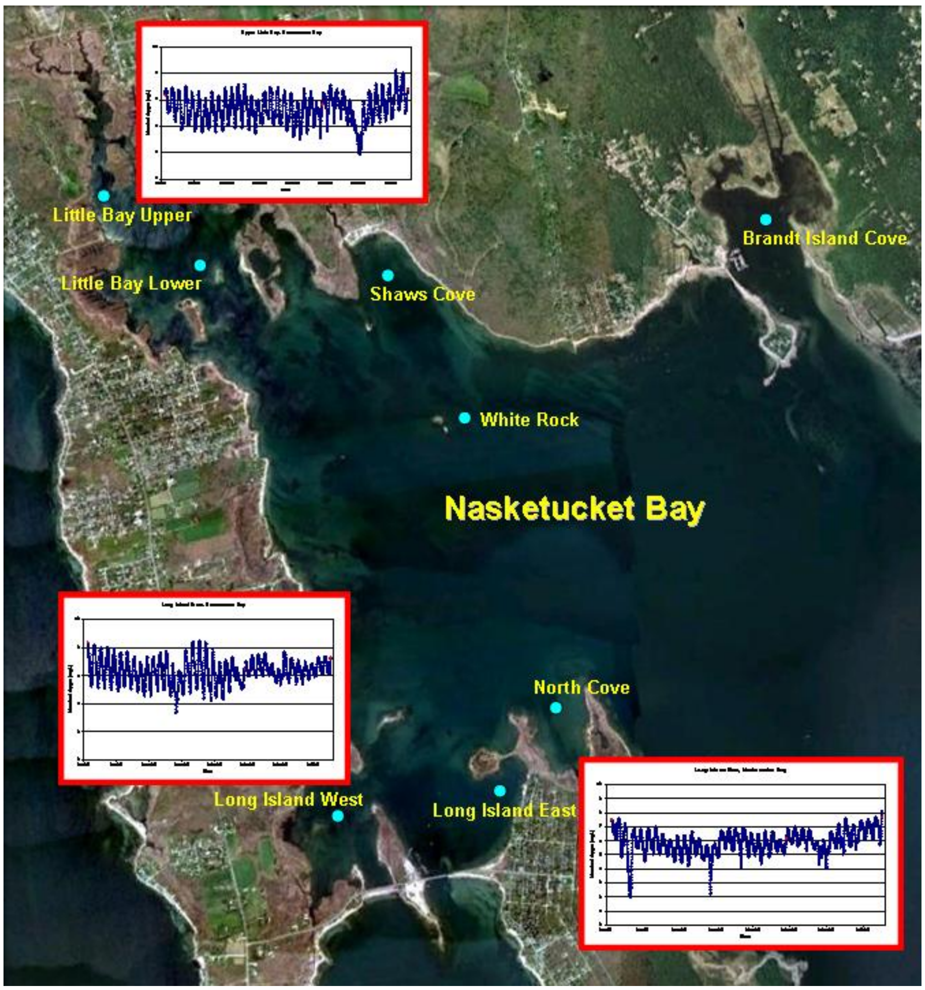
Massachusetts Estuaries Project

Linked Watershed-Embayment Approach to Determine Critical Nitrogen Loading Thresholds for the Nasketucket Bay Embayment System
Town of Fairhaven, Massachusetts



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Massachusetts Department of
Environmental Protection

REVISED FINAL REPORT – JULY 2013

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Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Nasketucket Bay Embayment System, Fairhaven, Massachusetts

Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Nasketucket River embayment system, a coastal embayment primarily within the Town of Fairhaven, Massachusetts but whose watershed is also shared with the Town of Mattapoisett. Analyses of the Nasketucket Bay embayment system was performed to assist the Town of Fairhaven with up-coming nitrogen management decisions associated with the current and future wastewater planning efforts of the Town, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and harbor maintenance programs. 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 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 Nasketucket Bay 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 Town) for the restoration of the Nasketucket Bay embayment system.

Wastewater Planning: 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. residential and agricultural 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 Nasketucket Bay embayment system within the Town of Fairhaven is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to this coastal system as well as ongoing agricultural activity. 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 Town of Fairhaven has recognized the severity of the problem of eutrophication and the need for targeted watershed nutrient management with an initial focus on the largest sources on nitrogen load to the Nasketucket Bay estuary. The MEP analysis of the Nasketucket Bay system is yielding results which can be utilized by the Town of Fairhaven to guide the development of a cost effective nutrient load reduction approach and will assist the Town of Fairhaven as it moves forward in implementing a unified approach to nutrient management in the Nasketucket Bay estuary. The Town of Fairhaven with associated working groups has recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Towns across southeastern Massachusetts. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict and evaluate the impacts on water quality from a variety of proposed management scenarios.

Nitrogen Loading Thresholds and Watershed Nitrogen Management: 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.

Massachusetts Estuaries Project Approach: The Massachusetts Department of Environmental Protection (DEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) and the Martha's Vineyard Commission (MVC) 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: The Linked Model was applied to the Nasketucket Bay embayment system by using site-specific data collected by the MEP and water quality data collected by the Buzzards Bay Coalition (CBB) BayWatchers Program (assisted technically until 2008 by the University of Massachusetts-SMAST Coastal Systems Program, see Section II). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Fairhaven Planning Department. Watershed boundaries for the Nasketucket Bay system were delineated by the USGS. This land-use data was used to determine watershed nitrogen loads within the Nasketucket Bay embayment system and the systems sub-embayments as appropriate (current and build-out loads are summarized in Table IV-3). 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 Nasketucket Bay embayment system given the vigorous mixing in the open water portion of the system adjacent Buzzards Bay as well as the shallow waters of the upper portion of the system and associated with the mouth of the Nasketucket River. 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 Nasketucket Bay 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 Section VIII-2 were used to determine, as necessary, the amount of total nitrogen mass loading reduction required for protection/restoration of eelgrass and infaunal habitats in the Nasketucket Bay embayment system. Typically, tidally averaged total nitrogen thresholds derived in Section VIII.1 are used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads are usually sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for a given system. In the Nasketucket Bay system, to maintain the threshold nitrogen concentration at the sentinel station, no reduction in load is required. By holding the present loading conditions within the system, the current eelgrass habitat and infaunal animal habitat can be maintained throughout the estuary.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction (as necessary) guidelines for nitrogen management of the Nasketucket Bay embayment system in the Town of Fairhaven. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Nasketucket Bay embayment system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. At present the Nasketucket Bay system is supporting and maintaining eelgrass habitat along the shallow margins of the bay. The system does not exhibit the normal impairments that result from watershed nitrogen inputs exceeding the nitrogen tolerance of the system, thus resulting in the loss of historical eelgrass beds and stress to infaunal communities. Nasketucket Bay is presently supporting and maintaining the historical eelgrass habitat around the bay. The Bay is presently receiving watershed nitrogen inputs below or at its tolerance level with the result that some additional nitrogen loading can occur before habitat impairment occurs. The Nasketucket Bay / Little Bay Estuary has reached its ability to assimilate nitrogen without impairment and is showing a low level of nitrogen enrichment in some basins, with indications of incipient impairment primarily associated with bottom water oxygen levels, elevated chlorophyll-*a* and infaunal habitats (Table VIII-1), indicating that nitrogen management of this system will be primarily focused on maintenance of an unimpaired system. Preventing additional nitrogen loading as watershed build-out is approached is the prudent course for a system that has reached its assimilative capacity for nitrogen.

Similar to other embayments in southeastern Massachusetts, the Nasketucket Bay / Little Bay Estuary evaluated in this MEP assessment showed high frequency variation related primarily 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. Oxygen excursions result from oxygen consumption (night) and production (day) primarily by phytoplankton within the estuarine waters. Additional oxygen uptake results from the microbial decay of organic matter, which in the case of Little Bay and specific portions of Nasketucket Bay is mainly from phytoplankton and eelgrass respiration and phytoplankton settling to bottom sediments.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 37-44 day deployment period that these parameters were below or above various benchmark concentrations. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels throughout the Nasketucket Bay / Little Bay Estuary indicates low to moderate levels of nutrient enrichment and generally moderate-high habitat quality, with the greatest depletions in the basins with highest nitrogen and chlorophyll-a levels in the upper portions of the system (e.g. Little Bay). The oxygen data is consistent with the organic matter loads from phytoplankton production (chlorophyll-a levels) indicative of the level of nitrogen enrichment within and estuary. Significantly elevated oxygen was not observed in any of the time-series oxygen records within this estuary, further evidence that while some oxygen depletion is occurring, the system is not significantly impaired.

Generally, the dissolved oxygen records throughout the Nasketucket Bay / Little Bay Estuary showed moderate depletions of oxygen (relative to the basin type) during the critical summer period. The greatest oxygen depletions were generally associated with the upper portions of the Little Bay system within the salt marshes at the mouth of the Nasketucket River. The D.O. record at this location shows oxygen depletion (below 5.0 mg/L) during 1/3 of the summer record with periodic depletions below 4.0 mg/L, consistent with its nitrogen and organic matter rich waters. However, it is important to note that a portion of this enrichment stems from the role of the Nasketucket River marshes and transport of high nutrient, high phytoplankton, low oxygen waters to the head of Little Bay on the ebbing tide. The lower portion of Little Bay as well as Shaws Cove shows lower levels and frequency of oxygen depletion (96% of record >4 mg L^{-1}) as well as moderate chlorophyll levels (average ~9 ug/L). The high turnover of water in the Nasketucket Bay portion of the overall estuarine system, that is closest to the low nutrient waters of Buzzards Bay, reduces that basin's ability to build up nutrients.

Overall, the distribution and temporal stability of eelgrass within Nasketucket Bay and its relationship to nitrogen and chlorophyll-*a* levels is consistent with other estuaries of similar configuration in Buzzards Bay and southeastern Massachusetts. The moderate watershed nitrogen loading coupled with the rate of tidal flushing and the tide range appears to be maintaining the system at a level that is supportive of eelgrass habitat not impaired by nitrogen enrichment at the present time. However, there is some indication that the system is at or very close to its nitrogen threshold so that maintenance of present conditions should be the focus of future MassDEP TMDL analysis.

The historical distribution of eelgrass within the Nasketucket Bay / Little Bay Estuary is consistent with both the natural history of eelgrass and the present nitrogen, oxygen and chlorophyll levels within the different component basins. The absence of eelgrass within Little Bay (present and historically) is consistent with the chlorophyll levels (9-10 ug/L) and tidally averaged TN levels of 0.415 - 0.391 mg N L^{-1} for upper and mid bay, respectively and 0.391 - 0.373 mg N L^{-1} for the mid to outer bay region. In contrast, the main eastern basin of Nasketucket Bay has lower chlorophyll levels (<5 ug L^{-1}) and TN levels (<0.368 mg N L^{-1}) and these areas currently support eelgrass beds. These latter watercolumn values are similar to other estuarine basins that are currently supportive of eelgrass at similar depths (Phinneys Harbor, West Falmouth Harbor, Quissett Harbor (0.35 mg L^{-1}) and shallow systems, Three Bays, Popponesset Bay, Lewis Bay (0.38 mg L^{-1}).

Benthic infaunal communities throughout the main basins of Nasketucket Bay were indicative of productive high quality benthic habitat in a low to moderately nitrogen enriched coastal areas. This is characterization of the infaunal community is consistent with the stable eelgrass coverage in this basin and the generally low chlorophyll-*a* levels (~5 ug/L) as well as limited periodic oxygen depletion events. Equally significant is the only rare occurrence of opportunistic organic matter or stress tolerant species, typical of nitrogen enriched areas in southeastern Massachusetts estuaries. Integrating the watercolumn, sediment and community indicators provides a clear assessment of Nasketucket Bay as supporting generally high quality benthic infaunal habitat, consistent with its significant eelgrass coverage.

Benthic infaunal communities within each of the major tributary basins to Nasketucket Bay (Little Bay-Shaws Cove-Brant Island Cove) are also generally supporting high quality habitat for their specific conditions. Shaws Cove, at the entrance to Little Bay, is a small cove with a tidal marsh and stream dominating its innermost reach. Assessment of the benthic community in the upper region did not reveal impairment, but rather a relatively high number of species and number of individuals with moderate diversity and Evenness. The community was dominated by polychaetes and crustaceans with some mollusks and few organic enrichment indicator species, consistent with the presence of adjacent salt marsh. Little Bay is the largest of the tributary basins to Nasketucket Bay and receives over 40% of the total watershed nitrogen input to the entire Nasketucket Bay / Little Bay Estuarine System. It also has the Nasketucket River within its upper reach, which supports significant salt marsh. In addition, as Little Bay has not historically supported eelgrass coverage, its key habitat for management is associated with benthic infauna. It was clear that within the tidal channel of the mouth of the Nasketucket River and its tidal wetlands, that a different benthic habitat was present, as seen in the dominance of organisms typical of salt marshes on Cape Cod, and the habitat was not impaired. Overall, Little Bay appears to be presently supporting moderate to high quality benthic habitat. However, the appearance (although few patches only) of stress indicator species at some sites (e.g. capitellids) and dominance of polychaetes at others coupled with the periodic oxygen depletions to <4 mg L^{-1}, suggest that Little Bay is near or at its habitat threshold related to nitrogen enrichment. By comparison, Shaws Cove and Brants Island Cove have typical chlorophyll levels $\leq$5 ug L^{-1} and less frequent and less intense periods of oxygen depletion. Nitrogen management within the Nasketucket Bay / Little Bay Estuary should therefore focus on maintenance of existing habitats, but should target Little Bay as the most sensitive to additional watershed nitrogen loading. It appears from integration of the nitrogen related habitat indicators that Little Bay infauna, and by extension the eelgrass beds at the margin of Little and Nasketucket Bays, should be the primary focus for nitrogen management within this estuary. Preventing decline in these habitats will also maintain conditions throughout much of the rest of the estuary.

3. Conclusions of the Analysis

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 maintain SA waters or high habitat quality. In this system, high habitat quality was defined as supportive of eelgrass and supportive of diverse benthic animal communities. Dissolved oxygen and chlorophyll-*a* were also considered in the assessment. Watershed nitrogen loads for the Town of Fairhaven Nasketucket Bay embayment system was comprised primarily of agricultural and wastewater nitrogen (54% and 22% respectively). A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of embayment specific nutrient analyses undertaken by the MEP in over 50 estuarine systems across southeastern Massachusetts (inclusive of nearby Westport River Estuary, Slocums River and Little River, New Bedford Harbor and Wareham River). This is almost certainly going to be true for the other embayments within the MEP area, as well, the Nasketucket Bay estuary system.

The threshold nitrogen levels for the Nasketucket Bay embayment system in the Town of Fairhaven were determined as follows:

Nasketucket Bay Threshold Nitrogen Concentrations

- Following the MEP protocol, the protection/restoration target for the Nasketucket Bay system should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Section VII), the Nasketucket Bay system is presently supportive of habitat in varying states of health/impairment, depending on the component sub-basins of the overall system but overall is only showing signs of moderate to low impairment.

- The tidally averaged TN level at the location of the sentinel station within the inner edge of the stable beds at the margin of Little and Nasketucket Bays is 0.368 mg L^{-1}, the highest TN level associated with eelgrass within this estuary. From the site specific analysis of the Nasketucket Bay / Little Bay Estuary and comparison to other similar systems throughout southeastern Massachusetts, it appears that the TN threshold to maintain stable eelgrass habitat in the Nasketucket Bay / Little Bay Estuary is 0.37 mg L^{-1}.

- Comparison of model results between existing loading conditions and the selected loading scenario to maintain the target TN concentrations at the sentinel station indicate that the system is very close to its assimilative capacity and only slight increases in nitrogen loading from the watershed to the estuary are need to exceed the threshold for the system. To maintain the threshold nitrogen concentration at the sentinel station, no reduction in load is required. By holding the present loading conditions within the system, the current eelgrass habitat and infaunal animal habitat can be maintained throughout the estuary.

- 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.

It is important to note that the analysis of future nitrogen loading to the Nasketucket Bay estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Nasketucket Bay estuarine system is that protection/restoration will necessitate maintaining future nitrogen loadings at present levels and management options are must be put in place o negate additional future nitrogen inputs.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Nasketucket Bay estuary system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

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. (mg/L)
SYSTEMS										
Little Bay	0.929	3.153	0.645	--	3.798	3.364	31.980	39.142	0.33-1.16	0.368
Shaw's Cove	0.104	0.515	0.165	--	0.680	0.356	5.938	6.974	--	--
Eastern Nasketucket Bay Watersheds	1.788	3.107	3.113	--	6.220	19.279	66.195	91.694	--	--
Brandt Island Cove	0.951	1.139	0.502	--	1.641	1.997	10.850	14.488	0.29-0.51	--
Western Nasketucket Bay Watersheds	1.864	8.578	0.612	--	9.190	21.016	-73.249	-43.043	0.30-0.45	--
West Island Outer Bay	0.512	1.419	0.666	--	2.085	0.408	-7.667	-5.174	--	--
Surface Water Sources										
Nasketucket Main and West Rivers	4.712	13.151	2.789	--	15.940	-	-	15.94	--	--
Nasketucket East River	0.074	0.638	0.249		0.887	-	-	0.887	--	--
Nonquitt Brook	0.285	1.279	0.803	--	2.082	-	-	2.082	--	--
Shaw's Cove Brook East and West	0.784	6.956	0.153	--	7.109	-	-	7.109	--	--
System Total	**12.003**	**39.935**	**9.697**	--	**49.632**	**46.42**	**34.047**	**130.099**	**0.29-1.16**	**0.370[8]**

[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 wastewater treatment facility discharges to groundwater
[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 1997 – 2011 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. Individual yearly means and standard deviations in Table VI-1.
[8] Threshold for sentinel site located in Nasketucket Bay is located along the stable eelgrass beds eelgrass at the margins of Little Bay and Nasketucket Bay.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Nasketucket Bay estuary system, Town of Fairhaven, Massachusetts.

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
SYSTEMS						
Little Bay	3.798	3.798	3.364	31.980	39.142	+0.0%
Shaw's Cove	0.680	0.680	0.356	5.938	6.974	+0.0%
Eastern Nasketucket Bay Watersheds	6.220	6.220	19.279	66.195	91.694	+0.0%
Brandt Island Cove	1.641	1.641	1.997	10.850	14.488	+0.0%
Western Nasketucket Bay Watersheds	9.190	9.190	21.016	-73.249	-43.043	+0.0%
West Island Outer Bay	2.085	2.085	0.408	-7.667	-5.174	+0.0%
Surface Water Sources						
Nasketucket Main and West Rivers	15.940	15.940	-	-	15.94	+0.0%
Nasketucket East River	0.887	0.887	-	-	0.887	+0.0%
Nonquitt Brook	2.082	2.082	-	-	2.082	+0.0%
Shaw's Cove Brook East and West	7.109	7.109	-	-	7.109	+0.0%
System Total	**49.632**	**49.632**	**46.42**	**34.047**	**130.099**	**0.00%**

(1) Composed of combined natural background, fertilizer, runoff, 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.

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I. INTRODUCTION

The Nasketucket Bay Estuarine System (inclusive of Nasketucket River and Little Bay) is located primarily within the Town of Fairhaven and to a lesser extent the Town of Mattapoisett to the east, in the region referred to as southeastern Massachusetts. The estuary is bounded to the west by a peninsula known as Sconticut Neck and to the south by a causeway that leads from Sconticut Neck to West Island which directs the flow of water from the western side of Nasketucket Bay to Buzzards Bay (Figure I-1). Of the 5 towns comprising the watershed to the Nasketucket Bay Estuarine System, the predominant area of the embayment surface and its watershed fall within the Town of Fairhaven. Nasketucket Bay, which exists along the northwestern shore of Buzzards Bay, has remained relatively unaltered structurally (with the exception of the causeway from Sconticut Neck to West Island. This is in stark contrast to the adjacent Acushnet River Estuary and associated harbor of New Bedford, located immediately to the west of Sconticut Neck, which is the major port within southeastern Massachusetts and has a long history as an active commercial seaport. As such, the latter estuary has been significantly altered by dredging, filling of wetlands and construction of piers and bulkheads to support marine industries. In contrast, Nasketucket Bay and Little Bay retain much of their natural salt marsh habitat and much of the Nasketucket River and Little Bay will continue to support high quality marine resources as long as nutrient related water quality is maintained.

The Nasketucket River flowing seaward from the Towns of Acushnet and Rochester comprising the upper portions of the Nasketucket Bay watershed, is the major surface water discharge to the headwaters of Little Bay, which is the main mixing zone for freshwater from Nasketucket River and marine waters of Nasketucket Bay. Small amounts of freshwater also flow to Nasketucket Bay via two small streams, one of which discharges to the eastern shore of Little Bay and the other which discharges to Shaws Cove. Together, the tidally influenced lower reach of the Nasketucket River, Little Bay, Nasketucket Bay and the associated small coves form a complex coastal marine environment that supports numerous natural, social, cultural, and economic resources of the region. There have been concerns that in the absence of comprehensive management, the system may suffer as development in the watershed to Nasketucket Bay continues to increase. However, at present it appears that there are no significant impairments to this system given the limited study that it has received prior to the present MEP effort.

The Nasketucket Bay Estuary is situated within the Buzzards Bay Basin. The Buzzards Bay Basin 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 tributary embayment system of Nasketucket Bay and Little Bay 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.

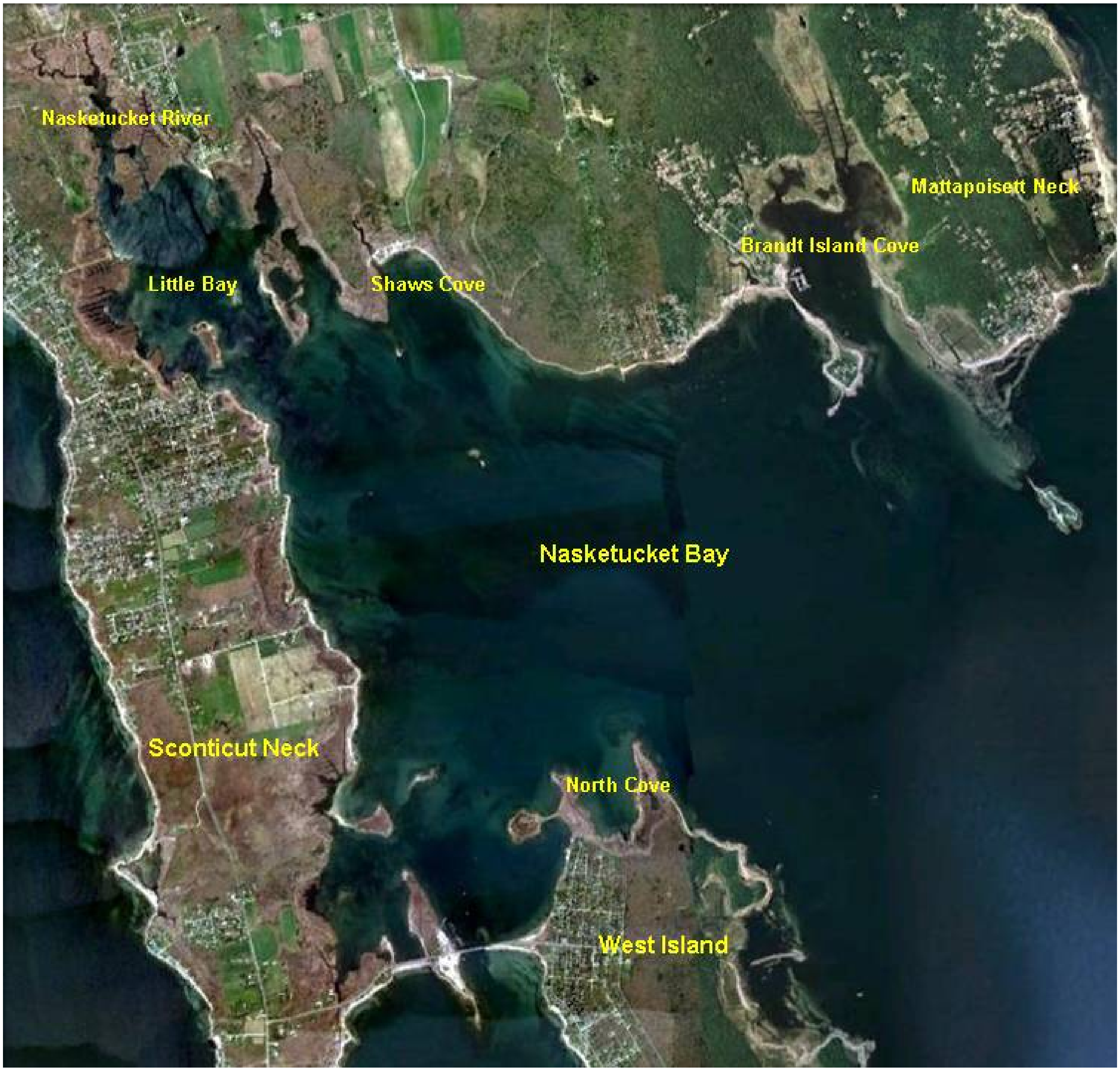


Figure I-1. Nasketucket Bay/Little Bay Estuarine System and its major coastal features for the Massachusetts Estuaries Project assessment and threshold analysis. Tidal waters from Buzzards Bay are directly connected to Nasketucket Bay and Little Bay from the south passing through the causeway that connects West Island to Sconticut Neck Road and east via the large passage between West Island and Mattapoisett Neck. Freshwater enters the estuary from the watershed primarily through the Nasketucket River (up-gradient of the bike path), small streams discharging to Knollmere (adjacent Little Bay) and Shaws Cove and via direct groundwater discharge.

The watershed to the Nasketucket Bay 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 some areas are 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 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 Nasketucket Bay, 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 lower portions of the Nasketucket River and Nasketucket Bay / Little Bay 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 Nasketucket River and the small streams such as the one that discharges to Shaws Cove. Stratified drift deposits can range from 0 to 200 feet bls.

The varying surficial deposits lead to variation in the 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 to be relatively uniform 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 Nasketucket/Little Bay Estuary watershed of 27.25 inches, as estimated by the US Geological Survey.

The Nasketucket Bay / Little Bay Estuarine System is a shallow mesotrophic (moderately nutrient enriched) coastal system. For the MEP analysis, the inner-most portion of this system (Little Bay) was analyzed as the focal point for watershed nutrient inputs which move through tidal flows to the much larger more open-water basin of Nasketucket Bay. Similar to other embayments in the region (e.g. Westport River, Acushnet River, West Falmouth Harbor and others), Nasketucket Bay has focused freshwater input to its major sub-basins (Little Bay, Shaws Cove). The nitrogen related habitat quality throughout Nasketucket/Little Bay Estuarine System is tightly coupled to exchange of tidal waters with the high quality waters of Buzzards Bay, due to its average tide range of about 5 ft and lack of significant restrictions to tidal flow. Since changes in water elevation (tide range in offshore basin) 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). While watershed nitrogen inputs are critical to potential impairment of coastal systems, in the case of the Nasketucket/Little Bay basins, the large open water areas and flushing with low nitrogen waters of Buzzards Bay has been the dominant factor maintaining the quality of the estuary's aquatic resources.

The Nasketucket Bay / Little Bay system is a true estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from Buzzards Bay. Salinity in the system ranges from approximately 31 ppt. in the outer basins of Nasketucket Bay around West Island to 29 ppt in Little Bay and 23 at the mouth of the Nasketucket River in Little Bay (just seaward of the bike path).

Although hydrodynamic characteristics of the Nasketucket Bay / Little Bay embayment system are currently maintaining habitat quality throughout this estuary, changes in quality depends on the level of nutrient loading from the watershed. Both aspects are analyzed as part of the MEP Approach.

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 Nasketucket Bay embayment system, because of their shallow nature and large shoreline area, are generally the first indicators of nutrient pollution from terrestrial sources. Unlike many other embayments in southeastern Massachusetts and on Cape Cod, the Nasketucket Bay / Little Bay Estuarine System does not presently exhibit eutrophic conditions or significant impairment to habitat quality (relative to dissolved oxygen, chlorophyll, eelgrass loss, macroalgal presence, infaunal species) as a result of nitrogen enrichment. This likely results, in part, from the sewering within the watershed with export of wastewater for treatment and discharge outside of the watershed (e.g. Arcene Street WWTF with discharge to Inner New Bedford Harbor). In addition, West Island, which would typically have wastewater treated by residential on-site septic systems, has significant sewering with treatment by a small treatment facility on the island, with discharge via a network of infiltration wells that recharge the coastal groundwater aquifer that flows to the salt marshes on the eastern shore of the island adjacent to the open waters of Buzzards Bay.

The Town of Fairhaven, as the primary stakeholder to the Nasketucket / Little Bay Estuarine System, has been concerned over the quality of this focal coastal resource. The community has worked to sewer critical areas of the town such as Sconticut Neck and West Island and the Town of Fairhaven has supported the Buzzards Bay Coalition's Water Quality Monitoring Program which has been collecting data on nitrogen related water quality within the Nasketucket / Little Bay System since 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data for this system. 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 provided by the Coastal Systems Program at SMAST-UMD until 2008. The common focus of the Buzzards Bay Coalition 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 Nasketucket Bay System by providing quantitative restoration targets for nitrogen for on-going efforts by the Town of Fairhaven.

In conjunction with 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. The critical nitrogen targets and the link to watershed nitrogen loads and 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 Town of Fairhaven, as well as the Towns of Mattapoisett and Acushnet. 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 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 Fairhaven) 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.

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 70 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. 55 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

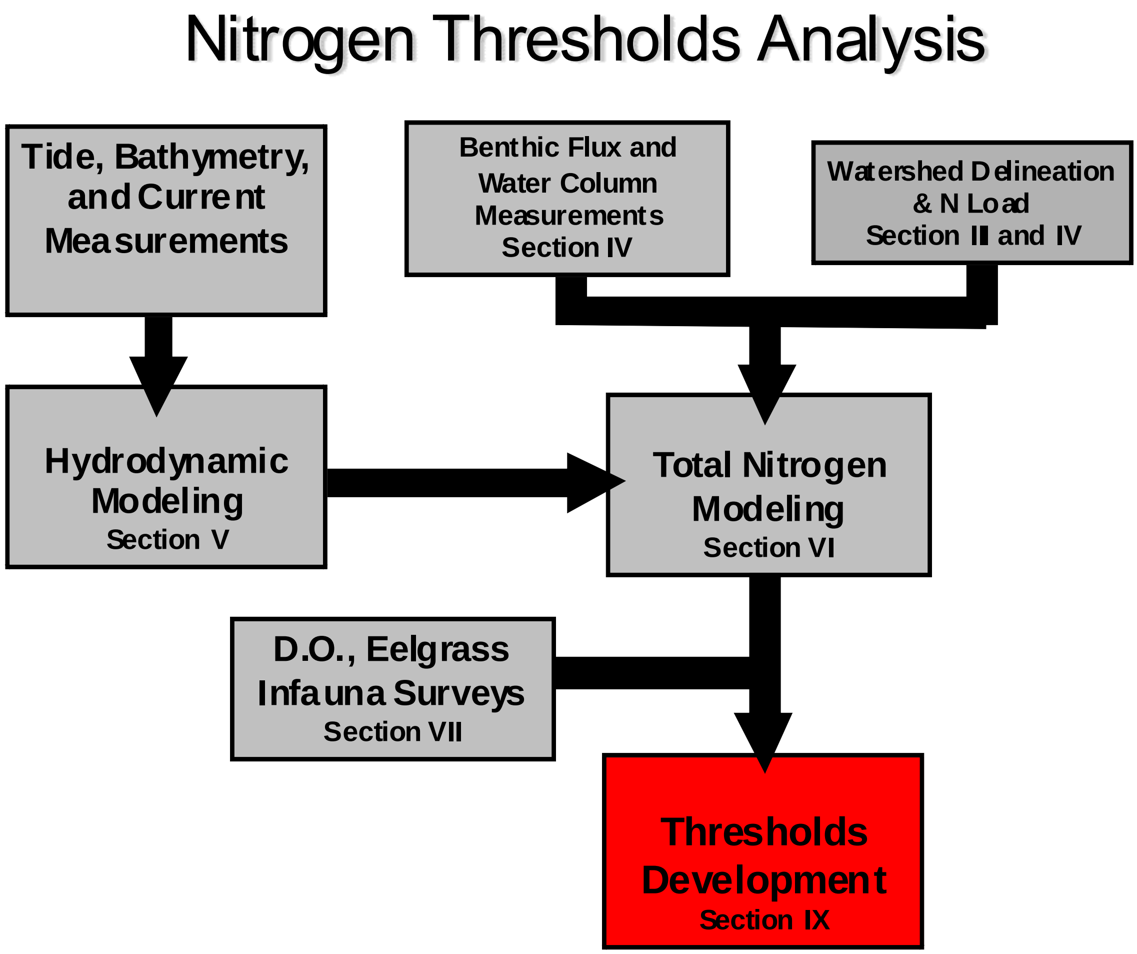


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

I.2 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 Nasketucket Bay embayment system and others in the region, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (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 Nasketucket / Little Bay Estuarine System follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen (Redfield N/P ratio <7, where $\geq$16 suggests nitrogen is not the nutrient to manage).

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 Nasketucket Bay / Little Bay Estuary 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 overall Nasketucket Bay Estuary, the upper most basin (Little Bay inclusive of the estuarine reach of the Nasketucket River) appears to be at the limit of its ability to assimilate additional nutrients without impacting ecological health. This suggests that continuing build-out of the Little Bay sub-watershed will result in nitrogen related impacts to this basin. In contrast, Nasketucket Bay currently supports low nutrient levels, clear waters, and low rates of organic matter deposition and extensive eelgrass beds. A prior preliminary analysis of watershed build-out for this system by the Buzzards Bay Project (Costa and Rasmussen, 1999) also indicated that the estuary was currently below its nitrogen loading level that would cause habitat impairments. The result is that nitrogen management of the system is aimed at protection (i.e. 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 increased nitrogen levels within the Estuary's sub-basins, particularly Little Bay, system appears to be presently unimpaired by nitrogen.

I.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” for water quality modeling of the Nasketucket Bay 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 Nasketucket Bay / Little Bay Estuarine System and each of its basins: Little Bay, Shaws Cove, Brant Island Cove and Nasketucket Bay. 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 Nasketucket and Little Bay system was taken from the Buzzards Bay Coalitions BayWatchers Monitoring Program and from additional sampling efforts within the embayment and Buzzards Bay nearshore waters by MEP staff and researchers at SMAST. 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.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Nasketucket Bay Estuarine System for the Town of Fairhaven. 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 are derived from SRPEDD and Town of Fairhaven Planning Department (Bill Roth) data and offshore water column nitrogen values were derived from an analysis of monitoring stations in Buzzards Bay (Section IV and VI respectively). 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 Nasketucket Bay System.

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 excessive plankton and macrophyte growth, which in turn lead to reduced water clarity, organic matter enrichment of waters and sediments. This has the concomitant effect of increased rates of oxygen consumption and periodic depletion of dissolved oxygen, especially in bottom waters, as well as limiting 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 both the local shell fisherman and to the sport-fishery and offshore fin fishery. Both the sport-fishery and the offshore fin fishery are dependent upon highly productive estuarine systems as a habitat and food resource during migration or during different phases of their life cycles. This process is of degradation 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 Nasketucket Bay System (inclusive of Nasketucket River and Little Bay), 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 and the concentrations of water column nitrogen that may result. 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 Nasketucket Bay / Little Bay Estuarine 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.

Few studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Nasketucket Bay System over the past 2 decades. In addition, watershed nitrogen management has been on-going in the watershed primarily through hook-ups to the Fairhaven WWTF with discharge outside of the watershed, thus removing a significant nitrogen load and most recently (1998), a wastewater treatment facility went online to service homes located on West Island. The MEP Technical Team was able to obtain the O&M Plan that was developed for the Town of Fairhaven that summarizes the general hydrogeology of the disposal beds and the down gradient discharge location for the treated effluent on West Island.

Operations and Maintenance Plan: West Island Wastewater Effluent Disposal Well System - The most salient information from the plan is the description of the basic hydrogeology of the effluent disposal bed and the general direction of the effluent once it has been pumped into the underlying aquifer. As excerpted from the O&M Plan, "The receiving strata for the treated wastewater effluent is a highly permeable zone (referred to herein as the disposal bed) the extent of which had been investigated through over 60 boreholes drilled between June 1993 and April 1996. The disposal bed forms a two to five foot thick stratigraphic horizon within the generally impermeable glacial till deposits, overlying the granitic bedrock in the northeastern portion of West Island. With the exception of the disposal bed, the glacial till on West Island is a dense, compacted, heterogeneous deposit with particle sizes ranging from boulders to silt. The till thickness averages 25 to 30 feet. In most boreholes the disposal bed directly overlays the top of bedrock surface. The depth of the disposal bed closely follows the depth of the top of bedrock surface. Because of this, the disposal bed tends to pinch out against higher areas on the bedrock surface. The horizontal extent of the disposal bed has been delineated by test borings to the west, northeast and southwest of the location of disposal wells. An extension of the disposal bed beneath the salt marsh to the east was confirmed during the March-April 1996 field investigations. The disposal bed is now interpreted to extend from the location of disposal wells to the southeast towards the salt marsh's tidal inlet."

This basic description of the disposal bed suggests that nutrient rich effluent from the facility discharges to the southeastern side of West Island, enters the tidal creeks of the salt marsh located along that shore and then discharges to Buzzards Bay. This is a significant consideration in the MEP assessment of nitrogen loading to Nasketucket Bay.

Nasketucket Bay Water Quality Monitoring Program - Beginning in 1993, summer measurement of nutrient levels (dissolved and particulate nitrogen; phosphorus); and other water quality indicators, (chlorophyll; secchi depth, dissolved oxygen and temperature) was begun in the Nasketucket and Little Bay embayment system by the Baywatchers program instituted by the Coalition for Buzzards Bay. The BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of the Nasketucket Bay Embayment System. The BayWatcher is a citizen-based water quality monitoring program that is run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD from its inception to 2008.

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. The program was tailored to the gathering of data specifically to support evaluations of nitrogen related water quality (Figure II-1). The BayWatcher Water Quality Monitoring Program in the Nasketucket Bay / Little Bay Estuarine System developed data used to establish a long-term water quality baseline for this system (1997-2011) used in the MEP's Linked Watershed-Embayment Approach.

After the first ten years of monitoring, the BayWatchers data set was reviewed in 1999 and summarized in a report for the first period, 1992-1998 (Howes et al. 1999). For the inner portion of the Nasketucket Bay system (specifically Nasketucket River and Little Bay) the Baywatchers data suggested that Little Bay may have reached its nitrogen loading limit, but it was unclear if habitat impairment had begun to occur. The authors concluded from the water quality data that "these values suggest a system which is currently receiving watershed nutrient loads at (or slightly beyond) levels sufficient to affect habitat quality." They went on to suggest that the assessment is confounded in the upper portion of Little Bay by the "large wetland areas adjacent to the Bay" and within the lower reach of the Nasketucket River. The MEP approach is to gauge the level of impairment likely from nitrogen enrichment relative to the sensitivity of the specific estuarine resource. The salt marshes associated with Little Bay are relatively tolerant of nitrogen enrichment, while the open waters of Little Bay are less tolerant. The distribution of nitrogen related water quality associated with the Little Bay waters, away from the salt marsh influences, is consistent with a system that is at but has not exceeded its tolerance for nitrogen loading, as indicated by the BBP study noted above.

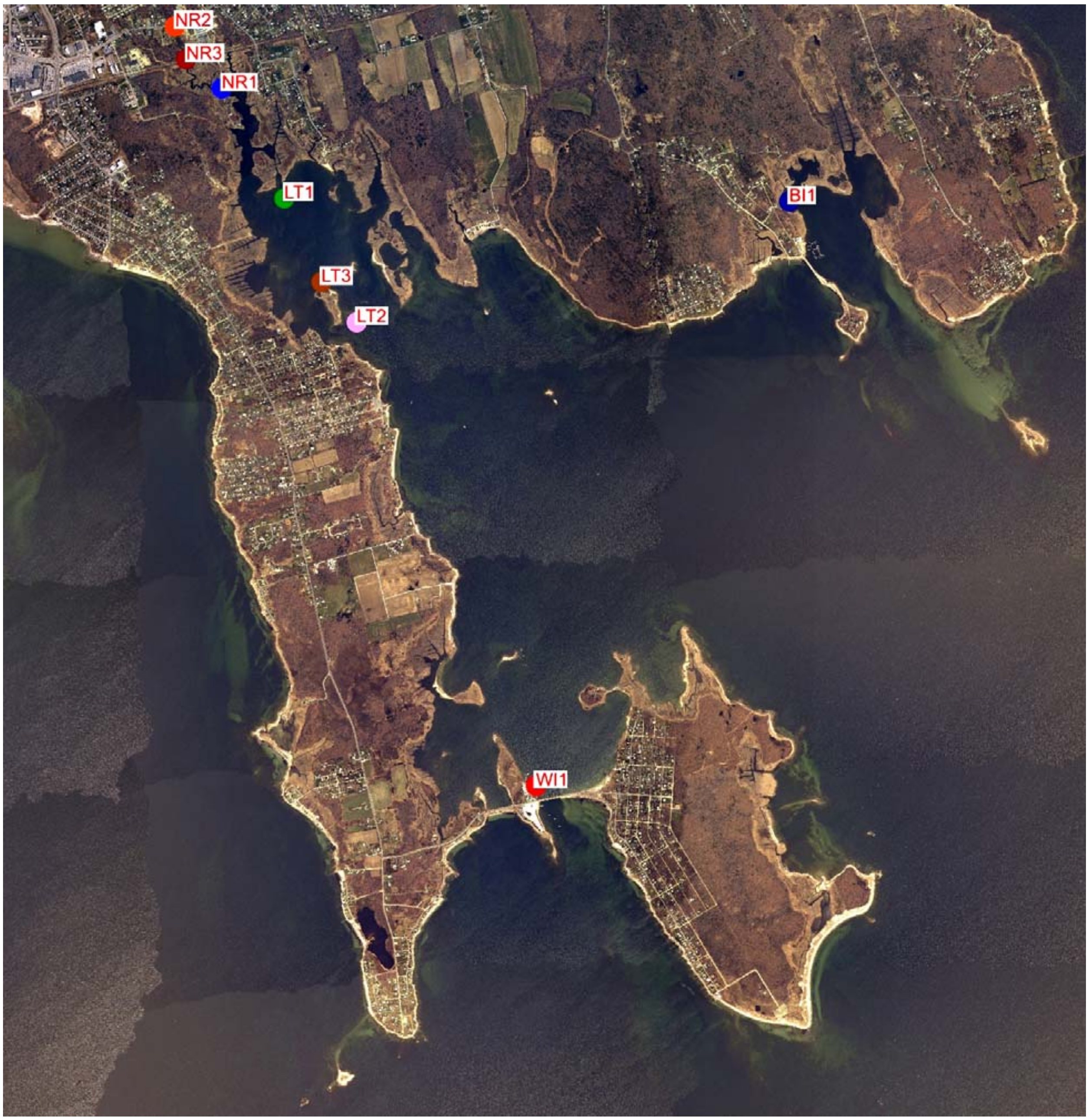


Figure II-1. Nasketucket / Little Bay sampling locations used for summer data collection by the BayWatcher Water Quality Monitoring Program. Stream water quality stations were associated with discharges to Little Bay and Shaws Cove and are depicted in Section 4.2 and were sampled weekly by the MEP.

***Little Bay, Fairhaven 1999 Nitrogen Management Report* -** As part of an analysis of BayWatcher water quality data 1993-1996, it was recommended that a targeted watershed loading analysis be undertaken for Little Bay, within the Nasketucket / Little Bay Estuary. As a result the Buzzards Bay Project (BBP) working with the Town of Fairhaven completed a preliminary build-out analysis of the Little Bay watershed. This assessment of future loading under full watershed development was then combined with a residence time estimate for Little Bay (Geyer et al. 1997) to allow the loading/flushing equation developed by the BBP to be used to assess Little Pond. The BBP loading assessment suggested that under existing watershed nitrogen loading, Little Bay should not have nutrient related impairments. However, under buildout watershed nitrogen loads, where the load was projected to increase ~1.5 fold, the bay would become overly enriched in nitrogen and habitat and water quality impairments would occur. The assessment that Little Bay was well below its nitrogen threshold, is consistent with the results of the surveys of Little Bay habitat quality conducted by the MEP and presented in Chapter VII of this report.

Regulatory Assessments of Nasketucket Bay Resources - The Nasketucket Bay / Little Bay Estuary contains a variety of natural resources of value to the citizens of Fairhaven as well as to the Commonwealth. As such, over the years surveys of natural resources have been conducted to support protection and management of these resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-2 through II-5) for reference by those providing stewardship for this estuary. For the Nasketucket Bay Estuary these include:

- Mouth of River designation - MassDEP (Figure II-2a,b,c,d,e)
- Designated Shellfish Growing Area – MassDMF (Figure II-3a,b)
- Shellfish Suitability Areas - MassDMF (Figure II-4)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-5)

The overall Nasketucket Bay system is subdivided into a number of smaller shellfish growing areas as designated by the Massachusetts Divisions of Marine Fisheries (Figure II-3a,b). Generally, Nasketucket Bay (BB21.0) is approved for shellfishing year round, consistent with the higher water quality observed in the open waters of the bay. Similarly, smaller shellfish growing areas around West Island are also classified as approved for year round shellfishing with the exception of areas closest to Earl’s Marina such as BB18.1 which is conditionally approved for shellfishing during specific times of the year, usually winter. Unlike the open water areas of Nasketucket Bay, the more enclosed waters of Little Bay (BB22.3) have been classified by the DMF as conditionally approved and further up-gradient, from the mouth of the Nasketucket River up to the former railroad bed where the Nasketucket River passes under the present bike path (BB21.0), the resources has been classified by the DMF as prohibited to shellfishing. This is most likely due to the poor water quality of waters discharging from the Nasketucket River as well as the potential for bacterial contamination from wildlife associated with the large areas of salt marsh adjacent the lower reach of the River and upper region of Little Bay. Salient aspects of the above listed resource surveys are further considered as part of the habitat assessment presented in Chapter 7.

The MEP effort also builds upon the previous watershed delineation and land-use analyses, river transport, embayment water quality and eelgrass surveys. This information is integrated with MEP collected higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nasketucket Bay System. The MEP has incorporated appropriate data from previous studies to which the MEP Technical Team had access in order to enhance the determination of nitrogen thresholds for the Nasketucket Bay / Little Bay Estuarine System and to reduce costs to the Town of Fairhaven.

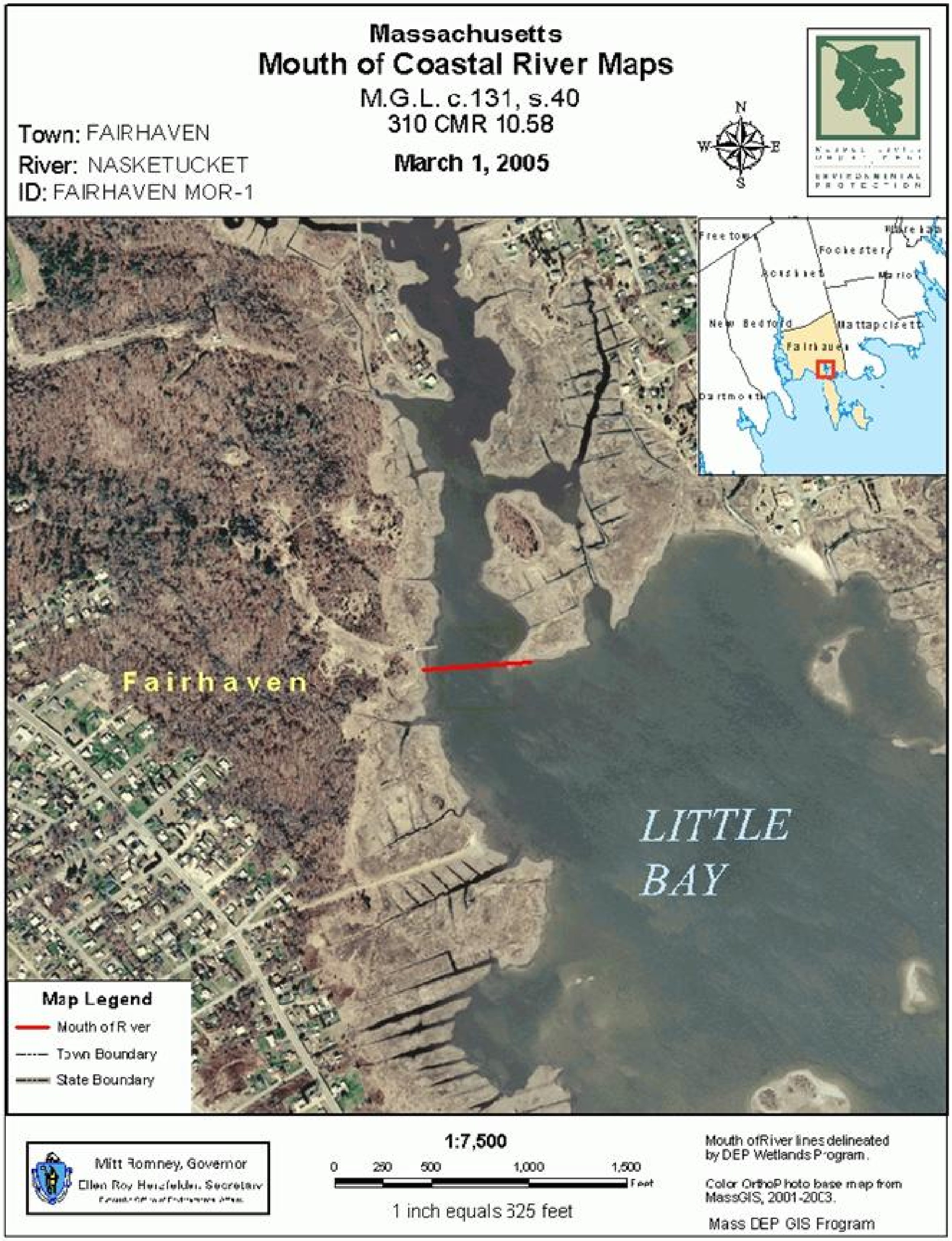


Figure II-2a. Regulatory designation of the mouth of the Nasketucket River under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

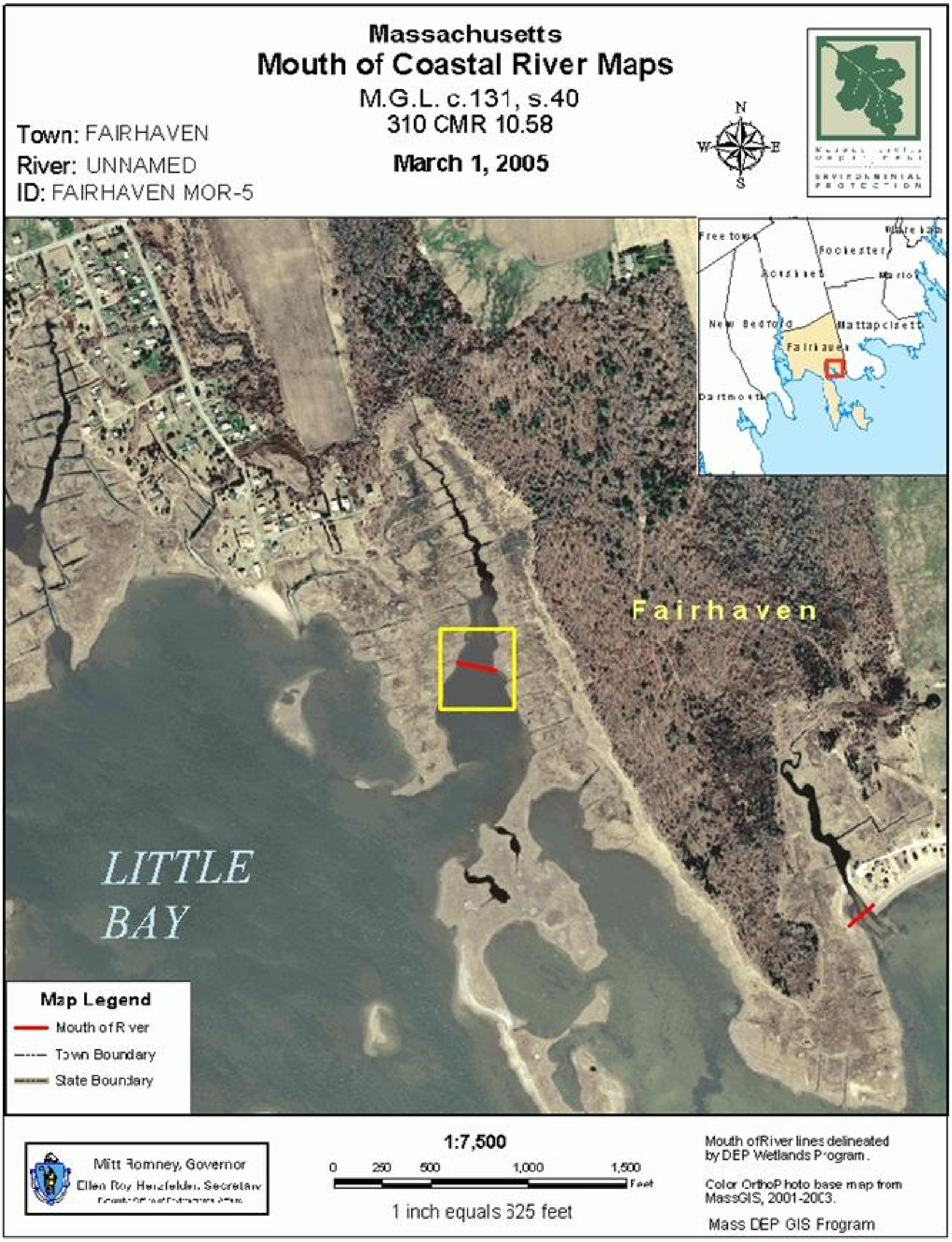


Figure II-2b. Regulatory designation of the mouth of un-named river discharging to Little Bay/Nasketucket Bay under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

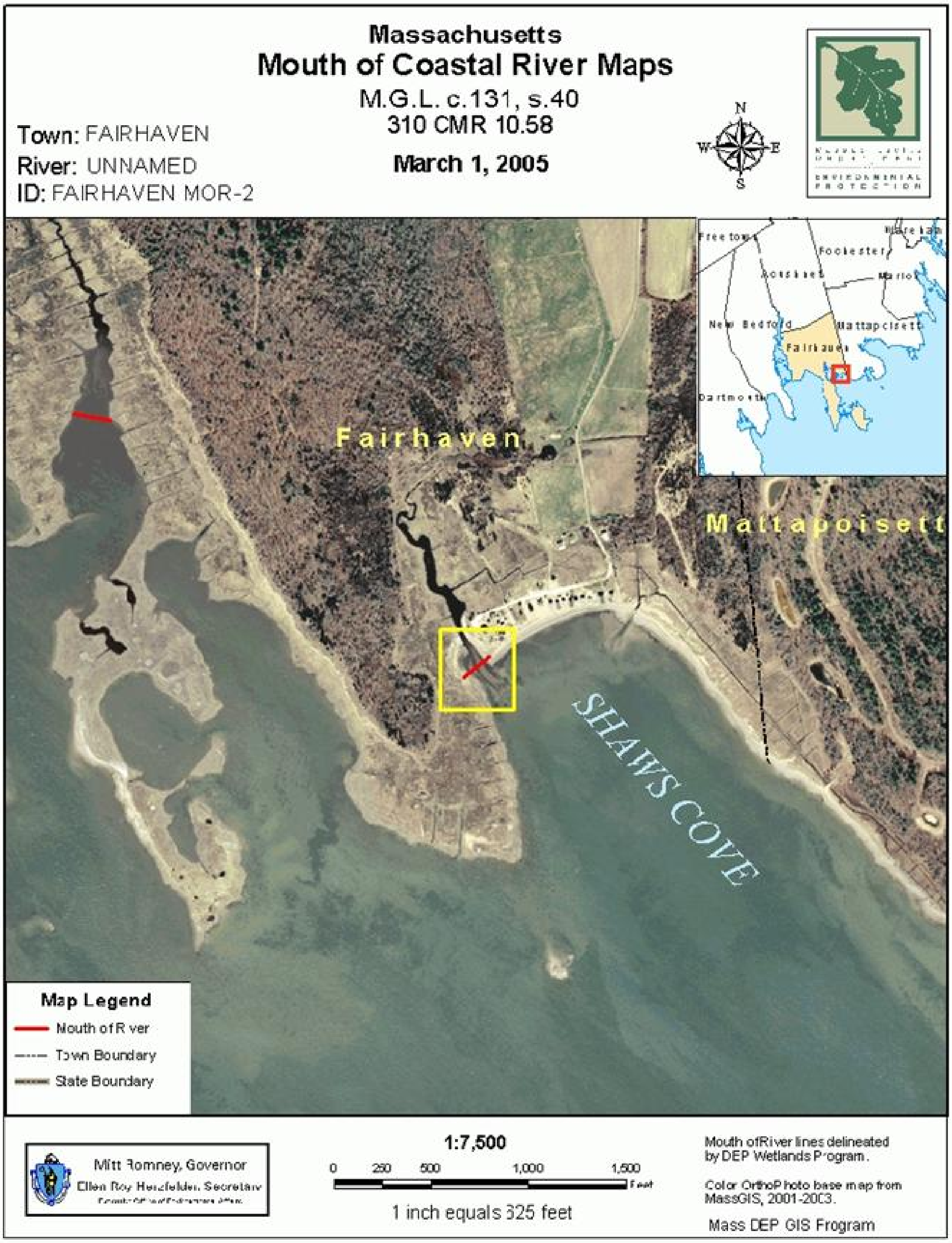


Figure II-2c. Regulatory designation of the mouth of un-named river discharging to Shaws Cove/Nasketucket Bay under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

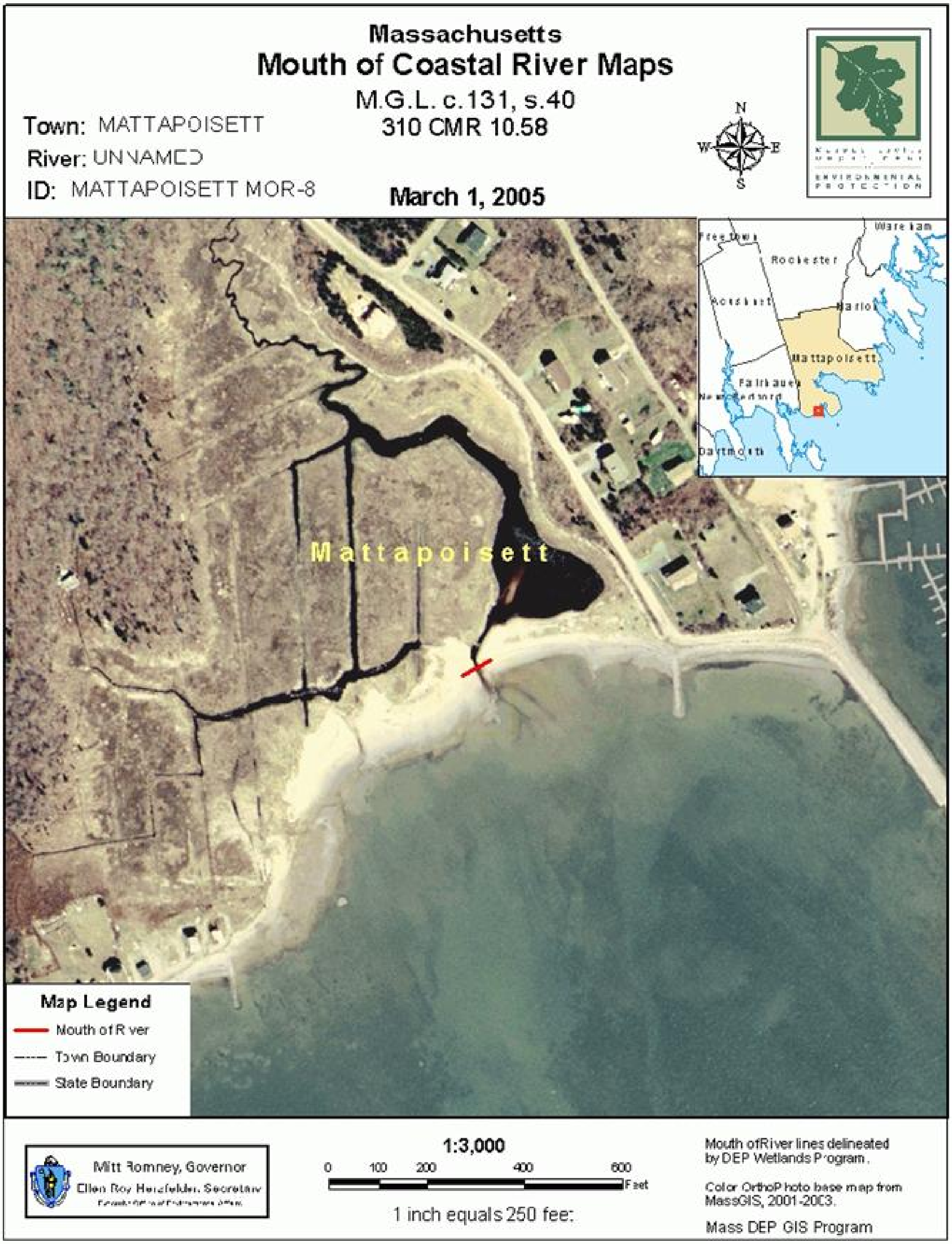


Figure II-2d. Regulatory designation of the mouth of un-named river discharging to Nasketucket Bay under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

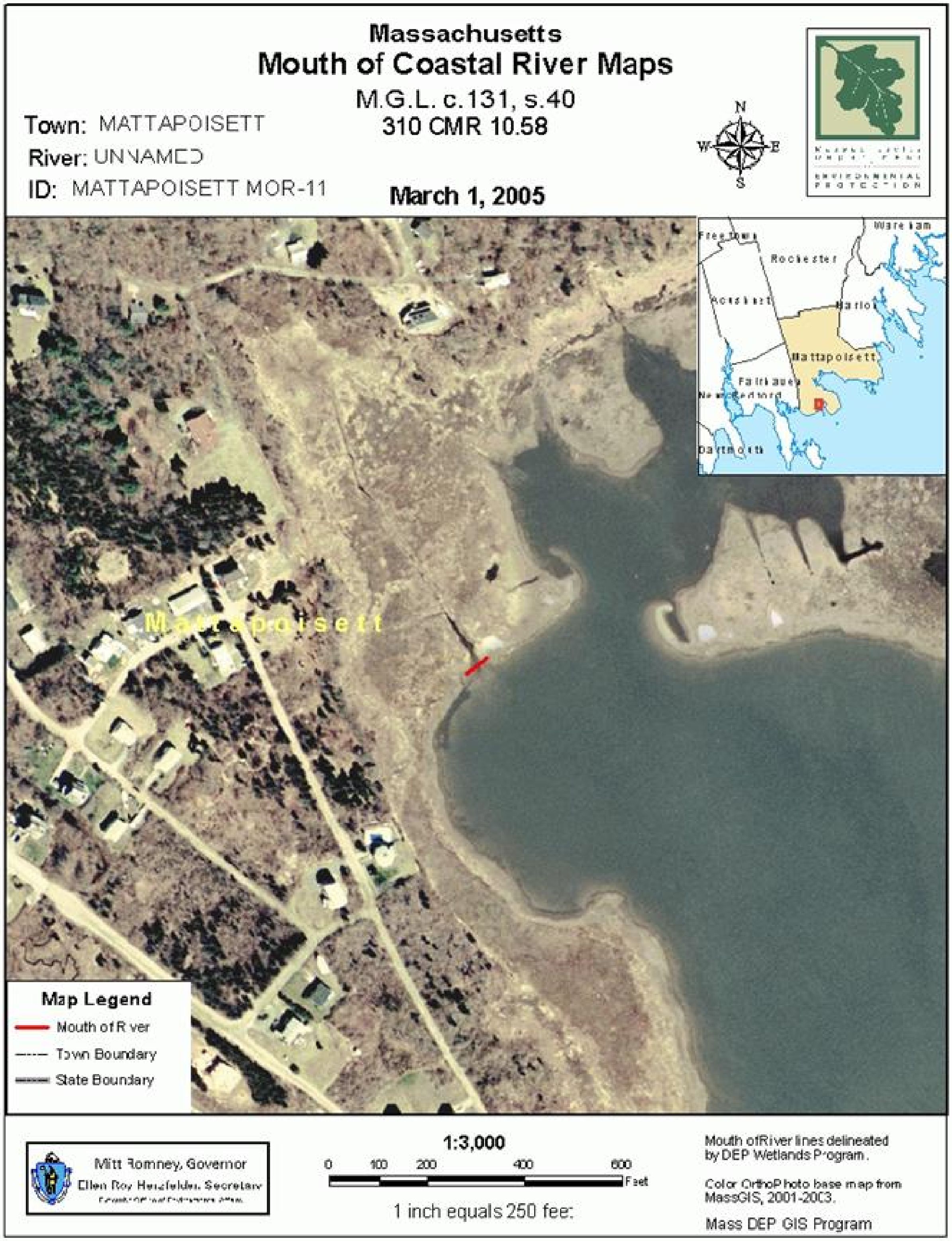


Figure II-2e. Regulatory designation of the mouth of un-named river discharging to Brandt Island Cove / Nasketucket Bay under the Massachusetts River Act (MassDEP). Upland adjacent the "river front" inland of the mouth of the river has restrictions specific to the Act.

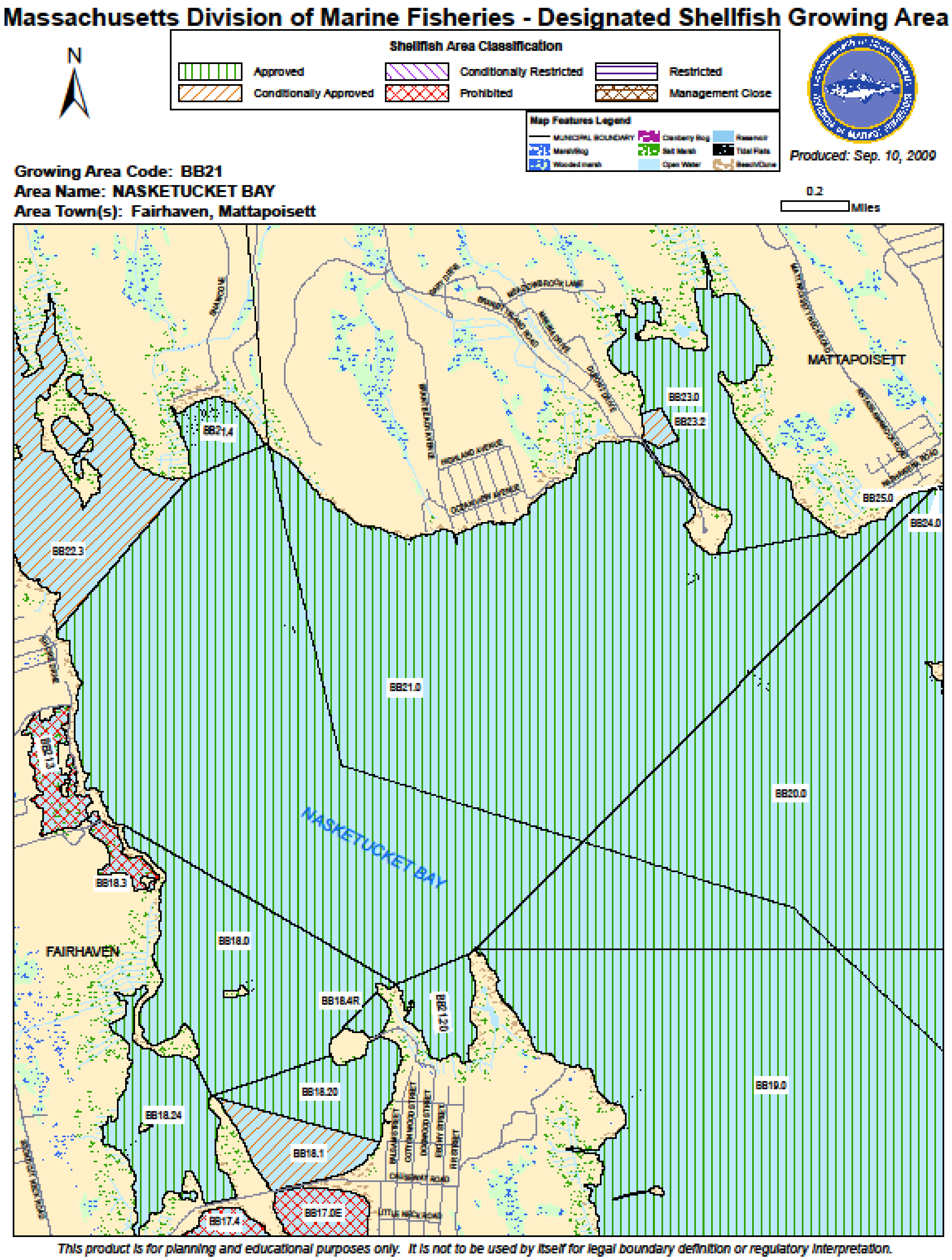


Figure II-3a. Location of shellfish growing areas and their status relative to shellfish harvesting (Nasketucket Bay) as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

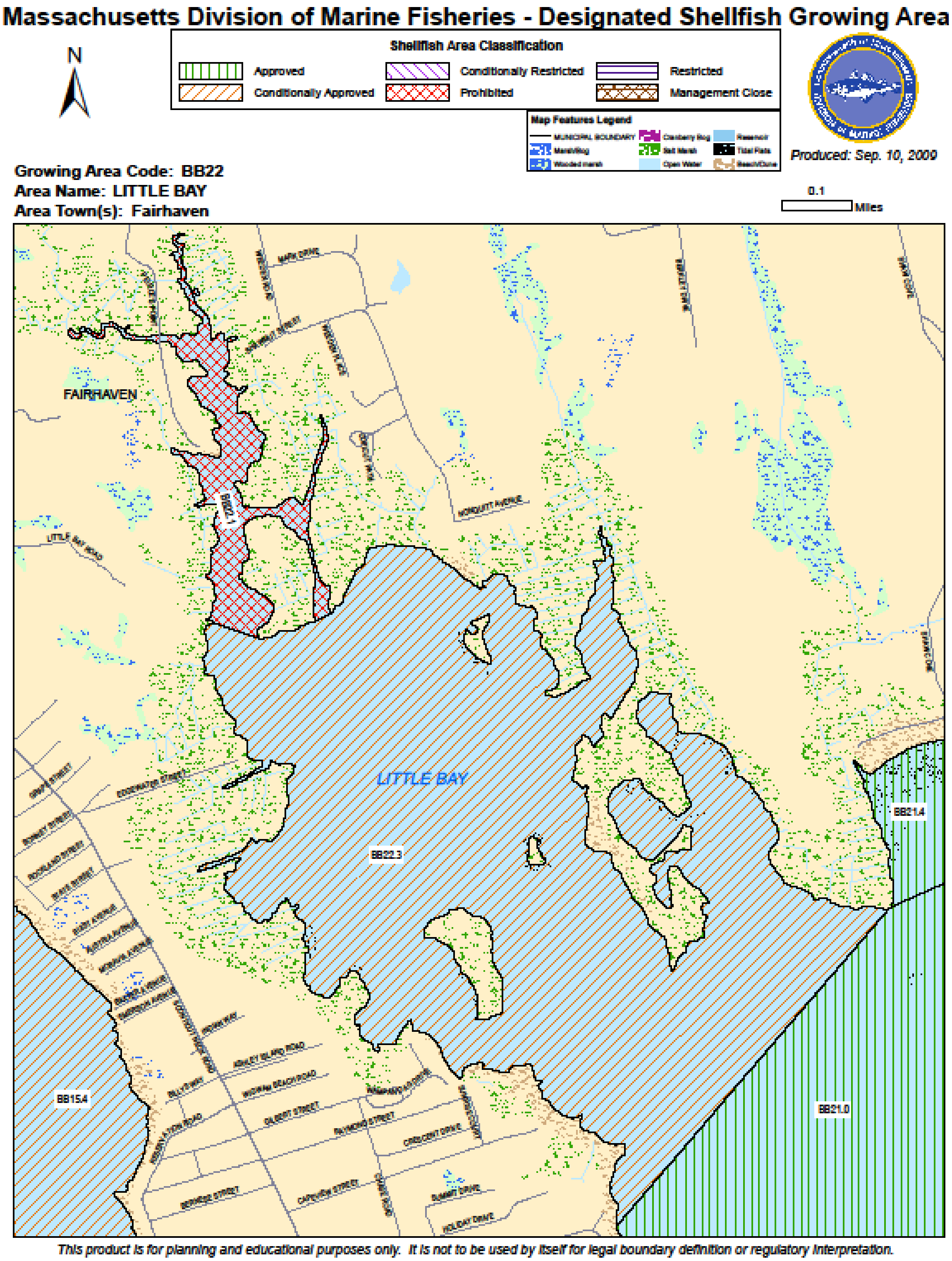


Figure II-3b. Location of shellfish growing areas in the Nasketucket River / Little Bay portion of the Nasketucket Bay Estuary and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

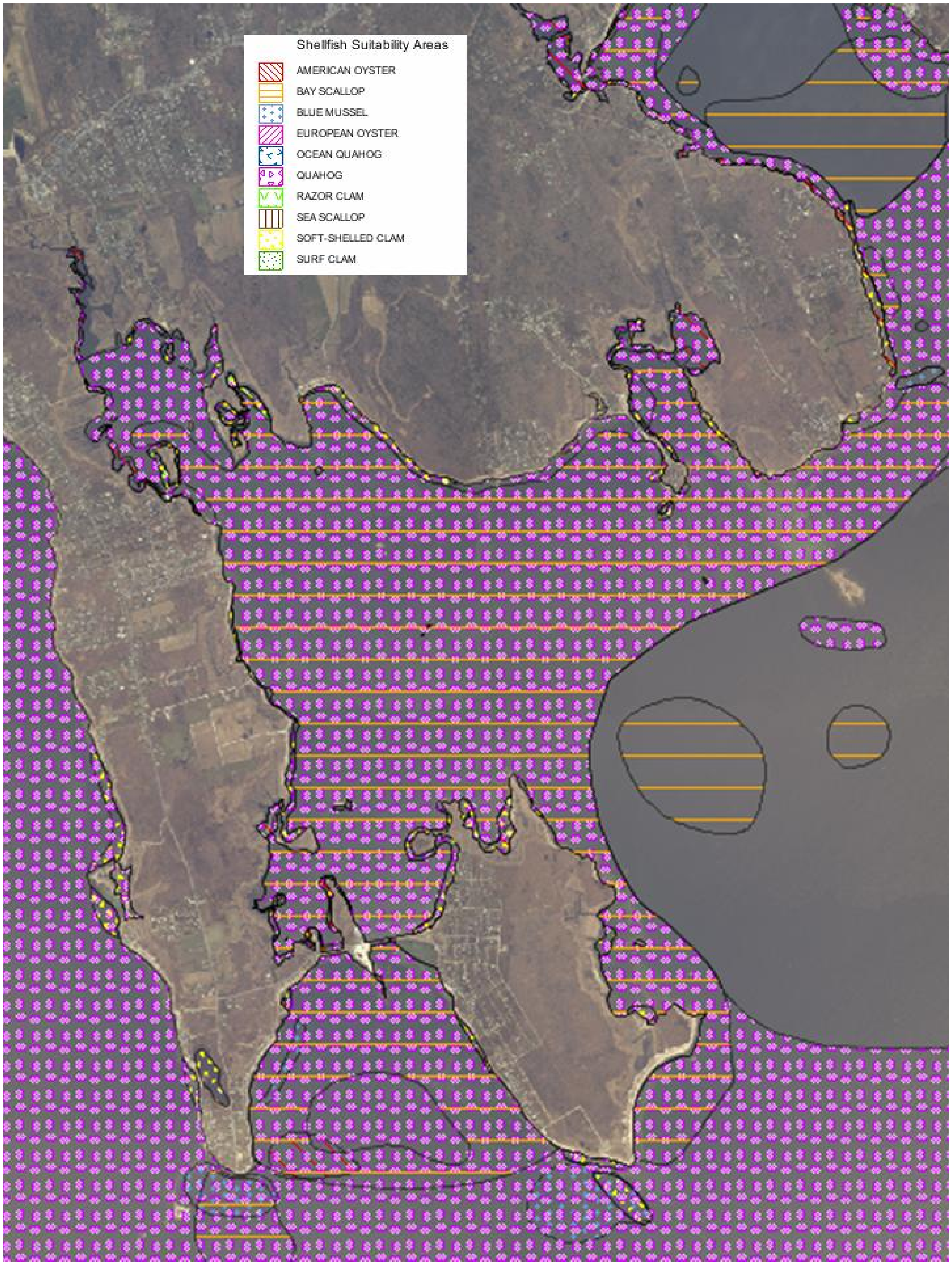


Figure II-4 Location of shellfish suitability areas within the Nasketucket Bay and Little Bay Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that a shellfish population is "present".

Figure II-5. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Nasketucket Bay / Little Bay Estuary as determined by the Massachusetts Natural Heritage and Endanger Species Program (NHESP).

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Nasketucket Bay 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

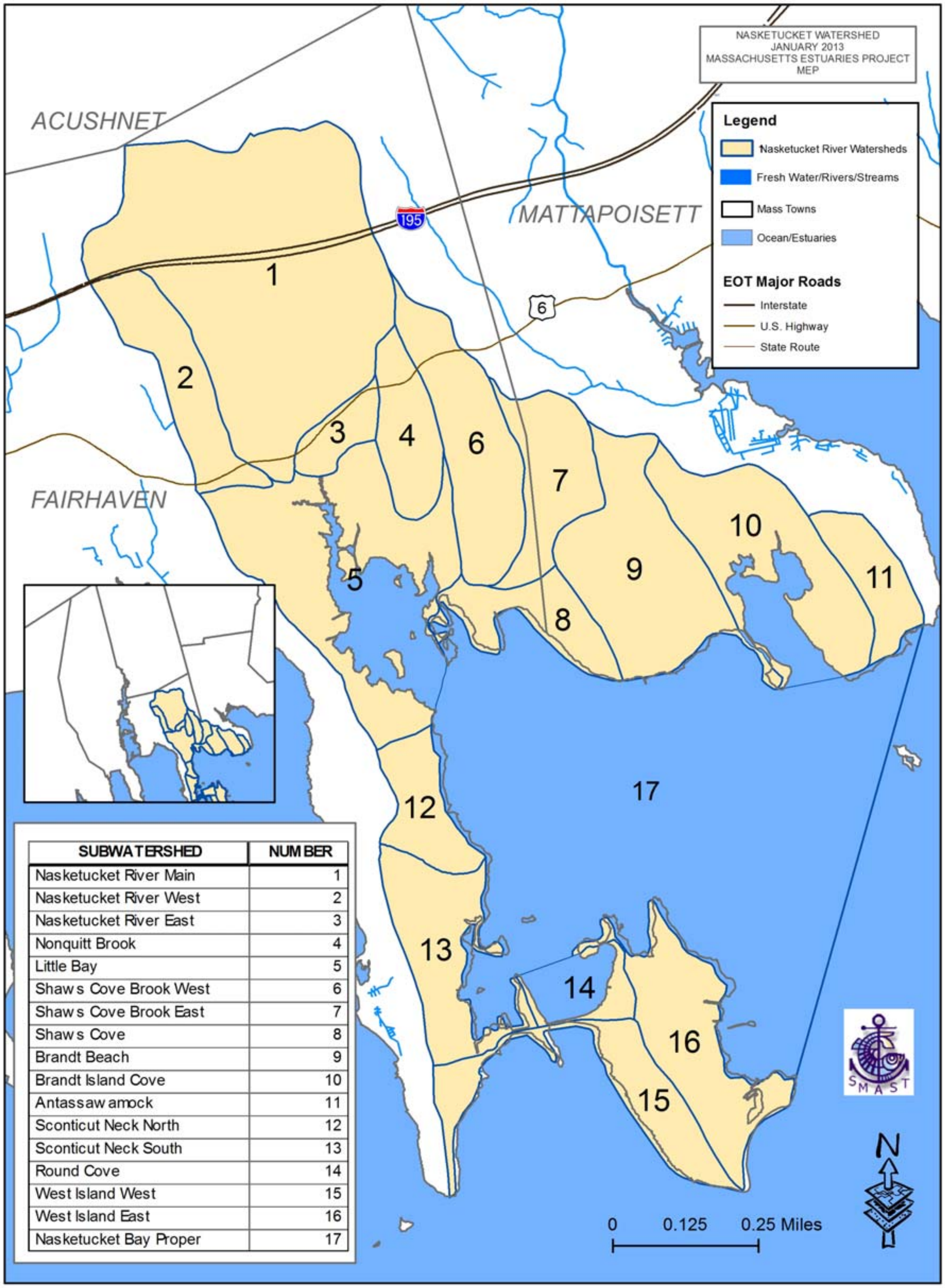
A watershed divide or boundary can be described as the line from which rainwater or snowmelt flows on the surface and through groundwater towards one stream, river or estuary, while rainfall and groundwater on the other side of the divide flows away to another water body. In addition, the water table, 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 Nasketucket Bay / Little Bay Estuary 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 Nasketucket Bay /Little Bay Estuary 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 Nasketucket Bay / Little Bay Estuary 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 inputs from streams to the estuary (*e.g.*, Nasketucket River and Nonquitt Brook) and to provide nitrogen loadings at spatial scales matching the sub-embayment segmentation of the MEP tidal hydrodynamic model (*e.g.,* Little Bay and Shaws Cove).

Seventeen (17) subwatersheds were delineated based on topographic inspection for the MEP analysis of the Nasketucket Bay Estuarine System (Figure III-1). The subwatersheds include contributing areas to the following streams: Nasketucket River Main, Nasketucket River West, Nonquitt Brook and Shaws Cover Brook West. Delineation of these subwatersheds allows direct comparison between the expected discharge flows and nitrogen loads from the delineated areas and measured data from MEP stream gauges. 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 streamflows were determined for comparison to measured streamflows collected by the MEP (Table III-1). 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 at New Bedford, which is close to the Nasketucket Bay watershed. 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 unofficial NOAA data from this site between 2005 and 2010, the period associated with the MEP analysis, shows an average annual precipitation of 53.0 inches. Precipitation in the complete hydrologic year (2006) of MEP stream flow measurements had an annual precipitation rate of 63.8 inches, but the preceding and subsequent years were both less than the long term averages (48.2 and 44.5 inches, respectively). Given uncertain issues regarding watershed release/saturation indices and the unofficial nature of the NOAA data, MEP staff concluded 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 Nasketucket Bay 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 Nasketucket Bay watershed. This recharge rate is used to develop the long-term freshwater inflows in Table III-1 and is also use in the watershed nitrogen loading estimates (see Section 4). It should be noted that this recharge analysis is used for comparison of 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).



SUBWATERSHED	NUMBER
Nasketucket River Main	1
Nasketucket River West	2
Nasketucket River East	3
Nonquitt Brook	4
Little Bay	5
Shaws Cove Brook West	6
Shaws Cove Brook East	7
Shaws Cove	8
Brandt Beach	9
Brandt Island Cove	10
Antassawamock	11
Sconticut Neck North	12
Sconticut Neck South	13
Round Cove	14
West Island West	15
West Island East	16
Nasketucket Bay Proper	17

Figure III-1. MEP Watershed Delineation for the Nasketucket Bay Embayment System. Watershed includes portions of two towns: Fairhaven and Mattapoisett.

Table III-1. Nasketucket Bay MEP Subwatershed Areas and Estimated Long-Term Freshwater Recharge.

Watershed Name	#	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Nasketucket River Main	1	1,354	11,613	410,117
Nasketucket River West	2	251	2,150	75,925
Nasketucket River East	3	85	732	25,857
Nonquitt Brook	4	182	1,564	55,233
Little Bay	5	629	5,396	190,543
Shaws Cove Brook West	6	372	3,192	112,717
Shaws Cove Brook East	7	250	2,148	75,855
Shaws Cove	8	166	1,425	50,310
Brandt Beach	9	503	4,316	152,426
Brandt Island Cove	10	428	3,671	129,641
Antassawamock	11	155	1,326	46,838
Sconticut Neck North	12	167	1,434	50,656
Sconticut Neck South	13	297	2,548	89,996
Round Cove	14	45	389	13,728
West Island West	15	235	2,020	71,319
West Island East	16	356	3,052	107,764
Nasketucket Bay Proper	17	57	487	17,211
NASKETUCKET BAY SYSTEM TOTAL			47,463	1,676,138

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 nearest long-term NOAA gauge: New Bedford);
3) these flows do not include precipitation on the surface of the estuary;
4) totals may not match due to rounding.

Based upon the cross-check comparison of measured and modeled annual stream flows and stream watershed areas, it became clear there was an issue with the area of subwatershed #2 and its measured volumetric discharge. As standard practice, this resulted in a detailed review of the topographic-based subwatershed delineation to Nasketucket River West (subwatershed #2) and the streamflow measurements. The topographic watershed delineation and the watershed recharge rate resulted in an estimated watershed flow of 2,871 m^3/d. In comparison, the measured streamflow for this watershed was 1,183 m^3/d (see Section IV.2). MEP staff reviewed the land uses in the watershed and found that Route 240 effectively blocks flow from the west in the southern portion of the topographic watershed. In addition, much of the stream/wetland areas that are shown connecting to this stream on the USGS topographic quad have been filled and/or constricted. Field surveys confirmed little or no flow or evidence of flow passing under Route 240 in this area. The subwatershed delineation was refined to include these observations and the flow measurements.

Using the Nasketucket Bay watershed recharge rate, the overall estimated long-term freshwater inflow into the Nasketucket Bay estuary from its MEP watersheds is 47,463 m^3/d. If recharge on the surface of the Bay (as delineated in Figure III-1) is included, the total average freshwater input to the Bay is 75,609 m^3/d. The watershed to the Nasketucket Bay system (inclusive of Little Bay) extends across two towns: Fairhaven and Mattapoisett. Based on the details presented above, the MEP Technical Team concluded that the watershed delineations, as presented in Figure III-1 for the Nasketucket Bay system are suitable for the MEP watershed nitrogen loading assessments and nutrient threshold analysis.

The evolution of the watershed delineation for the Nasketucket Bay estuary system has provided increasing accuracy as each new version adds new hydrologic data to that previously collected; the current re-evaluation allows all these data to be organized and to be brought into congruence with data from adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the watershed model is important as it adds confidence in the final calibrated and validated linked watershed-embayment model. The sub-watershed delineations also increase the utility of the watershed land-use loading model for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the downgradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the streams and non-stream subwatersheds and ultimately to the estuarine waters of the Nasketucket Bay / Little Bay Estuarine System (Section V.1).

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 Nasketucket Bay / Little Bay Estuarine System as well. Determination of watershed nitrogen inputs to this embayment system requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or watershed, (b) confirmation that watershed transported loads have 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 prior to reaching the estuary. This latter natural attenuation process results from biological processes that naturally occur within these 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 recycled. 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 and the watershed attenuation 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 Nasketucket Bay / Little Bay Estuarine 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 of Fairhaven and Mattapoisett, and used various datasets developed by the Buzzards Bay National Estuary Program (BBNEP) and the Coastal Systems Program, School for Marine Science and Technology (CSP-SMAST). The Nasketucket Bay sub-watersheds were delineated to define contributing areas to each of the major streams and other significant freshwater systems and to each major portion of the estuary. A total of 17 sub-watershed areas were delineated within the Nasketucket Bay / Little Bay study area, including watersheds to the following streams: Nasketucket River Main, Nasketucket River West, Nonquitt Brook and Shaws Cove Brook West (see Section III). Freshwater inflow to the Nasketucket Bay / Little Bay Estuary is predominately groundwater; stream discharges account for approximately 39% of the watershed freshwater input to this 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 watershed model. Although stream gauges were only placed on four of the streams discharging into Nasketucket Bay, review of USGS quadrangles show that most of the subwatersheds have streams or wetlands that nearly (<0.3 km) reach the system watershed boundary. 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 five years to reach the main stem. Of course, these areas have significant wetland areas that extend to within hundreds of feet of the sub-watershed boundaries, likely surrounded with small tributaries with the wetlands feeding the main stem of the river. These wetlands and small tributaries are short travel-time conduits, which significantly shorten travel time, such that travel time from the boundary areas to the estuary is much less than 5 years. Review of the lower, more groundwater-dominated subwatershed areas also show that the subwatershed boundaries are also generally less than 0.5 km from the estuary shoreline, which should result in travel times considerable shorter than the MEP 10 year time-of-travel standard. MEP reviews in other systems have shown that if most development is less than 10 years travel time to the estuary, then the watershed nitrogen loads are in relative balance with the estuary nitrogen concentrations. Therefore, there should be a high level of confidence that the present nitrogen load within the watershed to the Nasketucket Bay / Little Bay Estuary accurately reflects the present nitrogen input to its estuarine waters after accounting for natural attenuation (see below) As such, the estuarine habitats are reflecting the current watershed land-use loading.

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 Nasketucket Bay Embayment System, the model uses land-use data from the Towns of Fairhaven and Mattapoisett. 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 (e.g. removal) during transport is included at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea within the Nasketucket Bay / Little Bay watershed was determined based upon site-specific measurements of stream flow on each of the four gauged streams discharging to the estuary. Stream flow was characterized at the discharge of Nasketucket River Main, Nasketucket River West, Nonquitt Brook and Shaws Cove Brook West. A subwatershed to these stream discharge points allowed comparison between field-collected data from the streams 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 (<5%) 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 Nasketucket Bay 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 Nasketucket Bay / Little Bay Estuarine System includes portions of the Towns of Fairhaven and Mattapoisett, 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 Fairhaven are both from 2009 and were developed as part of the build-out assessment completed by the BBNEP (Rockwell, 2010). Additional assistance was subsequently provided by BBNEP to link water use and sewer account databases to the Fairhaven parcels. Mattapoisett parcels and land use/assessors databases are from 2008 and were developed under a separate SMAST project with the Town of Mattapoisett that also included the linking of five years of parcel-by-parcel water use. 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. Both the MEP and BBNEP staff have concluded that the present land-use datasets provide a solid basis to support watershed nitrogen analysis for this estuarine system.

Figure IV-1 shows the land uses within the Nasketucket Bay estuary watershed. Land uses in the study area are grouped into nine (9) land use categories: 1) residential, 2) commercial, 3) industrial, 4) agricultural, 5) recreational (golf courses and parks), 6) undeveloped, 7) forest land (Chapter 61 properties), 8) unclassified, and 9) public service/government, including road rights-of-way. These land use categories are aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MassDOR, 2012) and 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 Nasketucket Bay / Little Bay Estuary watershed, the predominant land use based on area is public service/government, which accounts for 36% of the overall watershed area (Figure IV-2). Much of this land area is government-owned lands, but a significant portion is also road rights-of-way, especially the areas assigned to Interstate 195, which crosses the northern portion of subwatershed #1, and the Route 24 clover leaf exit. Residential land use categories occupy the second largest area (27% of the overall watershed area), followed by parcels classified as undeveloped (14%) and agricultural parcels (11%). Other land use categories are less than 10% of the total area.

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 69% of all parcels in the watershed and 74% and 64% of the parcels in the Little Bay and Outer Bay subwatersheds, respectively. Undeveloped parcels are the second highest percentage of the watershed parcel counts, accounting for 20% 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 1.2 acres and varies between 0.4 and 5.2 acres in the individual subwatersheds. This finding suggests that the majority of the undeveloped parcels in the watershed are likely already subdivided and surrounded by

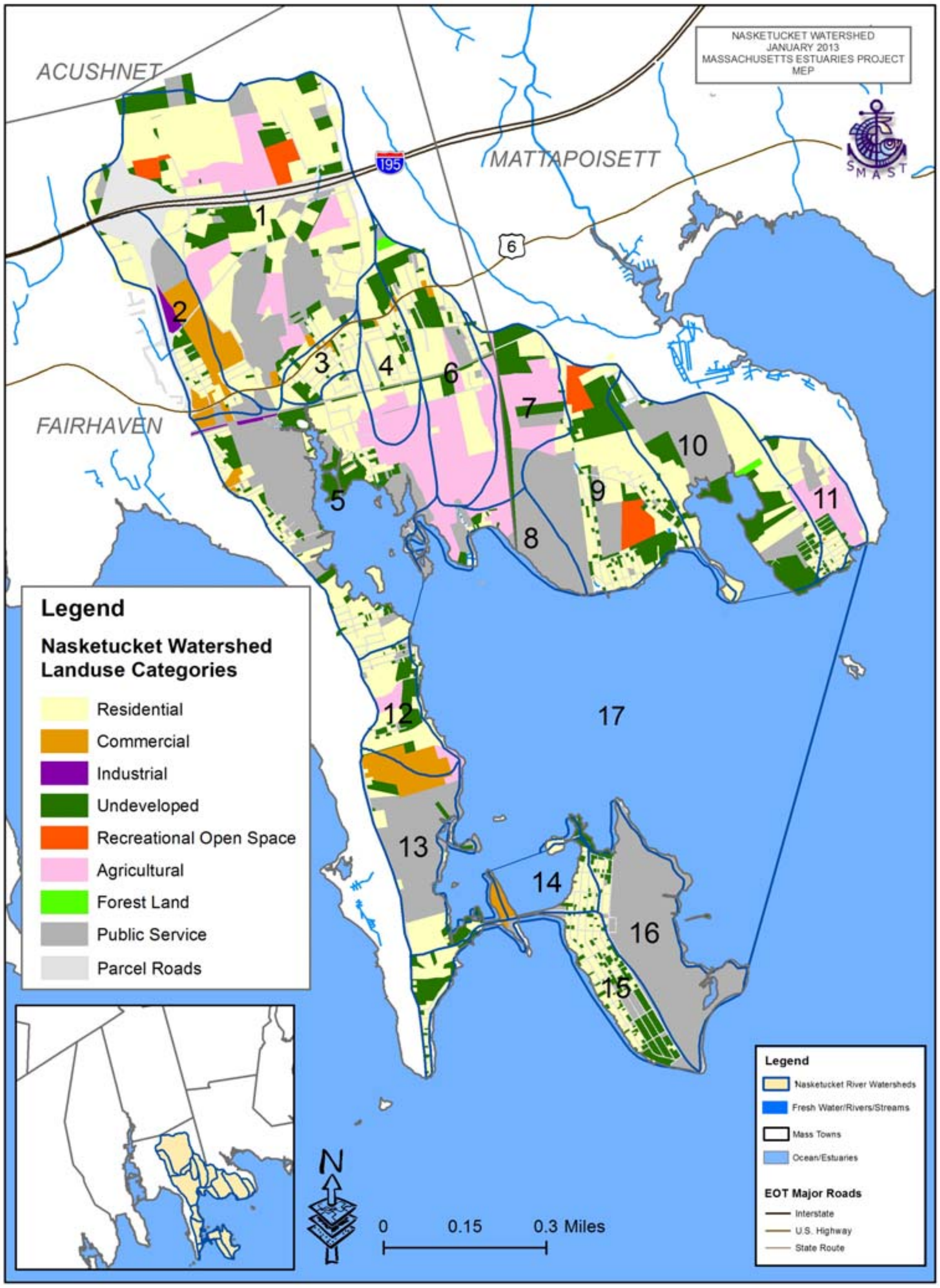


Figure IV-1. Land-use in the Nasketucket Bay / Little Bay Estuary watershed and sub-watersheds. The system watershed extends over portions of the towns of Fairhaven and Mattapoisett. Land use classifications are based on respective town assessor classifications and MADOR (2012) major categories. Digital parcels and land use/assessors data for Fairhaven are from 2009 and are from 2008 for Mattapoisett.

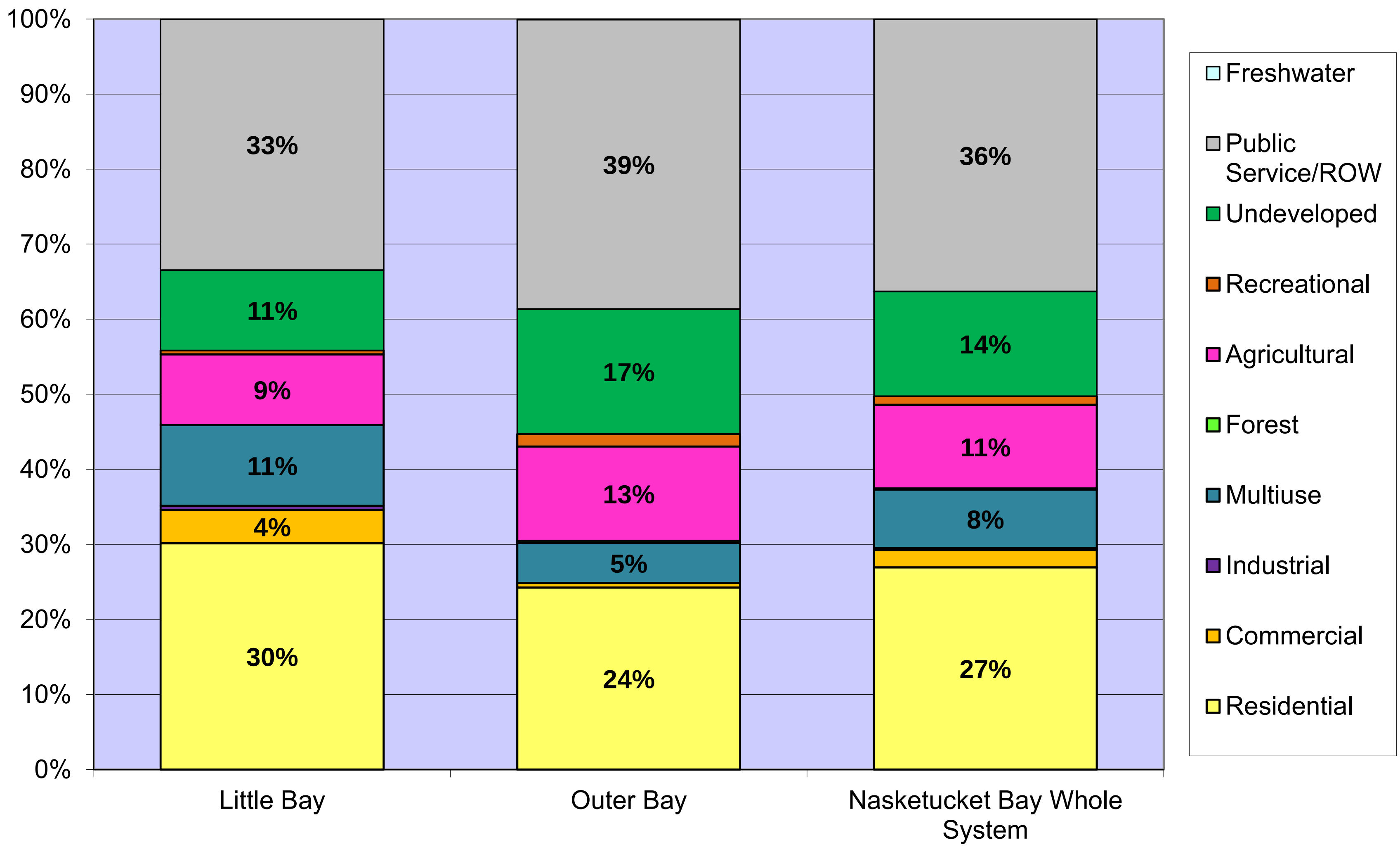


Figure IV-2. Distribution of land-uses by area within the Nasketucket Bay / Little Bay Estuary watershed and watershed areas contributing to two key estuarine basins. Land use categories are generally based on town assessors' land use classifications and major category groupings recommended by MADOR (2012). Only percentages greater than or equal to 4% are shown. Similar classification by parcel count show that residential parcels are the predominant parcel type; 69% of all parcels in the watershed and 74% and 64% of the parcels in the Little Bay and Outer Bay subwatersheds, respectively, are residential parcels.

developed parcels. Single-family residences (MassDOR land use code 101) are 71% to 100% of residential parcels in the individual sub-watersheds and 97% of the residential parcels throughout the Nasketucket Bay system watershed.

MEP analyses generally use water use as a proxy for wastewater flows and these loads are adjusted for any sewer collection systems. In the Nasketucket Bay watershed, the Town of Fairhaven provided water use and sewer connection databases for individual parcels. 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. Mattapoisett parcels are not connected to a sewer system and, as stated previously, water use information for individual parcels was linked by SMAST under a previous project with the town.

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 does not generally yield accurate estimates of total population except 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 rough 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 a rough independent validation of the average residential water use within the Nasketucket Bay / Little Bay sub-watersheds, the MEP Technical Team reviewed US Census population and housing information for the Towns of Fairhaven and Mattapoisett. The state on-site wastewater design regulations (*i.e.*, 310 CMR 15, Title 5) assume for the purposes of Title 5 each person generates 55 gpd of wastewater, with two people occupying each bedroom and each bedroom contributing a wastewater flow of 110 gallons per day (gpd). Based on data collected during the 2000 and 2010 US Censuses, average occupancy within Fairhaven was 2.44 and 2.38 people per housing unit, respectively, while Mattapoisett was 2.48 and 2.41, respectively. Seasonal properties are a relatively small percentage of the occupied housing units in both towns, although Mattapoisett has more seasonal properties. Year-round occupancy was 94% in Fairhaven in both the 2000 and 2010 Census, while Mattapoisett had year-round occupancy percentages of 83% and 81%, respectively. Based on the watershed water use data, the average single family residence water use is 109 gpd. If this flow is then divided by 55 gpd, the average estimated occupancy based on the water use in the study area is 2.0 people per household. However, this lower occupancy estimate is due to the fact that the Census blocks within the watershed (i.e. watershed as opposed to town-wide) have lower occupancy than the town-wide averages. For example, Census blocks associated with West Island and Brandt Beach have low occupancies that are likely lowering the average water use. These comparisons and the more detailed review of the 2010 Census information provide confidence in the water use information and show that water use is an appropriate basis for determining septic system wastewater nitrogen loads within the Nasketucket Bay / Little Bay watershed, while also underscoring the difficulties of using Census data in coastal communities.

The measured water uses are used for properties with water use accounts in Fairhaven and Mattapoisett. Not all developed properties have connections to the municipal water system, however, and these properties are assigned average water uses in the watershed nitrogen loading model based upon the type of land use assigned by the town assessor or a modified average based on individual site reviews completed by MEP staff and the water-use from comparable properties that have water-use data. For example, there are 40 multi-family residential parcels within the Nasketucket Bay / Little Bay watershed and, of these, 23 have water use with an average per parcel flow of 236 gpd. This average flow is assigned to the 17 other developed properties in this category that are assumed to utilize on-site wells for their drinking water. Other developed properties without water use accounts were reviewed and it was determined that they likely have small wastewater rates (*e.g.*, storage facilities). For consistency, these properties were assigned the average single family residence water use, which is likely a conservative flow. There are four commercial properties in the watershed without a water use account.

Site-specific Wastewater Estimates

During MEP assessments, MEP staff integrates information on large wastewater treatment facilities and connections to municipal sewers for site-specific modification of nitrogen loads. A portion of the Nasketucket Bay / Little Bay watershed is connected to the Town of Fairhaven sewer collection system. These parcels were identified in a GIS coverage provided by the Town to the BBNEP. Wastewater flows from these parcels were removed from the watershed since the municipal treatment plant discharges outside of the watershed. The Town also operates a smaller treatment plant on West Island, which has a MassDEP Groundwater Discharge Permit (GWDP) for 80,000 gpd of flow with a total nitrogen limit of 10 mg/L. This plant collects wastewater from the west side of the island and discharges treated effluent on the east side of the island. Review of groundwater plume characterization information related to the effluent discharge shows that total nitrogen in wells average ~8 mg/L nitrate+ammonia (Brown and Caldwell, 2009). Metered water use from connected properties in the town parcel database were used as influent flow and adjusted for consumptive use (-10%) for the effluent discharge. MassDEP staff indicated no other GWDPs exist within the watershed to the Nasketucket Bay / Little Bay Estuary. GWDPs are required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of watershed nitrogen load to the estuaries of southeastern Massachusetts is usually fertilized areas such as 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 Nasketucket Bay system, 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. There are no golf courses or cranberry bogs within the Nasketucket Bay watershed.

Residential lawn fertilizer use has rarely been directly measured in watershed-based nitrogen loading investigations. Instead, lawn fertilizer nitrogen loads have 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, as part of the MEP preparation work at the outset of the project, the MEP Technical Team 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). 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 Nasketucket Bay watershed (11% of the overall watershed area). MEP staff obtained counts of farm animals from the Town of Fairhaven (personal communication, Lisa Moniz, 7/12). During the parcel-by-parcel assignment of the nitrogen loads, 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 used to assign nitrogen loads for agricultural parcels after the removal of wetland areas. 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).

Nitrogen Loading Input Factors: Freshwater Wetlands

The data collected at the MEP gauge sites in the Nasketucket Bay 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-reviewing 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 Nasketucket Bay watershed that was not included in the preliminary model. A similar approach was taken in the Slocums River and Westport River 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 Nasketucket Bay streams is also 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 on atmospheric N deposition being only partially removed. This determination for the Nasketucket Bay 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 to the Nasketucket Bay streams, are structurally similar, have significant associated freshwater wetlands (especially the Nasketucket Main River), 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 Nasketucket Bay, 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 southwestern edge of the Buzzards Bay watershed are underlain by bedrock and till, have comparatively high stream flows, and extensive bordering freshwater wetlands. In these 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 do have threshold effects like those seen in estuaries and ponds. This means that these freshwater wetlands can become nearly completely loaded with nitrogen and 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).

All wetlands are treated as open water in all MEP reports, however, in the geologic settings typical of Cape Cod, removal of nitrogen by these wetland tends to be equal to or greater than the atmospheric load. As a result nitrogen loss is not apparent in the calculations. In the case of the different geologic setting of the western basins of the mainland side of Buzzards Bay, the wetlands take up less than the atmospheric deposition. This means that the residual is passed downstream, resulting in an apparent load from wetlands, which is really unattenuated atmospheric deposition. In addition, these latter wetlands are comprised primarily of freshwater wetlands which are retentive of phosphorus, while the primary wetlands in question on Cape Cod are generally salt marshes which are retentive of nitrogen. The approach employed for the Nasketucket Bay / Little Bay Estuary is consistent with ecological theory regarding nutrient retention and release form fresh and salt water wetlands, the literature and the stream measurements associated with this system. The result is a low total combined attenuation of all nitrogen sources in the Nasketucket River (main) being 13%. The results indicated that 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 Nasketucket Bay watershed, MEP staff assigned the water surface nitrogen loading factor to the wetland areas identified in a MassGIS/MassDEP wetland coverage (Figure IV-3). 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 Nasketucket Bay watershed system.

Figure IV-3. Wetland areas in the Nasketucket Bay / Little Bay sub-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.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas in the Nasketucket Bay 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 Nasketucket Bay watershed are summarized in Table IV-1.

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 Nasketucket Bay 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 17 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 a Nasketucket Bay 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.

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 Nasketucket Bay study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), lawn fertilizers, agricultural sources, freshwater wetlands, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to each component sub-embayment, by each source category (Figure IV-4). The annual watershed nitrogen input is then reduced by natural nitrogen attenuation in the rivers during transport and the estuary receives this reduced load. There are no ponds of significant size to provide additional attenuation within the watershed. The nitrogen loads used in the MEP embayment water quality sub-model are a combination of the estimated loads in Table IV-2 and the measured loads from the rivers discussed in Section IV.2.

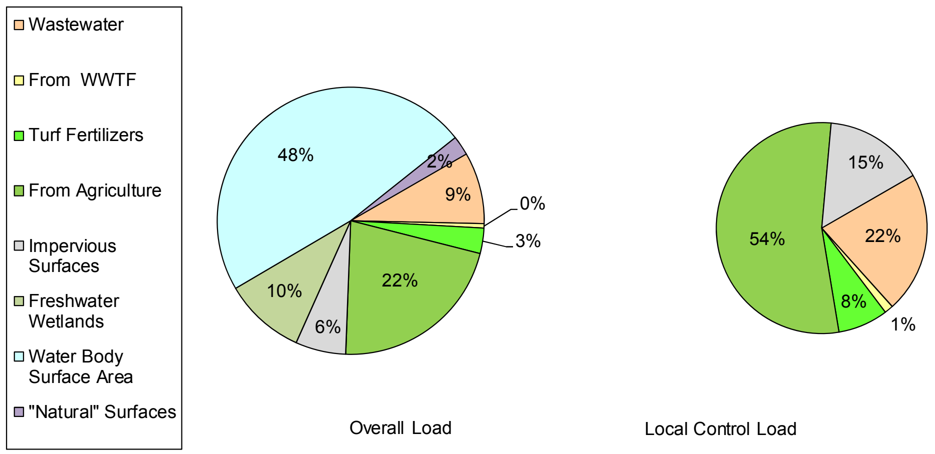
Table IV-1. Primary Nitrogen Loading Factors used in the Nasketucket Bay MEP analysis. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from watershed-specific data

Nitrogen Concentrations:	mg/l	Recharge Rates:[2]	in/yr
Road Run-off	1.5	Impervious Surfaces	45.7
Roof Run-off	0.75	Natural and Lawn Areas	30.46
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing developed parcels wo/water accounts and buildout single family residence parcels	109 gpd[3]
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)[1]	5,000	Multi-family residential parcels	236 gpd
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08	Existing developed parcels w/water accounts:	Measured annual water use
Nitrogen leaching rate	20%	Commercial and Industrial Buildings buildout additions[4]	
Average Single Family Residence Building Size (watershed average; sq ft)	1,504	Commercial	
Average other Residential Building Size (watershed average; sq ft)	2,337	Wastewater flow (gpd/1,000 ft2 of building):	136
Farm Animals	kg/yr /animal	Building lot coverage:	15%
Horse	32.4		
Cow/Steer	55.8	Industrial	
Goats	7.3	Wastewater flow (gpd/1,000 ft2 of building):	15
Hogs	14.5	Building lot coverage:	21%
Chickens	0.4	Crops	kg/ha/yr
Animal N leaching rate	40%	Hay, Pasture	5
		Hay, Pasture leaching rate	100%[5]
		Corn, Vegetables, Vineyard, Fruit	34
		Crop N leaching rate	30%

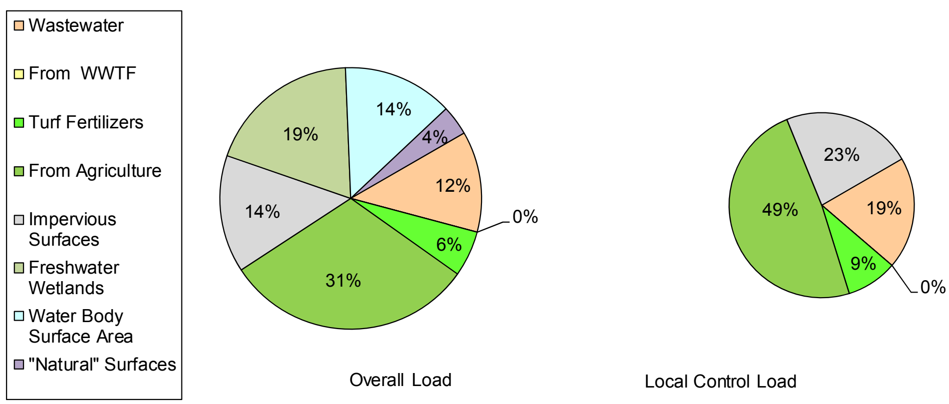
Notes:
1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
2) Based on precipitation rate of 50.77 inches per year (1971-2000 NOAA average for closest long-term precipitation gauge (New Bedford))
3) Nasketucket Bay watershed average from single-family residences with water use accounts
4) Based on characteristics of Town of Fairhaven land uses within the watershed: existing water use and building coverage for similarly classified properties (no commercial or industrial land uses are located in the Mattapoisett portion of the watershed)
5) Hay, Pasture leaching rate is 100% because the assigned nitrogen loading rate already incorporates a leaching rate

Table IV-2. Nasketucket Bay / Little Bay Watershed Nitrogen Loads. Existing and buildout unattenuated and attenuated nitrogen loads by subwatershed are shown along with breakdowns into component sources. Nitrogen loads for estuarine surface waters are shown in separate rows (green rows). Attenuated nitrogen loads are based on measured and assigned attenuation factors for streams (see Section IV.2). All nitrogen loads are kg N yr^{-1}.

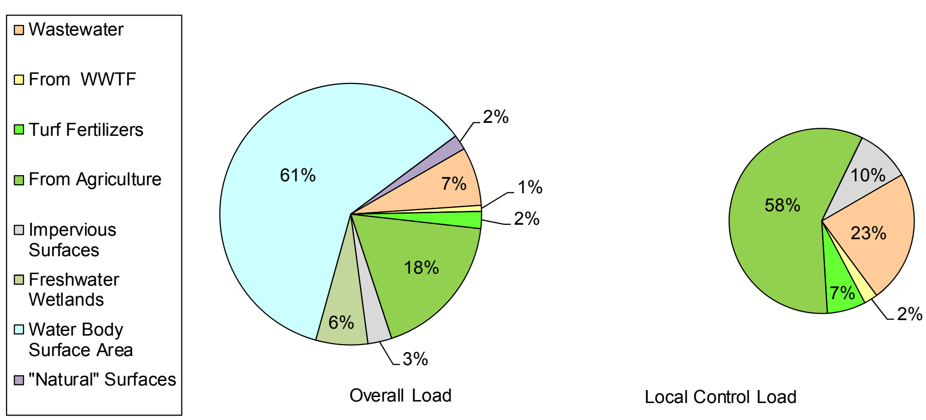
		Nasketucket Bay N Loads by Input (kg/y):									Present N Loads			Buildout N Loads		
Watershed Name	shed ID#	Wastewater	From WWTF	Turf Fertilizers	From Agriculture	Impervious Surfaces	Freshwater Wetlands	Water Body Surface Area	"Natural" Surfaces	Buildout	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Nasketucket Bay System		**3,099**	**194**	**1,098**	**7,732**	**2,178**	**3,522**	**17,056**	**841**	**9,046**	**35,719**		**34,557**	**44,765**		**42,973**
Little Bay		1,212	-	550	3,006	1,409	1,850	1,324	357	4,509	9,706		9,005	14,216		13,096
Nasketucket River Main	1	657	-	134	2,463	395	1,547	2	195	3,220	5,393	13%	4,692	8,613	13%	7,493
Nasketucket River West	2	184	-	37	4	497	109	-	32	375	864		864	1,238		1,238
Nasketucket River East	3	91	-	73	14	130	6	-	10	184	324		324	508		508
Nonquitt Brook	4	45	-	120	127	130	68	1	20	150	512		512	662		662
Little Bay	5	235	-	185	398	256	119	93	100	580	1,386		1,386	1,966		1,966
Little Bay Estuary Surface								1,228			1,228		1,228	1,228		1,228
Outer Bay		1,887	194	548	4,726	769	1,672	15,732	484	4,537	26,013		25,552	30,550		29,877
Shaws Cove Brook West	6	28	-	82	1,098	110	176	2	41	707	1,537	30%	1,076	2,244	30%	1,571
Shaws Cove Brook East	7	43	-	10	1,348	12	79	-	33	412	1,526		1,526	1,938		1,938
Shaws Cove	8	61	-	8	135	9	6	-	29	25	248		248	273		273
Brandt Beach	9	779	-	106	-	150	395	14	84	916	1,528		1,528	2,444		2,444
Brandt Island Cove	10	183	-	24	16	32	262	-	81	903	599		599	1,502		1,502
Antassawamock	11	333	-	45	167	41	116	0	17	149	718		718	867		867
Sconticut Neck North	12	87	-	45	1,035	62	25	-	29	434	1,282		1,282	1,716		1,716
Sconticut Neck South	13	51	-	7	922	35	264	-	53	105	1,332		1,332	1,437		1,437
Round Cove	14	37	-	45	-	66	-	-	5	79	154		154	233		233
West Island West	15	243	-	145	-	204	137	-	32	679	761		761	1,440		1,440
West Island East	16	24	194	24	-	42	211	-	68	96	562		562	659		659
Nasketucket Bay Proper	17	19	-	7	5	6	-	-	12	31	49		49	79		79
Shaws Cove Estuary Surface								130			130		130	130		130
Brandt Beach Estuary Surface								8			8		8	8		8
Brandt Island Cove Estuary Surface								729			729		729	729		729
Sconticut Neck South Estuary Surface								64			64		64	64		64
Round Cove Estuary Surface								480			480		480	480		480
West Island East Estuary Surface								98			98		98	98		98
West Island West Estuary Surface								149			149		149	149		149
Nasketucket Bay Proper Estuary Surface								14,058			14,058		14,058	14,058		14,058



a. Whole Nasketucket Bay System



b. Little Bay



c. Outer Bay

Figure IV-4. Land use-specific unattenuated nitrogen loads (by percent) to the a) whole Nasketucket Bay watershed, b) the Little Bay subwatershed and c) the Outer Bay subwatershed. “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. "Water body surface area" includes atmospheric inputs to both freshwater ponds and the estuary surface.

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, 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, and 4) results are discussed with town staff and/or planning board members and the analysis results are modified based on local knowledge.

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 Nasketucket Bay watershed initial MEP buildout did, however, include, a removal of wetland areas (based on the MassGIS coverage) prior to applying the minimum lot size calculations. Additional build-out scenarios can be run at the request of the Towns.

The fourth step, the discussions with town planners, and, town boards (and wastewater consultants), typically generates some additional insights on planned development, and includes discussion of developments planned for government or public service parcels, and updates to assessor classifications, including lands purchased by the town as open space. Other provisions of the MEP buildout assessment include differentiated treatment of undevelopable lots, commercial and industrial properties, and lots less than the minimum areas specified by zoning. Properties classified by the town assessor 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). 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.

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 located 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 of 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.

In the Nasketucket Bay watershed, the MEP buildout approach was used within the Town of Mattapoisett, but another approach was used within the Town of Fairhaven. The initial Mattapoisett buildout was forwarded to the Town Planning Board and the overall approach was discussed with board staff and the chair. 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 2010 estimates. The BBNEP buildout approach 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)]. 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 Nasketucket Bay watershed. The Fairhaven buildout also includes assignment of future sewer connections for buildout additions. The final Fairhaven buildout includes some future development on properties with land use categories that are excluded from additional development in the Mattapoisett buildout.

All the parcels with additional buildout potential within the Nasketucket Bay / Little Bay watershed under the MEP buildout scenario are shown in Figure IV-5 and details for individual parcels are included in the MEP Data Disk that accompanies this report. Refinements of the watershed 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.

The MEP buildout scenario for the Nasketucket Bay / Little Bay watershed includes 2,508 additional residential units (135 with sewer connections) and 82,930 square feet of commercial buildings. Each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces minus the sewer corrections in Fairhaven. Residential additions also include lawn fertilizer nitrogen additions. All wastewater loads in the watershed are assumed to come from on-site septic systems. Cumulative unattenuated and attenuated buildout loads are indicated in separate columns in Table IV-2. Buildout additions within the Nasketucket Bay / Little Bay watersheds will increase the attenuated nitrogen loading rate by 24%.

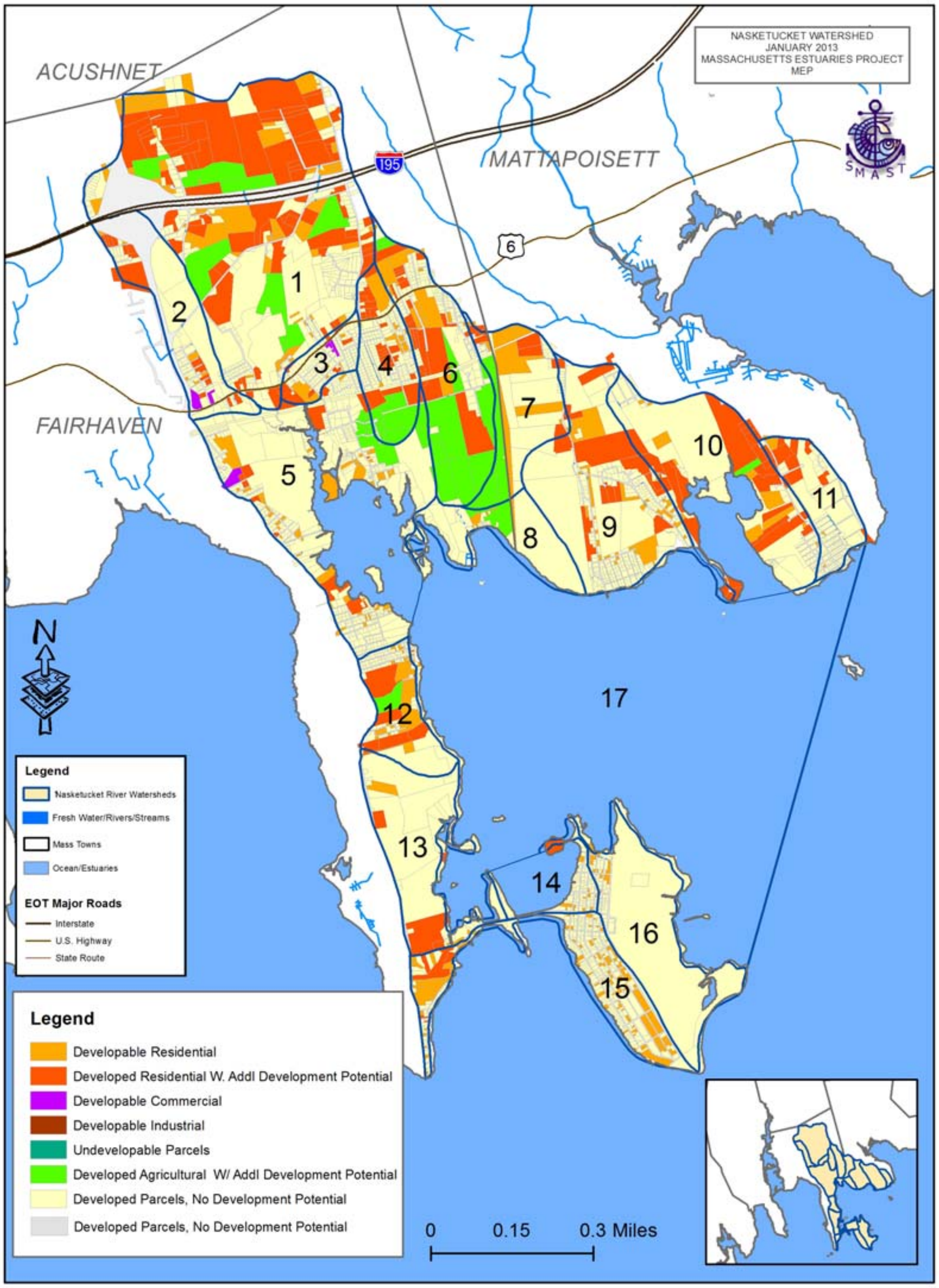


Figure IV-5. Parcels, Parcelized Watersheds, and Developable Parcels in the Nasketucket Bay / Little Bay watersheds. Parcels colored orange, purple, and brown are classified by the town assessors' as developable parcels (residential, commercial, and industrial, respectively). Parcels colored dark orange and bright green are developed parcels residential and agricultural parcels with additional development potential based on town zoning. The Fairhaven buildout assessment was completed by the BBNEP, while the Mattapoisett assessment was completed by MEP staff. The parcelized watersheds are drawn to minimize the division of properties for management purposes while achieving a match of area with the watershed delineations of 2% or less. Parcels with additional development potential are assigned nitrogen loads in the MEP buildout scenario.

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 relative to the tidal flushing and nitrogen cycling within the embayment basins. 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 Nasketucket Bay System being investigated under this nutrient threshold analysis were 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 watershed for the Nasketucket Bay embayment system, a portion of the freshwater flow and transported nitrogen passes through several surface water systems (e.g. the Nasketucket River (east and west tributaries) discharging to the head of Little Bay, an un-named stream discharging to the Knollmere salt marsh and Little Bay and an un-named stream discharging to Shaws Cove) prior to entering the 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 2000). Similarly, MEP analysis of the Quashnet River (Town of Falmouth, Cape Cod) indicated 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. Therefore, 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 in the Nasketucket Bay embayment system. MEP conducted long-term measurements of natural attenuation relating to the surface water discharges to the estuary in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). These additional site-specific studies were conducted in the 4 main surface water flow systems in the Nasketucket Bay embayment, 1) Nasketucket River west tributary (gauge 1), 2) Nasketucket River Main, east tributary (gauge 2), 3) Nonquitt Brook flowing to the Knollmere salt marsh and 4) creek discharging to Shaws Cove.

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 streams discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area upgradient from the various gauging sites. Flow and nitrogen load were measured at the gauges in each freshwater stream site for between 16 and 18 months of record depending on the stream gauging location (Figures IV-7 to IV-10). During each study period, velocity profiles were completed on each surface water inflow 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 at each gauge 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/stream/creek/brook. 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 lowest low tide stage values for any given day were utilized in the stage – discharge relation in order to compute daily flow as this stage value is most representative of freshwater flow. A complete annual record of stream flow (365 days) was generated for the surface water discharges flowing into the Nasketucket Bay embayment system.

The annual flow record for the surface water flow at each gauge was merged with the nutrient data set generated through the weekly water quality sampling performed at the gauge locations to determine nitrogen loading rates to the Nasketucket Bay system. Nitrogen discharge from the streams was calculated using the paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through a specific gauging site. For each of the stream gauge locations, weekly water samples were 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 gauged stream currently reduces (percent attenuation) nitrogen loading to the overall embayment systems.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Nasketucket River Gauge 1 (West Tributary) Discharge to headwaters of Little Bay

Like most surface water features in the MEP study region that typically emanate from a specific pond, the west tributary, which discharges into the estuarine reach of the Nasketucket River and the head of Little Bay and the Nasketucket Bay / Little Bay Estuary, does have a series of small up-gradient ponds through which the freshwater passes and from which the river discharges. The Nasketucket River is a moderately complex network of tributary channels that flow through upland habitat as well as bog/wetland areas and a few small ponds and ultimately form two channels (a west tributary {gauge 1} and an east tributary {gauge 2}, the east tributary being the largest of the two) both of which pass under the bike path and come together in a salt marsh to form one tidally influenced channel considered the Nasketucket River. Based on numerous previous studies completed by the MEP on other systems in southeastern Massachusetts, the outflow from the ponds/wetlands and the wooded areas up-gradient of the Nasketucket River (West Tributary) gauge has the potential to contribute to the attenuation of nitrogen and also provides for a direct measurement of the nitrogen attenuation. The combined rate of nitrogen attenuation by the biological processes that occur in the various surface water features was determined by comparing the present predicted (calculated from land use analysis) nitrogen loading to the sub-watershed region contributing to the ponds/wetlands and wooded areas above the gauge site and the measured annual discharge of nitrogen to the estuarine reach of the Nasketucket River at each gauge site, Figure IV-6.

Figure IV-6. Location of Stream gauges (red symbols) on streams discharging to the Nasketucket Bay / Little Bay Estuary. The two main discharges are the two branches of the Nasketucket River, West branch and Main branch (1 and 2 respectively). Nonquitt Brook and Shaws Cove Creek discharge to tributary coves in the system.

At the Nasketucket River gauge 1 site (established at the Fairhaven-Mattapoisett bike path crossing), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the channel that carries the flows and associated nitrogen load to the head of Little Bay and the Nasketucket Bay estuarine system. As the lower reach of the Nasketucket River is tidally influenced, the stage record from the gauge was checked to make sure there was no tidal influence in the record at low tide. To confirm that freshwater was being measured at low tide, the stage record was analyzed for any semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average salinity of the water samples taken from the west Tributary of the Nasketucket River at low tide over the study period was determined to be 0.5 ppt. Therefore, the gauge location was deemed acceptable for making low tide freshwater discharge measurements. Calibration of the gauge was checked monthly. The gauge 1 site on the west Tributary of the Nasketucket River at the bike path was established on June 11, 2005 and was set to operate continuously for 16 months such that a complete hydrologic year would be captured in the flow record. Stage data collection at gauge site 1 continued until December 13, 2006 for a total deployment of 18 months.

Stream flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to the estuarine portion of the Nasketucket River and is reflective of the biological processes occurring in the stream channel, ponds/wetlands and wooded areas contributing to nitrogen attenuation (Figure IV-7 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the U.S. Geological Survey/Buzzards Bay Project/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the gauge site based on area and average recharge.

The annual freshwater flow record for the western tributary of the Nasketucket River as measured by the MEP was compared to the long-term average flows determined by the USGS/BBP/MEP modeling effort (Table III-1). The measured freshwater discharge from the gauge 1 location at the bike path was 7% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year (low flow to low flow) beginning September 2005 and ending in August 2006 was 1,989 m^3/day compared to the long-term average flow determined by watershed water balance of 2,150 m^3/day. The negligible difference between the measured flow and the water balance approach indicate that the river is capturing the upgradient recharge (and loads) accurately.

Total nitrogen concentrations within the outflow of the west tributary of the Nasketucket River were moderately high, 1.584 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 3.15 kg/day and a measured total annual TN load of 1,150 kg/yr. In the west tributary of the Nasketucket River, nitrate made up significantly more than half of the total nitrogen pool (74%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the pond/wetland areas and stream bed up gradient of the gauge was not significantly taken up by plants within these different aquatic systems and transformed to organic forms. Given the relatively high levels of remaining nitrate in the stream discharge, the possibility for additional uptake by surface water systems might be considered for application within the sub-watershed to the western tributary of the Nasketucket River should a suitable location exist for enhancing natural attenuation of nitrogen load prior to discharge to Little Bay.

From the measured nitrogen load discharged by the west tributary of the Nasketucket River to the upper portion of estuarine reach of the Nasketucket River and the nitrogen load determined from the watershed loading analysis, it appears that there is little nitrogen attenuation of upper watershed derived nitrogen during transport to the Nasketucket River 1 gauge site. Based upon the higher total nitrogen load (1,150 kg yr^{-1}) discharged from the west tributary of the Nasketucket River compared to that added by the various land-uses to the associated watershed (864 kg yr^{-1}), the integrated attenuation in passage through the stream watershed prior to discharge to the estuary was set at 0%. This lack of attenuation compared to other streams evaluated under the MEP that also showed very low to no attenuation is expected given the lack of up-gradient pond/wetland conditions capable of attenuating nitrogen. To be conservative, the directly measured nitrogen load from the west tributary of the Nasketucket River was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

Table IV-3. Comparison of water flow and nitrogen load discharged by surface waters (freshwater) to the Nasketucket Bay / Little Bay Estuary. The "Stream" data are from the MEP stream gauging effort. Watershed data are based upon the MEP watershed modeling effort (Section IV.1) and the combination of USGS watershed delineations and watershed delineation information provided by the Buzzards Bay Project. Delineations were reviewed by MEP Technical Team and sub-watershed delineations were developed by the MEP (Section III).

Stream Discharge Parameter	Nasketucket River		Little Bay	Shaws Cove	Data Source
	Nasketucket River 1 Discharge[(a)] (west)	Nasketucket River 2 Discharge[(a)] (main)	Nonquit Brook Discharge[(a)]	Un-named Stream Discharge[(a)]	
Total Days of Record	365[(b)]	365[(b)]	365[(b)]	365[(b)]	(1)
Flow Characteristics					
Stream Average Discharge (m3/day) **	1989	11532	1504	2875	(1)
Contributing Area Average Discharge (m3/day)	2150	11613	1564	3192	(2)
Discharge Stream 2002-03 vs. Long-term Discharge	7%	1%	4%	10%	
Nitrogen Characteristics					
Stream Average Nitrate + Nitrite Concentration (mg N/L)	1.174	0.401	0.851	0.256	(1)
Stream Average Total N Concentration (mg N/L)	1.584	1.109	1.385	1.020	(1)
Nitrate + Nitrite as Percent of Total N (%)	74%	36%	61%	25%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	3.15	12.79	2.08	2.93	(1)
TN Average Contributing UN-attenuated Load (kg/day)	2.37	14.77	1.4	4.21	(3)
Attenuation of Nitrogen in Pond/Stream (%)	0%	13%	0%	30%	(4)

(a) Flow and N load to streams discharging to Nasketucket / Little Bay Estuary includes apportionments of Pond contributing area as appropriate.
(b) September 1, 2005 to August 31, 2006.
** Flow record for the stream (Knollmere) discharge to Little Bay is for the period 10/1/05 to 9/31/06

(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 streams to Little Bay and Nasketucket Bay;
and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates.
(4) Calculated based upon the measured TN discharge from the rivers vs. the unattenuated watershed load. (-) attenuation is considered as zero.

Table IV-4. Summary of annual volumetric discharge and nitrogen load from the four major surface water discharges to the Nasketucket Bay / Little Bay Estuarine System (based upon the data presented in Figures IV-7 through IV-10 and Table IV-3.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Nasketucket River 1 (MEP)	**September 1, 2005 to August 31, 2006**	**725945**	**852**	**1150**
Nasketucket River 1 (CCC)	Based on Watershed Area and Recharge	**784750**		
Nasketucket River 2 (MEP)	**September 1, 2006 to August 31, 2007**	**4209093**	**1689**	**4669**
Nasketucket River 2 (CCC)	Based on Watershed Area and Recharge	**4238745**		
Stream discharge to Little Bay (Knollmere) MEP	**September 1, 2006 to August 31, 2007**	**548854**	**467**	**760**
Stream discharge to Little Bay (Knollmere) CCC	Based on Watershed Area and Recharge	**570860**		
Stream discharge to Shaws Cove (MEP)	**September 1, 2006 to August 31, 2007**	**1049375**	**269**	**1071**
Stream discharge to Shaws Cove (CCC)	Based on Watershed Area and Recharge	**1165080**		

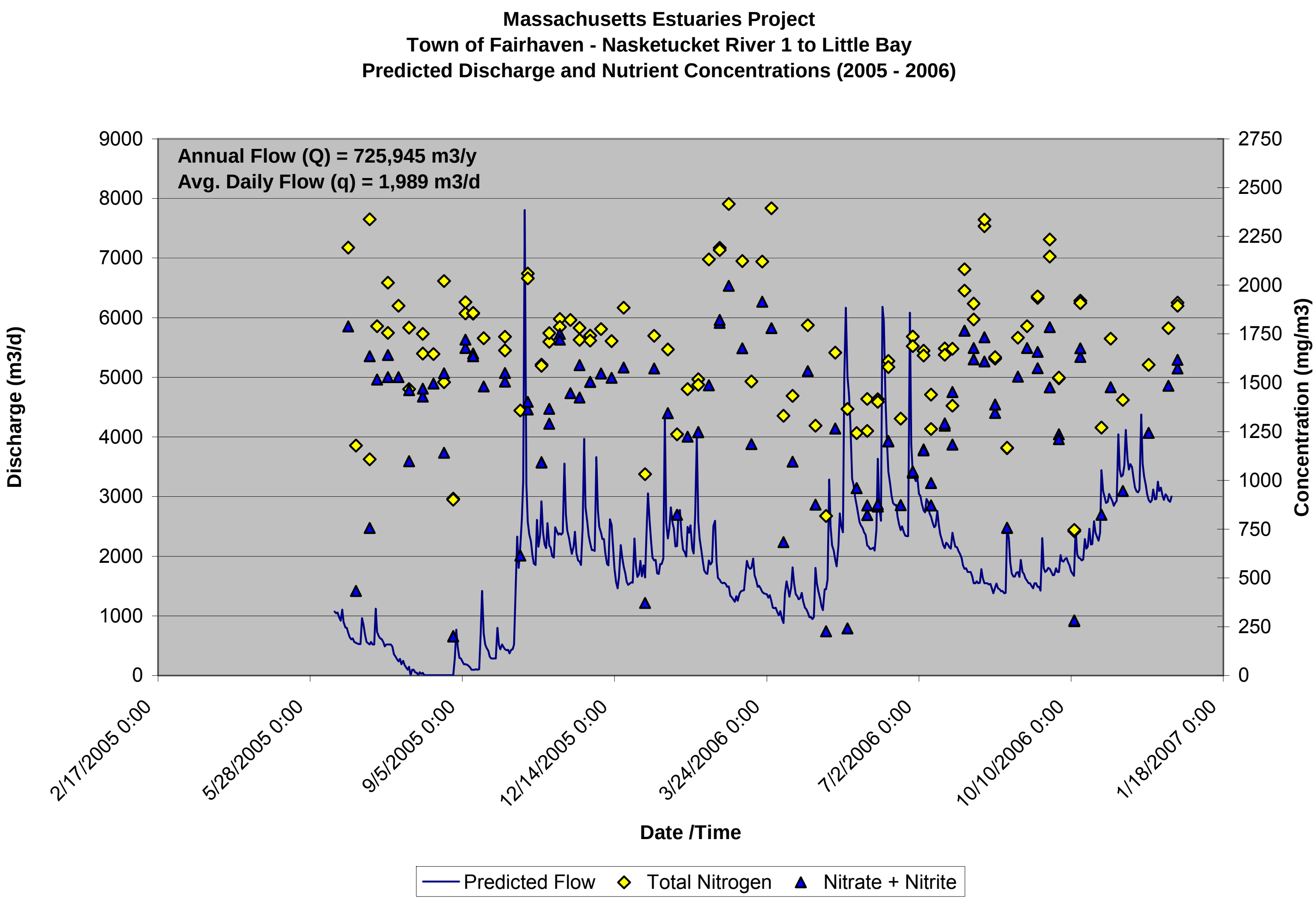


Figure IV-7. Discharge from Nasketucket River (Branch 1) (solid blue line), total nitrogen (yellow symbols) and NOx (blue symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of the Nasketucket River discharging to the head of Little Bay / Nasketucket Bay Estuary (Table IV-3).

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Nasketucket River Main, Gauge 2 (East Tributary) Discharge to headwaters of Little Bay

Like most surface water features in the MEP study region that typically emanate from a specific pond, the east tributary (considered the main reach of the Nasketucket River), which discharges into the estuarine reach of the Nasketucket River and the head of Little Bay and the Nasketucket Bay Estuary, does have a series of small up-gradient ponds through which the river flows and from which the river discharges. The Nasketucket River is a moderately complex network of tributary channels that flow through upland habitat as well as bog/wetland areas and a few small ponds and ultimately form two main channels (a west tributary {gauge 1} and an east tributary {gauge 2}, the east tributary being the largest of the two and both of which pass under the bike path and come together in a salt marsh to form one tidally influenced channel considered the Nasketucket River. Based on numerous previous studies completed by the MEP on other systems in southeastern Massachusetts, the outflow from the ponds/wetlands and the wooded areas up-gradient of the Nasketucket River (East Tributary) gauge very likely contribute to the attenuation of nitrogen and also provides for a direct measurement of the nitrogen attenuation. The combined rate of nitrogen attenuation by the biological processes that occur in the various surface water features was determined by comparing the present predicted (calculated from land use analysis) nitrogen loading to the sub-watershed region contributing to the ponds/wetlands and wooded areas above the gauge site and the measured annual discharge of nitrogen to the estuarine reach of the Nasketucket River and the head of the Little Bay portion of Nasketucket Bay, Figure IV-6.

At the Nasketucket River gauge 2 site (established at the Fairhaven-Mattapoisett bike path crossing), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the channel that carries the flows and associated nitrogen load to the head of Little Bay and the Nasketucket Bay estuarine system. As the lower reach of the Nasketucket River is tidally influenced, the stage record from the gauge was checked to make sure there was no tidal influence in the record at low tide. To confirm that freshwater was being measured at low tide, the stage record was analyzed for any semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average salinity of the water samples taken from the East Tributary of the Nasketucket River at low tide was determined to be 0.4 ppt. Therefore, the gauge location was deemed acceptable for making freshwater flow measurements at low tide. Calibration of the gauge was checked monthly. The gauge 2 site on the east Tributary of the Nasketucket River at the bike path was established on June 11, 2005 and was set to operate continuously for 16 months such that a complete hydrologic year would be captured in the flow record. Stage data collection continued until December 13, 2006 for a total deployment of 18 months.

Stream flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to the estuarine portion of the Nasketucket River and is reflective of the biological processes occurring in the stream channel, ponds/wetlands and wooded areas contributing to nitrogen attenuation (Figure IV-8 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the U.S. Geological Survey/Buzzards Bay Project/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the gauge site based on area and average recharge.

The annual freshwater flow record for the eastern tributary of the Nasketucket River (gauge 2) as measured by the MEP was compared to the long-term average flows determined by the USGS/BBP/MEP modeling effort (Table III-1). The measured freshwater discharge from the Nasketucket River gauge 2 location at the bike path was 1% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year (low flow to low flow) beginning September 2005 and ending in August 2006 was 11,532 m^3/day compared to the long term average flows determined by the watershed modeling effort (11,613 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the east tributary of the Nasketucket River discharging from the sub-watershed indicate that the river is capturing the upgradient recharge (and loads) accurately.

Total nitrogen concentrations within the outflow of the east tributary of the Nasketucket River were similar to those at western tributary gauge and were moderately high, 1.109 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 12.79 kg/day and a measured total annual TN load of 4,669 kg/yr. In the east tributary of the Nasketucket River, nitrate made up well less than half of the total nitrogen pool (36%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the pond/wetland areas and stream bed upgradient of the gauge was being transformed and likely attenuated within the upgradient aquatic systems. Given the relatively low levels of remaining nitrate in the stream discharge, the possibility for additional uptake by freshwater systems might be limited in the sub-watershed to the eastern tributary of the Nasketucket River.

From the measured nitrogen load discharged by the east tributary of the Nasketucket River to the upper portion of estuarine reach of the Nasketucket River and the nitrogen load determined from the watershed based land use analysis, it appears that there is moderate nitrogen attenuation of upper watershed derived nitrogen during transport to the Nasketucket River 2 gauge site and the upper portion of Little Bay and the broader Nasketucket Bay estuary. Based upon lower total nitrogen load (4,669 kg yr^{-1}) discharged from the east tributary of the Nasketucket River compared to that added by the various land-uses to the associated watershed (5,393 kg yr^{-1}), the integrated attenuation in passage through the stream and up-gradient freshwater ponds/wetlands prior to discharge to the estuary is 13% (i.e. 13% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the nature of the up-gradient watershed and the number of pond/wetland areas capable of attenuating nitrogen. The directly measured nitrogen load from the east tributary of the Nasketucket River was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

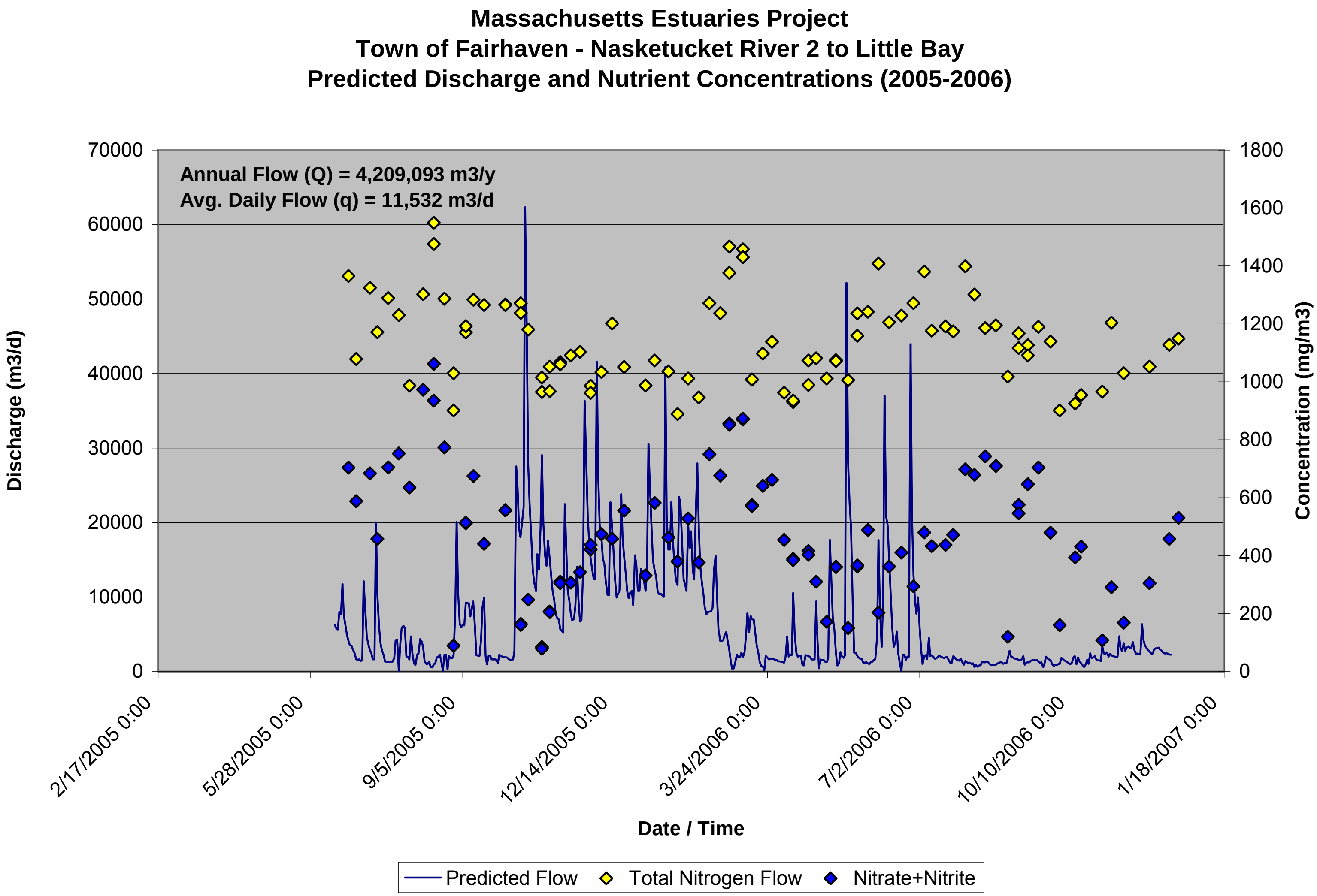


Figure IV-8. Discharge from Nasketucket River main (East Branch, gauge 2) (solid blue line), total nitrogen (yellow symbols) and NOx (blue symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of the Nasketucket River discharging to the head of Little Bay / Nasketucket Bay Estuary (Table IV-3)

V.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Nonquitt Stream Discharging to Knollmere Salt Marsh and Little Bay

Nonquitt Brook discharges into Knollmere Marsh and Little Bay with a watershed defined primarily by topography. Unlike most surface water features in the MEP study region that typically emanate from a specific pond, Nonquitt Brook emanates from a wooded sub-watershed and appears to be primarily groundwater fed, but is influenced directly by run-off from the land during precipitation events. Mostly, this stream flows through wooded upland, agricultural land and somewhat boggy areas up-gradient of the stream gauge site. The Nonquitt Brook outflow from the wooded uplands just prior to discharging to the salt marsh at Knollmere and then Little Bay allows for a direct measurement of the nitrogen attenuation that results primarily from stream riparian zones and channel bed as opposed to that which would be achieved by biological processes occurring in ponds (which would be more typical of streams previously monitored by the MEP in southeastern Massachusetts). The combined rate of nitrogen attenuation by the biological processes occurring as the water in the brook flows to the estuary was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the wooded areas above the gauge site and the measured annual discharge of nitrogen to the salt marsh portion of Little Bay (at Knollmere) relative to the gauge, Figure IV-6.

The freshwater flow carried by Nonquitt Brook was determined using a continuously recording vented calibrated water level gauge. As this surface water system was potentially tidally influenced, the creek discharge was checked to confirm the extent of tidal influence and whether freshwater flow could be measured at low tide in the estuary. To confirm that freshwater was being measured, salinity measurements were conducted on weekly water quality samples collected from the gauge site. Average measured sample salinity at low tide was found to be 0.1 ppt, indicating no tidal influence at the gauge location. As such, the stream gauge location was deemed acceptable for making flow measurements and obtaining an estimate of annual freshwater flow. Calibration of the gauge was checked monthly. The gauge was installed on June 18, 2005 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Actual stage data collection continued until December 15, 2006 for a total deployment of 18 months.

Flow in the brook to the Knollmere salt marsh (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to Little Bay and is reflective of the biological processes occurring in the wooded areas as precipitation recharges the groundwater flow system and freshwater flows over the channel bed of the stream. All these processes contribute to nitrogen attenuation (Figure IV-9 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the U.S. Geological Survey/Buzzards Bay Project/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the stream gauge site based on area and average recharge.

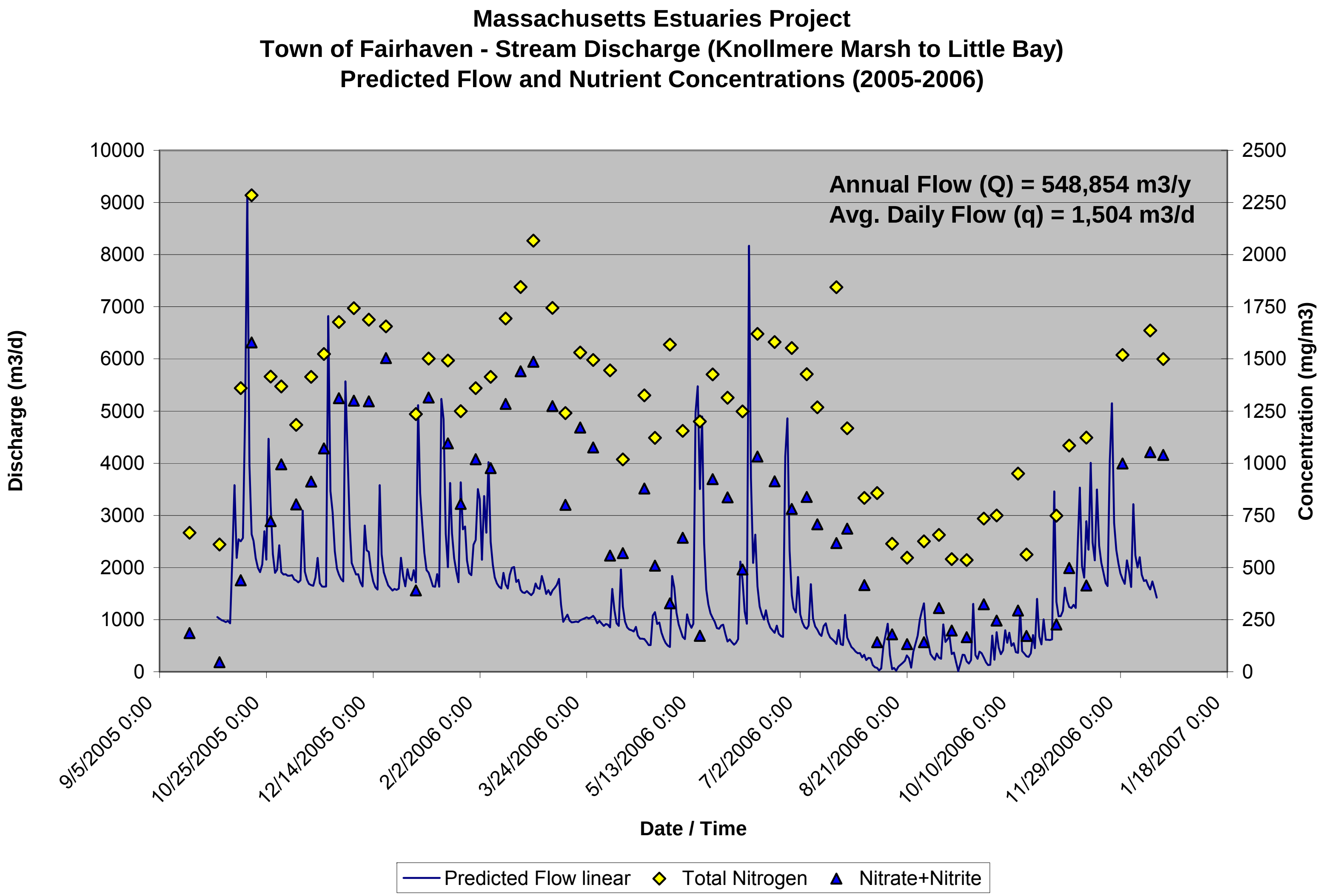


Figure IV-9. Discharge from Nonquitt Brook into Knollmere marsh and Little Bay (solid blue line), total nitrogen (yellow symbols) and NOx (blue symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of the stream discharging to Little Bay (Table IV-3).

The annual freshwater flow record for the stream as measured by the MEP was compared to the long-term average flows determined by the USGS/BBP/MEP modeling effort (Table III-1). The measured freshwater discharge from the stream was 4% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year beginning September 2005 and ending in August 2006 (low flow to low flow) was 1,504 m^3/day compared to the long term average flows determined by the watershed modeling effort (1,564 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in stream discharging from the sub-watershed to the brook at Knollmere indicates that the brook is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Nonquitt Brook outflow to Little Bay and Nasketucket Bay were high, 1.385 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 2.08 kg/day and a measured total annual TN load of 760 kg/yr. In this small stream, nitrate made up more than half of the total nitrogen pool (61%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the up-gradient wetland areas as well as the channel bed up gradient of the gauge was only transformed by plants within the stream system to dissolved and particulate organic nitrogen which together represent 37 percent of the total nitrogen pool in the stream discharge. Given the moderate levels (61% of total nitrogen) of remaining nitrate in the stream discharge, the possibility for additional uptake by freshwater systems should be considered in the stream sub-watershed if appropriate natural features exist that can be restored or managed in a way that enhances the potential for natural attenuation.

From the measured nitrogen load discharged by the brook to Knollmere marsh and the nitrogen load determined from the watershed based land use analysis, it appears that there is little to no nitrogen attenuation of upper watershed derived nitrogen during transport to the Nonquitt Brook gauge site and the upper portion of Little Bay and the broader Nasketucket Bay estuary. Based upon the higher total nitrogen load (760 kg yr^{-1}) discharged from the brook compared to that added by the various land-uses to the associated watershed (512 kg yr^{-1}), the integrated attenuation in passage through the stream watershed prior to discharge to the estuary was set at 0%. This lack of attenuation compared to other streams evaluated under the MEP that also showed very low to no attenuation is expected given the lack of up-gradient pond/wetland conditions capable of attenuating nitrogen. It is likely that the small loads in this stream made resolution of attenuation difficult. To be conservative, the directly measured nitrogen load from Nonquitt Brook was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Shaws Cove Brook Discharge to Shaws Cove Marsh – Shaws Cove to Outer Little Bay

Shaws Cove Brook discharges into Shaws Cove via a salt marsh and has a watershed defined primarily by topography. Unlike most surface water features in the MEP study region that typically emanate from a specific pond, Shaws Cove Brook (like nearby Nonquitt Brook) emanates from a wooded sub-watershed and appears to be primarily groundwater fed, but is influenced directly by run-off from the land during precipitation events. Mostly, this brook flows through wooded upland, agricultural land and somewhat boggy areas up-gradient of the stream gauge site. The Shaws Cove Brook outflow just prior to discharging to Shaws Cove Marsh allows for a direct measurement of the nitrogen attenuation that results primarily from stream riparian zones and channel bed as opposed to that which would be achieved by biological processes occurring in ponds (which would be more typical of streams previously monitored by the MEP in southeastern Massachusetts). The combined rate of nitrogen attenuation by the biological processes occurring during freshwater transport through the watershed was determined by comparing the present predicted nitrogen loading to the sub-watershed region above the gauge site and the measured annual discharge of nitrogen at the gauge site, Figure IV-6.

The freshwater flow carried by this small un-named stream discharging to Shaws Cove (called herein "Shaws Cove Brook") was determined using a continuously recording vented calibrated water level gauge. As this surface water system was potentially tidally influenced, the creek discharge was checked to confirm the extent of tidal influence and whether freshwater flow could be measured at low tide in the estuary. To confirm that freshwater was being measured, salinity measurements were conducted on weekly water quality samples collected from the gauge site. Average measured sample salinity at low tide over the study period was found to be 2.8 ppt, indicating an insignificant tidal influence at the gauge location. As stage at the gauge location showed tidal influence, only stage at the time of low tide was utilized to represent freshwater flow in the stream. The stream gauge location was deemed acceptable for making flow measurements and obtaining an estimate of annual freshwater flow. Calibration of the gauge was checked monthly. The gauge was installed on June 17, 2005 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Stage data collection continued until December 19, 2006 for a total deployment of 18 months.

Flow in the stream to Shaws Cove (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the gauge site based upon these flow measurements and the measured water levels at the gauge site. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to Shaws Cove and is reflective of the biological processes occurring in the wooded areas as precipitation recharges the groundwater flow system, the channel bed of the brook and the wetlands contributing to nitrogen attenuation (Figure IV-10 and Table IV-3 and IV-4). In addition, a water balance was constructed based upon the U.S. Geological Survey/Buzzards Bay Project/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the stream gauge site based on area and average recharge.

The annual freshwater flow record for the stream as measured by the MEP was compared to the long-term average flows determined by the USGS/BBP/MEP modeling effort (Table III-1). The measured freshwater discharge from the stream was 10% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year (low flow to low flow) beginning September 2005 and ending in August 2006 was 2,875 m^3/day compared to the long term average flows determined by the watershed modeling effort (3,192 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Shaws Cove Brook discharging from the sub-watershed to Shaws Cove indicates that the stream is capturing the up-gradient recharge (and loads) accurately.

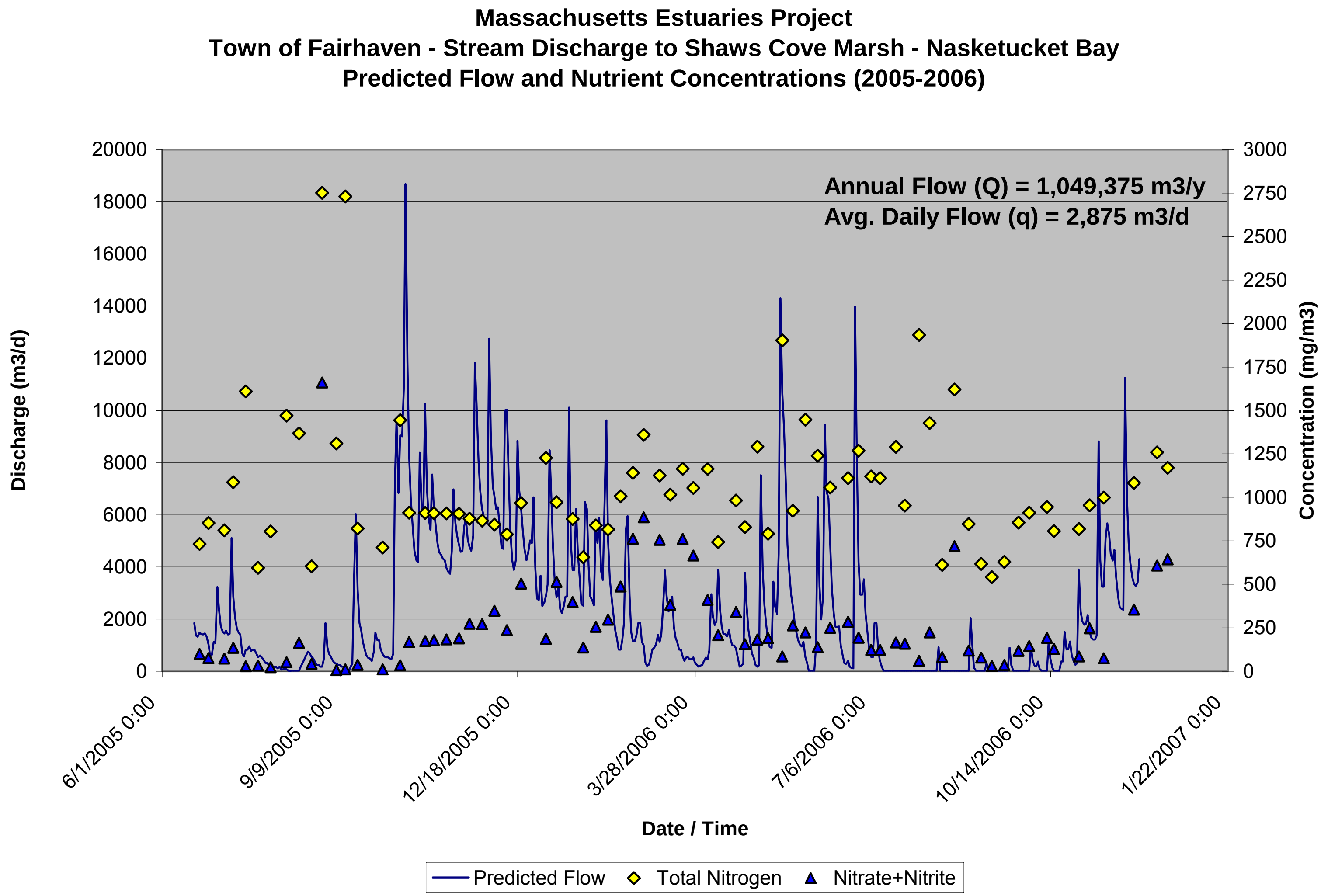


Figure IV-10. Discharge from Shaws Cove Brook into Shaws Cove marsh and Nasketucket Bay (solid blue line), total nitrogen (yellow symbols) and NOx (blue symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of the stream discharging to Shaws Cove / Nasketucket Bay Estuary (Table IV-3).

Total nitrogen concentrations within the stream outflow to Shaws Cove and Nasketucket Bay were high, 1.020 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 2.93 kg/day and a measured total annual TN load of 1,071 kg/yr. In this small stream, nitrate made up well less than half of the total nitrogen pool (25%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the up-gradient wetland areas as well as the channel bed up gradient of the gauge was mostly taken up by plants within these different aquatic systems and converted to dissolved and particulate organic Nitrogen which together represents 73 percent of the total nitrogen entering Shaws Cove and Nasketucket Bay. Given the relatively low levels of remaining nitrate in the stream discharge, the possibility for additional uptake by freshwater systems would be limited in the Shaws Cove sub-watershed.

From the measured nitrogen load discharged by the stream to Shaws Cove Marsh and the nitrogen load determined from the watershed based land use analysis, it appears that there is significant nitrogen attenuation of upper watershed derived nitrogen during transport to the stream and the Shaws Cove portion of the Nasketucket Bay estuary. Based upon lower total nitrogen load (1,071 kg yr^{-1}) discharged from the stream compared to that added by the various land-uses to the associated watershed (1,537 kg yr^{-1}), the integrated attenuation in passage through the stream and up-gradient wooded areas and wetlands prior to discharge to the estuary is 30% (i.e. 30% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the nature of the up-gradient wetland/wooded areas capable of attenuating nitrogen and the lack of ponds in the sub-watershed up-gradient of the stream gauging location. The directly measured nitrogen load from the stream to Shaws Cove was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

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 Nasketucket Bay / Little Bay Estuarine System, inclusive of coves around West Island as well as Brandt Island Cove, tributary to Nasketucket Bay. 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 Nasketucket Bay Estuary 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 sediments. 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 associated nitrogen "load" become incorporated into the surficial sediments of the system.

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 nitrogen enrichment 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 much of the bordering region to the Lewis Bay main basin in the Town of Barnstable, Cape Cod and in the present case, in the analogus open water areas in the western main basin of Nasketucket Bay to the south of West Island. In contrast, regions of high deposition like Hyannis Inner Harbor, also part of the Lewis Bay system, but essentially a dredged boat basin, typically support anoxic sediments with elevated rates of nitrogen release during summer months. The consequence of this deposition is that these basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

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 Nasketucket Bay 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 overall Nasketucket Bay 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 a total of 42 sites in the Nasketucket Bay system. Cores were spatially distributed throughout the estuarine reach of the Nasketucket River, Little Bay, Nasketucket Bay and the small coves around West Island. All the sediment cores for this system were collected in July-August 2005. 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 shoreside lab established at a private residence on West Island. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from core sites to replace the headspace water of each core prior to incubation. The number of core samples from each estuarine component (Figure IV-11) are as follows:

Nasketucket Bay / Little Bay Benthic Nutrient Regeneration Cores

- NSK-1 1 core (Nasketucket Bay-outer)
- NSK-2 1 core (Nasketucket Bay-outer)
- NSK-3 1 core (Nasketucket Bay-outer)
- NSK-4 1 core (Nasketucket Bay-outer)
- NSK-5 1 core (Nasketucket Bay-outer)
- NSK-6 1 core (East Cove - West Island)
- NSK-7 1 core (East Cove - West Island)
- NSK-8 1 core (Nasketucket Bay)
- NSK-9 1 core (Nasketucket River)
- NSK-10 1 core (Nasketucket River)
- NSK-11 1 core (Little Bay)
- NSK-12 1 core (Little Bay)
- NSK-13/14 2 cores (Little Bay)
- NSK-15 1 core (Little Bay)
- NSK-16 1 core (Little Bay)
- NSK-17 1 core (Little Bay)
- NSK-18 1 core (Little Bay)
- NSK-19 1 core (Little Bay)
- NSK-20 1 core (Nasketucket Bay)
- NSK-21 1 core (Nasketucket Bay)
- NSK-22 1 core (Nasketucket Bay)
- NSK-23 1 core (Nasketucket Bay)
- NSK-24 1 core (Nasketucket Bay)
- NSK-25 1 core (Brandt Island Cove)
- NSK-26 1 core (Brandt Island Cove)
- NSK-27 1 core (Brandt Island Cove)
- NSK-28 1 core (Brandt Island Cove)
- NSK-29 1 core (Nasketucket Bay)
- NSK-30 1 core (Nasketucket Bay)
- NSK-31 1 core (Nasketucket Bay)
- NSK-32 1 core (Nasketucket Bay)
- NSK-33 1 core (Shaws Cove)
- NSK-34 1 core (Shaws Cove)
- NSK-35 1 core (Shaws Cove)
- NSK-36 1 core (Nasketucket Bay)
- NSK-37 1 core (Nasketucket Bay – West Island)
- NSK-38 1 core (Nasketucket Bay – West Island)
- NSK-39/40 2 cores (Nasketucket Bay – West Island)

- NSK-41 1 core (South of West Island Causeway)
- NSK-42 1 core (South of West Island Causeway)

Sampling was distributed throughout the primary component basins of the Nasketucket Bay / Little Bay Estuary and the results were used for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Figure IV-11. Nasketucket Bay / Little Bay Estuary sediment sampling sites (red symbols) for determination of summer nitrogen regeneration rates. Numbers relate to the reference list of cores presented above.

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 at the West Island home of Bill and Judy Pittman, 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°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. (508-910-6325 or d1white@umassd.edu). 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 estuarine sediments most denitrification in sediments occurs as settled organic particles decompose and released ammonium is oxidized to nitrate. Some of this nitrate "escapes" to the overlying water and some is denitrified within the sediment column. Both pathways of denitrification are at work within the Nasketucket Bay System.

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-12).

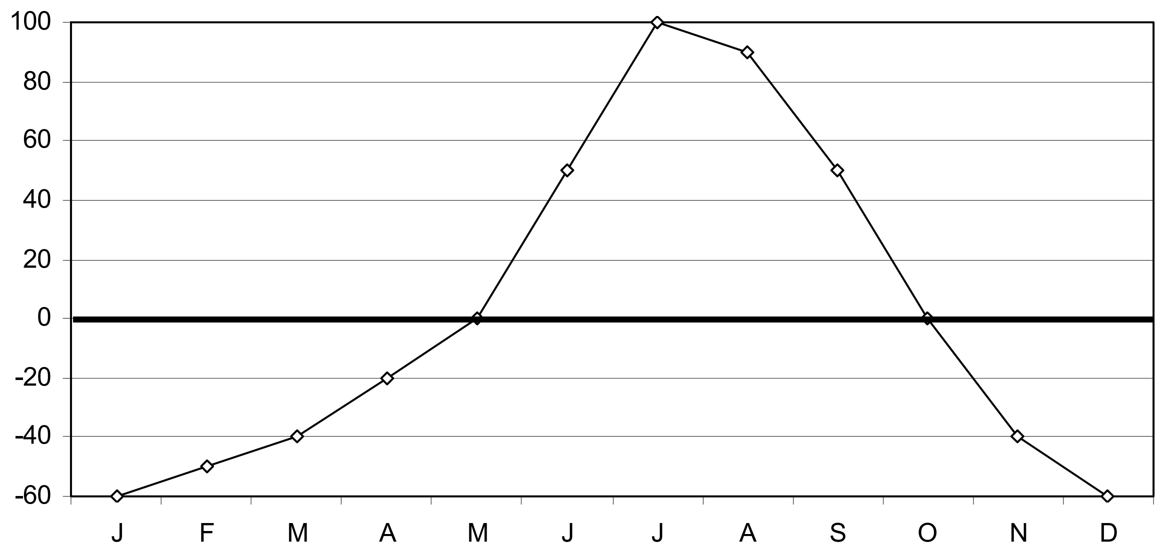


Figure IV-12. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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 each of the three harbors 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 component basins to this large complex estuary (e.g. Nasketucket Bay, Little Bay, Nasketucket River estuarine reach, Brandt Island Cove, Shaws Cove). These direct measurements were made in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model of the Nasketucket Bay /Little Bay Estuary The distribution of cores in each sub-basin 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). Varying levels of settling are 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 fine to medium sands and low organic content and high velocities, then half this settling rate was used and in the rare instance when clean coarse sand with negligible fines was present, than the rate was half again. 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 Nasketucket Bay / Little Bay Estuarine System were comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts. In addition, the spatial pattern of sediment N release was also similar to other systems, with the inner semi-enclosed less well flushed basins (Little Bay, Shaws Cove, Brant Island Cove) showing net moderate nitrogen release and the large well flushed open water basins of Nasketucket Bay showing low release to net uptake. This pattern of sediment release and uptake was consistent with the observed sediment properties where the outer basins were generally medium to coarse sand while the inner basin sediments were generally fine sands mixed with mud and localized depositional areas of organic muds.

Rates of net nitrogen release from the inner basins (Little Bay, Shaws Cove and Brant Island Cove) was moderate (10-17 mg N m^{-2} d^{-1}) and typical of semi-enclosed well flushed basins tributary to large open water bodies and with similarly structured watershed and land-uses. For example, the inner region of Phinneys Harbor (9 mg N m^{-2} d^{-1}), Uncle Roberts Cove tributary to main basin of Lewis Bay (17 mg N m^{-2} d^{-1}), and the upper region of Little Pleasant Bay (16 mg N m^{-2} d^{-1}). Similarly, the rates of net nitrogen release from the large open water basins of Nasketucket Bay (5 to -20 mg N m^{-2} d^{-1}) upper region of Little Pleasant Bay (16 mg N m^{-2} d^{-1}), were consistent with other large open water basins that are well flushed with high quality offshore waters. Nasketucket Bay is similar in these traits to the outer basins of Phinneys Harbor and West Falmouth Harbor (3 and –11 mg N m^{-1} d^{-1}, respectively) across Buzzards Bay, main basin of Madaket Harbor (6 mg N m^{-2} d^{-1}), the main basin of Lewis Bay (7 to -32 mg N m^{-1} d^{-1}), the highly flushed basin of Westport Harbor (-16 mg N m^{-1} d^{-1}), and the main large open water basin of Sengekontacket Pond (-9 to -17 mg N m^{-1} d^{-1}).

Overall, it is clear that the multiple component basins of Nasketucket Bay presently support rates of summertime sediment nitrogen release typical of open water embayment basins in other Southeast Massachusetts estuaries, with similar structure and sediment characteristics, that are also tributary to Buzzards Bay, as well as to Nantucket Sound, Vineyard Sound and the Atlantic Ocean.

Net nitrogen release rates for use in the water quality modeling effort for the main basins of the Nasketucket Bay Embayment System (Section VI) are presented in Table IV-5. There was a clear spatial pattern of sediment nitrogen flux, with moderate net release of nitrogen in the shallower less well flushed inner basins (Little Bay, Shaws Cove and Brant Island Cove) and low rates of release to net uptake in the large open water basins of Nasketucket Bay. The sediments within the Nasketucket Bay / Little Bay Estuarine System showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and are consistent with the level of nitrogen loading to this system and its rates of tidal flushing.

Table IV-5. Rates of net nitrogen return from sediments to the overlying waters of component basins comprising the Nasketucket Bay / Little Bay Estuarine System. 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})			Station I.D. * NSK-#
	Mean	S.E.	# sites	
Nasketucket Bay / Little Bay Estuarine System				
Little Bay	13.7	4	11	9,10,11,12,13,14, 15,16,17,18,19
Shaws Cove	10.2	2	3	33,34,35
Brandt Island Cove	16.9	13	4	25,26,27,28
Nasketucket Bay- East Main Basin	4.8	9	9	1,2,3,4,5,29,30, 31,32
Nasketucket Bay- West Main Basin	-20.3	3	11	6,7,8,21,22,23,24, 36,37,38,39,40
Outer Basin	-8.5	30	2	41,42

* Station numbers refer to Figure IV-11.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes the field data collection efforts and the development of hydrodynamic models for the Nasketucket Bay estuary system (Figure V-1). For this system, the final calibrated model offers an understanding of water movement through the estuary, and provides the first step towards evaluating water quality, as well as a tool for later determining nitrogen loading "thresholds". Tidal flushing information is utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the Nasketucket Bay area become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing estuarine water quality, as well as determining the likely positive impacts of various alternatives for improving overall estuarine health, enabling the bordering residents to understand how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

Figure V-1. Map of the Nasketucket estuary system (from United States Geological Survey topographic maps).

In general, water quality studies 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. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

Estuarine water quality is dependent upon nutrient and pollutant loading and the processes that help flush nutrients and pollutants from the estuary (e.g., tides and biological processes). Relatively low nutrient and pollutant loading and efficient tidal flushing are indicators of high water quality. The ability of an estuary to flush nutrients and pollutants is proportional to the volume of water exchanged with a high quality water body (i.e. Buzzards Bay). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For the Nasketucket Bay system, the most important parameters are the tide range along with the shape, length and depth of the estuary.

Shallow coastal embayments are the initial recipients of freshwater flows (i.e., groundwater and surfacewater) and the nutrients they carry. An embayment's shape influences the time that nutrients are retained in them before being flushed out to adjacent open waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increase the secondary impacts of nutrients recycled from the sediments. Degradation of coastal waters and development of the surrounding area are tied together through inputs of pollutants, in runoff and groundwater flows, and to some extent through direct disturbance, i.e. boating, oil and chemical spills, and direct discharges from land and boats. Excess nutrients, especially nitrogen, promote phytoplankton blooms and the growth of epiphytes on eelgrass and attached algae, with adverse consequences including low oxygen, shading of submerged aquatic vegetation, and aesthetic problems.

To understand the dynamics of the Nasketucket Bay, a hydrodynamic study was performed. The system is to the southeast of Fairhaven, MA. A site map showing the study area is shown in Figure V-1. The Nasketucket Bay system is a tidally dominated embayment with a southeastern/eastern opening to Buzzards Bay. There is minimal restriction from Buzzards Bay into Nasketucket Bay except for a tiny island, Ram Island that is approximately 250 ft. wide and 600 ft. in length. Along the north side of Nasketucket Bay is Brandt Island and Brandt Island Cove. Brandt Island Cove is a sub-embayment with a 0.35 mile opening to Nasketucket Bay and an average depth of approximately 4 ft. On the south side of Nasketucket Bay are West Island, Long Island, Round Cove and North Cove. West Island and Long Island are connected to Sconticut Neck by Goulart Memorial Drive, which has a 40 foot culvert that allows the water movement from the surrounding areas in between West Island and Sconticut Neck to Buzzards Bay. North of Nasketucket Bay is Little Bay and Shaws Cove, which are sub-embayments surrounded by marsh areas that drain into Nasketucket Bay. The approximate tidal range within this system is 5.5 feet, with Buzzards Bay tidal variations providing the hydraulic forcing that drives water movement throughout the system.

Since the water elevation difference between Buzzards Bay and Nasketucket Bay is the primary driving force for tidal exchange of this estuarine system, the local tide range limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) along the length of Nasketucket Bay is minimal, indicating a system that flushed efficiently. Any issues with water quality, therefore, would likely be due other factors including nutrient loading conditions from the system's watersheds, the water quality of rivers and creeks emptying into the estuary, and the tide range in Buzzards Bay.

Circulation in the Nasketucket Bay system was simulated using the RMA-2 numerical hydrodynamic model. To calibrate the model, field measurements of water elevations and bathymetry were required. Tide data were acquired within Buzzards Bay at a gauge station installed offshore of West Island near Rocky Point and at five stations located within the estuary (Figure V-2). All temperature-depth recorders (TDRs or tide gauges) were installed for at least a 37-day period to measure tidal variations through one spring-neap tidal cycle. In this manner, attenuation of the tidal signal as it propagates through the harbor and each branch was evaluated accurately.

Figure V-2. Aerial photograph of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. The six (6) gauges were deployed for at least a 37 day period between March 28, and May 24, 2006. The red dots represent the approximate locations of the tide gauges: (S-1) represents the gauge in Buzzards bay (Offshore), (S-2) east of West Island, (S-3) inside Brandt Island Cove, (S-4) inside Little Bay, (S-5) north of Little Bay in the marsh, and (S-6) north of Little Bay near the culvert on Pierces Point. The ADCP transect line is shown in yellow.

V.2 FIELD DATA COLLECTION AND ANALYSIS

Accurate modeling of system hydrodynamics is dependent upon measured conditions within the estuary for two important reasons:

- To define accurately the system geometry and boundary conditions for the numerical model
- To provide 'real' observations of hydrodynamic behavior to calibrate and verify the model results

System geometry is defined by the shoreline of the system, including all coves, creeks, and marshes, as well as accompanying depth (or bathymetric) information. The three-dimensional surface of the estuary is mapped as accurately as possible, since the resulting hydrodynamic behavior is strongly dependent upon features such as channel widths and depths, sills, marsh elevations, and inter-tidal flats. Hence, this study included an effort to collect bathymetric information in the field.

Boundary conditions for the numerical model consist of variations of water surface elevations measured in Buzzards Bay. These variations result principally from tides, and provide the dominant hydraulic forcing for the system, and are the principal forcing function applied to the model. Additional pressure sensors were installed at selected interior locations to measure variations of water surface elevation along the length of the system (gauge locations are shown in Figure V-2). These measurements were used to calibrate and verify the model results, and to assure that the dynamic of the physical system were properly simulated.

To complete the field data collection effort for this study, and to provide model verification data, a survey of velocities was completed at the entrance to Lewis Bay, Inner Hyannis Harbor, and Mill Creek. The survey was performed to determine flow rates at the inlets at discreet times during the course of a full tide cycle.

V.2.1 Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Nasketucket Bay system was assembled from a hydrographic survey performed specifically for this study and historical National Ocean Service (NOS) survey data. The National Ocean Service (NOS) Hydrographic Data, where available, were used for areas of Nasketucket Bay that were not covered by the more recent survey.

The hydrographic survey was conducted by CR Environmental, Inc. on May 9, 2006. The survey was designed to collect coverage of the shallow water areas in Nasketucket Bay, specifically Little Bay, northwest of Little Bay, Brandt Island Cove, the areas surrounding Brandt Island and the areas east of the northern part of West Island. The survey transects were densest in the vicinity of the inlets, where the greatest variability in bottom bathymetry was expected. Bathymetry in the inlet is important from the standpoint that it has the most influence on tidal circulation in and out of the estuary. Depth information was collected using an Odom CV-100 precision echo sounder, the system uses an acoustic signal to determine the water depth. Both depth and position are recorded on the computer within HYPACK. HYPACK is a survey and data collection software package that provides real-time navigation for the boat operator to steer the vessel, as well data storage for post survey reduction. The software matches the water depth with the position to generate an accurate horizontal location and vertical depth file. All this information is plotted real time on the screen as a cross-section and a boat track path.

The survey vessel utilized the follow system on board:

- Trimble Ag132 GPS,
- Fathometer – ODOM CV-100 single-beam I 200 kHz) echo sounder for water depth measurements,
- Laptop computer running Windows XP Professional.

Bar checks were performed twice daily at the beginning and end of survey operations to ensure proper calibration of the echo sounder for draft and sound velocity. Position checks were performed throughout the survey day to verify there were no changes in the vertical and horizontal components of the GPS positioning system. Weather conditions at the time of the survey were suitable for data acquisition on the vessel utilized for this survey.

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the NAVD88 vertical datum in feet. The tide gauge near West Island was used for the water surface elevation to correct the bathymetry data to NAVD 1988. Once rectified, the finished, processed data were archived as ‘xyz’ files containing x-y horizontal position (in Massachusetts Mainland State Plan 1983 coordinates in feet) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey described above and the NOS historical survey data are presented in Figure V-3.

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at six stations with five locations in the Nasketucket Bay and one location in Buzzards Bay. The station location in Buzzards Bay is located offshore West Island at Rocky Point (S-1). Stations within the Nasketucket Bay system were located to the east of West Island (S-2), inside Brandt Island Cove (S-3), inside Little Bay (S-4), north of Little Bay in the marsh (S-5), and north of Little Bay near the culvert on Pierces Point (S-6). TDRs were deployed at each gauge station. Station S-1, S-2, S-3, S-4 and S-5 were all deployed on March 28, 2006 while Station S-6 was deployed on April 9, 2006. Station S-1 was recovered on May 5, 2006 while the rest of the stations were recovered on May 24, 2006. Each station was deployed for at least 37 days. The duration of the TDR deployment allowed time to conduct the bathymetric surveys, as well as sufficient data to perform a thorough analysis of the tides in the system.

The tide records from Nasketucket Bay were corrected for atmospheric pressure variations and then rectified to the NAVD88 vertical datum. Atmospheric pressure data, available in one-hour intervals from the NDBC Buzzards Bay C-MAN platform, were used to pressure correct the raw tide data. Final processed tide data from the stations used for this study are presented in Figure V-4, for the complete 58-day period of the TDR deployment.

Tide records longer than 29.5 days are necessary for a complete evaluation of tidal dynamics within the estuarine system. Although a one-month record likely does not include extreme high or low tides, it does provide an accurate basis for typical tidal conditions governed by both lunar and solar motion. For numerical modeling of hydrodynamics, the typical tide conditions associated with a one-month record are appropriate for driving tidal flows within the estuarine system.

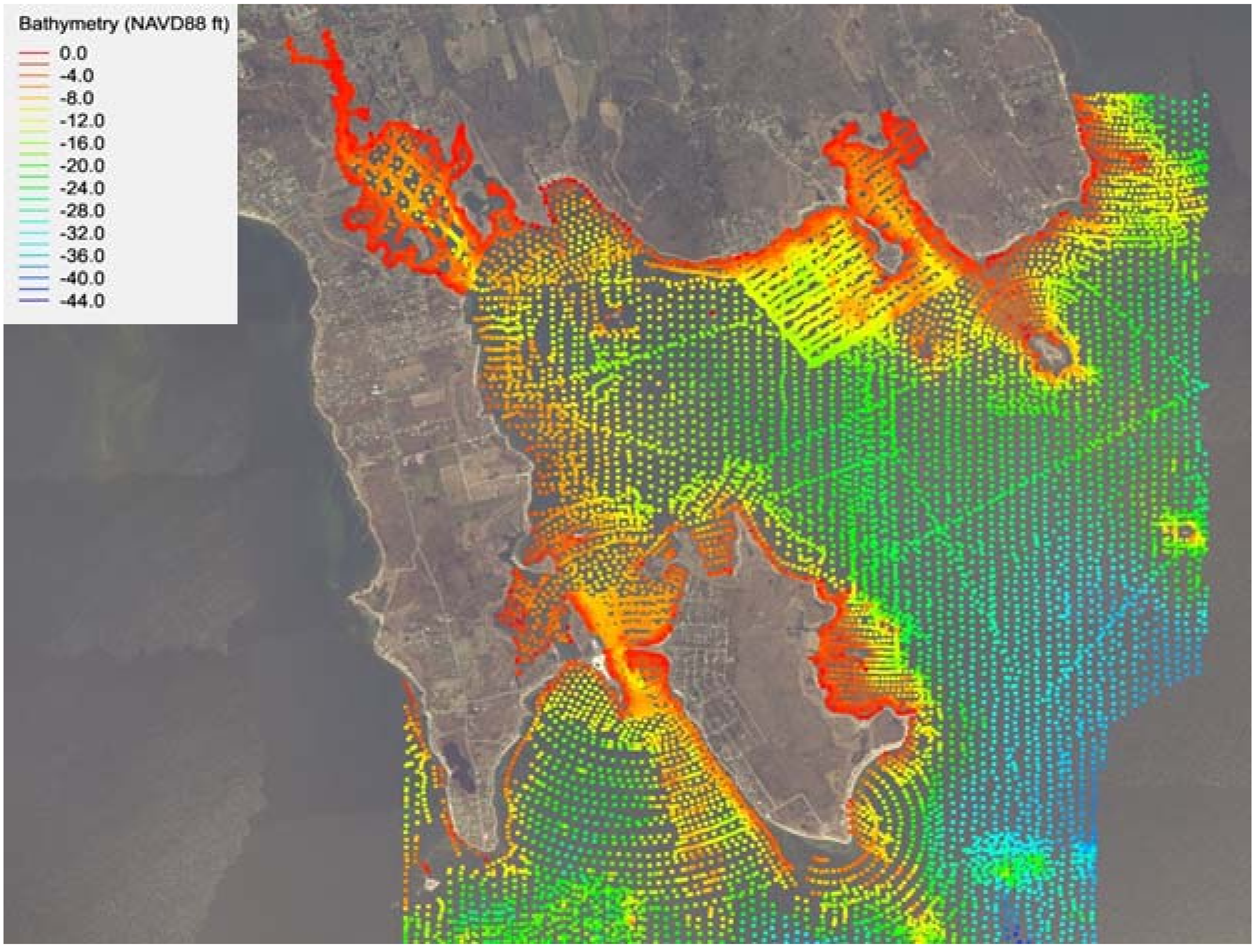


Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

The loss of amplitude together with increasing phase delay with increasing distance from the inlet is described as tidal attenuation. Tide attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the near-shore region, where channel restrictions (e.g., bridge abutments, roadway culverts, inlets) and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. Figure V-4 shows a visual comparison of the tide elevations at the offshore station (S-1) and the north culvert station (S-6). Figure V-5 demonstrates the little change in tidal range from Buzzards Bay to the farthest inland station in Nasketucket Bay. This provides an initial indication that flushing conditions in Nasketucket Bay are ideal, with minimal loss of tidal energy along the length of the system.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 27-day period where the TDR records overlap. These datums are presented in Table V-1. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW. The tides in Buzzards Bay are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels. The computed datums for Nasketucket Bay and Buzzards Bay compare well to similar datum computed for Newport using a 30-day record from April 2006 (MTL -0.02 ft., MHW 1.92 ft., MLW -1.97 ft. NAVD88).

For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. From the computed datums, it is further apparent that there is damping occurring in the Nasketucket Bay Estuary System. Again, the absence of tide damping exhibited in Nasketucket Bay indicates that it flushes efficiently.

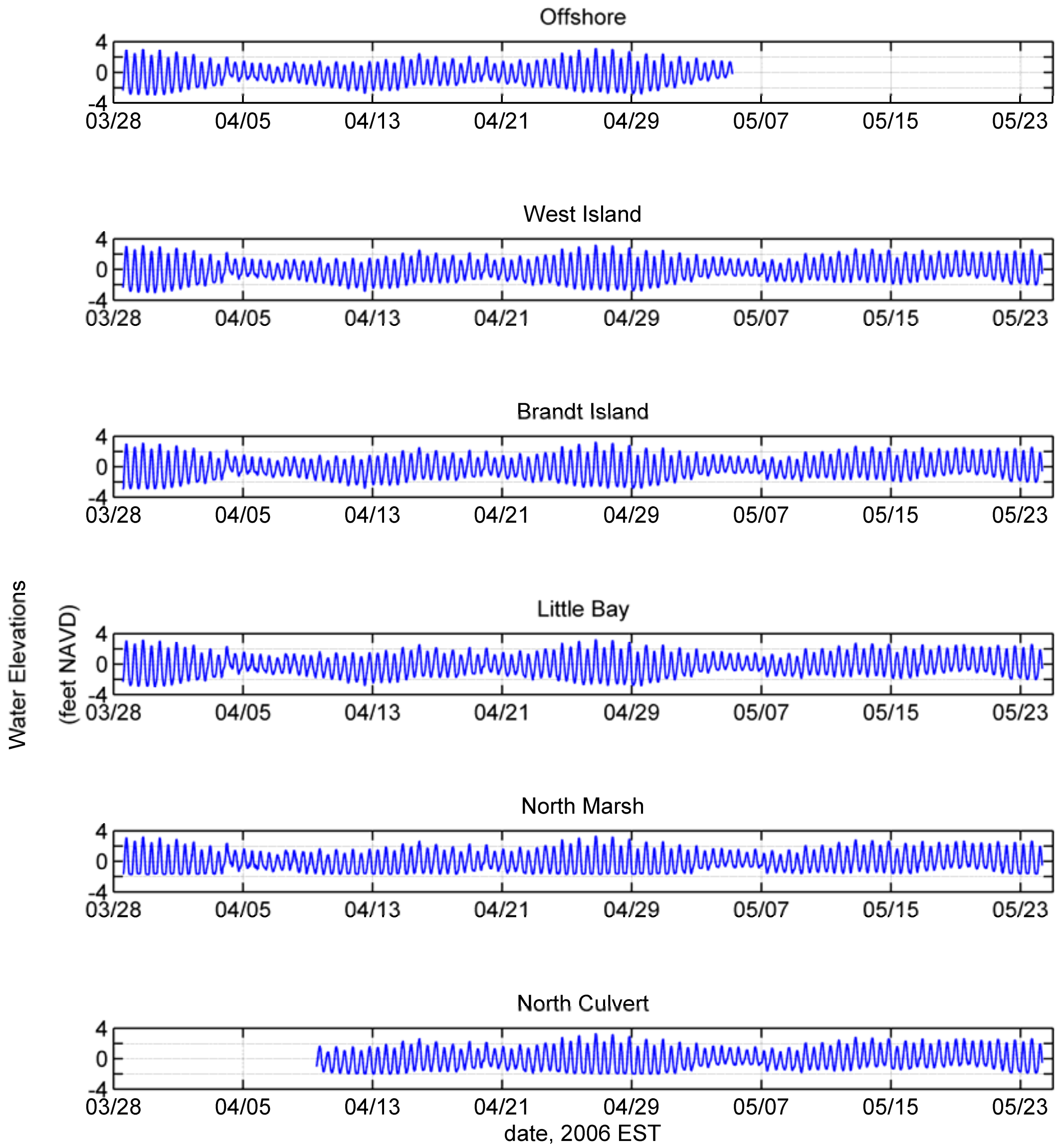


Figure V-4. Water elevation variations as measured at the six locations of the Nasketucket Bay system, from March 28th to May 24th 2006.

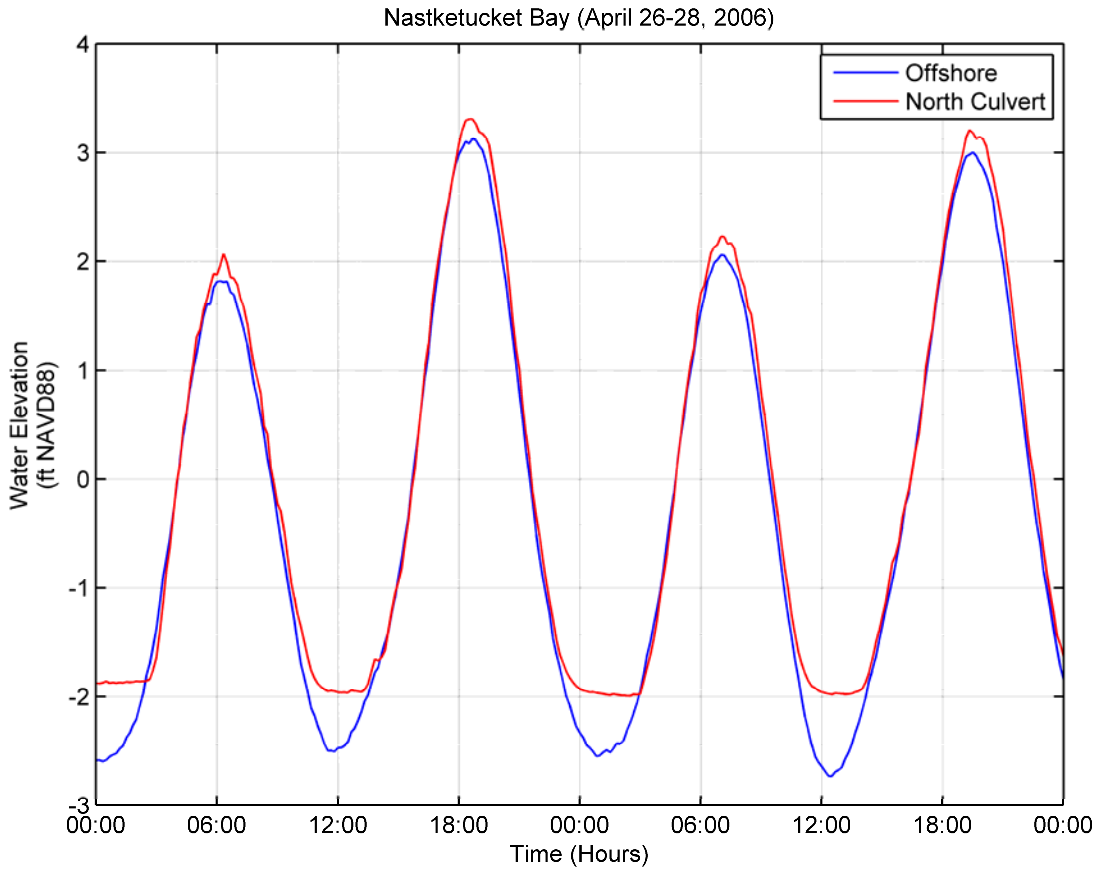


Figure V-5 Plot showing two tide cycles tides at the offshore and north culvert stations in the Nasketucket Bay system plotted together. Demonstrated in this plot is the phase delay and amplitude reduction as the tidal signal progresses through the estuarine system.

Table V-1. Tide datums computed from records collected in the Nasketucket Bay Estuarine system April 9 - May 5, 2006. Datum elevations are given relative to NAVD88 in feet.

Tide Datum	Offshore	West Island	Brandt Island	Little Bay	North Marsh	North Culvert
Maximum Tide	3.126	3.204	3.237	3.235	3.321	3.309
MHHW	2.048	2.138	2.108	2.165	2.252	2.240
MHW	1.74	1.839	1.798	1.858	1.942	1.933
MTL	-0.094	-0.071	-0.101	-0.071	0.202	0.109
MLW	-1.929	-1.982	-2.000	-2.000	-1.538	-1.716
MLLW	-2.089	-2.150	-2.169	-2.170	-1.612	-1.816
Minimum Tide	-2.789	-2.879	-2.830	-2.908	-1.716	-2.024

A more thorough harmonic analysis was also performed on the time series data from each gauge station in an effort to separate the various component signals which make up the observed tide. The analysis allows an understanding of the relative contribution that diverse physical processes (i.e. tides, winds, etc.) have on water level variations within the estuary. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 tidal constituents, with periods between 4 hours and 2 weeks, result from this procedure. The observed tide is therefore the sum of an astronomical tide component and a residual atmospheric component. The astronomical tide in turn is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-6.

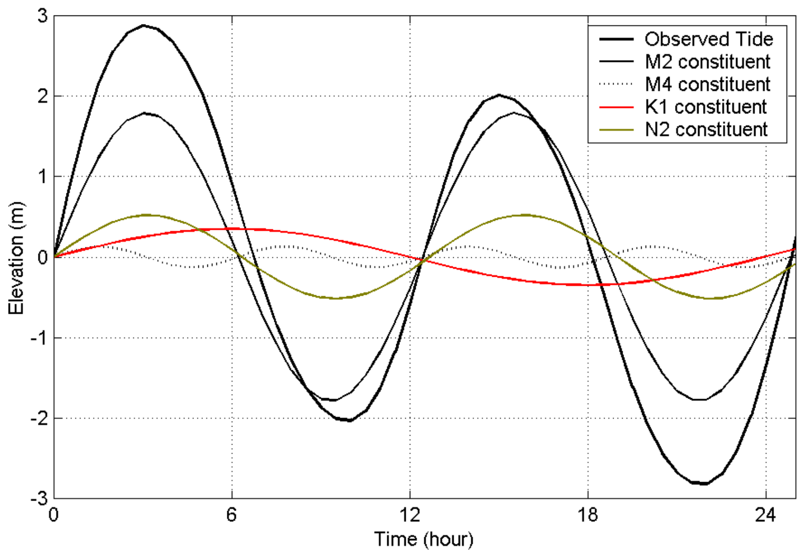


Figure V-6. An example of an observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-2 presents the amplitudes of eight significant 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 1.6 feet in Buzzards Bay. The range of the M_2 tide is twice the amplitude, or about 3.2 feet. The diurnal (once daily) tide constituents, K_1 (solar), O_1 (lunar), and S_2 (principal solar semidiurnal) possess amplitudes of approximately 0.28 feet, 0.19 feet, and 0.42-0.48 feet respectively and account for the higher high tide followed by the lower low tide seen in Figure V-5. The N_2 tide, a lunar constituent with a semi-diurnal period, has an amplitude of approximately 0.38 feet. The S_2 and N_2 are the highest constituents after M_2 and are more than three times smaller than M_2. The M_4 tide, a higher frequency harmonic of the M_2 lunar tide (twice the frequency of the M_2), results from frictional dissipation of the M_2 tide in shallow water. The M_2, S2 and N2 have more influence on the shape of the tide signal than the other constituents.

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M_2 tide at all tide gauge locations inside the system. The greatest delay occurs between the offshore gauge station and the north culvert gauge station. The largest changes in phase delay occur between the Brandt Island gauge station and north culvert gauge station. The degree of attenuation is not significant relative to the hydraulic efficiency of the system because the effects of attenuation are observed only in the phase delay across the system, and not as a reduction in the amplitude of the tide.

Table V-2. Tidal Constituents for the Nasketucket Bay System. Data collected April 9 – May 5, 2006. (*Tide Gauge became dry during deployment)

AMPLITUDE (feet)								
	M2	M4	M6	K1	S2	N2	O1	MSF
Period (hours)	12.42	6.21	4.14	23.93	12.00	12.66	25.82	354.61
Offshore	1.642	0.225	0.018	0.279	0.467	0.367	0.192	0.254
West Island	1.697	0.245	0.025	0.279	0.480	0.383	0.190	0.261
Brandt Island	1.692	0.244	0.025	0.285	0.477	0.380	0.194	0.237
Little Bay	1.697	0.247	0.028	0.281	0.479	0.382	0.193	0.242
North Marsh*	1.574	0.318	0.024	0.269	0.383	0.348	0.196	0.129
North Culvert	1.633	0.286	0.017	0.277	0.424	0.355	0.195	0.177

Table V-3. M_2 Tidal Attenuation, Nasketucket Bay Estuary System, April 9 - May 5, 2006 (Delay in minutes relative to the offshore station).

Location	Delay (minutes)
West Island	2.47
Brandt Island	2.22
Little Bay	3.13
North Marsh	3.53
North Culvert	4.73

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal 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 compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the original water elevation time series for the two river systems is presented in Table V-4 compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). 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 are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from Offshore, with the predicted tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-4 shows that the percentage contribution of tidal energy was essentially equal in all parts of the system, which indicates that local effects due to winds and other non-tidal processes are minimal throughout Nasketucket Bay. The analysis also shows that tides are responsible for approximately 97% of the water level changes in Nasketucket Bay. The remaining 3% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Buzzards Bay and Nasketucket Bay. The total energy content of the tide signal from each gauging station does not change significantly, nor does the relative contribution of tidal vs. non-tidal forces along the estuary basin. This is further indication that tide attenuation across the inlet and through the system is negligible. It is also indication that the source of the non-tidal component of the tide signal is generated completely offshore, with no additional non-tidal energy input inside the system (e.g., wind set-up).

The results from Table V-4 indicate that hydrodynamic circulation throughout Nasketucket Bay is dependent primarily upon tidal processes. While wind and other non-tidal effects can be a less significant portion of the total variance, the residual signal should not be ignored. Therefore, for the hydrodynamic modeling effort described below, the actual tide signal from Buzzards Bay was used to force the model so that the effects of non-tidal energy are included in the modeling analysis.

Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured at the Offshore Gauge (S-1).

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Nasketucket Bay, 2006.

Location	Total Variance (ft^2)	Total (%)	Tidal (%)	Non-tidal (%)
Offshore	1.817	100	97.7	2.3
West Island	1.939	100	97.7	2.3
Brandt Island	1.927	100	97.6	2.4
Little Bay	1.939	100	97.5	2.5
North Marsh	1.598	100	96.9	3.1
North Culvert	1.772	100	97.1	2.9

V.2.3 ADCP DATA ANALYSIS

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 approximately 12.5-hours to ensure measurements over the entire 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 scatter, 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.

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.

Current measurements were collected by the ADCP as the vessel navigated repeatedly a pre-defined transect line in Nasketucket Bay (Figure V-2). The line-cycles were repeated every hour throughout the survey. The first cycle was begun at 05:07 hours (Eastern Standard Time, EST) and the final cycle was completed at 17:38 hours (EST), for a survey duration of approximately 12.5 hours on April 27, 2006.

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Nasketucket Bay estuary system. Once calibrated, the model was used to calculate water volumes for selected sub-embayments (e.g., the Brandt Island Cove and Little Bay) as well as determine the volumes of water exchanged during each tidal cycle. These parameters are used to calculate system residence times, or flushing rates. The ultimate utility of the hydrodynamic model is to supply required input data for the water quality modeling effort described in Chapter VI.

V.3.1 Model Theory

This study of Nasketucket Bay utilized a state-of-the-art computer model to evaluate tidal circulation and flushing. 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. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies for estuary systems in southeast Massachusetts, including systems in Chatham, Falmouth's 'finger' ponds, and Popponesset Bay.

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). SMS is a front- and back-end software package that allows the user to easily modify model parameters (such as geometry, element coefficients, and boundary conditions), as well as view the model results and download specific data types. While the RMA model is essentially used without cost or constraint, the SMS software package requires site licensing for use.

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 criterion 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 the finite element grid was generated using digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the system based on the tide gauge data collected at the offshore gauge location. 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 each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid Generation

The grid generation process for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 2540 elements and 8276 nodes (Figure V-8). All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution was required to simulate the numerous marsh areas that significantly impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the NOAA data archive. The final interpolated grid bathymetry is shown in Figure V-9. The model computed water elevation and velocity at each node in the model domain.

Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the river channels was designed to provide a more detailed analysis in these regions of rapidly varying velocities and bathymetry. Widely spaced nodes were utilized in areas where velocity gradients were likely to be less acute; for example, in broad, deep channel sections in the model domain. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

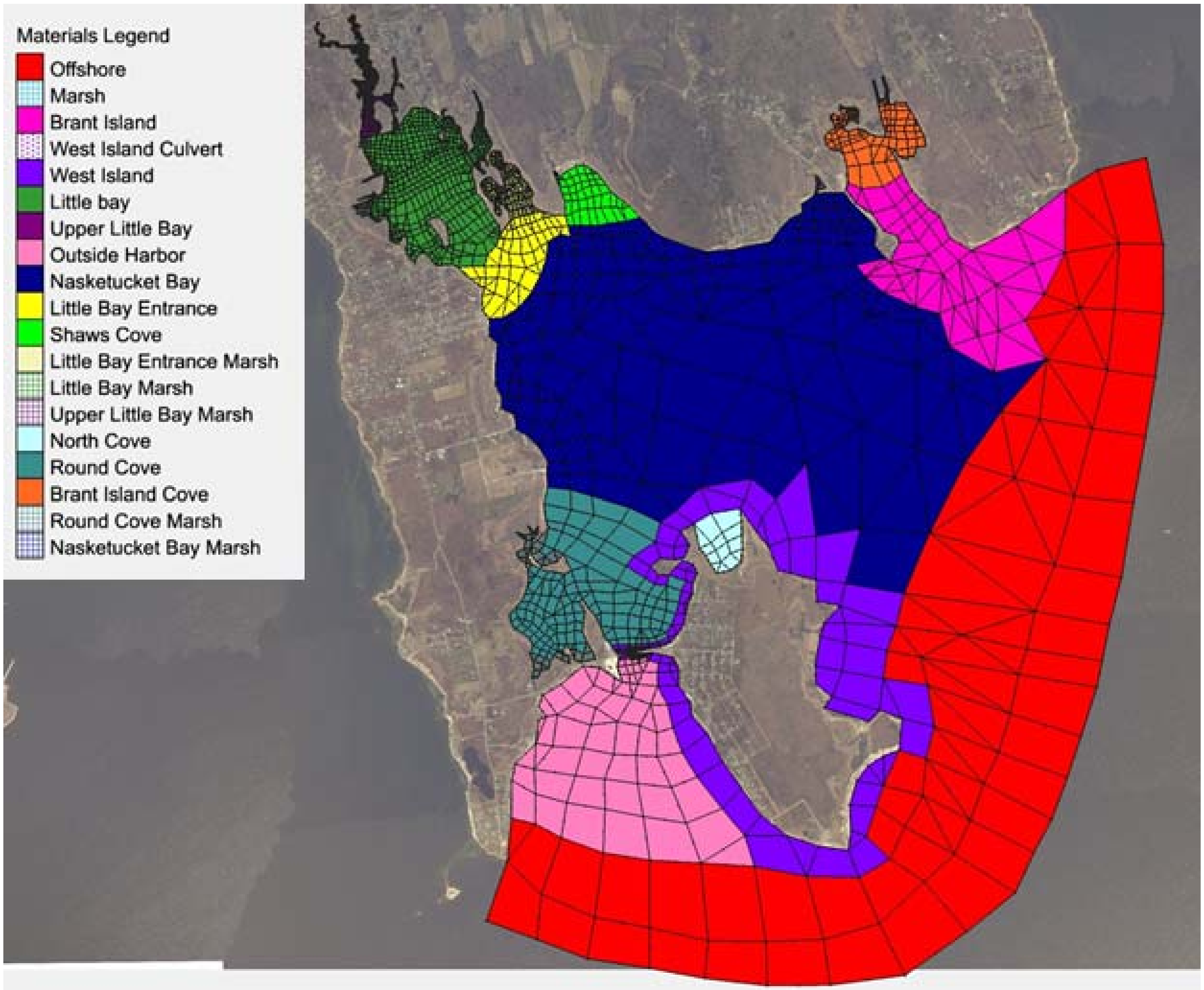


Figure V-8. The model finite element mesh developed for Nasketucket Bay estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained at the offshore Gauge (S-1).

V.3.2.2 Boundary Condition Specification

Three types of boundary conditions were employed for the RMA-2 model: 1) "slip" boundaries, 2) freshwater inflow, and 3) tidal elevation 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 freshwater inflow boundary condition was specified for the creek entering into Shaws Cove, for the creek that goes under the culverts at Phoenix Rail Trail and Peirces Point and for the creek that starts at the Phoenix Rail Trail and enters upper Little Bay.

The model was forced at the open boundary using water elevations measurements obtained in Buzzards Bay (described in section V.2.2). This measured time series consists of all physical processes affecting variations of water level: tides, winds, and other non-tidal oscillations of the sea surface. The rise and fall of the tide in Buzzards Bay is the primary driving force for the estuarine circulation. Dynamic (time-varying) model simulations specified a new water surface elevation at the offshore boundary every 10 minutes. The model specifies the water elevation at the offshore boundary, and uses this value to calculate water elevations at every nodal point within the system, adjusting each value according to solutions of the model equations. Changing water levels in Buzzards Bay produce variations in surface slopes within the estuary; these slopes drive water either into the system (if water is higher offshore) or out of the system (if water levels are higher in the bay).

V.3.3 Calibration

After developing the finite element grid and specifying boundary conditions, the model was calibrated. Calibration ensured the model predicts accurately what was observed during the field measurement program. Numerous model simulations were required to calibrate the model, with each run varying specific parameters such as friction coefficients, turbulent exchange coefficients, fresh water inflow, and subtle modifications to the system bathymetry to achieve a best fit to the data.

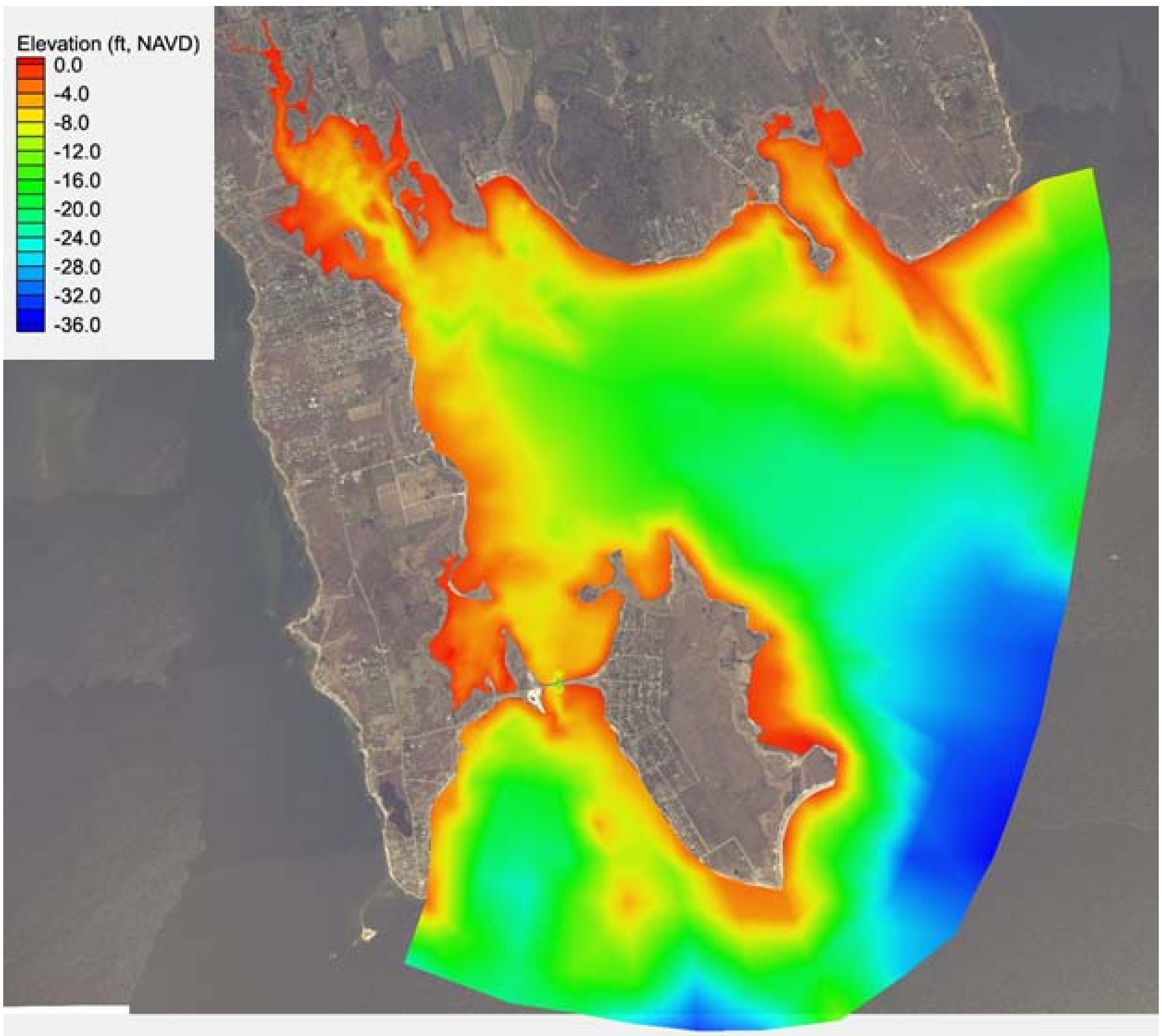


Figure V-9. Depth contours of the completed Westport River finite element mesh.

Calibration of the flushing model required a close match between the modeled and measured tides at each gauge station. Initially, the model was calibrated by the visual agreement between modeled and measured tides. To refine the calibration procedure, water elevations were output from the model at the same locations in the estuary where tide gauges were installed, and the data were processed to calculate standard error as well harmonic constituents (of both measured and modeled data) over the seven-day calibration period. The amplitude and phase of four constituents (M_2, M_4, M_6, and K_1) were compared and the corresponding errors for each were calculated. The intent of the calibration procedure is to minimize the error in amplitude and phase of the individual constituents. In general, minimization of the M_2 amplitude and phase becomes the highest priority, since this is the dominant constituent. Emphasis is also placed on the M_4 constituent, as this constituent has the greatest impact on the degree of tidal distortion within the system, and provides the unique shape of the modified tide wave at various points in the system.

The calibration was performed for an approximate seven-day period, beginning 1040 hours EST April 18, 2006 and ending 0520 hours EST April 25, 2006. This time period included a 12-hour model spin-up period, and a 12-tide cycle period used for calibration. This representative time period was selected because it included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time period also spanned the transition from neap (bi-monthly minimum) to spring (bi-monthly maximum) tide ranges, which is representative of average tidal conditions in the embayment system. Throughout the selected 7 day period, the tide ranged approximately 3.2 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where water depths can become shallow and velocities relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude attenuation and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. First, Manning's friction coefficient values of 0.025 were specified for all elements. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with pools and shoals with higher friction (Henderson, 1966). Final calibrated friction coefficients (listed in Table V-5) were largest for the marsh areas scattered throughout the system, where values were set at 0.035. Small changes in these values did not change the accuracy of the calibration.

Table V-5. Manning's Roughness coefficients used in simulations of modeled embayments.	
Embayment	Bottom Friction
Offshore	0.025
Outside Harbor	0.025
West Island	0.025
West Island Culvert	0.025
North Cove	0.025
Round Cove	0.025
Round Cove Marsh	0.025
Nasketucket Bay	0.025
Nasketucket Bay Marsh	0.025
Brandt Island	0.025
Brandt Island Cove	0.025
Shaws Cove	0.025
Little Bay Entrance	0.025
Little Bay Entrance Marsh	0.025
Little Bay	0.035
Little Bay Marsh	0.035
Upper Little Bay	0.035
Upper Little Bay Marsh	0.035
Marsh	0.035

V.3.3.2 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 swift, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). The model was mildly sensitive to turbulent exchange coefficients, with areas of marsh plain being the most sensitive. In other regions where the flow gradients were not as strong, the model was much less sensitive to changes in the turbulent exchange coefficients. Typically, model turbulence coefficients (D) are set between 20 and 100 lb-sec/ft^2 (as listed in Table V-6).

V.3.3.3 Wetting and Drying/Marsh Porosity Processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain included in the model as part of the Nasketucket Bay system. 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 change 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.

Table V-6. Turbulence exchange coefficients (D) used in simulations of modeled embayment system.

Embayment	D (lb-sec/ft^2)
Offshore	40
Outside Harbor	20
West Island	20
West Island Culvert	20
North Cove	20
Round Cove	20
Round Cove Marsh	20
Nasketucket Bay	20
Nasketucket Bay Marsh	20
Brandt Island	40
Brandt Island Cove	20
Shaws Cove	20
Little Bay Entrance	20
Little Bay Entrance Marsh	20
Little Bay	50
Little Bay Marsh	50
Upper Little Bay	50
Upper Little Bay Marsh	50
Marsh	50

V.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the six gauge locations are presented in Figures V-10 through V-15. At all gauge stations, RMS errors were less than 0.16 ft. (<0.2 inches) and computed R^2 correlation was either 0.95 or better for every station. Errors between the model and observed tide constituents were less than 0.06 feet for all of the stations excluding the North Marsh station, suggesting the model accurately predicts tidal hydrodynamics within the Nasketucket Bay system. As previously mentioned the North Marsh tide gauge became dry during some low tide events during the deployment resulting in bad data during those times. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values for the validation time period differ from those in Table V-2 because constituents were computed for only 7 days, rather than the entire period of the deployment represented in Table V-2. Errors associated with tidal constituent height were on the order of hundredths of feet, which was an order of magnitude better than the accuracy of the tide gauge ($\pm$0.12 ft). Time lag errors less than the time increment resolved by the model and measured tide data (10 minutes) for all gauges, indicating good agreement between the model and data.

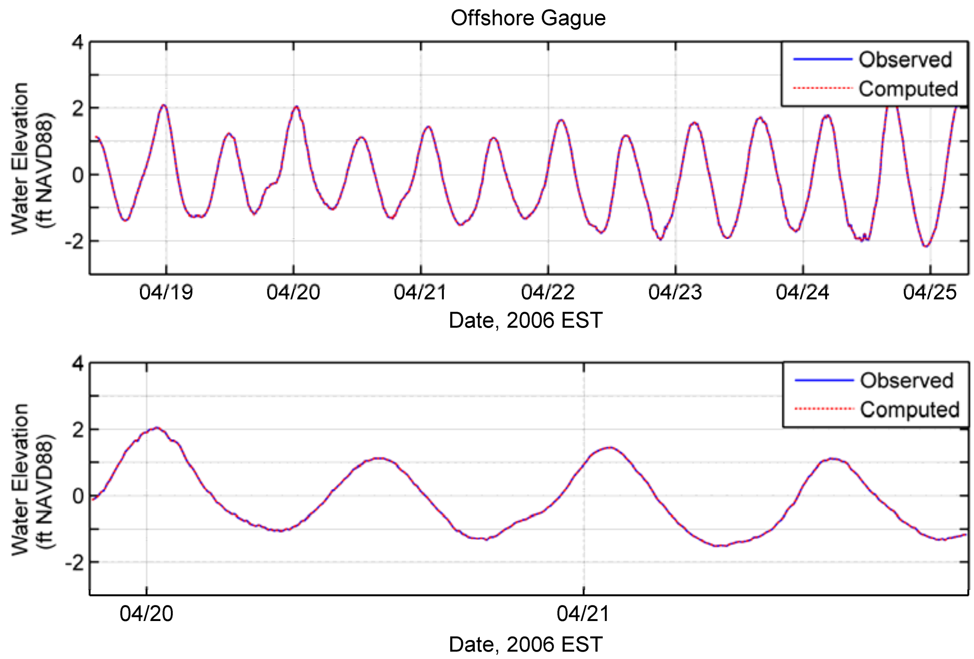


Figure V-10. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the offshore gauge station (S-1). The top plot shows the entire record with the bottom plot showing a 48-hour segment.

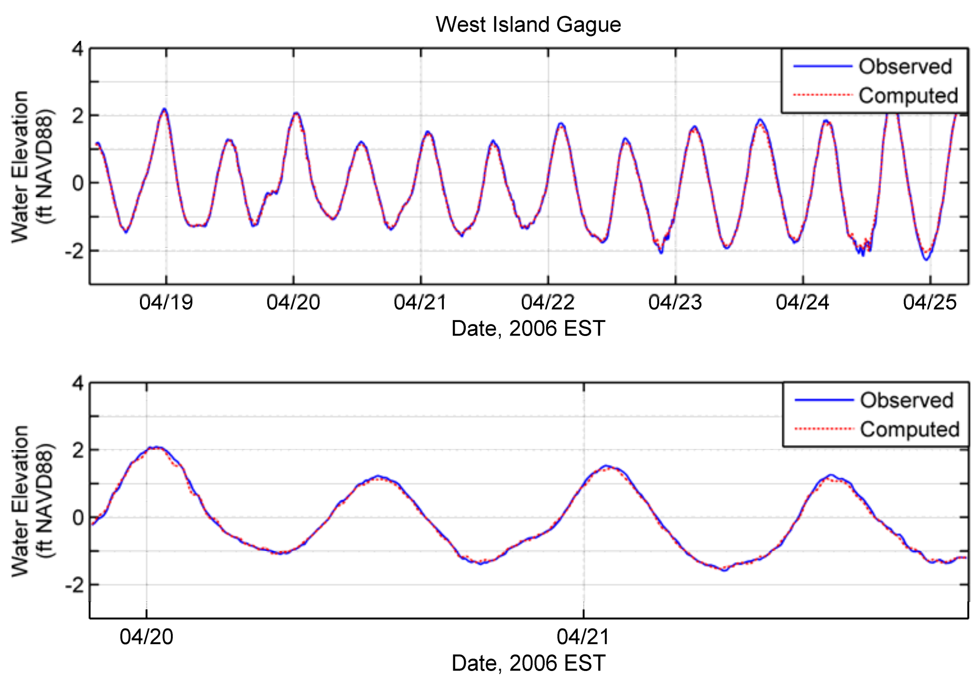


Figure V-11. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the West Island gauge station (S-2). The top plot shows the entire record with the bottom plot showing a 48-hour segment.

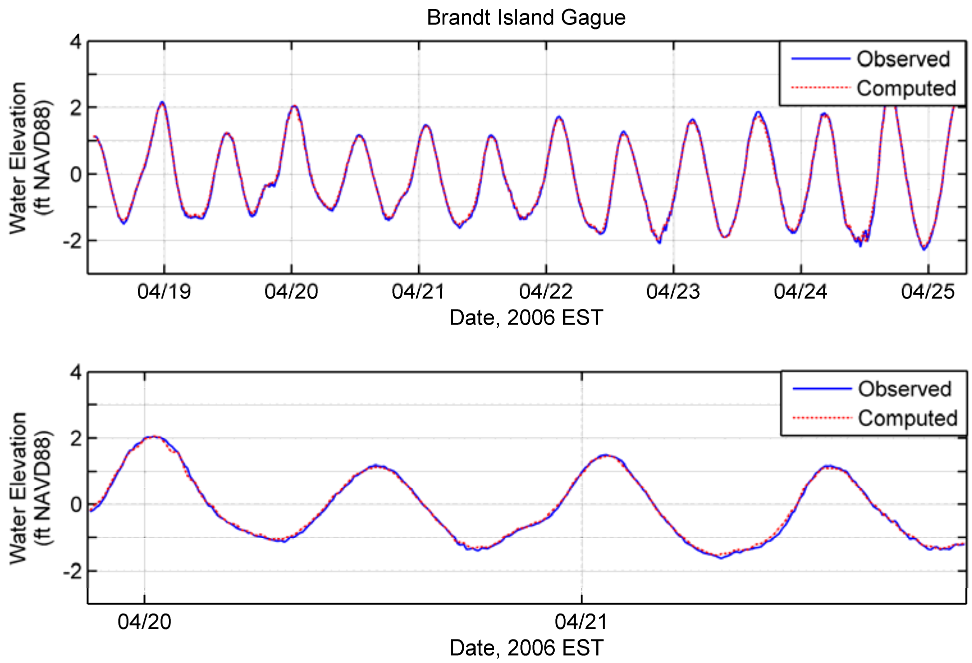


Figure V-12. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Brandt Island gauge station (S-3). The top plot shows the entire record with the bottom plot showing a 48-hour segment.

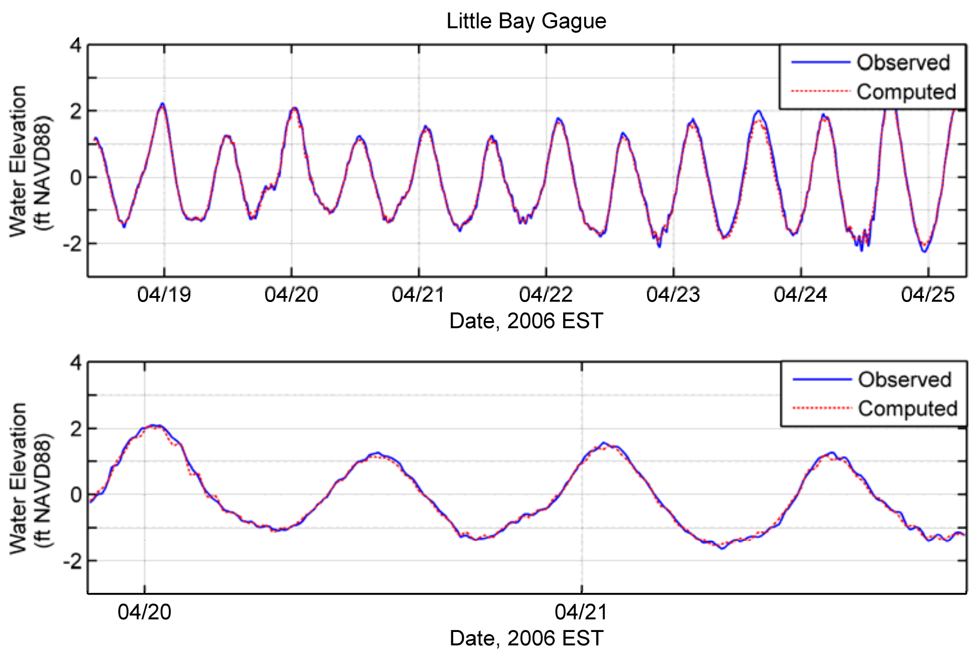


Figure V-13. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Little Bay gauge station (S-4). The top plot shows the entire record with the bottom plot showing a 48-hour segment.

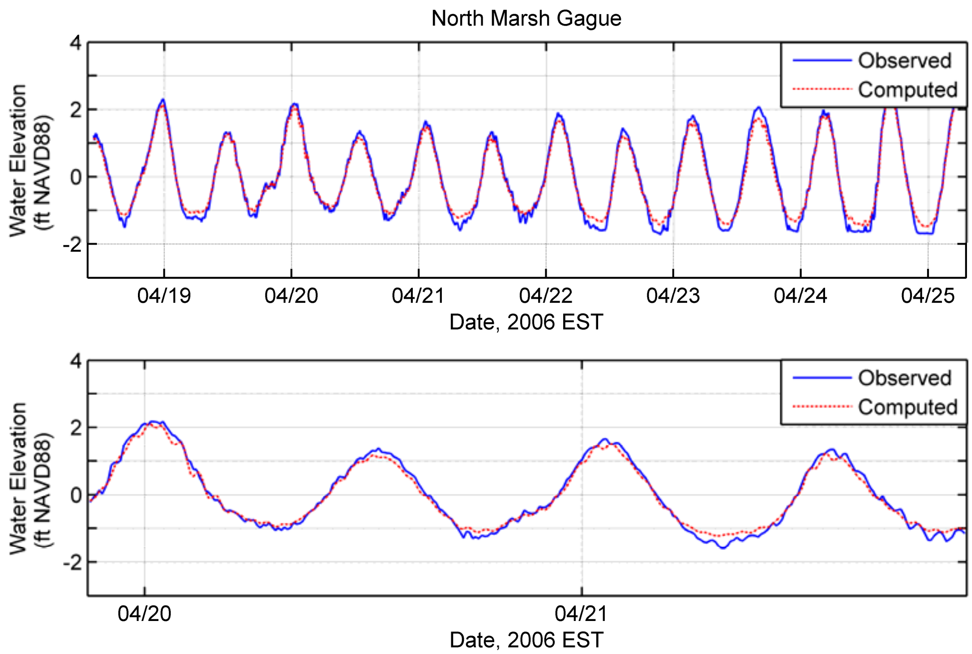


Figure V-14. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the north marsh gauge station (S-5). The top plot shows the entire record with the bottom plot showing a 48-hour segment.

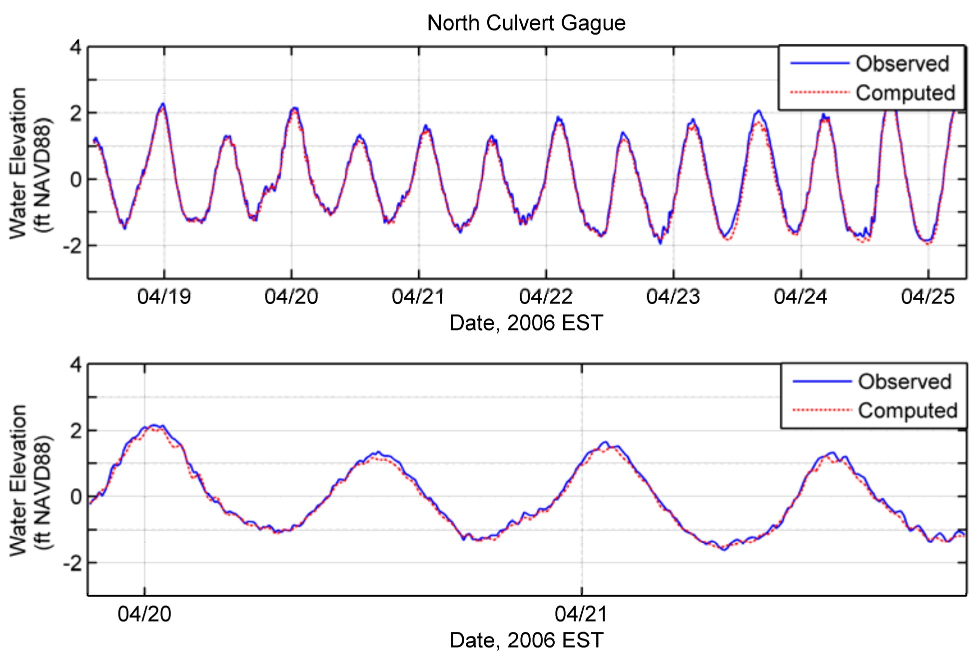


Figure V-15. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the north culvert gauge station (S-6). The top plot shows the entire record with the bottom plot showing a 48-hour segment.

Table V-7. Comparison of Tidal Constituents from the validated RMA2 model versus measured tidal data for the period April 18 to April 25, 2006.

Location	Constituent Amplitude (ft)				Phase (degrees)	
Model Calibration Run						
Location	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore	1.52	0.24	0.04	0.16	13.31	19.69
West Island	1.52	0.26	0.05	0.16	13.51	20.87
Brandt Island	1.53	0.25	0.05	0.16	13.45	19.75
Little Bay	1.52	0.26	0.05	0.16	13.77	21.30
North Marsh	1.36	0.32	0.05	0.14	14.88	23.27
North Culvert	1.51	0.28	0.05	0.16	16.09	18.14
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore	1.52	0.24	0.04	0.16	13.30	19.68
West Island	1.58	0.27	0.05	0.15	14.40	21.44
Brandt Island	1.57	0.27	0.05	0.16	14.43	20.96
Little Bay	1.57	0.27	0.05	0.15	14.84	21.33
North Marsh	1.55	0.29	0.06	0.16	15.07	23.91
North Culvert	1.55	0.29	0.06	0.16	15.52	22.52
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Offshore	0.00	0.00	0.00	0.00	0.00	-0.01
West Island	0.06	0.01	0.00	-0.01	1.84	0.59
Brandt Island	0.04	0.02	0.00	0.00	2.03	1.25
Little Bay	0.05	0.01	0.00	-0.01	2.22	0.03
North Marsh	0.19	-0.03	0.01	0.02	0.40	0.67
North Culvert	0.04	0.01	0.01	0.00	-1.17	4.53

V.3.4 ADCP Verification of the Nasketucket Bay System

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the model in representing the system dynamics. Computed flow rates from the model were compared to flow rates determined using the measured velocity data. The ADCP data survey efforts are described previously in Section V.2.3. For the model ADCP verification, the Nasketucket Bay model was run for period covered during the ADCP survey on April 27, 2006. The verification model period was performed for an approximate 7-day period, beginning 16:40 hours EST April 24, 2006 and ending 23:00 EST May 1, 2006. This time period included a 12-hour model spin-up period, and a tide cycle period used to compare to the ADCP data. Model flow rates were computed in RMA-2 at a continuity line (channel cross-section) that correspond to the actual ADCP transect followed in the survey (i.e., across the entrance to Little Bay).

Data comparisons of the Nasketucket Bay ADCP transect show good agreement with the model predictions, with a R^2 correlation coefficient of 0.94 between the data and model results. A comparison of the measured and modeled volume flow rates at the survey transect are shown in Figure V-16. In the figure, the top plot shows the flow comparison, and the lower plot shows the time series of tide elevation for the same period. Each ADCP point (black circles shown on the plots) is a summation of flow measured along the ADCP transect at a discrete moment in time. The ‘bumps’ and ‘skips’ of the flow rate curve (more evident in the model output) can be attributed mostly to the peculiar nature of the forcing tide in this region, but also to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through Little Bay. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

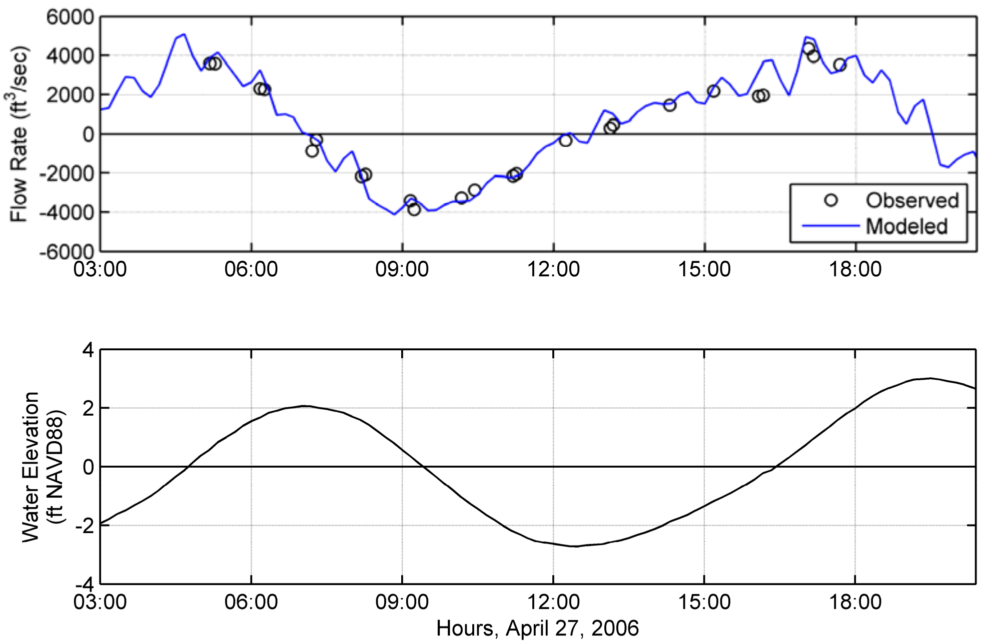


Figure V-16. Comparison of measured volume flow rates versus modeled flow rates (top plot) across Little Bay transect over a tidal cycle April 27, 2006 (R^2 = 0.94). Flood flows into the bay are positive (+), and ebb flows out of the bay are negative (-). The bottom plot shows the tide elevation offshore, in Buzzards Bay.

V.3.5 Model Circulation Characteristics

The final calibrated and validated model serves as a useful tool for investigating the circulation characteristics of the Nasketucket Bay estuary 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.

From the model run of Nasketucket Bay, maximum flood velocities at the Little Bay inlet are slightly smaller than velocities during the ebb portion of the tide. Maximum depth-averaged velocities in the model are approximately 2.1 feet/sec for flooding tides, and 3.2 ft/sec for ebbing tides. A close-up of the model output is presented in Figure V-17 which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow for a single model time step.

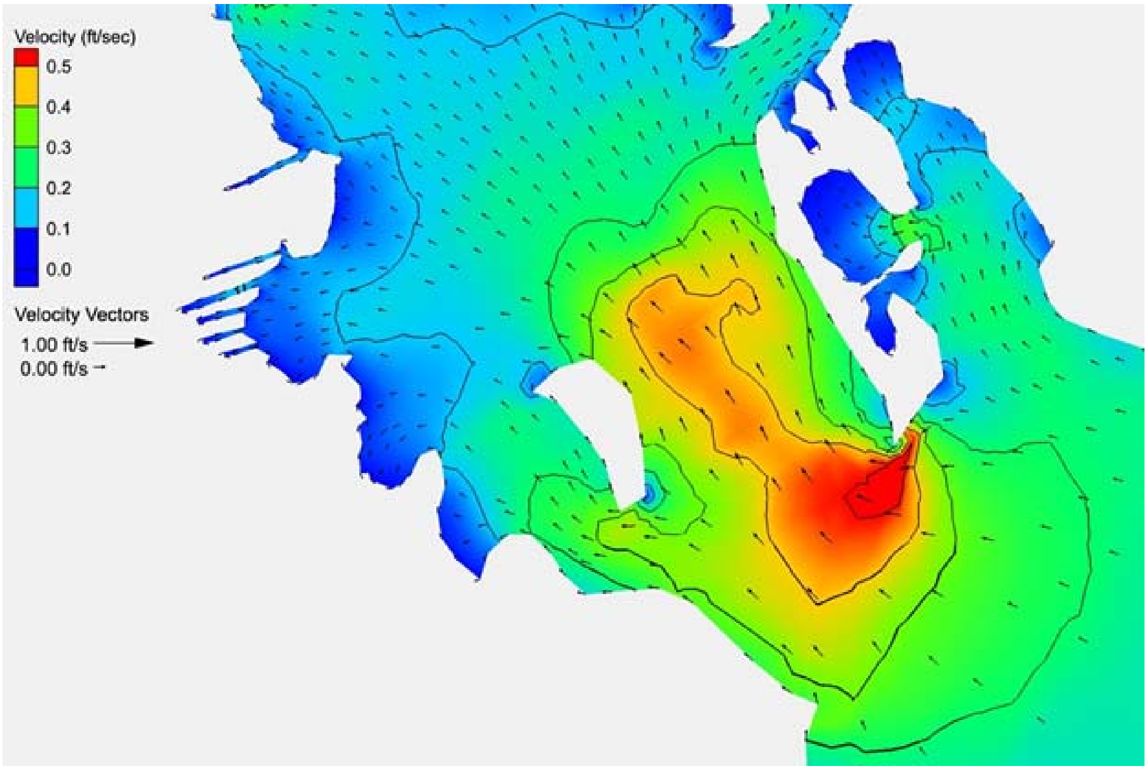


Figure V-17. An example of the hydrodynamic model output in Nasketucket Bay for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

V.4 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through the inlet, the primary mechanism controlling estuarine water quality within Nasketucket Bay 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 the Bay on an ebbing tide. This exchange of water between each system and the ocean 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 the head of the Little Bay and the adjoining marsh as an example, the system residence time is the average time required for water to migrate from the Phoenix Rail-Trail bridge, through the lower portions of the Little Bay into the Nasketucket Bay, and finally into Buzzards Bay, where the local residence time is the average time required for water to migrate from the Phoenix Rail-Trail bridge to Nasketucket Bay entrance of Little Bay (not all the way through Nasketucket Bay and out of the system). 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 modeled 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 a total nitrogen dispersion model (Section VI). The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Nasketucket Bay Estuary.

The volume of each sub-embayment, as well as their respective tidal prisms, was computed in cubic feet (Table V-8). Model divisions used to define the system sub-embayments for the system include 1) the entire Nasketucket Bay system, 2) Little Bay and the adjoining marsh, 3) Shaws Cove, 4) the inner portion of Nasketucket Bay (from Little Bay to Brandt Island and Round Cove), 5) the outer portion of Nasketucket Bay (from the inner portion to offshore), 6) Brandt Island and Brandt Island Cove, 7) Round Cove, and 8) the outside harbor, which goes from the culvert in Round Cove to the end of West Island in Buzzards Bay. The model computed total volume of each sub-embayment at every time step, and this output was used to calculate mean sub-embayment volume and average tide prism. Since the 7-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-8. Mean volumes and average tidal prism of the Nasketucket Bay system during calibration period.		
Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Entire System	1,868,972,816	541,648,832
Little Bay	73,341,486	49,930,987
Shaws Cove	10,748,029	6,402,108
Inner Nasketucket Bay	503,873,888	147,279,615
Outer Nasketucket Bay	855,401,542	182,491,417
Brandt Island	30,897,771	21,910,958
Round Cove	80,024,290	46,952,337
Outside Harbor	306,864,789	83,744,211

Residence times were averaged for the tidal cycles comprising a representative 7 day period (12 tide cycles), and are listed in Table V-9. Residence times were computed for the entire estuary, as well selected sub-embayments within the system. System residence times were only calculated for two of the sub-embayments, Little Bay and Shaws Cove because it is believed that these are the only two embayments where the water travels through the majority of the system. In addition, local residence times were computed for each sub-embayment to indicate the range of conditions possible for the system. Residence times were calculated as the volume of water (based on mean volumes computed for the calibration 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 whole Nasketucket Bay system has a low residence time (1.8 days) showing that the system has good flushing conditions. This is true of all the local residence times for the system. The system residence time for Little Bay and Shaws Cove do not provide a good indication of the water quality since the variation in basin volumes from both sub-embayments to the system volume is considerable. The resulting system residence times are long, especially for Shaws Cove, which should not be considered accurate characterization of the conditions occurring in Shaws Cove and Little Bay. A more comprehensive examination of nutrient loading is required to provide an accurate characterization (see Chapter VI).

Table V-9. Computed System and Local residence times for sub-embayments of the Westport River estuary system.		
Embayment	Local Residence Time (days)	System Residence Time (days)
Entire System	1.8	1.8
Little Bay	0.8	19.5
Shaws Cove	0.9	151.8
Inner Nasketucket Bay	1.8	--
Outer Nasketucket Bay	2.4	--
Brandt Island	0.7	--
Round Cove	0.9	--
Outside Harbor	1.9	--

Based on our knowledge of estuarine processes, we estimate that the combined errors associated with the method applied to compute residence times are within 10% to 15% of "true" residence times, for the Nasketucket Bay estuary system. 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. In addition, limited topographic measurements were available in some of the smaller sub-embayments of the system.

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 of the effects of the local winds and tidal induced mixing, the "strong littoral drift" assumption should cause only minor errors in residence time calculations.

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 Nasketucket Bay System. These include the output from the hydrodynamics model, calculations of external nitrogen loads and freshwater inflows from the watersheds and atmosphere, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen and salinity in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system embayment. Files of node locations and node connectivity for the RMA-2 model grid 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 output for the water quality model calibration was a 10-tidal cycle period in April 2006. 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 Embayment

Three primary nitrogen loads to the embayment 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 Nasketucket Bay System, 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 Embayment

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 Figure VI-1. The location of Station NR3 corresponds to a flow and water quality measuring Station NRM which was also used in the analysis, which shown below 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 is the minimum required to provide a baseline for MEP analysis. The periods of data collect varied with a maximum of fifteen years of data (collected between 1997 and 2011) for stations monitored in the Nasketucket Bay System by the Buzzards Bay Coalition (Bay Watchers) and the Coastal Systems Program at SMAST.

Table VI-1. Measured data, and modeled Total Nitrogen concentrations for the Nasketucket Bay System used in the model calibration plots of Figure VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data are provided courtesy of the Buzzards Bay Coalition and the Coastal Systems Program at SMAST.

Sub-Embayment	Nasketucket River	Nasketucket River	Nasketucket River	Little Bay Inner	Little Bay Mid	Little Bay Low	Brant Island Cove	West Island Inlet
Monitoring station	NR-2	NR-3 (NRM)	NR-1	LT-1	LT-3	LT-2	BI-1	WI-1
1997 mean	--	--	--	0.365	0.347	0.422	--	--
1998 mean	--	--	--	0.421	0.482	0.428	--	0.444
1999 mean	--	--	--	0.502	0.418	0.364	--	0.317
2000 mean	--	--	0.933	0.627	0.382	0.405	--	0.429
2001 mean	--	--	0.919	0.532	1.162	0.417	--	--
2002 mean	1.408	--	0.601	0.521	0.795	0.398	--	0.401
2003 mean	1.305	--	0.993	0.729	0.653	0.433	--	0.450
2004 mean	1.265	1.016	0.637	0.501	0.327	0.472	--	0.357
2005 mean	1.303	1.344	0.949	0.633	--	--	--	0.358
2006 mean	1.165	1.285	1.035	0.555	0.496	0.428	--	0.393
2007 mean	1.250	1.194	1.022	0.601	0.411	0.349	0.463	0.384
2008 mean	1.330	1.160	0.949	0.629	0.598	0.484	0.508	0.381
2009 mean	1.014	1.112	0.742	0.423	0.352	0.368	0.286	0.364
2010 mean	1.132	1.170	0.878	0.541	0.435	0.352	0.409	0.300
2011 mean	1.386	1.208	0.702	0.396	0.384	0.345	0.336	0.333
mean	1.234	1.190	0.861	0.531	0.482	0.399	0.403	0.367
s.d. all data	0.264	0.159	0.220	0.135	0.202	0.069	0.094	0.053
N	31	21	39	64	119	28	18	34
model min	--	1.179	0.577	0.394	0.368	0.354	0.337	0.358
model max	--	1.179	1.165	0.439	0.413	0.393	0.338	0.380
model average	--	1.179	0.889	0.415	0.391	0.373	0.338	0.368

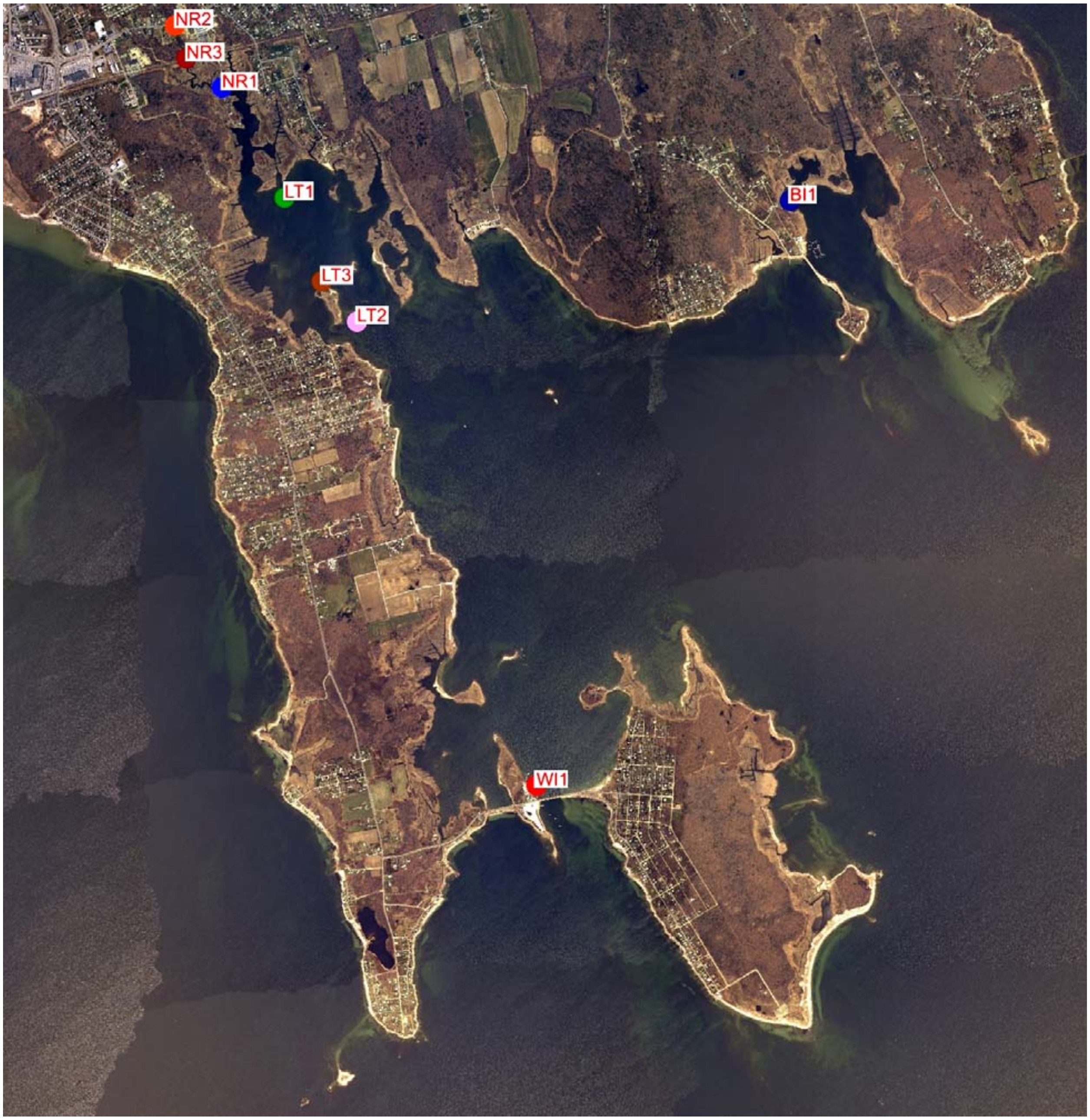


Figure VI-1. Estuarine water quality monitoring station locations in the Nasketucket Bay System. Station labels correspond to those provided in Table VI-1. The location of Station NR3 corresponds to a flow and water quality measuring Station NRM which was also used in the analysis.

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 Nasketucket Bay 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 the Nasketucket Bay System. 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. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod and Southern Massachusetts as part of the Massachusetts Estuaries Project.

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 watershed loading analysis (based on the MEP Technical Team and USGS watershed 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 system.

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 Nasketucket Bay 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 the Nasketucket Bay System were used for the water quality constituent modeling portion of this study.

Based on measured stream flow rates from SMAST and groundwater recharge rates from the watershed analysis, the hydrodynamic model was set-up to include the latest estimate of surface water flows from Nasketucket River (main), Nasketucket River West, Nasketucket River East, Nonquitt Brook (Knollmere), and Shaws Cove Brook East and West along with ground water flowing into the system from watersheds. The Nasketucket River (main) has a measured flow rate of 4.71 ft^3/sec (11,532 m^3/day), Nasketucket River West has a measured flow rate of 0.81 ft^3/sec (1,989 m^3/day), Nasketucket River East has a calculated flow rate of 0.30 ft^3/sec (732 m^3/day), Nonquitt Brook has a measured flow rate of 0.61 ft^3/sec (1,504 m^3/day), and Shaws Cove Brook East has a calculated flow rate of 0.88 ft^3/sec (2,148 m^3/day) and West has measured flow rate of 1.17 ft^3/sec (2,875 m^3/day). The overall groundwater flow rate into the system is 9.83 ft^3/sec (24,044 m^3/day) distributed amongst the watersheds.

For the 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 5 tidal-day (125 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 Nasketucket Bay System.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the watershed land-use analysis, 2) estimates of direct atmospheric deposition, 3) summer benthic regeneration, and 4) localized inputs developed from measured discharges of the Nasketucket River (main), Nasketucket River West, Nonquitt Brook, and Shaws Cove Brook West. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition load for Brandt Island Cove was evenly distributed at grid cells that formed the perimeter of the embayment. Benthic regeneration load was 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 Nasketucket Bay System are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Sections IV.1 and IV.2. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV.3. 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 the 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 present conditions, some sub-embayments have almost twice the loading rate from benthic regeneration as from watershed loads. For other sub-embayments, the benthic flux is relatively low or negative indicating 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 was set at 0.322 mg/L, based on monitoring data from measurement stations within Buzzards Bay. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Buzzards Bay.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Nasketucket Bay System, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions.**

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Little Bay	3.798	3.364	31.980
Shaw's Cove	0.680	0.356	5.938
Eastern Nasketucket Bay Watersheds	6.220	19.279	66.195
Brandt Island Cove	1.641	1.997	10.850
Western Nasketucket Bay Watersheds	9.190	21.016	-73.249
West Island Outer Bay	2.085	0.408	-7.667
Surface Water Sources			
Nasketucket Main and West Rivers	15.940	-	-
Nasketucket East River	0.887	-	-
Nonquitt Brook	2.082	-	-
Shaw's Cove Brook East and West	7.109	-	-

VI.2.4 Model Calibration

Calibration of the total nitrogen model proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs for the 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 Figure VI-2. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine dominated estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent areas of Nasketucket 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.

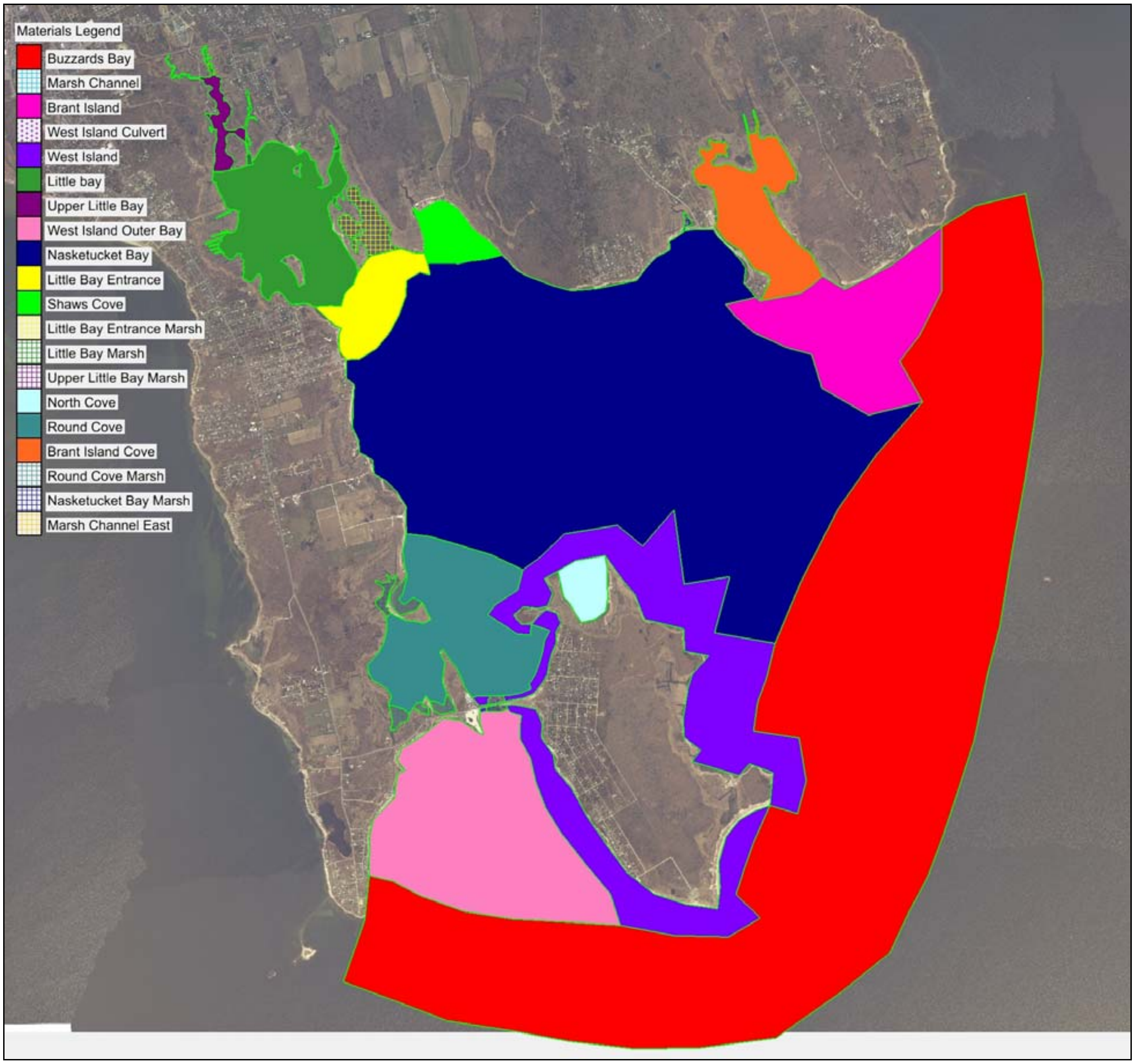


Figure VI-2. Map of Nasketucket Bay water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for Nasketucket Bay System.

Embayment Division	E m^2/sec
Buzzards Bay	23.0
Marsh Channel	1.5
Brandt Island	10.0
West Island Culvert	10.0
West Island	13.0
Little Bay	11.0
Upper Little Bay	15.0
West Island Outer Bay	13.0
Nasketucket Bay	18.0
Little Bay Entrance	17.0
Shaw's Cove	4.0
Little Bay Entrance Marsh	3.5
Little Bay Marsh	5.0
Upper Little Bay Marsh	4.0
North Cove	1.0
Round Cove	9.0
Brandt Island Cove	2.0
Round Cove Marsh	1.0
Nasketucket Bay Marsh	1.0
Marsh Channel East	5.0

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figure 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 water quality monitoring stations. The emphasis during calibration was to concentrate on representing the conditions measured at the data collection 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 between the modeled mean and maximum TN because the monitoring data are collected, as a rule, during mid ebb tide. Water quality monitoring station NSK-2 was not used during the calibration since it was outside the modeling domain.

Also presented in this figure are unity plot comparisons of measured data versus modeled target values for the system. The model provides a good representation for the Nasketucket Bay System, with rms error of 0.09 mg/L and an R^2 correlation coefficient of 0.86.

A contour plot of calibrated model output is shown in Figure VI-4 for Nasketucket Bay Estuaries. In the figure, color contours indicate nitrogen concentrations throughout the model domain. The output in the figure show average total nitrogen concentrations, computed using the full 5-tidal-day model simulation output period.

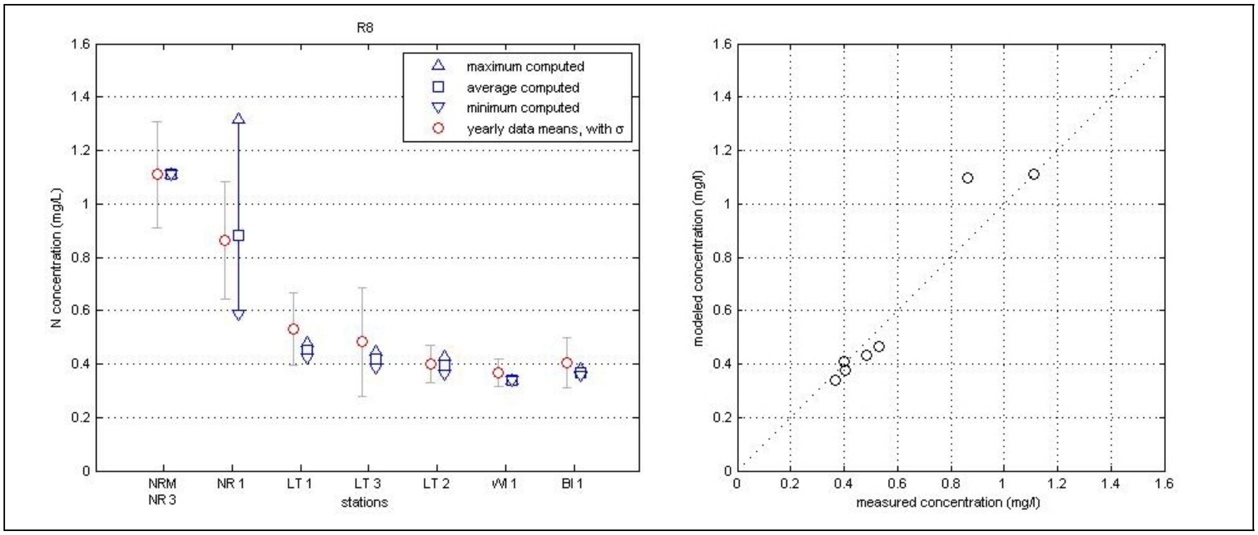


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Nasketucket Bay. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed 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. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

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 Nasketucket Bay System using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each 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 31.68 ppt. For groundwater inputs salinities were set at 0 ppt. Groundwater input used for the model was 9.83 ft^3/sec (24,044 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed on the border of individual watersheds in the model domain through the use of element input points positioned along the model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-5, with contour plots of model output shown in Figure VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in Nasketucket Bay System. The rms error of the models was 0.56 ppt, and correlation coefficient was 0.99. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical system.

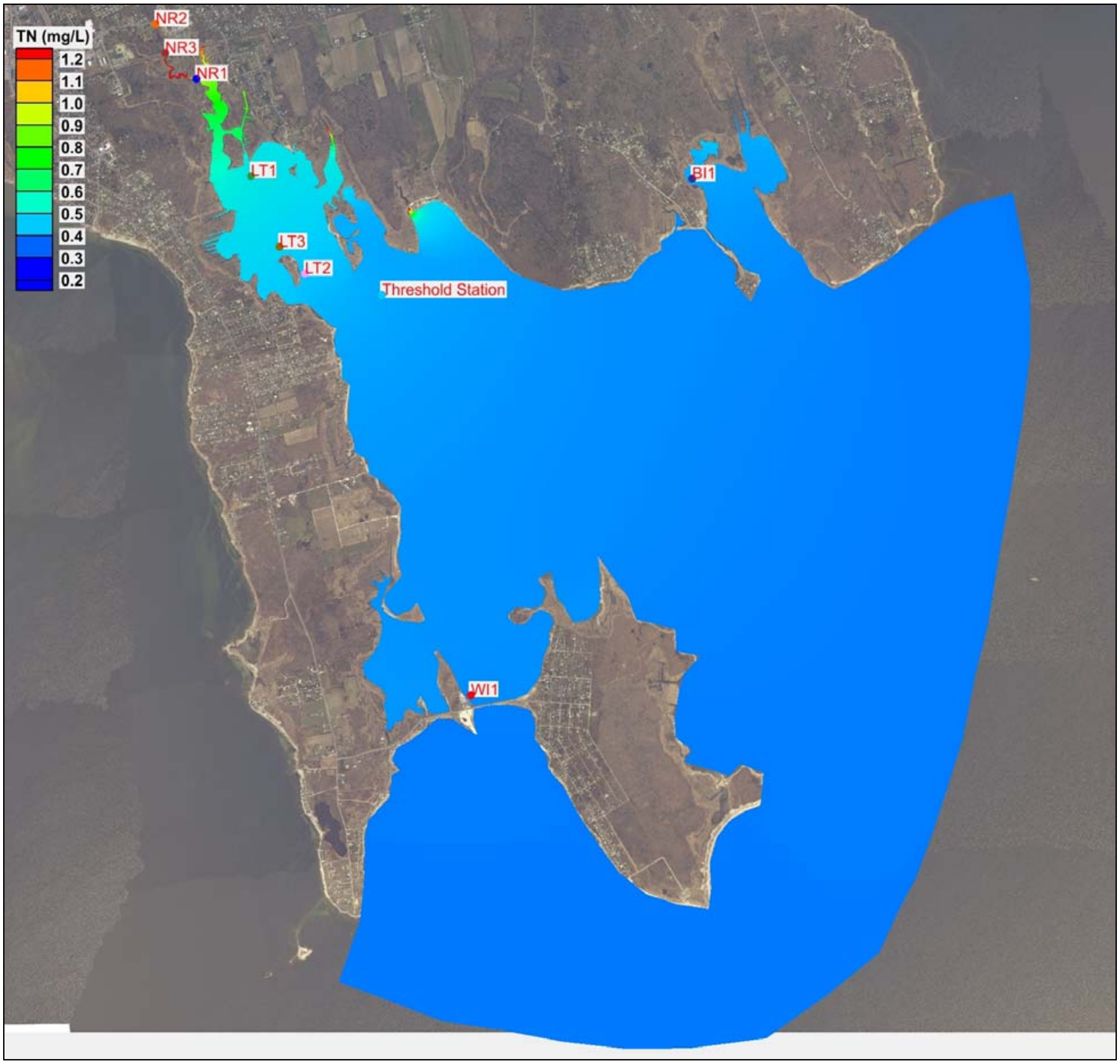


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for Nasketucket Bay. The approximate location of the sentinel threshold station for Nasketucket Bay is shown.

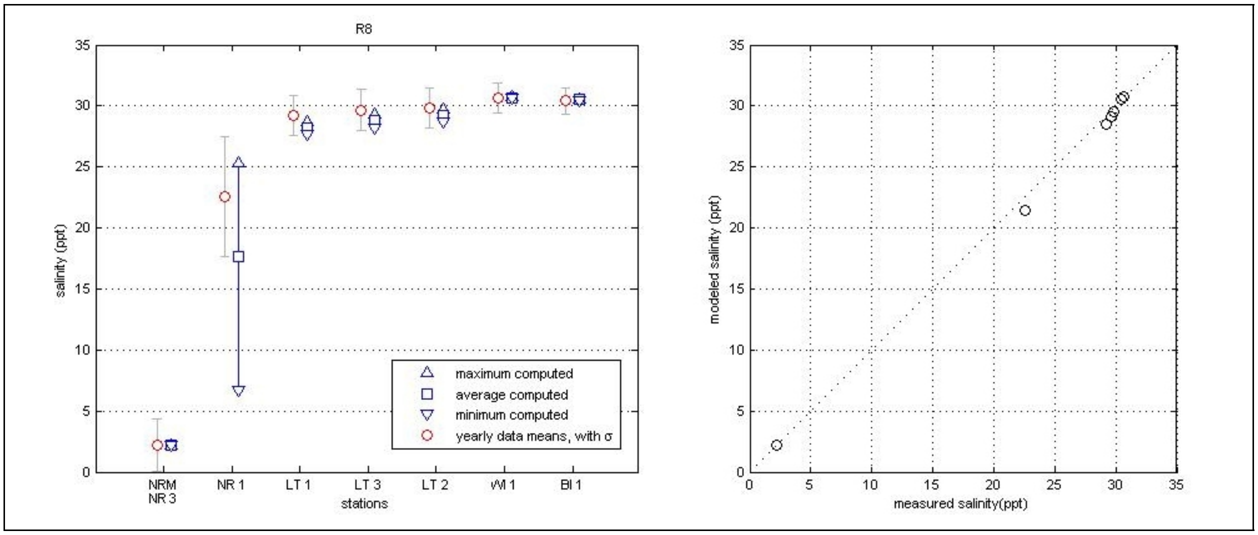


Figure VI-5. Comparison of measured and calibrated model output at stations in Nasketucket Bay. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle 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. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

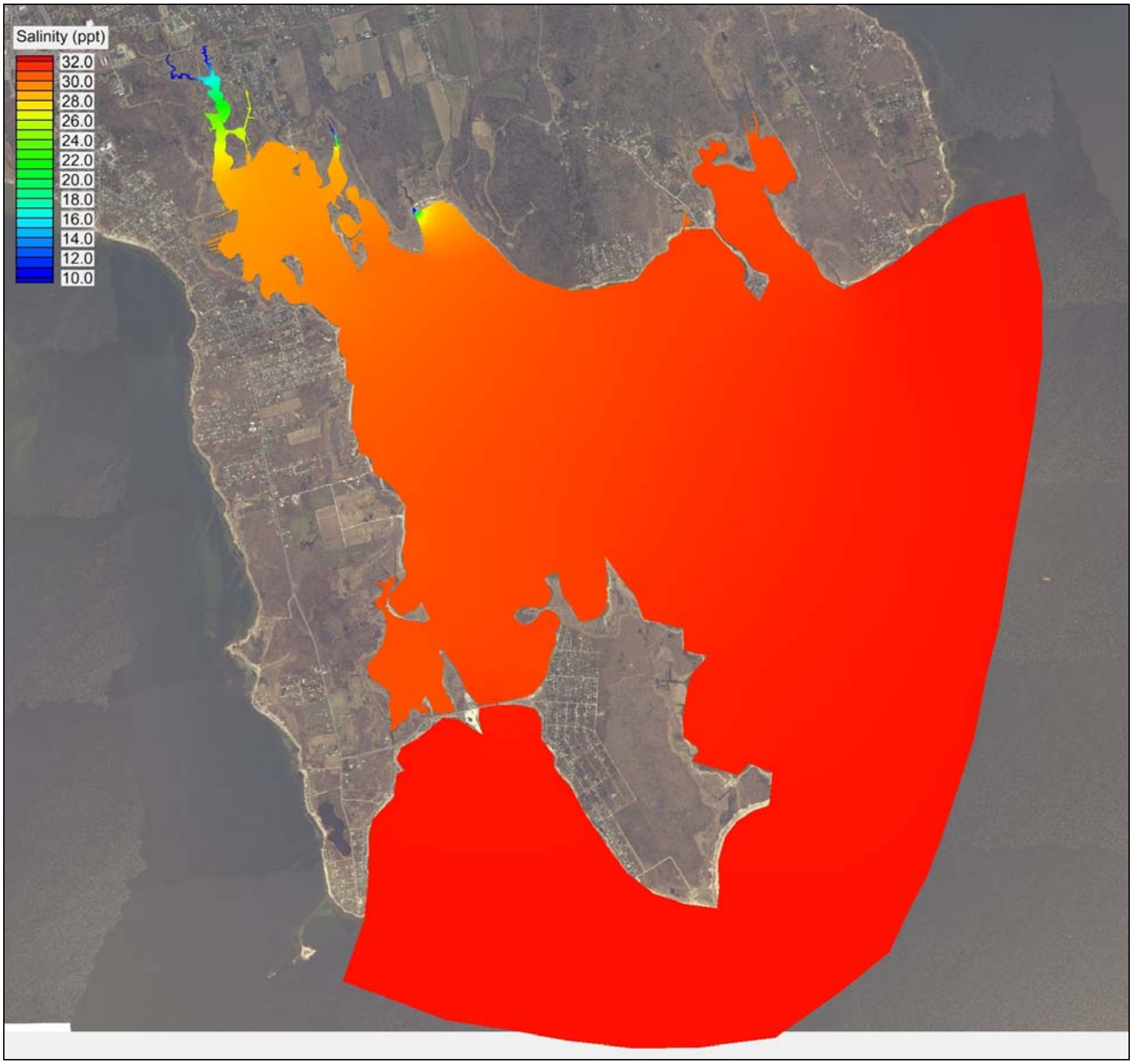


Figure VI-6. Contour plot of modeled salinity (ppt) in Nasketucket Bay.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the embayment system, two standard water quality modeling scenarios were run: 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.

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 Nasketucket Bay 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
Little Bay	3.798	5.386	+41.8%	0.929	-75.5%
Shaw's Cove	0.680	0.748	+10.0%	0.104	-84.7%
Eastern Nasketucket Bay	6.220	9.179	+47.6%	1.788	-71.3%
Brandt Island Cove	1.641	4.115	+150.7%	0.951	-42.1%
Western Nasketucket Bay	9.190	11.190	+21.8%	1.864	-79.7%
West Island Outer Bay	2.085	3.945	+89.2%	0.512	-75.4%
Surface Water Sources					
Nasketucket Main and West Rivers	15.940	24.638	+54.6%	4.712	-70.4%
Nasketucket East River	0.887	1.392	+56.9%	0.074	-91.7%
Nonquitt Brook	2.082	2.493	+19.7%	0.285	-86.3%
Shaw's Cove Brook East and West	7.109	9.595	+35.0%	0.784	-89.0%

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others under build-out conditions. The build-out scenario indicates that there would be more than a 100% increase in watershed nitrogen load to the Brandt Island Cove a result of potential future development, while most of the other watersheds have a more modest increase. For the no load scenarios, a majority of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by over 70% overall.

For the build-out scenario, a breakdown of the total nitrogen load entering the Nasketucket Bay System sub-embayments is shown in Table VI-5. 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 *vise 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 sub-embayment and surface water loads used for total nitrogen modeling of the Nasketucket Bay 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)
Little Bay	5.386	3.364	36.558
Shaw's Cove	0.748	0.356	6.578
Eastern Nasketucket Bay Watersheds	9.179	19.279	73.090
Brandt Island Cove	4.115	1.997	13.546
Western Nasketucket Bay Watersheds	11.190	21.016	-78.215
West Island Outer Bay	3.945	0.408	-8.208
Surface Water Sources			
Nasketucket Main and West Rivers	24.638	-	-
Nasketucket East River	1.392	-	-
Nonquitt Brook	2.493	-	-
Shaw's Cove Brook East and West	9.595	-	-

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Nasketucket Bay 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. Total N concentrations increased the most in the upper portion of Little Bay and at the mouth of Nasketucket River, with the largest change occurring at the head of Little Bay where Nasketucket River enters the system (60%) and the least change occurred in outer regions of the system where Brandt Island Cove had a modest increase of 1-percent. Color contours of model output for the build-out scenario are present in Figure VI-7. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Nasketucket Bay System. Sentinel threshold station is in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Nasketucket River Main	NRM & NR-3	1.109	1.774	+60.0%
Nasketucket River	NR-1	0.881	1.122	+27.4%
Little Bay Inner	LT-1	0.451	0.493	+9.2%
Little Bay Mid	LT-3	0.418	0.448	+7.3%
Little Bay Low	LT-2	0.395	0.418	+5.8%
Brandt Island Cove	BI-1	0.340	0.345	+1.4%
West Island Inlet	WI-1	0.369	0.396	+7.3%
Threshold Station	**--**	**0.368**	**0.382**	**+3.8%**

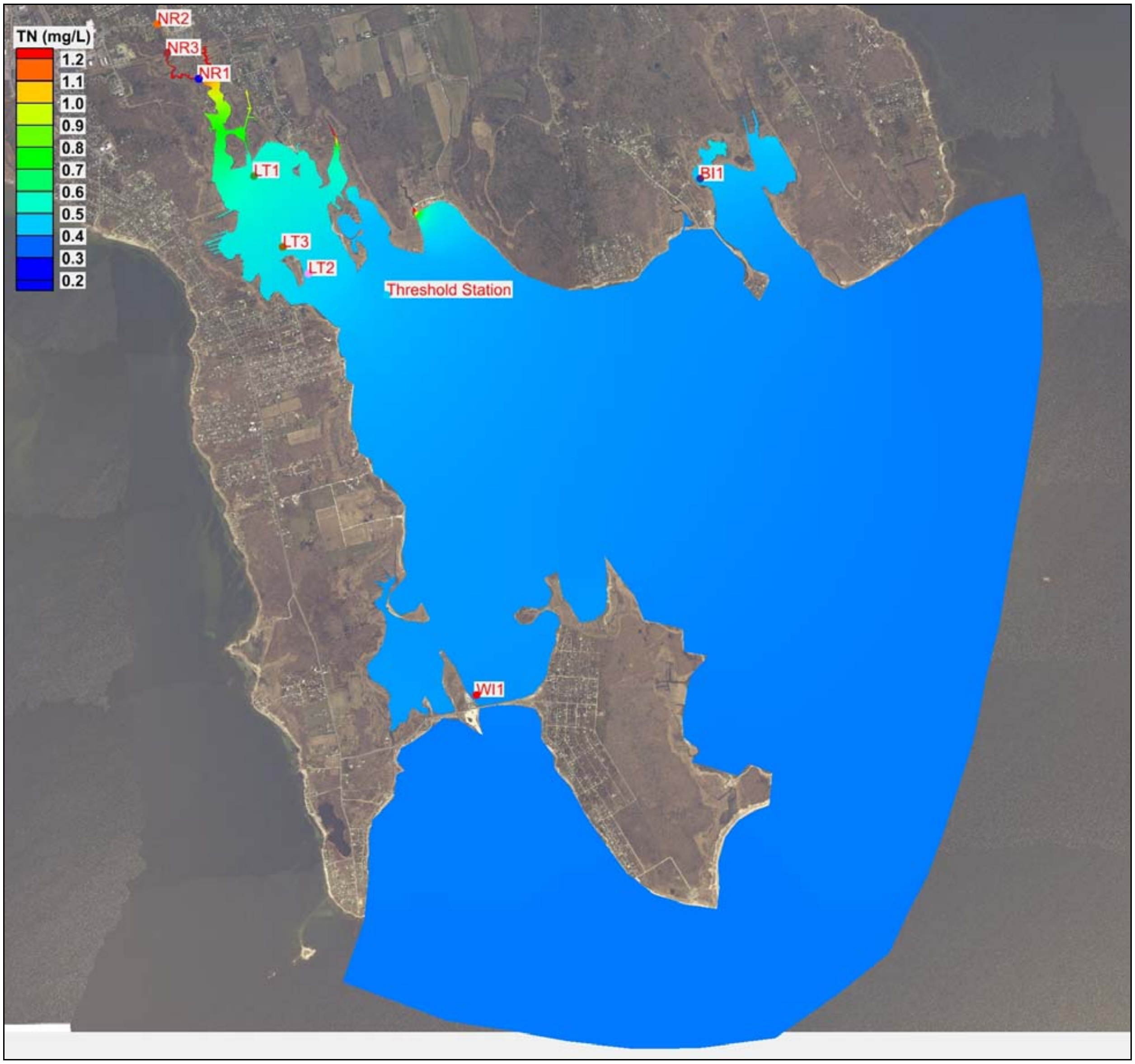


Figure VI-7. Contour plot of modeled total nitrogen concentrations (mg/L) in Nasketucket Bay, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Nasketucket Bay is shown.

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") scenario 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 Section 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 Nasketucket Bay 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)
Little Bay	0.929	3.364	19.942
Shaw's Cove	0.104	0.356	4.191
Eastern Nasketucket Bay Watersheds	1.788	19.279	56.541
Brandt Island Cove	0.951	1.997	9.116
Western Nasketucket Bay Watersheds	1.864	21.016	-64.558
West Island Outer Bay	0.512	0.408	-6.945
Surface Water Sources			
Nasketucket Main and West Rivers	4.712	-	-
Nasketucket East River	0.074	-	-
Nonquitt Brook	0.285	-	-
Shaw's Cove Brook East and West	0.784	-	-

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. 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" varied as shown in Table VI-8, with reductions ranging from 3% at the outer stations to approximately 70% at the mouth of the Nasketucket River. Results for each system are shown pictorially in Figure VI-8.

Table VI-8. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Nasketucket Bay System. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Nasketucket River Main	NRM & NR-3	1.109	0.368	-66.8%
Nasketucket River	NR-1	0.881	0.311	-64.7%
Little Bay Inner	LT-1	0.451	0.350	-22.4%
Little Bay Mid	LT-3	0.418	0.342	-18.1%
Little Bay Low	LT-2	0.395	0.337	-14.8%
Brandt Island Cove	BI-1	0.340	0.327	-3.9%
West Island Inlet	WI-1	0.369	0.355	-3.7%
Threshold Station	**--**	**0.368**	**0.330**	**-10.3%**

Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in Nasketucket Bay, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Nasketucket Bay is shown.

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 Nasketucket Bay embayment system in the Town of Fairhaven, MA, our assessment is based upon data from the water quality monitoring database (1993-2010) developed by the Coalition for Buzzards Bay with technical support from the Coastal Systems Program (UMASS-SMAST), surveys of eelgrass distribution (1951, 1995, 2001), benthic animal communities (fall 2005), sediment characteristics (summer 2005), and dissolved oxygen records (summer 2005). 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 both of these systems (Section VIII). It should be noted that nitrogen enrichment occurs through 2 primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with the low nitrogen waters of Buzzards Bay. Nasketucket Bay has increased nitrogen loading from the associated watersheds from shifting land-uses and the upper reaches of little Bay has periodically had restricted tidal exchange. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs.

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 threshold 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 autonomous dissolved oxygen sensors throughout Nasketucket Bay and Little Bay at locations that would be representative of the dissolved oxygen conditions at critical points in the system, namely the salt marsh dominated portion of Little Bay and the tributary coves to Nasketucket Bay such as Shaws Cove and North Cove (Figure VII-1). The dissolved oxygen moorings were deployed 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 throughout the overall Nasketucket Bay system 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. Surveying completed by the SMAST-MEP Technical Team in the summer of 2005 did reveal the presence of eelgrass, as would be expected given the structure of the embayment and served to confirm findings by the MassDEP surveying in 2001. Nutrient threshold determination for Nasketucket Bay was based on results from the dissolved oxygen and chlorophyll mooring data, the eelgrass surveying as well as the benthic infaunal community characterization.

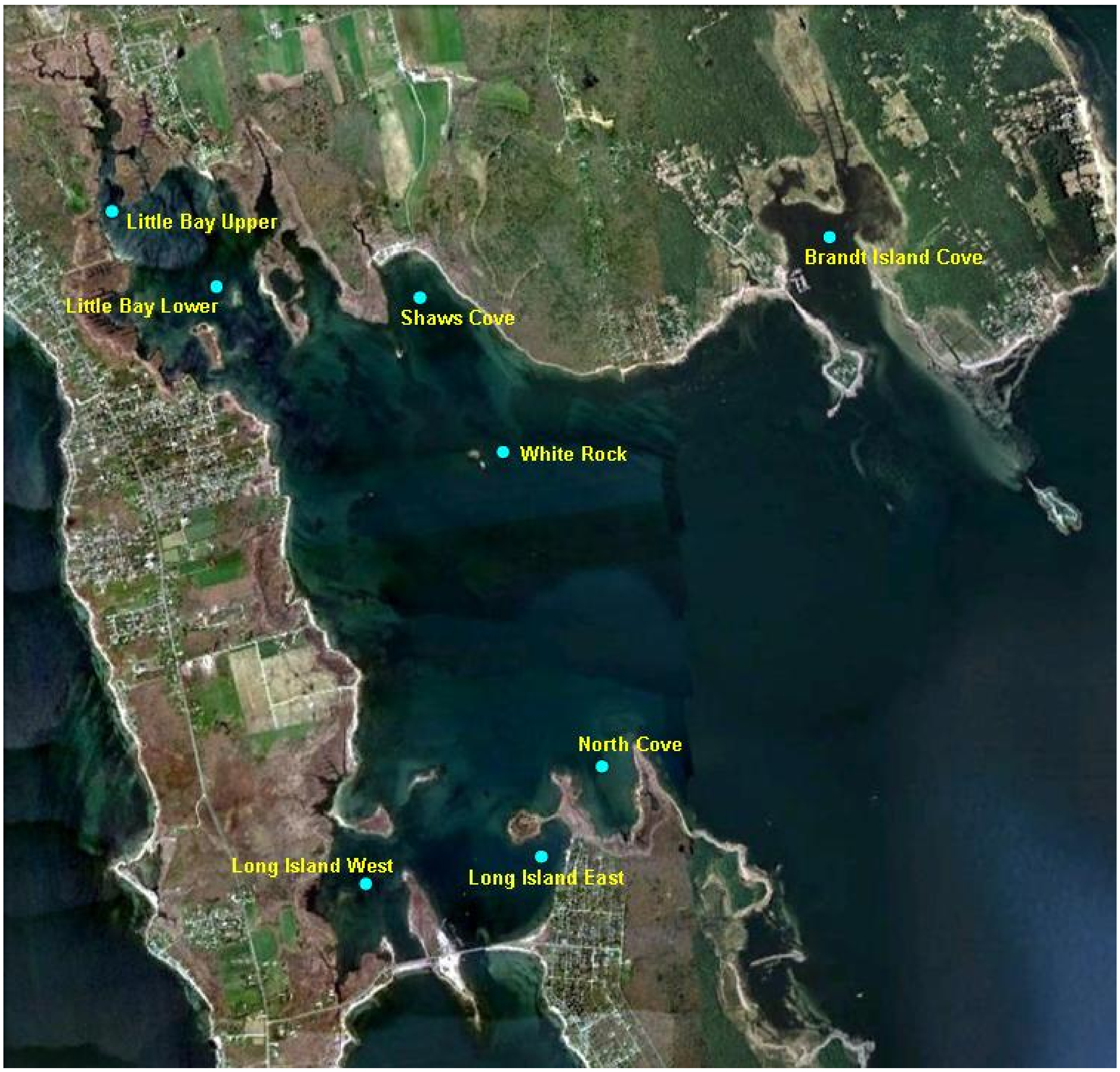


Figure VII-1. Aerial Photograph of the Nasketucket Bay / Little Bay Estuary within the Towns of Fairhaven and Mattapoisett showing the locations of the continuously recording Dissolved Oxygen / Chlorophyll-a sensors deployed during the Summer of 2005. Brant Island Cove mooring was lost.

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 their habitat. 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, USEPA[1] suggests that the chronic protective oxygen level to support growth of estuarine animals is 4.8 mg L^{-1}, with a limit for survival of juvenile and adult organisms of 2.3 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1} and SB waters above 5 mg L^{-1}. The tidal waters of the Nasketucket Bay Embayment System are currently listed under this classification as SA. 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 (Figure VII-2). 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 Nasketucket Bay Embayment System (Figure VII-1). Measurements were made close to the sediment surface so as to quantify the oxygen environment affecting benthic animal communities. 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 deployment of ~30 days within the interval from July through mid-September. All of the mooring data from the Nasketucket Bay and Little Bay embayment system was collected during the summer of 2005. Oxygen data from the BayWatchers Water Quality Monitoring Program was used to provide inter-annual information on oxygen levels for integration with the detailed 2005 time-series data.

[1] USEPA 2000. Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras (133 p.).

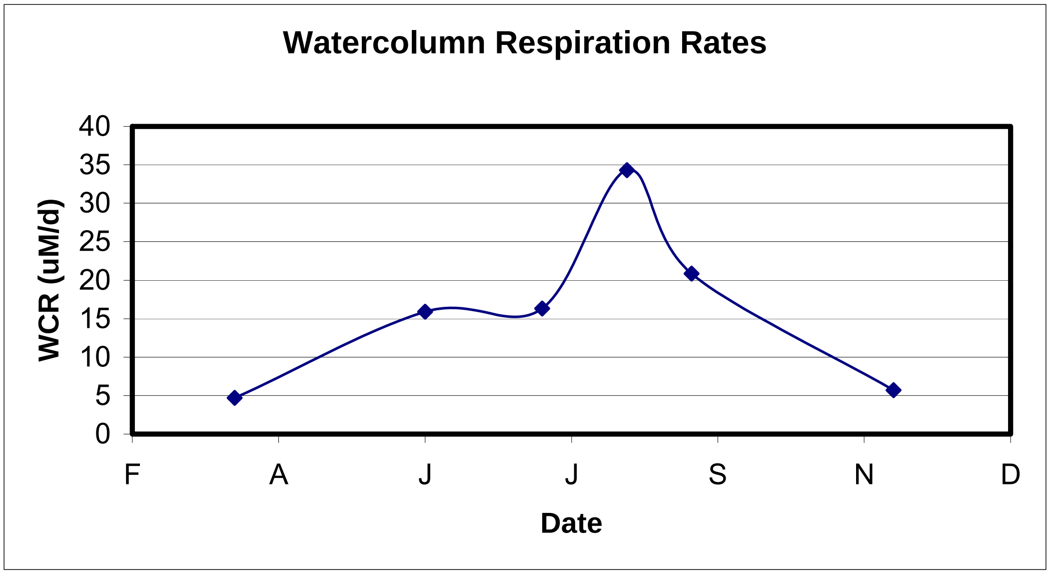


Figure VII-2. As an example, average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System are presented (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Nasketucket Bay / Little Bay Estuary evaluated in this MEP assessment showed high frequency variation related primarily 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. Oxygen excursions result from oxygen consumption (night) and production (day) primarily by phytoplankton within the estuarine waters. Additional oxygen uptake results from the microbial decay of organic matter, which in the case of Little Bay and specific portions of Nasketucket Bay is mainly from phytoplankton and eelgrass respiration and phytoplankton settling to bottom sediments. Oxygen levels in estuaries typically cannot be managed directly, but rather through management of nitrogen levels and mitigation of any direct organic matter inputs (e.g. outfalls).

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. However, the large number of oxygen samplings by the BayWatchers Water Quality Monitoring Program from 1997-2011 was sufficient to confirm and support the minimum oxygen levels measured by the detailed time-series measurements. The ability to better capture minimum oxygen levels by continuous measurement appears to be generally true for the estuaries of southeastern Massachusetts where periodic monitoring of oxygen and time-series oxygen recordings generally yield similar results, except that periodic low oxygen tends to be better captured in the continuous recordings.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 37-44 day deployment period that these parameters were below or 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.

Table VII-1. Days and percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Nasketucket Bay / Little Bay Estuary. Data collected by the Coastal Systems Program, SMAST.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Little Bay Upper	**8/1/2005**	**9/7/2005**	**36.93**	**69%**	**37%**	**11%**	**2%**
			Mean	0.83	0.30	0.18	0.27
			Min	0.26	0.01	0.03	0.18
			Max	3.61	1.47	1.00	0.35
			S.D.	0.63	0.24	0.20	0.13
Little Bay Lower	**8/1/2005**	**9/7/2005**	**36.92**	**72%**	**36%**	**4%**	**0%**
			Mean	1.49	0.44	0.13	0.02
			Min	0.03	0.01	0.03	0.02
			Max	12.97	2.83	0.27	0.02
			S.D.	3.00	0.55	0.08	N/A
Long Island East	**8/1/2005**	**9/7/2005**	**36.93**	**54%**	**11%**	**2%**	**2%**
			Mean	0.54	0.19	0.37	0.21
			Min	0.03	0.01	0.25	0.13
			Max	2.69	0.63	0.49	0.30
			S.D.	0.44	0.16	0.17	0.13
Long Island West	**8/1/2005**	**9/7/2005**	**36.98**	**36%**	**7%**	**0%**	**0%**
			Mean	0.32	0.13	0.15	N/A
			Min	0.01	0.02	0.15	0.00
			Max	0.83	0.51	0.15	0.00
			S.D.	0.21	0.12	N/A	N/A
North Cove	**8/1/2005**	**9/7/2005**	**36.89**	**63%**	**26%**	**3%**	**0%**
			Mean	0.61	0.24	0.09	N/A
			Min	0.11	0.03	0.03	0.00
			Max	1.79	0.72	0.17	0.00
			S.D.	0.27	0.19	0.05	N/A
Shaw's Cove	**8/1/2005**	**9/7/2005**	**36.96**	**47%**	**16%**	**4%**	**2%**
			Mean	0.45	0.23	0.10	0.06
			Min	0.02	0.04	0.02	0.04
			Max	2.00	0.68	0.20	0.07
			S.D.	0.38	0.17	0.06	0.01
White Rock	**8/1/2005**	**9/14/2005**	**43.83**	**42%**	**11%**	**3%**	**1%**
			Mean	0.28	0.13	0.08	0.05
			Min	0.01	0.01	0.01	0.01
			Max	2.78	1.42	0.39	0.17
			S.D.	0.48	0.25	0.13	0.08

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels throughout the Nasketucket Bay / Little Bay Estuary indicates low to moderate levels of nutrient enrichment and generally moderate-high habitat quality, with the greatest depletions in the basins with highest nitrogen and chlorophyll-a levels in the upper portions of the system (e.g. Little Bay) (Figures VII-3,5,7,9,11,13,15). The oxygen data is consistent with the organic matter loads from phytoplankton production (chlorophyll-a levels) indicative of the level of nitrogen enrichment within and estuary. The daily excursions of ~3 mg L^{-1} in oxygen concentration in the tributary coves Little Bay, Shaws Cove, North Cove, Long Island (east and West) also moderate organic matter 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). Clear evidence of oxygen levels above atmospheric equilibration is further evidence of nitrogen enrichment. However, significantly elevated oxygen was not observed in any of the time-series oxygen records within this estuary, further evidence that while some oxygen depletion is occurring, the system is not significantly impaired.

Table VII-2. Duration (days and % of deployment time) that chlorophyll a levels exceed various benchmark levels within the Nasketucket Bay / Little Bay Estuary. "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.

Mooring Location	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)
Little Bay Upper	**8/1/2005**	**9/7/2005**	**36.5**	**98%**	**43%**	**5%**	**1%**	**0%**
Mean Chl Value = 9.9 ug/L			**Mean**	5.98	0.29	0.19	0.15	NA
			Min	0.04	0.04	0.04	0.08	0.00
			Max	12.00	3.08	0.67	0.21	0.00
			S.D.	4.05	0.45	0.20	0.09	NA
Little Bay Lower	**8/1/2005**	**9/7/2005**	**36.38**	**98%**	**31%**	**5%**	**1%**	**0%**
Mean Chl Value = 9.3 ug/L			**Mean**	3.58	0.20	0.11	0.04	NA
			Min	0.42	0.04	0.04	0.04	0.00
			Max	10.92	0.58	0.33	0.04	0.00
			S.D.	4.16	0.14	0.08	0.00	NA
Long Island East	**8/1/2005**	**9/7/2005**	**36.63**	**38%**	**1%**	**0%**	**0%**	**0%**
Mean Chl Value = 4.8 ug/L			**Mean**	0.36	0.07	NA	NA	NA
			Min	0.04	0.04	0.00	0.00	0.00
			Max	1.25	0.08	0.00	0.00	0.00
			S.D.	0.32	0.02	NA	NA	NA
Long Island West	**8/1/2005**	**9/7/2005**	**36.63**	**89%**	**14%**	**0%**	**0%**	**0%**
Mean Chl Value = 7.5 ug/L			**Mean**	1.35	0.15	0.06	NA	NA
			Min	0.04	0.04	0.04	0.00	0.00
			Max	8.67	1.00	0.08	0.00	0.00
			S.D.	1.95	0.17	0.03	NA	NA
North Cove	**8/1/2005**	**9/7/2005**	**36.00**	**55%**	**1%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.2 ug/L			**Mean**	0.44	0.10	0.08	NA	NA
			Min	0.04	0.04	0.08	0.00	0.00
			Max	2.58	0.21	0.08	0.00	0.00
			S.D.	0.62	0.08	NA	NA	NA
Shaw's Cove	**8/1/2005**	**9/7/2005**	**36.96**	**51%**	**2%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.3 ug/L			**Mean**	0.57	0.16	NA	NA	NA
			Min	0.04	0.04	0.00	0.00	0.00
			Max	2.83	0.33	0.00	0.00	0.00
			S.D.	0.74	0.13	NA	NA	NA
White Rock	**8/1/2005**	**9/14/2005**	**37.04**	**42%**	**2%**	**1%**	**0%**	**0%**
Mean Chl Value = 5.2 ug/L			**Mean**	0.33	0.17	0.13	NA	NA
			Min	0.04	0.04	0.04	0.00	0.00
			Max	1.92	0.33	0.21	0.00	0.00
			S.D.	0.34	0.11	0.12	NA	NA

Generally, the dissolved oxygen records throughout the Nasketucket Bay / Little Bay Estuary showed moderate depletions of oxygen (relative to the basin type) during the critical summer period. The greatest oxygen depletions were generally associated with the upper portions of the Little Bay system within the salt marshes at the mouth of the Nasketucket River. The D.O. record at this location shows oxygen depletion (below 5.0 mg/L) during 1/3 of the summer record with periodic depletions below 4.0 mg/L, consistent with its nitrogen and organic matter rich waters (Table VII-1, Figure VII-3). However, it is important to note that a portion of this enrichment stems from the role of the Nasketucket River marshes and transport of high nutrient, high phytoplankton, low oxygen waters to the head of Little Bay on the ebbing tide. The lower portion of Little Bay as well as Shaws Cove shows lower levels and frequency of oxygen depletion (96% of record >4 mg L^{-1}) as well as moderate chlorophyll levels (average ~9 ug/L). The high turnover of water in the Nasketucket Bay portion of the overall estuarine system, that is closest to the low nutrient waters of Buzzards Bay, reduces that basin's ability to build up nutrients.

Upper Little Bay – Nasketucket **(Figures VII-3 and VII-4):**

The dissolved oxygen mooring that was deployed in the upper portion of Little Bay was situated at the mouth of the tidal creek portion of the Nasketucket River where it discharges to Little Bay after traversing the salt marsh that constitutes the head of Little Bay (Figure VII-1). Although modest, daily excursions in oxygen levels were frequent, ranging from air equilibration to ~4 mg L^{-1} over the 36 day deployment (Figure VII-3, Table VII-1). Oxygen levels in Upper Little Bay regularly reached 7-8 mg L^{-1}. The relatively moderate measured chlorophyll-*a* levels as well as the observed presence of a patch of macroalgae in the vicinity of the mooring location likely enhance the level of oxygen depletion and the diurnal cycle in oxygen concentration. Consistent with the oxygen record, chlorophyll-*a* concentrations were elevated during most of the deployment period, averaging 10 ug/L and ranging between 5-15 ug/L for 95% of record. Chlorophyll-*a* exceeded the 10 ug L^{-1} benchmark 43% of the time, with 2 blooms reaching 20 ug/L (Table VII-2, Figure VII-12). Average chlorophyll levels over 10 ug L^{-1} have been used to indicate nitrogen enrichment and the onset of eutrophic conditions in embayments, although the river and salt marsh influences soften that assessment in this case.

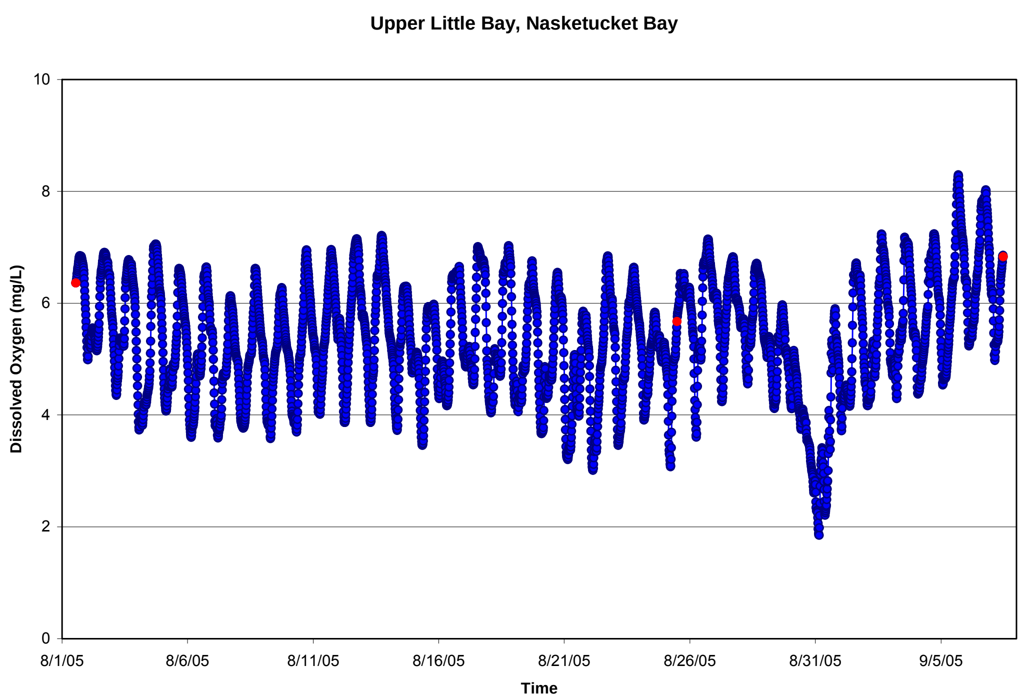


Figure VII-3. Bottom water record of dissolved oxygen at the upper Little Bay station tributary to Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

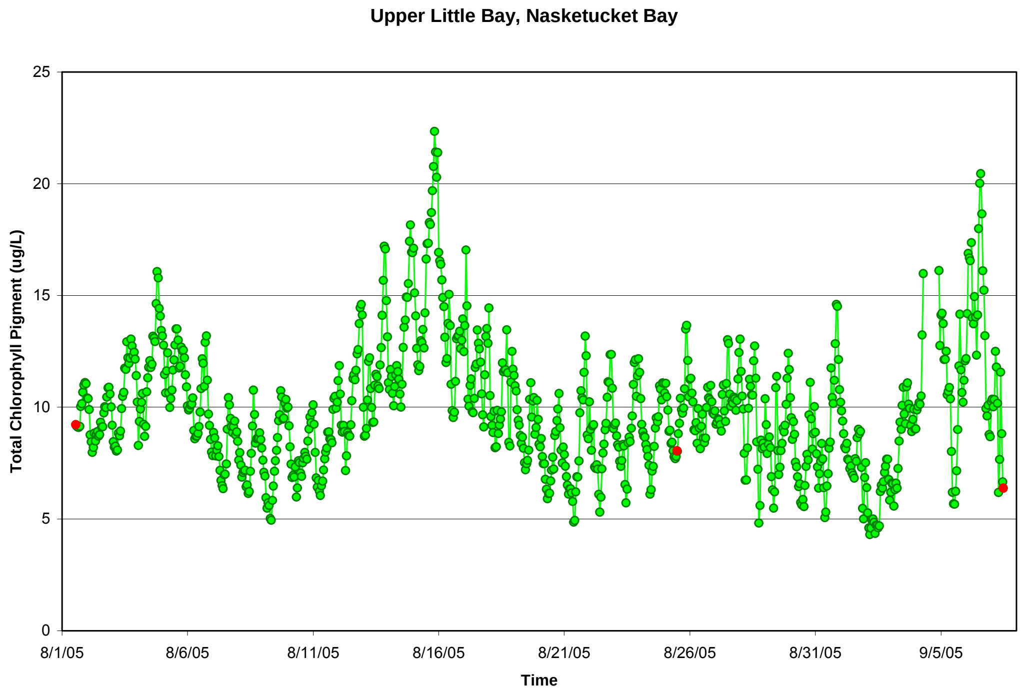


Figure VII-4. Bottom water record of Chlorophyll-*a* at the upper Little Bay station tributary to Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

***Lower Little Bay – Nasketucket* (Figures VII-5 and VII-6):**

Lower Little Bay is the outer tidal reach of Little Bay, a tributary sub-embayment to the larger Nasketucket Bay and is bounded by Sconticut Neck to the West and the Knollmere area of Fairhaven as well as the South Shore Marshes Wildlife Management Area to the east. Given the greater flushing of Lower versus Upper Little Bay and the lower nitrogen levels, oxygen depletions in this portion of the Bay were less and the diurnal variations smaller than in the upper reach. Daily excursions in oxygen levels were frequent but not indicative of over-enrichment (1-2 mg L^{-1}). Although oxygen depletion was frequent, levels were typically >4 mg L^{-1}. DO levels were generally between 4 mg L^{-1} and 6 mg L^{-1}, however, there was a clear increase in DO in the second half of the deployment period (Figure VII-5, Table VII-1). The moderate chlorophyll-*a* levels were consistent with the observed oxygen levels, chlorophyll-*a* concentrations were generally between 10 and 20 ug L^{-1} and averaged 9 ug/L over the record. The 10 ug L^{-1} benchmark was exceeded 31% of the time, but levels were rarely >15 ug L^{-1} (Table VII-2, Figure VII-6). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments. Given the measured chlorophyll concentrations and oxygen depletion, it appears that Little Bay (as a whole) has slightly exceeded its tolerance for nitrogen and organic matter loading and that further nitrogen enrichment will result in significant blooms and increases in the frequency and extent of oxygen depletion, with almost certain impairment of benthic habitats.

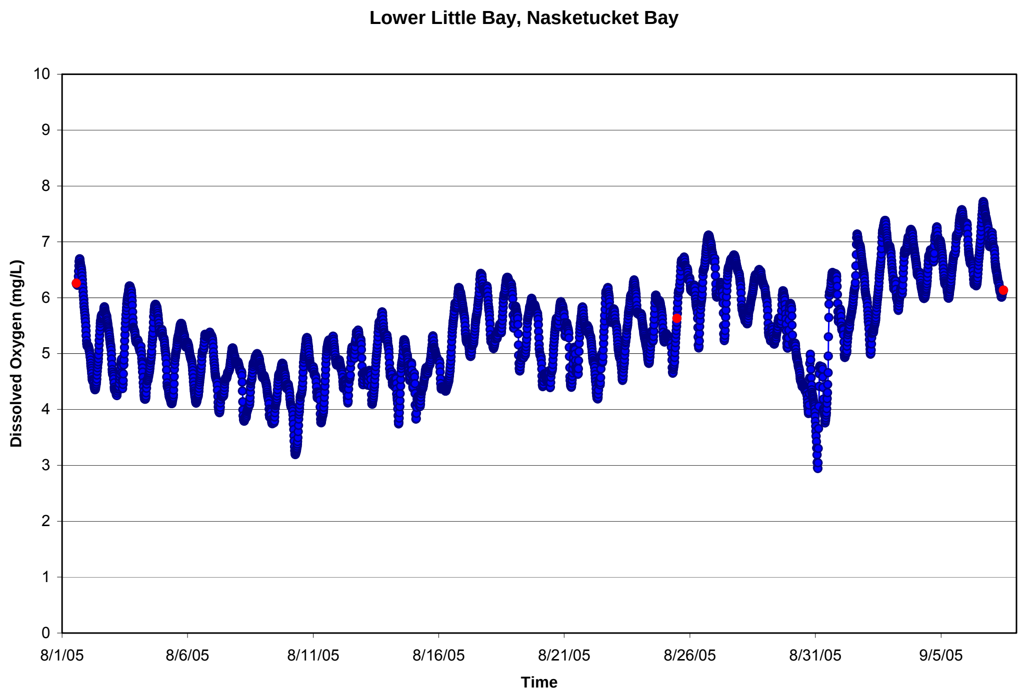


Figure VII-5. Bottom water record of dissolved oxygen at the lower Little Bay station tributary to Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

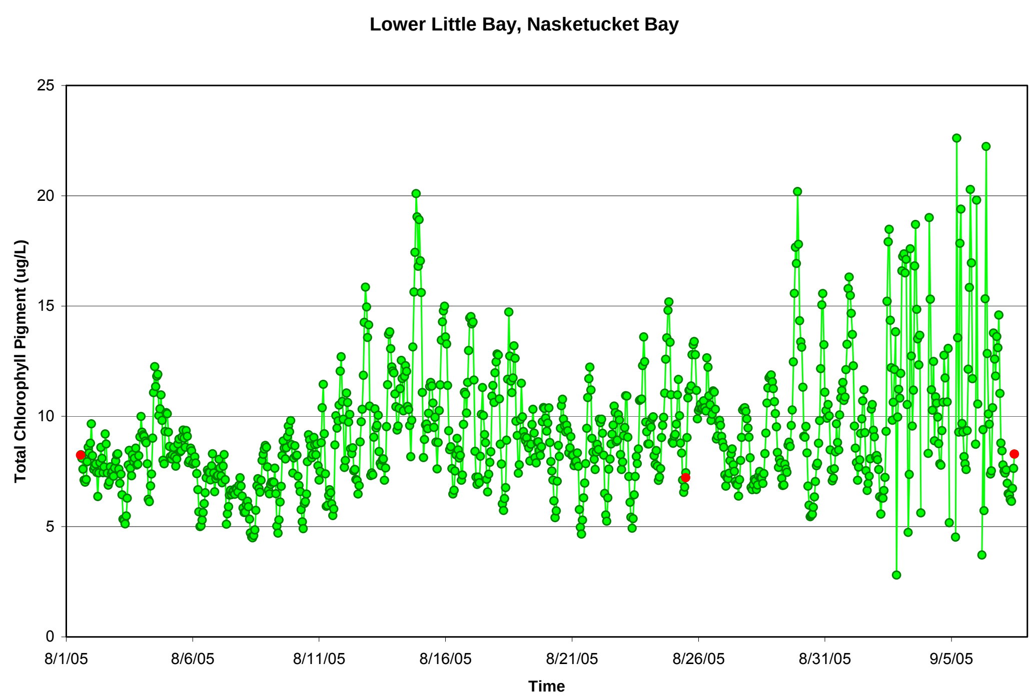


Figure VII-6. Bottom water record of Chlorophyll-*a* at the lower Little Bay station tributary to Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

***Shaws Cove – Nasketucket* (Figures VII-7 and VII-8):**

The Shaws Cove mooring location was located in the upper reach of the basin bordering the tidal wetland (Figure VII-1). High frequency data from Shaws Cove showed clear, periodic daily excursions of ~4 mg L^{-1}. The oxygen excursions resulted mainly from oxygen uptake associated with the diurnal cycle as well as wetland and tidal influences. Lowest dissolved oxygen was typically observed in the early morning. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs) for reasons noted above. However, dissolved oxygen only rarely declined to 4 mg L^{-1} and greater depletions only lasted hours (Figure VII-7). The oxygen levels did increase over air saturation infrequently and to only modest levels (~9 mg L^{-1}). Consistent with the oxygen data, chlorophyll-*a* was generally low, averaging 5.3 ug/L over the record and rarely exceeding 8 ug/L.. At the Shaws Cove mooring location, chlorophyll-*a* levels exceeded the 10 ug L^{-1} benchmark only 2% of the time (Table VII-2, Figure VII-6). The overall average chlorophyll level was 5.3 ug L^{-1} over the deployment and 6.3 by the Water Quality Monitoring Program. These data indicate that Shaws Cove is currently showing only modest oxygen depletion and chlorophyll levels and is typical of a wetland influenced cove.

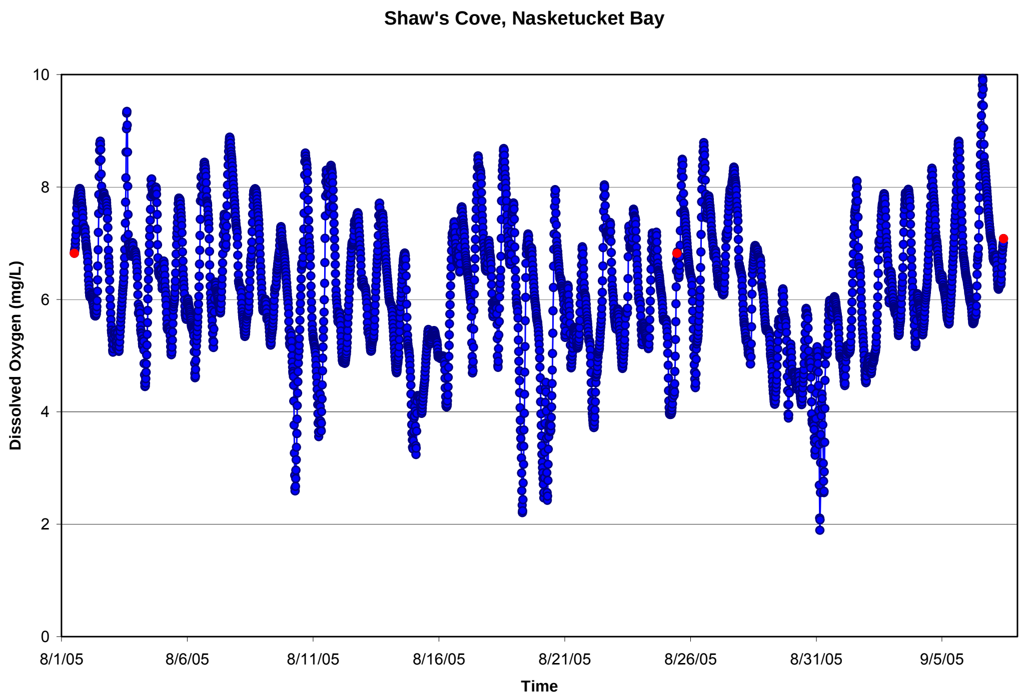


Figure VII-7. Bottom water record of dissolved oxygen at the Shaws Cove station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

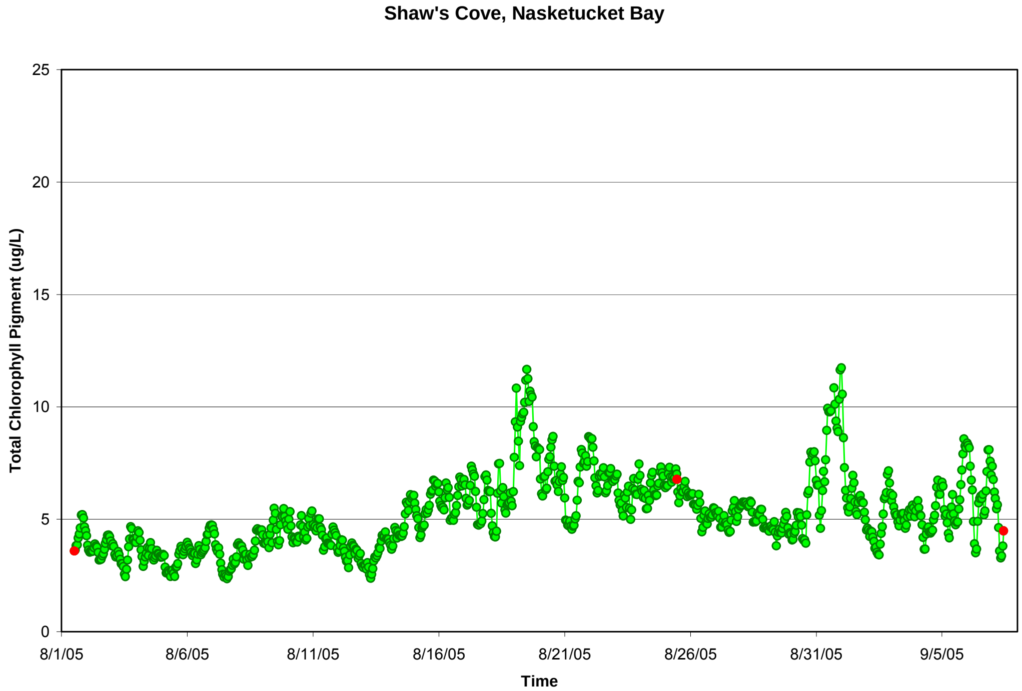


Figure VII-8. Bottom water record of Chlorophyll-*a* at the Shaws Cove station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

White Rock – Nasketucket **(Figures VII-9 and VII-10):**

The upper Nasketucket Bay mooring location (White Rock) was generally located in the central portion of upper Nasketucket Bay slightly north of the scallop aquaculture area (Figure VII-1). High frequency data from the White Rock mooring showed only small daily excursions similar to other large open water systems with low levels of nitrogen enrichment. Oxygen levels seldom exceeded 7 mg L^{-1} and never exceeded 8 mg L^{-1}. The oxygen excursions were associated with both the diurnal cycle of uptake and production as well as tidal exchange of lower (ebb) and higher (flood) DO waters. Lowest dissolved oxygen was typically observed in the early morning. Highest dissolved oxygen was observed at the end of the photocycle (ca. 1500 hrs) for reasons noted above. Dissolved oxygen was typically above 5 mg L^{-1} and only rarely declined to <4 mg L^{-1} (3% of record; Figure VII-5, Table VII-1). Given the relatively small excursions in dissolved oxygen and the only occasional decrease in concentrations to <4 mg L^{-1}, the data indicate only slight effects of nitrogen enrichment of this basin. Consistent with the oxygen data, chlorophyll-*a* was generally low, averaging 5.2 ug/L and was <5 for 58% of record, and only exceeded 10 ug L^{-1} for 2 percent of record (Table VII-2, Figure VII-6). The overall average chlorophyll level was 5.2 ug L^{-1} over the deployment and 4.6 ug L^{-1} based on the BayWatchers Water Quality Monitoring Program. Both the oxygen and chlorophyll-*a* data indicate that Nasketucket Bay is only showing slight nitrogen enrichment effects.

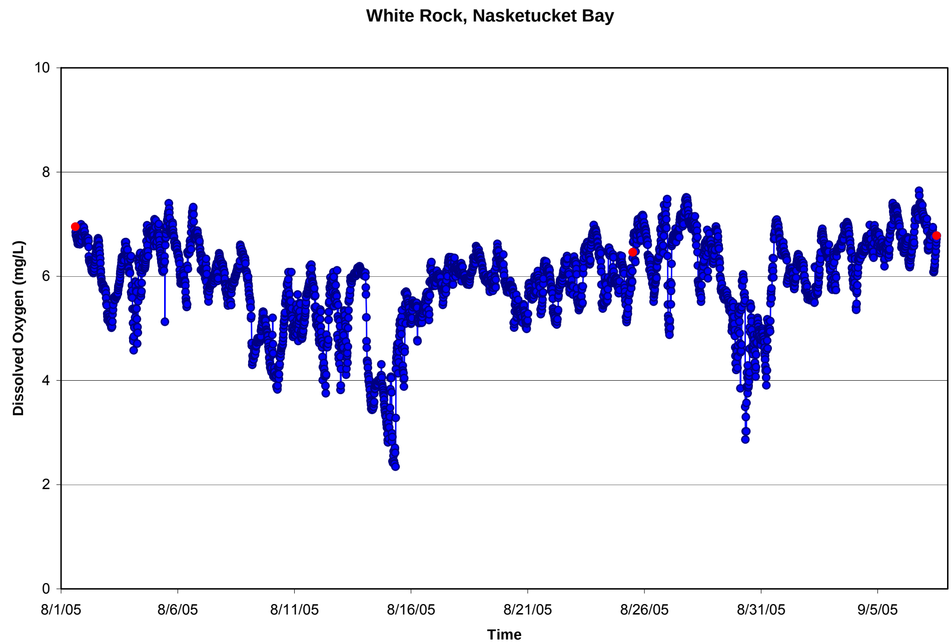


Figure VII-9. Bottom water record of dissolved oxygen at the White Rock station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

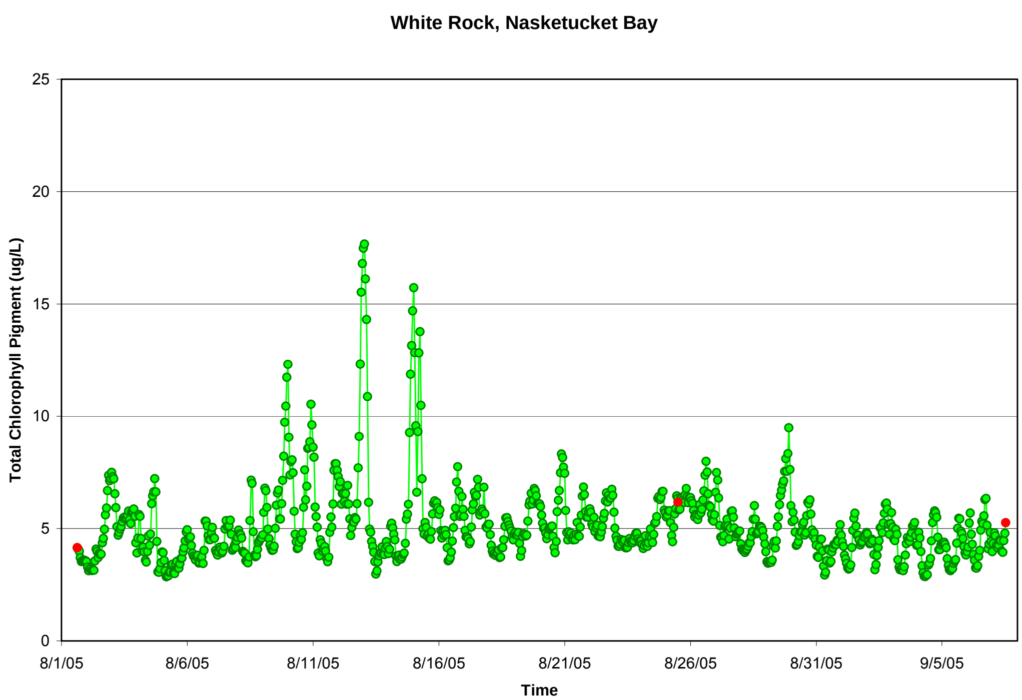


Figure VII-10. Bottom water record of Chlorophyll-*a* at the White Rock station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

North Cove – Nasketucket **(Figures VII-11 and VII-12:**

The North Cove mooring location was centrally located within this small tributary sub-basin that is situated along the north shore of West Island in the southern portion of Nasketucket Bay (Figure VII-1). High frequency data from North Cove periodically showed moderate - high daily excursions. The oxygen excursions resulted mainly from oxygen uptake associated with the diurnal cycle as well as tidal influence. Lowest dissolved oxygen was typically observed in the early morning. Highest dissolved oxygen was observed at the end of the photocycle (ca. 1500 hrs) for reasons noted above. Dissolved oxygen occasionally declined to <4 mg L^{-1} for short periods (hours), but did not decline below <3 mg L-1 (Figure VII-5, Table VII-1). The occurrence of oxygen levels significantly over air saturation was rare with levels only periodically reaching 9 mg L^{-1}. Given that DO excursions generally did not exceed 8 mg L-1 and that declines were generally to 4 mg L^{-1} it appears that the effects of nitrogen enrichment remain relatively minor in this basin. Consistent with the oxygen data, chlorophyll-*a* was low, averaging 5.2 ug/L and only rarely exceeded 10 ug L^{-1} (Table VII-2, Figure VII-6), indicative of high quality water. Similar to the average chlorophyll levels at the White Rock mooring deployment location, the overall average chlorophyll level in North Cove was 5.2 ug L^{-1} over the deployment. Both the oxygen and chlorophyll-*a* data indicate that Nasketucket Bay is only showing slight nitrogen enrichment effects.

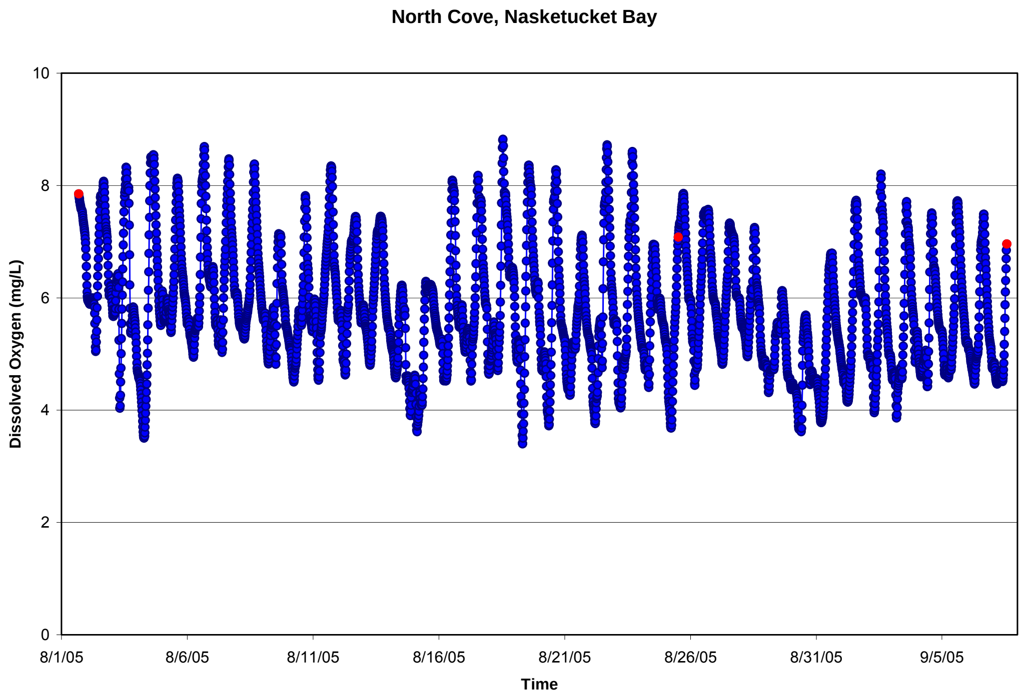


Figure VII-11. Bottom water record of dissolved oxygen at the North Cove station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

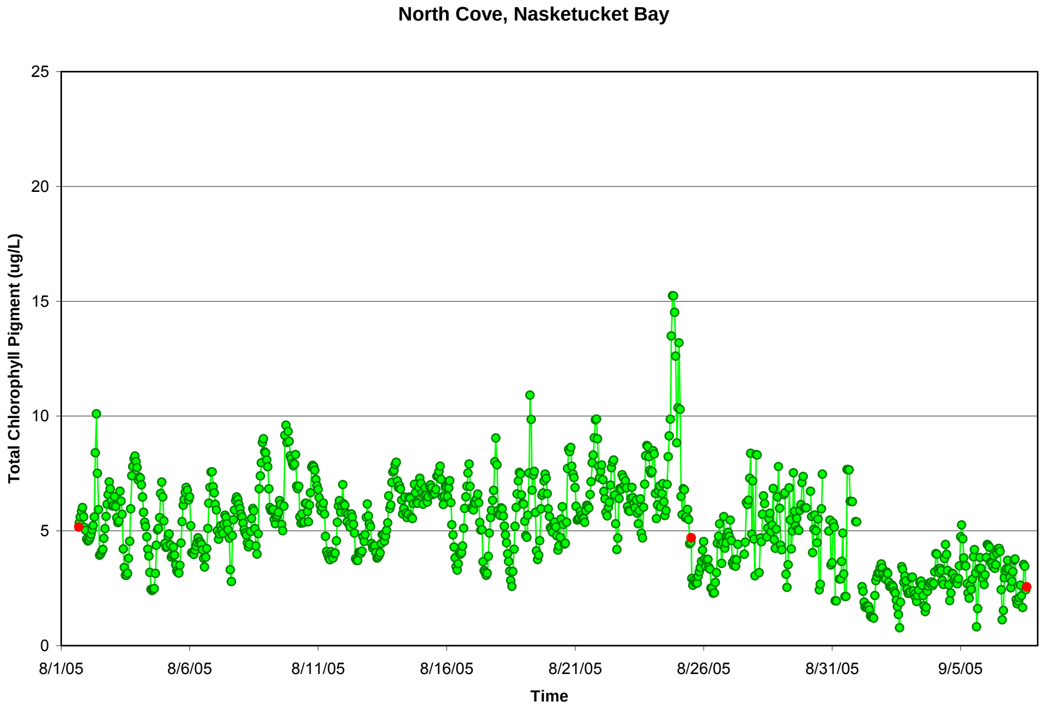


Figure VII-12. Bottom water record of Chlorophyll-*a* at the North Cove station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

Long Island (east) – Nasketucket **(Figures VII-13 and VII-14):**

The Long Island east mooring location was located in the upper portion of this small tributary sub-basin that is bounded to the east by West Island, the causeway to the south and is situated in the southern portion of Nasketucket Bay (Figure VII-1). High frequency data from the Long Island east mooring showed low to moderate daily excursions. The oxygen excursions resulted mainly from oxygen uptake and production associated with the diurnal cycle as well as tidal influence. Lowest dissolved oxygen was typically observed in the early morning. Highest dissolved oxygen was observed at the end of the photocycle (ca. 1500 hrs) for reasons noted above. Dissolved oxygen was generally >5 mg L^{-1} and rarely declined to <4 mg L^{-1} (2 events of few hours each; Figure VII-5, Table VII-1). The occurrence of oxygen levels over air saturation was not pronounced as was occasionally observed in the Little Bay sub-basin. Oxygen levels did not exceed air equilibration and seldom exceeded 7 mg L^{-1}. Given the relatively small excursions in dissolved oxygen and the generally high DO levels (~5 mg L^{-1}), the data indicate only slight effects of nitrogen enrichment in this basin. Consistent with the oxygen data, chlorophyll-*a* was also low averaging 4.8 ug/L and rarely reaching 9 ug/L. The overall average chlorophyll level was 4.5 ug L^{-1} over the deployment period with generally only modest levels of oxygen depletion. Both the oxygen and chlorophyll-*a* data indicate that this sub-basin of Nasketucket Bay is only showing slight nitrogen enrichment effects.

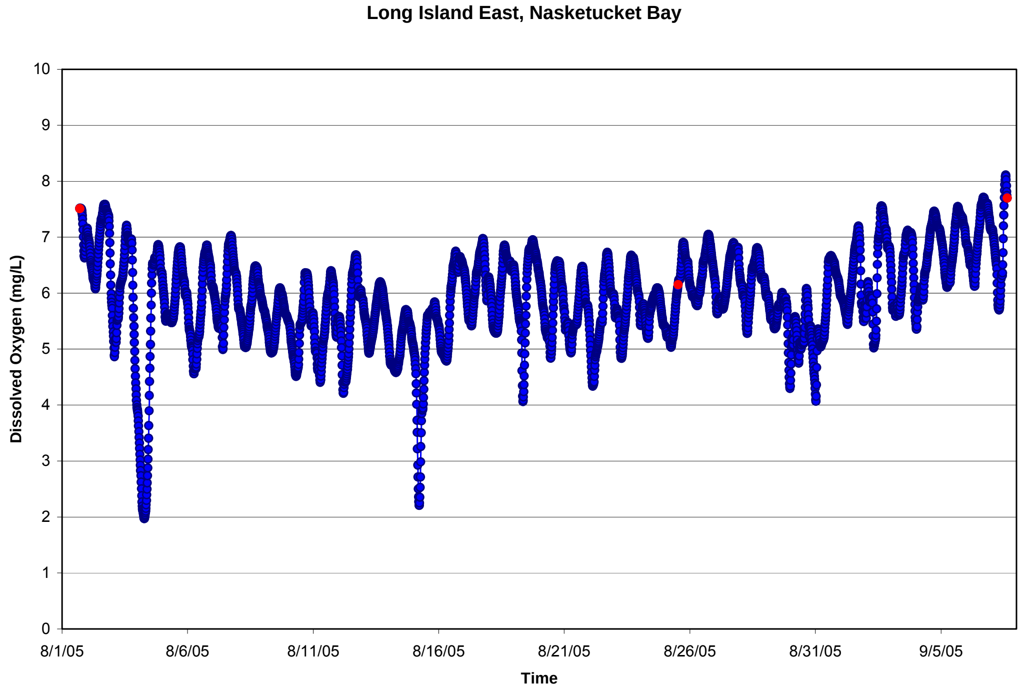


Figure VII-13. Bottom water record of dissolved oxygen at the Long Island (east) station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

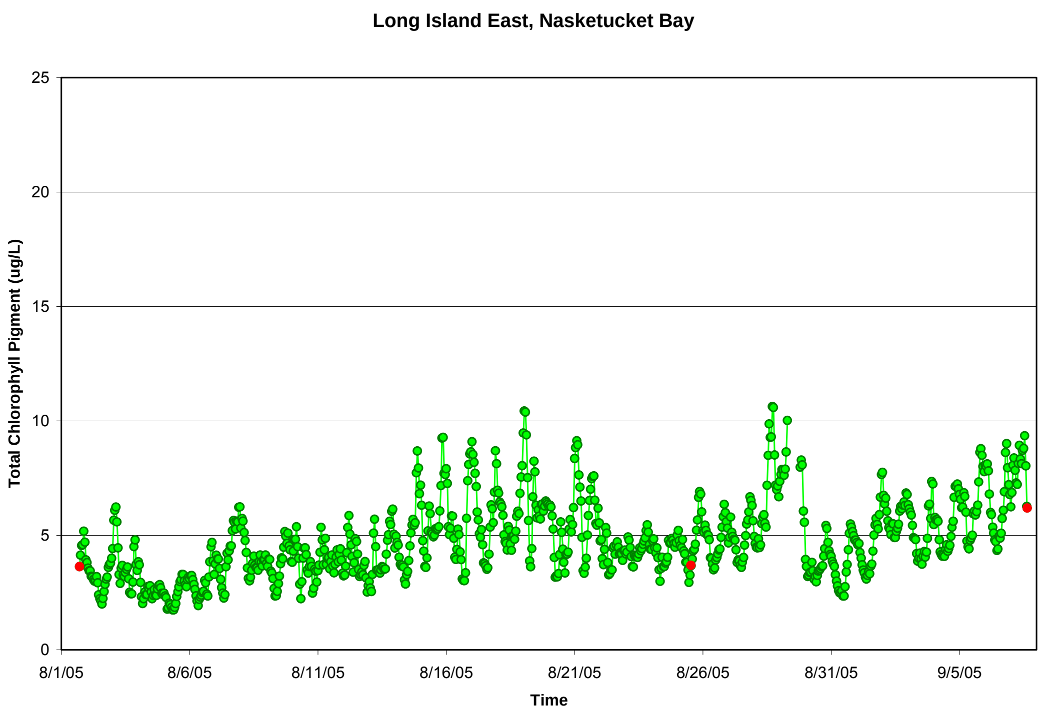


Figure VII-14. Bottom water record of Chlorophyll-*a* in the Long Island (east) station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

***Long Island (west) – Nasketucket* (Figures VII-15 and VII-16):**

The Long Island west mooring location was centrally located within this small tributary sub-basin that is bounded to the west by Sconticut Neck, the causeway to the south and Long Island to the east and is situated in the southern portion of Nasketucket Bay (Figure VII-1). High frequency data from the Long Island west mooring showed low-moderate daily excursions. The oxygen excursions resulted mainly from oxygen uptake and production associated with the diurnal cycle as well as tidal influence. Lowest dissolved oxygen was typically observed in the early morning. Highest dissolved oxygen was observed at the end of the photocycle (ca. 1500 hrs) for reasons noted above. Dissolved oxygen was virtually always >4.1 mg L^{-1} (except for few hrs) and generally > 5 mg L^{-1} (Figure VII-15, Table VII-1). The occurrence of oxygen levels over air saturation was rare and levels only exceeded 8 mg L^{-1} on 6 of 37 dates for a few hours and levels never reached 9 mg L-1. Given the lack of significant exceedences of air equilibration and moderate oxygen depletions, the data indicate only slight effects of nitrogen enrichment of this basin. Consistent with the oxygen data, chlorophyll-*a* was moderate, averaging 7.5 ug/L. At the Long Island west mooring location, chlorophyll-*a* levels exceeded the 10 ug L^{-1} benchmark 14% of the time (Table VII-2, Figure VII-16), still indicative of high quality water but more enriched than the eastern basin and North Cove and consistent with the magnitude of the diurnal excursions. The overall average chlorophyll level in this cove was 7.5 ug L^{-1} over the deployment period with generally only modest levels of oxygen depletion. Both the oxygen and chlorophyll-*a* data indicate that this sub-basin of Nasketucket Bay is only showing slight nitrogen enrichment effects

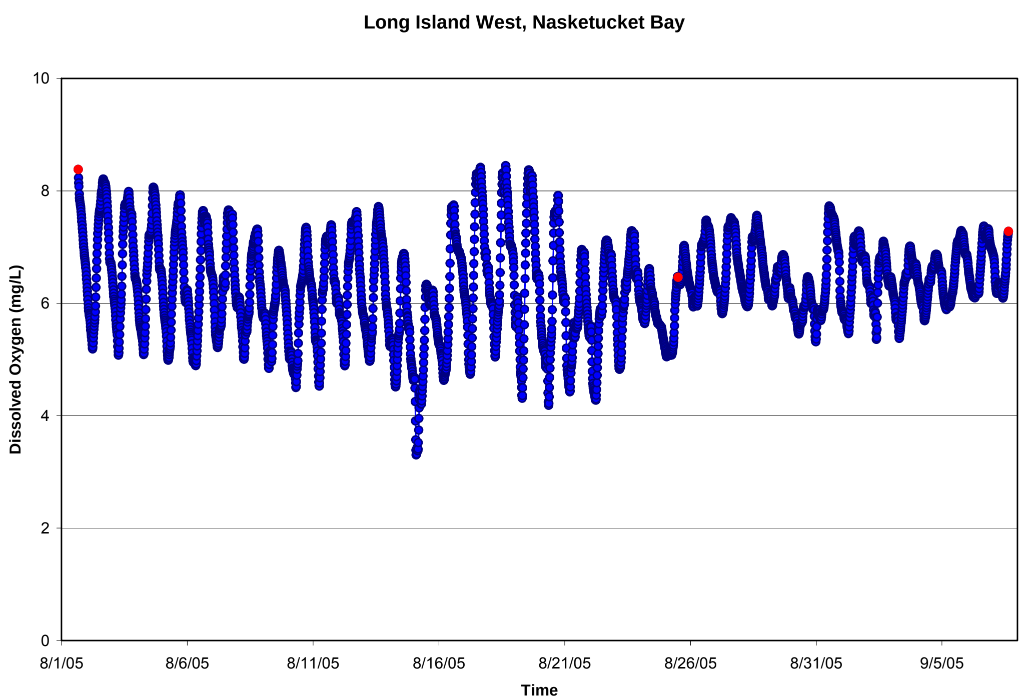


Figure VII-15. Bottom water record of dissolved oxygen at the Long Island (west) station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

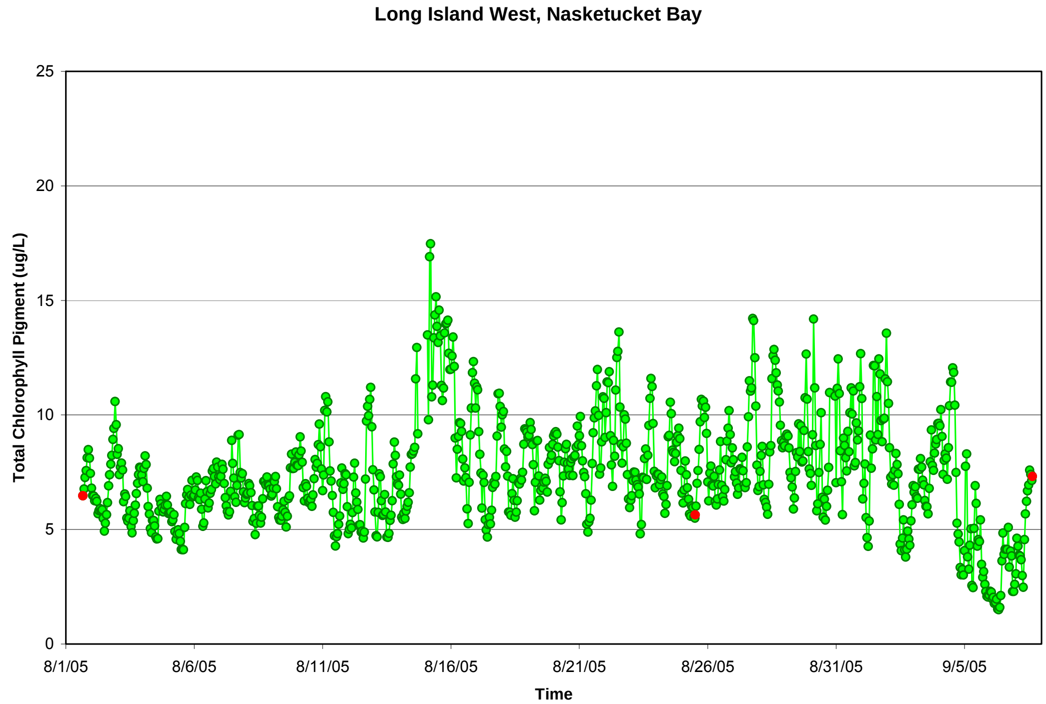


Figure VII-16. Bottom water record of Chlorophyll-*a* in the Long Island (west) station in Nasketucket Bay, Summer 2005. Calibration samples represented as red dots.

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data is a key part of the MEP Approach. Surveys were conducted by the MassDEP Eelgrass Mapping Program (C. Costello) in the Nasketucket Bay / Little Bay Estuarine System and extending to the area south of the causeway connecting Sconticut Neck to West Island as well as the eastern and southern shores of West Island. The most recent survey was conducted in 2001, as part of the MEP program with an earlier survey conducted in 1995. Additional analysis of available aerial photographs from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 2001 map was field validated by the MassDEP Eelgrass Mapping Program. The primary use of the data is to indicate (a) estuarine regions that have historically or presently support eelgrass habitat, 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-17a,b); the period in which watershed nitrogen loading significantly increased to its present level. These data were supplemented by field surveys conducted in 1984 and 1985 and aerial photographic interpretations (Costa, 1988) and a field survey in 2005 during MEP field data collection. Integration of the results of these surveys provided a robust time-series from which to evaluate temporal changes in eelgrass within this large estuarine systems to determine the stability of the eelgrass community.

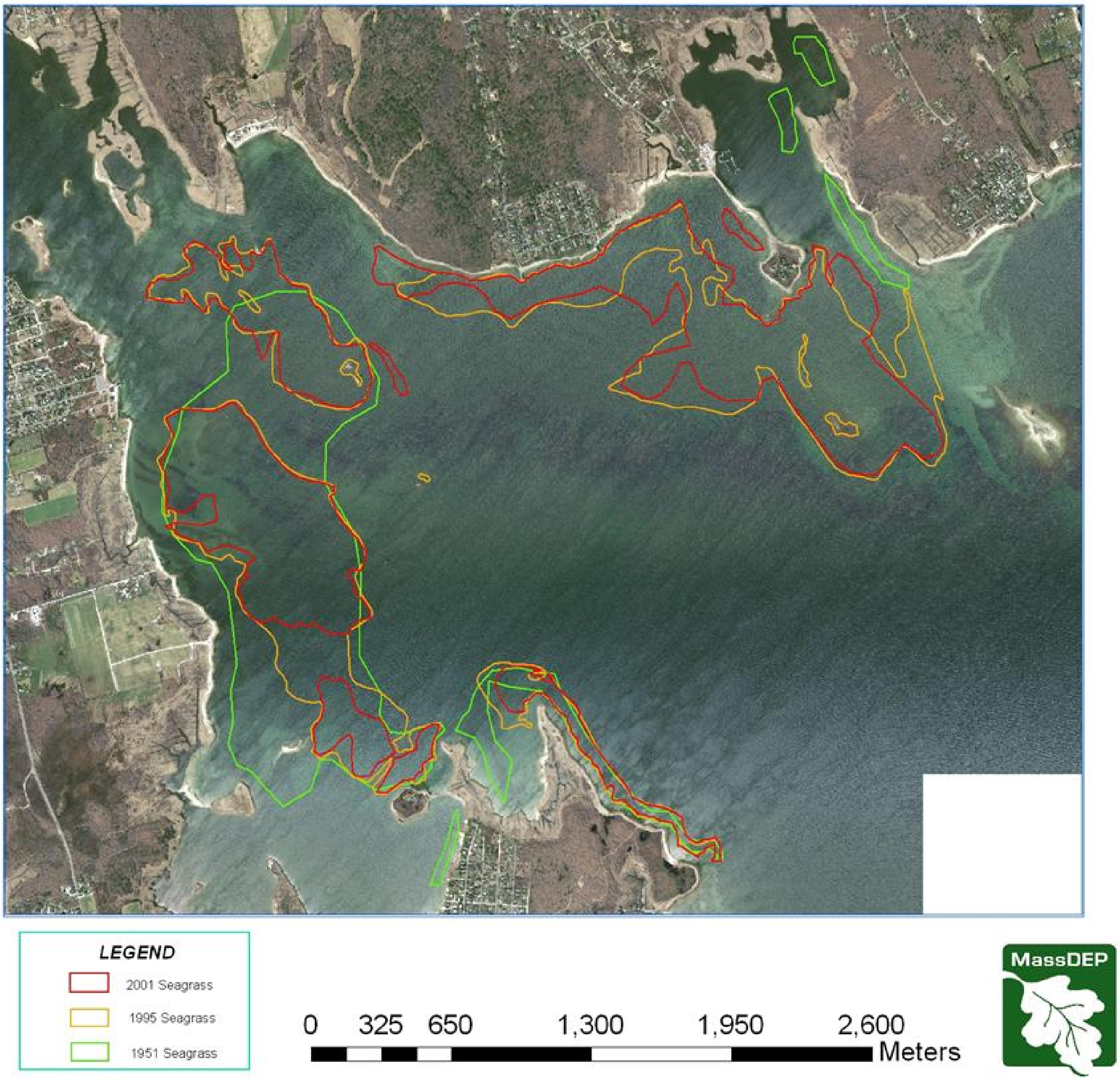


Figure VII-17a. Eelgrass bed distribution offshore within the western upper basin of Nasketucket Bay bounded by the entrance to Little Bay, Sconticut Neck and the north end of West Island. Beds delineated in 1995 are circumscribed by the tan outline and 2001 outlined in red (map from the MassDEP Eelgrass Mapping Program). The 1995 and 2001 bed distributions are comparable to distributions determined by Costa (1988).

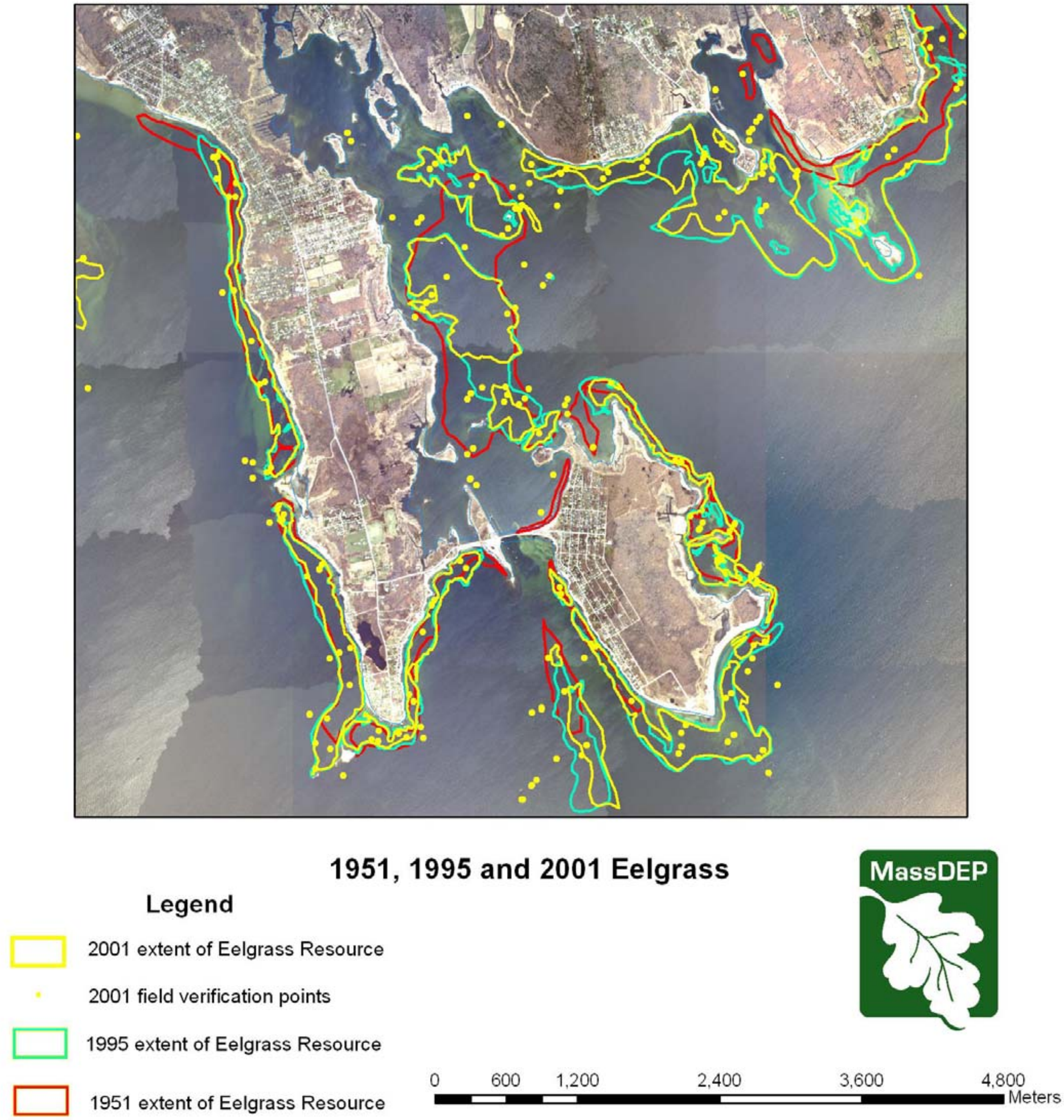


Figure VII-17b. Eelgrass bed distribution offshore of Sconticut Neck and West Island. Beds delineated in 1995 are circumscribed by the green outline and 2001 outlined in yellow (map from the MassDEP Eelgrass Mapping Program).

Nasketucket Bay has historically supported significant eelgrass coverage as noted by Lewis and Taylor (1933, cited in Costa 1988). However, during the eelgrass decline of the 1930's along the eastern seaboard, these beds diminished significantly, but then recolonized Nasketucket Bay over the following decades, with recovery appearing to reach near present conditions in the 1950's and 1960's based upon aerial photographic interpretations by Costa (1988) and by the MassDEP's Eelgrass Mapping Program (C. Costello). The assessment of possible eelgrass presence conducted by MassDEP based on the interpretation of 1951 aerial photography indicated beds primarily in the western portion of the main basin of Nasketucket Bay and along the shores of West Island and waters south of the West Island causeway to Sconticut Neck. Based upon the MassDEP analysis (Figure VII-17), there were extensive eelgrass beds in the main basin of Nasketucket Bay and areas fringing West Island by 1951, with eelgrass acreage increasing from 1951 to the field verified coverage of 1995. While there is a suggestion of a slight (~11%) decrease in eelgrass habitat acreage from 1995 to 2001 in the MassDEP analysis, it does not appear to be related to nitrogen enrichment as the regions of loss are inconsistent with the typical pattern due to nitrogen enrichment, i.e. the loss is distant from nitrogen inputs and in the middle of large beds, rather than at the outermost margins of beds. The stability of the northern most edges of existing beds, particularly at the margin of Little and Nasketucket Bays indicates that nitrogen enrichment is not resulting in eelgrass loss from this system. It is possible that apparent loss from other areas results from boat traffic or other in-water activities. It is equally possible that uncertainties in defining some of the bed margins is the cause. This appears likely as an 11% decline was found both in the upper region and the outer regions of Nasketucket Bay, i.e. the loss was uniform system-wide. It is also important to note that the 1984 and 1985 surveys by Costa provided coverages very similar to that in 1995 and that the 2005 MEP surveys also documented eelgrass in key areas noted in the 1995 and 2001 MassDEP surveys, i.e. the outer portions of Nasketucket Bay as well as the outer coves along the eastern shore of West Island.

Equally important is the lack of eelgrass at present and historically within the Little Bay basin. Eelgrass was not noted for this basin in the 1951 surveys or in field surveys of 1984-85, 1995, 2001 or 2005. As a result, the absence of eelgrass within this basin cannot be attributed to anthropogenic nitrogen enrichment and restoration of eelgrass is not indicated. However, it should be noted that there is some evidence that within the larger basins eelgrass may be beginning to be reduced in the deeper waters, and there appears to be colonization by an attached macroalgae, *Codium*. While these observations do not indicate impairment, they do support the contention (stated above) that the uppermost regions of this system are presently at their nitrogen loading limit.

A critical area for evaluating the onset of nitrogen impairment to eelgrass within the Nasketucket Bay / Little Bay Estuary is at the beds at the border between Little Bay and Nasketucket Bay. This area receives the moderately nitrogen enriched out-flowing waters from Little Bay and would reflect changes in watershed nitrogen loading in excess of the eelgrass threshold for this estuary. At present, the 1984-85, 1995 and 2001 eelgrass surveys and the 2005 MEP survey all indicate stable habitat in this region. This can be seen most clearly in the MassDEP Eelgrass Mapping Program coverages of 1995 and 2001 where the coverages are nearly identical (Figure VII-17a).

Overall, the historical distribution of eelgrass within the Nasketucket Bay / Little Bay Estuary is consistent with both the natural history of eelgrass and the present nitrogen, oxygen and chlorophyll levels within the different component basins. The absence of eelgrass within Little Bay (present and historically) is consistent with the chlorophyll levels (9 ug/L) and tidally averaged TN levels of 0.415 - 0.391 for upper and mid bay, respectively and 0.391 - 0.373 for the mid to outer bay region. In contrast, the main eastern basin of Nasketucket Bay has lower chlorophyll levels (<5 ug L^{-1}) and TN levels (<0.368 mg N L^{-1}) and these areas currently support eelgrass beds. These latter water column values are similar to other estuarine basins that are currently supportive of eelgrass at similar depths (Phinneys Harbor, West Falmouth Harbor, Quissett Harbor (0.35 mg L^{-1}) and is consistent with a number of MEP estuaries where eelgrass nitrogen thresholds were determined to be <0.38 mg L^{-1} (examples here). It should be noted that shallower basins (Bournes Pond, 0.40 mg L^{-1}) can support eelgrass at higher chlorophyll-*a* and TN levels due to their thinner water columns allowing sufficient light penetration. But the deeper waters of Nasketucket Bay makes it more sensitive to nitrogen enrichment impairment than nearby shallower basins.

Table VII-3a. Change in eelgrass coverage within the Nasketucket Bay / Little Bay Estuarine System, Towns of Fairhaven and Mattapoisett, as determined by the MassDEP Eelgrass Mapping Program (C. Costello). Spatial analysis and the pattern of nitrogen enrichment indicate that the apparent loss cannot be attributed to watershed nitrogen loading. There is no evidence of Little Bay supporting eelgrass beds over the past 60+ years. It should be noted that eelgrass coverage within this portion of the estuary has increased significantly since 1951, unlike coverages in many s. e. Massachusetts estuaries that are currently impaired by nitrogen enrichment.

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1995 to 2001)
Nasketucket Bay	454.08	578.37	515.00	11%

Table VII-3b. Change in eelgrass coverage within the Nasketucket Bay / Little Bay Estuarine System (including eelgrass identified in waters east and south of West Island and the causeway connecting Sconticut Neck Road to West Island, Towns of Fairhaven and Mattapoisett, as determined by the MassDEP Eelgrass Mapping Program (C. Costello). Spatial analysis and the pattern of nitrogen enrichment indicate that the apparent loss cannot be attributed to watershed nitrogen loading. It should be noted that eelgrass coverage within this portion of the estuary has increased significantly since 1951, unlike coverages in many s. e. Massachusetts estuaries that are currently impaired by nitrogen enrichment.

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1995 to 2001)
Little / Nasketucket Bay (inclusive of water east and south of West Island)	848.12	1232.90	1098.99	11%

It should be noted that basins of similar depth to Nasketucket Bay showed nearly identical relationships between eelgrass and tidally averaged TN levels. For example, Lagoon Pond no longer supports eelgrass in areas where tidally averaged total nitrogen is 0.378 mg N L^{-1} and 0.385 mg N L^{-1}, while in other areas eelgrass beds presently exist at nitrogen levels that are $\leq$ 0.371 mg N L^{-1}, nearly identical to the upper edge of the beds at the Little-Nasketucket Bay margin where TN is presently 0.368 mg L^{-1}. Additionally in Waquoit Bay at similar depths, eelgrass was found to slowly decline at average TN concentrations of 0.395 mg L^{-1} (lower basin of Waquoit Bay) and was lost from the Centerville River also at a tidally averaged TN of 0.395 mg L^{-1}, while in the deeper waters of West Falmouth Harbor Estuary, eelgrass declined when nitrogen enrichment resulted in levels over 0.35 mg L^{-1}.

Overall, the distribution and temporal stability of eelgrass within Nasketucket Bay and its relationship to nitrogen and chlorophyll-*a* levels is consistent with other estuaries of similar configuration in Buzzards Bay and s. e. Massachusetts. The moderate watershed nitrogen loading coupled with the rate of tidal flushing and the tide range appears to be maintaining the system at a level that is supportive of eelgrass habitat not impaired by nitrogen enrichment at the present time. However, there is some indication that the system is at or very close to its nitrogen threshold so that maintenance of present conditions should be the focus of future MassDEP TMDL analysis.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 26 locations within the Little Bay and Nasketucket Bay Embayment System (Figure VII-10), with replicate assays at each site. In all areas 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 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 and evenness of the community. It should be noted that, although there are presently no eelgrass beds within Little Bay and have not existed historically (e.g. 1951-TP) it appears that this relates to the structure of the basin rather than recent increases in watershed nitrogen loading. As such, to the extent that Little Bay can support healthy infaunal communities given specific nutrient conditions in the water column, the benthic infauna analysis is important for determining the level of impairment (healthy→moderately impaired→significantly impaired→severely degraded). 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 (Table VII-4). The evenness statistic 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 and eelgrass coverage, 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. From this analysis throughout the Nasketucket Bay / Little Bay Estuary virtually all benthic habitat showed diversity and Evenness indices >3.0 and ~0.7, respectively. This supports the contention that benthic habitat throughout this large estuarine system is not impaired by present watershed nitrogen loading. However, it does appear that Little Bay is near its nitrogen threshold and management for this basin should focus on managing future buildout nitrogen loads. It is virtually certain that the significant efforts made by the Towns to sewer parts of the watershed and export the wastewater load has contributed to the present high quality of the habitats within the receiving estuarine system.

Nasketucket Bay Infaunal Characteristics:

Benthic infaunal communities throughout the main basins of Nasketucket Bay were indicative of productive high quality benthic habitat in a low to moderately nitrogen enriched coastal areas.

Benthic communities were comprised of high numbers of species (20-23), high numbers of individuals (~200 per sample) with key community metrics, diversity (H' >3.1) and Evenness (>0.7) consistent with a high quality habitat. These results are not surprising given the stable eelgrass coverage in this basin, the generally low chlorophyll-*a* levels (~5 ug/L) and the limited periodic oxygen depletion events. It should be noted that these depletion events are typically brief (few hours) and oxygen infrequently declines to <4 mg/L and is typically ~5 mg/L. Another important indicator is that the sediments do not generally appear to be depositional and large areas are sandy with little organic matter accumulation and a clear oxidized surface layer. Drift algae accumulations are rare. Of equally significance are the rare occurrences of opportunistic organic matter or stress tolerant species, typical of nitrogen enriched areas in southeastern Massachusetts estuaries. Instead, the community is generally composed of polychaetes and crustaceans with some mollusks and some deep burrowers and head-down deposit feeders (e.g. *Clymenella*). Integrating the watercolumn, sediment and community indicators provides a clear assessment of Nasketucket Bay as supporting generally high quality benthic infaunal habitat, consistent with it significant eelgrass coverage.

Table VII-4. Benthic infaunal community data for the Nasketucket Bay and Little Bay 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 (Samples represent surface area of 0.0625 m2). Stations refer to map in Figure VII-17, (N) is the number of samples per site.

Basin	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)	Stations NSK# [1]
Nasketucket Bay / Little Bay Estuary						
Little Bay						
Mean =	22	287	15	3.04	0.69	9,1011,12
S.E. =	1	50	1	0.13	0.02	13,15,16,
N =	15	15	13	15	15	17,18
Shaws Cove						
Mean =	20	237	14	2.47	0.57	33
S.E. =	1	87	2	0.43	0.11	
N =	2	2	2	2	2	
Brant Island Cove						
Mean =	28	391	16	3.16	0.66	26,27
S.E. =	0	52	1	0.31	0.07	
N =	3	3	3	3	3	
West Island East Shore Salt Marsh						
Mean =	15	89	15	3.09	0.80	6,7
S.E. =	2	27	1	0.23	0.02	
N =	3	3	2	3	3	
Nasketucket Bay - West						
Mean =	23	237	16	3.23	0.71	20,21,
S.E. =	2	23	1	0.18	0.03	36,39,42
N =	6	6	6	6	6	
Nasketucket Bay - East						
Mean =	20	154	16	3.14	0.75	2,4,5,8
S.E. =	6	47	6	0.95	0.22	30,31,32
N =	11	11	7	11	11	

1- Station ID's refer to locations in Figures VII-18

Infaunal Characteristics of Major Coves (Little Bay-Shaws Cove-Brant Island Cove):

Benthic infaunal communities within each of the major tributary basins to Nasketucket Harbor (Little Bay-Shaws Cove-Brant Island Cove; Figure VII-18) are generally supporting high quality habitat for given their specific conditions and structures. Brant Island Cove, eastern-most along the northern shore of upper Nasketucket Bay and directly flushed with low nutrient high quality waters incoming from Buzzards Bay, supports a high number of species (28) with large numbers of individuals (~400 per 0.0625 m^{-2} grab). Community indices show a high diversity (H' >3.1) and Evenness (E) approaching 0.7. Consistent with these indications of a high quality benthic habitat, the sediments generally consist of fine sands with mud, low-moderate organic matter, dominated by polychaetes and crustaceans with some deep burrowers but few organic enrichment indicators.

Figure VII-18. Aerial photograph of the Little Bay / Nasketucket Bay Estuary showing location of benthic infaunal sampling stations (green symbols).

Shaws Cove at the entrance to Little Bay to the west of Brant Island Cove is a small cove with a tidal marsh and stream dominating its innermost reach. Assessment of the benthic community in the upper region did not reveal impairment, but rather a relatively high number of species (20) and high number of individuals (~250 per 0.0625 m^{-2} grab), with moderate diversity (H'= 2.5) and Evenness (E=0.6). Generally, high quality benthic habitat supports an average species number $\geq$ 20 per sample. The community was dominated by a mix of polychaetes and crustaceans with some mollusks and few organic enrichment indicator species. The lack of high organic enrichment was seen in the generally low organic matter sediments dominated by fine sands with mud with an oxidized surface. It appears that in the uppermost reach of this cove, there is some salt marsh influence on the adjacent benthic community.

Little Bay is the largest of the tributary basins to Nasketucket Bay and receives over 40% of the total watershed nitrogen input to the entire Nasketucket Bay / Little Bay Estuarine System. It also has the Nasketucket River within the upper reach of the bay which supports significant salt marshes. In addition, as Little Bay has not historically supported eelgrass coverage, its key habitat for management is associated with benthic infauna. It was clear that within the tidal channel at the mouth of the Nasketucket River and its tidal wetlands, a different benthic habitat was present, as seen in the dominance of organisms typical of salt marshes on Cape Cod. The community supported a high number of species (24) with a high number of individuals (~400), high diversity (>3.0) and Evenness (>0.70). Although, as expected within the transition between salt marsh and open water, there were a modest number of organic enrichment indicator species. Given that benthic habitat did not show a strong gradient across the basin, the habitat assessment for Little Bay incorporates the entire basin, making it more robust and reducing uncertainty. Little Bay is currently supporting moderate to high quality infauna habitat, with a relatively high number of species (22), high number of individuals (~300 per 0.0625 m^{-2} grab), high diversity (H' >3.0) and Evenness (E=0.69). Generally high quality benthic habitat supports an average species number $\geq$ 20 per sample. The community was dominated by a mix of polychaetes and crustaceans with some mollusks with deep burrowers present. However, 5%-10% of the samples had ~1/3 of the community as organic enrichment indicator species. Even so, the sediments at all sites showed oxidized surfaces, although there was a gradient from fine sand at the mouth of the bay to muds at the mouth of the Nasketucket River.

Overall, Little Bay appears to be presently supporting moderate to high quality benthic habitat. However, the appearance (although few patches only) of stress indicator species at some sites (e.g. capitellids) and dominance of polychaetes at others, suggests that Little Bay is near or at its habitat threshold relative to nitrogen enrichment. This is supported by the periodic moderate oxygen depletions and average summer chlorophyll levels of 9-10 ug L^{-1} (Table VII-1), which both indicate nitrogen enrichment of this basin. By comparison, Shaws Cove and Brants Island Cove have typical chlorophyll levels $\leq$5 ug L^{-1} and less frequent and less intense periods of oxygen depletion. Nitrogen management within the Nasketucket Bay / Little Bay Estuary should therefore focus on maintenance of existing habitats, but should target Little Bay as the most sensitive area to additional watershed nitrogen loading.

Other Resource Characteristics:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth and available. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-19, VII-20). As is the case with some systems on Cape Cod and that adjoin Buzzards Bay, a portion of the overall Little Bay / Nasketucket Bay embayment system is classified as prohibited and conditionally approved for the taking of shellfish during specific portions of the year, indicating the system is moderately impaired relative to the taking of shellfish. The upper portion of Little Bay is prohibited to shellfishing while the lower portion of Little Bay is conditionally approved. Moving out into the more open water portions of the system that constitute Nasketucket Bay, those areas are classified as approved to year round shellfishing, indicating little to no impairment of that aquatic resource. The tributary tidal creeks of Little Bay are classified as prohibited for shellfishing throughout the year and this is likely due to bacterial concerns which would be a result of both human activity (septic systems in the watershed) as well as natural fauna given the existing bordering salt marsh wetlands. Despite the existing shellfish area classifications, the Little Bay and Nasketucket Bay system is also classified as supportive of specific shellfish communities (Figure VII-21). The major shellfish species with potential habitat within the overall estuary are quahogs (*Mercenaria*) throughout the entire system along with Bay Scallops. Additionally, very small areas fringing the shoreline of the system were identified as suitable for soft shell clams (*Mya*).

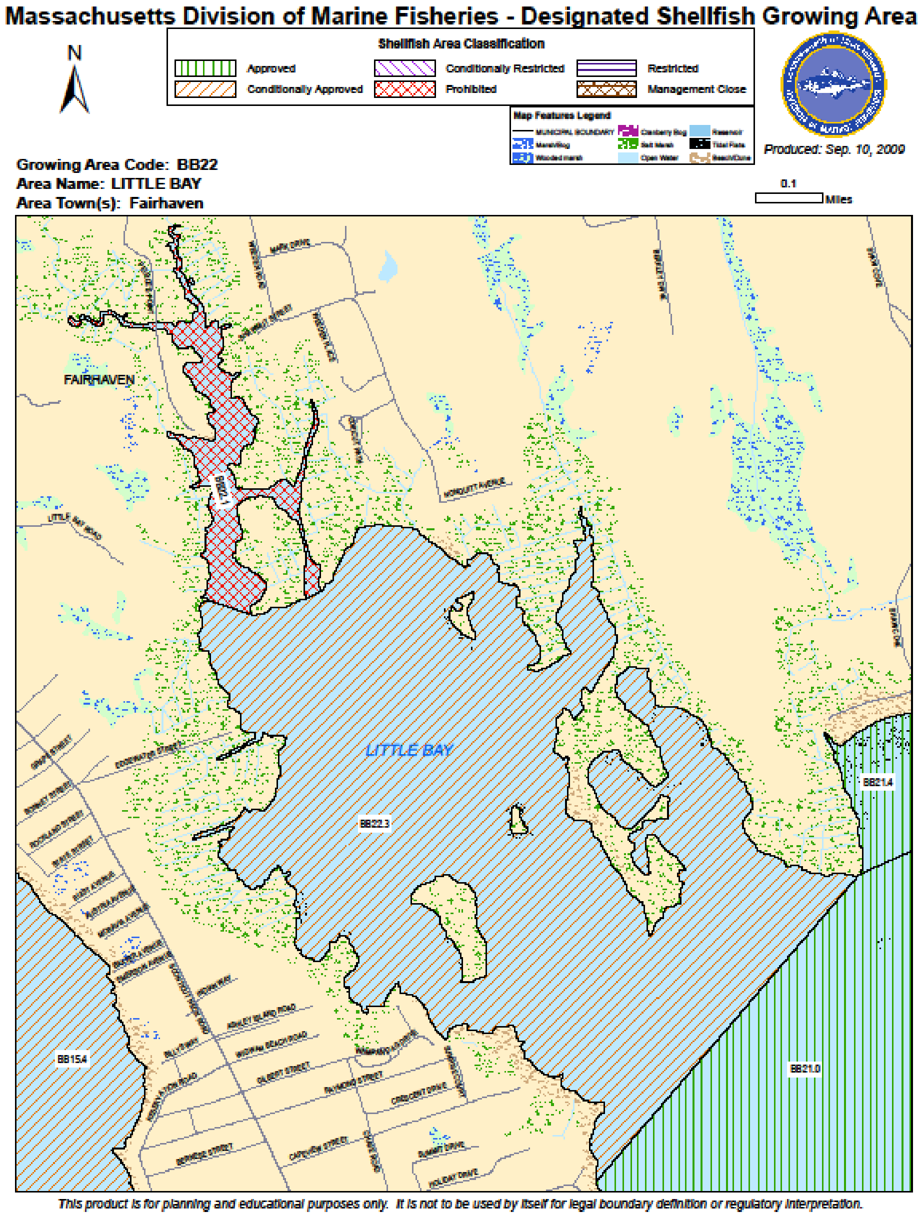


Figure VII-19. Location of shellfish growing areas in the Little Bay embayment system and the status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination from wildlife or "activities", such as the location of marinas

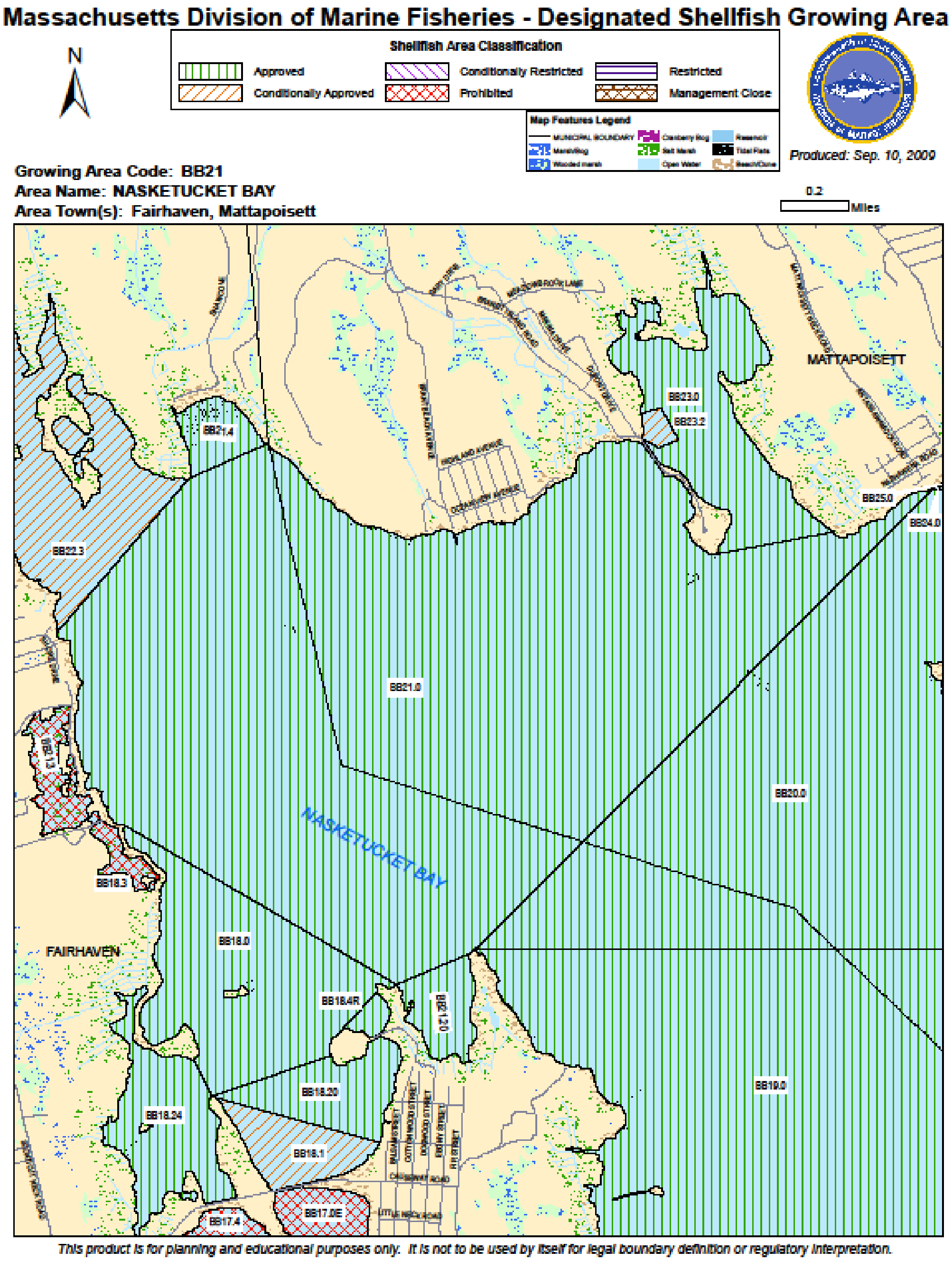


Figure VII-20. Location of shellfish growing areas in the Nasketucket Bay embayment system and the status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination from wildlife or "activities", such as the location of marinas.

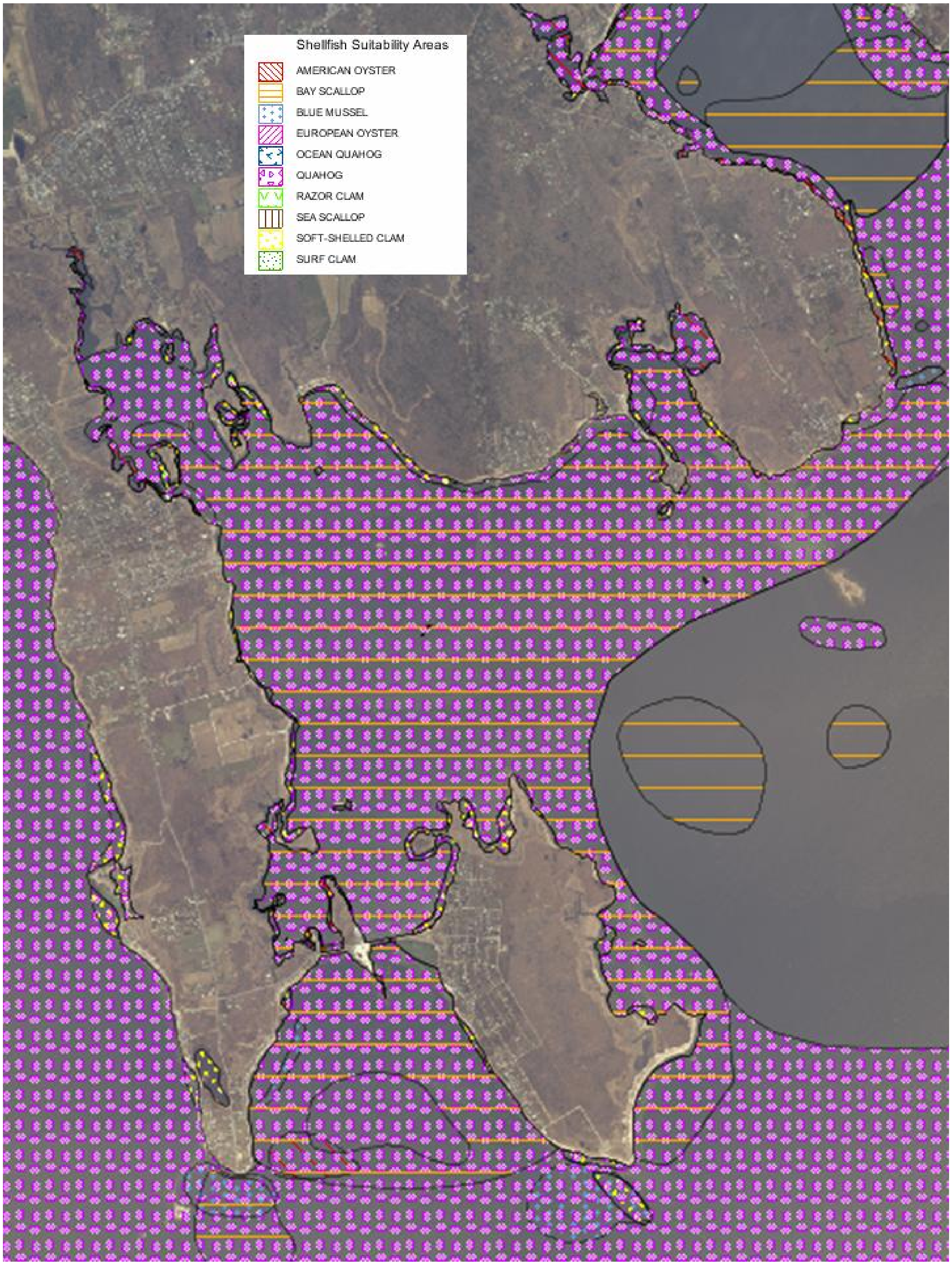


Figure VII-21 Location of shellfish suitability areas within the Little Bay / Nasketucket Bay Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily shellfish are present.

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 and chlorophyll). Additional information on temporal changes within each sub-embayment of an estuary, its associated watershed nitrogen load and geomorphological considerations of basin depth, stratification and functional type further strengthen the analysis. These data were collected to support threshold development for the Nasketucket Bay / Little Bay Estuarine System by the MEP and were discussed in Chapter 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.

The Nasketucket Bay / Little Bay Estuary is a complex estuary comprised of a drowned river valley estuary (Nasketucket River - Little Bay) and 2 major coves (Shaws Cove, Brant Island Cove) and a shallow broad open water basin bordering Buzzards Bay. The tide range of ~5 feet and unrestricted channels throughout the system result in a well flushed estuary with fully marine waters, salinities generally 29 ppt - 31 ppt, with greatest salinity dilution in Little Bay the recipient of Nasketucket River outflow. The well flushed nature of this system and its tidal exchanges with low nutrient high quality water from Buzzards Bay have maintained relatively high water quality throughout compared to other embayments in Buzzards Bay.

Both Little Bay and Shaws Cove support salt marsh in their upper reaches. While there is fringing salt marsh, these basins currently function as typical coastal embayments with free tidal exchange with Nasketucket Bay waters. Each of type of functional component to an estuary (salt marsh basin, embayment, tidal river, deep basin {sometimes drowned kettles}, shallow basin, etc.) has a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific basin and its ability to support eelgrass beds and infaunal communities. At present, the Nasketucket Bay / Little Bay Estuary has reached its ability to assimilate nitrogen without impairment and is showing a low level of nitrogen enrichment in some basins, with indications of incipient impairment primarily associated with bottom water oxygen levels, elevated chlorophyll-*a* and infaunal habitats (Table VIII-1), indicating that nitrogen management of this system will be primarily focused on maintenance of an unimpaired system and preventing additional nitrogen loading as watershed build-out is approached. Linking watershed inputs to estuarine response indicates that while the existing nitrogen loading has brought some of the basins to (but not over) their ecological tipping point, watershed buildout will sufficiently increase the nitrogen inputs in some basins (e.g. Little Bay) above their assimilative capacity.

The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follows the spatial pattern of total nitrogen levels in this system (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment. The spatial pattern indicated that the magnitude of oxygen depletion, enhancement of chlorophyll-*a* levels and total nitrogen concentrations increased from the offshore waters to Nasketucket Bay and were highest within the semi-enclosed tributary basins, particularly Little Bay.

Table VIII-1. Summary of nutrient related habitat quality within the Nasketucket Bay / Little Bay Estuary within the Towns of Fairhaven & Mattapoisett, MA, based on assessments in Section VII. Nasketucket Bay basins extend north and south of West Island and are relatively shallow and well flushed. Little Bay receives the highest areal watershed loading, but all 3 major coves are shallow and well flushed. WQM indicates: the BayWatcher Water Quality Monitoring Program.

Health Indicator	Nasketucket Bay / Little Bay Estuarine System			
	Major Coves			Nasketucket Bay
	Little Bay	Shaws Cove	Brant Island Cove	
Dissolved Oxygen	MI[1]	MI/H[2]	H[3]	H/MI[4]
Chlorophyll	H/MI[5]	H[6]	H[6]	H[7]
Macroalgae	H[8]	H[9]	H[9]	H[8]
Eelgrass	--[10]	--[10]	--[11]	H[12]
Infaunal Animals	H[13]	H[14]	H[15]	H[16]
Overall:	**H[17]**	**H[18]**	**H[19]**	**H[20]**

1 – oxygen generally >5 mg/L 2/3 of record, brief but frequent declines to 4 mg/L hypoxia not prolonged.
2 – oxygen >6 mg/L 53% of record, periodically <5 mg/L, rare, brief declines to ~2 mg/L, showing wetland influence on outgoing tides in headwaters of Cove.
3 – oxygen minimum WQM (2007-11) 5.1 mg/L, 5-6 mg/L 45% of samples, >6mg/L 55% of samples.
4 – oxygen generally >6 mg/L 5 mg/L, 58% of record and >5mg/L ~90% of record, infrequent declines to <4 mg/L; in basin adjacent West Island, >5 mg/L ~90% of record with depletions to <4 mg/L rare.
5 – moderate summer chlorophyll levels averaging 9-10 ug/L, <10 ug/L ~65% of record, average level in summer WQM samples (1997-2011) was 6.3 and 8.5 ug/L for outer and inner reaches, respectively.
6 – low-moderate summer chlorophyll levels Shaws Cove 5-10 ug/L (98% of time), average 5.3 ug/L. Average summer WQM samples (1997-2011) Shaws Cove 6.3 ug/L; Brant Island Cove 5.2 ug/L.
7 – low summer chlorophyll levels with average upper basin 5.2 ug/L and <5 ug/l ~60% of record; summer WQM samples (1997-2011) of 4.6 ug/L.
8 – absent or sparse drift algae, sparse patches of attached *Codium*.
9 – patches of moderate density attached *Codium*
10 – no evidence this basin has historically supported stable eelgrass beds, no eelgrass in MassDEP (C. Costello) assessments of 1995, 2001 and MEP 2005.
11 – MassDEP (C. Costello) indicates small patches possible in 1951 aerial, but only sparse patches in 1984-85, 2005 observations of patches of Codium at these sites. 1951 patches uncertain.
12 – MassDEP (C. Costello) and Costa (1988) maps indicate that eelgrass coverage has significantly expanded from 1951, variations 1995-2001 cover both upper and outer basins, no evidence due to nitrogen enrichment. WQM indicates in general light penetrates to bottom.
13 – high numbers of species (22) and individuals (~300 per sample), with high diversity (H'>3) and Evenness (E=0.69), few patches of organic tolerant opportunistic species.
14 – moderate/high numbers of species (20) and individuals (~250 per sample), diversity (H'~2.5) and Evenness (E=0.6), some organic tolerant opportunistic species. However, species are typical of wetland influenced benthic habitats and are consistent with the close proximity of the large salt marsh.
15 – high numbers of species (28) & individuals (~400 per sample), with high diversity (H'>3) and moderate Evenness (E=0.66), with deep burrowers, community dominated by polychaetes and crustaceans.
16 – high numbers of species (20-23) & individuals (~200 per sample), with high diversity (H'>3) and Evenness (E>0.7), with deep burrowers, community dominated by polychaetes and crustaceans.
17 – High quality habitat: primarily due to generally high quality benthic habitat and no historic eelgrass coverage (1951-TP). Concern that system is at it nitrogen enrichment threshold due to few patches of organic tolerant species, elevated chlorophyll and periodic, but brief, hypoxia, but lack of drift algae.
18 – High quality habitat: due to generally high quality benthic habitat, absence of drift algae, with attached Codium present and low chlorophyll a levels with only brief infrequent hypoxic events associated with exchanges with the adjacent tidal wetland..
19 – High quality habitat: due to high quality benthic habitat, no historic eelgrass coverage, absence of drift algal accumulations with colonization by *Codium*. Low chlorophyll levels and limited oxygen depletion.
20 – High quality habitat: primarily due to significant eelgrass coverage and stability of beds in upper reaches. high quality benthic habitat and no historic eelgrass coverage (1951-TP), absence of drift algal accumulations with colonization by *Codium*. Low chlorophyll a levels and limited oxygen depletion.
H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment; SD = Severe Degradation; -- = not applicable to this estuarine reach

Eelgrass surveys and analysis of historical data is a key part of the MEP Approach. Eelgrass coverages for the Nasketucket Bay / Little Bay Estuary were developed by the MassDEP Eelgrass Mapping Program (C. Costello) for 1951, 1995 and 2001. Coverages were also available for 1984-85 (Costa 1988) as well as MEP field surveys in 2005. Integration of the results of these surveys provided a robust time-series from which to evaluate temporal changes in eelgrass within this large estuarine system,

Nasketucket Bay has historically supported significant eelgrass coverage. However, during the eelgrass decline of the 1930's along the eastern seaboard, these beds diminished significantly, but then recolonized Nasketucket Bay over the following decades, with recovery appearing to reach near present conditions in the 1950's and 1960's. Based upon the MassDEP analysis (Figure VII-17), there were extensive eelgrass beds in the main basin of Nasketucket Bay and areas fringing West Island by 1951, with eelgrass acreage increasing from 1951 to the field verified coverage of 1995. While there is a suggestion of a slight (~11%) decrease in eelgrass habitat acreage from 1995 to 2001 in the MassDEP analysis, it does not appear to be related to nitrogen enrichment as the regions of loss are inconsistent with the typical pattern due to nitrogen enrichment, i.e. the loss is distant from nitrogen inputs and in the middle of large beds, rather than at the outermost margins of beds. The stability of the northern most edges of existing beds, particularly at the margin of Little and Nasketucket Bays indicates that nitrogen enrichment is not resulting in eelgrass loss from this system. It is possible that apparent loss from other areas results from boat traffic or other in-water activities. It is equally possible that uncertainties in defining some of the bed margins is the cause. This appears likely as an 11% decline was found both in the upper region and the outer regions of Nasketucket Bay, i.e. the loss was uniform system-wide, which is not consistent as a nitrogen enrichment response.

Equally important is the lack of eelgrass at present and historically within the Little Bay basin. Eelgrass was not noted for this basin in the 1951 surveys or in field surveys of 1984-85, 1995, 2001 or 2005. As a result, the absence of eelgrass within this basin cannot be attributed to anthropogenic nitrogen enrichment and restoration of eelgrass is not indicated. However, it should be noted that there is some evidence that within the larger basins that eelgrass may be beginning to be reduced in the deeper waters, and there appears to be colonization by an attached macroalgae, *Codium*. This macroalgae appears to replace eelgrass as light penetration declines. While these observations do not indicate impairment, they do support the contention (stated above) that the uppermost regions of this system are presently at their nitrogen loading limit.

A critical area for evaluating the onset of nitrogen impairment to eelgrass within the Nasketucket Bay / Little Bay Estuary is at the beds at the border between Little Bay and Nasketucket Bay. This area receives the moderately nitrogen enriched out-flowing waters from Little Bay and would reflect changes in watershed nitrogen loading in excess of the eelgrass threshold for this estuary. At present, the 1984-85, 1995 and 2001 eelgrass surveys and the 2005 MEP survey all indicate generally stable habitat in this region (Figure VII-17a).

The historical distribution of eelgrass within the Nasketucket Bay / Little Bay Estuary is consistent with both the natural history of eelgrass and the present nitrogen, oxygen and chlorophyll levels within the different component basins. The absence of eelgrass within Little Bay (present and historically) is consistent with the chlorophyll levels (9-10 ug/L) and tidally averaged TN levels of 0.415 - 0.391 mg N L^{-1} for upper and mid bay, respectively and 0.391 - 0.373 mg N L^{-1} for the mid to outer bay region. In contrast, the main eastern basin of Nasketucket Bay has lower chlorophyll levels (<5 ug L^{-1}) and TN levels (<0.368 mg N L^{-1}) and these areas currently support eelgrass beds. These latter watercolumn values are similar to other estuarine basins that are currently supportive of eelgrass at similar depths (Phinneys Harbor, West Falmouth Harbor, Quissett Harbor (0.35 mg L^{-1}) and shallow systems, Three Bays, Popponesset Bay, Lewis Bay (0.38 mg L^{-1}). It should be noted that deeper waters decrease the tolerance for nitrogen enrichment (due to increased distance for light penetration) and therefore have lower TN thresholds than shallower basins.

Overall, the distribution and temporal stability of eelgrass within Nasketucket Bay and its relationship to nitrogen and chlorophyll-*a* levels is consistent with other estuaries of similar configuration in Buzzards Bay and southeastern Massachusetts. The moderate watershed nitrogen loading coupled with the rate of tidal flushing and the tide range appears to be maintaining the system at a level that is supportive of eelgrass habitat not impaired by nitrogen enrichment at the present time. However, there is some indication that the system is at or very close to its nitrogen threshold so that maintenance of present conditions should be the focus of future MassDEP TMDL analysis.

Benthic infaunal communities throughout the main basins of Nasketucket Bay were indicative of productive high quality benthic habitat in a low to moderately nitrogen enriched coastal areas. Benthic communities were comprised of high numbers of species (20-23), high numbers of individuals (~200 per sample) with key community metrics, diversity (H' >3.0) and Evenness (>0.7) consistent with a high quality habitat. These results are not surprising given the stable eelgrass coverage in this basin and the generally low chlorophyll-*a* levels (~5 ug/L) as well as limited periodic oxygen depletion events. It should be noted that these depletion events are typically brief (few hours) and oxygen infrequently declines to <4 mg/L and is typically ~5 mg/L. Another important indicator is that the sediments do not generally appear to be depositional and large areas are sandy with little organic matter accumulation and a clear oxidized surface layer. Drift algae accumulations are rare. Equally significant is the only rare occurrence of opportunistic organic matter or stress tolerant species, typical of nitrogen enriched areas in southeastern Massachusetts estuaries. Instead, the community is generally composed of polychaetes and crustaceans with some mollusks and some deep burrowers and head-down deposit feeders (e.g. *Clymenella*). Integrating the watercolumn, sediment and community indicators provides a clear assessment of Nasketucket Bay as supporting generally high quality benthic infaunal habitat, consistent with its significant eelgrass coverage.

Benthic infaunal communities within each of the major tributary basins to Nasketucket Bay (Little Bay-Shaws Cove-Brant Island Cove; Figure VII-18) are also generally supporting high quality habitat for their specific conditions. Brant Island Cove supports a high number of species (28) with large numbers of individuals (~400 per 0.0625 m^{-2} grab). Community indices show a high diversity (H' >3.1) and Evenness (E) approaching 0.7. Consistent with these community indices, the sediments generally consist of fine sands with mud low-moderate organic matter, dominated by polychaetes and crustaceans with some deep burrowers but few organic enrichment indicators.

Shaws Cove, at the entrance to Little Bay, is a small cove with a tidal marsh and stream dominating its innermost reach. Assessment of the benthic community in the upper region did not reveal impairment, but rather a relatively high number of species (20) and number of individuals (~250 per 0.0625 m^{-2} grab), with moderate diversity (H'= 2.5) and Evenness (E=0.6). Generally high quality benthic habitat supports an average species number $\geq$ 20 per sample. The community was dominated by polychaetes and crustaceans with some mollusks and few organic enrichment indicator species, consistent with the presence of adjacent salt marsh. The sediments were dominated by fine sands with mud with an oxidized surface.

Little Bay is the largest of the tributary basins to Nasketucket Bay and receives over 40% of the total watershed nitrogen input to the entire Nasketucket Bay / Little Bay Estuarine System. It also has the Nasketucket River within its upper reach, which supports significant salt marsh. In addition, as Little Bay has not historically supported eelgrass coverage, its key habitat for management is associated with benthic infauna. It was clear that within the tidal channel of the mouth of the Nasketucket River and its tidal wetlands, that a different benthic habitat was present, as seen in the dominance of organisms typical of salt marshes on Cape Cod, and the habitat was not impaired. The habitat assessment for Little Bay incorporates the entire basin, making it more robust and reducing uncertainty. Little Bay is currently supporting moderate to high quality infauna habitat, a relatively high number of species (22) with high numbers of individuals (~300 per 0.0625 m^{-2} grab), as well as high diversity (H' >3.0) and Evenness (E=0.69). Generally high quality benthic habitat supports an average species number $\geq$ 20 per sample. The community was dominated by a mix of polychaetes and crustaceans with some mollusks with deep burrowers present. However, 5%-10% of the samples had ~1/3 of the community as organic enrichment indicator species (e.g. capitellids). Yet the sediments at all sites showed oxidized surfaces, although there was a gradient from fine sand at the mouth of the bay to muds at the mouth of the Nasketucket River.

Overall, Little Bay appears to be presently supporting moderate to high quality benthic habitat. However, the appearance (although few patches only) of stress indicator species at some sites (e.g. capitellids) and dominance of polychaetes at others coupled with the periodic oxygen depletions to <4 mg L^{-1}, suggest that Little Bay is near or at its habitat threshold related to nitrogen enrichment. This is supported by the periodic moderate oxygen depletions and elevated average summer chlorophyll levels of 9-10 ug L^{-1} (Table VII-1), which both indicate nitrogen enrichment of this basin. By comparison, Shaws Cove and Brants Island Cove have typical chlorophyll levels $\leq$5 ug L^{-1} and less frequent and less intense periods of oxygen depletion. Nitrogen management within the Nasketucket Bay / Little Bay Estuary should therefore focus on maintenance of existing habitats, but should target Little Bay as the most sensitive to additional watershed nitrogen loading. It appears from integration of the nitrogen related habitat indicators that Little Bay infauna, and by extension the eelgrass beds at the margin of Little and Nasketucket Bays, should be the primary focus for nitrogen management within this estuary. Preventing decline in these habitats will also maintain conditions throughout much of the rest of the estuary. Determining the nitrogen target to maintaining these habitats is the focus of the nitrogen management threshold analysis, below.

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates that will support 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 that will restore the location to the desired habitat quality. The sentinel location is selected such that the maintenance of habitat quality at that one site will necessarily sustain the other regions of the system at acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3. Determination of the critical nitrogen threshold for maintaining high quality habitat within any estuary is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the information on a variety of key habitat characteristics, it is possible to develop a site-specific threshold, which is a refinement upon more generalized threshold analyses frequently employed.

For the Nasketucket Bay / Little Bay Estuary, the habitat quality within the basins is manifested by: 1) the temporal changes in eelgrass coverage, particularly the stability of beds at the margin between Little and Nasketucket Bays, 2) benthic community characteristics, which are consistent with the observed levels of nitrogen and organic matter enrichment and 3) the magnitude of oxygen depletion, as well as the sediment characteristics and general absence to only sparse accumulations of drift macroalgae. The distribution and levels of habitat quality within the Nasketucket Bay / Little Bay Estuary is consistent with the low to moderate level of nitrogen enrichment. The semi-enclosed coves have not historically supported stable eelgrass habitat, which in the case of Little Bay likely results from its natural tendency to accumulate nutrients and organic matter, in addition to the salt marsh influences in the upper reach. In contrast, the open waters of Nasketucket Bay support significant eelgrass coverage and low nitrogen and chlorophyll-*a* levels, with generally only modest levels of oxygen depletion. However, the primary ecological issue within the estuary as a whole is the moderate levels of oxygen depletion in the coves, primarily Little Bay, and even extending into the main basins of Nasketucket Bay. Little Bay is the most nitrogen enriched and therefore has the highest chlorophyll-*a* levels (~10 ug/L) and extent of oxygen depletion. However, Little Bay like the other basins comprising this estuary maintains high quality benthic infauna habitat, although it does have areas with moderate numbers of opportunistic stress indicator species associated with nitrogen-impaired basins on Cape Cod. Also of concern is the colonization of coves and the uppermost reaches of Nasketucket Bay by *Codium*, an attached macroalgae that replaces eelgrass under initial phases of nitrogen enrichment (see Lewis Bay). To the extent that this is linked to nitrogen inputs, it would indicate that the system is at or near its nitrogen loading threshold. It appears from integration of the nitrogen related habitat indicators that Little Bay infauna, and by extension the eelgrass beds at the margin of Little and Nasketucket Bays, should be the primary focus for nitrogen management within this estuary. Preventing decline in these habitats will also maintain conditions throughout much of the rest of the estuary. Determining the nitrogen target to maintain these habitats is the focus of the nitrogen management threshold analysis.

Considering the key role of eelgrass to estuarine ecosystems, the stable beds at the margin of Little Bay and Nasketucket Bay provide an excellent guide for placement of the sentinel station in order to maintain present TN levels within Little Bay (and associated Shaws Cove) as well as the most sensitive portions of Nasketucket Bay. Since this marginal station (e.g. placed at the margin) receives outflows from Little Bay and Shaws Cove, it will also reflect changes in these semi-enclosed basins. Therefore, maintaining TN levels at the sentinel station to sustain eelgrass coverage, will also maintain TN levels within the adjacent basins. Since the sentinel station is associated with the uppermost eelgrass beds, it should also maintain lower TN levels down gradient in Nasketucket Bay, which will prevent increased oxygen depletion and phytoplankton blooms, with the effect of protecting eelgrass and infaunal habitats in this basin.

Eelgrass within the Nasketucket Bay / Little Bay Estuary is a critical habitat structuring the productivity and resource quality of the entire system. Nutrient management planning for preventing impairment to the eelgrass habitat at the boundary between Little and Nasketucket Bay should focus on maintaining the present nitrogen levels within basin waters through watershed nitrogen management. Site-specific data is used to develop the TN threshold target for the sentinel station. Since the station is associated with both eelgrass and infauna habitats, and since eelgrass is significantly more sensitive to nitrogen enrichment, an eelgrass threshold analysis was conducted.

Overall, the historical distribution of eelgrass within the Nasketucket Bay / Little Bay Estuary is consistent with both the natural history of eelgrass and the present nitrogen, oxygen and chlorophyll levels within the different component basins. The absence of eelgrass within Little Bay (present and historically) is consistent with the chlorophyll levels (9 ug/L) and tidally averaged TN levels of 0.415 - 0.391 for upper and mid bay, respectively and 0.391 - 0.373 for the mid to outer bay region. In contrast, the main eastern basin of Nasketucket Bay has lower chlorophyll levels (<5 ug L-1) and TN levels (<0.368 mg N L^{-1}) and these areas currently support eelgrass beds. The tidally averaged TN level at the location of the sentinel station within the inner edge of the stable beds at the margin of Little and Nasketucket Bays is 0.368 mg L^{-1}, the highest TN level associated with eelgrass within this estuary. This TN level is between that needed for maintaining high quality eelgrass habitat in other deeper and shallower systems, for example 0.35 mg L^{-1} (Phinneys Harbor, West Falmouth Harbor, Quissett Harbor) and other complex estuaries whose thresholds were set at 0.38 mg TN L^{-1} (Three Bays, Popponesset Bay, Lewis Bay). It should be noted that shallower basins can support eelgrass at higher chlorophyll-*a* and TN levels due to their thinner water columns allowing sufficient light penetration. But the deeper waters of Nasketucket Bay makes it more sensitive to nitrogen impairment compared to nearby shallower basins.

It should be noted that in basins of similar depth to Nasketucket Bay, the basins showed nearly identical relationships between eelgrass and tidally averaged TN levels. For example, Lagoon Pond (Town of Oak Bluffs, Martha's Vineyard) no longer supports eelgrass in areas where tidally averaged total nitrogen is 0.378 mg N L^{-1} and 0.385 mg N L^{-1}, while in other areas eelgrass beds presently exist at nitrogen levels are $\leq$ 0.371 mg N L^{-1}, nearly identical to the upper edge of the beds at the Little-Nasketucket Bay margin (0.368 mg L^{-1}). Additionally in Waquoit Bay (Town of Falmouth/Mashpee) and at similar depths, eelgrass was found to slowly decline at average TN concentrations of 0.395 mg L^{-1} (lower basin of Waquoit Bay) and was lost from the Centerville River (Town of Barnstable) also at a tidally averaged TN concentration of 0.395 mg L^{-1}. From the site specific analysis of the Nasketucket Bay / Little Bay Estuary and comparison to other similar systems throughout southeastern Massachusetts, it appears that the TN threshold to maintain stable eelgrass habitat in the Nasketucket Bay / Little Bay Estuary is 0.37 mg L^{-1}. 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

At present the Nasketucket Bay system is supporting and maintaining eelgrass habitat along the shallow margins of the bay. The system does not exhibit the normal impairments that result from watershed nitrogen inputs exceeding the nitrogen tolerance of the system, thus resulting in the loss of historical eelgrass beds and stress to infaunal communities. Nasketucket Bay is presently supporting and maintaining the historical eelgrass habitat around the bay. The Bay is presently receiving watershed nitrogen inputs below or at its tolerance level with the result that some additional nitrogen loading can occur before habitat impairment occurs.

The nitrogen thresholds discussed in the previous section are the loads developed for the Present Loading Conditions as presented in Section VI. Based on the analysis of watershed loads, water quality parameters, and eelgrass / infaunal habitat, it was determined the Present Loading Condition represent the amount of total nitrogen mass loading that can be tolerated to maintain eelgrass and infaunal habitats in the Nasketucket Bay system (Figure VIII-1).

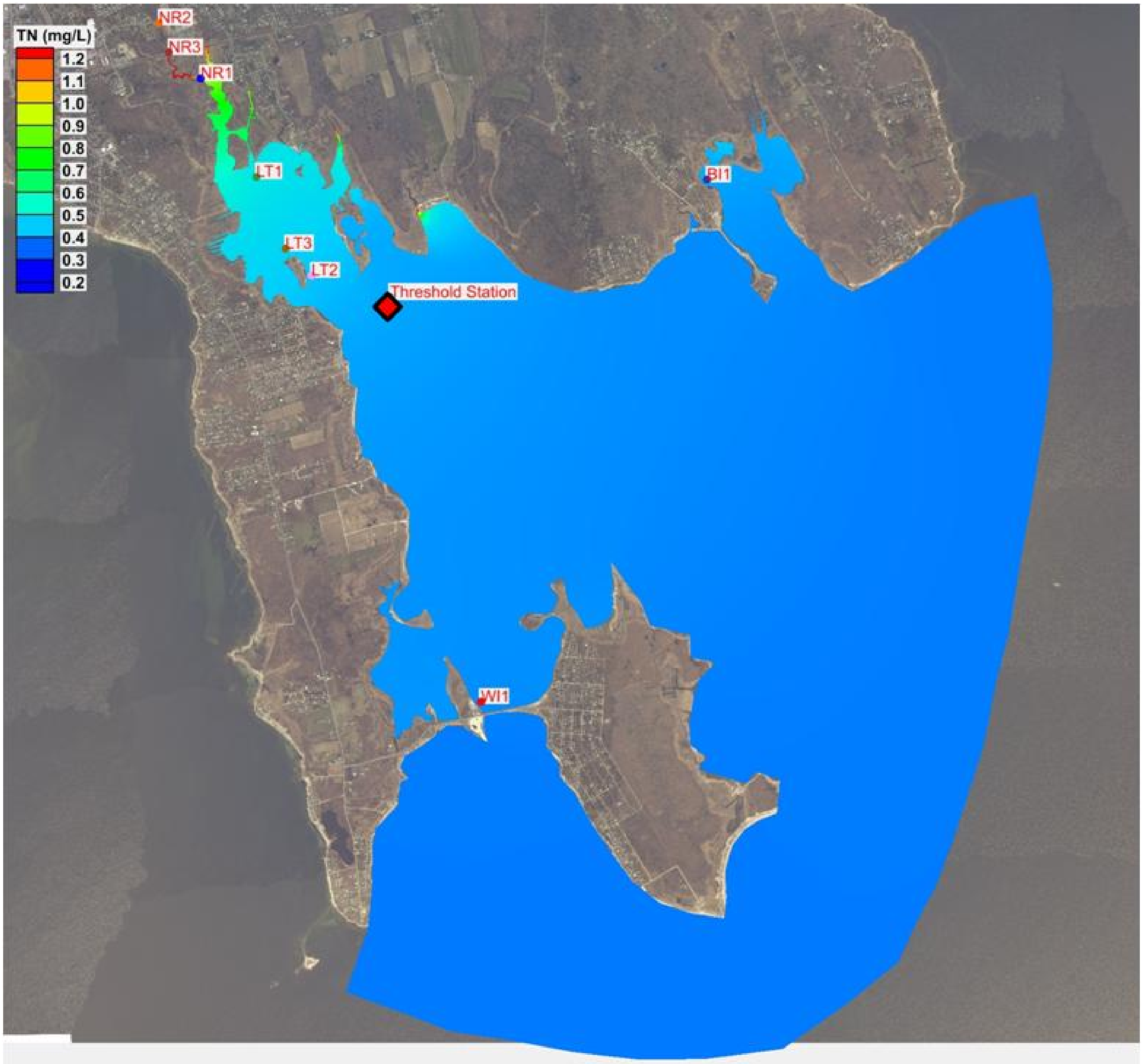


Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in the Nasketucket Bay System, for threshold conditions (<0.37 mg N L^{-1} at the sentinel station 'Threshold Station'). Nasketucket Bay is presently at its threshold rate of nitrogen loading.

The current nitrogen loads within the Nasketucket Bay represent the nitrogen loads necessary to maintain nitrogen concentrations which will sustain eelgrass within the system. The nitrogen loads are the same as those developed for Present Conditions within Section VI. It is possible that different distributions of nitrogen loading could be achieved that would maintain the threshold nitrogen concentrations within the system. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

The septic loading is shown in Table VIII-2. The nitrogen septic loads have not changed from the Present Conditions loads developed in Section VI.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Nasketucket Bay 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
Little Bay	0.645	0.645	+0.0%
Shaw's Cove	0.165	0.165	+0.0%
Eastern Nasketucket Bay	3.113	3.113	+0.0%
Brandt Island Cove	0.502	0.502	+0.0%
Western Nasketucket Bay	0.612	0.612	+0.0%
West Island Outer Bay	0.666	0.666	+0.0%
Surface Water Sources			
Nasketucket Main and West Rivers	2.789	2.789	+0.0%
Nasketucket East River	0.249	0.249	+0.0%
Nonquitt Brook	0.803	0.803	+0.0%
Shaw's Cove Brook East and West	0.153	0.153	+0.0%

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the septic loads depicted in Table VIII-2. The total nitrogen loads for Nasketucket Bay are presented in Table VIII-4. 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 (representative of summer time flux conditions), 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.

Table VIII-3. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of Nasketucket Bay 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
Little Bay	3.798	3.798	+0.0%
Shaw's Cove	0.680	0.680	+0.0%
Eastern Nasketucket Bay	6.220	6.220	+0.0%
Brandt Island Cove	1.641	1.641	+0.0%
Western Nasketucket Bay	9.190	9.190	+0.0%
West Island Outer Bay	2.085	2.085	+0.0%
Surface Water Sources			
Nasketucket Main and West Rivers	15.940	15.940	+0.0%
Nasketucket East River	0.887	0.887	+0.0%
Nonquitt Brook	2.082	2.082	+0.0%
Shaw's Cove Brook East and West	7.109	7.109	+0.0%

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Nasketucket Bay 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)
Little Bay	3.798	3.364	31.980
Shaw's Cove	0.680	0.356	5.938
Eastern Nasketucket Bay Watersheds	6.220	19.279	66.195
Brandt Island Cove	1.641	1.997	10.850
Western Nasketucket Bay Watersheds	9.190	21.016	-73.249
West Island Outer Bay	2.085	0.408	-7.667
Surface Water Sources			
Nasketucket Main and West Rivers	15.940	-	-
Nasketucket East River	0.887	-	-
Nonquitt Brook	2.082	-	-
Shaw's Cove Brook East and West	7.109	-	-

Comparison of model results between existing loading conditions and the selected loading scenario to maintain the target TN concentrations at the sentinel station is shown in Table VIII-5. To maintain the threshold nitrogen concentration at the sentinel station, no reduction in load is required. By holding the present loading conditions within the system, the current eelgrass habitat and infaunal animal habitat can be maintained throughout the estuary.

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change, for the Nasketucket Bay. Sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Nasketucket River Main	NRM & NR-3	1.109	1.109	0.0%
Nasketucket River	NR-1	0.881	0.881	0.0%
Little Bay Inner	LT-1	0.451	0.451	0.0%
Little Bay Mid	LT-3	0.418	0.418	0.0%
Little Bay Low	LT-2	0.395	0.395	0.0%
Brandt Island Cove	BI-1	0.340	0.340	0.0%
West Island Inlet	WI-1	0.369	0.369	0.0%
Threshold Station	**--**	**0.368**	**0.368**	**0.0%**

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.

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