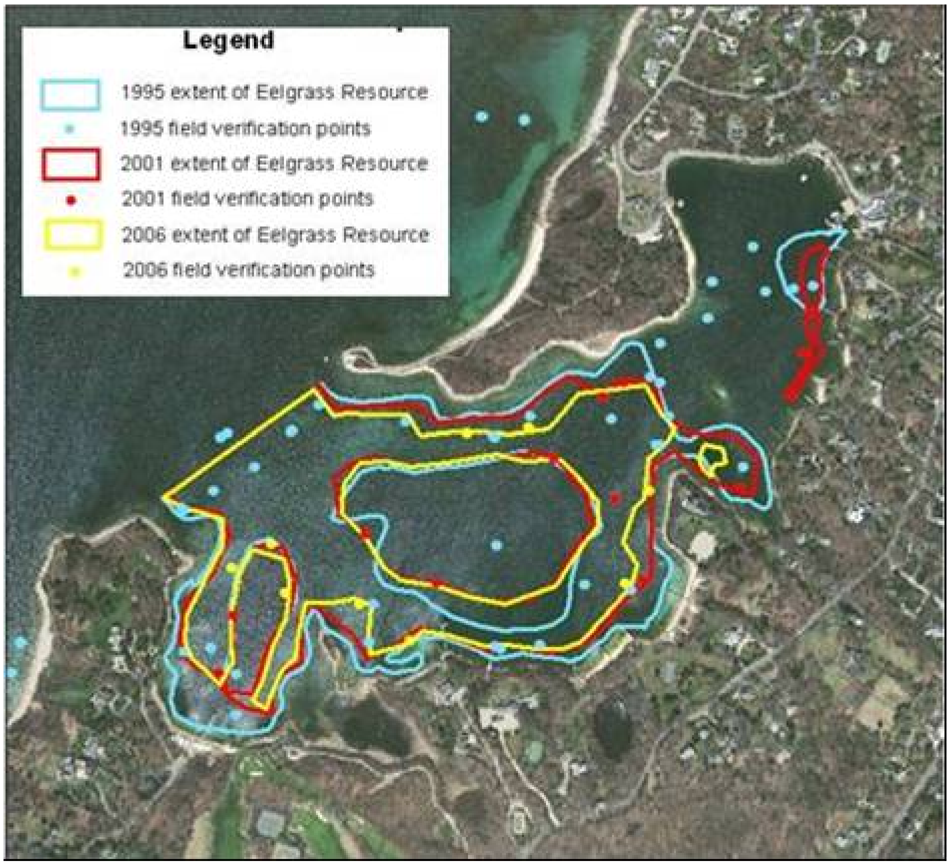
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Quissett Harbor Embayment System Town of Falmouth, Massachusetts



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Massachusetts Department of Environmental Protection

FINAL REPORT – March 2013

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Quissett Harbor Embayment System Town of Falmouth, Massachusetts

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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 Quissett Harbor embayment system, a coastal embayment within the Town of Falmouth, Massachusetts. Analyses of the Quissett Harbor embayment system was performed to assist the Town of Falmouth 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 Falmouth 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 Quissett Harbor embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration of the Quissett Harbor 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. 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 Quissett Harbor embayment system within the Town of Falmouth is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to this coastal system. 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 Falmouth has recognized the severity of the problem of eutrophication and the need for watershed nutrient management and is currently developing a Comprehensive Wastewater Management Plan which the Town plans to implement upon its completion. The Town of Falmouth has been working with the Town of Mashpee that has also completed and implemented wastewater planning in other nearby regions not associated with the Quissett Harbor system, specifically the Waquoit Bay embayment system. In this manner, this analysis of the Quissett Harbor system is yielding results which can be utilized by the Town of Falmouth along with MEP results developed for the other estuaries of the town (specifically, Rands Harbor, Fiddlers Cove, Wild Harbor, West Falmouth Harbor, Little Pond, Falmouth Inner Harbor, Oyster Pond, Great Pond, Green Pond, Bournes Pond, Eel Pond/Childs River and Waquoit Bay) in order to give the Town of Falmouth the necessary results to plan out and implement a unified town-wide approach to nutrient management. The Town of Falmouth 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. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict 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) 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 Quissett Harbor embayment system by using site-specific data collected by the MEP and water quality data from the Falmouth PondWatch Program (see Chapter 2) as well as the Coalition for Buzzards Bay (CBB) BayWatchers Program (assisted technically until 2008 by the University of Massachusetts-SMAST Coastal Systems Program). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Falmouth Planning Department, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Quissett Harbor 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 Quissett Harbor embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Buzzards Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Quissett Harbor embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

MEP Nitrogen Thresholds Analysis: The threshold nitrogen level for an embayment represents the average water column concentration of nitrogen that will support the habitat quality being sought. The water column nitrogen level is ultimately controlled by the watershed nitrogen load and the nitrogen concentration in the inflowing tidal waters (boundary condition).

The water column nitrogen concentration is modified by the extent of sediment regeneration. Threshold nitrogen levels for the embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. High habitat quality was defined as supportive of eelgrass and infaunal communities. Dissolved oxygen and chlorophyll a were also considered in the assessment.

The nitrogen thresholds developed in Section VIII-2 were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Quissett Harbor embayment system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for the Quissett Harbor system. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Quissett Harbor embayment system in the Town of Falmouth. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. For Illustrative purposes, the MEP analysis has initially focused upon nitrogen loads from on-site septic systems as a test of the potential for achieving the level of total nitrogen reduction for restoration of the embayment system. The concept was that since nitrogen loads associated with wastewater generally represent 80% - 85% of the controllable watershed load to the Quissett Harbor embayment system and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Quissett Harbor 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 Quissett Harbor Estuary is just beyond its ability to assimilate nitrogen without impairment and is showing a low level of nitrogen enrichment, with some moderate impairment of both eelgrass and infaunal habitats (Table VIII-1). This indicates that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system. In general, the habitat quality within the basins of this System is manifested by the temporal changes in eelgrass coverage and benthic community characteristics, which are consistent with the observed levels of nitrogen and organic matter enrichment and magnitude of oxygen depletion, as well as the sediment characteristics and general absence to only sparse macroalgal accumulations. The distribution and levels of habitat impairment within the Quissett Harbor Embayment System is consistent with the low to moderate level of nitrogen enrichment. The recent losses of historically stable eelgrass habitat at the inner boundary of the Outer basin makes restoration of this resource the primary focus for nitrogen management, with the associated goal of restoring impaired benthic habitat in the deep region of the Inner basin. Determining the nitrogen target to restoring these habitats is the focus of the nitrogen management threshold analysis provided in Section VIII.

The measured levels of oxygen depletion and enhanced chlorophyll a levels follows the spatial pattern of total nitrogen levels in this system (Chapter 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 the outer basin and were highest within the inner basin.

Oxygen records obtained from both the moorings deployed in Quissett Harbor show a greater degree of oxygen depletion in the Inner versus Outer basins, consistent with the basin structure, flushing, and nitrogen and chlorophyll a levels. The Inner basin mooring measured the deep bottom waters of the basin, and was placed to capture the greatest level of oxygen depletion in this embayment. Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at or just above air equilibration to slightly hypoxic conditions where levels decline to 4 mg L^{-1} and periodically to as low as 3.1 mg L^{-1}. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The oxygen levels are consistent with a system that is beginning to show the effects of nitrogen enrichment and is presently at the boundary of impairment to benthic communities. The oxygen decline paralleled enhanced phytoplankton biomass, with chlorophyll a reaching 10-15 ug L^{-1}. The periodic low levels of oxygen observed in the Inner basin is indicative of slight to moderate habitat impairment which is also consistent with the moderately elevated chlorophyll a levels, also indicative of nitrogen enrichment (mooring chlorophyll-a average 10.6 ug L^{-1}). Average chlorophyll levels over 10 ug L-1 have been used to indicate nitrogen enrichment in temperate embayments. Both the oxygen and chlorophyll a data indicate a system with a moderate level of nutrient enrichment, generally associated with stress to benthic (and eelgrass) habitat. However, this stress appears to be primarily focused on the deep central region of the basin.

In contrast, the Outer basin bottom water exhibited little diurnal or tidal variation in oxygen levels and generally supported oxygen levels between 5 and 7 mg L^{-1}, and rarely exceed air equilibration (over 8 mg L^{-1}). Moreover, oxygen levels rarely declined to 4 mg L^{-1} and the water quality monitoring samples did not observe oxygen declines to <5 mg L^{-1} from 1992 to 2010. The low organic enrichment in this portion of the system is also seen in the generally low phytoplankton biomass (e.g. chlorophyll a levels). Chlorophyll a remained between 5-10 ug L^{-1} and only occasionally increased to 10-15 ug L^{-1} (~5 days). Both oxygen and chlorophyll measurements indicate that the Outer basin is generally of high quality, showing little evidence of the effects of nitrogen enrichment.

All of the available information on eelgrass within the Quissett Harbor System indicates that the outer basin has and continues to support significant eelgrass beds, with the only clear decline in coverage along the boundary between the Inner and Outer basins. The Inner basin has not historically supported significant eelgrass habitat. Review of all of the available data indicate that the extent and cause of eelgrass "loss" along the western margin of the Inner basin cannot be unequivocally documented base upon the available data. In contrast the loss of eelgrass habitat along the boundary between the Outer and Inner basins is well documented (1951, 1987, 1995, 2001, 2006) and the temporal and spatial pattern of this loss from the inner margin of the existing beds is typical of nitrogen enrichment effects. This recent decline in eelgrass habitat indicates that this embayment is just slightly beyond its threshold level of nitrogen enrichment and further increases in nitrogen loading will almost certainly affect a significant decline in eelgrass habitat in the system. The loss of the innermost region of eelgrass beds in the Outer basin and the presence of stable high quality eelgrass habitat throughout the rest of this basin indicate that only a moderate level of impairment to eelgrass habitat exists at present.

Overall, the infauna survey indicated that both the Outer and Inner basins generally support high quality benthic habitat, although the Inner basin supports a slightly lower quality habitat compared to the Outer basin. However, relative to nitrogen enrichment affect, localized areas are showing a moderate level of impairment, specifically the deepest portion of the Inner basin. It appears that organic deposition in these areas is the cause of the stress, which is supported by the observed deep water oxygen levels.

Although the margins of the Inner basin support a high quality benthic animal habitat, the deep basin region is presently clearly impaired habitat. While the basin morphology, which tends to create a depositional environment, increases the system's sensitivity to organic enrichment, the levels of phytoplankton biomass, the levels of oxygen decline (<4 mg/L) and the organic enrichment of the sediments are clear evidence of nitrogen being the ultimate cause of the habitat impairment. Integration of all of the key metrics clearly indicates that the Outer basin is generally supporting high quality benthic animal habitat, while the Inner basin is just beyond its capacity to assimilate nitrogen loads without impairment (i.e. it is just beyond the nitrogen threshold). Since Quissett Harbor is also just beyond its nitrogen threshold to support healthy eelgrass habitat, a slight reduction to enhance this habitat should also reverse the moderate impairment of the benthic animal habitat within the Inner basin.

In general, the habitat quality within the basins of this System is manifested by the temporal changes in eelgrass coverage and benthic community characteristics, which are consistent with the observed levels of nitrogen and organic matter enrichment and magnitude of oxygen depletion, as well as the sediment characteristics and general absence to only sparse macroalgal accumulations. The distribution and levels of habitat impairment within the Quissett Harbor Embayment System is consistent with the low to moderate level of nitrogen enrichment. The recent losses of historically stable eelgrass habitat at the inner boundary of the Outer basin makes restoration of this resource the primary focus for nitrogen management, with the associated goal of restoring impaired benthic habitat in the deep region of the Inner basin. Determining the nitrogen target to restoring these habitats is the focus of the nitrogen management threshold analysis, below.

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 restore or maintain SA waters or high habitat quality. In this system, high habitat quality was defined as possibly supportive of eelgrass and supportive of diverse benthic animal communities. Dissolved oxygen and chlorophyll *a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Falmouth Quissett Harbor embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 80% - 85% of the controllable watershed nitrogen load to the embayment was from wastewater.

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 the Great, Green and Bournes Pond Systems, Popponesset Bay System, and the nearby Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay, among many other systems analyzed by the MEP. This is almost certainly going to be true for the other embayments within the MEP area, as well, inclusive of Quissett Harbor.

The threshold nitrogen levels for the Quissett Harbor embayment system in Falmouth were determined as follows:

Quissett Harbor Threshold Nitrogen Concentrations

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

- The Quissett Harbor Embayment System presently shows a moderate impairment to eelgrass habitat within its Outer basin. The impairment is based upon the recent temporal trend in loss of eelgrass from the inner margin of the basin, at the Inner basin boundary. Both the location and the temporal trend is consistent with nitrogen enrichment. However, as the rate of loss has been gradual and relatively recent, indicates that this estuary is only just beyond its nitrogen threshold (i.e. the level of nitrogen a system can tolerate without impairment). The presence of stable dense eelgrass beds throughout the outer harbor and the generally high quality benthic animal habitat throughout the embayment system (except for the deep region of the Inner basin) also indicates a system only just beyond its threshold.

- As eelgrass within the Quissett Harbor Embayment System is a critical habitat that structures the productivity and resource quality of the entire system, and as it is presently showing moderate impairment, restoration of this resource is the primary target for overall restoration of this system. Nutrient management planning for restoration of the eelgrass habitat at the boundary between the Outer and Inner basins should focus on reducing the level of nitrogen enrichment in basin waters through watershed nitrogen management. The absence of eelgrass within the bulk of the Inner basin and the loss of even sparse eelgrass coverage along its western margin are associated with tidally averaged nitrogen (total nitrogen, TN) levels of 0.354 mg N L^{-1}, while the Outer basin high quality eelgrass habitat is at lower TN levels, 0.304 mg N L^{-1}. These TN levels and habitat stability/decline are consistent with persistence and loss of eelgrass at similar depths in other estuaries in southeastern Massachusetts.

- Attaining a small decrease in nitrogen levels in the Inner basin should be sufficient to restore eelgrass habitat quality throughout this system. Based upon the present TN levels in the Quissett Harbor System and comparison to other similar estuaries a threshold for tidally averaged TN at the sentinel station in the Inner basin (QH-2) of 0.34

mg N L^{-1} was selected. It should be noted that while this threshold is well constrained by the available data, it is at the limits of the sensitivity of the MEP approach. This threshold is only slightly lower than that for West Falmouth Harbor and Phinneys Harbor, and is focused in part on restoring eelgrass where it had persisted until recently at the boundary between the Inner and Outer basins. In addition, lowering the level of nitrogen enrichment at the sentinel station will lower nitrogen levels throughout the estuary (Section VIII.3) with the parallel effect of improving infaunal habitats in the impaired region of the Inner basin.

It is important to note that the analysis of future nitrogen loading to the Quissett Harbor 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 Quissett Harbor estuarine system is that restoration will necessitate a reduction in the present (2009) nitrogen inputs and management options to negate additional future nitrogen inputs.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Quissett Harbor 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										
Quissett Harbor (Main)	0.099	0.335	1.123	--	1.458	0.928	-3.159	-0.773	0.30	--
Quissett Harbor (Upper)	0.071	0.337	1.584	--	1.921	0.409	4.060	6.390	0.35	--
System Total	**0.170**	**0.672**	**2.707**	**--**	**3.379**	**1.337**	**0.901**	**5.617**	**--**	**0.34[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 1993 – 2008 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 the Upper Harbor at water quality stations QH-2

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Quissett Harbor estuary system, Town of Quissett, 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						
Quissett Harbor (Main)	1.458	1.458	0.928	-3.159	-0.773	0.0%
Quissett Harbor (Upper)	1.921	1.192	0.409	3.840	5.441	-38.0%
System Total	**3.379**	**2.650**	**1.337**	**0.681**	**4.668**	**-21.6%**

(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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The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources of Falmouth and drove for the completion of the Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Quissett Harbor Embayment Systems. Without these stewards and their efforts, this project would not have been possible.

First and foremost we would like to recognize and applaud the commitment shown by the Town of Falmouth in carrying forward with the Massachusetts Estuaries Project and the restoration of all the estuaries of the Town. Significant time and attention has been dedicated to this effort by Jerry Potamis and Amy Lowell, whose efforts where instrumental to completion of these reports. We would also like to acknowledge the field support provided to the MEP by the Quissett Harbor Boatyard who gave us unrestricted use of the facility to complete critical field tasks. The MEP Technical Team would also like to acknowledge the efforts of the Coalition for Buzzards Bay in providing the water quality monitoring baseline for this system. Without this baseline water quality data the present analysis would not have been possible. We also would like to recognize the nutrient management committee and the CWMP review committee for the Town of Falmouth, in moving this MEP analysis forward to support estuarine management of one of the signature estuaries in the Town of Falmouth.

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I. INTRODUCTION

The Quissett Harbor Estuarine System is located within the Town of Falmouth, on Cape Cod Massachusetts. Once called Quamquisset Harbor, it is one of the deeper better flushed tributary estuaries to Buzzards Bay situated on the Bay's eastern shore immediately north of Woods Hole (Figure I-1). The Quissett Harbor system is constrained by the Knob to the north and Gansett point to the south, essentially creating a well protected harbor with a relatively open outer harbor and a semi-enclosed inner harbor. Quissett Harbor is directly connected to Buzzards Bay (Figure I-2). The inlet to Quissett Harbor is partially armored, however, given the rocky characteristics of the shoreline along Buzzards Bay in this area, the mouth of the harbor is generally more stable than most of the other embayments in the Town of Falmouth. The northern portion of the inlet, the peninsula running to The Knob, has been protected with revetments, for shoreline protection, which functionally armors this portion of the tidal inlet to the Harbor.

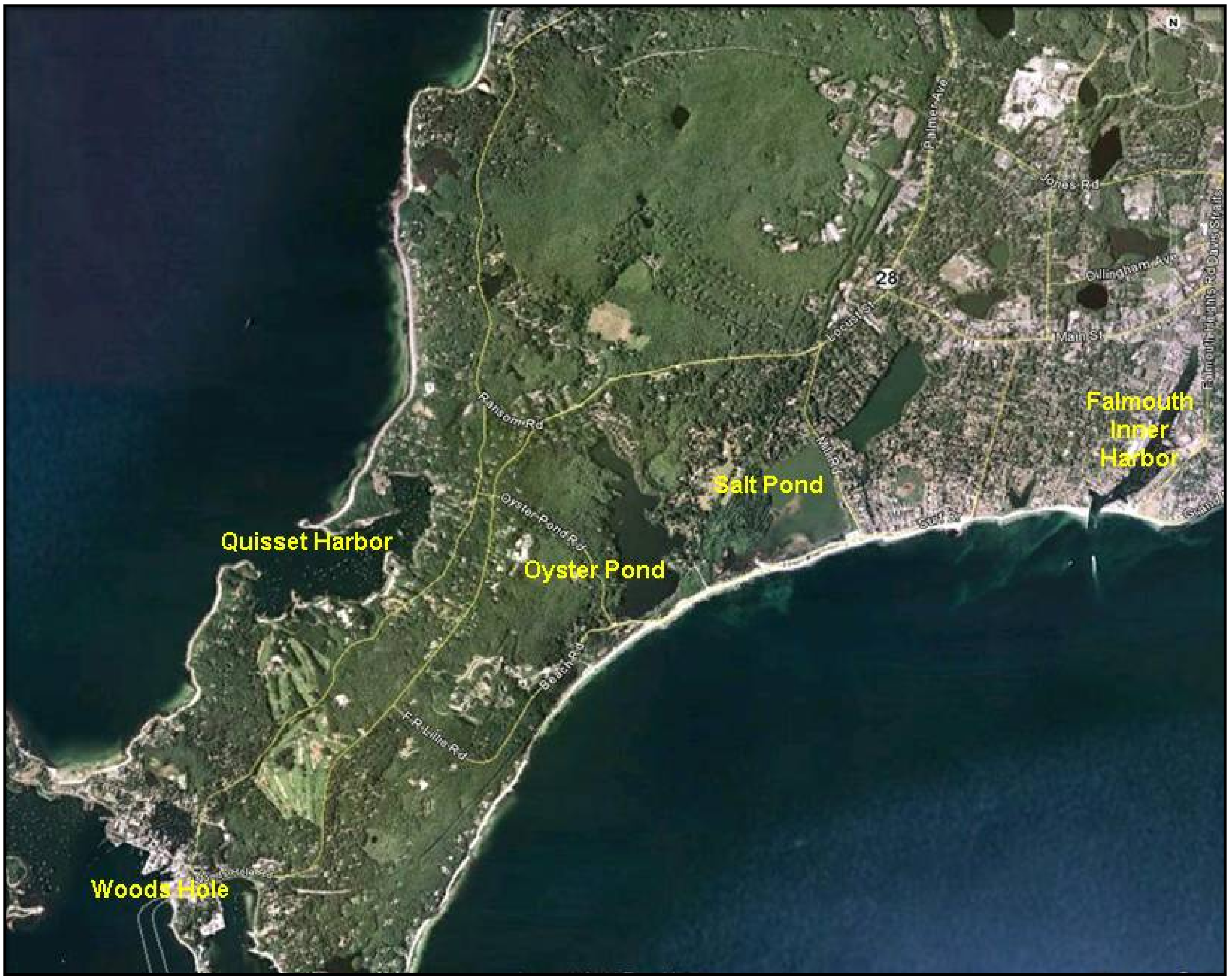

Figure I-1. Quissett Harbor region for the Massachusetts Estuaries Project nutrient assessment. Tidal waters enter the estuarine system directly from Buzzards Bay through a single inlet. The estuary is situated in the glacial moraine deposits of the Buzzards Bay lobe. Across the peninsula to the east lies the southern shore of the Town of Falmouth bordering Vineyard Sound. Buzzards Bay and Vineyard Sound waters exchange through the Woods Hole Channel.

Figure I-2. Tidal waters enter the Quissett Harbor estuarine system directly from Buzzards Bay through one deep partially armored inlet. Freshwater enters the Quissett Harbor system from the watershed through direct groundwater discharge. There are no significant streams flowing into Quissett Harbor.

The watershed for the Quissett Harbor embayment system is relatively small due to its location relative to the glacial moraine and is distributed entirely within the Town of Falmouth. The Quissett Harbor system is one of the Town of Falmouth's moderately sized marine resources and does support an active boatyard as is found in nearby Fiddlers Cove as well as a small yacht club. As such, boating activity is generally high during the summer months. At a time when many other coastal ponds and bays tributary to Buzzards Bay have been impaired by an overabundance of watershed nutrient inputs, water quality in Quissett Harbor has generally remained moderately high due to the relatively simple structure of the harbor (one basin and no small tributaries), the direct flushing of the harbor system with the low nutrient waters of Buzzards Bay and its small upland contributing area.

The Quissett Harbor system is a moderately complex estuarine system composed of a main outer basin and a smaller inner basin. The habitat quality of Quissett Harbor and its tributaries is linked to the level of tidal flushing through the wide inlet connecting the Harbor to Buzzards Bay. The tide range, ~5 feet, is moderate for the region, compared to tide heights off Stage Harbor Chatham, ~4.5 ft, Wellfleet Harbor, ~10 ft, and Vineyard Sound in Falmouth ~1.5 ft. Since it is the water elevation difference between the offshore waters and embayment waters that is the primary driving force for tidal exchange, unless a system has a restricted inlet, the greater the offshore tide, the greater rate of water exchange (flushing) of an embayment.). To the degree that an inlet may become occluded, this may also directly influence the nutrient related health of an embayment system. However, restriction of tidal flows is not a significant concern for this system given the rocky characteristics of the shoreline associated with its inlet.

Given the present hydrodynamic characteristics of the Quissett Harbor embayment system, it appears that estuarine habitat quality is mostly dependent on the level of nutrient loading to embayment waters. In Quissett Harbor, it does not appear that significant improvements to flushing of the system can be achieved as the system, in its present configuration, flushes relatively well, even with the presence of a small shoal that separates the inner basin from the outer basin of the harbor. As such, maintenance or enhancement of existing habitat quality in the overall Quissett Harbor system, will need to focus on nutrient loading from the surrounding watershed. The relationship of watershed nitrogen inputs to estuarine habitat quality are detailed in later sections of this report.

The watershed to Quissett Harbor is somewhat geologically complex, being composed primarily of Buzzards Bay Plain glacial deposits. These formations consist of material deposited during the retreat of the Cape Cod Lobe of the Laurentide Ice sheet. The material is highly permeable and as such, direct rainwater run-off is typically rather low for this type of coastal system. Therefore, most freshwater inflow to the estuarine system is via groundwater discharge or direct stormwater runoff into the harbor from storm drains. There are no significant groundwater fed surface water flows in this watershed. The basins of Quissett Harbor are thought to have been formed from the melting of a block of ice trapped in the moraine deposits. Originally the Quissett Harbor basins were isolated from the sea, but as a result of rising sea level following the last glaciation approximately 18,000 years BP, they became estuarine systems ~5,000-6,000 years BP.

Unlike many embayments on Cape Cod, Quissett Harbor is only moderately enriched in nitrogen and presently supports significant eelgrass and benthic animal habitats. Stable eelgrass beds have been documented throughout much of the outer basin in 1951, 1995, 2001,2006 surveys by MassDEP. The presence of eelgrass is particularly important to the use of Quissett Harbor as fish and shellfish habitat. The Quissett Harbor System and the nearshore waters represent an important potential shellfish resource to the Town of Falmouth, primarily for quahogs, and as such it is critical that the health of the habitat be maintained through appropriate nutrient management. Given the low levels of indicator bacteria in Quissett Harbor waters, shellfishing is approved by the Massachusetts Division of Marine Fisheries year round for the outer portion of the harbor and is conditionally approved for the inner portion of the harbor. The inner harbor's designation is in part the result of the presence of a small marina and mooring field, while the generally low levels of indicator bacteria likely result from the low level of surface water runoff, lack of stream discharge, and limited wetland area (which can be a natural source in some situations).

The nature of enclosed embayments in populous regions brings two opposing elements to bear: As protected marine shorelines they are popular regions for boating, recreation, and land development; but as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shoreline. Quissett Harbor, like all other embayment systems on Cape Cod, is at risk of eutrophication from increasing nitrogen loads in the groundwater from land-use changes to its watershed, however, given its structure, Quissett Harbor currently exhibits a higher overall habitat health then most estuaries in the Town of Falmouth and much of Cape Cod.

Currently, the primary ecological threat to Quissett Harbor marine resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has significantly increased over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to Quissett Harbor and other Falmouth embayments (Rands Harbor, Fiddlers Cove, Wild Harbor, Oyster Pond, Little Pond, Great Pond, Green Pond, Bournes Pond), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Falmouth has been among the fastest growing towns in the Commonwealth over the past three decades and does not have centralized wastewater treatment throughout its coastal watersheds nor general use of denitrifying decentralized wastewater treatment technologies. As a result, developed areas contribute significantly to the nitrogen loading of its estuaries, including the Quissett Harbor system. For Quissett Harbor, the primary pathway for transport of this nitrogen from its source to estuarine waters is through groundwater. As existing and future increased levels of nutrients impact the coastal embayments in Falmouth, water quality degradation increases and in some cases accelerates, with loss of valuable environmental resources.

The Town of Falmouth, as the municipal steward for the Quissett Harbor embayment system, has been concerned over the resource quality of the Town's significant coastal resources, inclusive of the Quissett Harbor system. In the mid-1980's the Town enacted an innovative Nutrient Overlay By-law that tied watershed development to water quality within the adjacent embayment. Nutrient limits were set for nitrogen in each of the Town's embayments. The goal was to keep nitrogen concentrations in the receiving systems below thresholds that were projected to cause water quality shifts. To acquire baseline water quality data necessary for ecological management of Falmouth's coastal salt ponds and harbors, a citizen-based water quality monitoring program was initiated by the Town of Falmouth. Falmouth Pondwatch, was established to provide on-going nutrient related embayment health information in support of the By-law. The water quality monitoring program was based on a collaborative effort between scientists, citizens and representatives of the Town of Falmouth. As originally conceived, the monitoring program focused on data collection in three original ponds, Oyster Pond, Little Pond and Green Pond. By 1990, the scope of water quality data collection expanded to include two additional ponds, Great/Perch Pond and Bournes Pond. In 1992, the scope of data collection was once again expanded to include West Falmouth Harbor in order to evaluate the effects from a nutrient enriched wastewater plume generated by the Falmouth Wastewater Treatment Facility. Since 1997, technical aspects of the Falmouth PondWatch Program have been coordinated through the Coastal Systems Program at SMAST-UMassD. In addition, the Town of Falmouth has supported the Coalition for Buzzards Bay's Water Quality Monitoring Program which, through its association with the Coastal Systems Program at UMASS-SMAST, collected data on nitrogen related water quality within the Falmouth estuaries that exist adjacent Buzzards Bay. The collaborative CBB/SMAST water quality monitoring effort covered systems such as Quissett Harbor, Wild Harbor and Megansett Harbor, Fiddlers Cove and Rands Harbor System beginning in 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of Falmouth's embayments and harbors adjacent Buzzards Bay. The BayWatchers is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD until 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 and determine the relationship between observed water quality and habitat health. This multi-year effort was initiated in 1992, with significant support from the Buzzards Bay Project. The BayWatcher Water Quality Monitoring Program in Quissett Harbor developed a water quality baseline for this system. Additionally, as remediation plans for various systems are implemented, the continued monitoring will help satisfy monitoring requirements by State regulatory agencies and provide quantitative information to the Town relative to the efficacy of remediation efforts. The MEP effort builds upon the Coalition for Buzzards Bay water quality monitoring program and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Quissett Harbor embayment system.

In conjunction with other Town efforts, the Town of Falmouth Planning Office continues to enhance its tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that continuing effort. The estuarine specific watershed based nutrient loading model, the hydrodynamic models and the water quality models being developed under the MEP for Quissett Harbor will be an additional set of tools the town can use to inform future nutrient management decisions. The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development needed by the Town of Falmouth. 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 the Town of Falmouth to develop and evaluate the most cost effective nitrogen management alternatives to restore the Town's valuable coastal resources 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 Falmouth) 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 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. 44 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 embayments: (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-3). 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

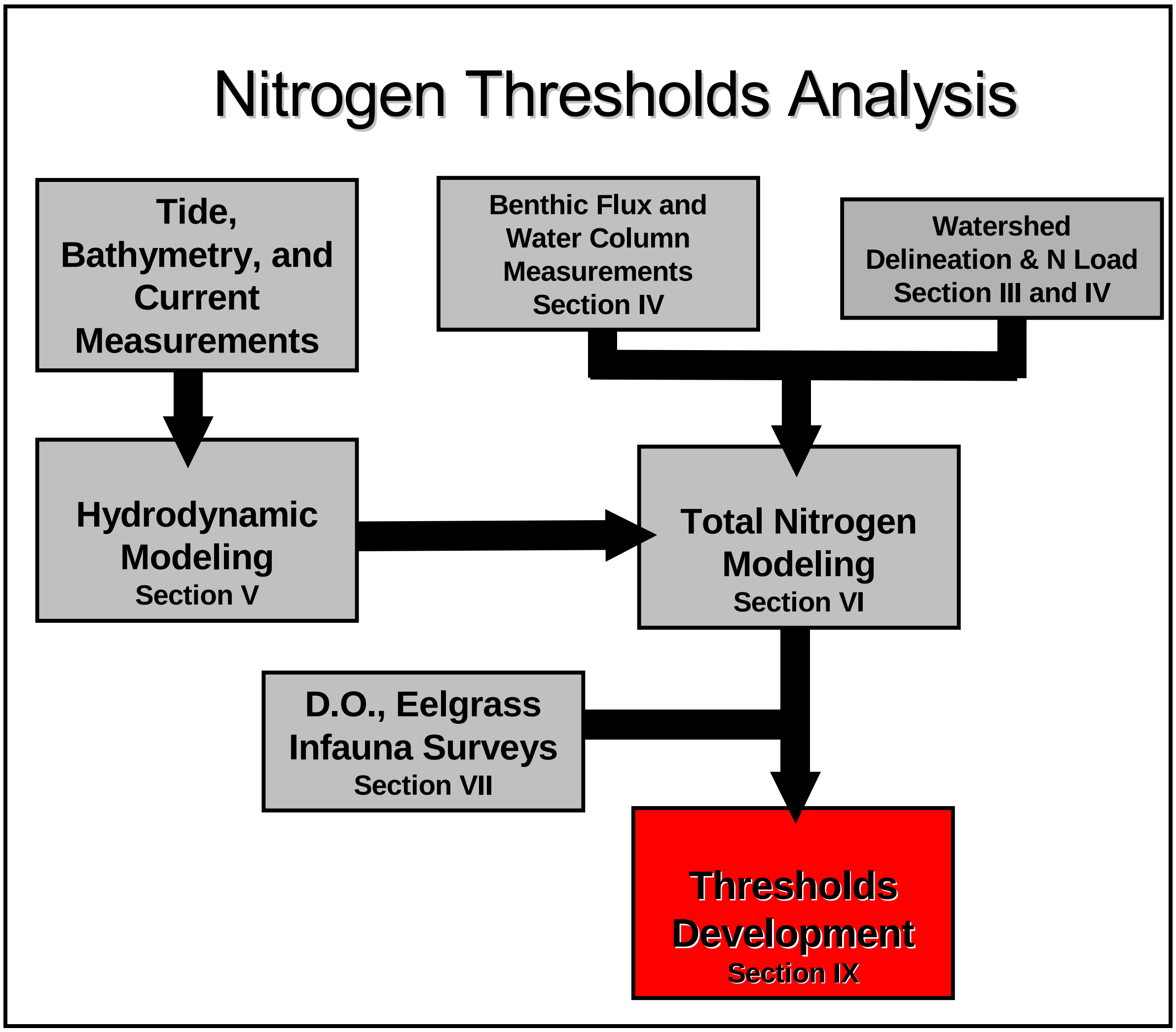

Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

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 sandy glacial outwash aquifers, such as in the watershed to the Quissett Harbor embayment system, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since even Cape Cod "rivers" 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 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 Quissett Harbor estuary follow this general pattern, where the primary nutrient of eutrophication in this system is nitrogen.

Nutrient related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters of southeastern Massachusetts. 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 Quissett Harbor as monitored by the Coalition for Buzzards Bay BayWatchers Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to “refine” general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Even while the Quissett Harbor embayment system currently supports relatively healthy habitat, it does appear to be approaching its ability to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated in the inner portions of the system, but the system is presently supports unimpaired animal habitat. Similarly, eelgrass beds within the outer harbor basin have been stable for many decades, although small areas that have persisted at the margins of the inner basin are declining. Together these habitat indicators indicate a presently unimpaired system, but one near its threshold (i.e. reaching its assimilative capacity). The result is that nitrogen management of this system is aimed at maintenance of existing conditions through the management of potential increases in watershed nitrogen loading.

I.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” for water quality modeling of the Quissett Harbor 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 Quissett Harbor System and the component basins of the system: the outer portion of the Quissett Harbor system and the more inner portion of the harbor which is demarcated by a small sand shoal. 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 in the estuarine receiving water.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model for the system 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 USGS using a modification of the West Cape model for sub-watershed areas designated by MEP. Virtually all nitrogen entering Falmouth’s embayment systems 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 as well as within Quissett Harbor were taken from the Coalition for Buzzards Bay BayWatchers Monitoring Program and from sampling of the Quissett Harbor system by MEP staff during MEP related data collection activities. Measurements of nitrogen and salinity distributions throughout the estuarine waters of the system were used to calibrate and validate the water quality models (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 Quissett Harbor Estuarine System for the Town of Falmouth. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission 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 (typically conducted by municipalities but in this case completed by CBB) as discussed in Section VI. 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 Town in developing a variety of alternative nitrogen management options for Quissett Harbor. Finally, any additional analyses of the system relative to potential alterations of circulation and flushing (for instance as would be considered for the removal of the sand shoal in the middle of the harbor), is presented in Section IX.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

In most marine and estuarine systems, such as the Quissett Harbor Embayment System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. As a result, there has been significant effort to develop tools for predicting how modification of watershed nitrogen loads and changes in tidal flushing quantitatively cause changes in the concentrations of water column nitrogen in the receiving estuary. Further development of these approaches 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. In contrast, some approaches can be tailored for each individual estuary of interest, but require large amounts of site-specific information and therefore are not generally applied. The present Massachusetts Estuaries Project (MEP) effort uses one such site-specific approach. The assessment 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 within individual estuaries. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process to the specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Quissett Harbor System. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of “data mining” and to gather additional information on an estuary’s habitat quality and unique features.

In the case of Quissett Harbor, there have been a few studies relating to environmental functioning and habitat health conducted over the past three decades that have been used to inform the MEP habitat assessment and threshold development process. Among these are several that directly support the present Massachusetts Estuaries Project effort to develop a nitrogen threshold for Quissett Harbor. The pertinent historical work is described briefly below.

While there has not been a detailed history of Quissett Harbor, the Quissett Harbor Preservation Trust has compiled a useful overview (www.qhpt.org). It appears that based on the 1790 U.S. census, the Quissett Harbor watershed had only 10 families totaling 68 individuals, while today there are almost 150 developed properties within the watershed. However, compared to most other watersheds on Cape Cod, the increase is relatively modest and helps to explain the persistence of only modest nitrogen enrichment of the Harbor waters. While presently human activities within the watershed are primarily related to residential uses, there remains some marine based enterprise. However, in the 1800's there were, at various times, 2 salt works and a shipbuilding company. With the coming of the railroad to Woods Hole in 1872, Quissett began to have a significant seasonal cycle of population increase in the warmer summer months, which led to a hotel later called the Quissett Harbor House and an increasing number of "summer homes". Although the Quissett Harbor House closed its doors finally in 1975, the importance of residential development to support both summer and year-around population has continued to this day.

Quissett Harbor Nutrient Related Water Quality Monitoring: The MEP analysis requires high quality water quality data in order to complete its assessment and modeling approach. The Coalition for Buzzards Bay's Water Quality Monitoring Program has been collecting data on nutrient related water quality throughout Buzzards Bay estuaries inclusive of Quissett Harbor, Wild Harbor, outer Megansett Harbor, Fiddlers Cove and Rands Harbor for more than a decade. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary to support ecological management of each of Buzzards Bay's embayments and harbors. The BayWatchers is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD until 2008. The program has a USEPA and MassDEP approved Quality Assurance Project Plan (QAPP), which was operational over the entire period of 1999-2009 (data period for this MEP analysis).

The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay to support evaluations of observed water quality and habitat health. The BayWatcher Water Quality Monitoring Program in the Quissett Harbor Embayment Systems developed a data set that elucidated the long-term water quality of this system (Figure II-1). The monitoring undertaken was a collaborative effort with CBB (Mr. Tony Williams) coordinating the field effort and chemical assays being completed by the SMAST Coastal Systems Analytical Facility. The Coastal Systems Analytical Facility is located in the School for Marine Science and Technology UMASS-Dartmouth, 706 S. Rodney French Blvd, New Bedford, MA, and the laboratory Points of Contact are Sara Sampieri 508-910-6325 (ssampieri@umassd.edu) or Mike Bartlett (mbartlett@umassd.edu). Use of the SMAST Analytical Facility ensured sufficient sensitivity and accuracy of the analytical protocols and that proper QA/QC procedures were followed to allow incorporation of the data into the MEP analysis. Baseline water quality data are a prerequisite to entry into the MEP. Implementation of the MEP's Linked Watershed-Embayment Approach necessarily incorporates the quantitative water column nitrogen data (1999-2009) gathered by the Monitoring Program and watershed and embayment data collected by MEP staff.

Figure II-1. Coalition for Buzzards Bay Water Quality Monitoring Program for Quissett Harbor. Estuarine water quality monitoring stations sampled by the Coalition and analyzed by SMAST staff during summers 1999 to 2008 (QH-1 and QH-2 only) and 2009 (all stations).

The results of the long term Water Quality Monitoring Program (1999-2009) and initial habitat assessments suggested that portions of the Quissett Harbor System are presently at the limit of their ability to assimilate nitrogen without significant declines in habitat quality. As a result, the Town of Falmouth undertook participation in the Massachusetts Estuaries Project to complete ecological assessment, nitrogen source identification and water quality modeling. The purpose of this effort being to quantitatively assess existing habitat quality of the Harbor basins and to develop nutrient thresholds to guide the Town's estuarine management planning relative to the Quissett Harbor System.

Regulatory Assessments of Quissett Harbor Resources - In addition to the limited locally generated studies of Quissett Harbor, the Commonwealth has conducted multiple environmental surveys to support regulatory needs. The Quissett Harbor System contains a variety of natural resources of value to the citizens of Falmouth as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP gathers the relevant available information on these resources as part of its assessment, and presents some of them here for general reference by those providing stewardship for this estuary, along with some more specific surveys in Section VII, which relate to the nitrogen thresholds analysis. For the Quissett Harbor Estuary this includes:

- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas – MassDMF (Figure II-3)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-4)

The MEP effort builds upon earlier watershed delineation and land-use analyses, the hydrodynamic modeling, historical eelgrass surveys and water quality surveys discussed above. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Quissett Harbor embayment. The MEP has incorporated appropriate and available data from pertinent previous studies to enhance the determination of nitrogen thresholds for the Quissett Harbor System and to reduce costs to the Town of Falmouth.

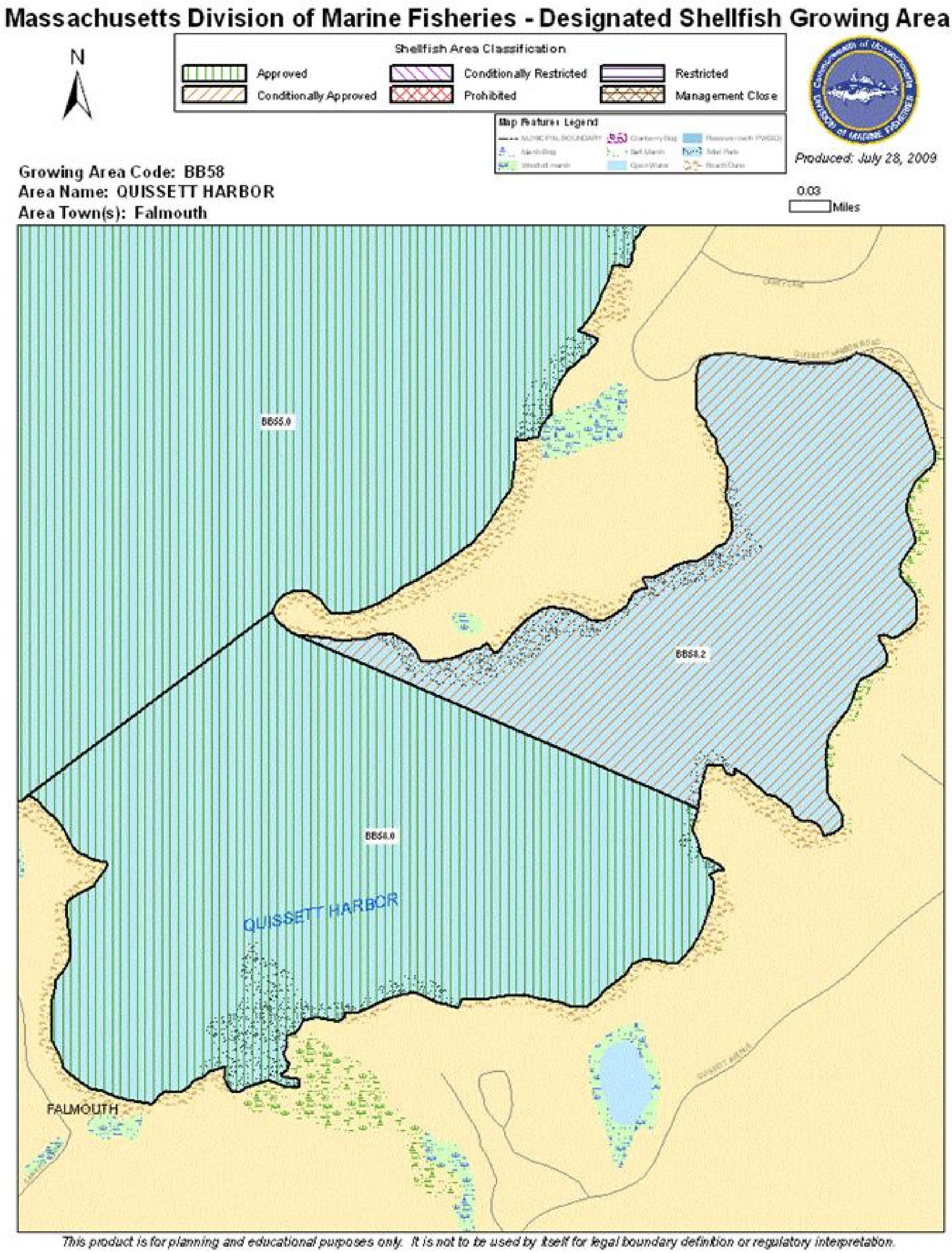

Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. Quissett Harbor supports significant mooring areas in both inner and outer basins in summer.

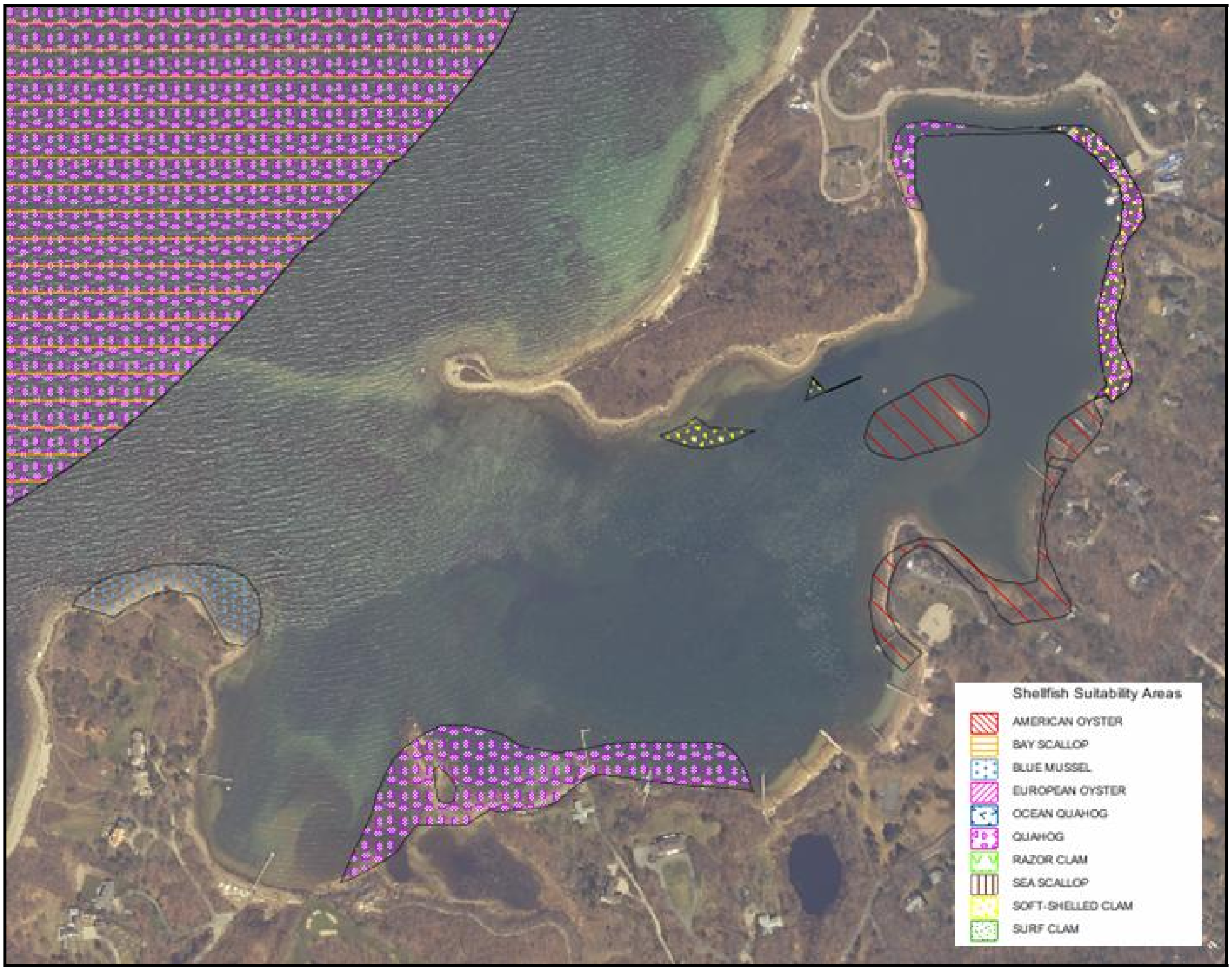

Figure II-3. Location of shellfish suitability areas within the Quissett Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that a species of shellfish is present.

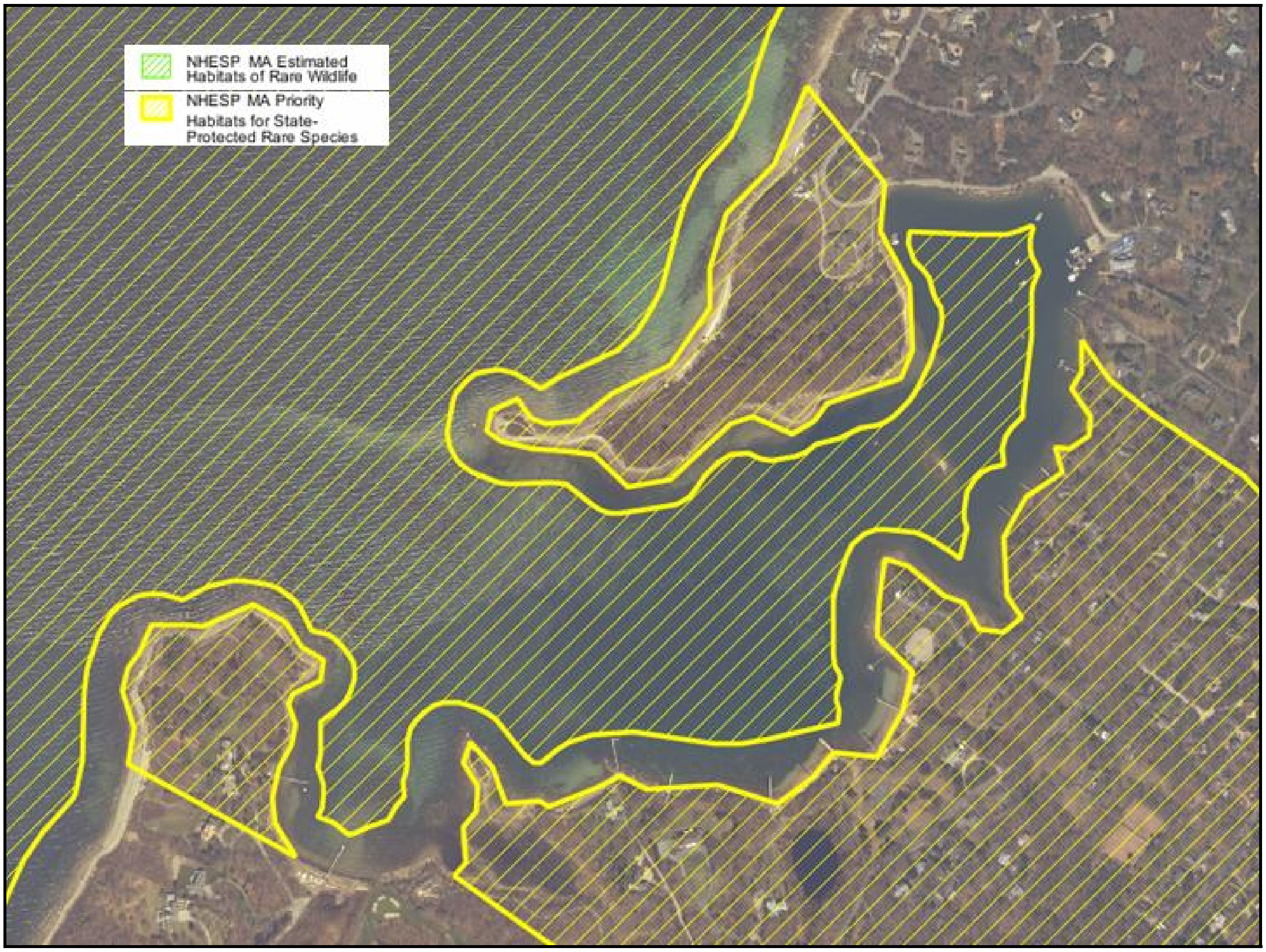

Figure II-4. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Quissett Harbor Estuary as determined by - NHESP.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). The USGS groundwater modelers were central to the development of the groundwater modeling approach used by the Estuaries Project. The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the groundwater models. The MODFLOW and MODPATH models utilized by the USGS organize and analyze the available data using up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation. These questions include surface water/groundwater interactions, groundwater travel times, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including the Quissett Harbor embayment system. The Quissett Harbor watershed is located entirely within the Town of Falmouth, Massachusetts.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Quissett Harbor embayment system under evaluation by the Project Team. The Quissett Harbor estuarine system is a relatively simple estuary with a wide inlet connection to Buzzards Bay. The watershed is located within the Sagamore groundwater flow cell. Watershed modeling was undertaken to sub-divide the overall watershed to the Quissett Harbor system into functional sub-units based upon defining inputs from contributing areas to each major portion within the embayment system. Typical MEP watershed delineations include delineating contributing areas to major freshwater aquatic systems which attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands) and defining the land areas with groundwater travel times that are greater and less than 10 years time-of-travel to the estuary. These travel distributions within each sub-watershed are used as a procedural check to gauge the potential mass of nitrogen from “new” development, which has not yet reached the receiving estuarine waters at the time of the MEP analysis. No contributing areas to freshwater ponds were delineated in the Quissett Harbor watershed and all groundwater in the Quissett Harbor watershed reaches the estuary within 10 years.

The relatively transmissive sand and gravel deposits that comprise most of Cape Cod create a hydrologic environment where watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow, and direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that they carry requires determination of the portion of the watershed that contributes directly to a stream and the portion of the groundwater system that discharges directly into an estuary as groundwater seepage. While this is the case in most of the estuaries in the MEP study region, in the case of Quissett Harbor, the analysis of freshwater inflow to the estuarine receiving water was based primarily on the role of the groundwater aquifer as there are no significant streams flowing into the harbor.

III.2 MODEL DESCRIPTION

The contributing areas to the Quissett Harbor system is divided into two sub-watersheds: Inner and Main. These areas were delineated using the regional model of the Sagamore Lens flow cells (Walter and Whealan, 2005). Quissett Harbor is located on the western boundary of the Sagamore Lens. The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to the Quissett Harbor sub-watersheds.

The Sagamore Flow Model grid consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 519 feet below NGVD 29 in the Sagamore Lens); since bedrock is 150 to 200 feet below NGVD 29 in the Quissett Harbor area the lowest model layer was inactive in this area of the model with variable thickness in the layer directly above. The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, was used to simulate the top of the water table, which varies in elevation depending on the location within the lens.

The glacial sediments that comprise the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The Quissett Harbor system watershed is located in the Buzzards Bay Moraine, which is thought to have material deposited in place by melting ice in a low energy depositional environment at the edge of the ice lobe (Walter and Whealan, 2005). Modeling and field measurements of contaminant transport at the Massachusetts Military Reservation have shown that similar materials are permeable (*e.g.*, Masterson, *et al.*, 1996) with lower hydraulic conductivity than the outwash plains that comprise most of the Cape. This distinction does not tend to impact groundwater flow direction and direct rainwater run-off is typically rather low as with most of the Cape. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters in the groundwater models were determined through calibration to observed water levels and stream flows where extant. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and stream flow data collected in 1989-1990 as well as 2003.

The Sagamore Lens groundwater model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. This recharge rate is based on the most recent USGS information. Large withdrawals of groundwater from pumping wells may have a significant influence on water tables and watershed boundaries and therefore the flow and distribution of nitrogen within the aquifer. After accounting for the consumptive loss, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within residential areas designated as using on-site septic systems.

III.3 QUISSETT HARBOR CONTRIBUTORY AREAS

The refined watershed and sub-watershed boundaries for the Quissett Harbor embayment (Figure III-1) were determined by the United States Geological Survey (USGS). Model outputs of the watershed boundaries were "smoothed" to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the coastal shoreline, (c) to include water table data in the lower regions of the watersheds near the coast (as available), and (d) to more closely match the sub-embayment segmentation of the tidal hydrodynamic mode. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team. Overall, two sub-watershed areas were delineated within the Quissett Harbor study area.

Table III-1 provides the daily freshwater discharge volumes for the two sub-watersheds as calculated from the groundwater model; these volumes were used in the salinity calibration of the tidal hydrodynamic models. The overall estimated freshwater flow into the Quissett Harbor system from the MEP delineated watershed is 2,380 m3/d. If annual average precipitation on the Harbor surface is included, the overall freshwater discharge to the Harbor is 3,212 m3/d.

The MEP watershed delineation is the second watershed delineation completed in recent years for the Quissett Harbor System. Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission as part of the Coastal Embayment Project (Eichner, *et al*., 1998). The CCC delineation was based on regional water table measurements collected from available well data over a number of years and normalized to average conditions. The Commission's delineation was incorporated into the Commission's regulations through the three versions of the Regional Policy Plan (CCC, 1996, 2001, and 2009).

The MEP watershed area for the Quissett Harbor system as a whole is 49% smaller (205 acres difference) than the 1998 CCC delineation. The majority of the difference is largely attributable to a shift in the location of the regional groundwater divide between Buzzards Bay and Vineyard Sound and the groundwater flow paths off the divide. The CCC watershed had the divide located closer to Oyster Pond, which made the watershed area significantly bigger. The MEP watershed delineation also includes delineation to the two sub-basins of the Quissett Harbor system, which were not included in the CCC delineation. These refinements are another benefit of the update of the regional groundwater model (Walter and Whealan, 2005).

The evolution of the watershed delineations for the Quissett Harbor system has allowed increasing accuracy as each new version adds new hydrologic data to that previously collected; the model allows all this data to be organized and to be brought into congruence with adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used 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 down gradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the significant aquatic systems as extant in the overall watershed and ultimately to the estuarine waters of the Quissett Harbor system (Section V.1).

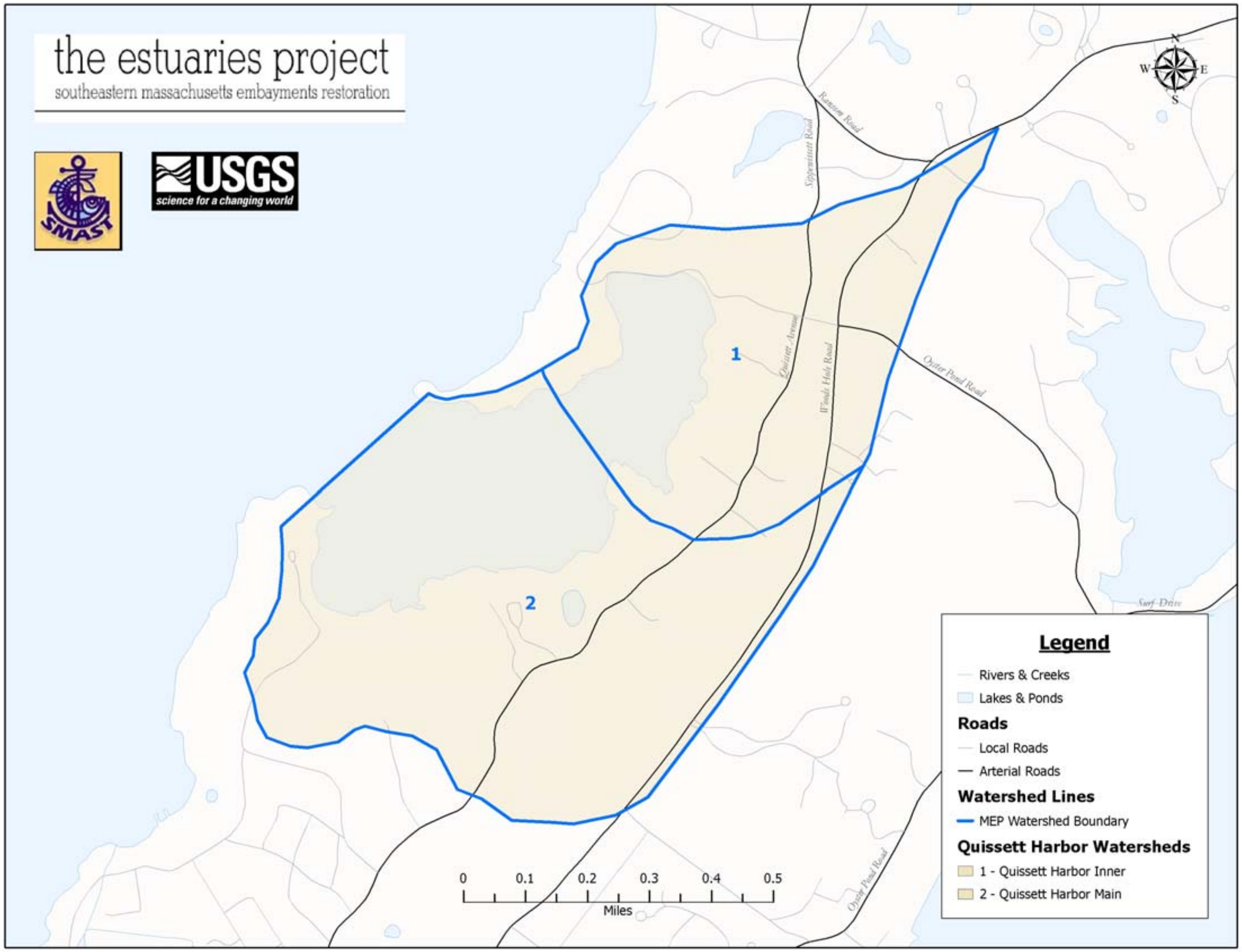

Figure III-1. Watershed delineation for the Quissett Harbor System used in the MEP analysis. Sub-watershed delineations are based on USGS groundwater model output (Walter and Whealan, 2005) with modifications to better match the shoreline. All groundwater reaches the Harbor within a ten-year time-of-travel. Sub-watersheds are selected based upon the functional estuarine sub-units (Harbor sub-basins) in the water quality model (see Section VI).

Table III-1. Daily groundwater discharge to each of the sub-watersheds in the watershed to the Quissett Harbor system estuary, as determined from the USGS groundwater model.

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge	
				m^3/day	ft^3/day
Quissett Harbor Inner	1	126	100	964	34,041
Quissett Harbor Main	2	185	100	1,417	50,024
TOTAL QUISSETT HARBOR SYSTEM				2,380	84,065

Note: discharge volumes are based on 27.25 in of annual recharge.

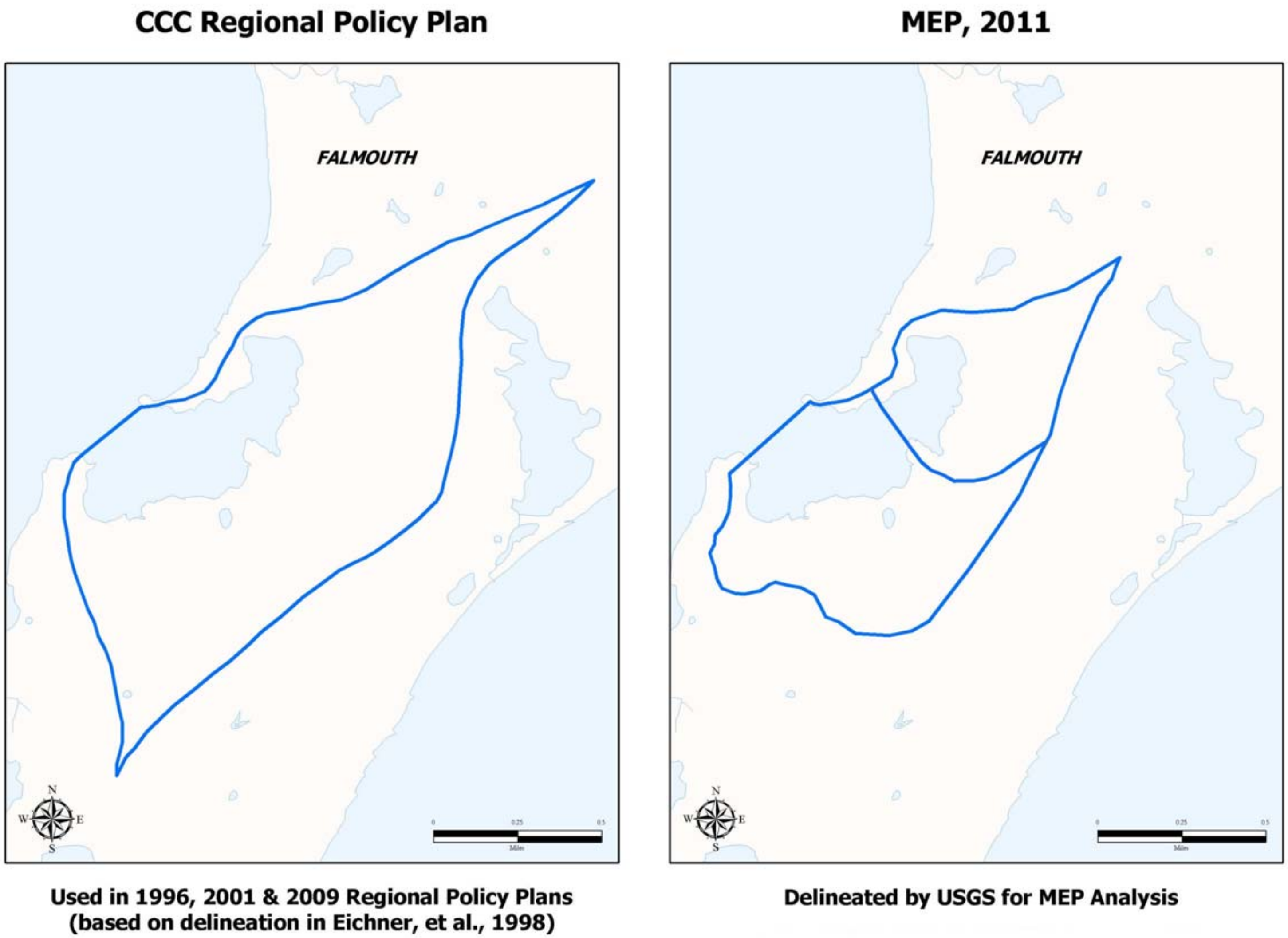

Figure III-2. Comparison of Quissett Harbor MEP watershed and sub-watershed delineations used in the current analysis and the Cape Cod Commission watershed delineation (Eichner, *et al*., 1998), which has been used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, 2009). The primary cause for the difference is incorporation of new information on the location of the groundwater divide.

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 Quissett Harbor estuary system. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes 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 in the sediments is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom. Failure to include the nitrogen balance of estuarine sediments 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 Quissett Harbor estuary system, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component of the estuary and its associated watersheds (Section III). The Quissett Harbor watershed was sub-divided to define contributing areas or sub-watersheds to each major portion of the estuary. A total of two sub-watersheds were delineated in the overall Quissett Harbor watershed. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to each portion of the estuary (see Chapter III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This involves a temporal review of land use changes, the time of groundwater travel provided by the USGS watershed model, and review of data at natural collections points, such as streams and ponds. Evaluation and delineation of ten-year time of travel zones are a regular part of the watershed analysis. All watershed areas in the Quissett Harbor watershed are within the less than 10 year travel time contour for the estuary (Table IV-1). Average year-built in the Town of Falmouth Assessor's records for single family residences in sub-watershed 1 and sub-watershed 2 are 1939 and 1934, respectively; this indicates that the predominant land use in the watershed has existed for more than 10 years. The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuary. Overall and based on the review of all this information, it was determined that the Quissett Harbor estuary is currently in balance with its watershed load.

Table IV-1. Percentage of unattenuated nitrogen loads in less than ten year time-of-travel sub-watersheds to Quissett Harbor.

WATERSHED	Shed #	LT10	GT10	TOTAL	%LT10
Name		kg/yr	kg/yr	kg/yr	
Quissett Harbor Inner	1	849	0	849	100%
Quissett Harbor Main	2	870	0	870	100%
Quissett Harbor Whole System		1,718	0	1,718	100%

Note: Loads include atmospheric loading on the estuary surface waters.

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data are used for some portion of the loads, while information developed from other detailed site-specific studies is applied to other portions. 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 regional analyses. For the Quissett Harbor estuary system, the model used land-use data from the Town of Falmouth transformed into nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel-by-parcel water use and golf course fertilizer applications). Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the "potential" or unattenuated nitrogen load to each receiving embayment, since attenuation during transport is included at a later stage as appropriate.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Quissett Harbor watershed is not substantial. Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present effort, no freshwater ponds have delineated sub-watersheds within the Quissett Harbor watershed and there are no significant streams. If smaller aquatic features that have not been included in this MEP analysis were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources within the watershed.

Based upon the evaluation of the watershed systems, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the sub-watersheds that directly discharge groundwater to the estuary. Internal nitrogen recycling was also determined throughout the tidal reaches of the Quissett Harbor Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Since the watershed to Quissett Harbor is completely contained within the Town of Falmouth, Estuaries Project staff obtained digital parcel and tax assessor's data directly from the town to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data from the Town of Falmouth are from 2009. These land use databases contain traditional information regarding land use classifications (MassDOR, 2009) plus additional information developed by the town. This effort was completed with the assistance from GIS staff from the Cape Cod Commission (CCC).

Figure IV-1 shows the land uses within the Quissett Harbor estuary watershed. Land uses in the study area are grouped into six land use categories: 1) residential, 2) commercial, 3) multi-use, 4) golf course, 5) undeveloped (including residential open space), and 6) public service/government, including road rights-of-way unclassified properties. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2009). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

Residential land uses are the dominant land use type in the overall Quissett Harbor watershed and occupy 51% of the watershed area (Figure IV-2). Examples of these land uses in this watershed are single family residences and two- and three-family residences. Undeveloped land uses occupy the second largest area with 20% of the watershed area. Undeveloped lands include properties classified by the Town Assessor as developable, as well as protected open space associated with residential development. These breakdowns are generally sustained in the sub-watershed areas, although residential development rises to 69% and public service lands are second largest area (19%) of the Inner Harbor sub-watershed.

In all the sub-watershed groupings shown in Figure IV-2, residential parcels are the dominant parcel type. In the Inner Harbor sub-watershed, residential parcels are 81% of all parcels, while in the Main Harbor sub-watershed, they are 69% of all parcels. Overall, they are 76% of all parcels in the Quissett Harbor system watershed. Single-family residences (MassDOR land use code 101) are the dominant type of residential parcel; these represent 87% of the residential parcels throughout the Quissett Harbor system watershed.

In order to estimate wastewater flows within the Quissett Harbor study area, MEP staff also obtained parcel-by-parcel water use data from the Town of Falmouth. Three years of water use information (2008 through 2010) was obtained from the Town of Falmouth, GIS Department (Bob Shea, GIS Coordinator, 11/10). The water use data were linked to the town assessor and parcel databases by the CCC GIS Department staff. Measured water use is used to estimate wastewater-based nitrogen loading from the individual parcels; average water use for each parcel is used for parcels with multiple years of data. The final wastewater nitrogen load for each parcel is based upon the measured water-use, wastewater nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2). All developed parcels within the watershed were assumed to use on-site septic systems; none of the parcels are connected to the town municipal sewer system based on town-provided sewer connections and service areas.

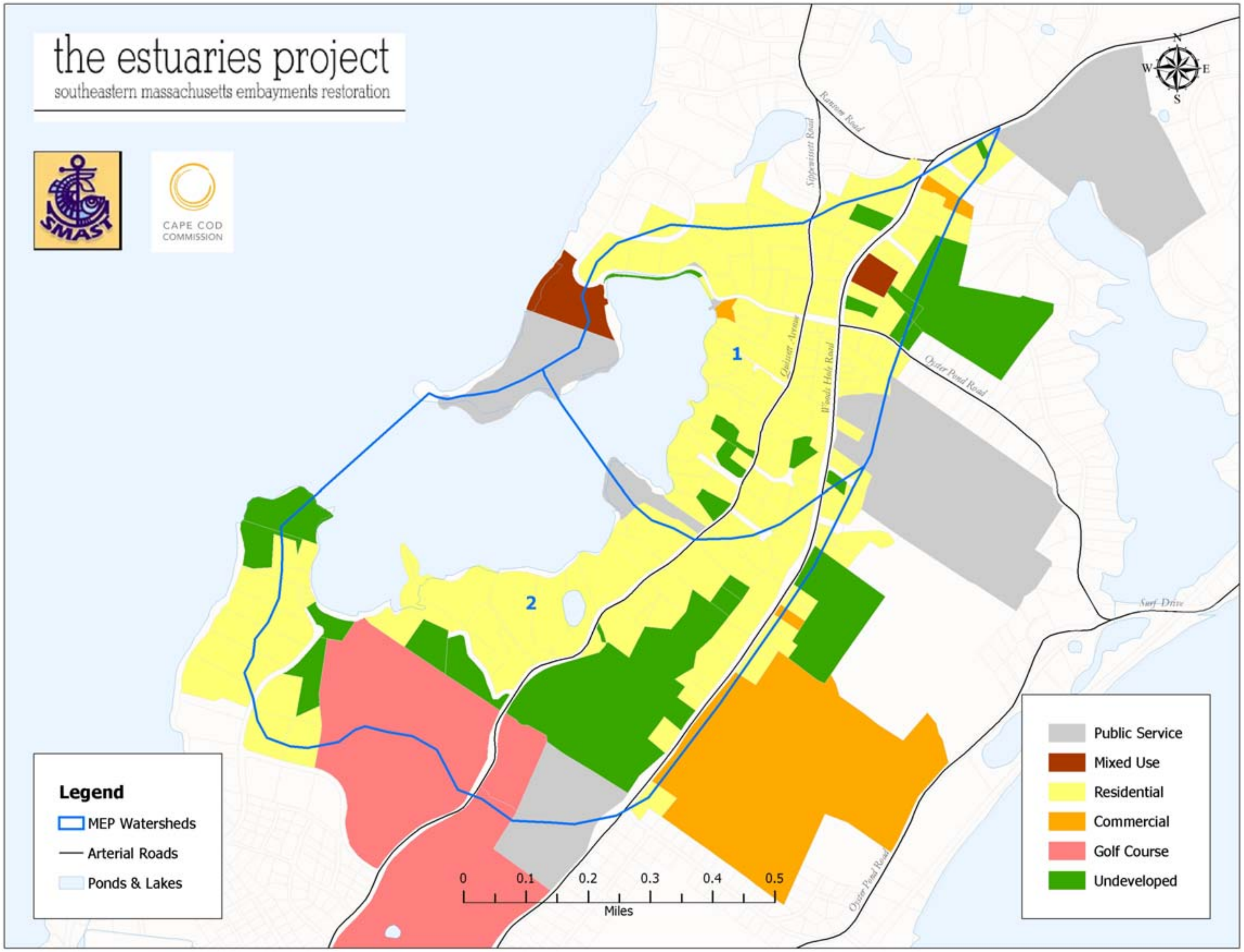

Figure IV-1. Land-use in the Quissett Harbor system watershed and sub-watersheds. The watershed is completely contained within the Town of Falmouth. Land use classifications are based on town assessor classifications and MADOR (2009) categories. Base assessor and parcel data are from the Town of Falmouth and are from the year 2009.

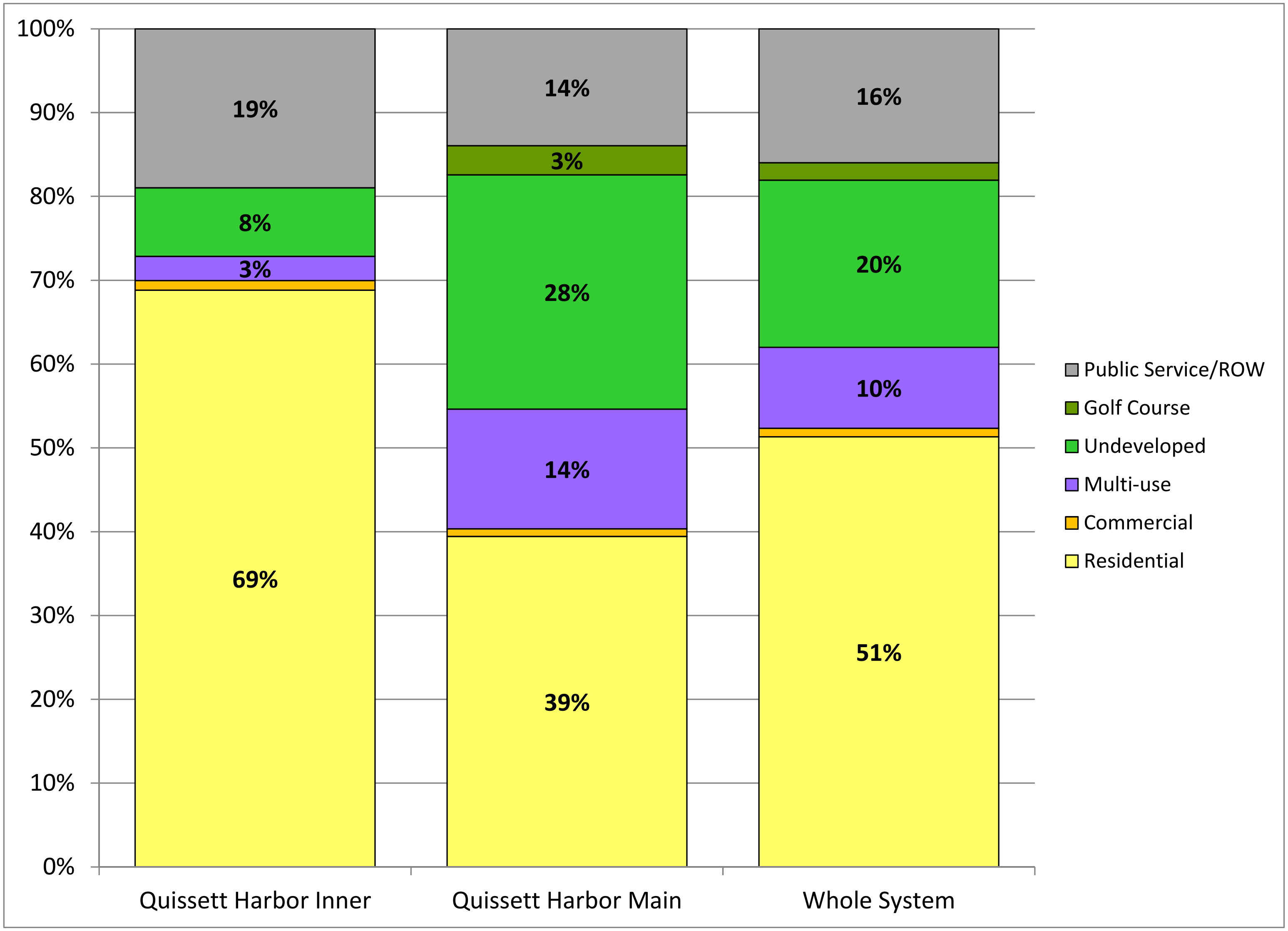

Figure IV-2. Distribution of land-uses by area within the Quissett Harbor system watershed and two component sub-watersheds. Land use categories are generally based on town assessor's land use classification and grouping recommended by MADOR (2009). Only percentages greater than or equal to 3% are shown.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP 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 are linked to assessor's parcel information using GIS techniques. The parcel specific water use data are 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 that reaches the aquatic receptors down gradient in the aquifer.

All nitrogen losses within the septic system are incorporated into the MEP analysis. For example, information developed at the MassDEP Alternative Septic System Test Center at the Massachusetts Military Reservation on Title 5 septic systems 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). Down gradient studies of septic system plumes in similar soils 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, MEP staff 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, MEP staff has derived a combined term for an effective N Loading Coefficient (consumptive use multiplied by 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 sub-watershed 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 have limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, which covers large areas and have significant year-round populations, the septic nitrogen loading based upon the census data are 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 soils and 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 connected to other MEP Nitrogen Loading Coefficients (e.g., stormwater, lawn fertilization); (c) the MEP septic nitrogen loading coefficient agrees with 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 the 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 for septic systems 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).

In order to provide an independent validation of the average residential water use within the Quissett Harbor watersheds, MEP staff reviewed US Census population values for the Towns of Falmouth and wastewater flows in state regulations. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. Average water use for single-family residences with municipal water accounts in the Quissett Harbor MEP study area is 200 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the estimated study area wastewater flow average is 180 gpd.

In order to provide a check on this wastewater estimate, Falmouth 2010 Census information was reviewed. Based on data collected during the 2010 US Census, average occupancy within Falmouth is 2.24 people per housing unit with 64% year-round occupancy of available housing units. Multiplying this occupancy by the state Title 5 estimate of 55 gpd of wastewater per capita results in an average estimated water use per residence in Falmouth of 123 gpd. Estimates of summer populations on Cape Cod derived from a number of approaches (*e.g.*, traffic counts, garbage generation, WWTF flows) suggest average population increases from two to three times year-round residential populations measured by the US Census. If it is assumed that seasonal properties are occupied at three times the year-round occupancy for three months in Falmouth, the estimated average town-wide water use would be 185 gpd. Since this is reasonably close (<10%) to the measured water use in the Quissett Harbor watershed, this analysis suggests that the average water use is reasonably reflective of average wastewater estimates.

At the outset of the MEP, project staff decided to utilize the water use approach for determining residential wastewater generation by septic systems because of the inherent difficulty in accurately gauging actual occupancy in areas impacted by seasonal population fluctuations such as most of Cape Cod. The above analysis suggests that water use, on average, is a reasonable estimate of wastewater generation within the study area.

Water use information exists for 95% of the 141 developed parcels in the Quissett Harbor watershed. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs, and do not have a listed account in the water use databases. Of the seven developed parcels without water use accounts, five (71%) are classified as single-family residences (land use code 101). The other two parcels are other forms of residential properties. All these parcels are assumed to utilize private wells and are assigned the Quissett Harbor study area average water use of 200 gpd in the watershed nitrogen loading modules. None of the parcels are connected to the Town of Falmouth sewer system.

Alternative Septic Systems

There are two alternative, denitrifying septic systems in the Quissett Harbor study area according to the Barnstable County Department of Health and the Environment database (personal communication, Brian Baumgaertel, 1/11). However, available performance monitoring data indicates only 1 and 3 total nitrogen measurements. Given the limited site-specific information, an annual nitrogen load was calculated for only the system with 3 measurements. The system (a RUCK system) at this property has total nitrogen concentrations readings collected in 2008, 2009, and 2010 of 5.7, 16.1 and 2.4 ppm, respectively, with an overall average of 8.1 ppm. Project staff used this site-specific average effluent total nitrogen concentration and the associated average measured water use from the town records to calculate an average annual load from this property. This load was incorporated into the watershed nitrogen loading module for the Quissett Harbor.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of watershed nitrogen loading to estuaries is usually fertilized areas: lawns, golf courses, and cranberry bogs. Residential lawns are usually the predominant source within this category. In order to add this source to the nitrogen loading model for the Quissett Harbor system, MEP staff reviewed available regional information about residential lawn fertilizing practices and incorporated site-specific information for the Woods Hole Golf Club.

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 in advance of the MEP, at the outset of the project the MEP Technical Staff undertook an assessment of lawn fertilizer application rates and a review of leaching rates for inclusion 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 nitrogen 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 is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should 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/yr.

In order to obtain a site-specific estimate of nitrogen loading from the Woods Hole Golf Club, MEP staff contacted Tom Flaherty, Woods Hole Golf Club, Grounds Supervisor, to obtain current (4/11) information about average fertilizer application rates. Golf courses usually have different fertilizer application rates for different turf areas, usually higher annual application rates for tees and greens (~3 to 4 pounds per 1,000 square feet) and lower rates for fairways and roughs (~2 to 3.5 pounds per 1,000 square feet). Mr. Flaherty submitted to the MEP Project Team the following annual nitrogen application rates (in pounds per 1,000 ft2) for the various turf areas: greens, 2.0; tees, 3.0; fairways, 2.0, and no fertilizer applications on rough areas.

As has been done in all MEP reviews, MEP staff reviewed the layout of the golf course from aerial photographs, and classified the various turf types. Only a portion of the Woods Hole Golf Club is located within the Quissett Harbor watershed; all of which is located within the Quissett Harbor Main sub-watershed. The golf course-specific nitrogen application rates were applied to the respective turf areas within this sub-watershed, a standard MEP 20% leaching rate was applied, and annual load from the golf course was calculated and included in the watershed nitrogen loading model.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas in the Quissett Harbor assessment are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the CCC's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and MassDEP's Nitrogen Loading Computer Model Guidance (1999) except where modified by local information. The recharge rate for natural areas and lawn areas is the same as utilized in the MEP-USGS groundwater modeling effort (Section III). Factors used in the MEP nitrogen loading analysis for the Quissett Harbor watershed are summarized in Table IV-2.

Road areas are based on Massachusetts Highway Department 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.

Building footprints are based on information supplied by the Town of Falmouth based on 2007 data. Where land use classification indicated that a residential parcel is developed and no footprint data were provided, project staff incorporated an average residential footprint area. Estimated non-residential footprints are based on average building coverage per lot area determined from town-wide data. MEP staff utilized the GIS to sum all building footprint areas by sub-watershed.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information is linked to the parcel coverages, parcels are assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel is located within a respective sub-watershed. Following the assigning of boundary parcels, all large parcels are examined individually and are split (as appropriate) in order to obtain less than a 2% difference between the total land area of each sub-watershed and the sum of the area of the parcels within each sub-watershed. The resulting "parcelized" watersheds to Quissett Harbor are shown in Figure IV-3.

The review of individual parcels straddling watershed boundaries includes 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.) is 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 Quissett Harbor estuary. The assignment effort is 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, all relevant nitrogen loading data are assigned to each sub-watershed. This step includes summarizing water use, parcel area, frequency, private wells, and road area. Individual sub-watershed information is then integrated to create the Quissett Harbor Watershed Nitrogen Loading module with summaries for each of the individual sub-watersheds. The sub-watersheds are generally paired with functional embayment/estuary units for the Linked Watershed-Embayment Model's water quality component.

Table IV-2. Primary Nitrogen Loading Factors used in the Quissett Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Town of Falmouth or Quissett Harbor watershed-specific data.

Nitrogen Concentrations:	**mg/l**	**Recharge Rates:**	**in/yr**
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Natural Area Recharge	0.072	**Water Use/Wastewater:**	
Direct Precipitation on Embayments and Ponds	1.09	Existing developed single-family residential parcels wo/water accounts and buildout single-family residential parcels:	200 gpd[1]
Wastewater Coefficient	23.63		
Fertilizers:		Existing developed parcels w/water accounts:	Measured annual water use
Average Residential Lawn Size (sq ft)[2]	5,000	Commercial and Industrial Buildings without/WU and buildout additions[3]	
Residential Watershed Nitrogen Rate (lbs/lawn)[2]	1.08	Commercial	
Woods Hole Golf Club[4] (N application, lbs/1,000 sq ft/yr)		Wastewater flow (gpd/1,000 ft2 of building):	180
Greens	2	Building coverage:	15%
Tees	3	Industrial	
Fairways	2	Wastewater flow (gpd/1,000 ft2 of building):	44
Roughs	0	Building coverage:	5%
		Average Single Family Residence Building Size (sq ft)[5]	1,905

Notes:
1) Based on average flow of all single-family residences in the watershed
2) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
3) based on existing water use and water use for similarly classified properties throughout the Town of Falmouth (2008 to 2010 water use data)
4) Application rate information from Tom Flaherty, Woods Hole Golf Club, Grounds Supervisor (4/4/11)
5) Based on Quissett Harbor watershed information supplied by Town of Falmouth

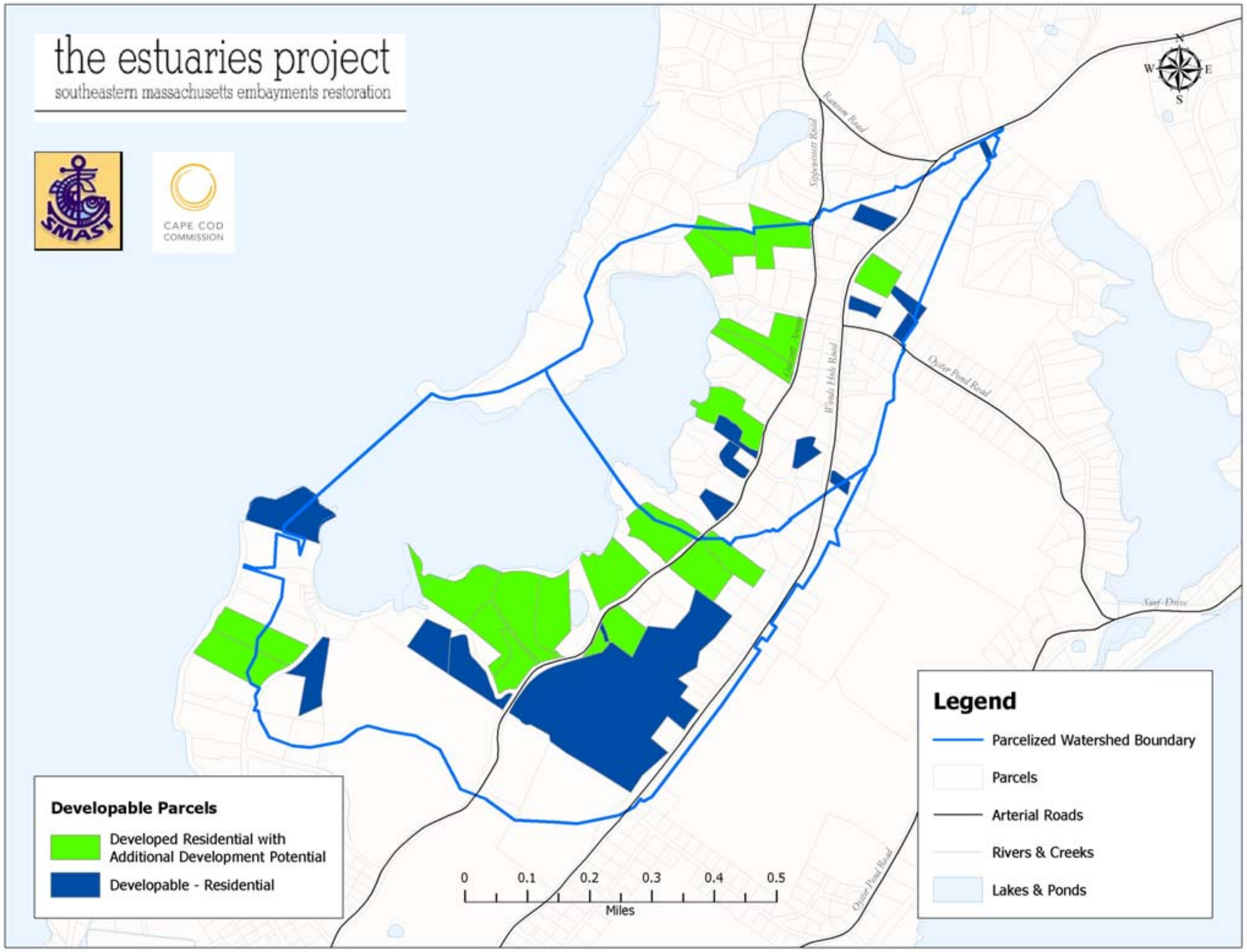

Figure IV-3. Parcels, Parcelized Watersheds, and Developable Parcels in the Quissett Harbor watersheds. Parcels colored green are developed residential parcels with additional development potential based on current zoning, while parcel colored blue are corresponding undeveloped parcels classified as developable by the town assessor. The parcelized watersheds are drawn to minimize the division of properties for management purposes while achieving a match of area with the modeled watersheds of 2% or less. Developable parcels are based on town assessor classifications and minimum lot sizes specified in town zoning; these parcels are assigned estimated nitrogen loads in MEP buildout calculations. All buildout results were reviewed with town staff (Brian Currie, 4/11/11).

For management purposes, the aggregated estuary watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Quissett Harbor study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), fertilizers (including contributions from the golf course), impervious surfaces (*e.g.*, roads), direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-3). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the overall estuary watershed by each source category (Figure IV-4). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model. Since there are no stream or pond sub-watersheds, there is no natural nitrogen attenuation included in the Quissett Harbor watershed nitrogen loading model.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development and accompanying nitrogen loads within the study area watersheds. The MEP buildout is relatively straightforward and is generally 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) parcels with existing development and 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 this buildout approach is relatively simple and does not include any modifications/refinements for lot line setbacks, wetlands, 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 40B affordable housing projects. The fourth step including the discussions with town planners, and, occasionally, town planning boards and wastewater consultants, often leads to additional insights on developments that are planned, especially developments planned on government or public service parcels, and updates to assessor classifications, including lands purchased by the town as open space. This final step may lead to removal and/or additions to the number of parcels initially identified as developable and application of more detailed zoning provisions.

As an example of how the MEP approach might apply, assume an 81,000 square foot lot is classified by the town assessor as a developable residential lot (land use code 130). This lot is divided by the 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.

Table IV-3. Quissett Harbor Watershed Nitrogen Loads. Existing and buildout nitrogen loads are shown. Components of the existing nitrogen loads are shown (*e.g.*, wastewater, fertilizers, etc.). The buildout loads are aggregates of all these components. No natural attenuation of loads is included because no freshwater ponds or streams are included in the watershed model. All nitrogen loads are kg N yr^{-1}.

		Quissett Harbor N Loads by Input (kg/y):							**Present N Loads**			**Buildout N Loads**		
Watershed Name	**Watershed ID#**	**Wastewater**	**Non-Golf Course Fertilizers**	**Golf Course Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Quissett Harbor System		988	67	32	94	485	53	499	1,718		1,718	2,218		2,218
Quissett Harbor Inner	1	578	45	-	56	-	21	123	701	-	701	824	-	824
Quissett Harbor Main	2	410	22	32	38	-	32	376	532	-	532	909	-	909
Quissett Inner Estuary Surface						148			148	-	148	148	-	148
Quissett Main Estuary Surface						338			338	-	338	338	-	338

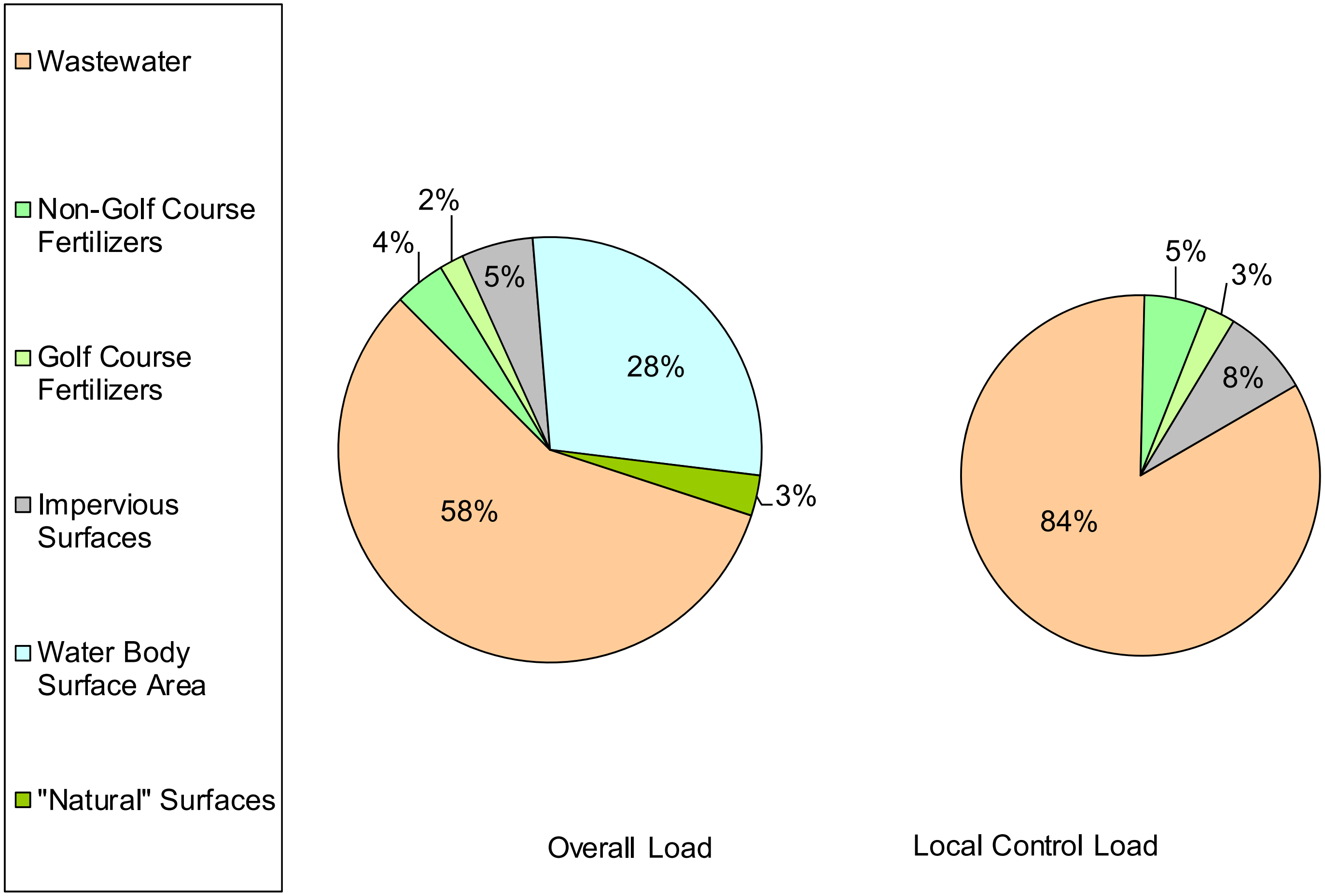

Figure IV-4. Land use-specific unattenuated nitrogen loads (by percent) to the whole Quissett Harbor watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents only those nitrogen sources that could potentially be under local regulatory control.

Other provisions of the MEP buildout assessment include undevelopable lots, commercial and industrial properties, and lots less than the minimum areas specified by zoning. Properties classified by the Town of Falmouth Assessor as “undevelopable” (*e.g*., MassDOR codes 132, 392, and 442) are not assigned any development at buildout; this may be modified when town staff reviews the initial results. Commercial and industrial properties classified as developable are not subdivided; the area of each parcel and the factors in Table IV-2 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 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. 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.

Following the completion of the initial buildout assessment for the Quissett Harbor watersheds, MEP staff reviewed the results with town officials. MEP staff reviewed the initial buildout results with Brian Currie of the Town of Falmouth Planning Department in April 2011. Suggested changes were incorporated into the final buildout for Quissett Harbor.

All the parcels with additional buildout potential within the Quissett Harbor watershed are shown in Figure IV-3. Each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces. Residential additions also include lawn fertilizer nitrogen additions. All wastewater loads are assumed to come from on-site septic systems. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-3. Buildout additions within the Quissett Harbor watersheds will increase the unattenuated loading rate by 29%.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out or sewering analysis) 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 watershed of the Quissett Harbor System 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 is exclusively through groundwater in sandy outwash aquifers as a result of the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. In the watershed to Quissett Harbor, unlike most watersheds in southeastern Massachusetts, nitrogen does not pass through a surface water ecosystem on its path to the adjacent embayment. Nitrogen transport through surface water systems, unlike aerobic aquifers, supports the conditions for nitrogen retention and denitrification. As there were no significant streams or great fresh ponds within the Quissett Harbor watershed, the watershed loading approach considered that nitrogen reaching the water table was transported without attenuation through the groundwater system until discharge to the estuary.

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 Quissett Harbor system. 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-Water column Exchange of Nitrogen

As stated in the above section, 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 Quissett Harbor system predominantly in highly bio-available forms from the surrounding upland watersheds 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 bio-available form nitrate. This nitrate and other bio-available forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton "particles". Most of these "particles" remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Buzzards Bay). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen "load" become incorporated into the surficial sediments of the embayments.

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 bio-available nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with deep depositional basins or 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 or Sesachacha Pond on the Island of Nantucket). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, for example in the margins of the main basin to Lewis Bay (Town of Barnstable, Cape Cod). In contrast, most embayments show low rates of nitrogen release throughout much of a basins area and, in regions of high deposition, typically support anoxic sediments with high release rates during summer months. The consequence of high deposition rates is that the basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

Failure to account for site-specific nitrogen balance of 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 Quissett Harbor 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-Water column Nitrogen Exchange

For the Quissett Harbor Embayment System, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. A total of 16 cores were collected from 15 sites (Figure IV-5) in July-August 2005, focusing on obtaining an aerial distribution that would be representative of nutrient fluxes throughout the system. Duplicate cores were taken at one site. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab established at the Quissett Harbor Boatyard. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The sampling locations and numbers of cores collected are listed below. The spatial distribution of the stations is presented in Figure IV-5.

Quissett Harbor System Benthic Nutrient Regeneration Cores

- QH-1 1 core (Inner Basin)
- QH-2 1 core (Inner Basin)
- QH-3 1 core (Inner Basin)
- QH-4 1 core (Inner Basin)
- QH-5 1 core (Inner Basin
- QH-6 1 core (Inner Basin)
- QH-7 1 core (Inner Basin)
- QH-8 1 core (Main Basin)
- QH-9 1 core (Main Basin)
- QH-10/11 1 core (Main Basin)
- QH-12 1 core (Main Basin)
- QH-13 1 core (Main Basin)
- QH-14 1 core (Main Basin)
- QH-15 1 core (Main Basin)
- QH-16 1 core (Main Basin)

Sampling was distributed throughout the system such that the results for each site could be combined to calculate the net nitrogen regeneration rates for the water quality modeling effort.

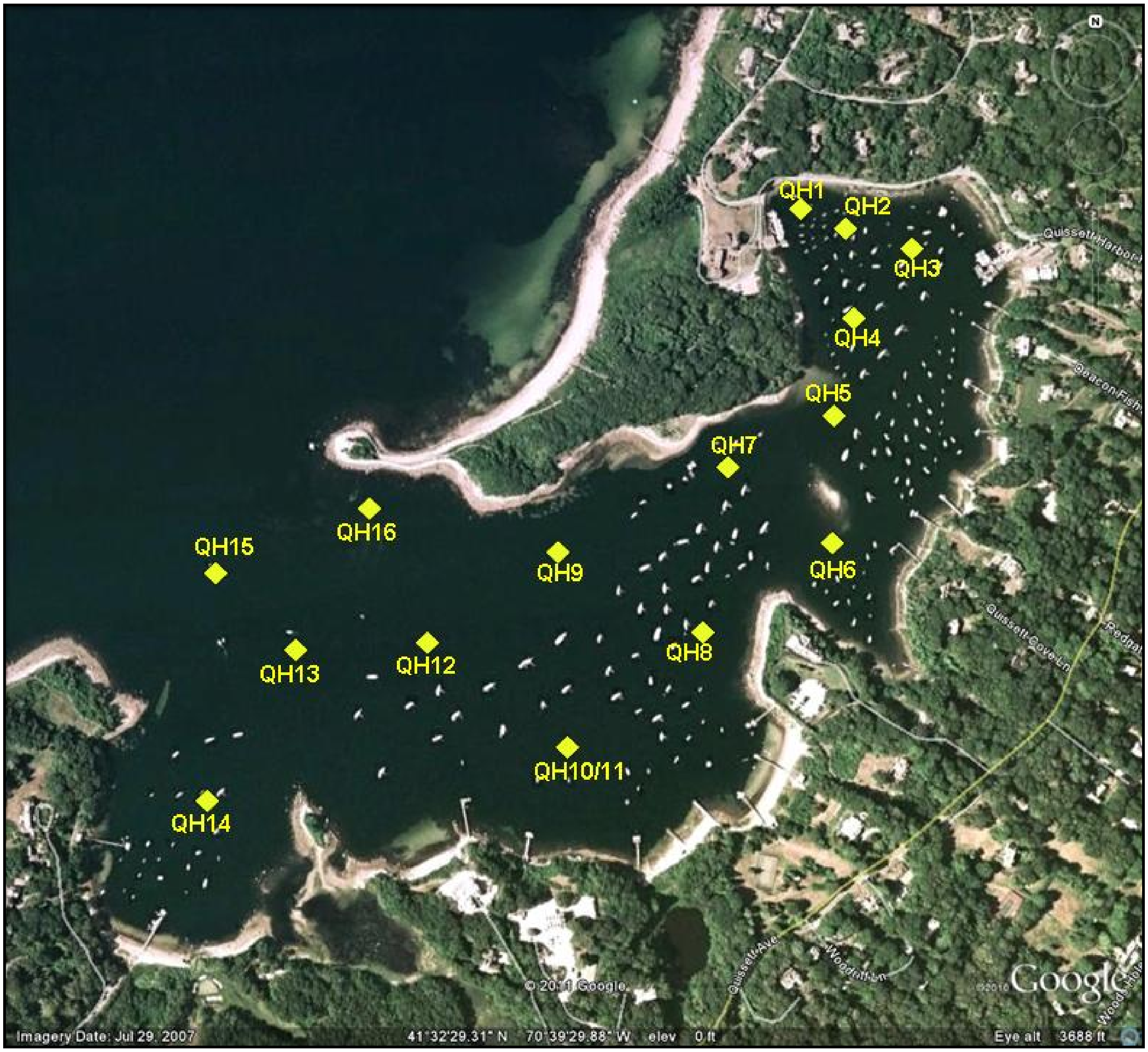

Figure IV-5. Quissett Harbor System locations (yellow symbols) of sediment sample collection for determination of nitrogen regeneration rates and/or infaunal community analysis. Numbers are for reference to station listing above. Not all stations were sampled for both parameters.

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 (Quissett Harbor Boatyard), 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 orthophosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20^{o}C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON

(D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA [*508-910-6325*]. The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

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

The relative balance of nitrogen fluxes ("in" versus "out" of sediments) is dominated by the rate of particulate settling (in), the rate of denitrification of nitrate from overlying water (in), and regeneration (out). The rate of denitrification is controlled by the levels of organic matter within the sediments, whether the sediments are oxic or 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-6).

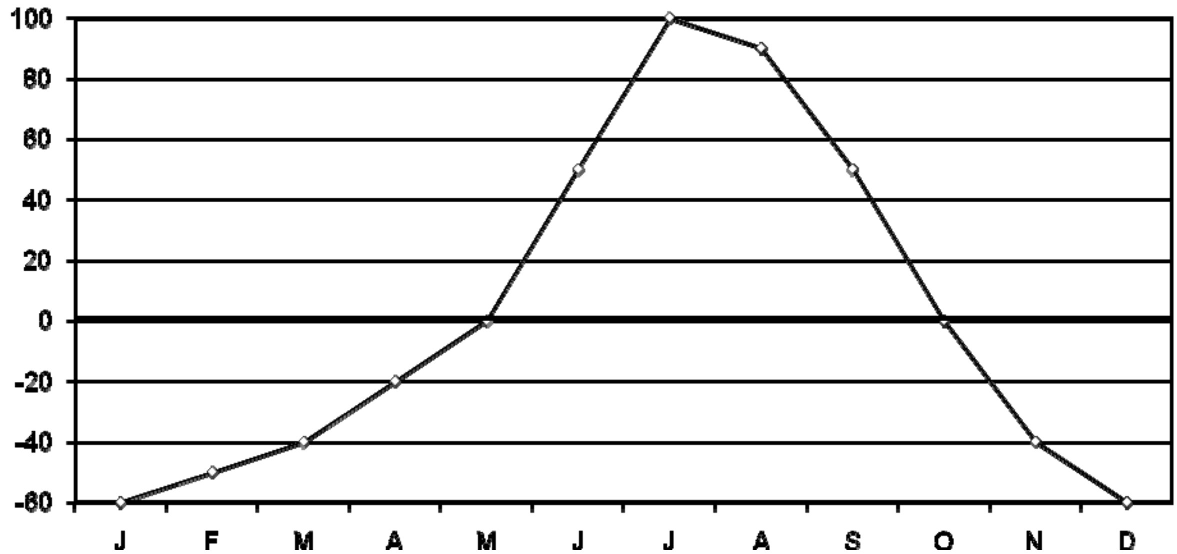

Figure IV-6. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment Nitrogen Release by Standard Core Approach: Sediment sampling was conducted throughout the main and inner embayment basins of the Quissett Harbor system. Generally, the distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content, as well as sediment type and an analysis of each site's tidal flow velocities. As expected flow velocities are generally low throughout the Quissett Harbor system with the exception of the area in the immediate vicinity of the mouth to Buzzards Bay. 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). Based upon the low velocities, a water column particle residence time of ~8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas that are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham) 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 other 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.

Rates of net nitrogen release or uptake from the sediments within the Quissett Harbor embayment system were comparable to other embayments of similar depth and configuration in southeastern Massachusetts. There was a clear pattern of sediment N flux. The inner basin appears to be depositional with depths in the central region in excess of 5 meters. The main basin reaches similar depths but is less isolated (see bathymetric map, Section V). Consistent with the morphology of the basins, the inner basin sediments consist mainly of muds, while the main basin sediments are mainly sands or compacted muds. Sediments at all sites exhibited an oxidized surface layer and were "non-sulfidic". Summertime nitrogen exchange between sediments and overlying water indicated that the inner basin sediments were a net source of nitrogen to the waters (39.0 mg N m^{-2} d^{-1}), while the main basin sediments showed net uptake (-12.2 mg N m^{-2} d^{-1}; Table IV-4). The spatial pattern of sediment-watercolumn exchange is consistent with basin morphology, sediment type and water depth. The difference in sediment nitrogen flux may also be correlated with the occurrence of eelgrass beds throughout the main basin, with only sparse patches in the inner basin.

There was a clear pattern of sediment N flux, with the main basin of Quissett Harbor having generally oxidized sandy to sand/mud (mix) sediments and showing net uptake, -12.2 mg N m^{-2} d^{-1}. In contrast, the more depositional and organic sediments of the inner basin supporting a moderate level of net nitrogen release, 39.0 mg N m^{-2} d^{-1}. Both the observed rates and their spatial distribution are similar to other estuarine basins in the region. A similarly configured estuary, Lagoon Pond (Martha's Vineyard) was found to have net nitrogen uptake in the basin formed behind the barrier beach (-2.3 mg N m^{-2} d^{-1}) and net release in the inner depositional basins of 8.4 and 31.8 mg N m^{-2} d^{-1}. Similarly, the sandy oxidized sediments at comparable depths within the main basins of the Nantucket Harbor Embayment System also show net nitrogen uptake in summer of -7.9 to -38.8 mg N m^{-2} d^{-1}, while the tributary embayment of Polpis Harbor showed net nitrogen release (East Polpis, 14.6 mg N m^{-1} d^{-1}; West Polpis 65.9 mg N m^{-1} d^{-1}). The outer basins of West Falmouth Harbor also support similar sediments and rates of summer uptake of -11.8 mg N m^{-1} d^{-1}, while the Three Bays System showed a similar pattern of net uptake in the outer basins ranging to net release in the inner basins (Seapuit River to North Bay, -37.7 to 57.7 mg N m^{-1} d^{-1}). Overall, the sediment nitrogen flux in the basins of Quissett Harbor appear to be in balance with the overlying waters and the nitrogen flux rates are consistent with the level of nitrogen loading to this system, the basin morphology and tidal exchange. Net nitrogen flux rates for use in the water quality modeling effort for the component sub-basins of the Quissett Harbor Embayment System (Chapter VI) are presented in Table IV-4.

Table IV-4. Rates of net nitrogen return from sediments to the overlying waters of the Quissett Harbor Embayment 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})			i.d. *
	Mean	S.E.	N	
Quissett Harbor Embayment System				
Quissett Harbor Inner Basin	39.0	9.3	7	1-7
Quissett Harbor Main Basin	-12.2	8.9	7	8,10,11,13,14,15,16

* Station numbers refer to Figure IV-5.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes the field data collection efforts and the development of hydrodynamic models for the Quissett Harbor 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 Quissett Harbor 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 residence to understand how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

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. Buzzard’s Bay). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For the Quissett Harbor 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.

The Quissett Harbor system (Figure V-1) is a tidally dominated embayment, with a north-west facing inlet to Buzzard's Bay on the western shoreline of Falmouth, MA. The harbor is a popular port for a fleet of recreational boats with a 110 acre surface area.

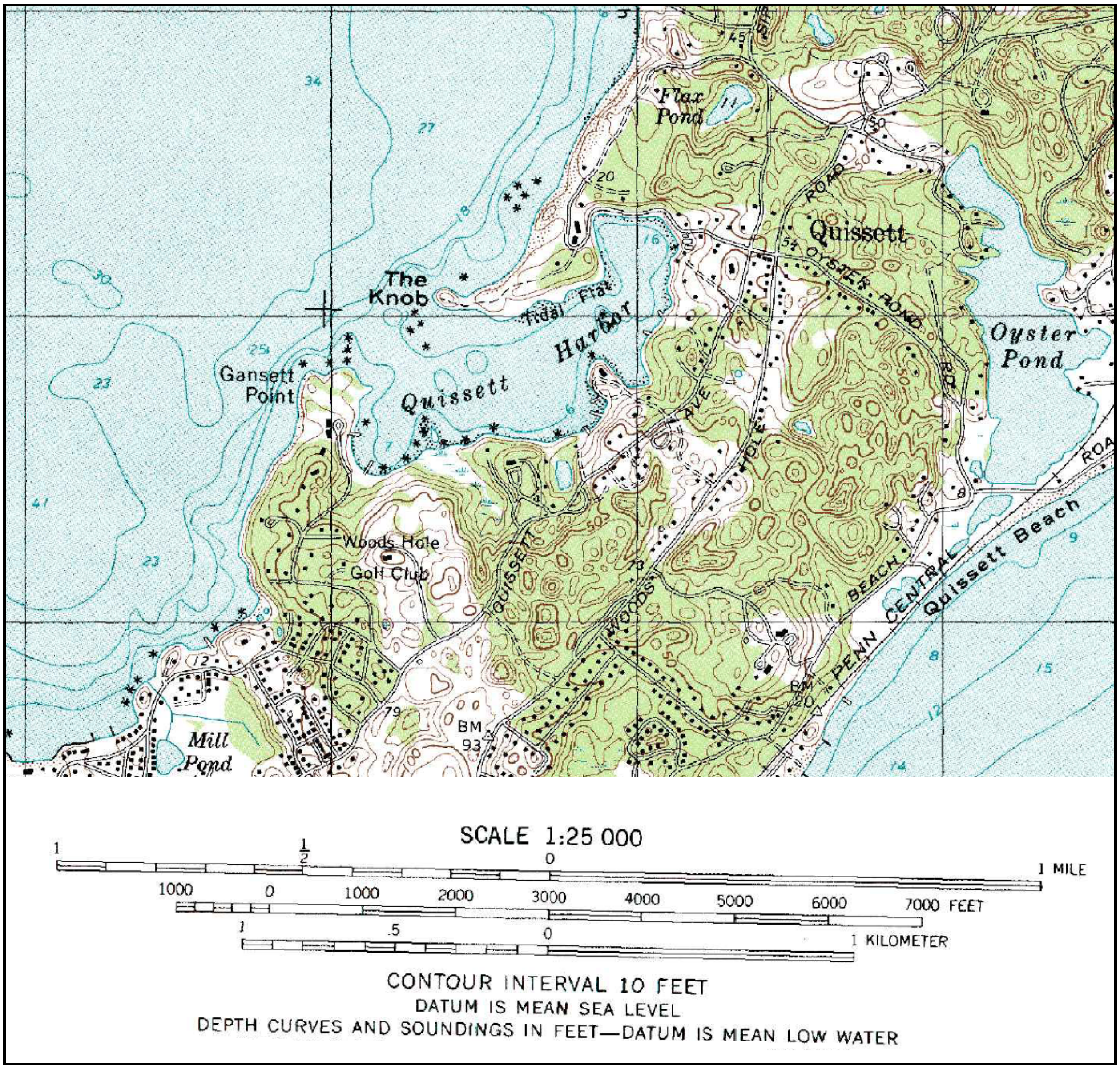

Figure V-1. Map of the Quissett Harbor estuary system (from United States Geological Survey topographic maps).

Since the water elevation difference between Buzzard's Bay and the Harbor is the primary driving force for tidal exchange, the local tide range limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) along the length of Quissett Harbor is negligible, indicating systems that flush efficiently. Any issues with water quality, therefore, would likely be due to other factors including nutrient loading conditions from the system's watersheds, and the tide range in Buzzard's Bay.

Circulation in the Quissett Harbor estuarine 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 for the system at a gage station installed in Buzzard's Bay and at one location within the system (Figure V-2). All temperature-depth recorders (TDRs or tide gages) were installed for a 37-day period to measure tidal variations through two bi-monthly spring-to-neap tide cycles. In this manner, attenuation of the tidal signal as it propagates through the harbor and into the embayment was evaluated accurately.

Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. The two (2) gages were deployed for a 37-day period between April 22, and May 30, 2007. Each yellow dot represents the approximate locations of the tide gauges: (S-1) represents the Buzzard's Bay gage (Offshore) and (S-2) the Quissett Harbor gage.

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 Buzzard's 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 (gage 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.

V.2.1 Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Quissett Harbor system was assembled from a recent hydrographic survey performed specifically for this study in early May 2007. Survey transects were densest in the upper reach of the system, were the greatest variability in bottom bathymetry was encountered. Bathymetry in the inlet is important from the standpoint that it has the most influence on tidal circulation in and out of the estuary. The survey was conducted from a shallow draft outboard boat with a precision fathometer installed (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder (fathometer) and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position (latitude/longitude).

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the North American Vertical Datum of 1988 (NAVD88) vertical datum in feet. Once rectified, the finished, processed data were archived as 'xyz' files containing x-y horizontal position (in Massachusetts Mainland State Plan 1983 coordinates) 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 are presented in Figure V-3. The Harbor has an average depth of 10.3 feet and a maximum depth of 24 feet near the head of the system.

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at a station in Quissett Harbor and at a station in Buzzard's Bay. The offshore station (S-1) is located in Buzzard's Bay. The Quissett Harbor station (S-2) is located at Quissett Boat Yard at the eastern end of the estuary. TDRs were deployed at each gage station from the beginning of April 22nd through May 30th 2007. 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 Quissett Harbor 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 37-day period of the TDR deployment.

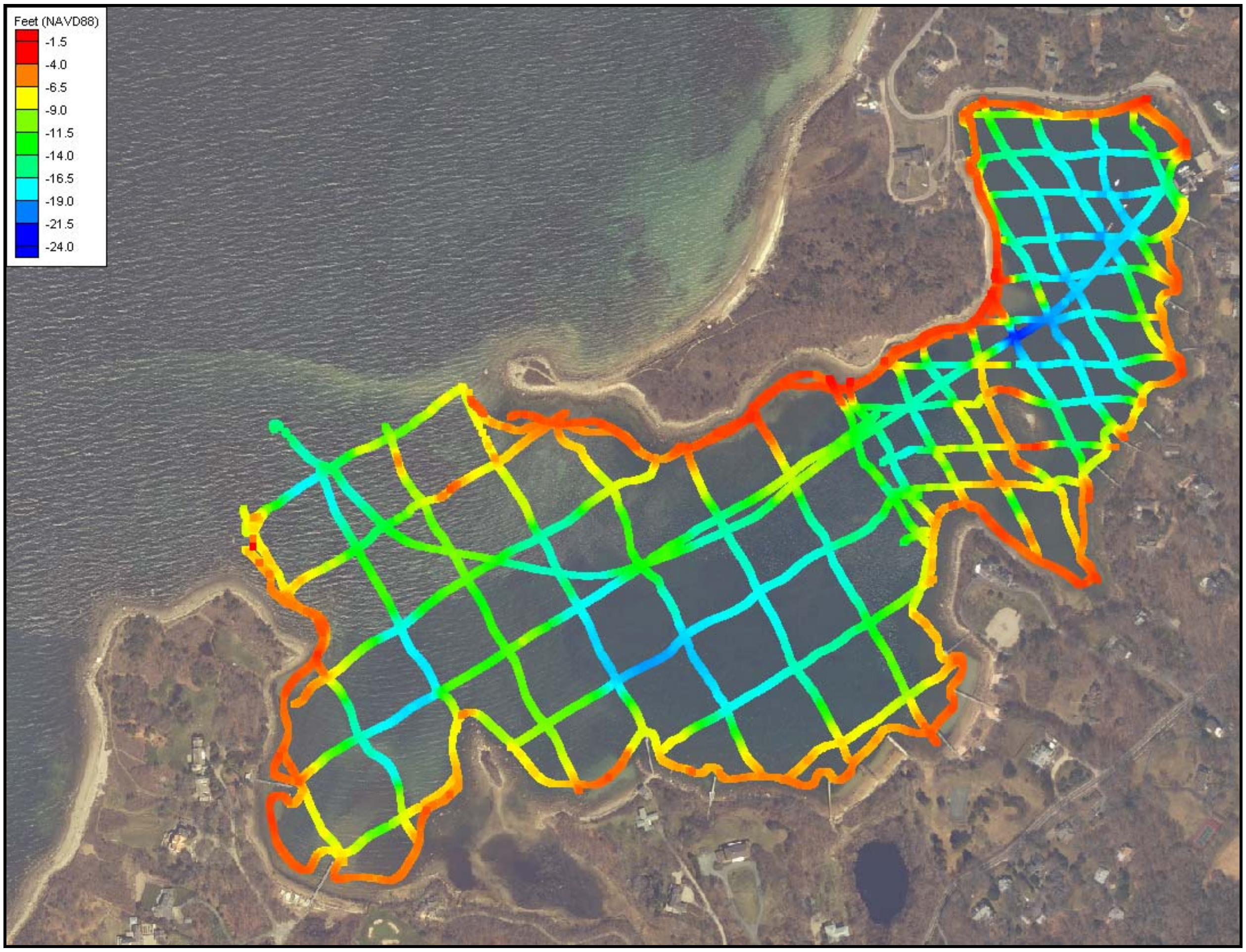

Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

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.

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., at the entrance between Gansett Point and the Knob) and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. A visual comparison of the two stations throughout the Quissett Harbor estuary (Figure V-5), demonstrates no discernable attenuation in the system.

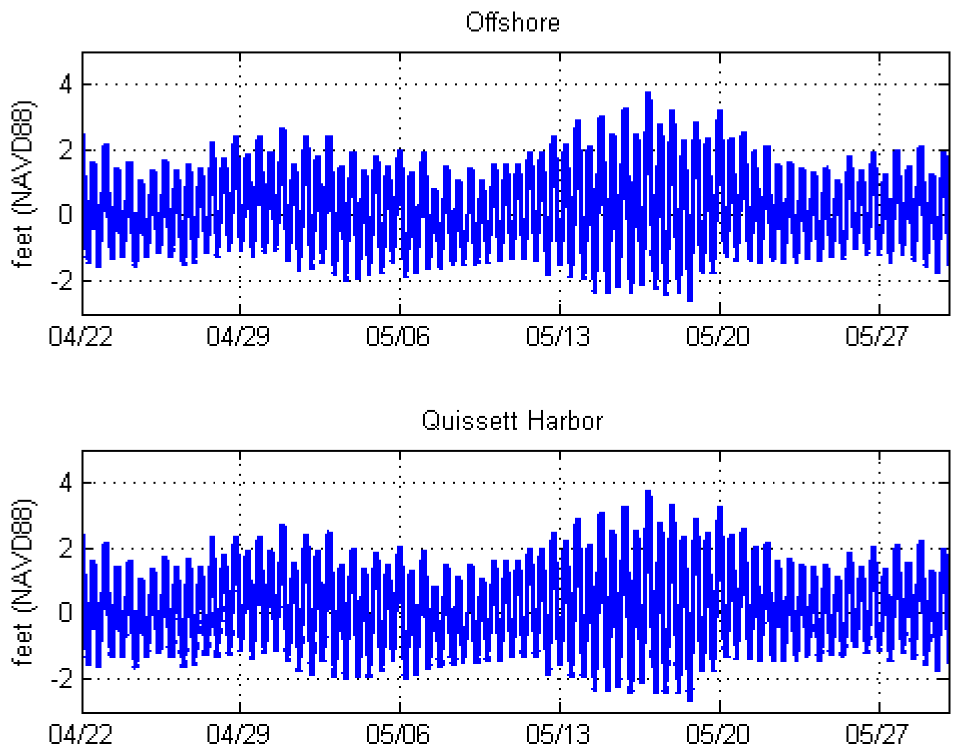

Figure V-4. Water elevation variations as measured at the two locations of the Quissett Harbor system, from April 22nd to May 30th 2007.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 36-day records. 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, respectively. 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 Buzzard's 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

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 further apparent that there is negligible damping occurring between Quissett Harbor and Buzzard's Bay.

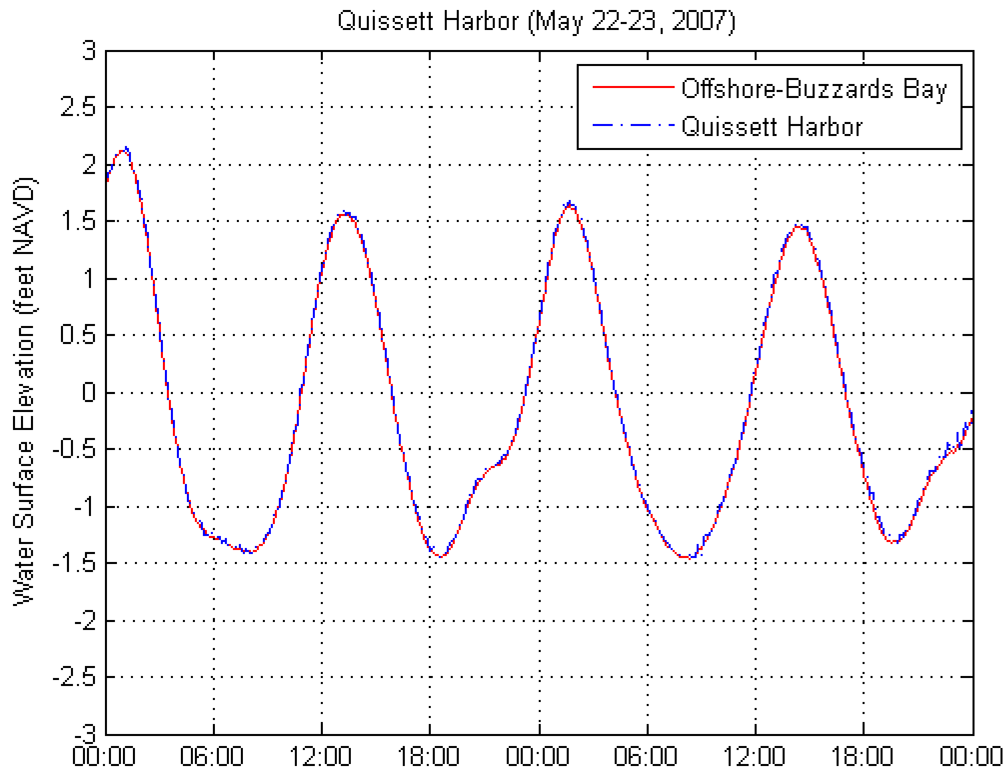

Figure V-5 Plot showing two tide cycles tides at two stations in the Quissett Harbor system plotted together. Demonstrated in this plot is lack of attenuation in the tidal signal

Table V-1. Tide datums computed from records collected in the Quissett Harbor Estuarine system April 22 - May 30, 2007. Datum elevations are given relative to NAVD88

Tide Datum	Offshore	Quissett Harbor
Maximum Tide	3.730	3.774
MHHW	2.223	2.269
MHW	1.923	1.967
MTL	0.180	0.181
MLW	-1.563	-1.605
MLLW	-1.632	-1.672
Minimum Tide	-2.607	-2.638

A more thorough harmonic analysis was also performed on the time series data from each gage 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.

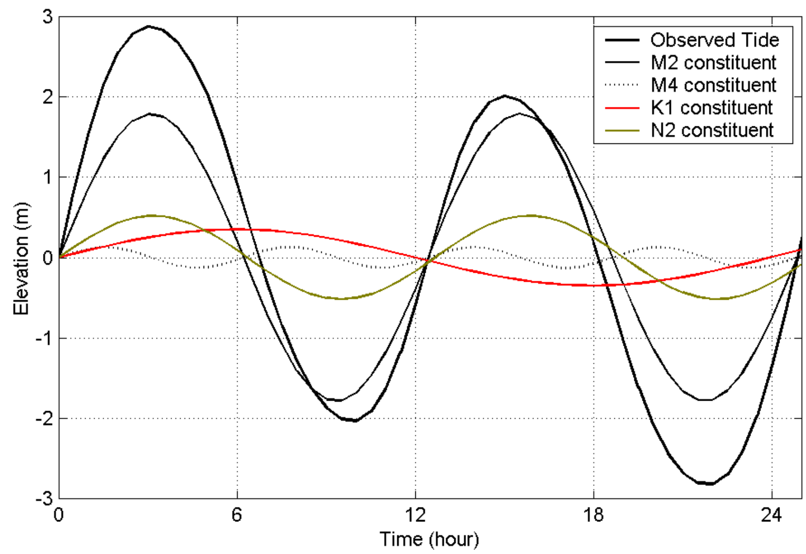

Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-2 presents the amplitudes of seven significant tidal constituents. The M_2, or the familiar twice-a-day lunar, semi-diurnal, tide is the strongest contributor to the signal for the entire system. The M2 amplitude fluctuation is an order of magnitude smaller than the resolution of the bathymetry survey, implying almost no attenuation of the tide in the entire system. The range of the M_2 tide is twice the amplitude, or about 3.38 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar) possess amplitudes of approximately 0.59 feet and 0.38 feet respectively. These constituents account for the semi-diurnal variance one high/low tide to the next, as seen in figure V-5. 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.

Table V-2. Tidal Constituents for the Quissett Harbor Estuary System, April 22 - May 30, 2007.

	AMPLITUDE (feet)						
	M2	M4	M6	K1	S2	N2	O1
Period (hours)	12.42	6.21	4.14	23.93	12.00	12.66	25.82
Offshore	1.669	0.240	0.023	0.293	0.350	0.434	0.192
Quissett Harbor	1.676	0.241	0.022	0.298	0.352	0.436	0.192

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. This confirms that there is no appreciable attenuation in this system, since the computed delay is less than the time step of the data record (10 minutes).

Table V-3. M2 Tidal Attenuation, Quissett Harbor Estuary System, April 22 - May 30, 2007 (Delay in minutes relative to Offshore).	
Location	Delay (minutes)
Quissett Harbor	2

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 the Offshore gage, with the predicted tide resulting from the harmonic analysis, and the resulting non-tidal residual.

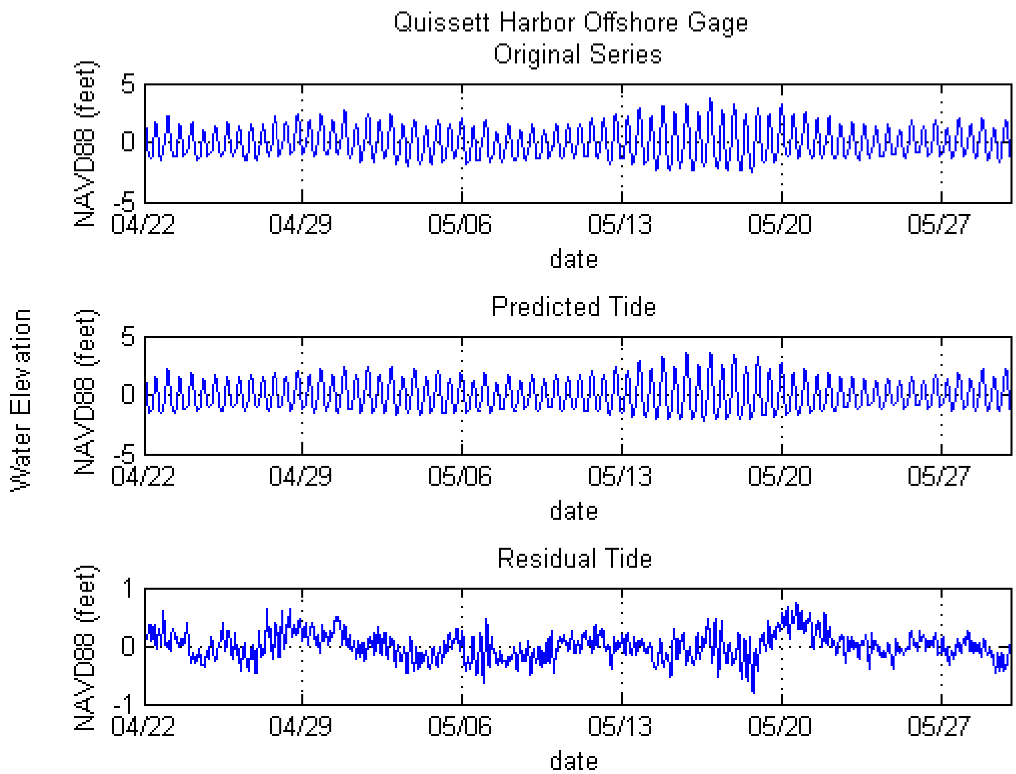

Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured at the Offshore Gage (S-1).

Table V-4 shows that the percentage contribution of tidal energy was the driving force of the observed tidal signal in the Quissett Harbor Estuarine System. The analysis also shows that tides are responsible for 97% of the water level changes in the system. The remaining 3% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of the system. The total energy content of the tide signal should carry over from one embayment to the next unless tidal flow is inhibited, which is clearly demonstrated in the consistency of the total variance and the percent of non-tidal factors influencing the tidal signal.

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Quissett Harbor, 2007.

Location	Total Variance (ft^2)	Total (%)	Tidal (%)	Non-tidal (%)
Offshore	1.588	100	96.90	3.10
Quissett Harbor	1.605	100	96.80	3.20

The results from Table V-4 indicate that hydrodynamic circulation throughout the Quissett Harbor Estuarine System is primarily dependent 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 the Offshore gage was used to force the model so that the effects of non-tidal energy are included in the modeling analysis.

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Quissett Harbor estuary system. Once calibrated, the model was used to calculate water volumes for selected sub-embayments (e.g., Quissett Harbor) 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 Quissett Harbor 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 gage 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 (5+) 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 1079 elements and 3174 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 inner harbor 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.

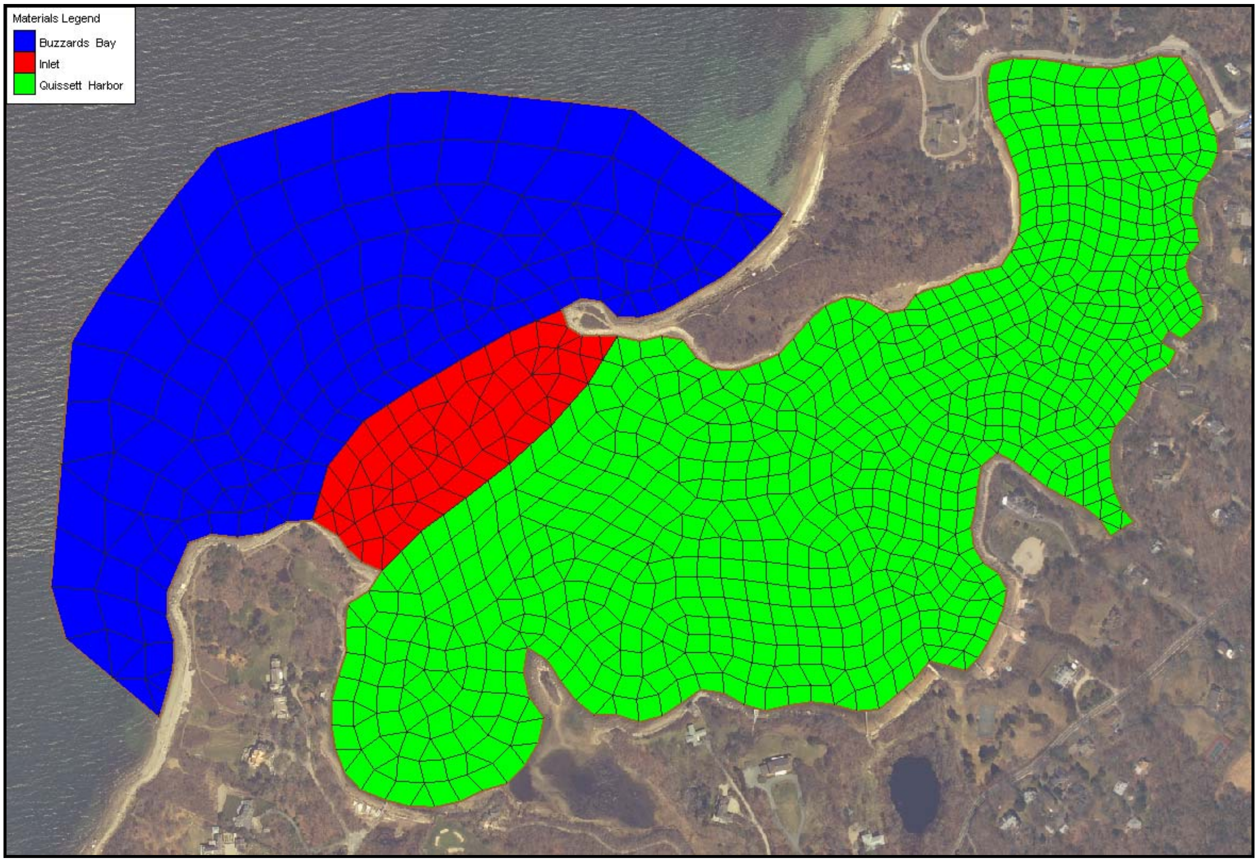

Figure V-8. The model finite element mesh developed for Quissett Harbor estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained at the Offshore Gage (S-1).

V.3.2.2 Boundary Condition Specification

Two types of boundary conditions were employed for the RMA-2 model: 1) "slip" boundaries and 2) 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.

The model was forced at the open boundary using water elevations measurements obtained in Buzzard's 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 Buzzard's 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 Buzzard's 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 Harbor).

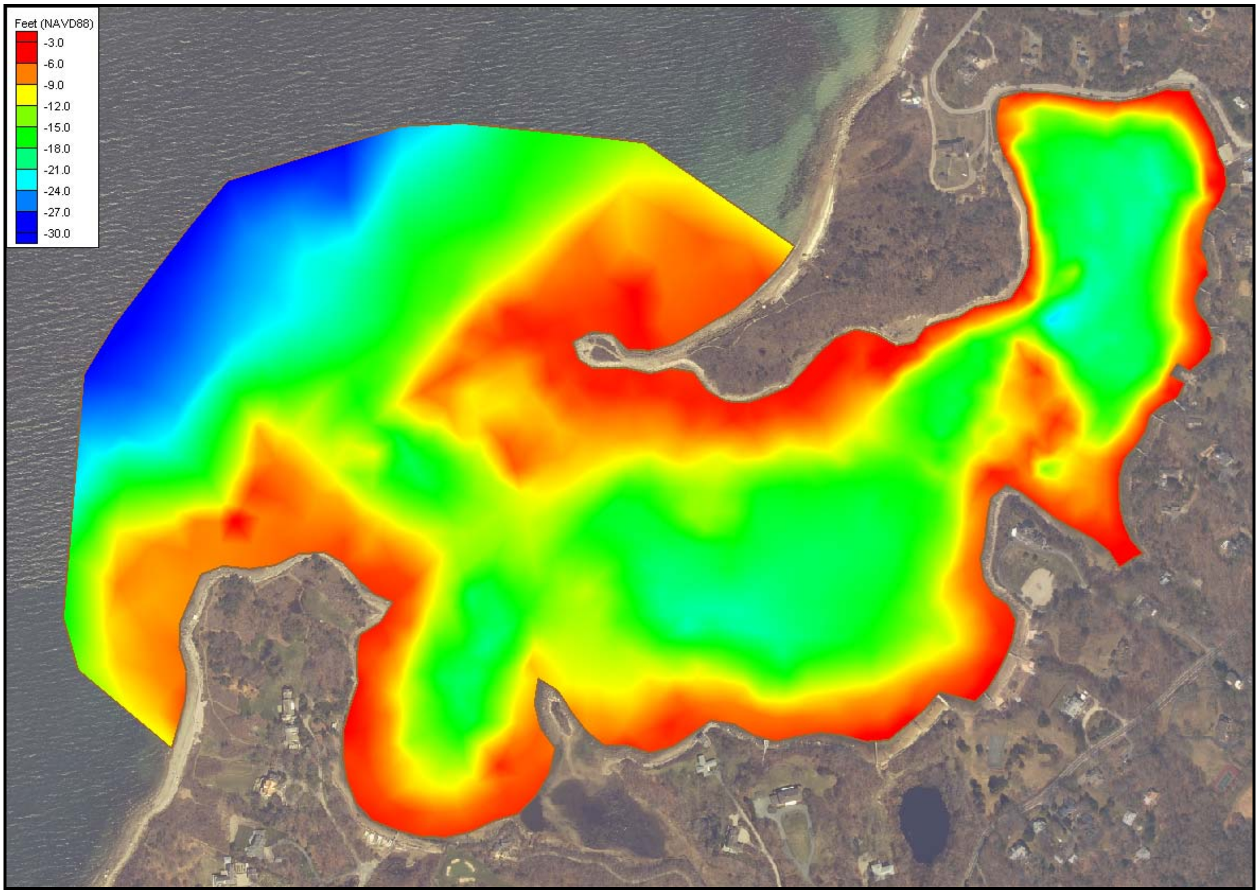

Figure V-9. Depth contours of the completed Quissett Harbor finite element mesh.

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.

Calibration of the flushing model required a close match between the modeled and measured tides at each gage 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 five constituents (M_2, M_4, K_1, S_2, and N_2) 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 ten-day period, beginning 1000 hours EDT May 3, 2007 and ending 1000 hours EDT May 13, 2007. This time period included a 24-hour model spin-up period, and a 18-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 spring (bi-monthly maximum) to neap (bi-monthly minimum) tide ranges, which is representative of average tidal conditions in the embayment system. Throughout the selected 9 day period after the spin-up, the tide ranged approximately 4.0 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). 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
Inlet	0.025
Quissett Harbor	0.025

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). Small changes in these values did not change the accuracy of the calibration. Typically, model turbulence coefficients (D) are set between 10 and 100 lb-sec/ft^2 (as listed in Table V-6).

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

Embayment	D (lb-sec/ft$^{2)}$
Offshore	20
Inlet	20
Quissett Harbor	20

V.3.3.3 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 two gauge locations are presented in Figures V-10 and V-11. RMS errors were roughly 0.05 ft (<0.60 inches) and computed R^2 correlation was 0.99 for every station. Errors between the model and observed tide constituents were less than 0.02 feet for all locations, suggesting the model accurately predicts tidal hydrodynamics within Quissett Harbor. 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 calibration time period differ from those in Table V-2 because constituents were computed for only 9 days, rather than the entire 37-day period 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 gage gauges (±0.12 ft). Time lag errors were less than the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes) for both gage stations, indicating good agreement between the model and data.

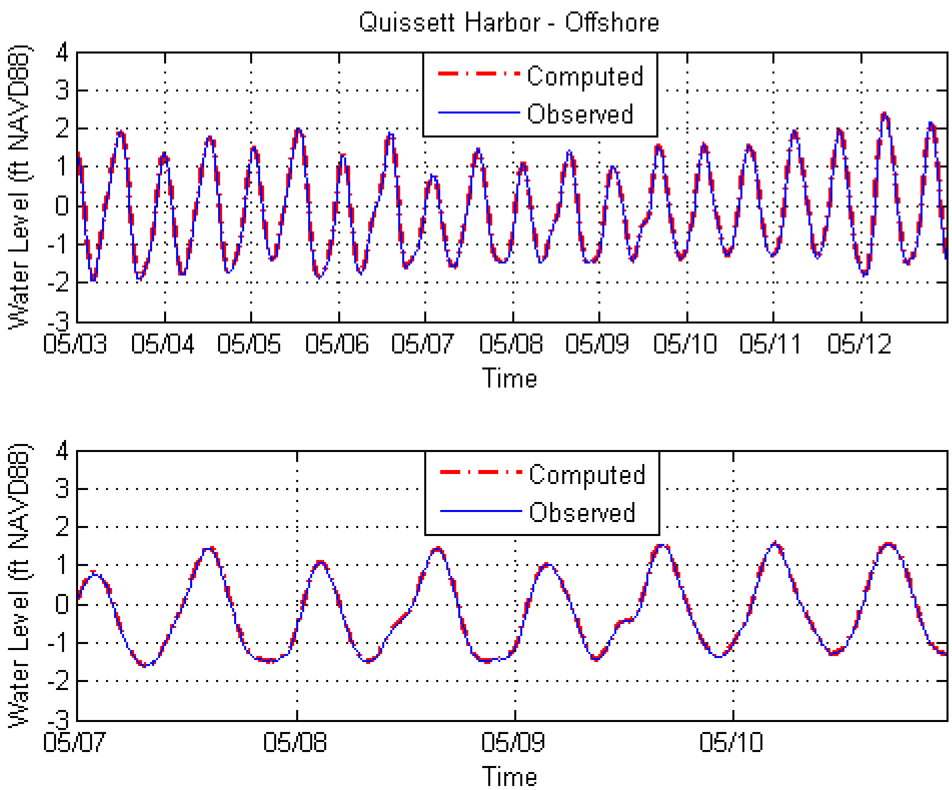

Figure V-10. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Offshore Station. The top plot shows the entire record with the bottom plot showing a 4-day segment.

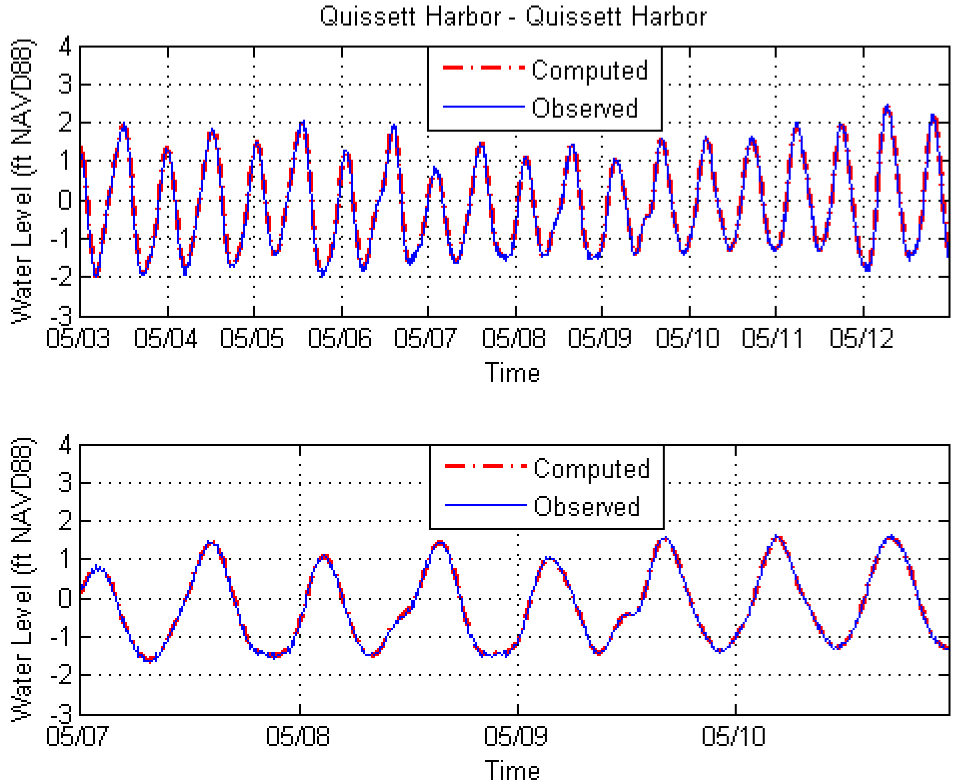

Figure V-11. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Quissett Harbor Gage Station. The top plot shows the entire record with the bottom plot showing a 4-day segment.

Table V-7. Comparison of Tidal Constituents validated RMA2 model versus measured tidal data for the period May 15 to May 24, 2007.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	K_1	N_2	ΦM_2	ΦM_4
Offshore	1.766	0.352	0.337	0.643	134.3	-59.5
Quissett Harbor	1.767	0.353	0.337	0.643	134.3	-59.5
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	K_1	N_2	ΦM_2	ΦM_4
Offshore	1.786	0.355	0.338	0.636	134.7	-59.1
Quissett Harbor	1.776	0.353	0.337	0.632	134.7	-59.3
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	K_1	N_2	ΦM_2	ΦM_4
Offshore	-0.020	-0.003	-0.001	0.007	0.93	0.43
Quissett Harbor	-0.010	-0.001	-0.000	0.011	0.82	0.22

V.3.4 Model Circulation Characteristics

The final calibrated and validated model serves as a useful tool for investigating the circulation characteristics of the Quissett Harbor 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 the estuary system, maximum flood velocities at the entrance to Quissett Harbor inlet are slightly larger than velocities during the ebb portion of the tide. Maximum depth-averaged velocities in the model are approximately 0.22 feet/sec for flooding tides, and 0.20 ft/sec for ebbing tides. An example of model output is presented in Figure V-12, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum flood velocities occur at the inlet.

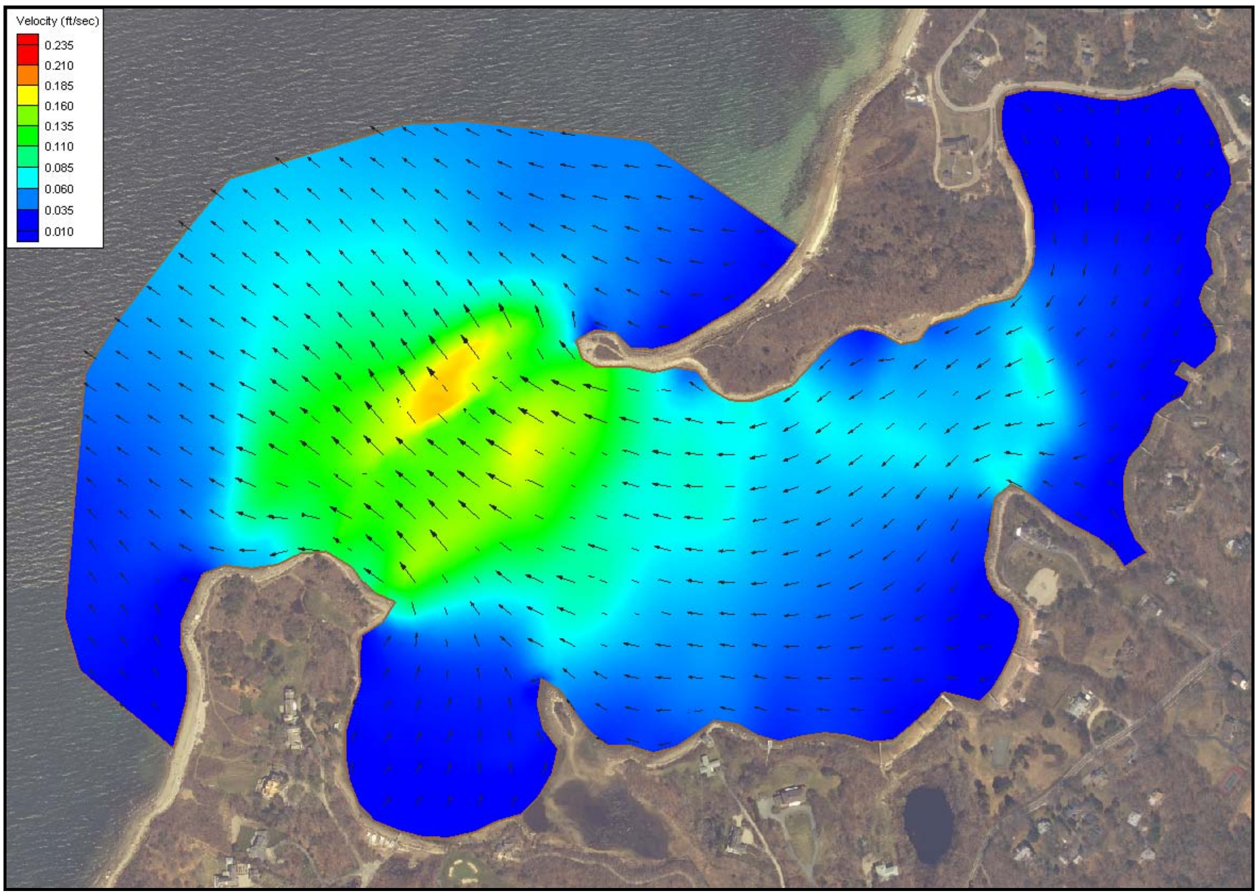

Figure V-12. Example of hydrodynamic model output in Quissett Harbor for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs through the Quissett Harbor Estuarine system is seen in Figure V-13. During the simulation time period, maximum modeled flood tide flow rates through the Quissett Harbor inlet were 1469 ft^3/sec and ebb tide flow rates were 1943 ft^3/sec.

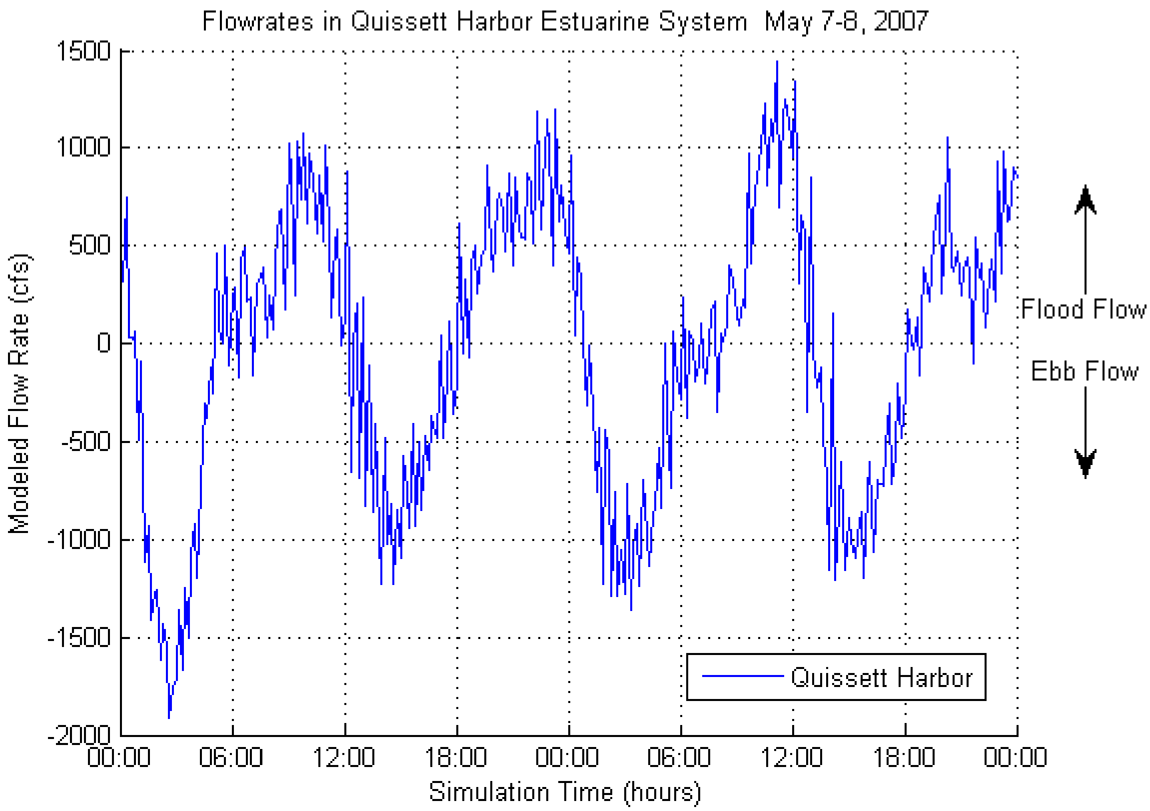

Figure V-13. Time variation of computed flow rates for Quissett Harbor. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are likewise large compared to neap tide conditions. Positive flow indicates flooding tide, while negative flow indicates ebbing tide.

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 Quissett Harbor is tidal exchange. A rising tide offshore in Buzzard's 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 Quissett Harbor as an example, the system residence time is the average time required for water to migrate from the head of Quissett Harbor, through the lower portions of the Harbor, and finally into Buzzard's Bay, where the local residence time is the average time required for water to migrate from the head of the Harbor to just the mid portion of the Harbor (not all the way to the inlet 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 Buzzard's 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 Quissett Harbor and its sub-embayments.

The volume of each sub-embayment, as well as their respective tidal prisms, was computed in cubic feet (Table V-8). Due to the small size of the estuary, the system was modeled as a single embayment. The model computed total volume of the embayment at every time step, and this output was used to calculate mean embayment volume and average tide prism. Since the 9-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 Quissett Harbor estuary system during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Quissett Harbor	56,318,000	15,217,000

Residence times were averaged for the tidal cycles comprising a representative 9 day period (17 tide cycles), and are listed in Table V-9. Residence times were computed for the entire estuary. In addition, system and local residence times were computed 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 simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The moderate local residence time (1.9 days) of the whole Quissett Harbor estuary system shows that the outer harbor area most likely flushes reasonably well.

Table V-9. Computed System and Local residence times for sub-embayments of the Quissett Harbor estuary system.

Embayment	Local Residence Time (days)	System Residence Time (days)
Quissett Harbor	1.9	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 Quissett Harbor 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.

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 Buzzard's 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 Quissett Harbor System. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the 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-2V 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 15-tidal cycle period in May 2007. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 40-hour spin-up period, to allow the model had reached 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 Quissett Harbor System, consisting of the background concentrations of total nitrogen in the waters entering from Buzzard's 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 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. Seventeen years of data (collected between 1993 and 2009) were available for stations analyzed by SMAST (1993-2008) and others (2009) in the Quissett Harbor System.

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 Quissett Harbor 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 Quissett Harbor 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 has utilized this model in water quality studies of other Cape Cod embayments, including systems in Falmouth (Ramsey *et al*., 2000); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

Table VI-1. Quissett Harbor water quality monitoring data, and modeled Nitrogen concentrations for the Quissett Harbor System used in the model calibration plots of Figure VI-2. "Data mean" values are calculated as the average of the separate yearly means. All concentrations are given in mg/L N.

Sub-Embayment	Monitoring station	mean	s.d. all data	N	model min	model max	model average
Quissett Harbor (Main)	QH1	0.302	0.055	61	0.2956	0.3119	0.3016
Quissett Harbor (Inner)	QH2	0.354	0.069	66	0.3514	0.3554	0.3537

Figure VI-1. Estuarine water quality monitoring station locations in the Quissett Harbor System. Station labels correspond to those provided in Table VI-1.

The overall approach involves modeling total nitrogen as a non-conservative constituent, where bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. This modeling represents summertime conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the Cape Cod Commission watershed loading analysis (based on the USGS watersheds), 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 Quissett Harbor System.

VI.2.2 Water Quality Model Setup

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

USGS the overall groundwater flow rate into the system is 0.97 ft^3/sec (2,381 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 spin-up period of just 16 days. At the end of the spin-up period, the model was run for an additional 14 tidal-cycle (174 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Quissett Harbor System.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition load for the main basin of Quissett Harbor was evenly distributed at grid cells that formed the southern edge 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 Quissett Harbor System are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment, resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For 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 in Buzzard's Bay was set at 0.289 mg/L, based on SMAST data from Buzzard's Bay. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Buzzard's Bay.

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 of each system were required to match the water column measurements. Dispersion coefficient (E) values were varied through the modeled system by setting different values of E for each grid material type, as designated in Figure VI-2. Observed values of E (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent areas of Quissett Harbor 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 systems 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.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Quissett Harbor 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)
Quissett Harbor (main)	1.46	0.93	-3.16
Quissett Harbor (Inner)	1.92	0.41	4.06

Figure VI-2. Map of Quissett Harbor 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 Quissett Harbor System.	
Embayment Division	E m^2/sec
Buzzards Bay	10.0
Inlet	10.0
Quissett Harbor (main)	10.0
Quissett Harbor (Inner)	0.6

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 SMAST monitoring stations.

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

Also presented in this figure are unity plot comparisons of measured data versus modeled target values for the system. The model fit is exceptional for the Quissett Harbor System, with rms error of less than 0.001 mg/L and an R^2 correlation coefficient of 0.99.

A contour plot of calibrated model output is shown in Figure VI-4 for Quissett Harbor System. 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 7-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Quissett Harbor 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 31.7 ppt. For groundwater inputs, salinities were set at 0 ppt. Groundwater input used for the model was 0.97 ft^3/sec (2,381 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly in each model through the use of several rainwater element input points positioned along each 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 Quissett Harbor System. The rms error of the models was 0.068 ppt, and correlation coefficient was 0.98. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems

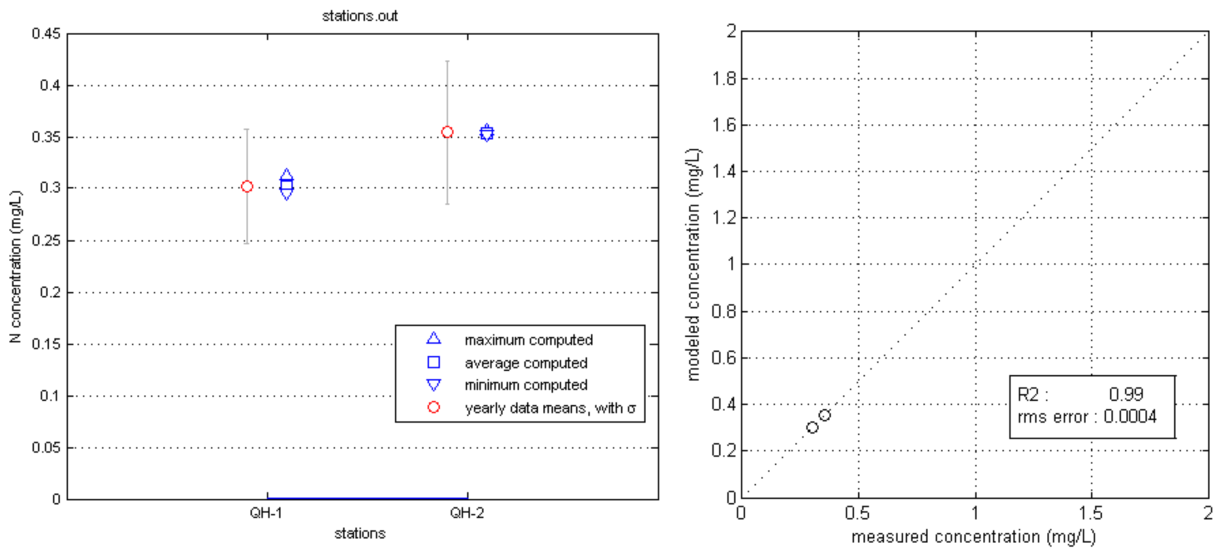

Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Quissett Harbor System. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during 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. Computed correlation (R^2) and error (rms) for the model are also presented.

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.

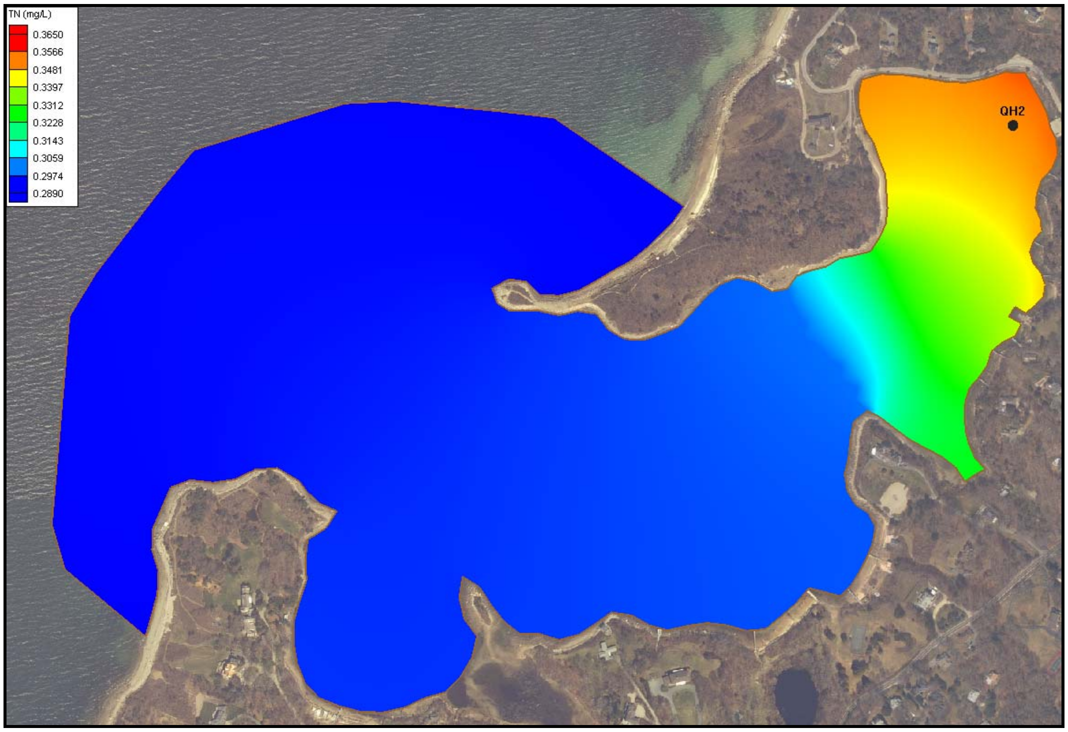

Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Quissett Harbor System. The approximate location of the sentinel threshold station for Quissett Harbor System (QH2) is shown.

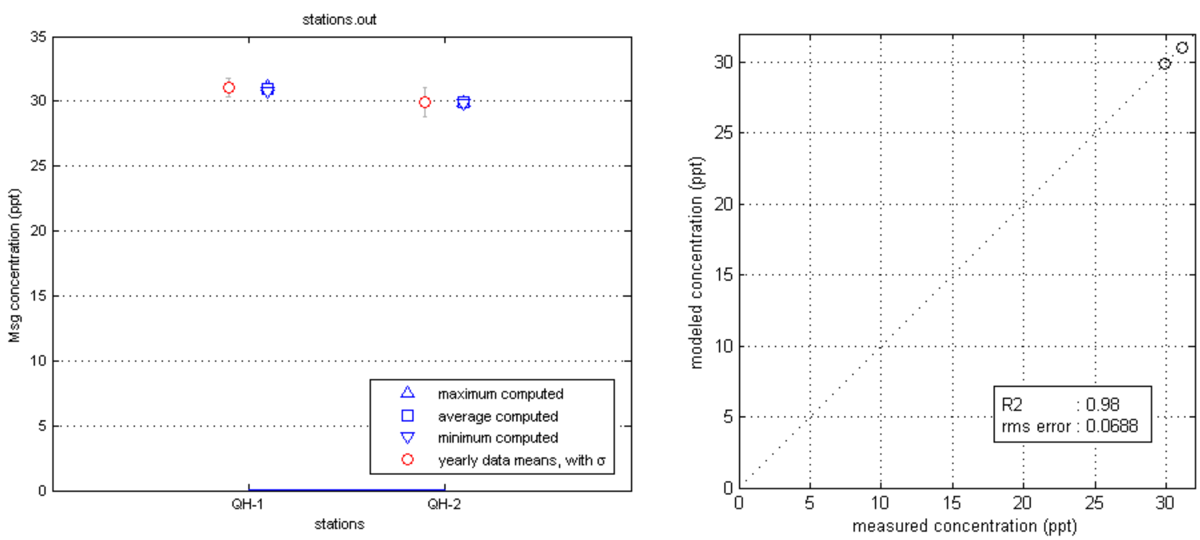

Figure VI-5. Comparison of measured and calibrated model output at stations in Quissett Harbor System. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (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. Computed correlation (R^2) and error (rms) for each model are also presented.

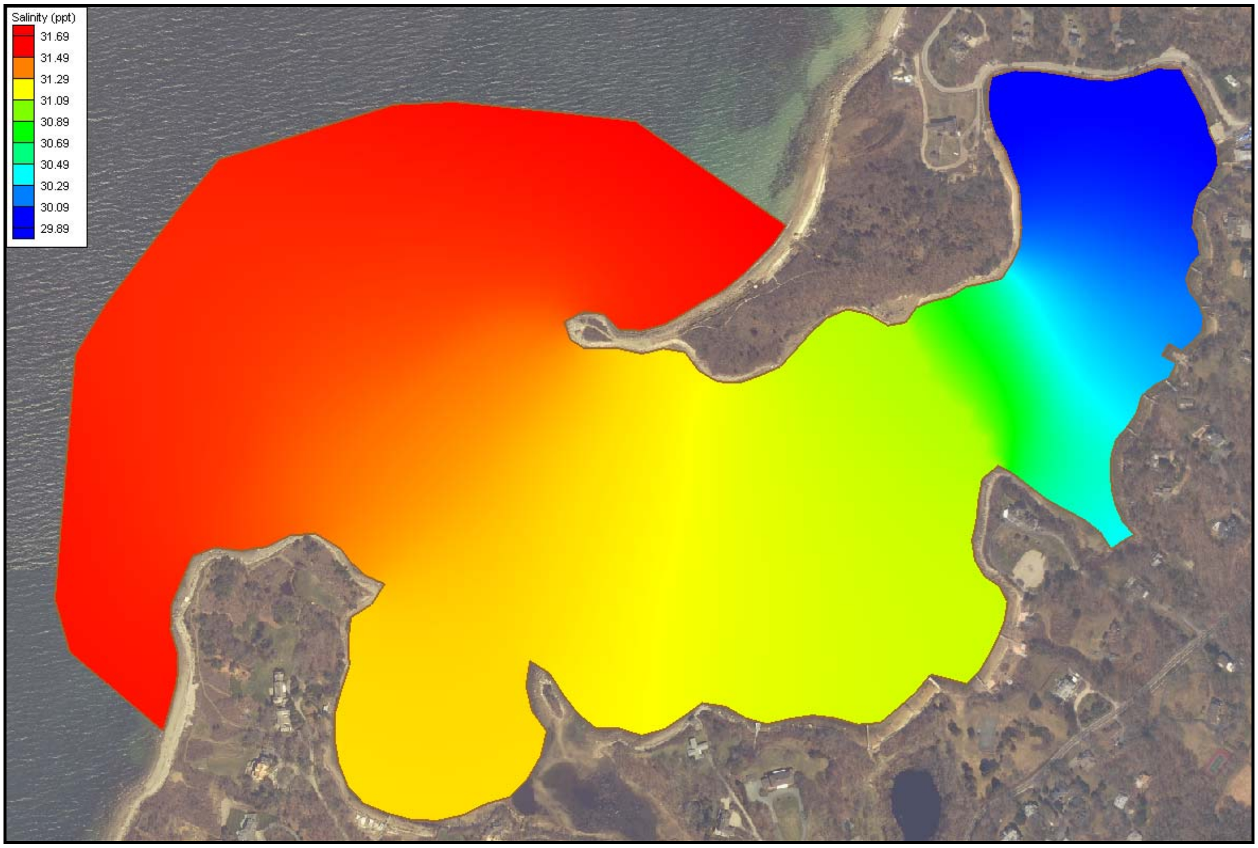

Figure VI-6. Contour plots of modeled salinity (ppt) in Quissett Harbor System.

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

sub-embayment	present load (kg/day)	build out (kg/day)	build out % change	no load (kg/day)	no load % change
Quissett Harbor (main)	1.46	2.49	70.6%	0.10	-93.2%
Quissett Harbor (Inner)	1.92	2.26	17.6%	0.07	-96.3%

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be more than a 17.6% increase in watershed nitrogen load to the Upper Harbor as a result of potential future development, with an increase of 70.6% for the Main Harbor watershed. For the no load scenario, a majority of the load entering the watershed is removed; therefore, the load is lower than existing conditions by over 93%.

For the build-out scenario, a breakdown of the total nitrogen load entering the Quissett Harbor 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 *vice versa*.

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Quissett Harbor (main)	2.49	0.93	-3.24
Quissett Harbor (Inner)	2.26	0.41	4.56

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Quissett Harbor System was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Buzzard's Bay) remained identical to the existing conditions modeling scenarios. At buildout, the greatest increase in Total N concentrations occurred in the head of the system (2.29%), as compared to a 0.63% increase in the lower sub-embayment (Quissett Harbor-main). 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 Quissett Harbor System. The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Quissett Harbor (main)	QH1	0.3016	0.3035	0.63%
Quissett Harbor (Inner)	**QH2**	**0.3537**	**0.3618**	**2.29%**

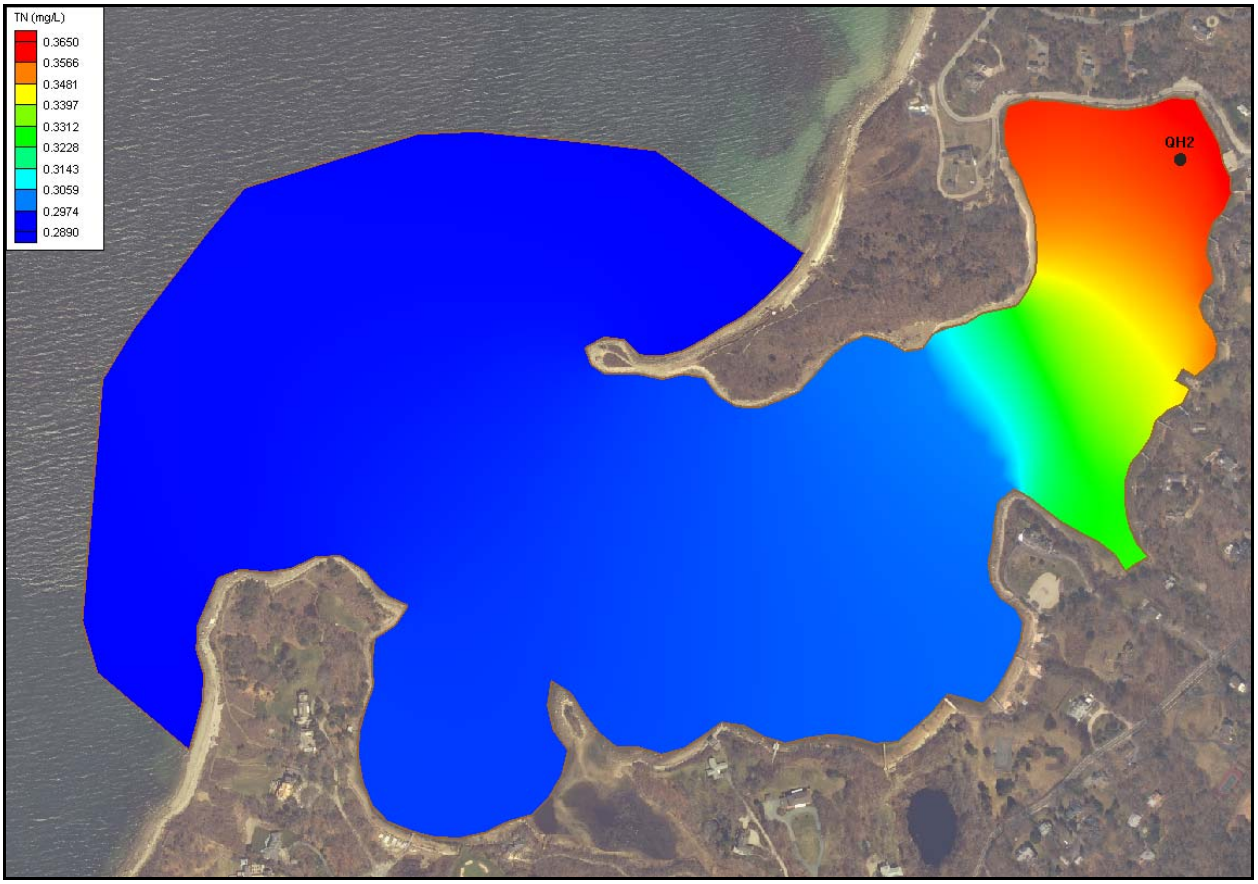

Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Quissett Harbor System, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Quissett Harbor System (QH2) is shown.

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 §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 Quissett Harbor System, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Quissett Harbor (main)	0.10	0.93	-2.98
Quissett Harbor (Inner)	0.07	0.41	3.61

The relative change in total nitrogen concentrations resulting from "no load" was relatively minor for the outer portion of the Harbor (Quissett Harbor-main), as shown in Table VI-8, with reductions on the order of 2%. The Upper Harbor station (Quissett Harbor-inner) experienced significantly larger change in total nitrogen concentrations, with a “no load” condition nearly 11% below existing conditions, which is the range of uncertainty of the linked model approach. Results for the 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 Quissett Harbor System. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Quissett Harbor (main)	QH1	0.3016	0.2940	-2.52%
Quissett Harbor (Inner)	**QH2**	**0.3537**	**0.3150**	**-10.94%**

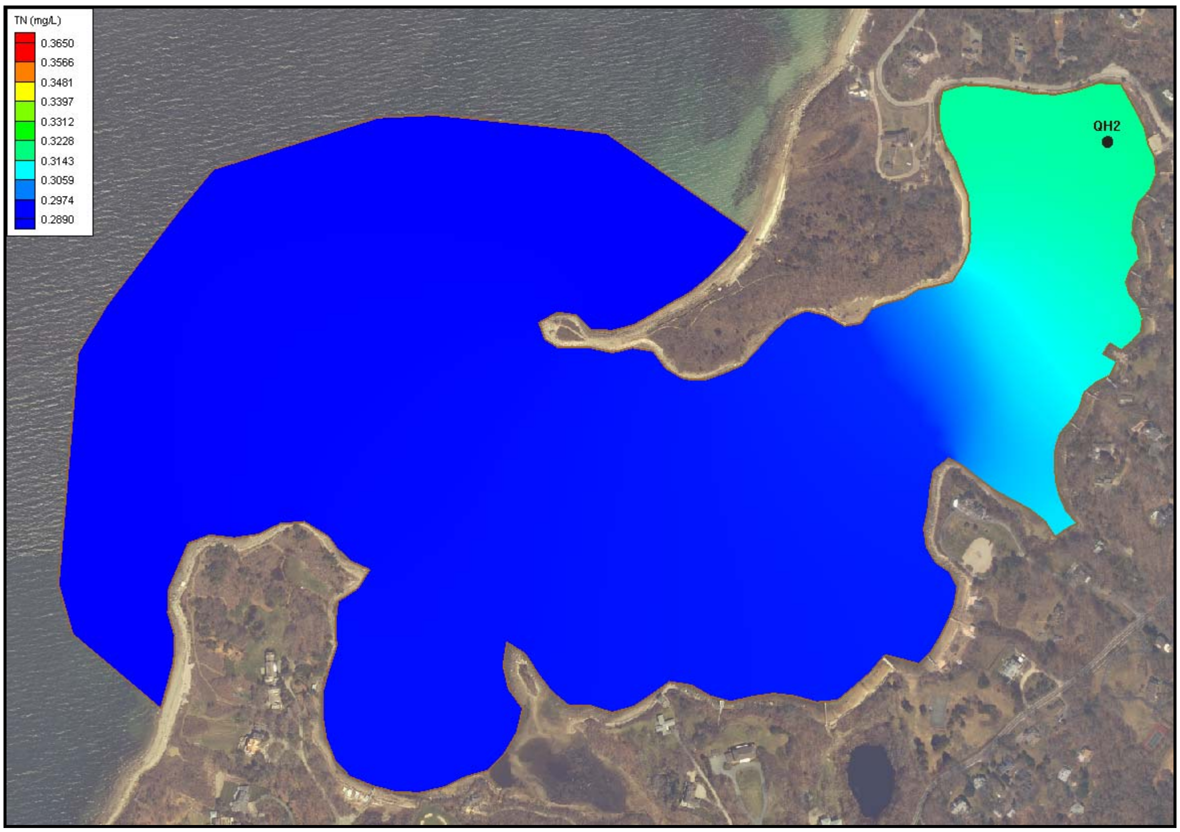

Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Quissett Harbor System, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Quissett Harbor System (QH2) is shown.

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 Quissett Harbor embayment system in the Town of Falmouth, MA, our assessment is based upon data from the water quality monitoring database (1999-2009) developed by the Coalition for Buzzards Bay, surveys of eelgrass distribution (1951, 1995, 2001, 2006), 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 the overall system (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. Quissett Harbor has enhanced nitrogen loading from the associated watershed from shifting land-uses and has circulation modified by a sand shoal separating the 2 component basins. Fundamentally, tidal exchange or circulation alters the sensitivity of an estuary or sub-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 in Quissett Harbor at locations that would be representative of the dissolved oxygen conditions at critical locations across the system, namely a mid-location in the outer portion of the harbor and a location centrally located within the inner most portion of the system (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 within the Quissett Harbor 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

Figure VII-1. Aerial Photograph of the Quissett Harbor system in the Town of Falmouth showing the location of the continuously recording Dissolved Oxygen / Chlorophyll-a sensors deployed during the Summer of 2005.

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. Analysis of inorganic N/P molar ratios within the watercolumn of Quissett Harbor supports this contention that nitrogen is the nutrient to be managed, as the ratio in the inner and outer basins are 4 and 2, respectively, clearly below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production in this system. Within the Quissett Harbor system, temporal changes in eelgrass distribution could provide a basis for evaluating recent increases (nitrogen loading) or decreases in nutrient enrichment as there was identifiable eelgrass in 1951, 1995, 2001 and 2006. As a result, nutrient threshold determination was based on results from the dissolved oxygen and chlorophyll mooring data, the eelgrass distribution as well as the benthic infaunal community characterization.

In areas that do not support eelgrass beds presently (such as the inner most portion of the Quissett Harbor system), 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 (Sanders, H.L. 1960, Sanders, H.L. *et.al.*, 1980, Tian, Y.Q., J.J. Wang, J. A. Duff, B.L. Howes and A. Evgenidou. 2009) and New Bedford (Howes, B.L. and C.T. Taylor, 1990), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H') and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4 mg L-1. Massachusetts State Water Quality Classification indicates that SA (high quality) waters be able to maintain oxygen levels above 6 mg L-1. The tidal waters of the Quissett Harbor embayment 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 and that it is the designated water quality that is the target of TMDLs generated under the U.S. Clean Water Act. It is through the MEP and TMDL processes that site specific management targets are developed and under the Town's CWMP that management alternatives are designed 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 bottom of the embayment within key regions of the Quissett Harbor system (Figure VII-1). The dissolved oxygen sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployments. In addition periodic calibration samples were collected at the depth of each sensor and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 20-30 days within the interval from July through mid-September. All of the mooring data from the Quissett Harbor system were collected during the summer of 2005. These data are supplemented by the traditional "grab" sampling data from the water quality monitoring program, which generally collects <15 time points per summer, but is conducted over several years.

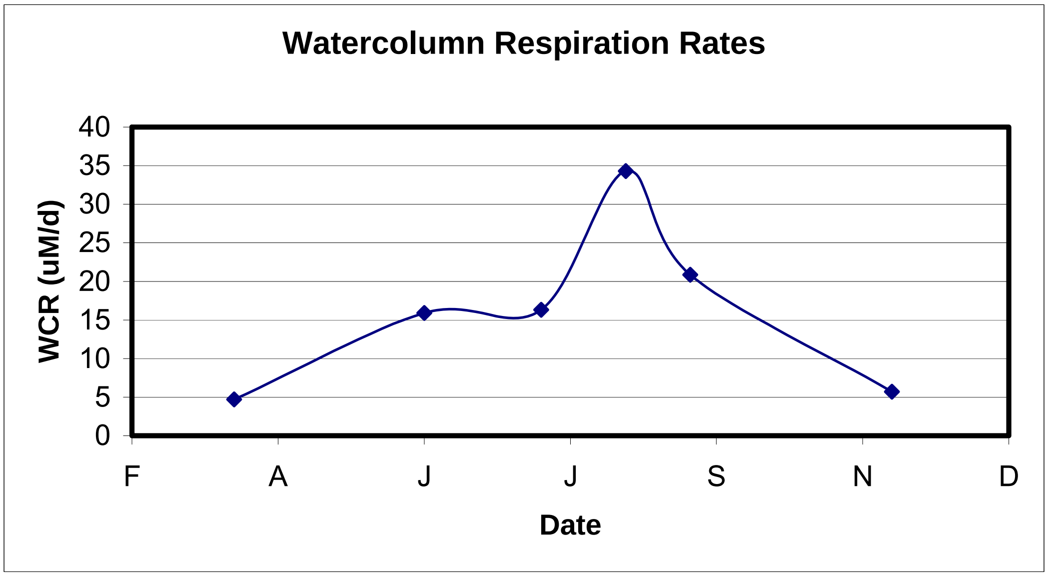

Figure VII-2. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

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

Dissolved oxygen and chlorophyll-a records were examined both for temporal trends and to determine the percent of the 24 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1 and VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

The level of bottom water oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels indicate moderately nutrient enriched waters within the innermost region of the inner basin of the Quissett Harbor system and slightly nutrient enriched waters within the outer basin. The bottom water dissolved oxygen data is further described below and depicted in Figures VII-3 through VII-6). The oxygen data is consistent with organic matter deposition in the inner basin, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-a. The measured levels of oxygen depletion and enhanced chlorophyll-a levels follows the spatial pattern of total nitrogen levels in this system (Chapter VI), and the parallel variation in these water quality parameters is consistent with the moderate level of watershed based nitrogen enrichment of the Quissett Harbor System.

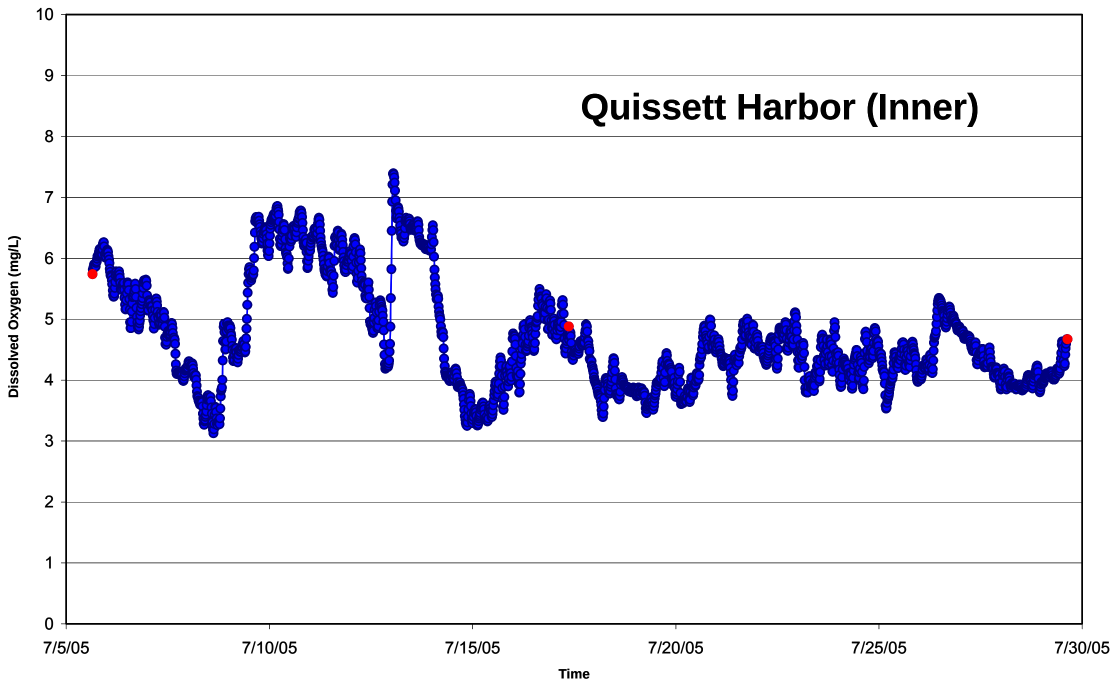

Figure VII-3. Bottom water record of dissolved oxygen at the innermost portion of the Inner Basin to Quissett Harbor (Inner station) in Summer 2005. The mooring was placed to capture the greatest level of oxygen depletion within the estuary. Calibration samples represented as red dots.

The oxygen records obtained from both the moorings deployed in Quissett Harbor show a greater degree of oxygen depletion in the inner versus outer harbor, consistent with the basin structure, flushing, and nitrogen and chlorophyll-a levels. The northern most basin (Quissett Harbor-inner) has modest daily oxygen excursions indicative of low-moderate nitrogen enrichment, while the outer basin shows only a small range in diurnal oxygen excursion. However, dissolved oxygen levels were observed to regularly drop below the 4 mg L^{-1} oxygen threshold in the deep waters of the inner basin indicating a moderate level of dissolved oxygen stress. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The infrequent excursions above atmospheric equilibration indicate that both Quissett Harbor basins are showing the effects of nitrogen enrichment. It should be noted, however, that the dissolved oxygen record in this part of the harbor is not significantly above atmospheric equilibration levels as observed in other significantly impaired systems on Cape Cod. The embayment specific results are as follows:

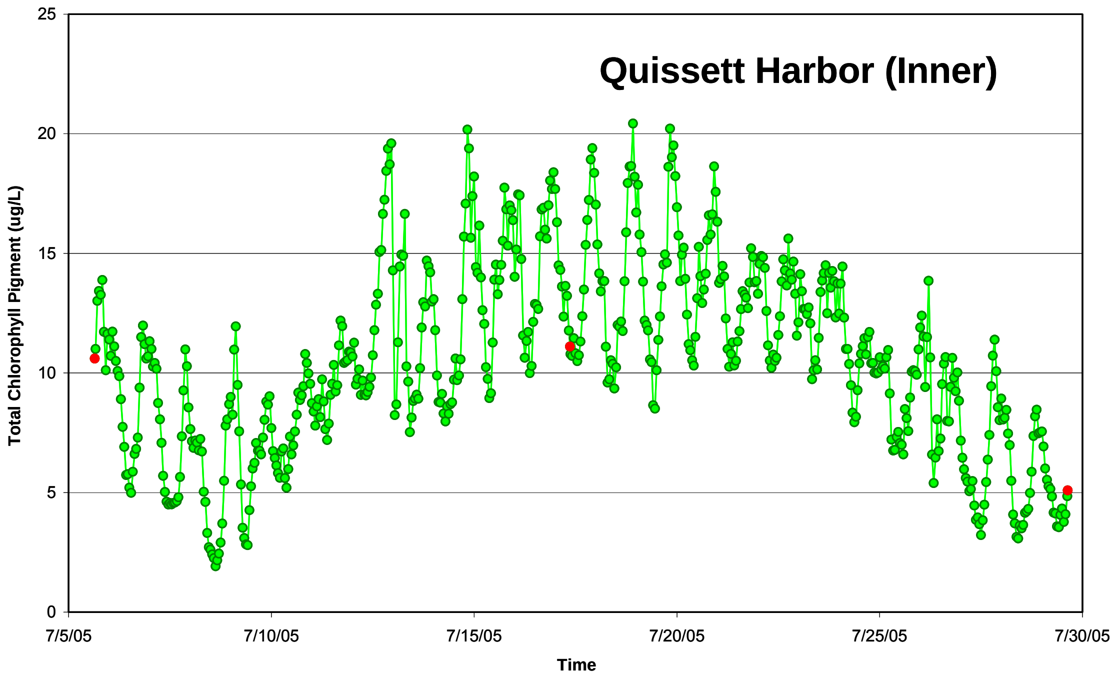

Figure VII-4. Bottom water record of Chlorophyll-*a* in the Quissett Harbor (Inner) station, Summer 2005. Calibration samples represented as red dots.

Quissett Harbor-Inner Basin DO/CHLA Mooring (Figures VII-3 and VII-4):

Two moorings were deployed in the Quissett Harbor system. One of the two instrument moorings was located in the inner most portion of the inner basin of the Harbor, farthest from the inlet connecting the estuary to the low nutrient water in Buzzards Bay. The mooring measured the deep bottom waters of the basin, and was placed to capture the greatest level of oxygen depletion in this embayment. Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at or just above air equilibration to slightly hypoxic conditions where levels decline to 4 mg L^{-1} and periodically to as low as 3.1 mg L^{-1} (Figure VII-3, Table VII-1). The water quality monitoring program (Coalition for Buzzards Bay) found only 4 of 175 samples to be in the 3 to 4 mg L^{-1} range, the remainder being >4 mg L^{-1} from 1993 to 2010. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The organic enrichment of the system is demonstrated by the moderate level of phytoplankton biomass (e.g. chlorophyll-a, Figure VII-4) observed during the MEP DO meter deployment period. It should be noted that the range of the observed oxygen excursions is small compared to other estuarine systems in the Town of Falmouth, which also have higher chlorophyll levels, nitrogen enrichment and oxygen depletion consistent with their observed significant habitat impairments.

Based on the MEP DO mooring program, oxygen levels exceeded 6 mg L^{-1} only 21 percent of the deployment period and rarely exceeded 7 mg L^{-1}. Moreover, oxygen levels dropped below 4 mg L^{-1} 22 percent of the deployment period but never declined to 3 mg L^{-1}. Declines to <3 and to 1.0 mg L-1 are a common occurrence in the moderately to highly impaired systems on Cape Cod. These oxygen levels, are consistent with a system that is beginning to show the effects of nitrogen enrichment and is presently at the boundary of impairment to benthic communities. The slight to moderate diurnal oxygen excursions result from the combined effects of day time photosynthesis and night time respiration, primarily in the water column. Over the 24 day deployment there does appear to be a clear period of enhanced phytoplankton biomass where chlorophyll-a increased to 10-15 ug L^{-1}. The periodic low levels of oxygen observed in this system is indicative of slight to moderate habitat impairment which is also consistent with the somewhat elevated chlorophyll-a levels, also indicative of nitrogen enrichment (mooring chlorophyll-a average 10.6 ug L^{-1}). In the innermost portion of the inner basin of the Quissett Harbor system, chlorophyll-a exceeded the 10 ug L^{-1} benchmark 57 percent of the time (Table VII-2, Figure VII-4). Average chlorophyll levels over 10 ug L-1 have been used to indicate nitrogen enrichment in temperate embayments (Cooksey, C. J. Harvey, L. Harwell, J. Hyland, and J. Summers. 2010).

Quissett Harbor-Main Basin DO/CHLA Mooring (Figures VII-5 and VII-6):

The second of the two instrument moorings (Quissett Harbor-main) deployed in the Quissett Harbor system was located approximately midway in the outer basin toward the southern shore. This mooring is relatively well exposed to low nutrient waters entering Quissett Harbor from Buzzards Bay and was positioned to capture the general conditions of the deep waters of the outer basin. Oxygen conditions at this location exhibited little diurnal or tidal variation in oxygen levels. Oxygen concentrations generally ranged between 5 and 7 mg L^{-1} and rarely exceed air equilibration (over 8 mg L^{-1}). Moreover, oxygen levels rarely declined to 4 mg L^{-1} (Figure VII-5, Table VII-1) and the water quality monitoring samples (Coalition for Buzzards Bay) did not show oxygen to be <5 mg L^{-1} from 1992 to 2010. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The low organic enrichment in this portion of the system is also seen in the generally low phytoplankton biomass (e.g. chlorophyll-a levels).

Based on the MEP DO mooring program, oxygen levels rarely exceeded 8 mg L^{-1} and were typically between 5 and 7 mg L^{-1}. This oxygen regime is consistent with low nutrient concentrations and low phytoplankton biomass in this basin coupled with tidal exchange with the high quality waters of Buzzards Bay. Chlorophyll-a regularly remained between 5-10 ug L^{-1} and only occasionally increased to 10-15 ug L^{-1} (~5 days). The levels of oxygen observed in this system is indicative of a generally high quality system showing little evidence of the effects of nitrogen enrichment. In this basin of the Quissett Harbor system, chlorophyll-a exceeded the 10 ug L^{-1} benchmark 12 percent of the time (Table VII-2, Figure VII-6). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments (Cooksey, C. J. Harvey, L. Harwell, J. Hyland, and J. Summers. 2010).

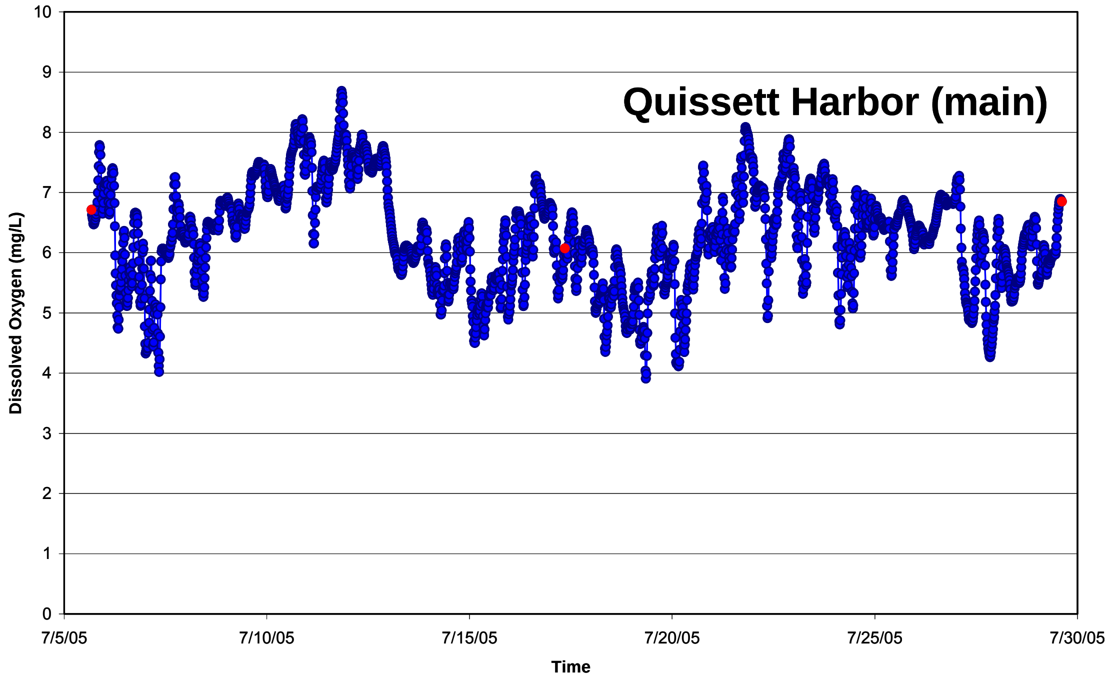

Figure VII-5. Bottom water record of dissolved oxygen at the Quissett Harbor (main) station, Summer 2006. Calibration samples represented as red dots.

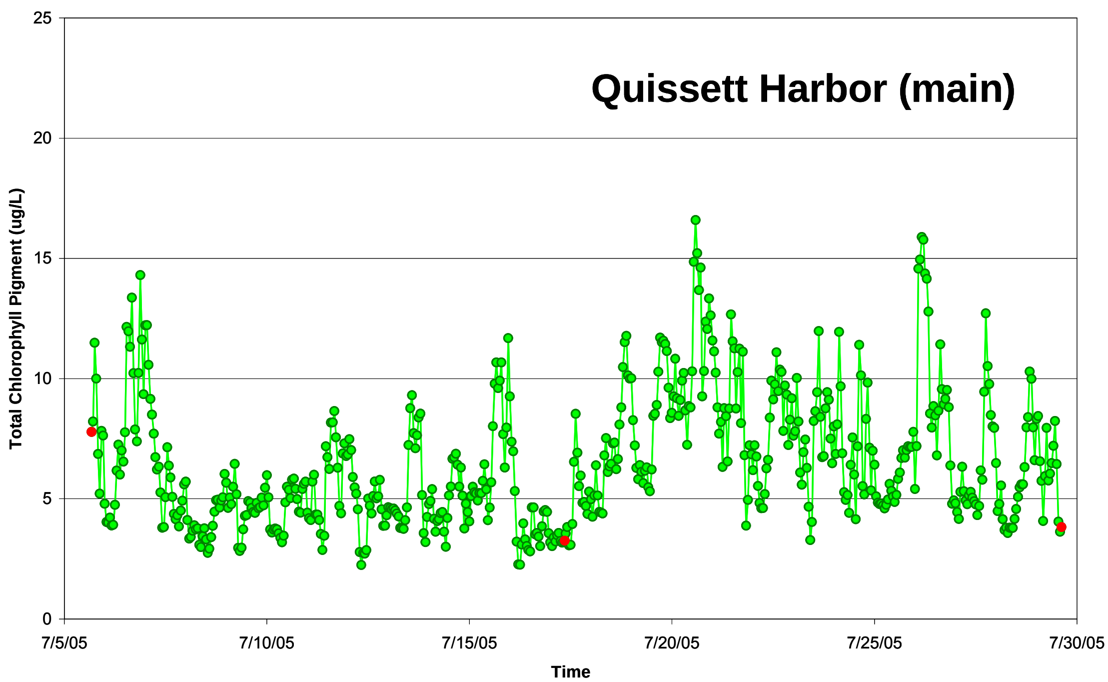

Figure VII-6. Bottom water record of Chlorophyll-*a* in the Quissett Harbor (main) station, Summer 2005. Calibration samples represented as red dots.

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 Quissett Harbor embayment system. 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)
Quissett (Inner)	**7/5/2005**	**7/29/2005**	**24.00**	**86%**	**60%**	**22%**	**0.0%**
			Mean	1.72	0.91	0.16	NA
			Min	0.01	0.03	0.01	0.00
			Max	15.58	4.51	1.03	0.00
			S.D.	4.48	1.41	0.25	NA
Quissett (Main)	**7/5/2005**	**7/29/2005**	**23.95**	**36%**	**7%**	**0.1%**	**0.0%**
			Mean	0.18	0.10	0.02	NA
			Min	0.01	0.02	0.02	0.00
			Max	0.95	0.23	0.02	0.00
			S.D.	0.21	0.07	NA	NA

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

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)
Quissett Harbor (main)	**7/5/2005**	**7/29/2005**	**23.94**	**64%**	**12%**	**1%**	**0%**	**0%**
Mean Chl Value = 6.5 ug/L			**Mean**	0.37	0.10	0.08	NA	NA
			Min	0.04	0.04	0.08	0.00	0.00
			Max	3.50	0.33	0.08	0.00	0.00
			S.D.	0.59	0.09	0.00	NA	NA
Quissett Harbor (Inner)	**7/5/2005**	**7/29/2005**	**23.99**	**91%**	**57%**	**13%**	**1%**	**0%**
Mean Chl Value = 10.6 ug/L			**Mean**	2.43	0.47	0.21	0.04	NA
			Min	0.04	0.04	0.04	0.04	0.00
			Max	17.88	3.83	0.46	0.04	0.00
			S.D.	5.80	0.77	0.16	0.00	NA

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass distribution and analysis of historical data was conducted for the Quissett Harbor Embayment System by the MassDEP Eelgrass Mapping Program as part of the MEP technical effort. Assessment of eelgrass coverage within the Harbor basins was conducted in 1995, 2001 and 2006 by MassDEP, as part of this program. Additional observations during summer and fall 2005 were conducted by the SMAST/MEP Technical Team as part of associated MEP field data collection efforts. Analysis of available aerial photography from 1951 was conducted to reconstruct the eelgrass distribution prior to the present level of development in the watershed, however, there is some uncertainty as to the validity of the 1951 coverage in the innermost deep basin of the harbor. The primary use of the eelgrass data within the MEP approach is to indicate (a) if eelgrass once or currently colonizes a basin and (b) identify any large-scale system-wide shifts in distribution. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 to 2006 (Figure VII-7). These data were also compared with an eelgrass survey in the mid 1980's (Costa 1988), thus increasing the validity of the overall assessment of eelgrass trends in Quissett Harbor. Temporal changes in eelgrass distribution are frequently used to determine the stability of the eelgrass community in coastal systems.

All of the available information on eelgrass within the Quissett Harbor System indicates that the Quissett Harbor main basin has and continues to support significant eelgrass beds, though there is some evidence of a decline in acreage over the past 6 decades. The importance of the apparent loss of the eelgrass in the Quissett Harbor inner basin in the vicinity of the Quissett Harbor Yacht Club and the Quissett Harbor Boatyard is worth noting, as that area did support some eelgrass based on the 1995 and 2001 MassDEP surveys. However, the mid-1980's survey only indicated a sparse eelgrass patch in this region. By comparison, the noted coverage in the Quissett Harbor main basin is similar to the 1951 and 1995 MassDEP survey results. Therefore it appears that the real extent of eelgrass "loss" along this margin of the Quissett Harbor inner basin cannot be unequivocally documented based upon the available data. While Quissett Harbor does support some of the highest water quality of estuaries on Buzzards Bay, recent apparent decline in eelgrass habitat indicates that this system is at or just beyond its threshold level of nitrogen enrichment and further increases in nitrogen loading will almost certainly drive a significant decline in eelgrass habitat in the system.

Other factors which influence eelgrass bed loss in embayments may also be at play in the Quissett Harbor system, though the general loss seems completely in-line with nitrogen enrichment. Localized losses within the Harbor from these other factors are possible. Therefore, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as the Quissett Harbor system generally supports a high density of boat moorings in the areas where eelgrass habitat is prevalent as well as in areas where loss has occurred. Similarly, pier construction and boating pressure may be adding additional stress but seem to be relatively minor factors in the overall system. However, stress associated with boating activities cannot be ruled out relative to the possible loss from the margin of the inner basin near the Quissett Harbor Yacht Club and the Quissett Harbor Boatyard. While in other systems, pressure on eelgrass from shellfishing activity can be significant, that would not be the case in Quissett Harbor as shellfishing is approved year round in the area that has the most eelgrass presently and is prohibited during much of the year in the inner most area of the harbor where eelgrass no longer exists.

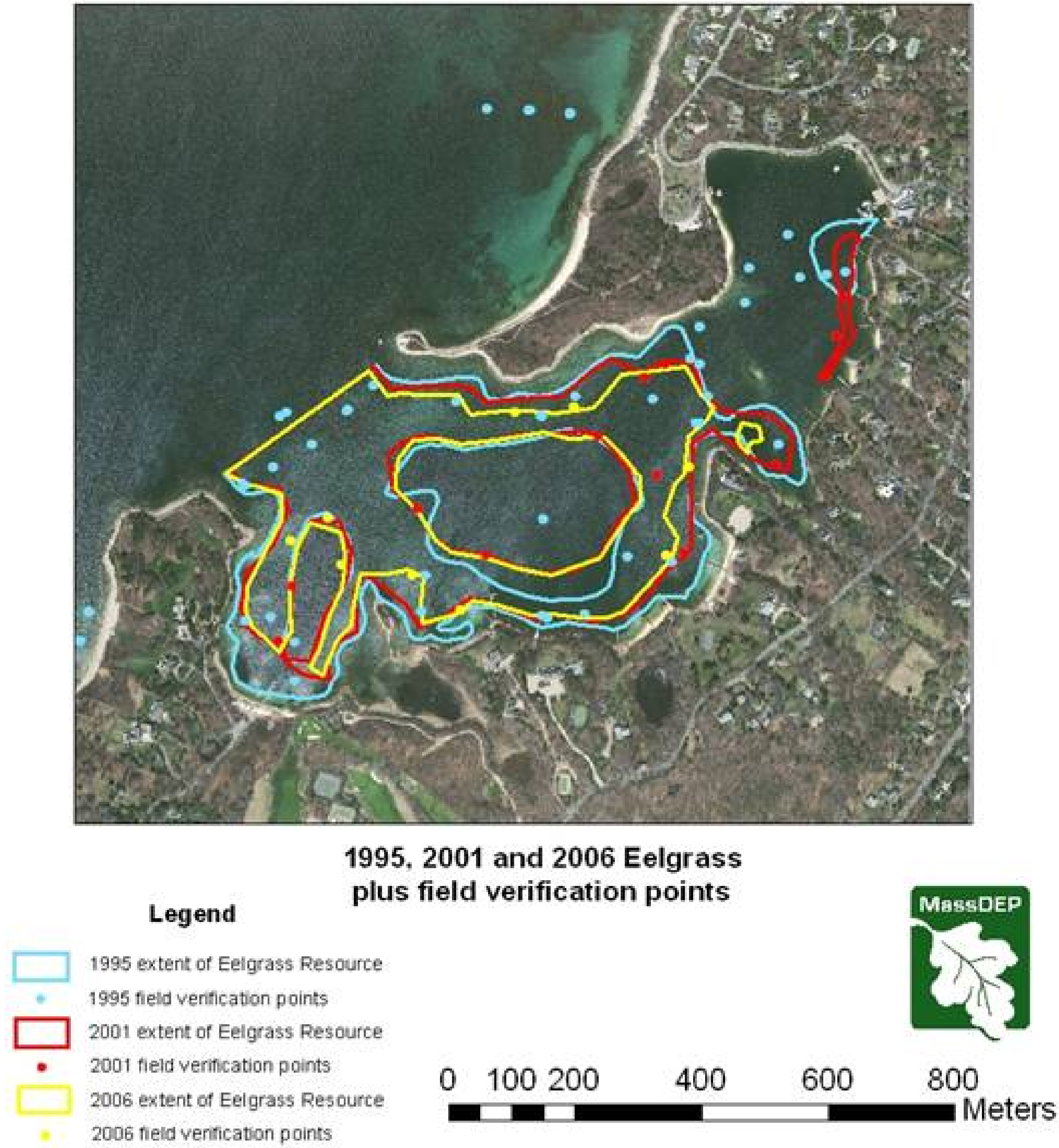

Figure VII-7. Eelgrass bed distribution throughout Quissett Harbor. Beds delineated in 1995 beds are circumscribed by the blue outline, 2001 beds are circumscribed by the red line and 2006 beds are circumscribed by the yellow line (map from the MassDEP Eelgrass Mapping Program). Eelgrass was observed during the SMAST-MEP survey conducted in 2006 during other data collection efforts.

Based on the available data, it is possible to utilize the 1995 coverage data as an indication that eelgrass beds might be recovered if nitrogen management alternatives were implemented (Table VII-3). This determination is based upon the MassDEP Mapping Program and would indicate that an area of eelgrass habitat within Quissett Harbor of approximately 15 acres could be recovered at a minimum. If one were to base the comparison to the more uncertain 1951 coverage which shows some eelgrass in the innermost basin of Quissett Harbor, closer to 39 acres could be recovered, assuming that basin can really support eelgrass and that there really was eelgrass present in that basin in 1951.

The relative pattern of habitat quality based upon the eelgrass data is consistent with the results of the oxygen and chlorophyll time-series data (Section VII.2), nitrogen levels within the inner and outer basins (Section VI) and the benthic infauna analysis (Section VII.4). The absence of eelgrass beds from the inner basin and significant coverage in the outer basin is supported by the low phytoplankton levels (low turbidity) and low nitrogen levels in the outer versus inner basin waters and both the pattern of coverage and the associated levels of the key nutrient related water quality parameters that are typical of nutrient enriched shallow embayments.

Table VII-3. Temporal changes in eelgrass coverage in the Quissett Embayment System within the Town of Falmouth 1951 to 2006 (MassDEP, C. Costello).

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	2006 (acres)	% Difference (1995 to 2006)
Quissett Harbor	indeterminate	51.72	44.40	36.38	30%

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 15 locations within the Quissett Harbor Embayment System (Figure VII-8), 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 it is clear that eelgrass habitat within the main (outer) basin of Quissett Harbor has been relatively stable from 1951 to present, with only some apparent loss at the border with the Quissett Harbor inner basin. This apparent loss may be the result of the system reaching its assimilative capacity of nitrogen. To the extent that the overall system can support not only eelgrass but more diverse benthic infaunal communities, the benthic infauna analysis is important for determining the level of habitat impairment (healthy→moderately impaired→significantly impaired→severely degraded) and what nutrient concentrations are supportive of healthy habitat. This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

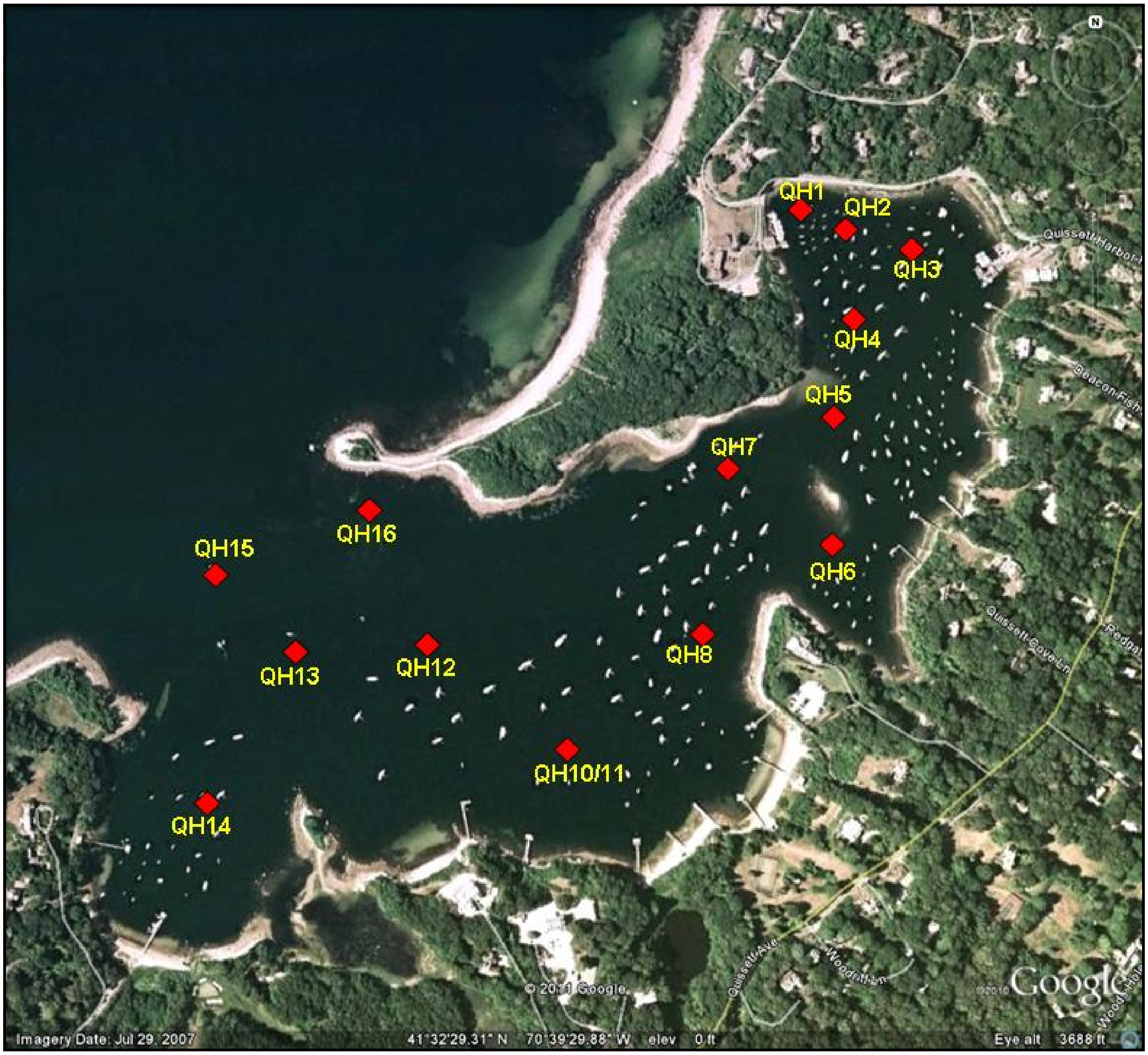

Figure VII-8. Aerial photograph of the Quissett Harbor system showing location of benthic infaunal sampling stations (red symbols). QH10/11 is the location of a duplicate sample.

Analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information. The evenness statistic 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.

Quissett Harbor Infaunal Characteristics:

Overall, the infauna survey indicated that both the Quissett Harbor main basin and Quissett Harbor inner basins generally support high quality benthic habitat, although the inner basin supports a slightly lower quality habitat than the main (outer) basin. However, localized areas are showing a moderate level of impairment, specifically the deepest portion of the inner basin and the deep region of the cove in the main basin. It appears that organic deposition in these areas is the cause of the stress, which is supported by the deep water oxygen levels at the inner basin sites (Table VII-4).

Throughout Quissett Harbor, infaunal animal communities colonizing sediments at depths less than 4.5 meters or throughout the main basin are diverse ($\geq$22 species) and productive (>400 individuals per sample). The Quissett Harbor main basin generally ranked high based upon the key community indices, the Weiner Diversity Index (H') and Eveness, which had values greater than 3.4 and 0.77, respectively. The more enriched nature of the inner basin can be seen in the slightly lower Index values of >2.6 (H') and ~0.60 (E). Equally important the species dominating the communities were generally representative of non-stressed environments, except for the deep stations in the inner basin. These stations (QH-3, QH-4) were dominated by organic enrichment indicators (tubificids, capitellids) and low numbers of individuals. The marginal areas in the inner basin were dominated by a mixture of species indicative of low and moderate levels of enrichment (amphipods, and a variety of crustaceans, mollusks and polychaete worms). The main basin supported diverse communities of polychaetes, molluscs and crustaceans typically associated with high quality coastal environments. The levels of diversity and the species numbers present in the main basin of Quissett Harbor are among the highest encountered throughout the MEP region. While the inner basin is supporting a productive benthic animal habitat, it is clearly moderately impaired, as evidenced by the diversity <3 and Evenness <0.7, the lower number of species present, the dominance of stress tolerant species in some samples and the occurrence of periodic oxygen declines to 3-4 mg L-1 level of organic matter enrichment. This pattern of higher organic enrichment and lower habitat quality in the inner versus main basin (outer) regions is common to estuaries in general.

The high quality benthic animal habitat regions of Quissett Harbor are similar to other low nutrient estuarine basins. For example, the outer stations within Lewis Bay in Barnstable currently support high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Eveness (0.74). Equally important the community is not consistent with nutrient enrichment and is composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms.

However, the reason for the moderate to healthy benthic animal habitat in the inner basin appears to result from its low level of nitrogen enrichment coupled to its basin morphology, which tends to create a depositional environment. The depositional nature of the deep region of the inner basin is confirmed by its organic enriched sediments and the periodic oxygen declines to <4 mg L^{-1}. The importance of the basin morphology can be seen in the sample from the small deep basin comprising the cove situated on the southern shore of the main basin, which showed similar habitat to the deep region of the Inner Basin. Integration of all of the metrics clearly indicates that the main basin is generally supporting high quality benthic animal habitat, while the inner basin is just beyond its capacity to assimilate nitrogen loads without impairment (i.e. is just beyond its nitrogen threshold). Since Quissett Harbor is also just beyond its nitrogen threshold to support healthy eelgrass habitat, a slight reduction to enhance this habitat should also reverse the moderate impairment presently observed in the inner basin benthic relative to animal habitat.

Table VII-4. Benthic infaunal community data for the Quissett Harbor embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Stations refer to map in Figure VII-8.

	Station	Total Species	Total Individuals	#Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Quissett Harbor (Inner)						
Inner Margin	**1,2**	**23**	**720**	**13**	**2.64**	**0.59**
Central	**3,4,**	**9**	**52**	**NA**	**2.59**	**0.82**
Outer Margin	**5,6,7**	**22**	**499**	**12**	**2.70**	**0.60**
Quissett Harbor (Main)						
Inner Margin	**8**	**33**	**543**	**19**	**3.97**	**0.79**
Central	**10,12,13**	**28**	**412**	**19**	**3.70**	**0.77**
Cove	**14**	**16**	**336**	**15**	**3.41**	**0.85**
Outer Margin	**15,16**	**24**	**411**	**17**	**3.53**	**0.77**
Station numbers refer to ID's on maps presented above.						

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-9). As is the case with some systems on Cape Cod, a portion of the enclosed waters of Quissett Harbor are classified as conditionally approved for the taking of shellfish during specific periods of the year. This would indicate the system is impaired relative to the taking of shellfish. This is most likely due to the potential influence of the Quissett Harbor Boatyard as well as the density of moored boats in the inner portion of the harbor, as well as inputs from natural fauna (though this is likely a minor factor in this system) in the least well flushed region of this embayment. Unlike the inner harbor, the better flushed outer harbor is approved for shellfishing year round.

Despite the status of conditionally approved for the inner harbor, the Quissett Harbor system has also been classified as supportive of specific shellfish communities (Figure VII-10). The major shellfish species with potential habitat within the Quissett Harbor Estuary is mainly quahogs (*Mercenaria*). A small portion of the harbor along the shore of the inner basin as well as the harbor side shore of the peninsula that terminates at the Knob has been identified as potential habitat supportive of soft shell clams (*Mya*). A small area off Gansett Point was also identified as suitable habitat for blue mussel. Lastly, the shallow water along the shoreline in the middle reach of the harbor as well as in the vicinity of the sand shoal that separates the outer harbor from the inner harbor was classified as suitable for the American oyster. It should be noted that the observed pattern of shellfish suitability area is consistent with the observed depositional organic matter enriched sediments within the inner portion of the Quissett Harbor system.

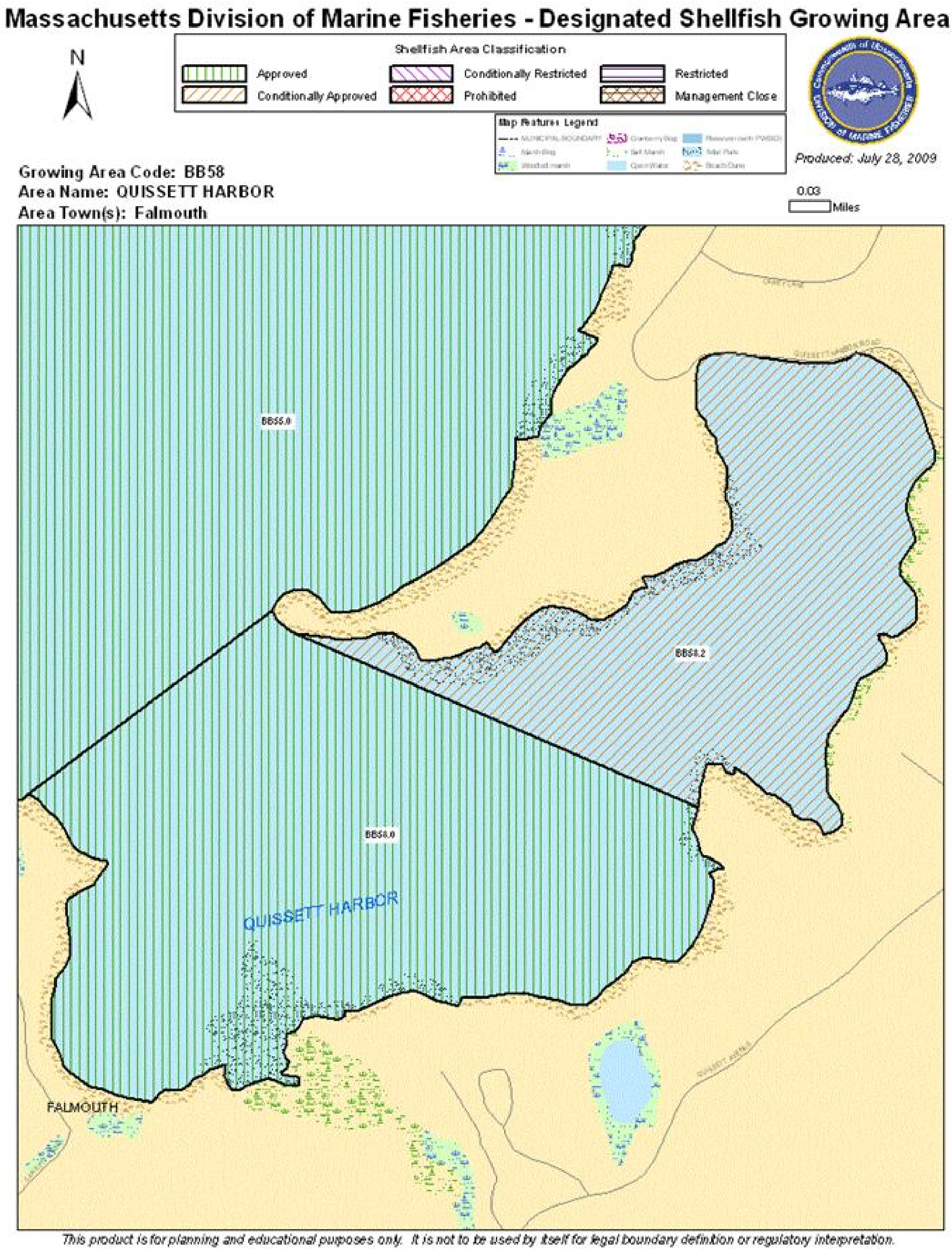

Figure VII-9. Location of shellfish growing areas in the Quissett Harbor embayment system and the status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

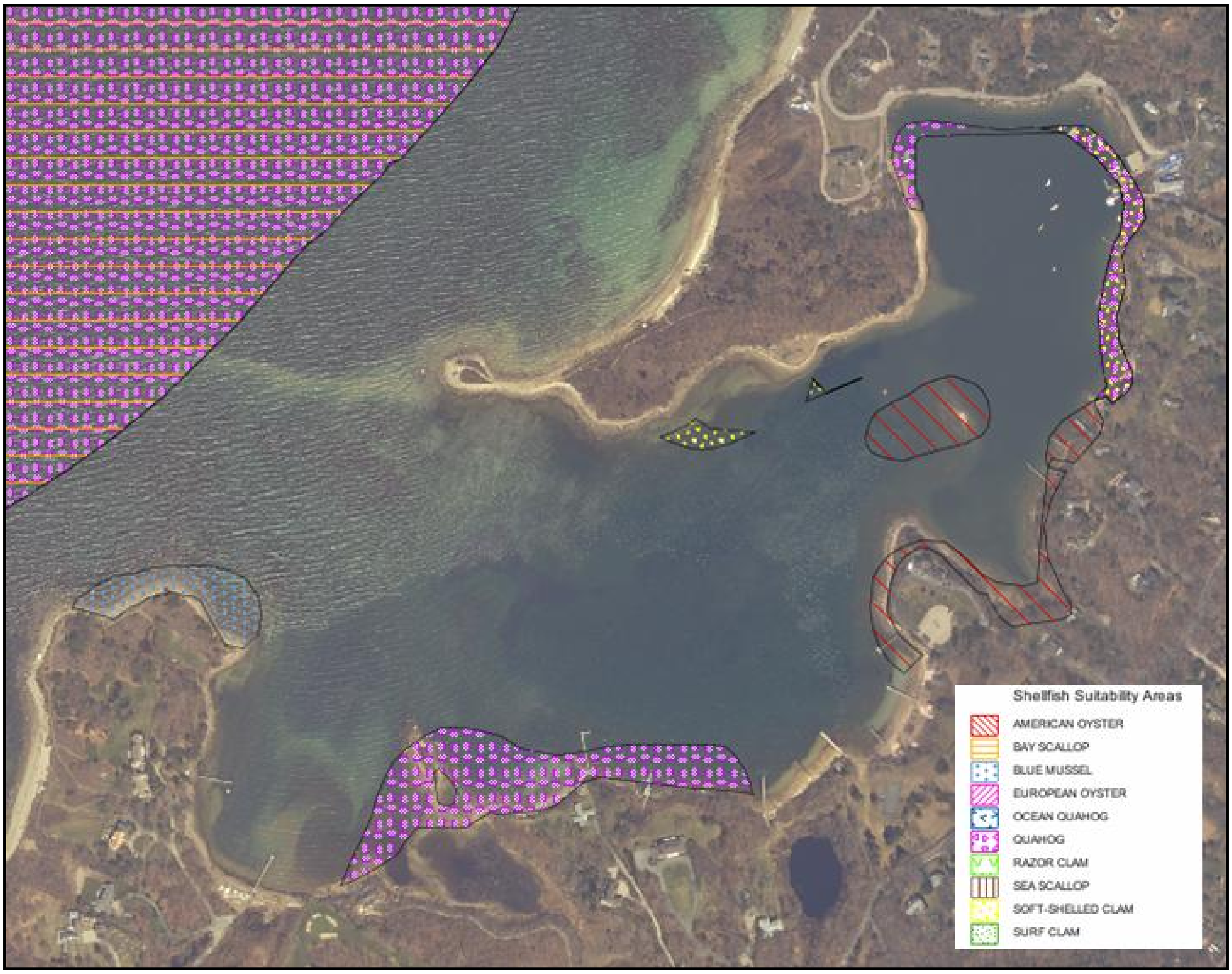

Figure VII-10 Location of shellfish suitability areas within the Quissett Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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 by the MEP to support threshold development for the Quissett Harbor Embayment System 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 Water Quality Monitoring Program conducted by the Coalition for Buzzards Bay's BayWatcher, with analytical support from the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

The Quissett Harbor Embayment System is a simple estuary created by the drowning of a coastal kettle on the southern Cape Cod margin of Buzzards Bay by rising sea levels several thousand years ago. The Harbor consists of an inner and outer basin with deep central regions (>5 meters). While there is fringing salt marsh, Quissett Harbor is currently functioning as a typical coastal embayment with free tidal exchange with the waters of Buzzards Bay. Each type of functional component to an estuary (salt marsh basin, embayment, tidal river, deep basin {sometimes drown 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 Quissett Harbor Estuary is just beyond its ability to assimilate nitrogen without impairment and is showing a low level of nitrogen enrichment, with some moderate impairment of both eelgrass and infaunal habitats (Table VIII-1). This indicates that nitrogen management of this system will be for restoration rather than for protection or maintenance of an unimpaired system.

The measured levels of oxygen depletion and enhanced chlorophyll a levels follows the spatial pattern of total nitrogen levels in this system (Chapter 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 the outer basin and were highest within the inner basin.

Oxygen records obtained from both the moorings deployed in Quissett Harbor show a greater degree of oxygen depletion in the Inner versus Outer basins, consistent with the basin structure, flushing, and nitrogen and chlorophyll a levels. The Inner basin mooring measured the deep bottom waters of the basin, and was placed to capture the greatest level of oxygen depletion in this embayment. Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at or just above air equilibration to slightly hypoxic conditions where levels decline to 4 mg L^{-1} and periodically to as low as 3.1 mg L^{-1} (Figure VII-3, Table VII-1). Oxygen levels exceeded 6 mg L^{-1} only 21 percent of the deployment period and rarely exceeded 7 mg L^{-1}. Moreover, oxygen levels dropped below 4 mg L^{-1} 22 percent of the deployment period but never declined to 3 mg L^{-1}. Declines to <3 and to <1.0 mg L-1 are a common occurrence in the moderately to highly impaired systems on Cape Cod. Instantaneous oxygen levels that

Table VIII-1. Summary of nutrient related habitat quality within the Quissett Harbor Embayment within the Town of Falmouth, MA, based upon assessments in Section VII.

Health Indicator	Quissett Harbor Embayment System	
	Main Basin	**Inner basin**
Dissolved Oxygen	H/MI[1]	MI[2]
Chlorophyll	H[3]	H/MI[4]
Macroalgae	H[5]	H[5]
Eelgrass	H/MI[6]	--[7]
Infaunal Animals	H[8]	H/MI[9]
Overall:	**H/MI[10]**	**MI[11]**

1- deep water mooring oxygen always >4 mg/L, >5 mg/L 93% of time,
WQMP: always >5 mg/L and >6 mg/L 90% of time
2 -deep water mooring oxygen always > 3mg/L , 3-4 mg/L 22% of time,
WQMP: <6 mg/L 23% of samples, 2% of samples <4 mg/L, none <3mg/L.
3 - levels low for a coastal basin, averaging 6.5 ug L^{-1}, <10 ug L^{-1} 88% of record;
WQMP: 94% of samples <5 ug L^{-1}, long-term average 3 ug L^{-1}
4 - levels low to moderate for a coastal basin, mooring average 10.6 ug L^{-1}, but "bloom" event 10-15 ug L-1; WQMP 23% of samples >5 ug L^{-1} , long-term average 4 ug L^{-1}
5- drift algae generally absent, some small patches
6- most of the basin supports high quality eelgrass habitat, loss of some fringing beds within the boundary region between the Outer and Inner basins. The temporal and spatial pattern of this loss from the inner margin of the beds is typical of nitrogen enrichment effects.
7- evidence of eelgrass "presence" in this basin, but density unclear.
8- high numbers of individuals, species (25), diversity (>3) and Evenness (>0.7), community dominated by non-stress indicator species with crustaceans and mollusks, some deep burrowers.
9 - community includes crustaceans and mollusks and some deep burrowers, with some organic enrichment tolerant species; moderate to high diversity and Evenness, numbers of species and individuals. Deep region has organic enriched sediments and low number s of individuals from enrichment tolerant species consistent with the sediments and periodic D.O. depletion to <4 mg/L.
10 - Stable high quality eelgrass habitat from 1951 to present with only recent loss at the margin to the Inner basin; benthic infaunal animal communities are among the most diverse and productive on Cape Cod, with the exception of the deep Cove basin. Loss of marginal eelgrass coverage is indicative of a nitrogen enrichment and rates a designation of "Moderate Impairment" coupled with a "High Quality" habitat designation based upon the general eelgrass and benthic habitat indicators, low chlorophyll and generally high D.O.
11 - The moderate levels of phytoplankton biomass, coupled with periodic D.O. depletion (3-4 mg/L) in the deep basin, results in impaired benthic animal habitat, coupled with the recent loss of eelgrass habitat at the boundary between the Inner and Outer basins all indicate moderate impairment from nitrogen enrichment. Increasing nitrogen loading will cause impairments to the high quality benthic animal habitats bordering the deep portion of this basin.

H = High quality habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severely Degraded; -- = not applicable to this estuarine reach
WQMP: Water Quality Monitoring Program

drop below 4 mg L^{-1} are indicative of oxygen stress. The oxygen levels are consistent with a system that is beginning to show the effects of nitrogen enrichment and is presently at the boundary of impairment to benthic communities. The oxygen decline paralleled enhanced phytoplankton biomass, with chlorophyll a reaching 10-15 ug L^{-1}. The periodic low levels of oxygen observed in the Inner basin is indicative of slight to moderate habitat impairment which is also consistent with the moderately elevated chlorophyll a levels, also indicative of nitrogen enrichment (mooring chlorophyll-a average 10.6 ug L^{-1}). In the deep region of the Inner basin of the Quissett Harbor system, chlorophyll-a exceeded the 10 ug L^{-1} benchmark 57 percent of the time (Table VII-2, Figure VII-4). Average chlorophyll levels over 10 ug L-1 have been used to indicate nitrogen enrichment in temperate embayments. Both the oxygen and chlorophyll a data indicate a system with a moderate level of nutrient enrichment, generally associated with stress to benthic (and eelgrass) habitat. However, this stress appears to be primarily focused on the deep central region of the basin.

In contrast, the Outer basin bottom water exhibited little diurnal or tidal variation in oxygen levels and generally supported oxygen levels between 5 and 7 mg L^{-1}, and rarely exceed air equilibration (over 8 mg L^{-1}). Moreover, oxygen levels rarely declined to 4 mg L^{-1} (Figure VII-5, Table VII-1) and the water quality monitoring samples did not observe oxygen declines to <5 mg L^{-1} from 1992 to 2010. The low organic enrichment in this portion of the system is also seen in the generally low phytoplankton biomass (e.g. chlorophyll a levels). Chlorophyll a remained between 5-10 ug L^{-1} and only occasionally increased to 10-15 ug L^{-1} (~5 days). Both oxygen and chlorophyll measurements indicate that the Outer basin is generally of high quality, showing little evidence of the effects of nitrogen enrichment.

All of the available information on eelgrass within the Quissett Harbor System indicates that the outer basin has and continues to support significant eelgrass beds, with the only clear decline in coverage along the boundary between the Inner and Outer basins. The Inner basin has not historically supported significant eelgrass habitat. Although there is some evidence of eelgrass presence within the Inner basin over the past 25 years, in the vicinity of the Quissett Harbor Yacht Club and the Quissett Harbor Boatyard, the density of the coverage is unknown and the pattern of "loss" does not clearly indicate nitrogen enrichment. Review of all of the available data indicate that the extent and cause of eelgrass "loss" along the western margin of the Inner basin cannot be unequivocally documented base upon the available data. In contrast the loss of eelgrass habitat along the boundary between the Outer and Inner basins is well documented (1951, 1987, 1995, 2001, 2006) and the temporal and spatial pattern of this loss from the inner margin of the existing beds is typical of nitrogen enrichment effects. This recent decline in eelgrass habitat indicates that this embayment is just slightly beyond its threshold level of nitrogen enrichment and further increases in nitrogen loading will almost certainly affect a significant decline in eelgrass habitat in the system. The loss of the innermost region of eelgrass beds in the Outer basin and the presence of stable high quality eelgrass habitat throughout the rest of this basin indicate that only a moderate level of impairment to eelgrass habitat exists at present.

Overall, the infauna survey indicated that both the Outer and Inner basins generally support high quality benthic habitat, although the Inner basin supports a slightly lower quality habitat compared to the Outer basin. However, relative to nitrogen enrichment affect, localized areas are showing a moderate level of impairment, specifically the deepest portion of the Inner basin. It appears that organic deposition in these areas is the cause of the stress, which is supported by the observed deep water oxygen levels.

In basin areas less than 4.5 meters depth throughout the Quissett Harbor Embayment System, infaunal animal communities were generally diverse, with a high number of individuals. The Outer basin generally ranked highly based upon the key community indices, the Weiner Diversity Index (H') and Eveness, which had values greater than 3.4 and 0.77, respectively. The more enriched nature of the Inner basin can be seen in the slightly lower Index values of >2.6 (H') and ~0.60 (E). Equally important the species dominating the communities were generally representative of non-stressed environments, except for the deep stations in the Inner basin. These stations (QH-3, QH-4) were dominated by organic enrichment indicators (tubificids, capitellids) and low numbers of individuals. The marginal areas in the Inner basin were dominated by a mixture of species indicative of low to moderate levels of enrichment (amphipods, and a variety of crustaceans, mollusks and polychaete worms). The Outer basin supported diverse communities of polychaetes, mollusks and crustaceans typically associated with high quality coastal environments. The levels of diversity and the species numbers present in Outer basin of Quissett Harbor are among the highest encountered throughout the MEP region. While the Inner basin is supporting a productive benthic animal habitat, it is clearly showing moderate impairment, as evidenced by the diversity <3 and Evenness <0.7, the lower number of species present, the dominance of stress tolerant species at some sites, the occurrence of periodic oxygen declines to 3-4 mg L-1 and level of organic matter enrichment. This pattern of higher organic enrichment and lower habitat quality in the inner versus outer regions is common to estuaries in general.

Although the margins of the Inner basin support a high quality benthic animal habitat, the deep basin region is presently clearly impaired habitat. While the basin morphology, which tends to create a depositional environment, increases the system's sensitivity to organic enrichment, the levels of phytoplankton biomass, the levels of oxygen decline (<4 mg/L) and the organic enrichment of the sediments are clear evidence of nitrogen being the ultimate cause of the habitat impairment. Integration of all of the key metrics clearly indicates that the Outer basin is generally supporting high quality benthic animal habitat, while the Inner basin is just beyond its capacity to assimilate nitrogen loads without impairment (i.e. it is just beyond the nitrogen threshold). Since Quissett Harbor is also just beyond its nitrogen threshold to support healthy eelgrass habitat, a slight reduction to enhance this habitat should also reverse the moderate impairment of the benthic animal habitat within the Inner basin.

In general, the habitat quality within the basins of this System is manifested by the temporal changes in eelgrass coverage and benthic community characteristics, which are consistent with the observed levels of nitrogen and organic matter enrichment and magnitude of oxygen depletion, as well as the sediment characteristics and general absence to only sparse macroalgal accumulations. The distribution and levels of habitat impairment within the Quissett Harbor Embayment System is consistent with the low to moderate level of nitrogen enrichment. The recent losses of historically stable eelgrass habitat at the inner boundary of the Outer basin makes restoration of this resource the primary focus for nitrogen management, with the associated goal of restoring impaired benthic habitat in the deep region of the Inner basin. Determining the nitrogen target to restoring 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 restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined (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 the Quissett Harbor Embayment System 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.

The Quissett Harbor Embayment System presently shows a moderate impairment to eelgrass habitat within its Outer basin. The impairment is based upon the recent temporal trend in loss of eelgrass from the inner margin of the basin, at the Inner basin boundary. Both the location and the temporal trend is consistent with nitrogen enrichment. However, as the rate of loss has been gradual and relatively recent, indicates that this estuary is only just beyond its nitrogen threshold (i.e. the level of nitrogen a system can tolerate without impairment). The presence of stable dense eelgrass beds throughout the outer harbor and the generally high quality benthic animal habitat throughout the embayment system (except for the deep region of the Inner basin) also indicates a system only just beyond its threshold. The indication of impairment to eelgrass and infaunal animal habitat, to the extent that it was observed, is supported by the observed levels of oxygen depletion and clearly enhanced chlorophyll a levels in the Inner basin waters. The spatial distribution of high quality and impaired habitats and associated oxygen and chlorophyll a levels also parallels the gradient in watercolumn total nitrogen levels within this estuary. The tidally averaged total nitrogen being 0.354 and 0.302 mg N L-1 within the Inner and Outer basins, respectively. The relatively low levels of nitrogen are consistent with the general high quality of eelgrass and benthic animal habitat within this system, but the clear enrichment of the Inner basin (and therefore the boundary area losing eelgrass) is consistent with the low level of impairment documented for this estuary. Restoring the impairments to eelgrass and benthic animal habitats is the focus of the nitrogen management threshold analysis (Section VIII.3).

As eelgrass within the Quissett Harbor Embayment System is a critical habitat that structures the productivity and resource quality of the entire system, and as it is presently showing moderate impairment, restoration of this resource is the primary target for overall restoration of this system. Nutrient management planning for restoration of the eelgrass habitat at the boundary between the Outer and Inner basins should focus on reducing the level of nitrogen enrichment in basin waters through watershed nitrogen management.

Based upon the information above and in Chapter VII, and the level of eelgrass impairment it appears that the system is presently only slightly beyond its nitrogen threshold for sustainable eelgrass coverage. This assessment is based upon the distribution of the remaining eelgrass habitat, the observed loss of eelgrass at the boundary of the nitrogen enriched Inner basin and that the decline is slow and relatively recent.

The absence of eelgrass within the bulk of the Inner basin and the loss of even sparse eelgrass coverage along its western margin are associated with tidally averaged nitrogen (total nitrogen, TN) levels of 0.354 mg N L^{-1}, while the Outer basin high quality eelgrass habitat is at lower TN levels, 0.304 mg N L^{-1}. These TN levels and habitat stability/decline are consistent with persistence and loss of eelgrass at similar depths in other estuaries in southeastern Massachusetts.

For example, with the Nantucket Harbor Estuary tidally averaged levels in the lower reach of Head of the Harbor (0.340-0.353) were associated with recent loss of eelgrass coverage, while eelgrass was lost from West Falmouth Harbor when tidally averaged TN exceeded 0.35 mg L^{-1}. The recent relatively small loss (as a percentage of total coverage) of eelgrass from Quissett Harbor indicates a system just beyond its threshold to support an unimpaired eelgrass resource. Therefore, attaining a small decrease in nitrogen levels in the Inner basin should be sufficient to restore eelgrass habitat quality throughout this system. Based upon the present TN levels in the Quissett Harbor System and comparison to other similar estuaries a threshold for tidally averaged TN at the sentinel station in the Inner basin (QH-2) of 0.34 mg was selected.
It should be noted that while this threshold is well constrained by the available data, it is at the limits of the sensitivity of the MEP approach.

This threshold is only slightly lower than that for West Falmouth Harbor and Phinneys Harbor, and is focused in part on restoring eelgrass where it had persisted until recently at the boundary between the Inner and Outer basins. In addition, lowering the level of nitrogen enrichment at the sentinel station will lower nitrogen levels throughout the estuary (Section VIII.3) with the parallel effect of improving infaunal habitats in the impaired region of the Inner basin. Therefore, the goal is to achieve the nitrogen target at the sentinel location and restore the historical eelgrass habitat within Quissett Harbor, resulting also in the restoration of infaunal habitat throughout the System. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Quissett Harbor system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were lowered by reductions in septic effluent discharges, until the nitrogen levels reached the threshold level at the sentinel station chosen for Quissett Harbor. It is important to note that load reductions can be produced by reduction of any or all sources. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment. A comparison between present septic and total watershed loading and the loadings for the two modeled threshold scenarios is provided in Tables VIII-2 and VIII-3.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required 27% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

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

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Quissett Harbor (outer basin)	1.12	1.12	0.0%
Upper Harbor (inner basin)	1.58	0.86	-46.0%
System Total	2.70	1.98	-26.7%

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Quissett Harbor (outer basin)	1.46	1.46	0.0%
Upper Harbor (inner basin)	1.92	1.19	-38.0%
System Total	3.38	2.65	-21.6%

Tables VIII-3 and VIII-4 provide additional loading information associated with the nutrient threshold analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. For Example, removal of 46% of the septic load from the Upper Harbor watershed to the Inner Harbor Basin results in a 38% reduction in total watershed nitrogen load. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent 'worst-case' summertime conditions.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN total watershed load of 22% are required in the system.

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

Table VIII-4. Threshold sub-embayment loads used for total nitrogen modeling of the Quissett Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux			
sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Quissett Harbor (outer basin)	1.46	0.93	-3.16
Upper Harbor (inner basin)	1.19	0.41	3.84
System Total	2.65	1.34	0.68

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Quissett Harbor System. The threshold station is in bold print (0.34 mg/L for QH2).				
Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Quissett Harbor (outer basin)	QH1	0.3016	0.2991	-0.8%
Upper Harbor (inner basin)	**QH2**	**0.3537**	**0.3400**	**-3.9%**

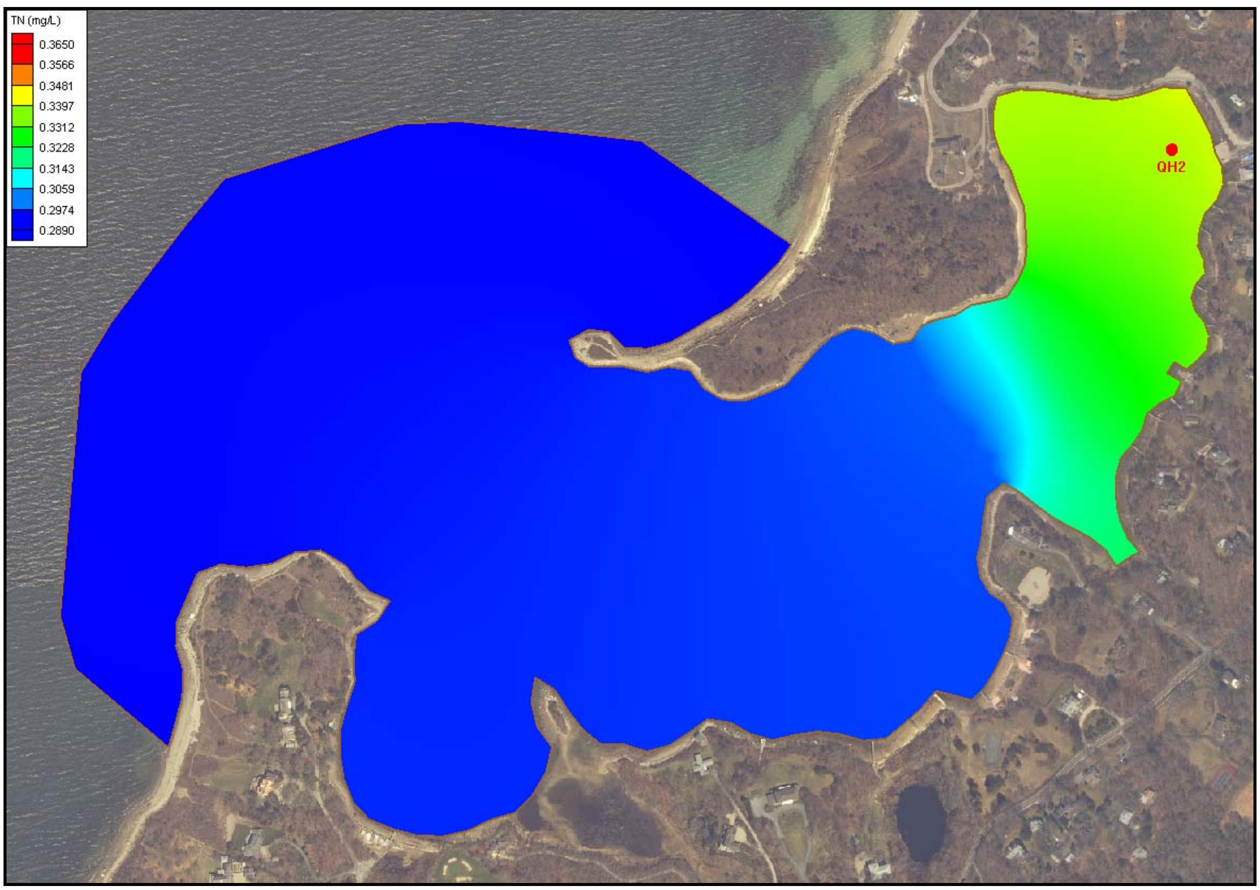

Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Quissett Harbor estuary, for threshold conditions. Threshold station is shown (0.34 mg/L at QH2 in the Upper Harbor).

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