the marina activities and localized bloomlets periodically influenced the oxygen record at this site. However, while oxygen levels were generally >6 mg L-1 (81% of time) at this site, it also showed the greatest oxygen depletion event within the Inner Harbor (Table VII-1). While oxygen concentrations oscillated around air equilibration for the first week of the deployment, thereafter concentrations were typically either consistently above air equilibration or consistently below air equilibration (September 4 and after September 12). The shifts in oxygen depletion appear to be related, in part, to a phytoplankton bloom beginning around September 4 (Table VII-2). However, chlorophyll data during September from this site is somewhat compromised by periodic fouling of the chlorophyll sensor. In any case the oxygen minima and later chlorophyll a levels do not appear to be representative of the greater basin area. The mooring data indicate a moderate level of nutrient enrichment and moderate habitat impairment.

***Lower Basin west* (Figures VII-6 and VII-10):**

The mooring was located west of the main shipping channel approximately one half mile north of the hurricane barrier in 5.8 m of water. Oxygen concentrations (Table VII-2) fell to <6, <5 and <4 mg L^{-1} for 45%, 15% and 3% of the time, respectively. Oscillations above and below air equilibration had a small diurnal signal and no discernible tidal component. Despite the chlorophyll a levels (>10, >15 and >20 ug L^{-1} for 33%, 6% and 1% of the deployment [Table VII-2]) oxygen levels were not consistently depleted below the average air equilibration of 6.9 mg L^{-1} until the end of the deployment starting around August 10. Tidal circulation and proximity to the tidal inlet likely help to maintain oxygen levels at this deep station, where organic matter enrichment of sediments and resulting oxygen demand might otherwise be expected to result in greater levels of oxygen depletion and habitat impairment.

Figure VII-2. Aerial Photograph of the New Bedford Inner Harbor System (Acushnet River Estuary) within the City of New Bedford (west) and Town of Fairhaven (east) showing locations of Dissolved Oxygen/Chlorophyll *a* mooring deployments conducted in the summer of 2002.

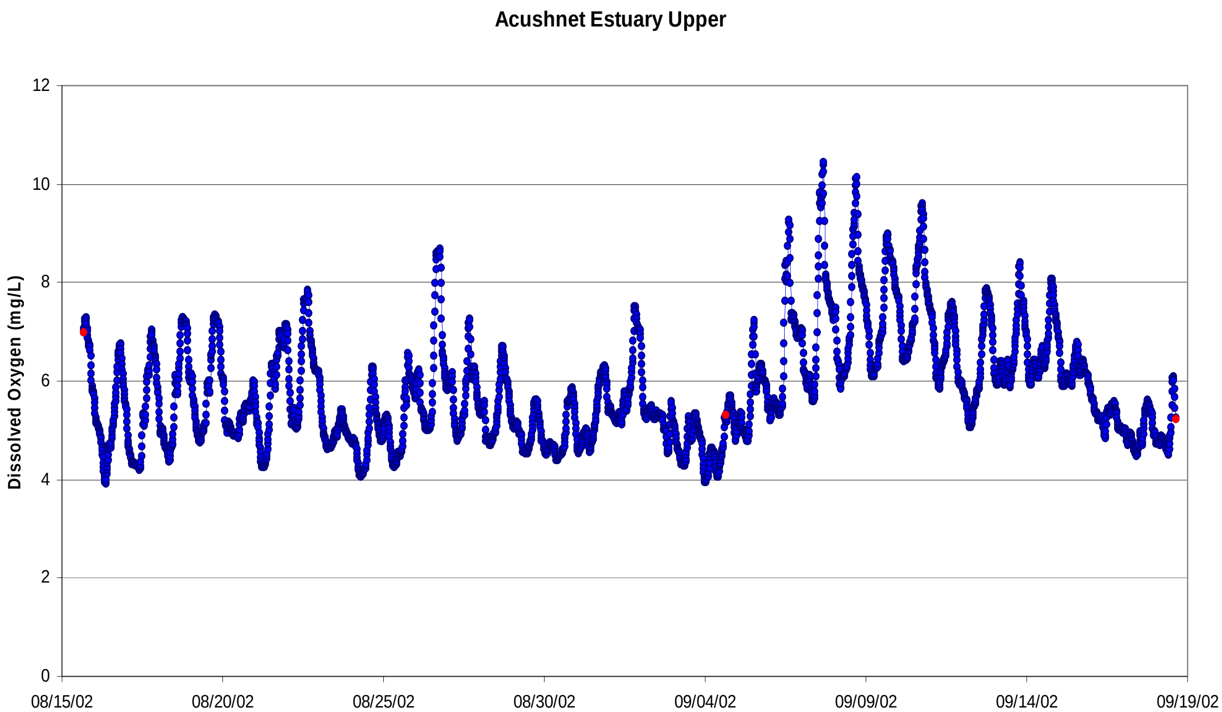


Figure VII-3. Bottom water record of dissolved oxygen at the New Bedford Inner Harbor upper basin, summer 2002. Calibration samples represented as red dots.

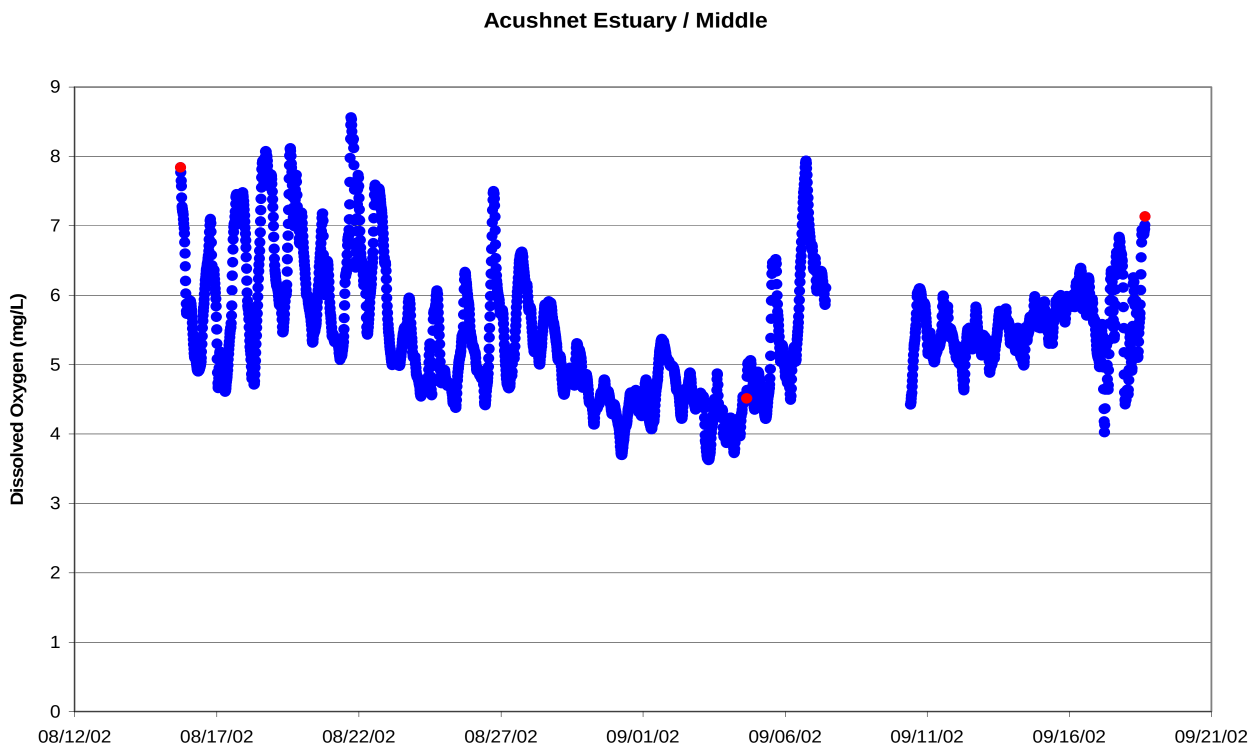


Figure VII-4. Bottom water record of dissolved oxygen at the New Bedford Inner Harbor middle basin, summer 2002. Calibration samples shown as red dots, data gap due to fouling of sensor.

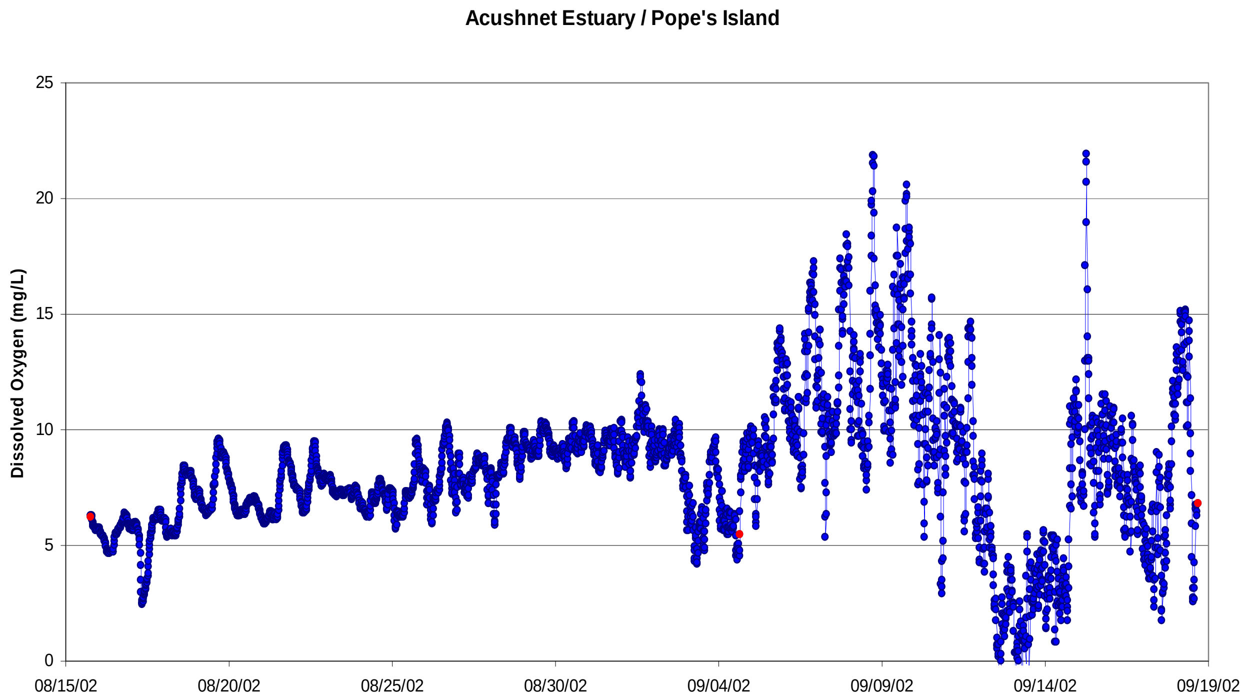


Figure VII-5. Bottom water record of dissolved oxygen at the New Bedford Inner Harbor Pope's Island-south (upper reach of lower basin), summer 2002. Calibration samples represented as red dots.

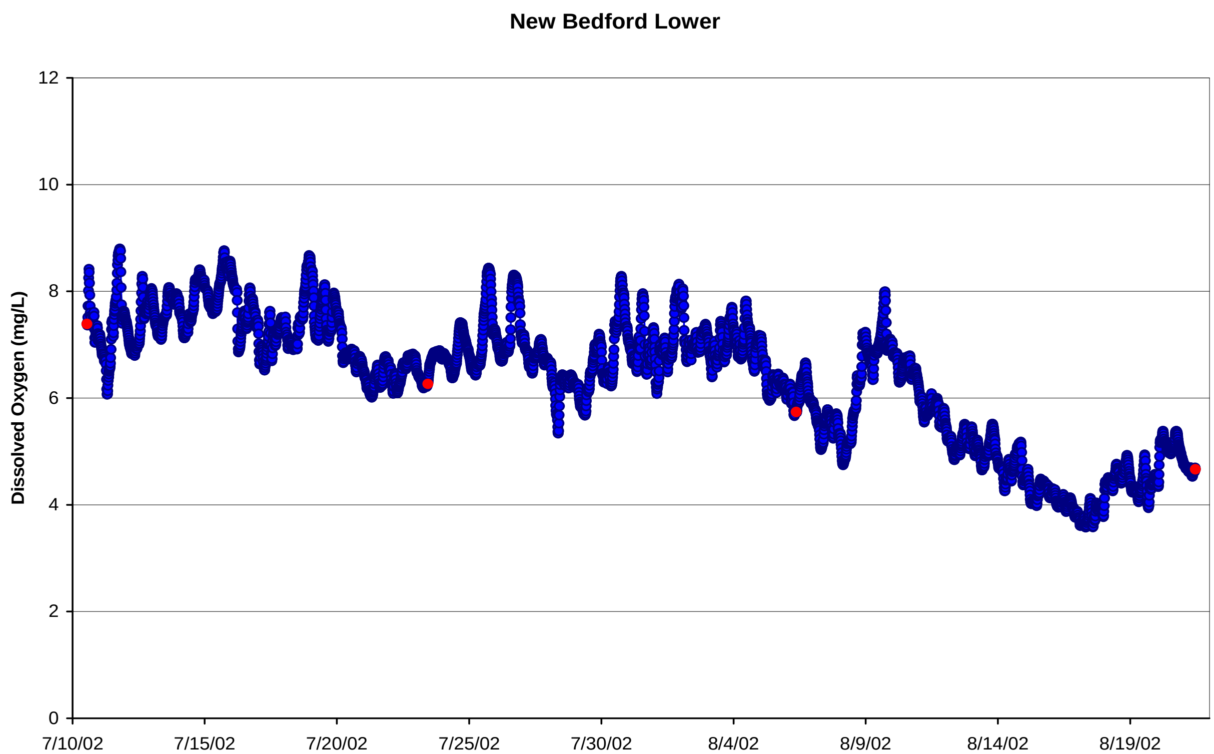


Figure VII-6. Bottom water record of dissolved oxygen at the New Bedford Inner Harbor Lower Basin (west), summer 2002. Calibration samples represented as red dots.

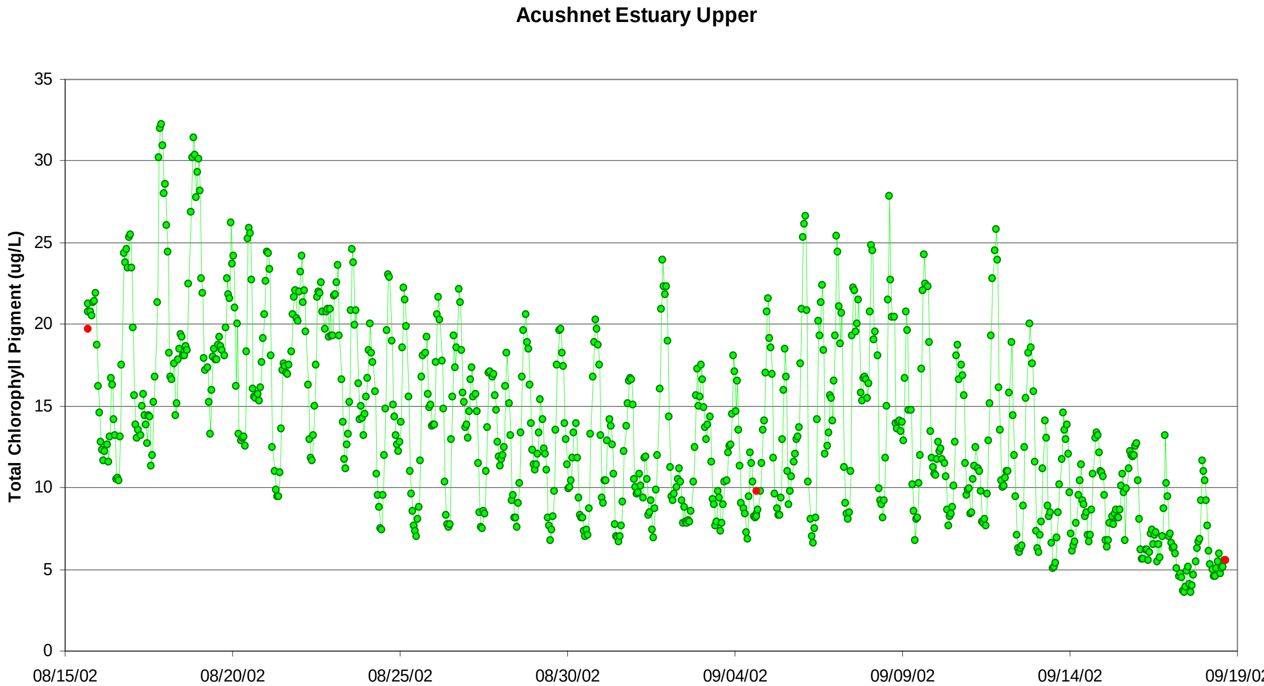


Figure VII-7. Bottom water record of Chlorophyll-*a* in New Bedford Inner Harbor upper basin, summer 2002. Calibration samples represented as red dots.

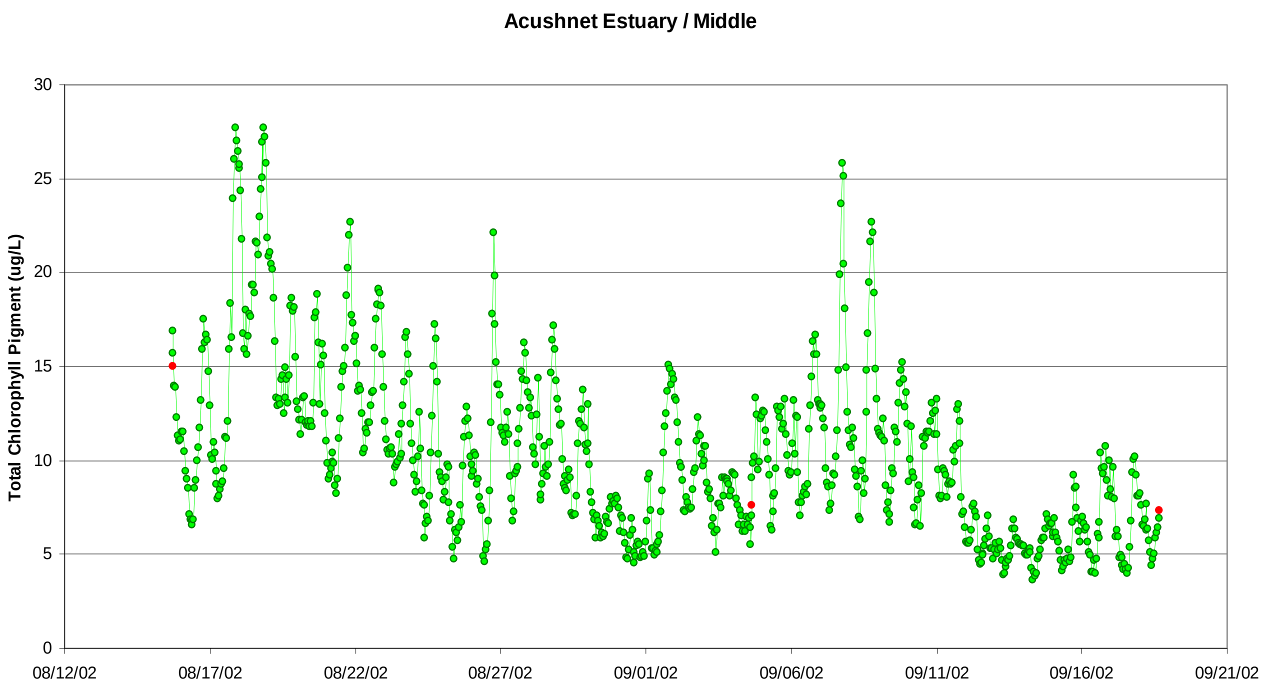


Figure VII-8. Bottom water record of Chlorophyll-*a* in New Bedford Inner Harbor middle basin, summer 2002. Calibration samples represented as red dots.

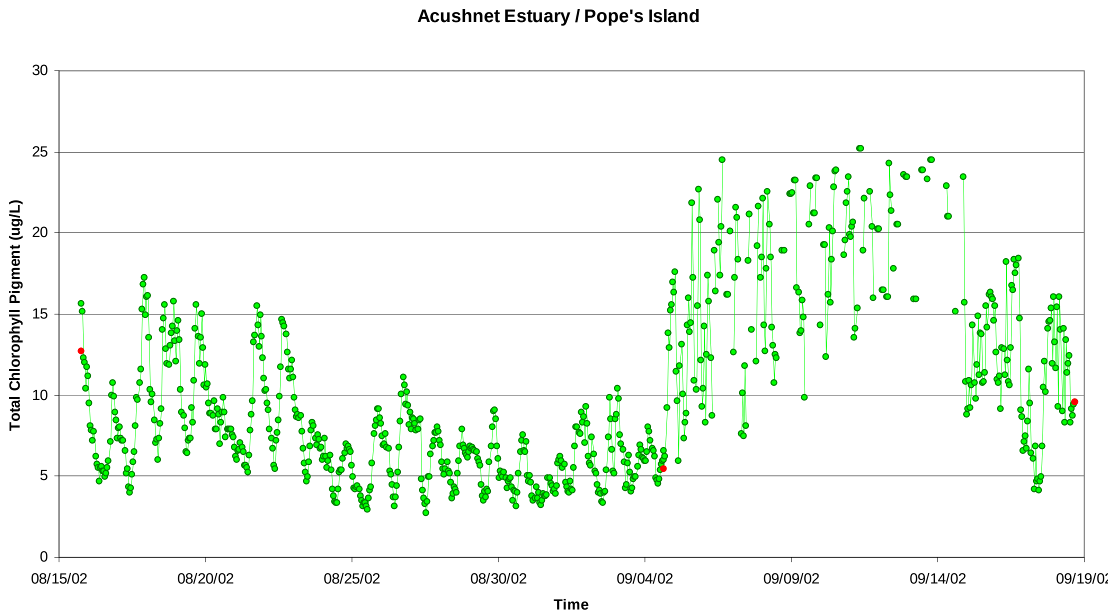


Figure VII-9. Bottom water record of Chlorophyll-*a* in New Bedford Inner Harbor lower basin (upper reach of lower basin), summer 2002. Calibration samples represented as red dots.

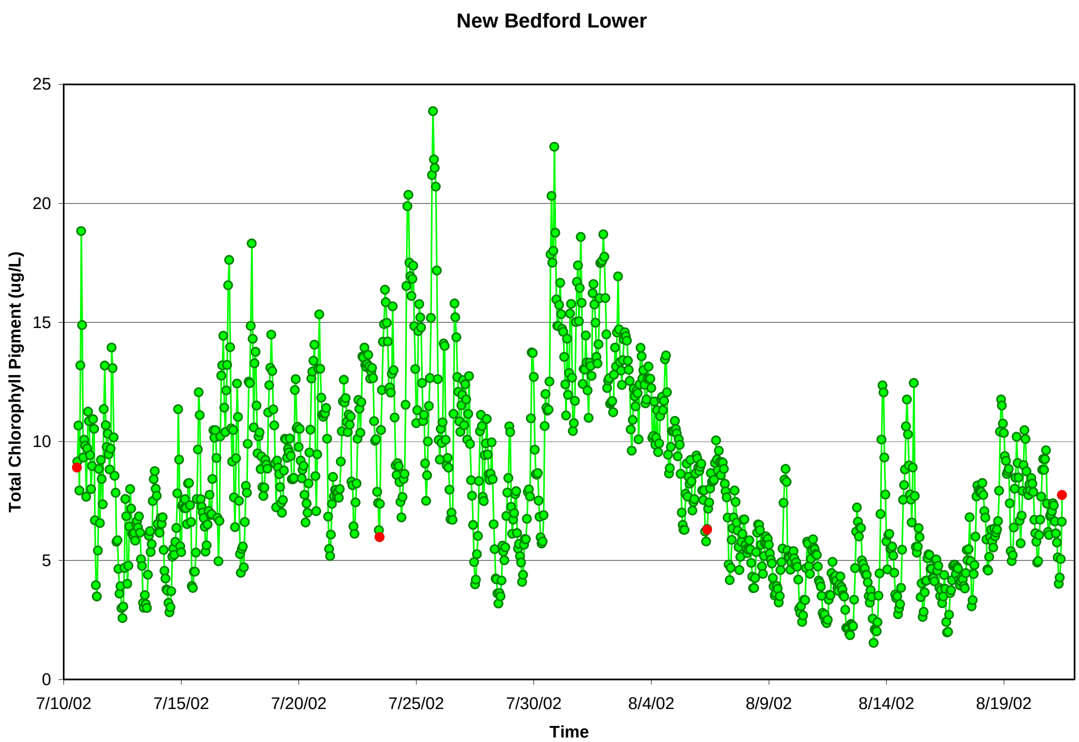


Figure VII-10. Bottom water record of Chlorophyll-*a* in New Bedford Inner Harbor lower basin (west), summer 2002. Calibration samples represented as red dots.

Table VII-1. Percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels. New Bedford Inner Harbor (Acushnet River Estuary) within the City of New Bedford and Town of Fairhaven, MA a sub-embayment to Buzzards Bay.

Massachusetts Estuaries Project New Bedford Inner Harbor	Dissolved Oxygen: Continuous Record, Summer 2002				
	Deployment Days	< 6 mg/L (% of days)	< 5 mg/L (% of days)	< 4 mg/L (% of days)	< 3 mg/L (% of days)
Lower Basin (west)	42.9	45%	15%	3%	0%
Lower Basin: Marina Pope's Island	34.5	19%	11%	7%	5%
Middle Basin	31.0	76%	33%	2%	0%
Upper Basin	34.0	62%	27%	0%	0%

Table VII-2. Duration (% of deployment time) that chlorophyll a levels exceed various benchmark levels within the embayment system. “Mean” represents the average duration of each event over the benchmark level and “S.D.” its standard deviation. Data collected by the Coastal Systems Program, SMAST.

Embayment System	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Acushnet River-New Bedford Inner Harbor								
Acushnet Lower	7/10/2002	8/21/2002	**41.9**	**80%**	**33%**	**6%**	**1%**	**0%**
			Mean	1.02	0.29	0.14	0.08	N/A
			Min	0.08	0.04	0.04	0.04	0.00
			Max	9.79	3.71	0.33	0.21	0.00
			S.D.	2.15	0.56	0.11	0.08	N/A
Acushnet Pope's Island	8/15/2002	9/18/2002	**34.5**	**73%**	**33%**	**17%**	**7%**	**0%**
			Mean	0.43	0.19	0.10	0.08	0.08
			Min	0.04	0.04	0.04	0.04	0.08
			Max	5.96	0.83	0.38	0.17	0.08
			S.D.	0.86	0.19	0.07	0.04	N/A
Acushnet Middle	8/15/2002	9/18/2002	**33.9**	**93%**	**45%**	**14%**	**4%**	**2%**
			Mean	1.66	0.45	0.25	0.24	0.18
			Min	0.04	0.04	0.04	0.04	0.08
			Max	11.17	3.50	1.63	0.63	0.25
			S.D.	3.27	0.64	0.36	0.22	0.09
Acushnet Upper	8/15/2002	9/18/2002	**34.0**	**98%**	**70%**	**39%**	**16%**	**3%**
			Mean	6.68	0.62	0.29	0.15	0.13
			Min	0.04	0.08	0.04	0.04	0.04
			Max	32.58	5.58	1.00	0.46	0.33
			S.D.	14.48	0.96	0.24	0.11	0.11

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the New Bedford Inner Harbor Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP technical effort. Field surveys were conducted in 1995 and 2001 by MassDEP, as part of this program, with additional observations during summer and fall 2002 by the SMAST/MEP Technical Team. Analysis of available aerial photography from 1951 was conducted to reconstruct the eelgrass distribution prior to any substantial development of the watershed. In addition, the MEP Technical Team has incorporated additional data from a survey of the New Bedford Harbor System (Costa 1988) based upon aerial photography (1971, 1974, 1975, 1981) and field surveys (1985) and recent field surveys by the Coastal Systems Program at SMAST-UMass-Dartmouth (2003, 2004, 2005). The primary use of the eelgrass data within the MEP approach is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figures VII-11a,b) and 1985. This temporal information can be used to determine the stability of the eelgrass community in many systems.

All of the available information on eelgrass relative to New Bedford Inner Harbor indicates that this embayment has not supported eelgrass over the past 2 decades and likely has not supported eelgrass for over a century. No eelgrass was detected in the 1985 survey and subsequent field surveys. The MassDEP analysis indicates that eelgrass habitat was not present within the Inner Harbor in 1951 which is consistent with the bathymetry of the Harbor basins (see below) and consistent with a recent reconstruction of the ecological history of the Inner Harbor (Pesch et al. 2002). This reconstruction strongly suggests that the harbor is unlikely to have supported eelgrass over the past century, even if the structure of the basins could have supported it. It appears that while long-term and present watershed and harbor activities would likely contribute to an impairment of eelgrass habitat, the depth of the basins plays the major role. Specifically, the large lower basin of the Inner Harbor sustains depths of 5-10 meters, deeper than eelgrass habitat within the other sub-embayments of Buzzards Bay (Westport Rivers to Quissett Harbor), which do not appear to have supported eelgrass habitat at these depths over the past 60 years.

It should be noted that while no eelgrass habitat could be documented within the Acushnet River/New Bedford Inner Harbor Estuary, the adjacent region of the Outer Harbor of the overall New Bedford Harbor system does support eelgrass habitat. The acreage of eelgrass in the Outer Harbor (outside of the hurricane barrier), appears to be relatively stable, although about 1/3 of the acreage was lost between 1951 and 2001 (Table VII-3). This MassDEP analysis is based upon available aerial photos from 1951 and field surveys in 1995 and 2001, combined with surveys by others. While there has possibly been some small loss between the 1995 and 2001 surveys, the loss (<5%) is within the uncertainty of the data. It is probable that eelgrass habitat within the Outer Harbor has improved by the upgrade in effluent quality from the New Bedford WWTF and the remediation of CSOs within the Inner Harbor region since 1995. It is important to note that the historical and present distribution of eelgrass within the Outer Harbor is at depths <3 meters, consistent with the lack of eelgrass within the deeper lower and middle Inner Harbor basins, which are generally >5 m and >3 m, respectively. Eelgrass habitat at these depths requires low turbidity waters generally not found within the middle basins of riverine estuaries within the region. For example, even within the outer basin

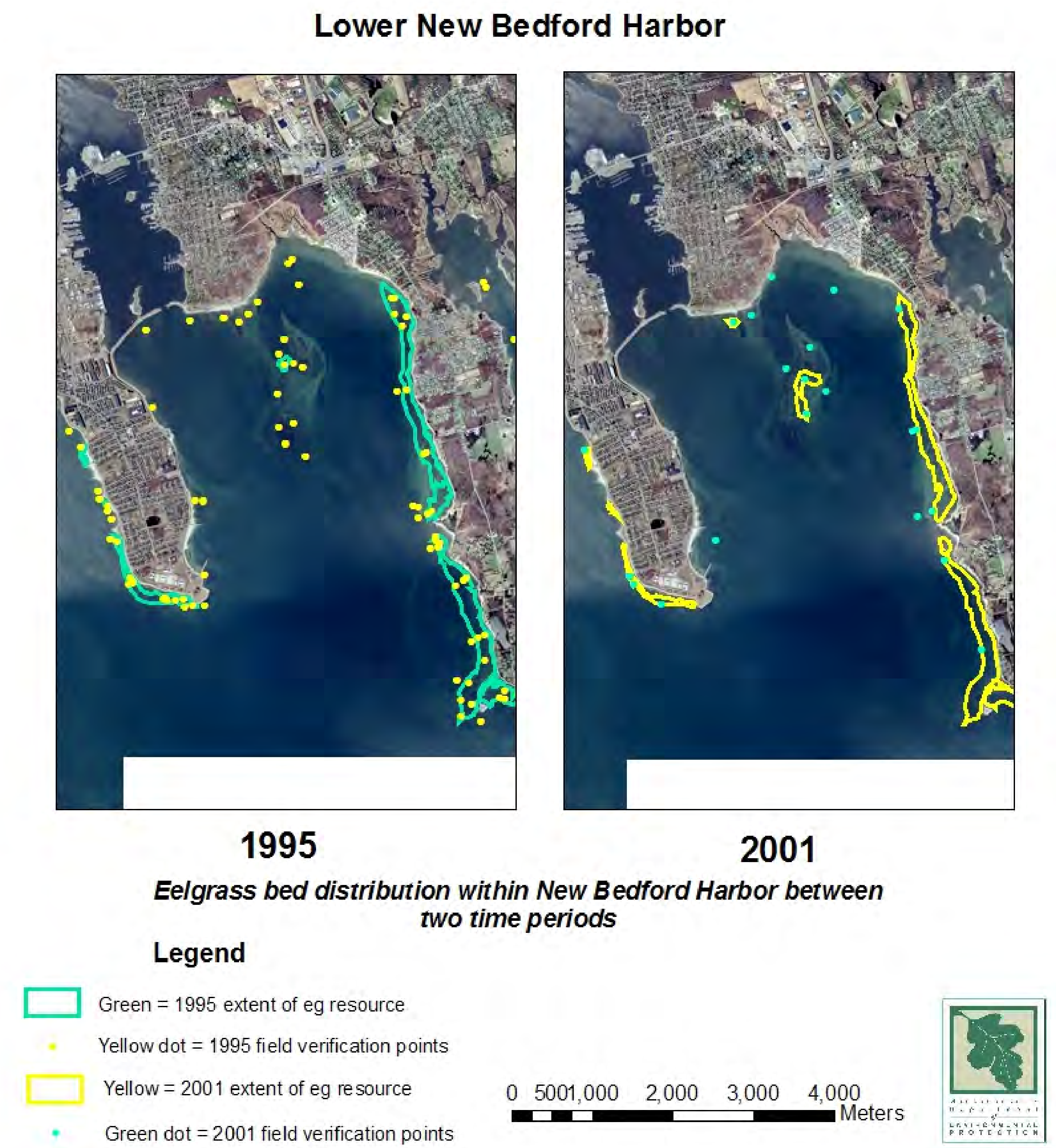


Figure VII-11a. Eelgrass bed distribution within the Acushnet / New Bedford Harbor System. No *Zostera marina* was found to exist within the New Bedford Inner Harbor Estuary during recent surveys (1985-2004) or the 1951 analysis. Field surveys from 1995 and 2001 show eelgrass coverage by the green and yellow outlines, respectively, which circumscribe the eelgrass beds. All data was provided by the MassDEP Eelgrass Mapping Program.

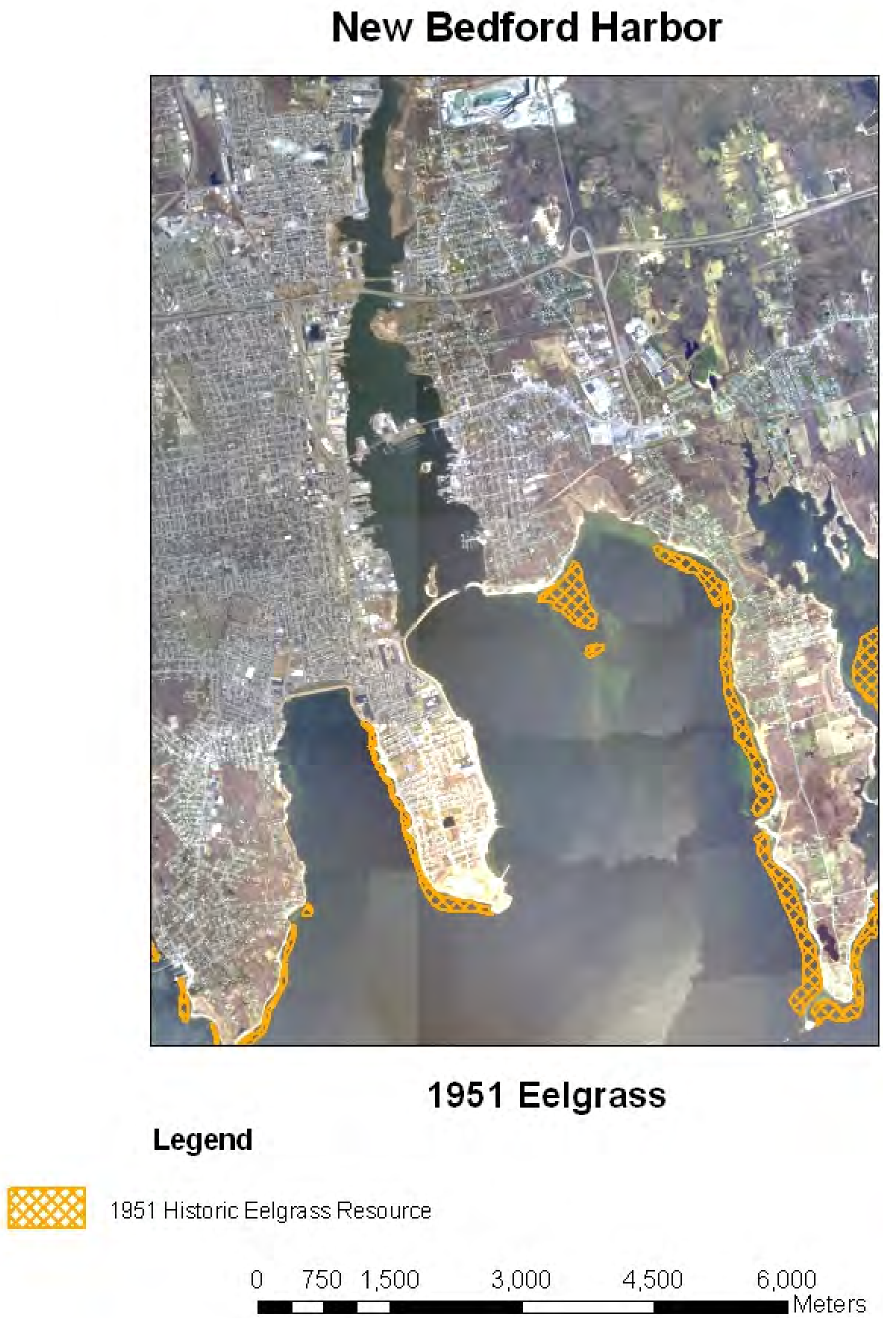


Figure VII-11b. Eelgrass bed distribution within the Acushnet / New Bedford Harbor System. No *Zostera marina* was found to exist within the New Bedford Inner Harbor Estuary during recent surveys (1985-2004) or the 1951 analysis. The 1951 coverage is depicted by the orange hatch area inside of which circumscribes the eelgrass beds. All data was provided by the MassDEP Eelgrass Mapping Program

Table VII-3. Changes in eelgrass coverage in the New Bedford Harbor system within the City of New Bedford and Town of Fairhaven over the past half century.

Temporal Change in Eelgrass Coverage[1]				
New Bedford Inner Harbor	**1951 (Acres)**	**1995 (Acres)**	**2001 (Acres)**	**% Loss 1951-1995**
Upper Basin	**0**	**0**	**0**	**NA[2]**
Middle Basin	**0**	**0**	**0**	**NA[2]**
Lower Basin	**0**	**0**	**0**	**NA[2]**
Outer Harbor	**163.1**	**105.9**	**100.8**	**38%**

1- Data and analysis by MassDEP Mapping Program.
2- No evidence that Little River has historically supported eelgrass habitat.

of Phinneys Harbor in 1951, eelgrass beds were restricted primarily to the shallower water depths (<2 m) along the northern shore (Mashnee Island) and colonized most of the basin to depths of ~2 meters (1951-1985). The accumulated evidence supports the contention that the bathymetry of New Bedford Inner Harbor plays an important role in the absence of eelgrass habitat within this estuary.

As eelgrass habitat could not be documented to exist, either historically or presently, within New Bedford Inner Harbor, the thresholds analysis for this system should focus on restoration of the impaired infaunal animal habitats. However, it is likely that nitrogen management within the Inner Harbor will improve eelgrass and infaunal habitat within the down-gradient basins of the Outer Harbor. This down-gradient effect, to the extent that it occurs, will be a by-product of the Inner Harbor restoration and was not part of the Inner Harbor thresholds analysis.

The lack of eelgrass within New Bedford Inner Harbor is consistent with the structure of the Inner Harbor basins (e.g. bathymetry), its long-term function as an active port and the multi-century effects of watershed activities on this estuarine system.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 10 locations throughout the Acushnet River/New Bedford Inner Harbor Embayment System, 8 were sampled in a 2003 MEP survey and 9 in the 2011 survey (Figure VII-12), with 7 of the stations sampled in both surveys. In some cases multiple assays were conducted. In all estuarine basins, and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related

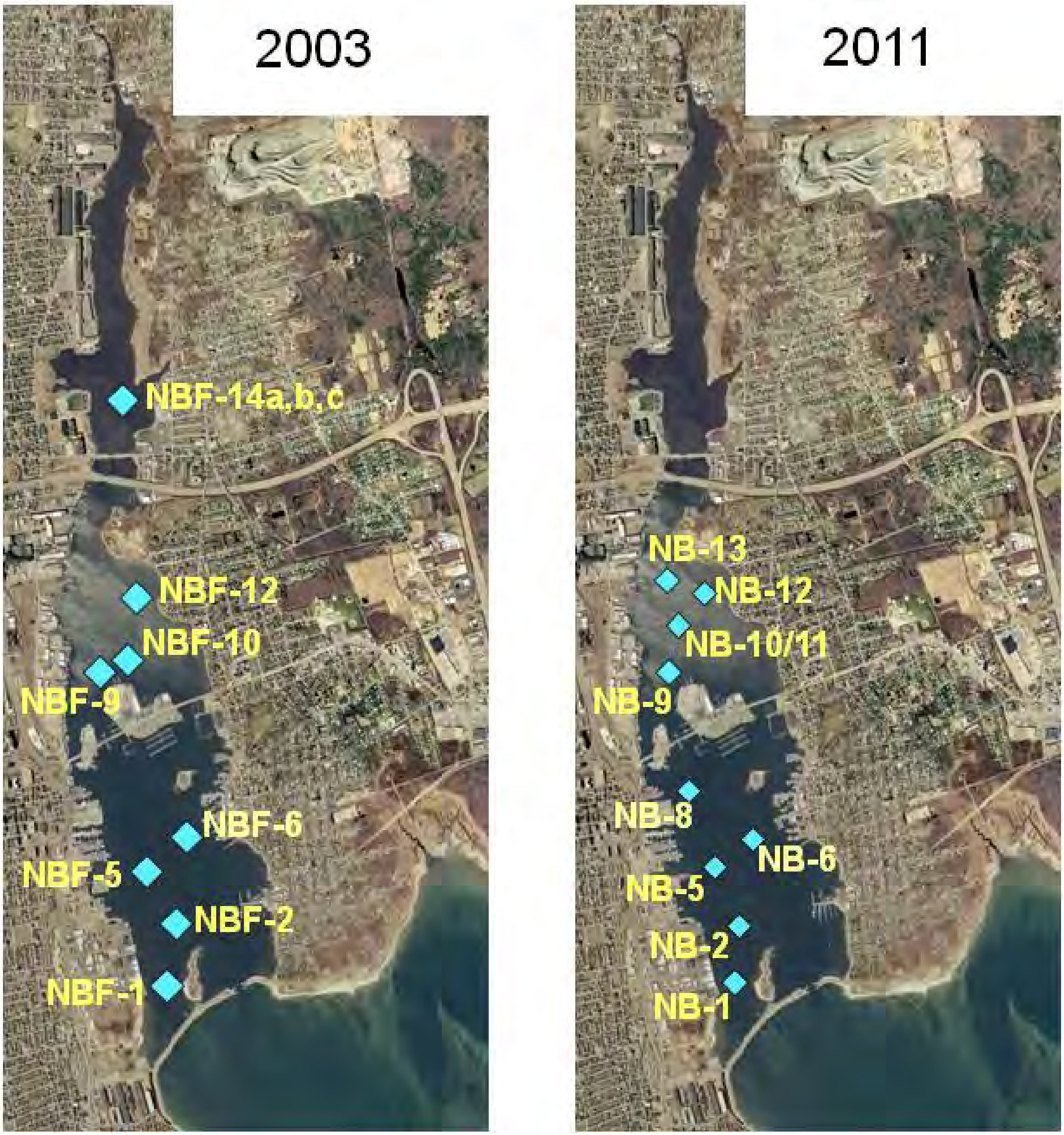


Figure VII-12. Aerial photograph of the Acushnet River Estuary/New Bedford Inner Harbor System showing location of benthic infaunal sampling stations (blue symbol) for 2003 and 2011. Station 14 was only sampled in 2003; stations 8 & 13 were only sampled in 2011.

stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity (H) and Evenness of the community. It should be noted that given the documented absence of eelgrass habitat within the New Bedford Inner Harbor Estuary, infaunal animal habitat quality is the primary focus of thresholds analysis and restoration goals. As New Bedford Inner Harbor supports infaunal communities throughout its estuarine reach, the benthic infauna analysis was used for determining the level of impairment (not impaired→moderately impaired→significantly impaired→severely degraded) within its three main basins. This assessment is also important for the establishment of site-specific nitrogen thresholds (Section VIII).

Analysis of the Evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information. The Evenness statistic (E) can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. The highest quality habitat areas, as shown by the oxygen and chlorophyll records, have the highest diversity (generally >3) and Evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.5. The assessment of infaunal habitat quality (below) is based upon both the infaunal community characteristics, and the type of ecosystem (basin, salt marsh, eelgrass bed) and stresses represented by salinity variation, macroalgal accumulations, organic matter enrichment (e.g. nitrogen loading), periodic hypoxia and whether a basin has high or low organic matter deposition.

The benthic infauna communities showed little change in key metrics (H, E, number of individuals and species) between the surveys for each of the three basins. The areas that were showing organic enrichment and depauperate communities, and the areas of moderately high quality habitat yielded nearly identical results in both surveys (2003, 2011). The similarity of the results allowed integration of the data sets to give a more accurate and robust indication of the distribution of benthic habitat quality throughout the estuary. The results also indicate the relative stability of this estuary, although longer term trends may be occurring.

The benthic analysis indicates that the New Bedford Inner Harbor Estuary is presently supporting a range of habitat quality for infaunal animal communities (Table VII-4). While each of the 3 major basins contains significant regions where the habitat is significantly impaired to severely degraded, areas within the lower basin showed only moderate impairment of benthic habitat. These impairments are associated with organic enrichment by phytoplankton blooms and periodic oxygen depletion, with the addition of macroalgal accumulations within the upper basin. Depositional areas such as adjacent the hurricane barrier and the western channel are currently support few species of benthic animals and few to low numbers of individuals. In the 2003 survey the channel location (NB-5) was thought to be disturbed by dredging activities within the harbor at the time. But the area yielded similar low numbers of individuals and species in the 2011 survey as well, 2 and 34 individuals among 2 species, respectively. These values do not compare well with the 20-25 species and 400-500 individuals typical of a high quality benthic environment. Overall, there was a trend of lower quality to higher quality habitat from the upper basin to the lower basin, with the specific habitat assessments for each basin detailed below.

The upper basin of New Bedford Inner Harbor is that region above the Rt. 195 bridge, which is highly eutrophic with the added stress of high levels of pcb's in the sediments. Because of the pcb contamination, it was not possible to conduct a detailed spatial survey of this basin, however the large accumulations of macroalgae and low oxygen indicate a significantly impaired habitat. This assessment is confirmed by the benthic infaunal survey which showed low numbers of species (8) and moderate numbers of individuals (~300), but with poor diversity (1.44) and Evenness (0.54). Diversity indices >3.0 and Evenness >0.7 are associated with high quality benthic environments. Equally diagnostic the community is dominated by organic enrichment tolerant/stress indicator opportunistic species (tubificids) which comprise >3/4 of the community. This portion of the estuary generally functions as a tidal river with bordering wetlands, with the upper reach influenced by freshwater inflows from the Acushnet River.

Table VII-4. Integrated benthic infaunal community data for 2003 and 2011 for the Acushnet River Estuary/New Bedford Inner Harbor embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (surface area = 0.0625 m^2). The benthic communities were very similar in both years in terms of community metrics and contribution of organic enrichment species.

	Sites	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Acushnet River Estuary/New Bedford Inner Harbor						
Upper Basin	**Sta. 14 a,b [C]**	**8**	**307**	**6**	**1.44**	**0.54**
Middle Basin	**Sta. 9-13 [C]**	**10**	**393**	**6**	**2.09**	**0.68**
Lower Basin:						
Open Basin	**Sta. 2,6 [D]**	**20**	**252**	**15**	**3.33**	**0.77**
West Channel	**Sta. 5[A]**	**2**	**18**	**N/A**	**0.91**	**0.91**
Palmers Cove	**Sta. 1[B]**	**5**	**122**	**3**	**1.16**	**0.49**

A - Station influenced by dredging operations
B - In cove bounded by Palmers Island and Hurricane Barrier, depositional area
C - Station 14 only sampled in 2003; Stations 8 & 13 were only sampled in 2011
D - Sites improved from 2003 to 2011 (post-dredging), data represents recent survey only

The observed benthic community is consistent with the significant nitrogen enrichment of this basin, with total nitrogen levels >0.7 mg N L^{-1}, high chlorophyll levels and frequent depletions of oxygen. Significantly, this basin also has accumulations of opportunistic drift algae (*Ulva*), further evidence of a significant level of nitrogen enrichment. The drift algae were common, but do not appear to occur in dense accumulations under the present conditions. The infaunal community within the upper basin was distributed among a relatively few species, primarily those tolerant of organic rich sediments and tolerant of periodic oxygen depletion. The dominant species were Tubificids, primarily *Tubificoides intermedius*. These organisms are also relatively tolerant to varying salinity levels in overlying water, a periodic condition within the shallow regions of this basin. However, there were also numerous mature quahogs (*Mercenaria*) and epibenthic animals, primarily snails and hermit crabs. The upper basin did support moderate numbers of individuals, although community diversity and evenness were generally low. The community indicators are consistent with the water quality parameters, indicating habitat impairment due to nitrogen enrichment. The interacting influences of nutrient enrichment, salinity and wetland effects in this shallow tidal environment, underscores the need for the use of multiple indicators in determining habitat health.

The middle reach of the New Bedford Inner Harbor Estuary is a moderately "deep" basin formed between the narrows of the upper basin and Popes Island. The structure of this basin facilitates deposition and results in the fine organic rich bottom sediments. The moderate to high chlorophyll-*a* levels result from nitrogen enrichment from the watershed and play a major role in organic matter enrichment of this system and causes periodic bottom water oxygen depletion upon decomposition. The result is sulfidic anoxic organic-rich sediments. Macroalgal accumulation does not appear to play a role in infaunal habitat quality within this basin, as macroalgae was not generally observed throughout its depths. Given the middle basin's depth and depositional nature, *in situ* growth of benthic algae appears to be limited by light penetration.

The middle basin functions as a classic sub-embayment basin and does not typically undergo large salinity variations (Section VI). However, the waters are nitrogen enriched, with tidally averaged total nitrogen levels 0.51-0.62 mg N L^{-1}, moderate to high chlorophyll levels and frequent depletions of oxygen, sometimes to 3.5 mg L^{-1}. The infaunal community within the middle basin consisted of a low-moderate number of species with high numbers of individuals (~400), with moderate diversity (H'=2.1) and moderate-high Evenness (E=0.68). The dominant species were those associated with moderate levels of organic matter and nitrogen enrichment (*Strebliospio, Gemma, and Mediomastis in 2003 replaced by Mulinia in 2011)*, but with a variety of deposit feeders evident. The infauna community is reflective of oxygen levels generally >4 mg L^{-1} and the organic matter enrichment, including the organic rich fine anoxic sediments. However, the basin is clearly less diverse and supporting many less species (10 vs. 20-25) than what is typical of unimpaired benthic habitats in southeastern Massachusetts Estuaries.

The benthic animal communities can be compared to high quality environments, such as the Outer Basin of nearby Quissett Harbor, as a benchmark. The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Evenness (0.74). Equally important these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms.

For the middle basin of New Bedford Inner Harbor, the benthic habitat metrics and community indicators are consistent with the water quality parameters and indicate a moderate-significant level of habitat impairment consistent with the observed level of nitrogen enrichment.

The lower reach of the New Bedford Inner Harbor Estuary is less nitrogen and organic matter enriched than the upper and middle basins and supports a range of infaunal habitat quality, primarily resulting from nitrogen enrichment effects and localized disturbances. In general the trend is for increasing impairment moving from the tidal inlet into the upper basin.

The lower basin is formed by Popes Island to the north and the Hurricane Barrier at its southern limit. The thresholds analysis necessarily focused upon the nitrogen enrichment effects, although the other factors were noted. For example, infaunal communities directly adjacent the recently dredged channel had few organisms (in both surveys). The artificial "cove" formed by the Hurricane Barrier and Palmers Island is also a localized area of significant impairment. The restricted flow within this "cove" and the deposition of phytoplankton and detritus from the localized inflows support the organic rich sediments. Moreover, the shallow waters allow patches of surficial algal mat to grow. The result is a low diversity community dominated by the disturbance indicator species *Capitella capitata* that accounted for more than half of the individuals present. While the habitat at this site is clearly degraded, it appears to be related to localized inputs and circulation effects due to the location of the Hurricane Barrier and Popes Island, more than general eutrophication of the Harbor. This is also consistent with the general gradient in decreasing nitrogen enrichment and parallel reduction in habitat impairment from the upper basin to the tidal inlet.

The greater main basin generally showed only low-moderate nutrient related habitat impairment, consistent with the moderate levels of chlorophyll and oxygen depletion and tidal velocities that reduce organic matter deposition, thereby reducing sediment organic enrichment in the central area. In addition, the lower basin does not appear to support significant habitat for macroalgae or accumulations of drift algae. Although, within some shallower areas, attached macroalgae (Codium, brown algae) were observed growing on shells and other hard substrates. The densities were low, with a likely result being an increase in habitat diversity. As a result, the larger main basin supports communities with moderate to high numbers of species (20) and moderate numbers of individuals (~250), with high diversity (H'>3.0) and Evenness (E>0.7). The dominant species are tolerant of some organic matter enrichment, but are also found in low nitrogen habitats (e.g. Buzzards Bay). The organic enrichment indicator species diagnostic of significant impairment found in other parts of the Harbor are not found in the central basin of the lower Harbor In addition, deposit feeders, deep burrowers and larger organisms are common. The overall species numbers and diversity and the lack of organic enrichment indicator species indicate only slight impairment within the central region of this basin, also consistent with its tidally averaged total nitrogen level of generally 0.47-0.51 mg N L^{-1}. Habitat quality throughout most of the lower basin appears to be structured by nitrogen related processes with transport of low oxygen and high chlorophyll waters from the upper basins also playing a likely role.

Overall, the infaunal habitat quality throughout the New Bedford Inner Harbor Embayment is consistent with the distribution of drift and attached macroalgae, the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin and localized effects. Based upon each of the metrics it appears the depositional middle basin is clearly impaired predominantly as a consequence of nitrogen based organic matter nitrogen enrichment. Infaunal restoration should focus on this region. The upper basin while also showing impairment, has "stresses" to infaunal habitats by freshwater/saltwater fluctuations, wetland influences and industrial contaminants (e.g. PCB's, metals, etc). Nitrogen management focused upon restoration of infaunal habitat quality within the middle basin will also necessarily result in significant improvements in the upper basin as to organic enrichment and macroalgal accumulations and will also result in a lowering of enrichment in the lower basin relieving the slight habitat impairment of the central basin area.

VIII. CRITICAL NUTRIENT THRESHOLD DETERMINATION AND DEVELOPMENT OF WATER QUALITY TARGETS

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen, chlorophyll-*a* and macroalgae). Additional information on temporal changes within each sub-embayment and its associated watershed nitrogen load further strengthens the analysis. These data were collected by the MEP Technical Team to support threshold development for the Acushnet River/New Bedford Inner Harbor embayment system and were discussed in Section VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline BayWatcher Water Quality Monitoring Program (2000-2006), conducted by the Coalition for Buzzards Bay with technical support from the Coastal Systems Program at SMAST, and supplemented by water quality surveys conducted by the New Bedford Oceanarium and the Coastal Systems Programs at SMAST-UMass Dartmouth.

The New Bedford Inner Harbor System is a riverine estuary composed of an upper tidal river with fringing wetlands, a middle depositional basin and a lower reach bounded by the New Bedford Hurricane Barrier. Each of these functional components has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of each system and the ability of the system to support eelgrass beds and specific types of infaunal communities. At present, the New Bedford Inner Harbor System is showing variations in nitrogen enrichment and habitat quality among its various component basins. In general the upper component system is showing moderately impaired benthic habitat within the upper tidal reach. As a wetland dominated basin, impairment is only moderate resulting mainly from the patches of drift macroalgal accumulation and to high chlorophyll-a levels and a preponderance of stress tolerant species. The middle basin is depositional with sediments consisting of organic rich mud. Organic enrichment appears to result from the moderate to high chlorophyll levels, as macroalgae are generally sparse to absent. The infaunal community is consistent with a moderate level of impairment, as consistent to the tidally averaged nitrogen levels of 0.51-0.62 mg N L^{-1} across this basin. Finally, the lower basin is generally slightly to moderately impaired by nitrogen enrichment, with significant impairment only in localized areas of physical disturbance or altered flushing. While the lower basin still exhibits moderate oxygen depletions and elevated chlorophyll-a, drift algae are not common, although attached forms can be found. The moderate level of nitrogen enrichment (tidally average generally 0.47 to 0.51 mg N L^{-1}) is consistent with the infaunal community within the lower main basin, with larger and deep burrowing forms evident.

Analysis of eelgrass habitat relative to the New Bedford Inner Harbor System, based upon MassDEP mapping (1951, 1995, 2001) and supplemented by field surveys by others in 1985 (Costa 1988) and SMAST/MEP scientists, indicate that this system has not supported eelgrass over at least the last half century. Coupling the available eelgrass data with the land-use history of the watershed and the relation to Harbor ecosystems strongly suggests that this estuary has not supported eelgrass for more than a century. It is likely that the lack of eelgrass results in part from watershed nitrogen loadings, but also from the depth of the basins. The bathymetric survey data (Section VI) suggests that most of the middle and lower basins of the Inner Harbor are deeper than the depths where eelgrass is commonly found in Buzzards Bay's embayment systems. Therefore, it is likely the combination of water depth and reduced light penetration (from nitrogen enrichment) drives the lack of eelgrass within this system. Eelgrass in the adjacent Outer Harbor is generally found at depths of <2 m, while depths of the middle basin and lower basin are generally >2 m and >5 m, respectively. The structure of the upper basin, as a shallow tidal river with wetland influences, generally does not lend itself to potential eelgrass habitat within southeastern Massachusetts estuaries. Based upon these lines of evidence, the New Bedford Inner Harbor Estuary should not be managed to restore eelgrass habitat. Instead, as this system currently supports moderately impaired habitat for infaunal animals (in all basins) as a result of accumulations of drift macroalgae in the upper basin, moderate to high chlorophyll levels and periodic oxygen depletions within the middle and lower basins, restoration of this estuary should focus on the impaired infauna habitat. As the habitat impairment is clearly associated with watershed nitrogen loading within the middle (and to a lesser extent) the lower basin, nitrogen management should focus on reducing nitrogen enrichment and associated effects on infaunal habitats within this basin.

Eelgrass:
All of the available information on eelgrass relative to New Bedford Inner Harbor, indicates that this embayment has not supported eelgrass over the past 6 decades and likely has not supported eelgrass for over a century. No eelgrass was detected in the 1985 and subsequent field surveys. The MassDEP analysis indicates that eelgrass habitat was not present within the Inner Harbor in 1951, consistent with the bathymetry of the Harbor basins (see below) and consistent with a recent reconstruction of the ecological history of the Inner Harbor (Pesch et al. 2002). This reconstruction strongly suggests that the harbor is unlikely to have supported eelgrass over the past century even if the structure of the basins could have supported it. It appears that while long-term and present watershed and harbor activities would likely contribute to an impairment of eelgrass habitat, the depth of the basins plays the major role. Specifically, the large lower basin of the Inner Harbor sustains depths of 5-10 meters, deeper than eelgrass habitat within the other sub-embayments to Buzzards Bay (Westport Rivers to Quissett Harbor), which do not appear to have supported eelgrass habitat at these depths over the past 60 years.

It should be noted that while no eelgrass habitat could be documented within the Acushnet River/New Bedford Inner Harbor Estuary, the adjacent region of the Outer Harbor of the overall New Bedford Harbor system does support eelgrass habitat. The acreage of eelgrass in the Outer Harbor (outside of the hurricane barrier), appears to be relatively stable, although about 1/3 of the acreage was lost between 1951 and 2001. While there has possibly been some small loss between the 1995 and 2001 surveys, the loss (<5%) is within the uncertainty of the data. It is probable that eelgrass habitat within the Outer Harbor has improved as a result of the upgrade in effluent quality from the New Bedford WWTF and the remediation of CSOs within the Inner Harbor region since 1995. It is important to note that the historical and present distribution of eelgrass within the Outer Harbor is at depths <3 meters, consistent with the lack of eelgrass within the deeper, lower and middle Inner Harbor basins, which are generally >5 m and >3 m, respectively. Eelgrass habitat at these depths requires low turbidity waters generally not found within the middle basins of riverine estuaries within the region. For example, even within the outer basin of Phinneys Harbor in 1951, eelgrass beds were restricted primarily to the shallower water depths (<2 m). The accumulated evidence supports the contention that the bathymetry of New Bedford Inner Harbor plays an important role in the absence of eelgrass habitat within this estuary.

As eelgrass habitat could not be documented to exist, either historically or presently, within New Bedford Inner Harbor, thresholds analysis for this system should focus on restoration of the impaired infaunal animal habitats. However, it is likely that nitrogen management within the Inner Harbor will improve eelgrass and infaunal habitat within the down-gradient basins of the Outer Harbor. This down-gradient effect, to the extent that it occurs, will be a by-product of the Inner Harbor restoration and was not part of the Inner Harbor thresholds analysis.

Macroalgae:
Macroalgae grows within the New Bedford Inner Harbor Embayment System in both attached and drift forms. The predominant drift algae is *Ulva lactuca* or sea lettuce with some Gracillaria present as well. *Ulva* is generally associated with nitrogen enrichment in both embayment basins and salt marsh creeks. It can form dense accumulations which "smother" the bottom communities, significantly impairing both infaunal animal communities and even eelgrass beds. Accumulations of drift macroalgae are indicative of significant to severe impairment of estuarine habitat. In contrast, macroalgal species which grow as attached forms, are not indicative of nitrogen enrichment and can be associated with high water quality and may even provide additional animal habitat (e.g. as SAV) in some cases.

New Bedford Inner Harbor presently has only small accumulations or sparse patches of macroalgae within its 3 major basins. The upper basin generally had the highest accumulations of drift algae and indicates a significant level of nitrogen enrichment. However, drift algae are clearly growing within this basin, likely having localized effects and the potential for transport to down-gradient basins. The drift algae were common but did not appear to occur in dense accumulations. The middle basin did not appear to support macroalgae throughout its depths. As the middle basin is both deep and depositional, growth of benthic algae appears to be limited by light. Similarly, the lower basin did not appear to support significant habitat for macroalgae or accumulations of drift algae. However, within the shallower areas of the lower basin, attached macroalgae (Codium, brown algae) were observed growing on shells and other hard substrates. The densities were low, with likely increase in habitat diversity. Overall, the habitats within this estuary are not structured by macroalgal accumulations like nearby Waquoit Bay or Slocums River. Nonetheless, nitrogen enrichment and the accumulation of drift algae within the upper basin is of concern.

Water Quality:
The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels indicate nutrient enriched waters and some impairment of infaunal habitat quality at all mooring sites within the Inner Harbor system (Figures VII-3 through VII-10). The oxygen data parallels the level of organic matter enrichment from phytoplankton production (chlorophyll-a levels) indicative of moderate to high nitrogen loading rates. The oxygen records further indicate that the upper tidal basin has the largest daily oxygen excursion, which further supports the assessment of a high degree of nutrient enrichment. The clear evidence of oxygen levels above atmospheric equilibration indicates that the upper basin is nitrogen and organic matter enriched. However, this basin is also influenced by its bordering wetlands, and to some extent is naturally organic matter rich sediments. The relationship of watershed nitrogen loading versus ecosystem function (wetland/tidal river) also suggests impairment of habitat within this basin, but at a lower level than based upon the water quality indicators alone.

Overall, the dissolved oxygen records indicate a gradient in oxygen depletion and chlorophyll-a levels from the upper to the lower basins of the Acushnet River / New Bedford Inner Harbor system (Table VII-1). Consistent with estuarine response to over-enrichment with nitrogen, the extent of bottom water oxygen depletion parallels the levels of phytoplankton biomass (e.g. chlorophyll-a, Table VII-2). Based upon the basin type and configuration, oxygen depletion and organic matter enrichment, it appears that infaunal habitat is impaired at a moderate level within the upper tidal river basin and also within regions of the lower basin. A slightly higher level of habitat impairment occurs within the depositional middle basin. All basins showed periodic oxygen depletions below 5 mg L^{-1} and generally to <4 mg L^{-1}. The exceptional depletion at the Popes Island site in the lower basin was apparently associated with the semi-isolated marina basin and not a larger spatial phenomenon.

The spatial distribution of infaunal habitat impairment follows the tidally averaged total nitrogen levels within the water column of each basin. Although the upper basin has TN levels generally >0.70 mg N L^{-1}, it is also "naturally" nitrogen enriched to some extent. In contrast, the depositional middle basin is relatively sensitive to nitrogen and organic matter enrichment and also shows significant nitrogen enrichment, ranging from 0.51 to 0.62 mg N L^{-1}. The lower basin presently supports the highest quality infaunal habitat and the lowest nitrogen levels, <0.51 mg N L^{-1}. As it is clear that the Inner Harbor is currently impaired by nitrogen enrichment, it appears that watershed nitrogen management will be required to restore the infaunal habitats within its estuarine basins.

The assessments of moderately impaired habitat quality within the basins of the Inner Harbor due to macroalgal accumulations and site-specific water quality analysis is consistent with the conclusions of the eelgrass and infaunal animal surveys.

Infaunal Communities:

The Infauna Study indicated that the New Bedford Inner Harbor Estuary is presently supporting a range of habitat quality for infaunal animal communities (Table VII-4). However, each of the 3 major basins contains significant regions where the habitat is impaired by nitrogen enrichment. These impairments are associated with organic enrichment by phytoplankton blooms and periodic oxygen depletion, with the addition of macroalgal accumulations within the upper basin. The assessment of infaunal habitat quality is based upon both the infaunal community characteristics, and the type of ecosystem (basin, salt marsh, eelgrass bed) as well as stresses represented by salinity variation, macroalgal accumulations and organic matter enrichment (e.g. nitrogen loading).

The habitat quality of the upper basin of New Bedford Inner Harbor, relative to nitrogen enrichment, is generally reflective of its function as a tidal river with bordering wetlands. This upper reach of the estuary is influenced by freshwater inflows from the Acushnet River, is nitrogen enriched (>0.7 mg TN L^{-1}), and has high chlorophyll levels with frequent depletions of oxygen. Significantly, this basin had accumulations of drift algae (patches), indicative of "excessive" nitrogen enrichment. The drift algae, to the extent that it accumulates, represents a nitrogen related "stressor" to infaunal communities. However, while the presence of drift algae was common, it did not appear to occur in dense accumulations under the present conditions.

The infaunal community within the upper basin was distributed among a relatively few species, primarily those tolerant of organic rich sediments and tolerant of periodic oxygen depletion. The dominant species were Tubificids, primarily *Tubificoides intermedius*. These organisms are also relatively tolerant to varying salinity levels in overlying water, a periodic condition within the shallow regions of this basin. There were also numerous mature quahogs (*Mercenaria*) and epibenthic animals, primarily snails and hermit crabs. The upper basin did support moderate numbers of individuals, although community diversity and evenness were generally low. The community indicators are consistent with the water quality parameters, salinity and wetland influences in this shallow tidal environment. While this basin is showing some nutrient related impairment of infaunal habitat, its structure argues against it being the primary focus of nitrogen management. Rather, the middle and lower basins typical of open water embayments to Buzzards Bay, with the more typical infaunal habitats and greater sensitivities to nitrogen enrichment, were used to focus the thresholds analysis, below.

The middle reach of the New Bedford Inner Harbor Estuary, is a moderately "deep" basin formed between Popes Island to the south and the narrows leading into the upper basin. The structure of this middle basin facilitates deposition and results in the fine organic rich bottom sediments. The moderate to high chlorophyll-a levels result from nitrogen enrichment from the watershed and play a major role in organic matter enrichment of this system as well as periodic bottom water oxygen depletion. Macroalgal accumulation does not appear to play a role in infaunal habitat quality within this basin, as macroalgae was not generally observed throughout its depths. The waters are nitrogen enriched, with tidally averaged total nitrogen levels of 0.51 to 0.62 mg N L^{-1}, moderate to high chlorophyll levels and frequent depletions of oxygen, sometimes to 3.5 mg L^{-1}. The infaunal community within the middle basin was generally diverse with high evenness. However, the dominant species were those associated with moderate levels of organic matter and nitrogen enrichment (*Mediomastus, Strebliospio, Gemma, Macoma*). This estuarine reach did support moderate numbers of individuals. However, the community indicators are consistent with the water quality parameters indicating a moderate level of habitat impairment due to nitrogen enrichment.

The lower reach of the New Bedford Inner Harbor Estuary currently supports higher quality infaunal habitat than the middle basin. The main lower basin generally showed only slight nutrient related habitat impairment, consistent with the moderate levels of chlorophyll and oxygen depletion and tidal velocities that reduce organic matter deposition, reducing sediment organic enrichment in some areas. In addition, the lower basin did not appear to support significant habitat for macroalgae or accumulations of drift algae. As a result, the larger main basin supports communities with moderate numbers of species and individuals, with moderate diversity and evenness. The dominant species are tolerant of some organic matter enrichment, but are also found in low nitrogen habitats (e.g. Buzzards Bay). In addition, deposit feeders, deep burrowers and larger organisms are common. The overall species numbers and diversity, along with the occurrence of organic enrichment tolerant species, indicates a low to moderate level of impairment within this basin. This is consistent with its tidally averaged total nitrogen level of generally 0.47-0.51 mg N L^{-1}, with habitat quality throughout most of the lower basin being structured by nitrogen related processes. Transport of low oxygen and high chlorophyll waters from the upper basins is also likely to be playing a role in defining this basins habitat quality.

Overall, the infaunal habitat quality throughout the New Bedford Inner Harbor Embayment was consistent with the distribution of drift and attached macroalgae, the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin. Based upon this analysis it appears the depositional middle basin is clearly impaired, predominantly as a consequence of organic matter nitrogen enrichment. Infaunal restoration should focus on this region. The upper basin, while also showing impairment, has additional "stresses" to infaunal habitats by freshwater/saltwater fluctuations, wetland influences and industrial contaminants (e.g. PCB's, metals, etc). Nitrogen management focused upon restoration of infaunal habitat quality within the middle basin will also necessarily result in significant improvements in the upper basin as to organic enrichment and macroalgal accumulations and to the down-gradient lower basin, as well.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Acushnet River/New Bedford Inner Harbor Estuary on Buzzards Bay within the City of New Bedford and Town of Fairhaven, MA., based upon assessment data presented in Section VII. The Acushnet River Estuary is a typical riverine estuary, without tributary basins.

Health Indicator	Acushnet River/New Bedford Inner Harbor Estuary		
	Upper Basin[A]	**Middle Basin**	**Lower Basin**
Dissolved Oxygen	MI[1]	MI-SI[2]	MI[3]
Chlorophyll	MI-SI[4]	MI[5]	MI[6]
Macroalgae	MI[7]	--[8]	H-MI[9]
Eelgrass	--[10]	--[10]	--[10]
Infaunal Animals	MI[11]	MI[12]	MI[13a]-SI[13b]
Overall:	**MI[14]**	**MI[15]**	**H-MI[16]**

A -- basin supports fringing salt marsh areas.
1 – wetland influenced tidal river, frequent oxygen depletions to 4-4.5 mg/L.
2 -- oxygen depletions frequently to 4.5 mg/L, with periodic declines to 4.0-3.5 mg/L.
3 – oxygen levels generally >5mg/L with depletion rarely to 4 mg/L
4 – high chlorophyll a levels generally 7-20 ug/L, frequently >25 ug/L (32% of record)
5 – moderate to high, generally 4-18 ug/L, frequently >20 ug/L (14%of record)
6 – moderate chlorophyll a levels generally 3-15 ug/L, lower basin >15 ug/L only 6% of time, upper basin >15 ug/L 17% of time; gradient of decreasing chlorophyll approaching inlet.
7 -- drift algae (*Ulva, Gracillaria*) in patches, indicative of nitrogen enrichment
8 -- drift algae absent or sparse.
9 -- drift algae sparse/absent, some attached (*Codium*), patches of surface microphyte mat
10 – no evidence this basin is supportive of eelgrass (no eelgrass over the past century)
11 -- Infauna: moderate # of individuals, low # species, moderate diversity and Eveness; dominated by organic enrichment indicators (Tubificids) tolerant to salinity "stress", organic sediments sulfidic below. Dense accumulations of bivalves (*Mercenaria*) and epifauna (snails, hermit crabs).
12 -- moderate # of individuals, moderate-low # species, moderate-high diversity and Eveness. Indication of moderate organic enrichment (*Mediomastus, Streblospio, Leitoscolopios*). Depositional basin with predominantly soft organic rich muds.
13 -- spatially variable, habitat ranging from moderate impairment in areas of organic enrichment, to significant impairment due to localized dredging disturbance, marina activities, depositional areas.
(a) Main Basin: moderate to high quality infaunal habitat, moderate # individuals & species, moderate Diversity & Evenness, some organic enrichment species, but deep burrowers;
(b) Channel: depleted community, indicative of recent disturbance and Palmer Cove: depositional area of soft organic muds, moderate # individuals, low # species, dominated by organic enrichment/disturbance species (*Capitella capitata*).
14 -- Moderate to significant impairment based upon patches of drift macroalgae and moderate-high chlorophyll levels, community dominated by organic enrichment indicators,
15 -- Moderate impairment of infaunal habitat, with moderate chlorophyll levels resulting in soft organic sediments in this depositional basin and basin-wide periodic oxygen depletion.
16 -- Based mainly upon nitrogen related impairment to main basin, rather than localized areas of moderate to significant impairment of infaunal habitat, (e.g. Popes Island and Palmers Island depositional areas) and basin-wide periodic oxygen depletion.

H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment; SD = Severe Degradation; -- = not applicable to this estuarine reach

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

For the Acushnet River/New Bedford Inner Harbor Estuary, determination of the critical nitrogen threshold for maintaining high quality habitat is based primarily upon the nutrient and oxygen levels, macroalgal accumulations and current benthic community indicators. Given the database developed by the MEP, it is possible to generate a site-specific threshold which is a refinement upon general threshold analyses frequently employed. All of the habitat assessment data clearly indicate that the Inner Harbor is presently beyond its ability to tolerate nitrogen inputs. The result is that its 3 main basins are supporting moderately impaired infaunal habitat. Restoration of these impaired habitats is the primary target of the MEP thresholds analysis.

New Bedford Inner Harbor has not supported eelgrass over the past 6 decades and likely has not supported eelgrass for over a century. This conclusion is consistent with the bathymetry of the Harbor basins and with a recent reconstruction of the ecological history of the Inner Harbor (Pesch et al. 2002). That being said, restoration of the infaunal habitat within the New Bedford Inner Harbor System focused on the depositional middle basin. The infaunal habitat quality within the Inner Harbor was consistent with the distribution of drift and attached macroalgae, the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin. Based upon this analysis it appears the depositional middle basin is clearly impaired predominantly as a consequence of organic matter nitrogen enrichment, is more sensitive to nitrogen loading than the upper basin and presently has higher nitrogen levels than the lower basin. Nitrogen management focused upon restoration of infaunal habitat quality within the middle basin will necessarily result in significant improvements in the upper basin as to organic enrichment and macroalgal accumulations and to the down-gradient lower basin, as well. In addition, the middle and lower basins are more typical of open water embayments to Buzzards Bay, with more characteristic infaunal habitats and greater sensitivities to nitrogen enrichment being used to focus the thresholds analysis presented below.

The target total nitrogen concentration for restoration of infaunal habitat within the New Bedford Inner Harbor Estuary, is $\leq$0.50 mg TN L^{-1} (tidally averaged) at the sentinel location (head of the middle basin, just below the entrance to the channel to the upper basin) as depicted in Figure VIII-1. As the present TN level at this site is ~0.6 mg TN L^{-1}, watershed nitrogen management will be required for restoration of the estuarine habitats within this system. As nitrogen management alternatives are implemented and the nitrogen threshold is attained, a consequence will also be a lowering of nitrogen enrichment in both the upper and lower basins. Nitrogen levels within the lower basin will likely be significantly reduced compared to present conditions.

The threshold nitrogen level is similar to that for the nearby Slocums River, where infaunal habitat is presently impaired at an average TN level of 0.594 mg N L^{-1}. Similarly, a threshold of 0.5 mg N L^{-1} has been documented for a number of enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat and in deeper enclosed basins in Buzzards Bay (e.g. Eel Pond in Bourne) where healthy infaunal habitat had a slightly lower threshold level, 0.45 mg N L^{-1}. Conversely, the Centerville River Estuary was found to support moderately impaired infaunal habitat at tidally averaged TN levels of 0.526 mg N L^{-1} in its upper basin and at 0.543 mg N L^{-1} within its middle reach. While the Wareham River and Broad Marsh River sub-basins of the Wareham River System were found to have moderately impaired infaunal habitat at total nitrogen (TN) levels in the range of 0.535 - 0.600 mg N L^{-1}, analogous to the 0.51-0.62 mg TN L^{-1} presently found in the middle basin of New Bedford Inner Harbor.

Based upon the above analysis, infaunal habitat should be the primary nitrogen management goal for the New Bedford Inner Harbor System. These goals are the focus of the MEP management threshold loading analysis (Section VIII.3) and alternatives analysis (Section IX). It must be stressed that the nitrogen threshold for this estuary is at the sentinel location. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The New Bedford Inner Harbor Estuary does not contain eelgrass habitat. However, this estuary is presently supporting moderately impaired infaunal habitat within its 3 three main basins, with the critical focus for nitrogen management on the depositional middle basin. Impairments result from watershed nitrogen inputs that exceed the tolerance of these basins, resulting in the loss of diversity and larger, deep burrowing forms. The stress to infaunal communities is by organic enrichment through phytoplankton blooms, macroalgal accumulations and periodic oxygen depletion. The threshold nitrogen loading represents the target for lowering nitrogen levels and the associated habitat impacts, and to restore the impaired infaunal habitats throughout the Inner Harbor Basins by targeting a tidally averaged threshold level of 0.5 mg N L^{-1} at the sentinel station within the middle basin.

The nitrogen thresholds developed above were used to determine the amount of total nitrogen mass loading reduction required for restoration of infaunal habitats in the New Bedford Harbor system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges, lowering of load from the Fairhaven Wastewater Treatment Plants and reduction in CSO load to the harbor, until the nitrogen levels reached the threshold level at the sentinel stations chosen for New Bedford Harbor. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation here is made to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

In the development of the threshold loading scenario presented in this report, all CSO loads were removed (9,706 kg/yr) as was 70% of the Fairhaven wastewater plant (FWP) load. This percentage reduction for the FWP is based on the maximum likely achievable by upgrading the plant to tertiary treatment with a 5 mg/l discharge TN concentration at a buildout flow of 3.17 mgd. Additional load throughout the watershed, beyond the FWP (in the lower basin) and

CSOs, must be removed in order to meet the threshold requirements of a 0.50 mg/L TN concentration at the upper 1/3 of the mid Harbor basin.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required 77% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system in addition to the CSO load reduction and removal of the Fairhaven Treatment Facility discharge to the lower Inner Harbor basin.

Tables VIII-2 and VIII-3 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. For example, removal of 70% of the septic load together with removal of all CSO discharges from the upper Harbor basin watershed results in a -52% reduction in total watershed nitrogen load. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Buzzards Bay, as discussed in Section VI.2.6.1.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations within the water column of typically greater than 8% is required in the system, between the main harbor basin and the marsh.

The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds may have merit, since this example of nitrogen remediation is focused on watersheds where groundwater is flowing directly into the estuary. For nutrient loads entering the systems through surface flow, natural attenuation in freshwater bodies (i.e., streams and ponds) can help by significantly reducing the load that finally reaches the estuary. Presently, this attenuation is occurring in the freshwater reach of the Acushnet River due to natural ecosystem processes and the extent of attenuation being determined by the mass of nitrogen which discharges to these systems. Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, “planned” use of natural systems has to be done carefully and with the full analysis to ensure that degradation of these systems will not occur. One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

Although the above modeling results provide one manner of achieving the selected threshold level for the sentinel site within the estuarine system, the specific example does not represent the only method for achieving this goal. However, the thresholds analysis provides general guidelines needed for the nitrogen management of this embayment.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the New Bedford Inner Harbor System. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Upper Basin	7.562	2.268	-70.0%
Mid Basin	2.137	0.641	-70.0%
Lower Basin	5.973	1.792	-70.0%
Acushnet River – fresh water	38.279	7.656	-80.0%
System Total	53.951	12.357	-77.1%

Table VIII-3. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer, CSOs and the WWTF) used for modeling of present and threshold loading scenarios of the New Bedford Inner Harbor system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Upper Basin	47.899	22.948	-52.1%
Mid Basin	17.600	12.219	-30.6%
Lower Basin	165.512	62.668	-62.1%
Acushnet River – fresh water	99.444	68.820	-30.8%
System Total	330.455	166.656	-49.6%

Table VIII-4. Threshold sub-embayment loads used for total nitrogen modeling of the New Bedford Inner Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Basin	22.948	2.836	45.081
Mid Basin	12.219	3.614	-28.561
Lower Basin	62.668	7.011	52.147
Acushnet River – fresh water	68.820	-	-
System Total	166.656	13.460	68.667

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the New Bedford Inner Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold "station" is shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Upper Basin	2	0.764	0.639	-16.4%
Coggeshall Bridge	3	0.626	0.545	-12.9%
Popes Island East Bridge	6	0.517	0.468	-9.6%
Lower Basin (North)	7	0.509	0.462	-9.2%
Lower Basin (Mid)	8	0.498	0.454	-8.7%
LowBasin South of FTP	12	0.485	0.446	-8.1%
LowBasin-Inside Inlet	9	0.470	0.437	-7.0%
Upper 1/3 of mid Basin	**-**	**0.566**	**0.503**	**-11.3%**

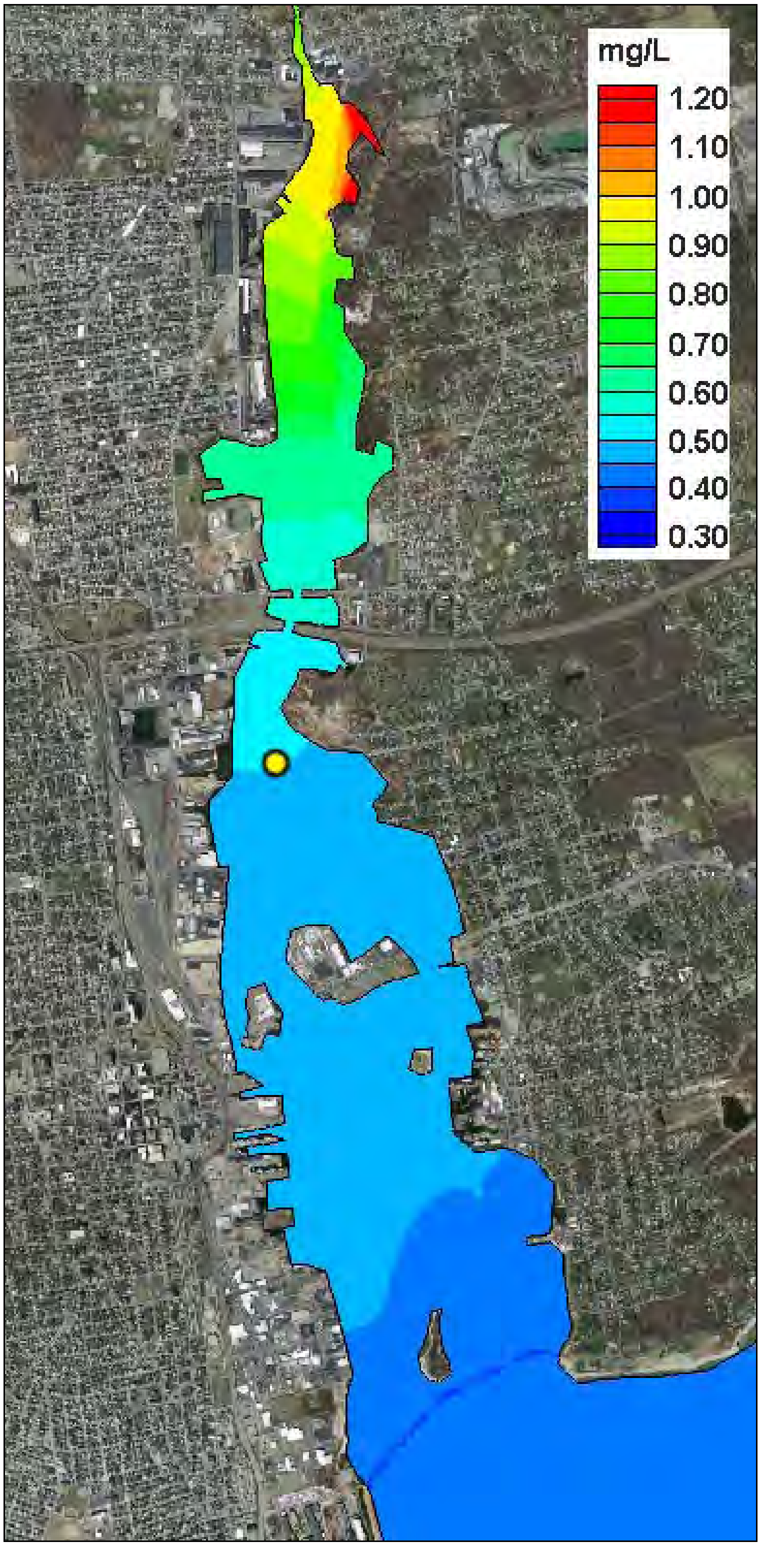


Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the New Bedford Inner Harbor Estuary, for threshold conditions (0.50 mg/L at the head of the middle basin, just south of the entrance to the channel to the upper basin. The threshold (sentinel) station is indicated on the plot by the yellow circle marker.

IX. MODEL SCENARIOS

As part of this analysis, model runs were made to investigate the effect of proposed modifications to the hurricane barrier, and separately, different N loading scenarios. These scenarios were conducted under the 2008 Watershed N Loading assessment that has been updated (2010 collaboration with BBP) with new information for the prior sections (I-VIII) of this report. The modest differences in the N loading used in the modeling in Section IX.1 (below) do not affect the conclusions as the focus in these scenarios was to address questions related to effects of changes in hydrodynamics associated with the Hurricane Barrier, rather than alternatives related to changing watershed loads. The scenarios in Section IX.2 did relate to evaluating watershed N loading and therefore were used only as guidance and background for developing Section VIII.3. Tables provided below are included solely to provide historical background.

IX.1 HYDRODYNAMIC MODEL ALTERNATIVES TO IMPROVE TIDAL FLUSHING AND WATER QUALITY

The objective of evaluating modifications to the New Bedford Harbor Hurricane Barrier is to assess potential improvements to the water quality within the harbor. Existing data show that the opening in the barrier is large enough to only cause a delay of approximately 5 minutes in water elevation between the entrance of the harbor and the northern end of the harbor during an incoming tide. It appears that the present opening is providing good volumetric exchange between the inner and outer harbor regions. However, water quality within the inner harbor is not just influenced by total volume exchange, but also circulation or mixing of waters within the harbor. At present, the Hurricane Barrier results in circulation cells around the inlet and depositional areas west of Palmer Island, and possibly east of the inlet on the Fairhaven side.

As described in Chapter VI, a total nitrogen model for existing conditions has been developed. This model, in conjunction with the two-dimensional hydrodynamic model, have been utilized to evaluate the potential for improved mixing and associated water quality created by the addition of more culverts (2 are already in place within the western barrier). As part of this evaluation the role of the Hurricane Barrier in producing the present hydrodynamic and total nitrogen related water quality conditions was modeled using site specific field data collected by the Massachusetts Estuaries Project. The calibrated and validated model was then used to determine the efficacy of different culvert sizes and placements in enhancing existing hydrodynamic and water quality (primarily total nitrogen) conditions. Aside from the main opening in the hurricane barrier, there are two culverts within the western part of the barrier. Each of the conduits is 12 feet wide by 9 feet high. These culverts are open, unless the barrier is closed due to a storm event. The relatively small openings of the existing culverts compared to the ~700 ft opening of the main inlet, indicates that these culverts are relatively unimportant in the total tidal exchange between the inner and outer harbors. However, they may serve to promote local high velocity zones which may promote the transport of particles (live and dead phytoplankton, TSS and possibly bivalve larvae) to the outer harbor, resulting in localized reduced deposition.

The specific hydrodynamic alternatives were selected based on discussions representatives from the U.S Army Corps of Engineers, NOAA, and the U.S. EPA. The results of the initial selection process were outlined in a memorandum (Memo #NBHM-03) dated May 31, 2007. The following is a list of the alternative scenarios modeled to date:

- *Model Scenario NB-01*: Existing Conditions (described in Chapters V and VI)

- *Model Scenario NB-02*: Hurricane Barrier Removed
- *Model Scenario NB-03*: 24-ft Wide Culvert between Locations 5 and 6 (Figure IX-1)

The modeling results focused on quantifying the effects of installing additional openings in the Hurricane Barrier to both tidal circulation and water quality in Inner New Bedford Harbor. Since total nitrogen is the primary “pollutant” responsible for eutrophication in Massachusetts estuaries, modeling of nitrogen concentrations was utilized to assess water quality improvements.

Figure IX-1. Map with 'Locations' marked along the Hurricane Barrier to indicate the placement of potential openings. The culvert modeled in NB-03 is between numbers 5 and 6.

Model Scenario NB-02

Prior to assessing hydrodynamic and water quality conditions associated with culvert additions, a "best-case" alternative was developed based on the complete removal of the existing Hurricane Barrier. This alternative was modeled to provide an end–point for the models, where this condition represents the best circulation and associated water quality that could be achieved without additional upland management of nutrient sources. For this model scenario, modern bathymetric conditions were provided as input to the hydrodynamic model, since any consideration of future Hurricane Barrier removal would likely retain existing navigation channel depths. Bathymetry in the footprint of the existing Hurricane Barrier was interpolated from existing data adjacent to the barrier.

To determine the circulation and water quality impacts the Hurricane Barrier has upon New Bedford Harbor, the hydraulic model was modified to remove the Hurricane Barrier and then rerun over the same time period that was used to evaluate the existing system. The model grid for this scenario is shown in Figure IX-2.

An efficient way to assess the magnitude of change associated with the removing the barrier is to evaluate the change in flushing characteristics of the system. Mean volumes, tidal prisms and residence times are presented in Tables IX-1 and IX-2 for the simulation period. Comparing the tidal prisms and residence times with and without the barrier shows very minor differences, less than a half of percent of improvement in tidal prisms and flushing times. The minor improvements are not unexpected. The tidal constituent analysis in Table IX-1 revealed that the system had very minor attenuation through the barrier and into the upper reaches of the system. Therefore, only a minor improvement to the tidal propagation into the system will be achieved by removing the barrier.

While removal of the barrier does not lead to significant system-wide changes, it does have significant impacts on circulation in the vicinity of the barrier. For example, the area of the harbor along the northwest side of the barrier shows signs of diminished circulation currently. With the barrier removed, a significant improvement in the local tidal exchange is observed. Figures IX-3 through IX-8 illustrate the differences in flow with and without the barrier. The figures illustrate the variations in flow pathways which can result in potential water quality improvements that would otherwise not be realized by strictly examining tidal prisms and residence times.

Table IX-1. Embayment mean volumes and average tidal prism during simulation period for Scenario NB02 (hurricane barrier removed)

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
New Bedford Harbor (entire embayment)	608,514,944	189,108,626
Above Popes Island	207,345,624	92,815,067
Acushnet River	43,278,417	38,839,247

Table IX-2. Computed System and Local residence times for embayments in the Acushnet River system, for Scenario NB02 (hurricane barrier removed).

Embayment	System Residence Time (days)	Local Residence Time (days)
New Bedford Harbor (entire embayment)	1.673	1.673
Above Popes Island	3.409	1.162
Acushnet River	8.147	0.579

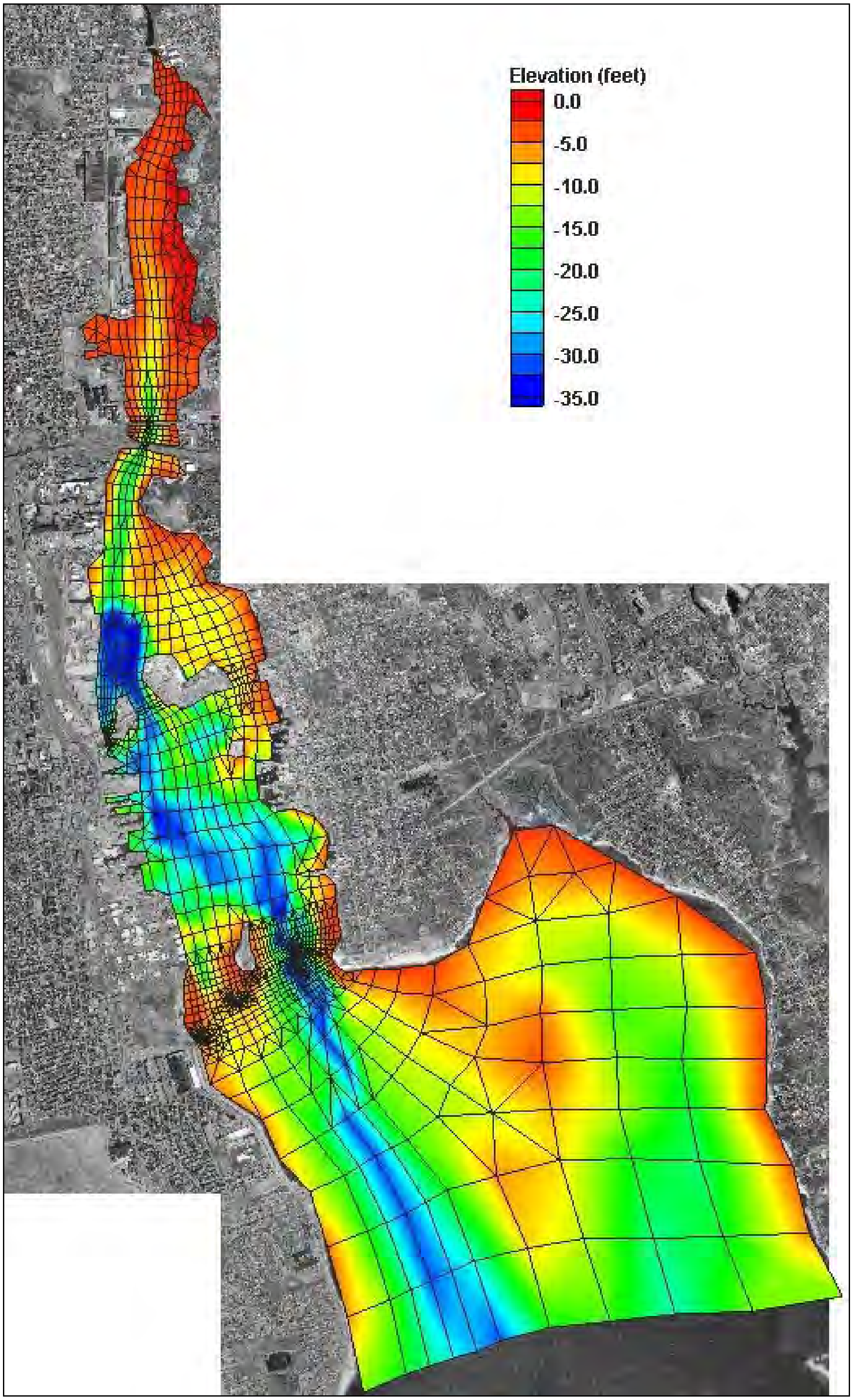


Figure IX-2. Hydrodynamic model grid for Scenario NB-02: Hurricane Barrier Removed.

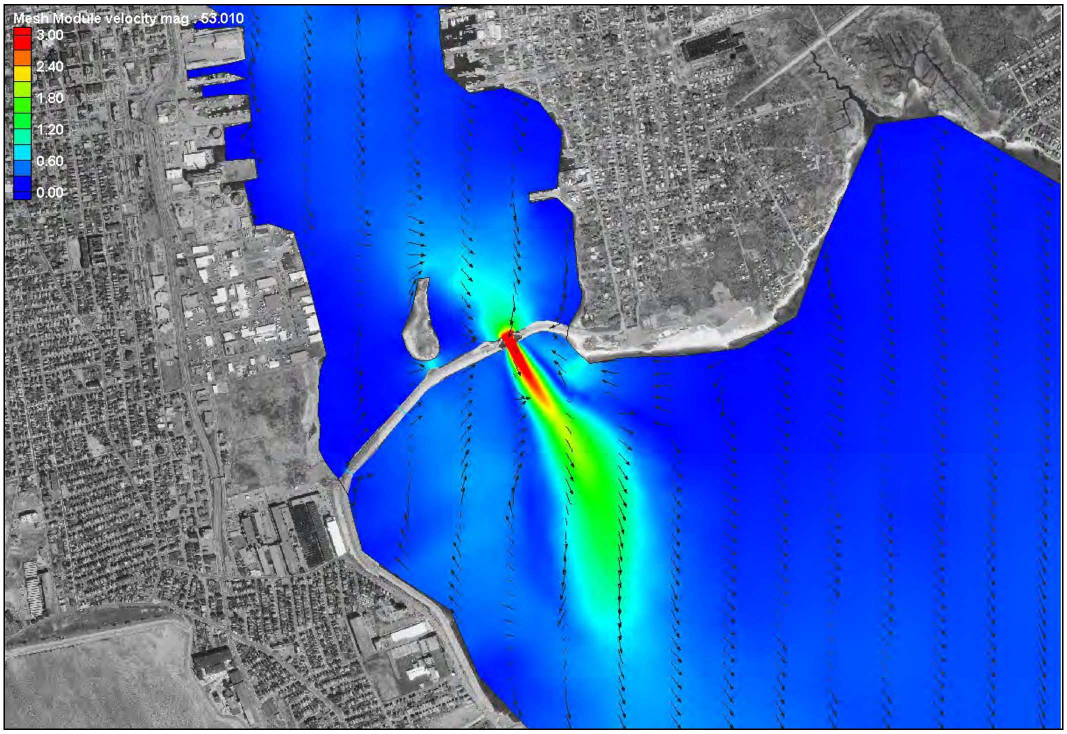


Figure IX-3. Example of hydrodynamic model output for a single time step where maximum ebb velocities occur for this tide cycle with the Hurricane Barrier. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

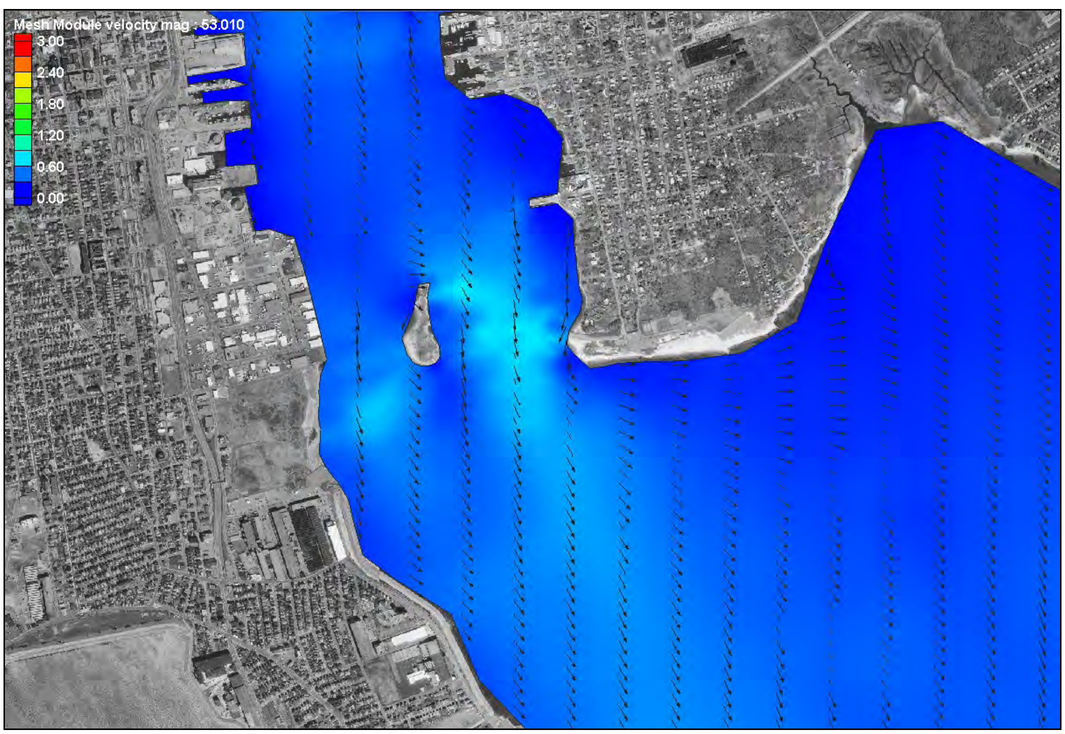


Figure IX-4. Example of hydrodynamic model output for a single time step where maximum ebb velocities occur for this tide cycle without the Hurricane Barrier. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

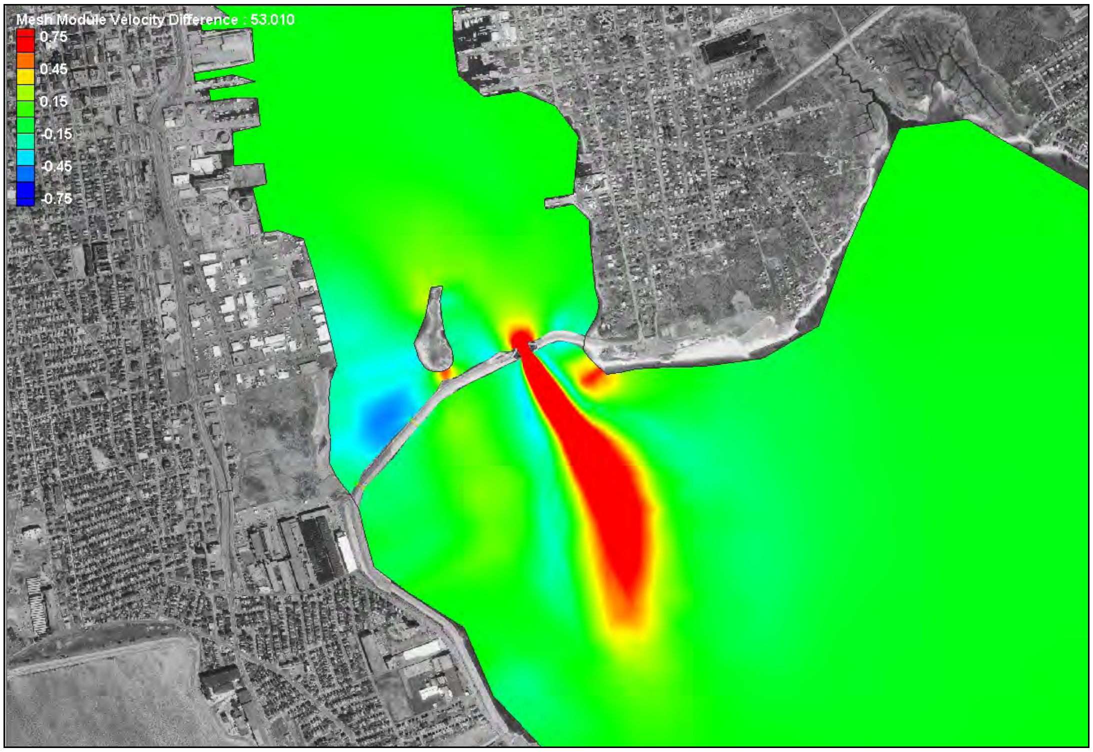


Figure IX-5. Difference in tidal ebb velocities with and with the Hurricane Barrier. Color contours indicate velocity change; reds are areas of increase and blues are areas decrease.

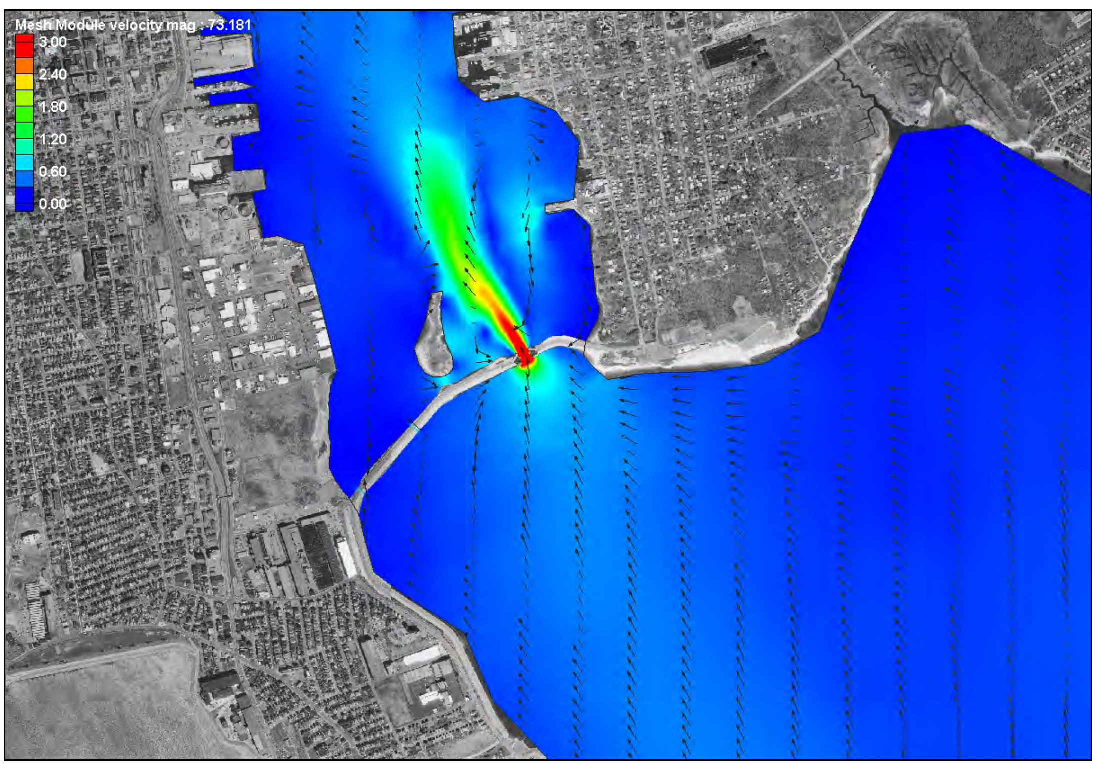


Figure IX-6. Example of hydrodynamic model output for a single time step where maximum flood velocities occur for this tide cycle with the Hurricane Barrier. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

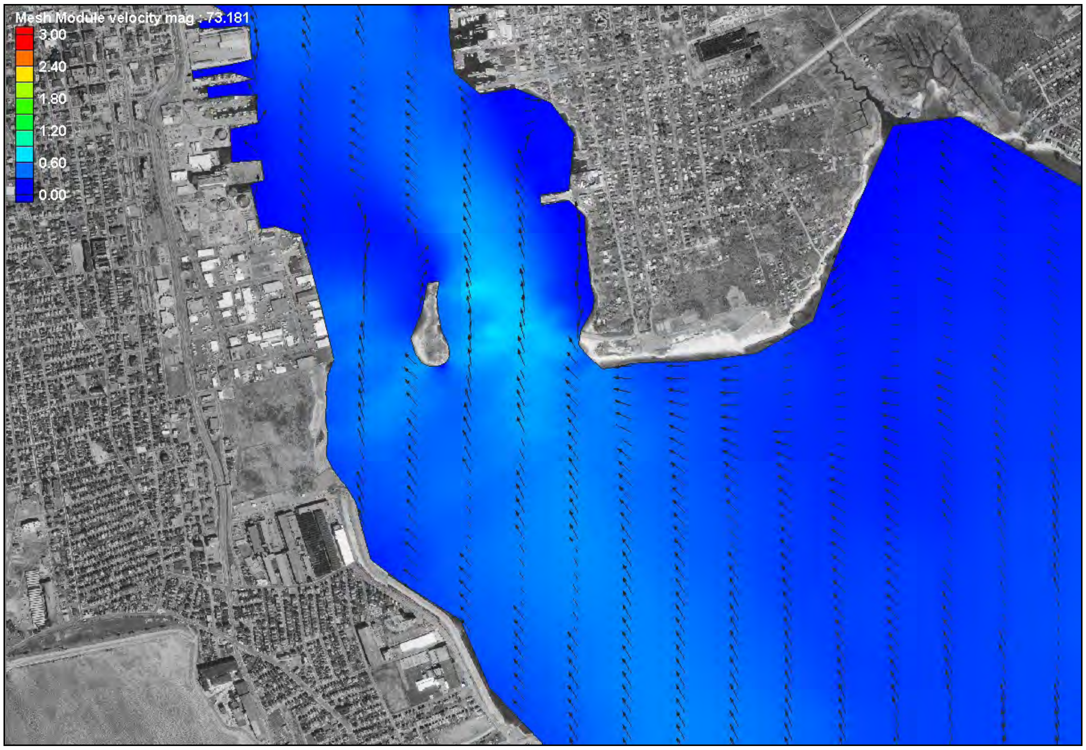


Figure IX-7. Example of hydrodynamic model output for a single time step where maximum flood velocities occur for this tide cycle without the Hurricane Barrier. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

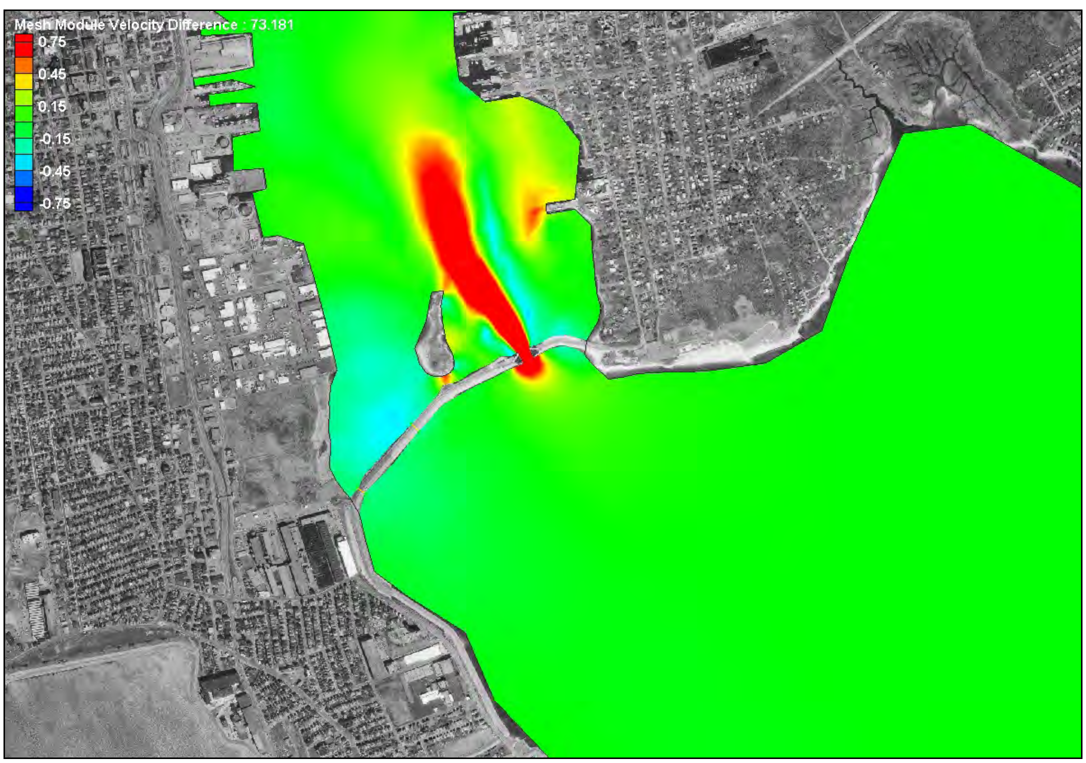


Figure IX-8. Difference in tidal flood velocities with and with the Hurricane Barrier. Color contours indicate velocity change; reds are areas of increase and blues are areas decrease.

Following modification of the hydrodynamic model, the simulation results from Scenario NB-02 were input into the RMA-4 water quality model with the other loading parameters described in Chapter VI. Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient.

For the water quality modeling of Scenario NB-02, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 7 tidal-day (174 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the New Bedford Harbor model.

To quantitatively evaluate changes to total nitrogen concentrations at various sites within the model domain, a number of locations were selected for water quality model output as shown in Figure IX-9. Locations preceded by MEP represent long-term nutrient monitoring stations within the harbor (described in Chapter VI). Locations designated by letters in the southwest portion of the inner harbor were selected for evaluation, since this area experiences the largest modeled reduction in overall total nitrogen concentrations.

Model output consisted of tidally averaged total nitrogen concentrations as shown in Figure IX-10. Differences in tidally-averaged total nitrogen concentrations between Scenario NB-02 and existing conditions are shown graphically in Figure IX-11. In addition, a quantitative assessment of water quality improvements for selected locations (Figure IX-9) is provided in Table IX-3. Overall, a minor improvement in total nitrogen concentrations would result from removal of the Hurricane Barrier. Due to the relative hydrodynamic efficiency of the Hurricane Barrier main channel, tidal attenuation across the barrier is minor. This lack of tidal attenuation indicates that the Hurricane Barrier does not cause large-scale degradation of inner harbor water quality. Model results indicate a marked improvement in the region southwest of Palmer Island, where total nitrogen reductions would be on the order of 4% or 0.2 mg/L.

Table IX-3. Comparison of model average total N concentrations from present conditions and **Scenario NB02** (complete removal of the hurricane barrier), with percent change, for the New Bedford Harbor system. The locations of stations A through E in the southwest lower basin are indicated in Figure IX-9.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	Scenario NB02 (mg/L)	% change
Estuary Upper Basin	2	0.754	0.756	0.3%
Coggeshall Bridge	3	0.621	0.621	0.1%
Popes Island East Bridge	6	0.505	0.503	-0.3%
Lower Basin (North)	7	0.496	0.495	-0.3%
Lower Basin (Mid)	8	0.485	0.482	-0.5%
Lower Basin South of FTP	12	0.474	0.471	-0.5%
Lower Basin-Inside Inlet	9	0.458	0.455	-0.7%
Southwest Lower Basin - A	-	0.473	0.452	-4.3%
Southwest Lower Basin - B	-	0.473	0.454	-4.1%
Southwest Lower Basin - C	-	0.473	0.455	-3.8%
Southwest Lower Basin - D	-	0.475	0.459	-3.2%
Southwest Lower Basin - E	-	0.475	0.462	-2.8%

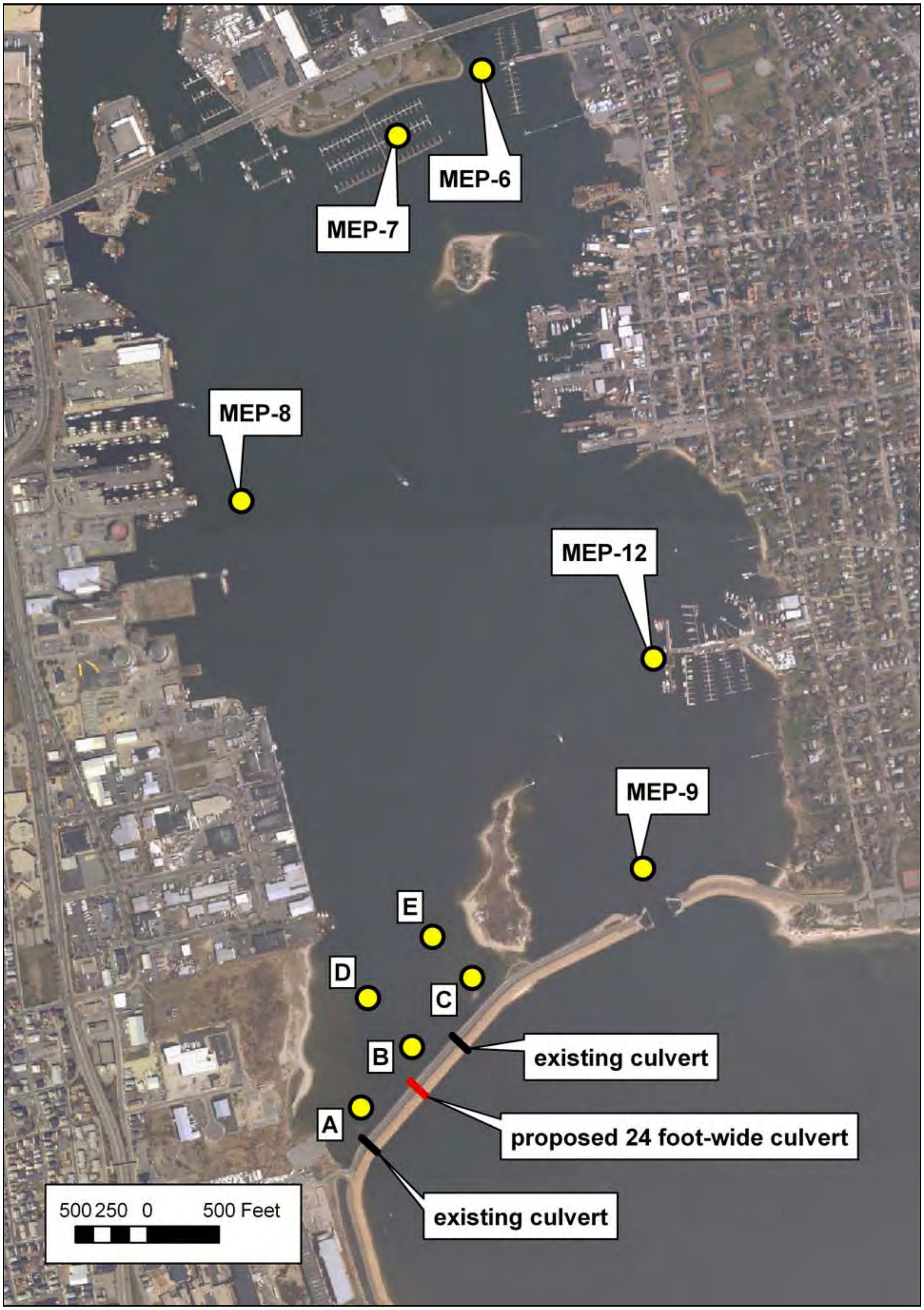


Figure IX-9. Map showing 1) water quality monitoring stations in the lower basin of New Bedford Harbor; 2) the locations of five stations (A though E) used in the comparison of present conditions and the modeled scenarios NB02 and NB03; and 3) the locations of the existing and proposed new culverts through the hurricane barrier.

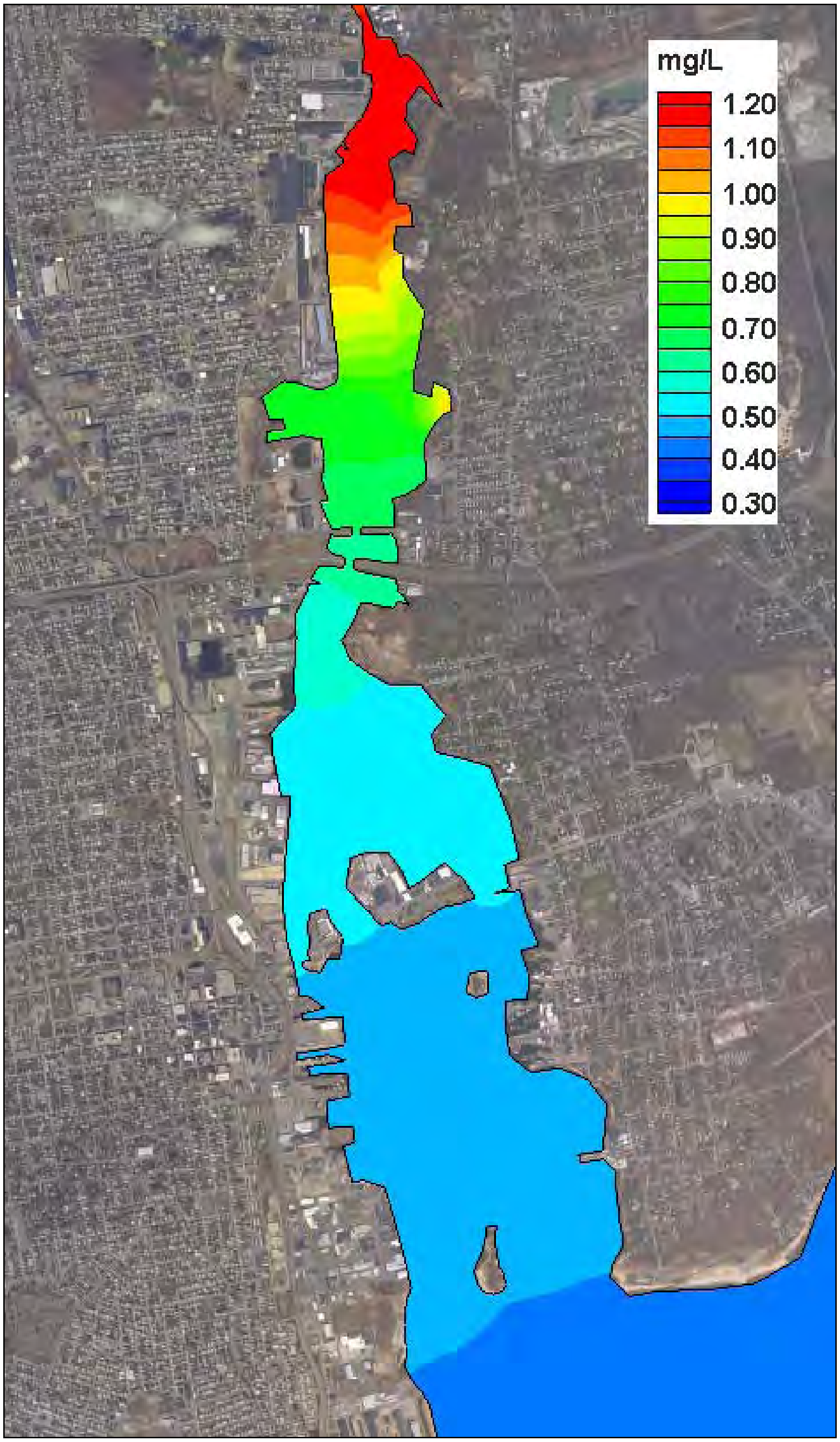


Figure IX-10. Contour plot of modeled total nitrogen concentrations (mg/L) in New Bedford Harbor, for scenario NB02 (complete removal of the hurricane barrier).

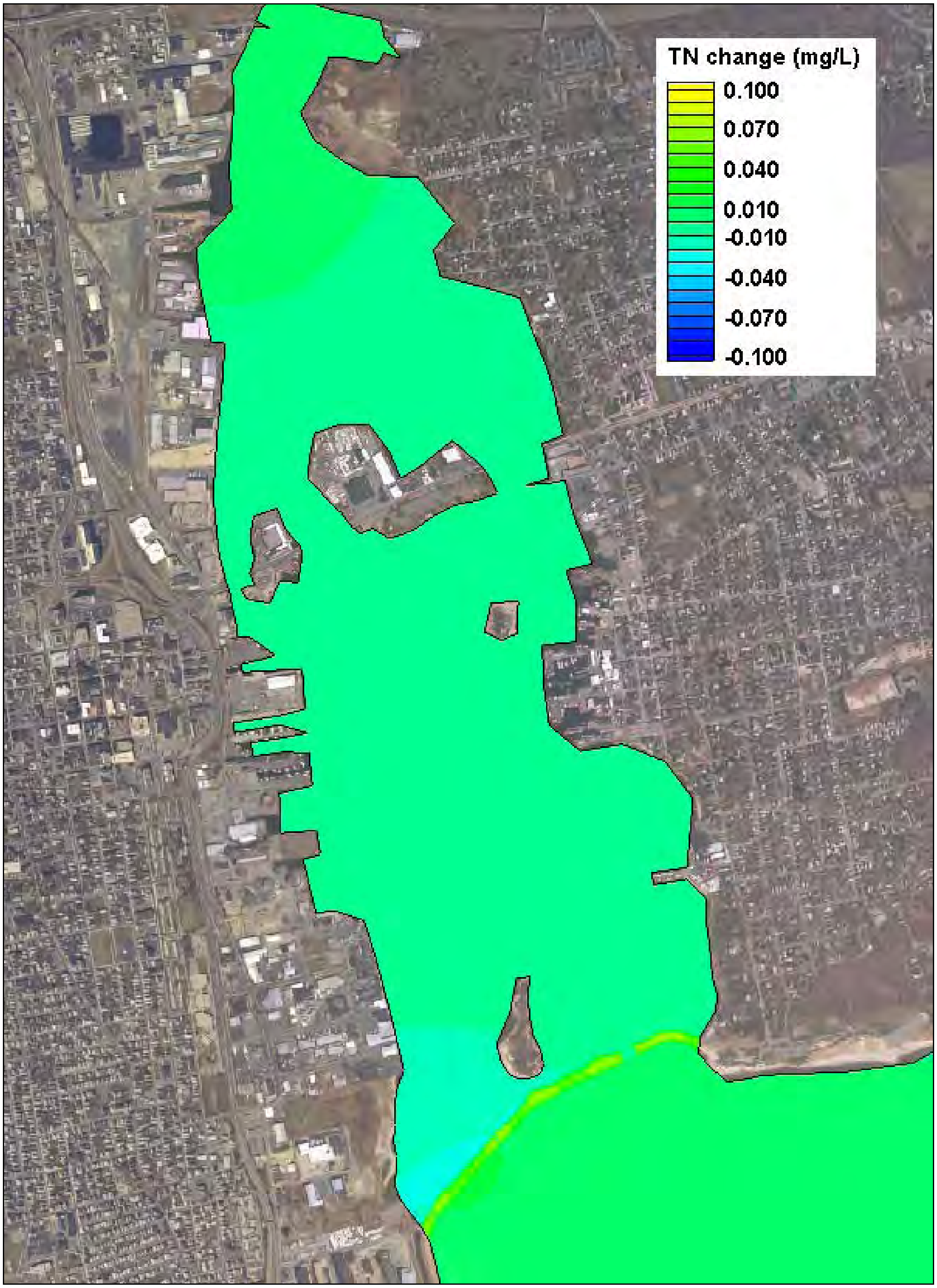


Figure IX-11. Contour plot of differences in modeled total nitrogen concentrations (mg/L) in New Bedford Harbor between scenario NB02 (complete removal of the hurricane barrier) and existing conditions. Negative values indicate a reduction in total nitrogen concentrations associated with Scenario NB-02 and vice versa.

Model Scenario NB-03

The first culvert alternative included a 24-ft wide structure placed between locations 5 and 6 (Figure IX-1) and set at the same elevation as the existing culverts through the Hurricane Barrier. To determine the circulation and water quality impacts this alternative has upon New Bedford Harbor, the hydraulic model was modified to add the 24-ft culvert and then rerun over the same time period that was used to evaluate the existing system. The relevant portion of the model grid for this scenario is shown in Figure IX-12.

To assess the magnitude of change associated with Scenario NB-03 an evaluation of the change in flushing characteristics of the system was performed. Mean volumes, tidal prisms and residence times are presented in Tables IX-4 and IX-5 for the simulation period. Comparing the tidal prisms and residence times with and without the 24-ft culvert shows negligible differences, less than 0.1% improvement in tidal prisms and flushing times.

Table IX-4. Embayment mean volumes and average tidal prism during simulation period for Scenario NB03 (new 24 foot-wide culvert through hurricane barrier)

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
New Bedford Harbor (entire embayment)	602,559,842	184,051,131
Above Popes Island	207,499,653	91,621,613
Acushnet River	43,306,975	38,319,754

Table IX-5. Computed System and Local residence times for embayments in the Acushnet River system, for Scenario NB03 (new 24 foot-wide culvert through hurricane barrier).

Embayment	System Residence Time (days)	Local Residence Time (days)
New Bedford Harbor (entire embayment)	1.702	1.702
Above Popes Island	3.420	1.178
Acushnet River	8.177	0.588

While addition of the 24-ft culvert does not lead to measurable system-wide changes, it does have impacts on circulation in the vicinity of the culvert. Specifically, the area immediately adjacent to the culvert experiences an increase in depth-averaged current speeds of over 0.2 feet per second (Figures IX-13 and IX-14), as a result of the proposed culvert.

Under existing hydrodynamic conditions, the region encompassed by Palmers Island, the Hurricane Barrier and the western shore of the Inner Harbor has slow tidal velocities, supportive of a depositional basin. Field data collected by scientists from the Coastal Systems Program at SMAST supports this analysis. Data collected indicates accumulations of fine-organic sediments in excess of 1 meter in some areas (Figure IX-15). These deposits show a high rate of accretion in this “basin”, since the pre-Hurricane Barrier (1963) sand surface can be found underlying the fine materials. These high deposition rates result in high rates of sediment oxygen demand, sulfidic sediments and poor infaunal habitat, as documented by the Massachusetts Estuaries Project studies. It is likely that a small increase in ambient current velocities may allow resuspension of this material and a restoration of the presently impaired habitat areas. However, a sediment toxics analysis would have to be performed to ensure that contaminated sediments would not be transported. In the latter case, a targeted dredging might be required.

Following modification of the hydrodynamic model, the simulation results from Scenario NB-03 were input into the RMA-4 water quality model with the other loading parameters described in Chapter VI. Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient.

For the water quality modeling of Scenario NB-03, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 7 tidal-day (174 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the New Bedford Harbor model.

To quantitatively evaluate changes to total nitrogen concentrations at various sites within the model domain, a number of locations were selected for water quality model output as shown in Figure IX-9. Locations preceded by MEP represent long-term nutrient monitoring stations within the harbor (described in Chapter VI). Locations designated by letters in the southwest portion of the inner harbor were selected for evaluation, since this area experiences the largest modeled reduction in overall total nitrogen concentrations.

Model output consisted of tidally averaged total nitrogen concentrations as shown in Figure IX-16. Differences in tidally-averaged total nitrogen concentrations between Scenario NB-03 and existing conditions are shown graphically in Figure IX-17. In addition, a quantitative assessment of water quality improvements for selected locations (Figure IX-9) is provided in Table IX-6.

As shown in Table IX-6, only a minor improvement in total nitrogen concentrations would result from installation of the 24-ft culvert, and this area would be limited to the region south of Popes Island. The region southwest of Palmer Island indicated the largest water quality improvement, where total nitrogen reductions were on the order of 1% or 0.06 mg/L.

In addition, small improvements in flushing created by the additional culvert may actually reduce water quality within the upper regions of the system. Based on the water quality model results, total nitrogen concentrations show a very slight increase (~0.5%) within the upper reaches of the estuary as a result of the 24-ft culvert. Since the existing configuration of the estuary creates relatively efficient flushing, the addition of the 24-ft culvert actually redirects a small portion of the incoming tidal flow into the basin to the southwest of Palmer Island. However, the slight change in tidal circulation and the shape of the tidal signal relative to existing conditions causes an increase in mean volume of the upper portions of the estuary, allowing total nitrogen levels within this region to increase between 0.002 and 0.004 mg/L (Table IX-6).

Although the construction of additional culverts through the Hurricane Barrier will have a minimal influence on total nitrogen concentrations, placement of these additional structures within the barrier west of the main channel may enhance re-suspension of fine-grained organic matter that has settled within the region southwest of Palmer Island. Based on observations made by SMAST biologists, the primary cause of benthic habitat degradation in this region is the nature of the bottom sediments, rather than high concentrations of nutrients in the water column. Therefore, there may be some merit in improving tidal circulation within this enclosed basin immediately north of the western segment of the Hurricane Barrier.

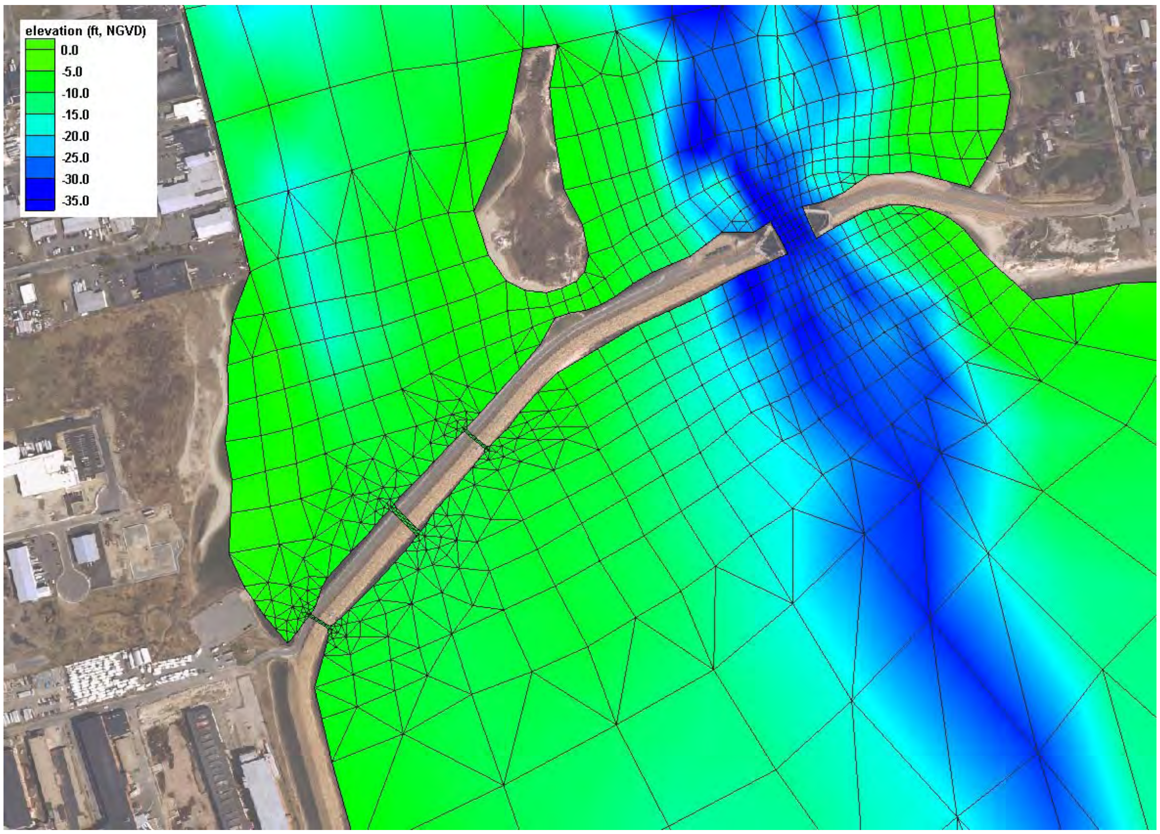


Figure IX-12. Relevant portion of hydrodynamic model grid for Scenario NB-02: 24-ft wide culvert between locations 5 and 6 (shown on Figure IX-1).

Figure IX-13. Difference plot of maximum flood tide velocity magnitudes between present conditions and scenario NB03. Positive values indicate increased velocities compared to present conditions.

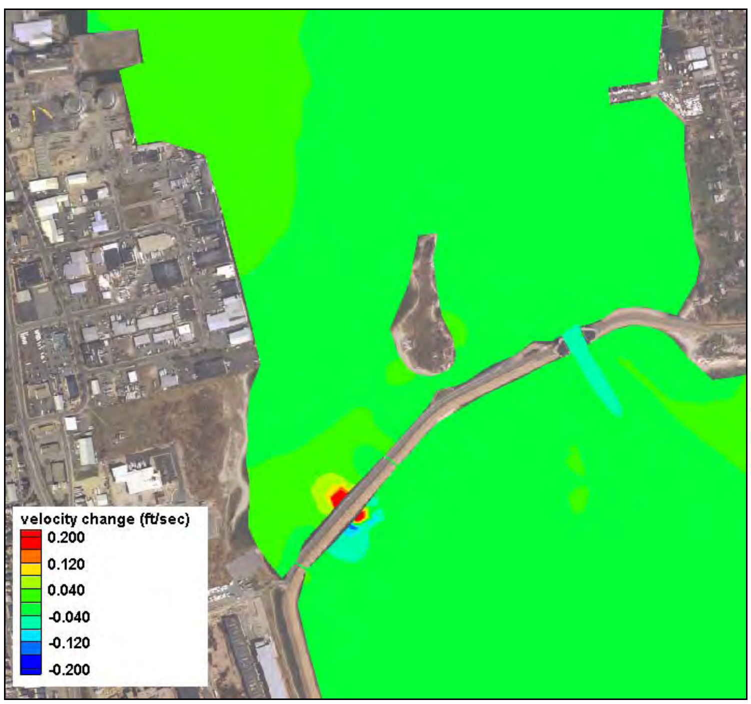


Figure IX-14. Difference plot of maximum ebb tide velocity magnitudes between present conditions and scenario NB03. Positive values indicate increased velocities compared to present conditions.

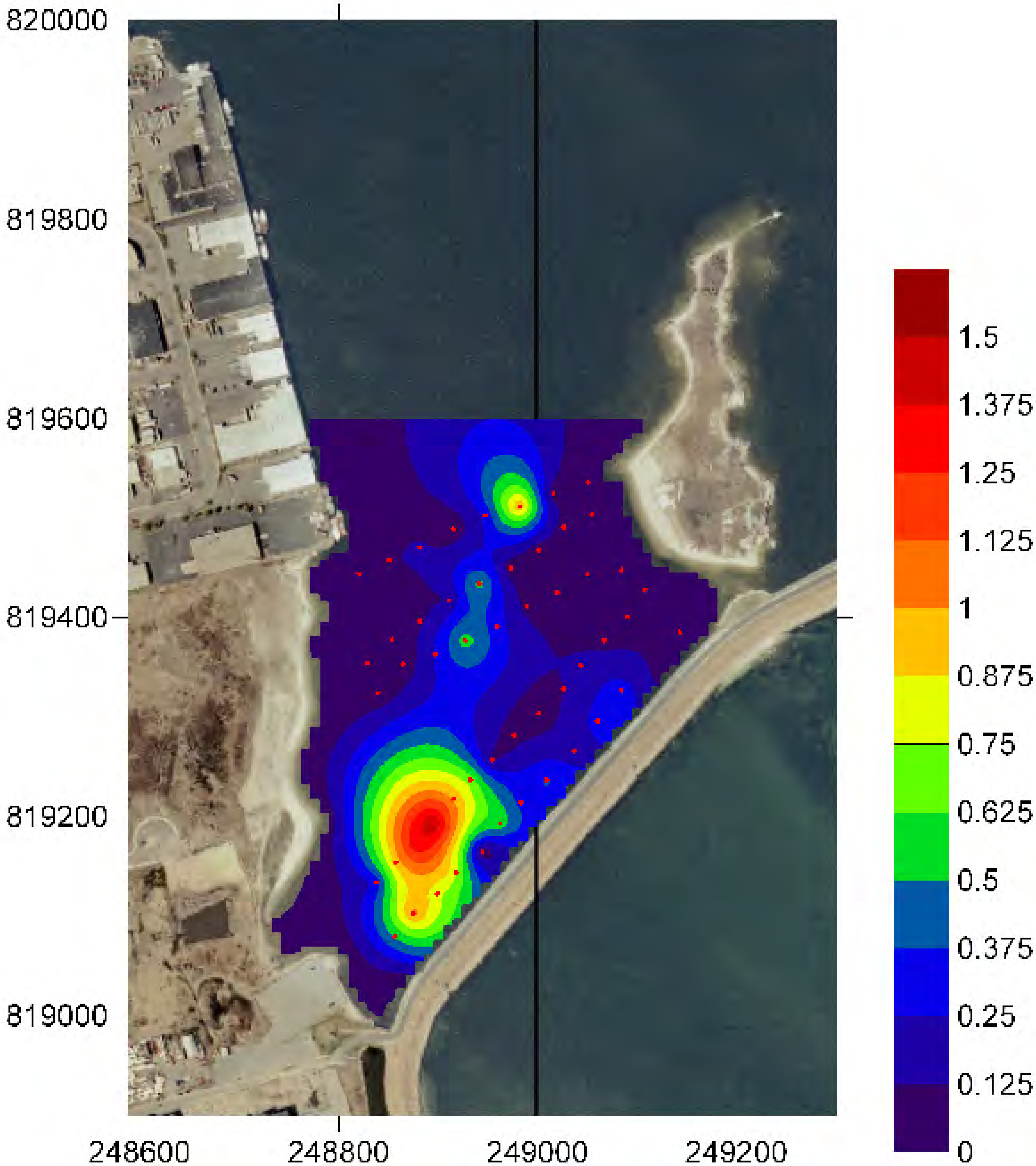


Figure IX-15. Thickness of fine-grained organic sediments within the region of Palmers Island, New Bedford Inner Harbor. Sediment thickness was measured at each of the red dots along each transect. Locations were determined by GPS, State Plane Coordinates NAD83. All of the accumulated fine sediments appears to have been deposited after the installation of the Hurricane Barrier.

Table IX-6. Comparison of model average total N concentrations from present conditions and **Scenario NB03** (new 24 foot-wide culvert at the mid-point between the two existing culverts), with percent change, for the New Bedford Harbor system. The locations of stations A through E in the southwest lower basin are indicated in Figure IX-9.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	Scenario NB03 (mg/L)	% change
Estuary Upper Basin	2	0.754	0.758	0.6%
Coggeshall Bridge	3	0.621	0.623	0.4%
Popes Island East Bridge	6	0.505	0.505	0.0%
Lower Basin (North)	7	0.496	0.496	-0.1%
Lower Basin (Mid)	8	0.485	0.484	-0.2%
Lower Basin South of FTP	12	0.474	0.472	-0.3%
Lower Basin-Inside Inlet	9	0.458	0.457	-0.2%
Southwest Lower Basin - A	-	0.473	0.467	-1.2%
Southwest Lower Basin - B	-	0.473	0.469	-0.9%
Southwest Lower Basin - C	-	0.473	0.470	-0.7%
Southwest Lower Basin - D	-	0.475	0.471	-0.7%
Southwest Lower Basin - E	-	0.475	0.472	-0.6%

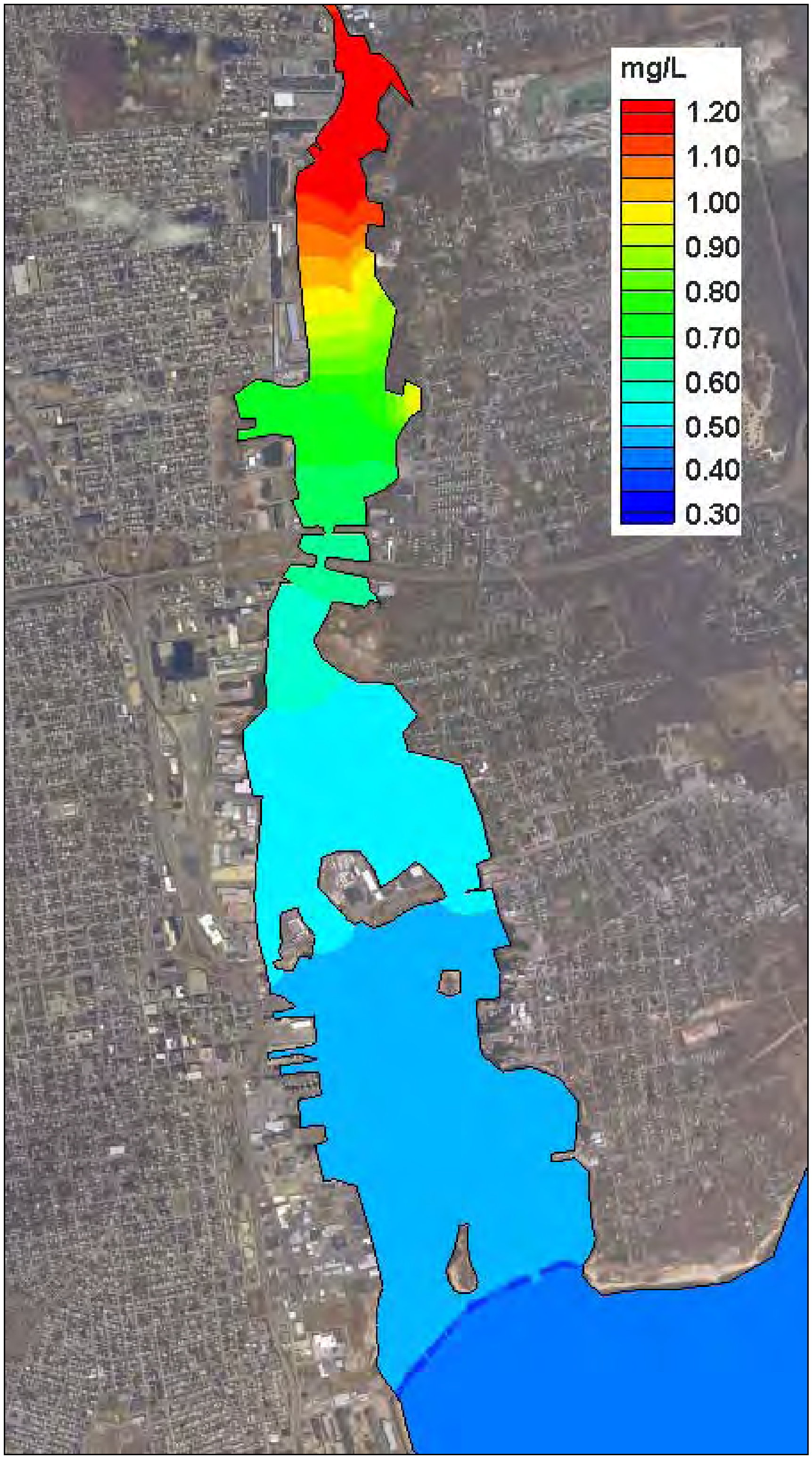


Figure IX-16. Contour plot of modeled total nitrogen concentrations (mg/L) in New Bedford Harbor, for Scenario NB03 (new 24-ft wide culvert through the hurricane barrier, as indicated in Figure IX-12).

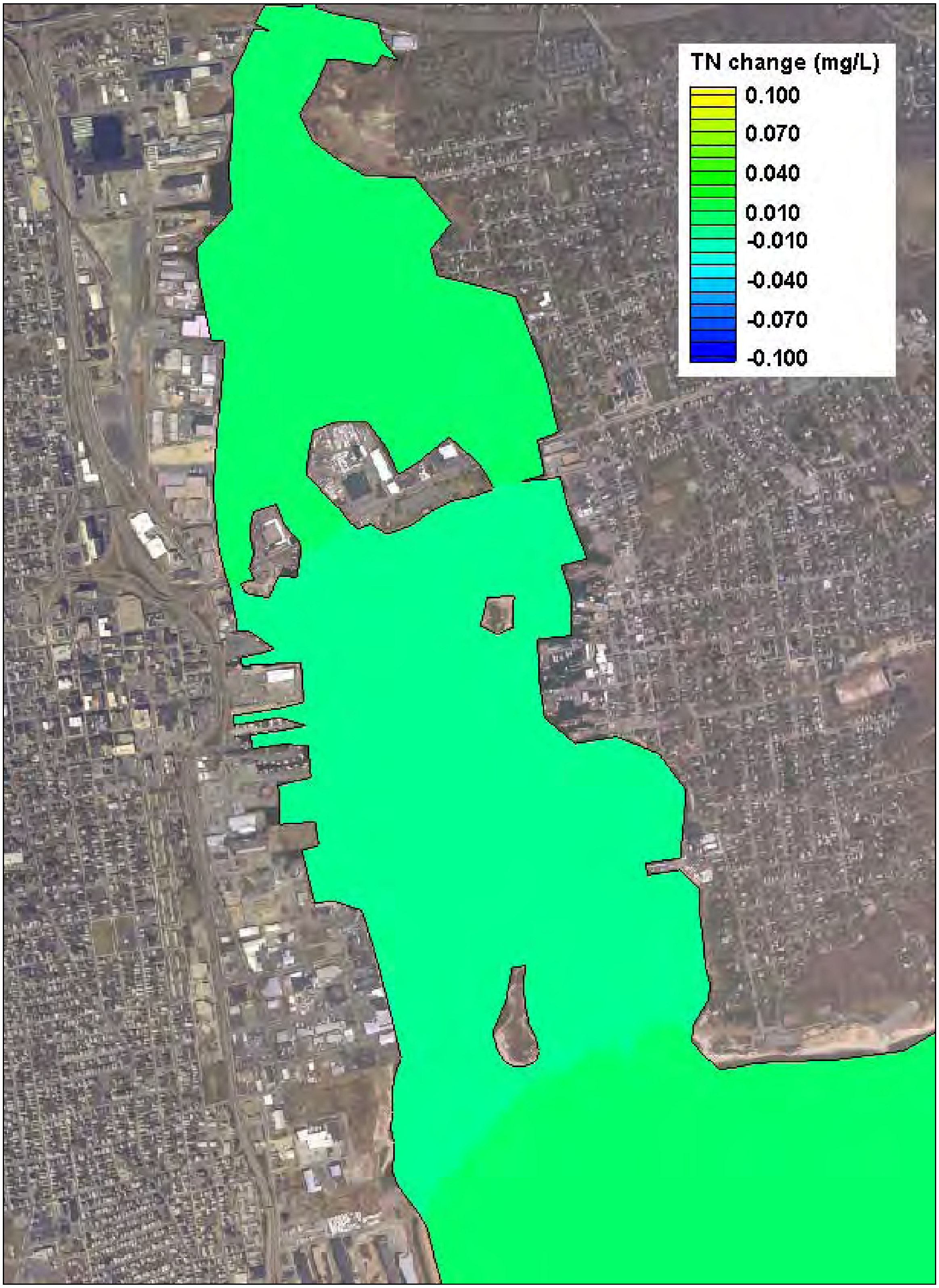


Figure IX-17. Contour plot of differences in modeled total nitrogen concentrations (mg/L) in New Bedford Harbor between scenario NB-03 (24-ft wide culvert through the hurricane barrier) and existing conditions. Negative values indicate a reduction in total nitrogen concentrations associated with Scenario NB-03 and vice versa.

IX.2 NITROGEN LOADING SCENARIOS

These scenarios were conducted under the 2008 Watershed N Loading assessment that has been updated with new information for the prior sections (I-VIII) of this report. The modest differences in the N loading used in the modeling in this Section (IX.2, below) in some cases affect the specific results. The scenarios in Section IX.2 relate to evaluating watershed N loading and therefore can be used only as guidance and background. They are only included to show relative effects of changing N loads to the New Bedford Inner Harbor Estuary and to provide historical background.

New Bedford Inner Harbor, as an urban estuary, has a greater variety of nitrogen sources that most other systems in s.e. Massachusetts where the land-use is predominantly single family residential housing. As a result, there are a greater variety of management scenarios that need to be assessed for th Inner Harbor, than for other embayments. To this end, the 2007 Draft MEP Nitrogen Threshold Report contained multiple land-use and 3 hydrodyanmic scenarios. While the Linked Watershed-Embayment model for this estuary is always available to evaluate additional nitrogen management scearios, it became clear during discussions with officials in Acushnet, Fairhaven and New Bedford, that an addtional scenario related to non-point sources would be beneficial at this time. The MEP Technical Team working with MassDEP developed 4 nitrogen source scenarios, of which 1 was presented in Section VIII.3 and 3 are evaluated here (Scenarios 1,3,4).

The prior scenarios assessed the impact of improvements to Combined Sewer Overflows (CSOs) and modification fo the Fairhaven wastewater treament facility outfall. The focus of the additional 3 scenarios is to evaluate nitrogen management alternatives involving primarily residential development in areas served by on-septic treatment of wastewater coupled to removal of CSOs. It must be stressed that these scenarios address specific municipal questions and are not presented as the recommended nitrogen management approach. Multiple nitrogen management options need to be evaluated in the formulation of any comprehensive planning effort, if it is to be effcient and if the plan is to be the most cost effective possible. The details of each nitrogen management alterantive are presented below:

Scenario 1 - Existing Conditions with:

(1) All existing and future lots in Fairhaven within the Harbor watershed with on-site septic treatment of wastewater connect to the Fairhaven WWTF, with treatment yielding an effluent averaging 3 ppm TN and discharge at current outfall;
(2) 186 residences in watershed #3 (primarily in Acushnet), 1500 of 1983 residences in watershed #2 and 400 of 780 residences in watershed #1 shifted from Septic Systems to New Bedford WWTF discharged at current outfall;
(3) Completion of planned removal of all CSOs discharging to Inner Harbor.

Scenario 3 - Build-Out Conditions with:

(1) All existing and future lots in Fairhaven within the Harbor watershed with on-site septic treatment of wastewater connect to the Fairhaven WWTF, with treatment yielding an effluent averaging 3 ppm TN and discharge at current outfall;
(2) CSOs discharging to Inner Harbor at planned 2030 level (same as targetted in the buildout scenario in the MEP Technical Report)

Scenario 4 - Build-Out Conditions with:

(1) All existing and future lots in Fairhaven within the Harbor watershed with on-site septic treatment of wastewater connect to the Fairhaven WWTF, with treatment yielding an effluent averaging 3 ppm TN and discharge at current outfall;
(2) 186 existing and all future residences in watershed #3 (primarily in Acushnet), 1500 of 1983 existing and all future (1207) residences in watershed #2 and 400 of 780 existing and all future (1224) residences in watershed #1 shifted from Septic Systems to New Bedford WWTF discharged at current outfall;
(3) Completion of planned removal of all CSOs discharging to Inner Harbor

The projected changes in the nitrogen load to the Inner Harbor associated with each of these scenarios was developed based on the 2008 watershed nitrogen module. These loads were then used to parameterize the calibarated and validated Linked Watershed-Embayment Model to determine water quality improvements associated with each management scenario. The N loads input into each scenario run (including watershed, atmospheric and benthic loading) are provided in Tables IX-7 through IX-9.

Tidally averaged TN concentrations taken from the output of the three TN model runs are provided in Tables IX-10 through IX-12 and Figures IX-18 through IX-20. From the tables, it can be seen that scenarios 1 and 4 both achieve TN concentraions that are lower than the threshold concentation of 0.50 mg/L at the sentinel station. Both of these scenarios show decreased TN concentations throughout the system, comparied to present conditions. Scenario 3 does not achieve the threashold, and has increased TN concentraitons in the Upper Basin station (MEP-2) compared to present condtions.

Table IX-7. **Scenario 1** sub-embayment loads (2008) used for total nitrogen modeling of the New Bedford Inner Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Basin	26.016	2.836	40.139
Mid Basin	10.433	3.614	-35.211
Lower Basin	48.414	7.011	14.886
Acushnet River – fresh water	61.471	-	-
System Total	146.334	13.460	19.814

Table IX-8. **Scenario 3** sub-embayment loads (2008) used for total nitrogen modeling of the New Bedford Inner Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Basin	44.110	2.836	50.864
Mid Basin	14.521	3.614	-42.079
Lower Basin	53.479	7.011	16.341
Acushnet River – fresh water	132.805	-	-
System Total	244.915	13.460	25.126

Table IX-9. **Scenario 4** sub-embayment loads (2008) used for total nitrogen modeling of the New Bedford Inner Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Upper Basin	19.784	2.836	40.849
Mid Basin	10.633	3.614	-35.647
Lower Basin	50.430	7.011	14.954
Acushnet River – fresh water	71.808	-	-
System Total	152.655	13.460	20.155

Table IX-10. Comparison of model average total N concentrations from present loading and loading **Scenario 1**, with percent change, for the New Bedford Inner Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold station is shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Upper Basin	2	0.754	0.577	-23.5%
Coggeshall Bridge	3	0.621	0.505	-18.6%
Popes Island East Bridge	6	0.505	0.443	-12.2%
Lower Basin (North)	7	0.496	0.439	-11.6%
Lower Basin (Mid)	8	0.485	0.433	-10.7%
Low Basin South of FTP	12	0.474	0.427	-9.8%
Low Basin-Inside Inlet	9	0.458	0.420	-8.3%
Upper 1/3 of mid Basin	**-**	**0.555**	0.470	-15.3%

Table IX-11. Comparison of model average total N concentrations from present loading and loading **Scenario 3**, with percent change, for the New Bedford Inner Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold station is shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Upper Basin	2	0.754	0.796	5.5%
Coggeshall Bridge	3	0.621	0.624	0.5%
Popes Island East Bridge	6	0.505	0.490	-2.9%
Lower Basin (North)	7	0.496	0.481	-3.1%
Lower Basin (Mid)	8	0.485	0.468	-3.4%
Low Basin South of FTP	12	0.474	0.457	-3.6%
Low Basin-Inside Inlet	9	0.458	0.445	-2.9%
Upper 1/3 of mid Basin	**-**	**0.555**	0.549	-1.1%

Table IX-12. Comparison of model average total N concentrations from present loading and loading **Scenario 4**, with percent change, for the New Bedford Inner Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold station is shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Upper Basin	2	0.754	0.592	-21.4%
Coggeshall Bridge	3	0.621	0.513	-17.4%
Popes Island East Bridge	6	0.505	0.446	-11.7%
Lower Basin (North)	7	0.496	0.441	-11.1%
Lower Basin (Mid)	8	0.485	0.435	-10.2%
Low Basin South of FTP	12	0.474	0.429	-9.4%
Low Basin-Inside Inlet	9	0.458	0.422	-7.9%
Upper 1/3 of mid Basin	**-**	**0.555**	0.475	-14.4%

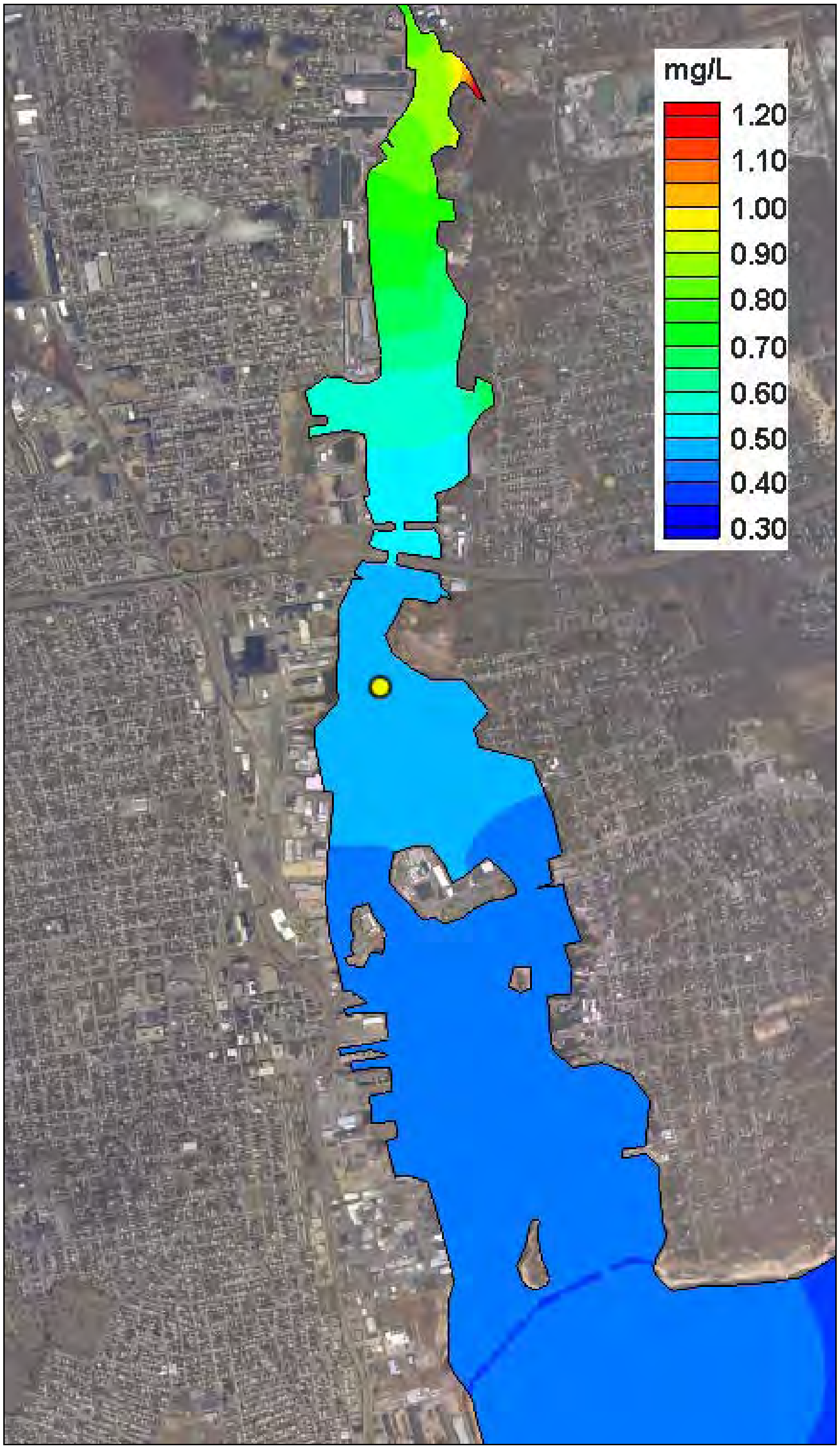


Figure IX-18. Contour plot of modeled total nitrogen concentrations (mg/L) in the New Bedford Inner Harbor Estuary, for **Scenario 1** loading conditions. The threshold (sentinel) station is indicated on the plot by the yellow circle marker.

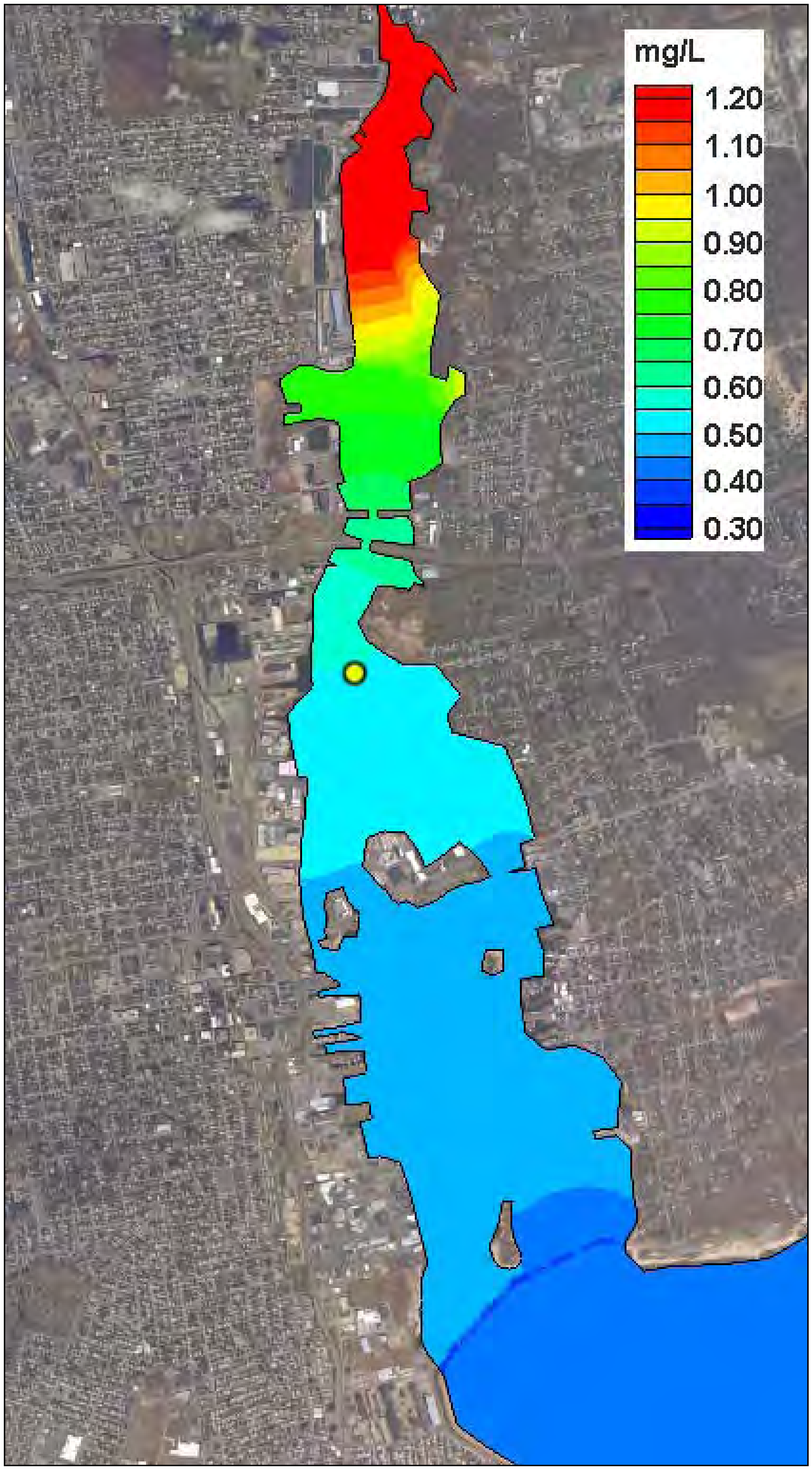


Figure IX-19. Contour plot of modeled total nitrogen concentrations (mg/L) in the New Bedford Inner Harbor Estuary, for **Scenario 3** loading conditions. The threshold (sentinel) station is indicated on the plot by the yellow circle marker.

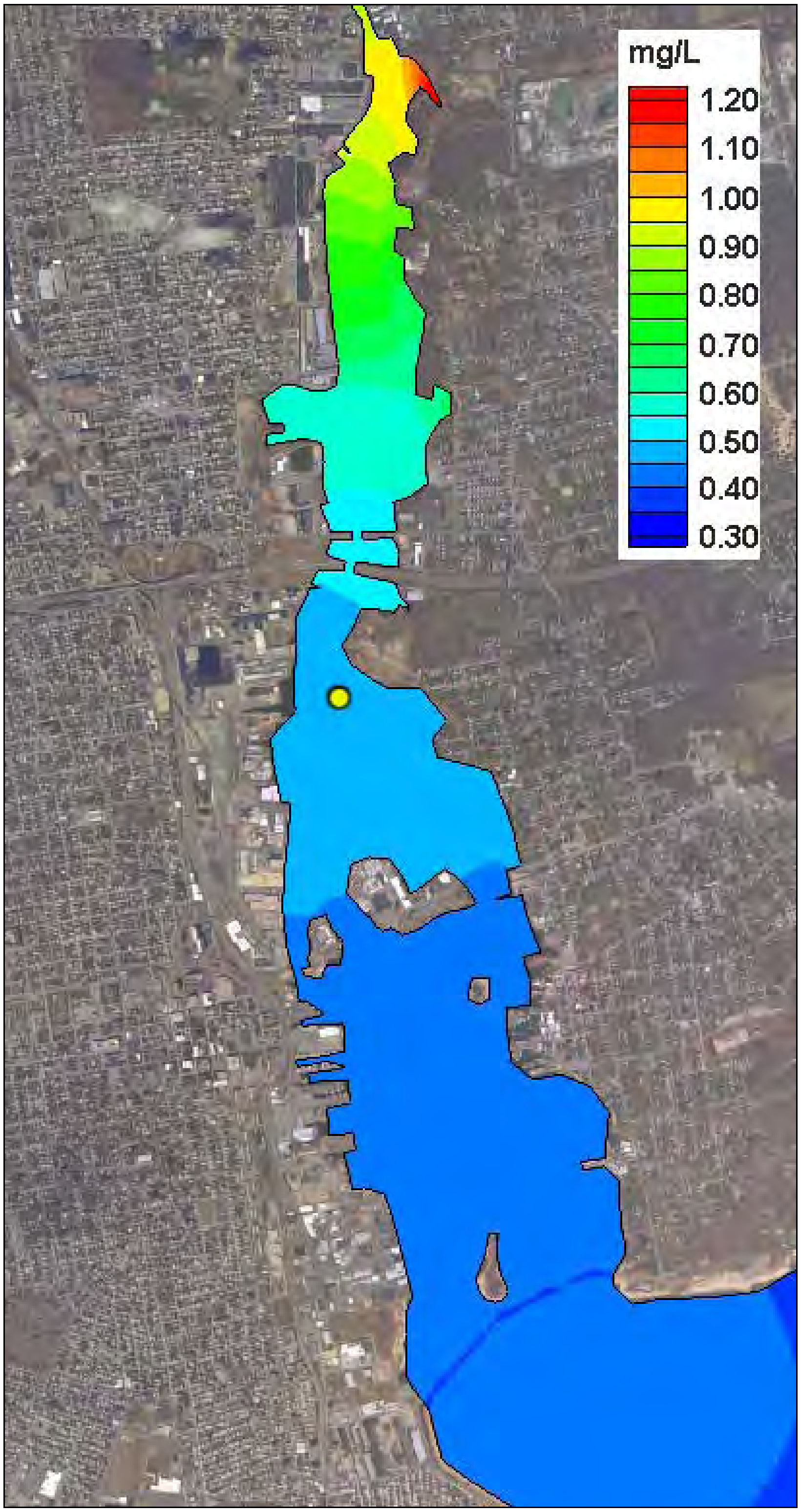


Figure IX-20. Contour plot of modeled total nitrogen concentrations (mg/L) in the New Bedford Inner Harbor Estuary, for **Scenario 4** loading conditions. The threshold (sentinel) station is indicated on the plot by the yellow circle marker.

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